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MEASUREMENT, KNOWLEDGE, AND REPRESENTATION

A Sociological Study of Arctic Sea-Ice Science

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Measurement, Knowledge, and Representation

A Sociological Study of Arctic Sea-Ice Science

Laura Jane Seddon

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Doctor of Philosophy

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Abstract

Satellite-derived observations of Arctic sea ice are instrumental in contemporary sea-ice research. Through the production and dissemination of data products, these observations shape our understanding of Arctic sea-ice conditions, knowledge of which is essential for informing policy responses, decision-making, and action in the face of unprecedented climate change. However, due to the complex, dynamic, and indeterminate nature of sea ice and various scientific and technological challenges involved in its observation, measurement, and representation, the accuracy to which these products depict Arctic sea ice is limited. Moreover, the methodologies used to acquire, process, and report satellite data vary between scientific institutions, resulting in inconsistent estimates of key sea-ice parameters.

Informed by social constructivist arguments developed within science and technology studies and critical cartography, this thesis contends that satellite-derived sea-ice data products represent a particular way of observing, interpreting, and classifying complex geophysical conditions that is socially and culturally contingent. This raises important questions about how sea-ice knowledge is constructed through the interactions between sea ice, sensing technologies, and social practices. Accordingly, this thesis integrates ethnographic and visual methodologies to critically explore how dynamic and indeterminate geophysical data are acquired, processed, and reported in Arctic sea-ice science. By examining sea-ice data products in terms of their underlying practices and technologies, institutional settings, and the broader socio-cultural, political, and historical contexts in which they are embedded, this thesis provides insights into the sociological nature of contemporary sea-ice research. It concludes that greater recognition of the social contingencies shaping how sea-ice data products are generated and disseminated is needed to foster more democratic and socially responsible forms of scientific knowledge. The findings presented in this thesis may provide valuable starting points for critically examining how sea-ice science may be made more equitable and enriched or improved by alternative perspectives.

Table of Contents

Abstract ..... **i**
Table of Contents ..... **ii**
List of Figures ..... **vi**
List of Tables ..... **x**
List of Equations ..... **xii**
List of Abbreviations ..... **xiii**
Acknowledgements ..... **xix**
1. Measuring, Knowing, and Representing Arctic Sea Ice: An Introduction **1**
1.1. Introduction 1
1.2. Satellite Observations of Sea Ice 5
1.2.1. Passive Microwave Satellite Observations of Sea-Ice Parameters 5
1.2.2. Sea-Ice Data Products 10
1.2.3. Uncertainties and Limitations 12
1.3. A Sociological Study of Sea-Ice Science 13
1.3.1. Research Focus, Aim, and Objectives 13
1.3.2. Overview of the Thesis 17
2. Theory and Context **20**
2.1. Introduction 20
2.2. An Overview of Social Constructivism 21
2.3. The Sociology of Science and Scientific Knowledge 23
2.3.1. Challenging the Popular Notions of Science and the Emergence of STS 23
2.3.2. Kuhn's Revolutions 24
2.3.3. The Sociology of Scientific Knowledge and the Strong Programme 27
2.3.4. Studying Science in Context 32
2.3.5. The Turn to Technology 37
2.3.6. Co-production and the Politics of SSK 41
2.3.7. STS and Geography 44
2.4. Critical Cartography 49
2.4.1. Introduction 49
2.4.2. Cartographic Positivism 50
2.4.3. The Critical Turn: Maps as Social Constructions and Expressions of Power 51
2.4.4. Beyond Representation 55

2.5. Conclusion: A Social Constructivist Approach to Arctic Sea-Ice Science 57
3. Studying Sea-Ice Science in Context 61
3.1. Introduction 61
3.2. A Social Constructivist Examination of Sea-Ice Data Products 61
3.3. Research Approach 66
3.3.1. Ethnography 67
3.3.2. Visual Methodologies 70
3.3.3. Integrating Ethnographic and Visual Methodologies 73
3.4. Methods and Materials 73
3.4.1. General Overview 73
3.4.2. Research Settings and Sea-Ice Data Products 74
3.4.3. Stage 1: A Historical Review of Arctic Sea-Ice Science 78
3.4.4. Stage 2: A Critical and Comparative Examination of Sea-Ice Data Products 79
3.4.5. Stage 3: Ethnographic Fieldwork 85
3.5. Research Challenges and Limitations 92
3.5.1. Participant Observation 92
3.5.2. Positionality and Generalisability 93
3.5.3. Methodological Implications of COVID-19 94
3.6. Conclusion 95
4. A History of Scientific Encounters with Arctic Sea Ice 96
4.1. Introduction 96
4.2. Sea Ice as a Barrier 97
4.2.1. An Arctic Eden (Antiquity to the Middle Ages) 97
4.2.2. The Arctic and the Expansion of Early Modern Europe (1500s to 1600s) 99
4.3. Sea Ice as a Habitat and a Resource Frontier 103
4.3.1. Arctic Whaling (1600s to 1800s) 103
4.3.2. Scientific Nationalism and a Frozen Mirage (1700s to 1800s) 108
4.3.3. International Collaboration in Sea-Ice Science (1800s to 1900s) 111
4.4. Sea Ice as a Military Space 117
4.4.1. A Soviet Arctic (Late-1800s to Mid-1900s) 117
4.4.2. The Cold War on Ice (Mid-1900s) 125
4.5. Sea Ice as an Indicator and an Amplifier of Climate Change 130
4.5.1. The Emergence of Climate Science (Mid-1900s) 130
4.5.2. The Satellite Era: Breaking the Polar Observational Barrier (1950s Onwards) 133
4.6. Conclusion 141
5. Sensing and Classifying Arctic Sea Ice 144
5.1. Introduction 144
5.2. Sensing Sea Ice 146
5.2.1. Passive Microwave Radiation and the Electromagnetic Spectrum 147
5.2.2. Microwave Radiation Properties of Sea Ice 151
5.2.3. The Transformation of Radiation Data into Sea-Ice Parameters 156

5.2.4. Uncertainties, Observational Constraints, and Unwanted Signals 157
5.3. Classifying Sea Ice: Constructing Sea-Ice Data Products 160
5.3.1. NSIDC SII 161
5.3.2. OSI-450 SIC v2.0 176
5.3.3. C3S SIE v1.0 and SITy v1.0 191
5.4. Conclusion: Uncertainties, the Absence of 'Truth', and Interpretive Flexibility 199
6. Visualising Arctic Sea Ice: A Critical Examination of Sea-Ice Maps 211
6.1. Introduction 211
6.2. The Cartographic Composition and Discourse of Arctic Sea Ice 213
6.2.1. Map Projection 216
6.2.2. Map Orientation 220
6.2.3. Selection, Symbology, and Silences 226
6.3. Alternative Mappings of Arctic Sea Ice 236
6.3.1. Sea-Ice Extent and the Conventional 'Ice Edge' 236
6.3.2. Results and Discussion 238
6.4. Conclusion: Towards a More Reflexive Sea-Ice Science? 255
7. Sea-Ice Science in a Socio-Cultural Context 257
7.1. Introduction 257
7.2. Product Development: Requirements, Evolution, and Users 258
7.2.1. MET Norway and Climate Research 258
7.2.2. Top-Level Requirements 261
7.2.3. The Constitutive Role of Users 265
7.2.4. Product Evolution and the Niche Effect of Algorithms 268
7.2.5. Networks of Authority and Knowledge Geographies 271
7.3. Credibility, Visibility, and Knowledge Dissemination 274
7.3.1. Sea-Ice Indicators and the Importance of Institutional Visibility 274
7.3.2. Participation, Communication, and Accountability 280
7.4. Politics and Sea-Ice Science 285
7.4.1. The Barents Sea Management Plan: Politicising the 'Ice Edge' 285
7.4.2. Ageing Satellites and a New Era of Satellite Observation 289
7.3. Conclusion 294
8. Conclusions 297
8.1. Introduction 297
8.2. Summary of the Research Purpose and Findings 297
8.3. Research Implications 301
8.4. Avenues for Further Research 304
Appendices 307
Appendix 1: References to and applications of the data products 307
Appendix 2: List of Satellite-Sensors and Associated Characteristics 311
Appendix 3: List of Documents Analysed 314
Appendix 4: R-Shiny Code 318

Appendix 5: Python Code 322
Appendix 6: Producing NSIDC Alternative Maps in ArcPRO 323
Appendix 7: Information Sheet 326
Appendix 8: MET Norway Intercomparison Project 328
Appendix 9: Observational Questions 374
Appendix 10: Interview Questions 375
Appendix 11: Interview Consent Form 377
Appendix 12: Sea-Ice Extent Differences 379
Appendix 13: Institutional Networks 382
Appendix 14: Online Responses to NSIDC Error 385
References 387

List of Figures

Figure 1.1.: Example sea-ice data product outputs showing Arctic sea-ice conditions 3

Figure 1.2.: A screenshot taken on Friday 29th October of a banner featured on the Guardian's home webpage in the days leading up to the UN Climate Conference (COP26) 4

Figure 1.3.: Illustrated definitions of sea-ice concentration, area, and extent. 6

Figure 1.4.: A map of the Arctic Ocean showing colour-coded, daily-average brightness temperatures captured at the vertically polarised microwave frequency channel of 19 GHz, on 1st April 2016. 8

Figure 1.5.: Flow diagram showing the key processes involved in determining sea-ice concentration, area, and extent measurements from brightness temperatures (K) retrieved using passive microwave satellite sensors. 9

Figure 1.6.: Arctic and Antarctic sea-ice extent values calculated from different sea-ice data products, 2015-2017. 13

Figure 3.1.: Continuum of participant observation roles. 68

Figure 3.2.: The sites, modalities, research questions, and methods for a critical visual methodology framework. 72

Figure 3.3.: EUMETSAT member and cooperating states. 76

Figure 3.4.: R ShinyApp online web application developed to present the Alternative Mappings of Arctic Sea-Ice Extent. 85

Figure 3.5.: An example of a code map developed to analyse the data collected during the participant observation carried out at MET Norway. 91

Figure 4. 1.: Maps of the Arctic produced during the European Age of Exploration. 102

Figure 4.2.: Sample maps from the Arctic Climate System Study (ACSYS) Historical Ice Chart Archive. 103

Figure 4.3.: The locations of sea-ice observations made from whaling ships during a) May, b) July, and c) September, in the 1850s. 106

Figure 4.4.: Map of the locations of the principal research stations of the first IPY, 1882-83. 113

Figure 4.5.: Fram expedition track 116

Figure 4.6.: An example ice chart produced by the Arctic Institute and compiled by the NSIDC from August 1933. 121

Figure 4.7.: An example of a sea-ice chart 'The State of the ice in the Arctic Seas', compiled by the Danish Meteorological Institute for June 1924. 124

Figure 4.8.: Radar imagery of the T1 ice island, captured during reconnaissance flights of the U.S. Air Force, January 1952. 127

Figure 4.9.: TIROS 2 photographs of sea ice, Natashquan Point area, January 1961. 135

Figure 4.10.: Example average-monthly sea-ice concentration maps, derived from Nimbus-7 SMMR imagery for March and September 1984-86. 139

Figure 4.11.: Monthly September sea-ice extent, 1979-2021. 141

Figure 5.1.: Electromagnetic spectrum. 147

Figure 5.2.: Typical atmospheric transmissivity of the atmosphere at different humidity levels (dry, polar, midlatitude, and tropical) and microwave frequencies.. 149

Figure 5.3.: A vertically polarised electromagnetic wave.. 150

Figure 5.4.: An example of the different brightness temperatures captured using the Nimbus-7 SMMR sensor at a 1.7 cm microwave wavelength (approximately 18 GHz frequency) for different polarisations.. 150

Figure 5.5.: Typical emissivity signatures of first-year ice, multi-year ice, and open water obtained at various microwave frequencies and vertical and horizontal polarisations. 153

Figure 5.6.: A schematic diagram depicting the typical emissivity characteristics of first-year and multi-year sea-ice types in relation to their changing physical and chemical properties throughout the year. 155

Figure 5.7.: Example brightness temperature scatterplots obtained by the DMSP SSM/I satellite-sensor over the Arctic Ocean on 11th March 1988. 157

Figure 5.8.: Different development stages of sea ice: (a) grease ice, (b) nilas ice, (c) pancake ice, (d) pack ice, (e) meltwater ponds on the pack ice, and (f) hummocks. 159

Figure 5.9.: NSIDC SII example outputs. 163

Figure 5.10.: GSFC dataset processing sequence and main contributors. 165

Figure 5.11.: Example polarisation and gradient ratios for brightness temperatures obtained from 28th February 2018 using the DMSP-F18 SSMIS satellite-sensor. 168

Figure 5.12.: Time series showing the jump in brightness temperatures obtained at 18/19 GHz vertically (a) and horizontally (b) polarised channels following the switch from the SMMR to SSM/IS sensor in 1987. 169

Figure 5.13.: NSIDC SII processing chains for the final GSFC subset of the product. 174

Figure 5.14.: Example sea-ice concentration image derived using the OSI-450 SIC data product. 178

Figure 5.15.: Example sea-ice extent and area data outputs from the OSI SAF Sea Ice Index v2.1. 179

Figure 5.16.: OSI-450 SIC processing sequence and main contributors. 181

Figure 5.17.: OSI-450 SIC Level 1-4 processing chains. 181

Figure 5.18.: (a) Bootstrap polarisation mode for brightness temperatures captured at 37v and 37h GHs. (b) Bootstrap frequency mode for example brightness temperatures captured at 37v and 19h GHz. (c) An illustration of the geometric approach used to calculate sea-ice concentration. 185

Figure 5.19.: A 3D representation of the SICCI2 algorithm showing the projected brightness temperatures for 37v, 37h, and 19v GHz channels.. 187

Figure 5.20.: Example images for the C3S SIE and SITy data products. 192

Figure 5.21.: C3S SIE and SITy processing sequence and main contributors. 195

Figure 5.22.: OSI-450 SIC Level 1-4 processing chains. 195

Figure 5.23.: Example images of ice cover fractions. 204

Figure 5.24.: Example U.S. National Ice Center sea-ice chart, produced for 2nd September 2021. 206

Figure 5.25.: Example Norwegian Ice Service sea-ice chart, produced for 2nd September 2021, and underlying Seninel-1 data used in the production of the ice chart. 207

Figure 6.1.: NSIDC SII maps. 214

Figure 6.2.: OSI-450 SIC daily sea-ice concentration map for 1st March 2015. 215

Figure 6.3.: C3S SIE daily sea-ice edge map and C3S SITy daily sea-ice type map for 1st March 2015. 215

Figure 6.4.: Polar stereographic projection types. 218

Figure 6.5.: The different projection types that define the EASE-Grid 2.0. 219

Figure 6.6.: Examples of early sea-ice concentration maps produced by GSFC researchers and archived by the NSIDC. 223

Figure 6.7.: Sea-ice concentration maps orientated at 45°, 90°, and 180° E. 225

Figure 6.8.: Examples of C3S SITy and SIE maps produced in the Python programming software, PyCharm, using a selection of pre-defined colour palettes. 230

Figure 6.9.: NSIDC SII sea-ice extent and sea-ice concentration data mapped onto NASA's Blue Marble images. 234

Figure 6.10.: Derivation of sea-ice extent based on a 15% sea-ice concentration threshold, illustrated at grid cell level with a spatial resolution of 25 km x 25 km. 237

Figure 6.11.: Monthly Arctic sea-ice extents from 1979 to 2019, calculated using sea-ice concentration thresholds of 15%, 30%, 50%, and 60%.. 239

Figure 6.12.: Monthly differences between sea-ice extent values calculated using sea-ice concentration thresholds 30%, 50%, and 60% and the conventional 15% threshold. 240

Figure 6.13.: Monthly sea-ice extent maps for August 2017, produced using sea-ice concentration thresholds of 15%, 30%, 50%, and 60%. 241

Figure 6.14.: Differences in monthly-averaged sea-ice extent values calculated using 15%, 30%, 50%, and 60% sea-ice concentration thresholds, for each month of the year between 1979 and 2019. 244

Figure 6.15.: Monthly sea-ice extent map showing the different locations of the sea-ice edges derived using sea-ice extent thresholds at 15%, 30%, 50%, and 60% for August 2016. 245

Figure 6.16.: An example sea-ice extent map whereby the different 'ice edges' either permit or block maritime travel along the sea routes.. 247

Figure 6.17.: Monthly sea-ice extent map showing the different locations of the 'sea-ice edges' derived using sea-ice extent thresholds at 15%, 30%, 50%, and 60% for September 2016. 249

Figure 6.18.: Sea-ice extent trends for March and September between 1979 and 2019, calculated using sea-ice concentration thresholds at 15%, 30%, 50%, and 60%. 251

Figure 6.19.: The different timings of the first ice-free summer based on the sea-ice extent trends for September between 1979 and 2019, calculated using sea-ice concentration thresholds at 15%, 30%, 50%, and 60%. 253

Figure 6.20.: Sea-ice extent trends for August and September between 1979 and 2019, calculated using sea-ice concentration thresholds at 15%, 30%, 50%, and 60%. 254

Figure 7.1.: Institutional framework supporting the OSI-450 SIC data product. 260

Figure 7.2.: Institutional framework supporting the C3S data products. 261

Figure 7.3.: Knowledge geographies of the OSI-450 SIC and C3S data products, based on the institutional affiliations of the authors referenced in the associated documentation. 272

Figure 7.4.: Monthly Arctic sea-ice extent anomalies for September and March, 1979-2019, relative to 1981-2010 averages. 276

Figure 7.5.: NSIDC's erroneous reporting of Arctic sea-ice extent on 25th February 2021. . 283

Figure 7.6.: Sea-ice frequency used to mark the 'ice edge' in the Barents Sea. 287

List of Tables

Table 1.1.: Example sea-ice data products developed using passive microwave satellite-derived observations. ... 11

Table 2.1.: Features of 'artistic' and 'scientific' maps. ... 51

Table 2.2.: Elements of the 'paramap'. ... 56

Table 3.1.: Different research frameworks and their corresponding ontologies, epistemologies, purposes, and types. ... 65

Table 3.2.: Summary of the four sea-ice data products examined in this thesis. ... 78

Table 3.3.: List of questions guiding document analysis. ... 81

Table 3.4.: List of questions guiding cartographic analysis. ... 83

Table 4.1.: Sample of research papers from the US scientific activities in the Arctic during the 1950s and 1960s. ... 128

Table 5.1.: Typical emissivity signatures for different ice types in the Arctic, measured at various microwave frequencies and vertical and horizontal polarisations. ... 152

Table 5.2.: The general processing sequence common to the four sea-ice data products... 161

Table 5.3.: The frequency channels and corresponding sampling grid cell resolution used by the NASA Team algorithm. ... 167

Table 5.4.: Gradient ratios used in the application of a weather filter. ... 169

Table 5.5.: NASA's Earth Observing System Data and Information System data processing levels. ... 182

Table 5.6.: List and descriptions of the key variables included in the final OSI-450 SIC data product. ... 191

Table 5.7.: Main differences between the climate and operational NRT versions of the SIE and SITy data products. ... 194

Table 5.8.: The satellite-sensors, frequency channels, and corresponding sampling grid cell resolution used to produce the C3S SIE and SITy. ... 197

Table 5.9.: List and descriptions of the key variables included in the final C3S data products. ... 199

Table 5.10.: The main methodological differences of the NSIDC SII, OSI-450 SIC, and C3S SIE and SITy data products. ... 201

Table 6.1.: Map characteristics and variables of the four sea-ice data products. ... 227

Table 6.2.: The top ten dates where the different thresholds yield the greatest differences in monthly sea-ice extent values. ... 242

Table 7.1.: GCOS ECV target requirements for sea-ice concentration, extent, and edge parameters 263

Table 7.2.: EUMETSAT OSI SAF and Copernicus C3S data product requirements 264

Table 7.3.: Gross domestic spending on research and development in 2019. 274

Table 7.4.: Timelines of passive microwave satellite remote sensing instruments that provide, or have to potential to provide, observations of sea-ice cover. 290

List of Equations

Equation 1 148
Equation 2 166
Equation 3 166
Equation 4 166
Equation 5 186
Equation 6 196

List of Abbreviations

ACSYS	Arctic Climate System Study
AMSR-E	Advanced Microwave Scanning Radiometer-Earth Observing System (US instrument)
AMSR2	Advanced Microwave Scanning Radiometer 2 (Japanese instrument)
ANT	Actor-Network Theory
ARLIS	Arctic Research Laboratory Ice Stations
ASINA	Arctic Sea Ice News and Analysis (NSIDC, US)
BFM	Bootstrap algorithm, frequency mode
BRI	Bristol algorithm
C3S	Copernicus Climate Change Service (Europe)
C3S SIE	Sea-Ice Edge (C3S data product)
C3S SITy	Sea-Ice Type (C3S data product)
CDOP	Continuous Development and Operations Phase (OSI SAF, Europe)
CIRES	Cooperative Institute for Research in Environmental Sciences (US)
CMA	China Meteorological Agency (CMA)
CPG	Critical Physical Geography
DMI	Danish Meteorological Institute
DMSP	Defense Meteorological Satellite Program (US)
DoD	Department of Defence (US)
EASE-Grid 2.0	Equal-Area Scalable Earth 2
EC	European Commission
ECMWF	European Centre for Medium-Range Weather Forecasts
EPOR	Empirical Programme of Relativism
ESA	European Space Agency
ESA CCI	European Space Agency Climate Change Initiative
ESA SICCI	European Space Agency Sea Ice Climate Change Initiative
ESMR	Electronically Scanning Microwave Radiometer (US instrument)
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
FAR	First Assessment Report (IPCC)

FCDR	Fundamental Climate Data Record
FTP	File Transfer Protocol
GCM	Global Climate Model
GCOM-W	Global Climate Observing Mission-Water (JAXA satellite mission, Japan)
GCOS	Global Climate Observing System
GFDL	Geophysical Fluid Dynamics Laboratory (US)
GR	Spectral Gradient Ratio
GSFC	Goddard Space Flight Center (NASA)
GUSMP	Glavsevmorput', the Main Administration of the Northern Sea Route (Soviet Union)
HL	High Latitude (division of OSI SAF hosted by MET Norway and DMI)
ICES	International Council for Exploration of the Seas
IGY	International Geophysical Year
IPCC	Intergovernmental Panel on Climate Change
IPY	International Polar Year
JAXA	Japan Aerospace Exploration Agency
LTS	Large-Scale Technological Systems
MET Norway	Norwegian Meteorological Institute
MODIS	Moderate-Resolution Imaging Spectroradiometer (US instrument)
MSIZ	Marginal Sea Ice Zone
NASA	National Aeronautics and Space Administration (US)
NCAR	National Center for Atmospheric Research (US)
NEP	Northeast Passage
NHO	U.S. Navy Hydrographic Office (US)
NMI/MET Norway	Norwegian Meteorological Institute (Norway)
NOAA	National Oceanic and Atmospheric Administration (US)
NRTSI	Near-Real-Time Sea-Ice Concentrations (NSIDC data product)
NSAU	National Space Agency of Ukraine (Ukraine)
NSC	National Security Council (US)
NSIDC	National Snow and Ice Data Center (US)
NSIDC SII	Sea Ice Index (NSIDC data product)
NSOAS	National Satellite Ocean Application Service (China)
NSR	Northern Sea Route
NWP	Northwest Passage
OSI SAF	Ocean and Sea Ice Satellite Application Facility (EUMETSAT facility)
OSI-450 SIC	Sea-Ice Concentration (OSI SAF data product)

PR	Polarisation ratio
Roscosmos	Russian Federal Space Agency (Russia)
RSS	Remote Sensing Systems Inc. (US)
RTM	Radiation Transfer Model
SCOT	The Social Construction of Technology
SICCI2	SICCI hybrid sea-ice concentration algorithm (used by OSI SAF)
SIPRE	Snow, Ice, and Permafrost Research Establishment (US)
SMMR	Scanning Multi-channel Microwave Radiometer (US instrument)
SSK	Sociology of Scientific Knowledge
SSM/I	Special Sensor Microwave Imager (US instrument)
SSMIS	Special Sensor Microwave Imager and Sounder (US instrument)
SST	Sea Surface Temperature
STS	Science and Technology Studies
TB	Brightness Temperature
TIROS	Television Infrared Observation Satellite
WDC	World Data Center
WMO	World Meteorological Organisation

The copyright of this thesis rests with the author. No quotation from it should be published without the author's prior written consent and information derived from it should be acknowledged.

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For Mum and Dad

[T]he most objective view we can achieve will rest on an unexamined subjective base.

- Thomas Nagel, *The View from Nowhere* (1986: 68)

1. Measuring, Knowing, and Representing Arctic Sea Ice: An Introduction

1.1. Introduction

In August 2021, the Intergovernmental Panel on Climate Change (IPCC) issued the first part of the Sixth Assessment Report (AR6), *Climate Change: The Physical Science Basis* (IPCC, 2021). The report conveyed a sombre message: observed changes in the global climate system are rapid, intensifying, unprecedented, and will have far-reaching and catastrophic implications unless society takes urgent mitigative and adaptive action. While the effects of climate change are already being experienced globally, the IPCC report stresses that these are amplified in the Arctic. Over the past fifty years, the Arctic has warmed at approximately 2-3 times the global rate, leading to transformational changes in terrestrial snow cover, permafrost, land ice (glaciers and ice sheets), regional weather patterns, flora and fauna, and sea ice (AMAP, 2021; WMO, 2021). These changes in the Arctic have significant global implications. To recite a widely used statement: "what happens in the Arctic does not stay in the Arctic".

Declines in Arctic sea-ice cover represent one of the most prominent changes. Satellite observations captured since the late 1970s show unprecedented reductions in the spatial extent and distribution of sea ice across all seasons (Gloersen *et al*., 1993; Cavalieri *et al*., 2012; Stroeve *et al*., 2012; WMO, 2021). The characteristics of Arctic sea ice are also changing, with thicker and older ice being replaced by thinner, weaker, and more ephemeral ice-types (Kwok, 2018). These changing characteristics increase the susceptibility of sea ice to melting. Based on these observations, the IPCC predict the Arctic will experience at least one ice-free summer before 2050 (IPCC, 2021).

The loss of sea ice has the potential to elicit profound climatic, ecological, and societal consequences that transcend local to global scales. In the context of the climate system, sea-ice decline serves as both an indicator and an amplifier of change. The presence of sea ice plays a vital role in modulating atmospheric and oceanic exchanges (e.g., Chylek

et al., 2009; Perovich *et al*., 2007, 2011), Earth's surface albedo (e.g., Flanner *et al*., 2011; McPhee, 2017), and oceanic circulation (e.g., Kilworth, 1983; Cottier *et al*., 2017). Variation in the seasonality and extent of sea ice has been associated with changes in mid-latitudinal weather patterns (Coumou *et al*., 2018). Changing sea-ice characteristics present a significant threat to the Arctic's rich marine ecosystem, which relies upon sea ice as a habitat, a shelter, a hunting ground, and a place for reproduction (CAFF, 2017; Kovacs *et al*., 2021). For Indigenous communities living in the Arctic, sea-ice loss threatens the security of their culture, livelihoods, and well-being (Durkalec *et al*., 2015). At the same time, receding ice cover presents new economic and political opportunities around the growing viability of trans-Arctic sea routes and prospects for increased commercial access to oil, gas, and other natural resources (Bird *et al*., 2008; Ng *et al*., 2018; Lasserre and Faury, 2019).

Continued monitoring and effective reporting of sea-ice conditions are paramount to advancing knowledge of the spatial and temporal distribution of sea ice and is essential to informing appropriate action, decision-making, and policy responses (Grosfeld *et al*., 2016; GCOS, 1992, 2018). Scientific institutions worldwide are involved in measuring, managing, and communicating Arctic sea-ice data. Data on sea-ice properties are obtained through various *in situ* and remote sensing observational methods, with satellites taking precedence (Tedesco, 2015). Through visual and numerical outputs, sea-ice data products are the primary means by which observations of sea ice are transformed into meaningful knowledge and disseminated to various audiences (Figure 1.1). However, due to challenges around the observation and measurement of sea ice, as well as the transient and indeterminate nature of sea ice, the knowledge these products provide is characterised by many uncertainties and limitations.

Arctic sea ice is exceptionally complex, dynamic, and indeterminate: it covers a vast area, it is characterised by extreme seasonal signatures, it is constantly in motion in response to wind and ocean currents, and it differs substantially in material form through space and time. Moreover, as alluded to above, sea ice holds diverse meanings and functions depending on the circumstances in which it is encountered and by whom (Steinberg and Kristoffersen, 2017). These characteristics present challenges to observing sea ice and complicate attempts to measure and define it, compounded further by the Arctic's extreme climate and long periods of darkness. They also raise essential questions about how sea-ice data products, such as those shown in Figure 1.1, are created: What practices and technologies enable sea ice to be measured on daily timescales and on these vast spatial scales? How are the complexities of sea ice managed? What processes and decisions are involved in simplifying, translating, and stabilising sea-ice characteristics in ways that can be projected into quantitative and cartographic visualisations that are used for informing public and policy? What elements of the Arctic Ocean are selected or

omitted in these static and simplified representations? Who participates in constructing these products?

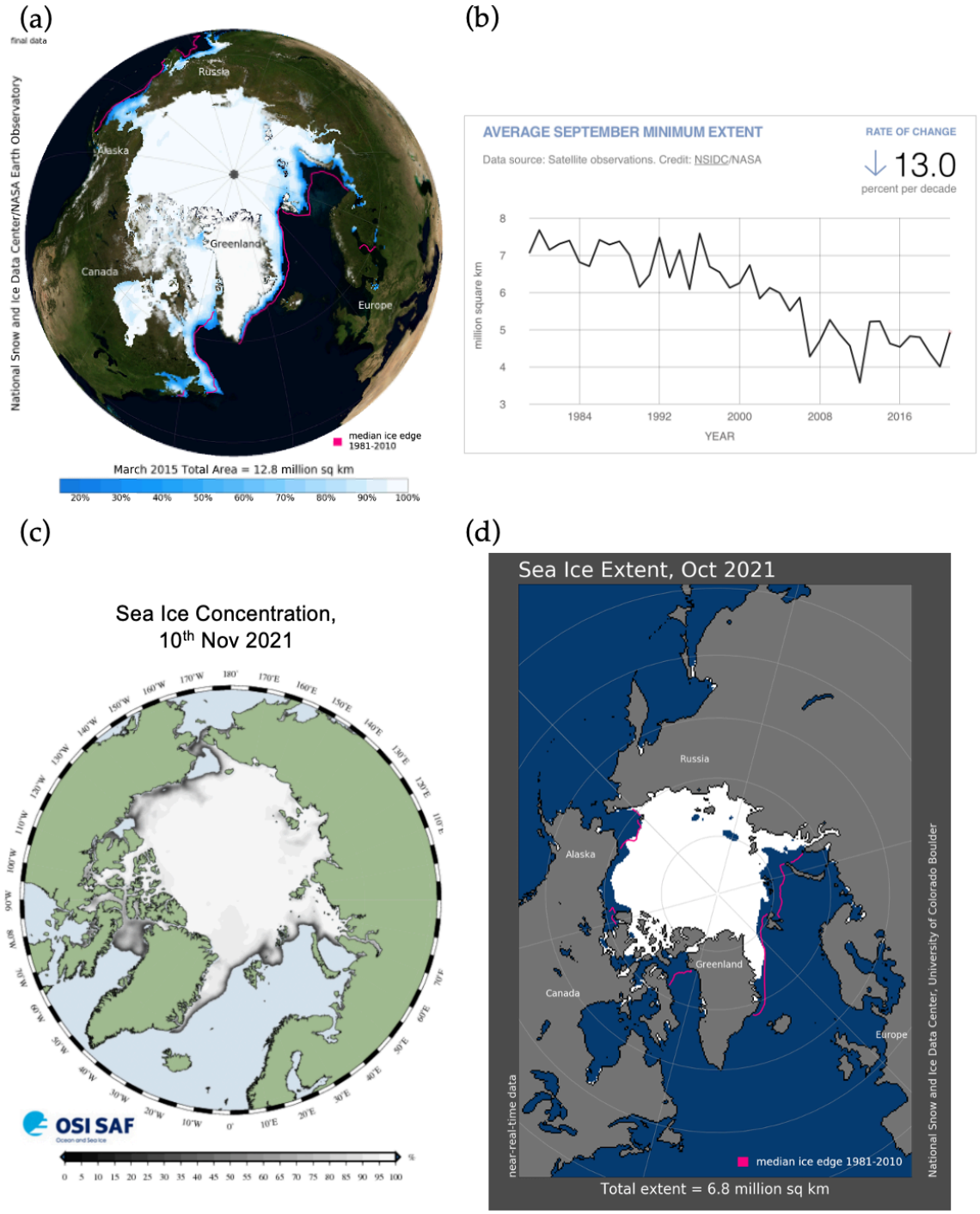


Figure 1.1.: Example sea-ice data product outputs showing Arctic sea-ice conditions: (a) NSIDC Sea Ice Index, monthly sea-ice concentration map for March 2015; (b) NSIDC/NASA average September sea-ice extent minimum time series, 1979-2020; (c) OSI SAF daily sea-ice concentration map for 10th November 2021; (d) NSIDC Sea Ice Index, monthly sea-ice extent map for October 2021. *Sources:* the National Snow and Ice Data Center/NASA Earth Observatory; the Ocean and Sea Ice Satellite Application Facility; Fetterer *et al.* (2017).

With escalating concerns over the implications of sea-ice decline, data products like those shown in Figure 1.1 are evermore present in the media, high-level scientific reports, and online spaces.[1] A recent and notable example of the media reporting of sea ice occurred during the lead up to the 2021 United Nations Climate Change Conference of the Parties (COP26). In the days prior to the conference, the Guardian's home webpage featured a time series of Arctic sea-ice data on a banner titled "Climate crisis data" (Figure 1.2). The inclusion of Arctic sea-ice data over other climate change indicators (e.g., temperature change, sea-level rise, hurricane activity) indicates the significance attached to sea ice in climate change discourse.

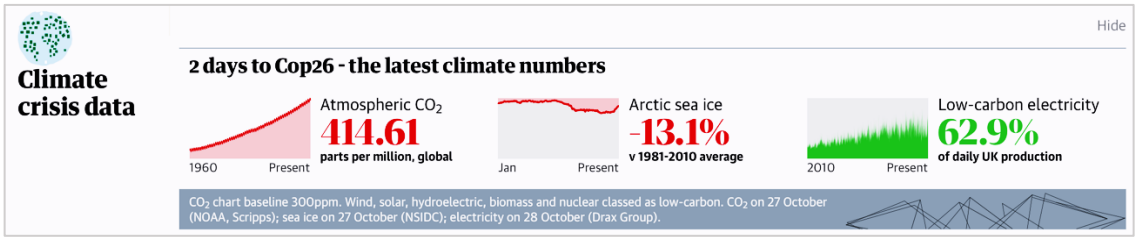


Figure 1.2.: A screenshot taken on Friday 29th October of a banner featured on the Guardian's home webpage in the days leading up to the UN Climate Conference (COP26). This same banner featured on the UK and US editions. *Source:* https://www.theguardian.com/uk?INTCMP=CE_UK

Through these various means of communication, these scientific products shape our knowledge of Arctic sea ice, enable us to visualise complex changes, inform policies, and help us predict, imagine, and prepare for future scenarios. Crucially, however, they also place limits on what can be known: by giving order to the complexities of sea ice, these products shape and structure what aspects of the Arctic are seen and how the region is perceived, interpreted, and acted upon. The wide circulation of sea-ice data products and their ubiquity in broader climate change discourse means that we have become used to seeing and understanding the Arctic through these highly conventionalised, simplified, and scientific forms of representation. This familiarity means that we often accept these products with little critical contemplation about the circumstances involved in their production or the socio-political and cultural possibilities they permit or constrain. Given that relatively few people inhabit the Arctic, and even fewer encounter sea ice directly, for many, these scientific products appear as seemingly objective and authoritative accounts of Arctic sea ice.

Motivated by the above questions and issues, the research carried out in this thesis attempts to better understand how scientists produce and disseminate knowledge about Arctic sea ice. Informed by some of the parallel and converging ideas from the fields of science and technology studies (STS) and critical cartography, this research adopts a social constructivist approach to interrogate and compare the dominant scientific

[1] A list of examples is presented in Appendix 1.

practices used to measure, represent, and communicate Arctic sea ice. The thesis begins with the central assumption that scientific practice can be understood as the product of a complex interplay between nature, science, and the interests of society. The main interconnected implications of this assumption are: 1) scientific knowledge is never wholly objective or neutral; 2) scientific knowledge is socially shaped: it is the product of a particular set of practices and relations that are *situated* within specific social and cultural contexts; 3) scientific knowledge about a particular phenomenon is neither inevitable nor fixed; and 4) scientific knowledge reflects and reinforces particular perspectives, interests, and values while marginalising others (Bloor, 1991; Haraway, 1988; Golinski, 1998; Hacking, 1999; Jasanoff, 2004a; Jasanoff and Martello, 2004; Harding, 1991, 2015).

In adopting a social constructivist perspective in the study of sea-ice science, this thesis aims not to deny the reality of sea-ice decline nor undermine the overall purpose of sea-ice data products. Instead, the focus is on exploring how our knowledge of Arctic sea ice is shaped by interactions between sea ice, sensing technologies, and social practices during the construction and dissemination of sea-ice data products. The following sections develop these themes further by introducing the dominant satellite-based approaches used for measuring and reporting key sea-ice parameters and reviewing some of the main uncertainties and limitations involved. Following this, the chapter presents the research focus, aim, objectives, and agenda before concluding with an outline of the thesis structure.

1.2. Satellite Observations of Sea Ice

1.2.1. Passive Microwave Satellite Observations of Sea-Ice Parameters

The importance of Arctic sea ice as a dynamic, interactive, and amplifying component of the Earth's climate system has long been recognised and documented through climate modelling, proxy-based reconstructions, and statistical analyses (e.g., Manabe and Souffer, 1980; Maykut, 1978, 1986; Crane, 1981; Parkinson *et al*., 1987; Gloersen *et al*., 1999; Cavalieri and Parkinson, 2012; Notz 2020). Several sea-ice parameters have been identified as key indicators of changes in Arctic sea-ice cover, and their continued observation and monitoring are of utmost importance for understanding crucial feedbacks in the global climate system (GCOS, 1992). These parameters include sea-ice concentration, area, extent, and type, among various others.

Sea-ice concentration refers to the fractional coverage of sea ice over a given area, usually expressed as a percentage. Sea-ice concentration is a particularly important determinant of ocean-surface albedo and energy and gas exchanges between the ocean and the atmosphere (Crane, 1981; Notz, 2020). It also forms the basis of sea-ice area and sea-ice extent – two important measures of the spatial and temporal distribution of sea-ice cover.

Sea-ice area is defined as the portion of a particular area covered in sea-ice, expressed in square kilometres. It is calculated by multiplying sea-ice concentration by the total area. *Sea-ice extent* is usually a binary measure indicating the area of the ocean covered in sea ice above a certain concentration threshold, usually 15%. Thus, in contrast to sea-ice concentration and sea-ice area, sea-ice extent defines a region as simply 'ice-covered' or 'ice-free' depending on whether the concentration exceeds or falls short of the threshold, and it is expressed in square kilometres. Figure 1.3 illustrates these definitions and the important differences between them.

Sea-ice type differs from the previous three indicators in that it is a classification that differentiates between *first-year* and *multi-year* ice. Knowledge of ice-type distribution is important for understanding changes in the seasonality and the geophysical composition and structure of the ice (Kwok, 2018).

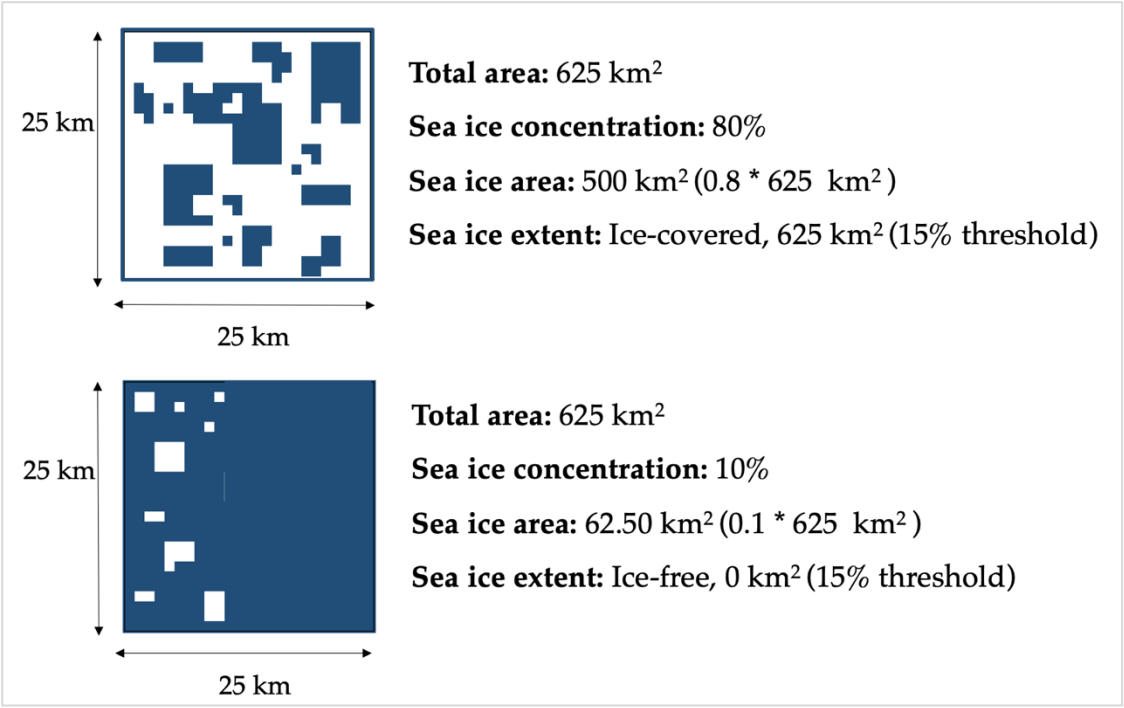


Figure 1.3.: Illustrated definitions of sea-ice concentration, area, and extent. Sea ice is represented schematically by white and ocean surface by blue.

Due to the Arctic's extreme climate, dark winters, and the exceptionally mobile and expansive nature of sea ice, *in situ* ground- or ocean-based measurements are spatially and temporally sparse. Thus, the continued observation and monitoring of sea-ice parameters rely upon remote sensing techniques that enable the study of Earth/ocean surface processes and phenomena without the need for direct contact with the object(s) under examination (Tedesco, 2015). Advances in satellite remote sensing technologies have rendered the most inaccessible and extreme places amenable to scientific observation. In particular, the development and implementation of polar-orbiting

satellite passive microwave radiometers (PMRs) during the 1970s transformed the observational capabilities of sea-ice research.

PMR satellite technologies are particularly advantageous over other methods of observation due to an essential characteristic: they can retrieve surface observations irrespective of the amount of cloud cover and solar illumination (Meier and Markus, 2015). Since the late 1970s, PMRs have consistently acquired Arctic sea-ice observations on a near-continuous basis. A series of different PMRs have operated during this period; Appendix 2 lists the satellite-sensors and details their associated characteristics. Except for a small gap at the North Pole, known as the Pole Hole, these satellite-sensors have provided a complete coverage of the Arctic Ocean every 24 hours.[2] The observations obtained through these sensing technologies represent one of the longest, most consistent climate data records available, enabling scientists to analyse sea-ice variability on seasonal, interannual, and decadal timescales (e.g., Cavalieri and Parkinson, 2012; Stroeve and Notz, 2018). Prior to satellites, ocean-wide measurements of Arctic sea ice were virtually non-existent. Historical observations (pre-satellite) were obtained from aircraft and ground- and ship-based *in situ* measurements. Recorded observations of Arctic sea-ice extent have appeared in ship logbooks, diaries, hand-drawn maps, and whaling records since the sixteenth century. Recent efforts have collated and digitised these records to support the analysis of the longer-term variability in sea-ice conditions and extend the temporal context of recent trends beyond the past few decades (e.g., ACSYS, 2003; Divine and Dick, 2006; Walsh *et al*., 2017). However, although the frequency and spatial coverage of these records increases significantly with time, as maritime travel in the Arctic became more desirable and viable, they remain spatially and temporally sporadic.

Notably, the observations acquired using passive microwave sensors are not direct measurements of sea ice. PMRs measure the microwave radiation naturally emitted by the surface – known as the *brightness temperature* – from which information about sea-ice conditions can be estimated using empirically-based algorithms (Tedesco, 2015). The brightness temperature of a surface varies significantly depending on its physical and chemical properties (Eppler *et al*., 1992). Although there is some variability between ice characteristics, sea ice generally emits greater amounts of microwave radiation than open water and has a higher brightness temperature signature (Figure 1.4). As Chapter 5 explores in more detail, this contrast in brightness temperatures forms the theoretical basis underpinning passive microwave satellite observations of sea ice.

Sea-ice retrieval algorithms exploit varying brightness temperature signatures to calculate sea-ice concentration, area, and extent and differentiate between ice types. The data obtained using passive microwave sensors are usually converted and processed

[2] Early sensors (1978-1987) operated on a bi-diurnal basis. See Appendix 2.

using *gridded data fields*. These fields organise the data into discrete cells (or pixels) that correspond to specific areas on the ocean surface. The size of each grid cell is determined by the characteristics of the satellite sensor and the resolution at which it senses the surface; for PMR observations, the data are usually mapped to grid cells with a spatial resolution ranging between 39 and 625 km^2. Each grid cell represents the average brightness temperature measured over a 24-hour period, which is subsequently transformed into sea-ice parameters using retrieval algorithms. This process is represented schematically in Figure 1.5 for sea-ice concentration, area, and extent.

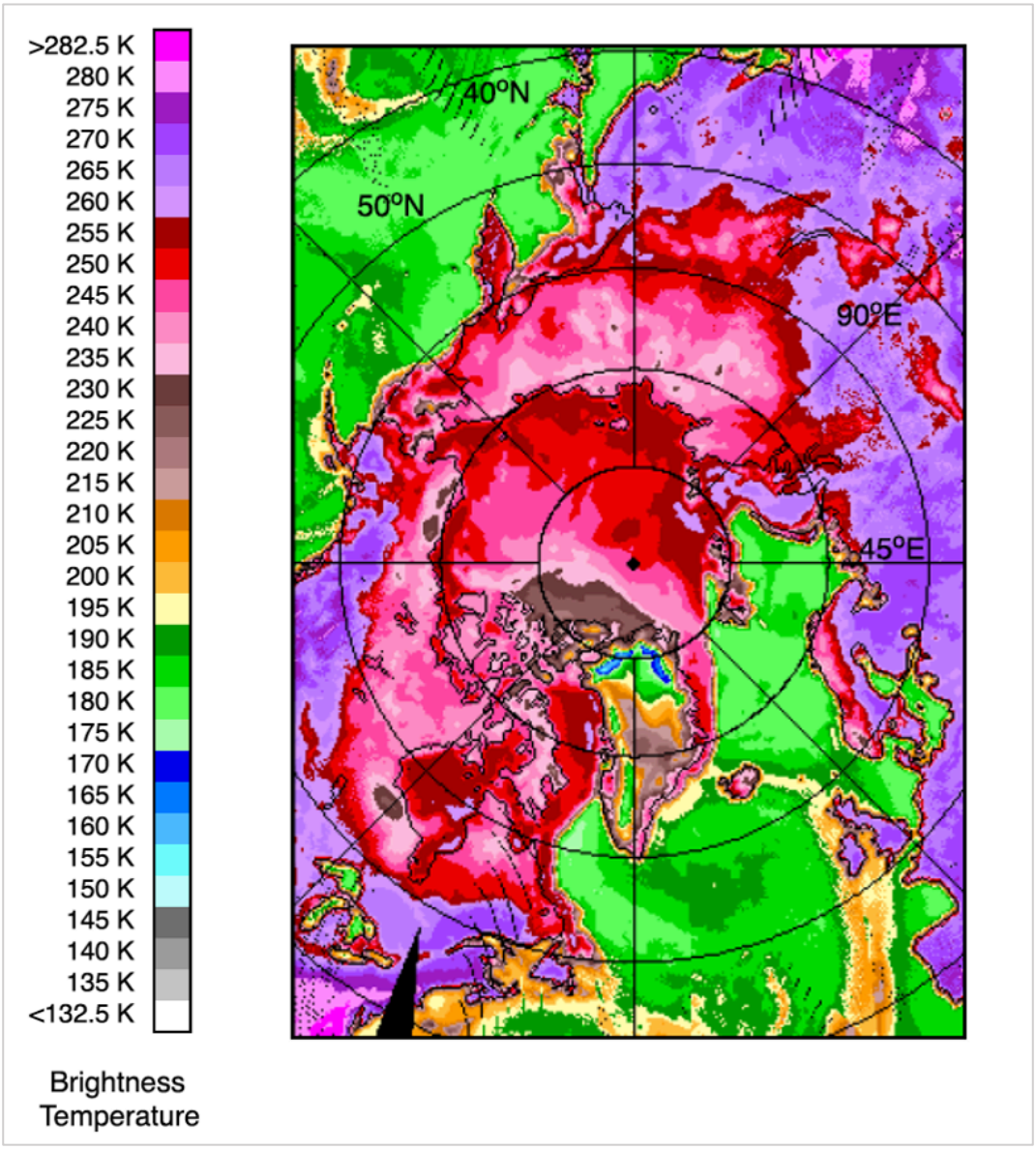


Figure 1.4.: A map of the Arctic Ocean showing colour-coded, daily-average brightness temperatures captured at the vertically polarised microwave frequency channel of 19 GHz, on 1st April 2016. The ice-covered portions of the ocean have higher brightness temperatures and are shown in shades of pink. The open water areas have lower brightness temperatures and are shown in shades of green. *Source*: Comiso *et al*. (2017).

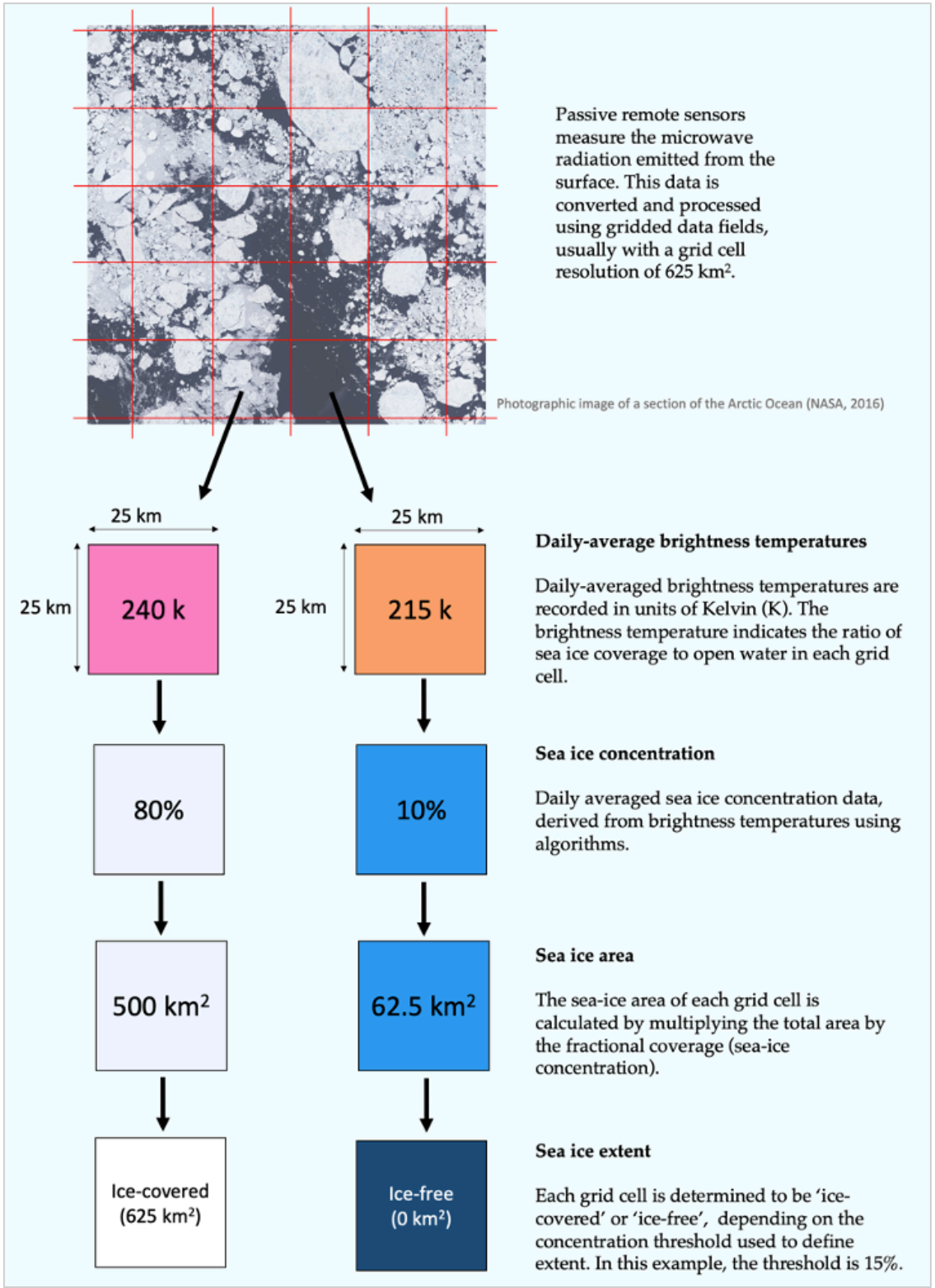


Figure 1.5.: Flow diagram showing the key processes involved in determining sea-ice concentration, area, and extent measurements from brightness temperatures (K) retrieved using passive microwave satellite sensors. The values shown here correlate with Figure 1.3 to illustrate the processes involved prior to defining the sea-ice parameters. Note that the values and symbols used here are purely indicative and not precise measurements of sea-ice conditions.

1.2.2. Sea-Ice Data Products

Sea-ice data products are an important means through which scientists report Arctic sea-ice conditions for use in various applications. The climate science community predominantly uses data products derived using PMR satellite technologies for assessing long-term trends and predicting future scenarios (GCOS, 2011; ESA CCI, 2020). They also play an important role in communicating sea-ice conditions to governments, commercial stakeholders, and the public.

Various scientific agencies and institutions contribute to and support scientific research into Arctic sea-ice variability, through which numerous sea-ice data products are developed. Table 1.1 lists some examples of sea-ice data products that are developed using PMR satellite observations. These products encompass various modes of data representation, including time series, maps, and interactive images, most of which are publicly available for viewing and download from data producers' respective websites. The characteristics of sea-ice data products, such as their spatial and temporal coverage and resolution, vary depending on the data source and processing methods used. All the products listed in Table 1.1 are produced on daily timescales with pan-Arctic coverage. Except for the C3S SITy, all products also include observations of Antarctic sea-ice conditions.

Table 1.1.: Example sea-ice data products developed using passive microwave satellite-derived observations. Note that interim data products extend the OSI-450 SIC and C3S data products to the present day.

Product name	*Data producer*	*Reported sea-ice parameter (s)*	*Data source (sensors)*	*Gridded resolution*	*Temporal coverage*	*Data formats*	*Source*
Sea Ice Index (SII), v3.0	National Snow and Ice Data Center (NSIDC)	Sea-ice concentration Sea-ice extent Sea-ice area	SMMR, SSM/I, SSMIS	625 km^2	1979-present	Time series, maps, animations, numerical values, shapefiles	Fetterer *et al*. (2017)
OSI-450 SIC, v2.0	Ocean and Sea Ice Satellite Application Facility (OSI SAF)	Sea-ice concentration Sea-ice extent	SMMR, SSM/I, SSMIS	625 km^2	1979-2015	Time series, maps, numerical values	EUMETSAT OSI SAF (2017)
C3S SIE, v1.0	Copernicus Climate Change Service (C3S)	Sea-ice edge (concentration boundaries)	SMMR, SSM/I, SSMIS	156.25 km^2 & 625 km^2	1979-2015	Data provided for user processing (quick-look data formats are not provided)	C3S (2018)
C3S SITy, v1.0	Copernicus Climate Change Service (C3S)	Sea-ice type	SMMR, SSM/I, SSMIS	156.25 km^2 & 625 km^2	1979-2015	Data provided for user processing (quick-look data formats are not provided)	C3S (2018)
VISHOP, v2.0	Japan Aerospace Exploration Agency (JAXA)	Sea-ice concentration Sea-ice extent	SMMR, SSM/I, AMSR-E, WindSat, AMSR2	100 km^2	1980-present	Time series, maps, animations, numerical values	NiPR (2016)
University of Bremen	University of Bremen	Sea-ice concentration Sea-ice extent	AMSR2 AMSR-E	39 km^2	1979-present	Time series, maps, animations, numerical values	Spreen *et al*. (2008)

1.2.3. Uncertainties and Limitations

Scientists' knowledge of Arctic sea ice has benefitted considerably from the comprehensive and consistent coverage of PMR satellite sensors. Observations derived through this method have been pivotal to detecting the long-term declining trends and have enabled important links between sea ice and the climate system to be identified. However, passive microwave satellite technologies are characterised by various limitations that introduce uncertainties and ambiguities in the measurement and parameterisation of Arctic sea ice. Chapter 5 examines these uncertainties and limitations in detail, and a brief summary is provided below.

Uncertainties in sea-ice retrieval broadly arise due to the inability of current technologies to accurately capture and represent the complex nature of sea ice. A major source of uncertainty is the coarse spatial resolution of passive microwave satellite sensors. Note that Table 1.1 lists the *gridded resolution* of data products. This represents the resolution to which raw satellite observations are aggregated during data processing – a necessary step for *quantifying* sea-ice characteristics. The actual resolution of the observations, known as the *footprint* or *field of view*, is often significantly coarser, ranging up to ~3150 km^2 depending on the sensor characteristics (see Appendix 2). Consequently, the satellites do not resolve small-scale dynamics and localised features (Meier and Markus, 2015). In other words, the measured brightness temperatures represent an integrated signal that can obscure the complexities at the surface and provide a generalised view.

A second major source of uncertainty is atmospheric and oceanic interference. The algorithms used to retrieve sea-ice parameters are based on the fundamental assumption that the measured brightness temperatures are comprised of the combined microwave emissions of open water and sea ice (Meier and Markus, 2015). However, various atmospheric and oceanic features, such as sea-surface roughness and atmospheric water vapour, can complicate the microwave signatures through attenuation and contamination. This *noise* can make it difficult to accurately differentiate between open water and sea ice and quantify the spatial and temporal distribution of sea-ice parameters.

The uncertainties introduced by the coarse spatial resolution and atmospheric and oceanic interference are compounded further by differences in data processing methodologies. Sea-ice data products developed using passive microwave satellite technologies are guided by the same fundamental principles introduced in Section 1.2.2. However, different products and institutions use varied methodologies to process, transform, and represent sea-ice parameters. For instance, more than thirty different algorithms exist for retrieving sea-ice concentration, and different products use varying methods for managing the uncertainties and limitations (Comiso *et al*., 2017; Pedersen *et al*., 2017).

A consequence of the diverging methodologies is that estimates of key sea-ice parameters are not consistent. Between different data producers, the seasonal variability and long-term declining trends are generally consistent; however, absolute values can exhibit substantial variability. Recent studies have demonstrated that differences in data processing methodologies – namely algorithm choice – result in stark differences in sea-ice concentration, area, and extent (e.g., Comiso *et al*., 2017; Meier and Stewart, 2019). As illustrated by Figure 1.6, differences in sea-ice extent estimates have been shown to vary by as much as 1 million km^2. Differences in the mapped position of the 'ice edge' at 15% sea-ice concentration can also vary by as much as 25 to 75 km (Meier and Stewart, 2019).

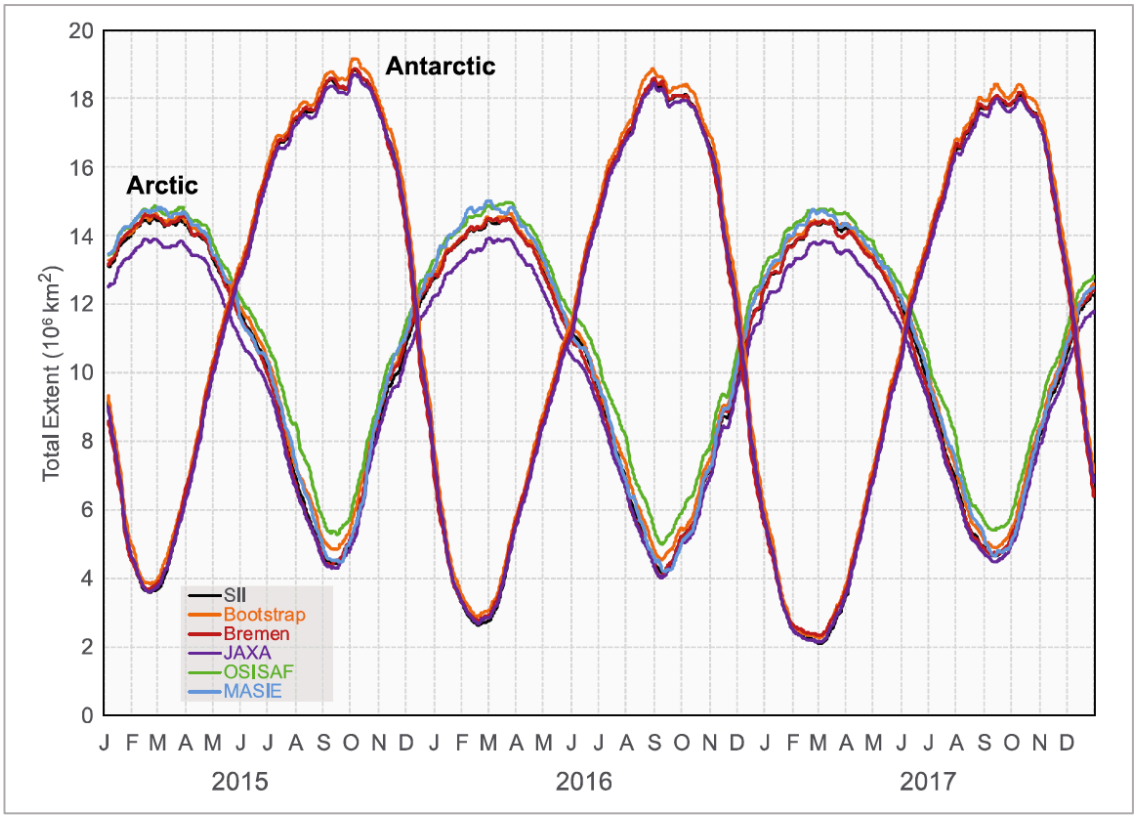


Figure 1.6.: Arctic and Antarctic sea-ice extent values calculated from different sea-ice data products, 2015-2017. *Source:* Meier and Stewart (2019).

1.3. A Sociological Study of Sea-Ice Science

1.3.1. Research Focus, Aim, and Objectives

The discrepancies between data products are problematic. The significant disagreement in absolute estimates of sea-ice parameters introduces further uncertainties and undermines our ability to fully understand the role of sea ice in the broader climate system and to project future changes (Kattsov *et al*., 2010). Moreover, these uncertainties challenge scientific authority, particularly as the data products feed directly into public and policy arenas (Shackley and Wynne, 1996). In the sea-ice community, the inconsistencies have warranted an increased focus in recent years. Several

intercomparison studies have been carried out with the aim to identify and reduce the causes of the discrepancies between different data products (e.g., Ivanova *et al.*, 2014, 2015; Comiso *et al.*, 2017; Kern *et* al., 2019; Meier and Stewart, 2019). These previous studies have tended to focus on improving algorithmic processes, quantifying uncertainties, and developing new methods to correct for limitations.

While reducing and quantifying the uncertainties and biases in sea-ice data products is of obvious importance, this thesis contends that the uncertainties and limitations described in the previous section point to a much broader issue regarding the role of sea-ice science as both a producer of knowledge and a product of society. From a sociological perspective, the divergences in data product methodologies and resulting outputs emphasise the multiplicity of potential interpretations and meanings that can emerge from satellite observations of sea ice. These differences indicate that sea-ice data products are not wholly objective or unmediated representations of Arctic sea-ice conditions; rather, their character and persistence are shaped by the social contexts of their production.

Recent work within the social sciences has called for greater recognition of the social dimensions that shape how knowledge about the climate system is produced, how associated problems are identified and structured, and what types of solutions and responses are required. For instance, several studies have contended that the prevalence given to the technical and geophysical aspects of the climate system fails to adequately account for the social contexts and implications of climate change (e.g., Jasanoff, 2004b; Findlater *et al.*, 2021; Lahsen and Turnhout, 2021). Others have shed light on the institutional biases and political values that shape how climate change is framed and what types of knowledge are produced and disseminated (e.g., Oreskes *et al.*, 2019). More broadly, STS research has compellingly shown how the outputs of science are socially and culturally contingent and subsequently reflect and reinforce particular values, perspectives, and interests while marginalising others (e.g., Latour and Woolgar, 1979; Bloor, 1991; Jasanoff, 2004a; Pickles, 2004; Harding, 2009; Felt *et al.*, 2017).

Acknowledging the social contingencies of scientific knowledge offers productive means for thinking about how scientific practices give rise to contestable and partial ways of knowing Arctic sea ice. The knowledge of sea ice produced through passive microwave remote sensing systems represents a specific way of encountering, defining, and measuring sea ice derived primarily through Western interpretive frameworks, conventions, and notions of nature. Identifying and using sea-ice parameters to monitor sea-ice conditions and variability reflects a treatment of sea ice as a distinct geophysical object that can be ordered, explained, and predicted using science and reason. However, as the definitions introduced in Section 1.2.1 indicate, the dominant parameters of sea-ice cover are not based solely on natural entities but on categories and thresholds established according to particular scientific interests and objectives. They bring about

ways of knowing that depend upon distinct, binary, and static divisions of and between sea ice and water that rarely exist in reality: sea ice occurs in many material forms in space and time; it continually exists in a transformative state between formation and dissolution; it is constantly in motion in response to wind and ocean currents (Steinberg *et al*., 2020). As Steinberg *et al*. (2020) argue, this dynamism and material complexity defy attempts to locate, delineate, and map areas of sea ice using singular definitions and binary classifications. Moreover, parameterising the complexities of sea ice obscures the multiple physical, biological, ecological, and social functions it serves. For instance, in *The Meaning of Ice,* Gearheard *et al.* (2013) detail the diverse and nuanced meanings that sea ice has for the Inuit, Inughuit, and Iñupiat communities whose lives are intimately connected to its existence. As later chapters address, these meanings cannot be captured using physical and mathematical principles alone; as such, they are often precluded in the conventional practices of knowledge production and communication that prevail in contemporary sea-ice science.

Crucially, the issues relating to the discrepancies in scientific practices or the mechanisms through which the complexities of sea ice are simplified, consolidated, and stabilised have important implications for how the Arctic is understood and acted upon in broader socio-political and cultural contexts. Satellite-derived sea-ice products have become powerful modes of knowledge transfer, forming the basis of many scientific studies that are used to predict future variability, inform public policy and planning, and communicate scientific knowledge to the public (e.g., Stroeve *et al*., 2012; Grosfeld *et al*., 2016; GCOS, 2015, 2016, 2018; WMO, 2020; IPCC, 2019, 2021). The notion that these products and their underlying practices are in some way socially contingent necessitates their critical examination. It calls for sea-ice data products to be examined in terms of their institutional, socio-cultural, and political contexts and raises crucial questions regarding representation, accountability, and participation in the production, dissemination, and implementation of sea-ice knowledge.

With the above in mind, the overarching aim of this thesis is as follows:

> *To identify how dynamic and indeterminate geophysical data are acquired, processed, and reported in Arctic sea-ice science, in order to improve understanding of the sociological nature of scientific knowledge.*

Five specific research objectives have been developed to address this aim:

1. Review the history of Arctic sea-ice science and consider how advances in science and technology have influenced the production of scientific knowledge through time and to what extent contemporary Arctic science is a product of political, economic, and cultural frameworks.
2. Examine and compare the key scientific methodologies used to acquire and process passive microwave remote sensing observations of Arctic sea ice.

3. Critically analyse how sea ice is simplified, consolidated, and represented through maps, and consider how uncertainties in data acquisition and processing are managed in sea-ice data products.
4. Investigate and compare the institutional settings of leading scientific agencies involved in the measurement, management, and communication of sea-ice research, in order to better understand how the key underlying processes and ideologies have been established.
5. Integrate the insights gained from the previous four objectives to develop a better understanding of the sociological nature of scientific knowledge.

Situated within a social constructivist framework, this thesis explores the production and dissemination of Arctic sea-ice knowledge by examining several sea-ice data products and the social and cultural *contexts* in which they are embedded. As detailed in the methodological framework outlined in Chapter 3, the examinations centre specifically on sea-ice data products produced at the United States' National Snow and Ice Data Center (NSIDC) and the Norwegian Meteorological Institute (MET Norway). These scientific institutes represent two significant players in the production and dissemination of sea-ice knowledge. The focus is on understanding how the complexities of sea ice are managed and how the practices of Arctic sea-ice science are influenced by particular values, perspectives, and power relations that shape and constrain the types of knowledge produced. As Chapter 2 reviews, this focus is influenced by previous social studies of scientific knowledge, which have argued that sociological factors necessarily underpin *all* knowledge claims (e.g., Latour and Woolgar, 1979; Bloor, 1991; Jasanoff, 2004a). Given the prevalence of mapped forms of representation in sea-ice data products, the thesis is also guided by critical approaches to cartography that challenge the authority and power of maps as seemingly objective and neutral representations of knowledge (e.g., Harley, 1989; Pickles, 2004; Wood, 2010). This focus on cartographic representations complements previous studies that have explored the technical limitations of passive microwave satellite observations (e.g., Ivanova *et al.*, 2014, 2015; Comiso *et al.*, 2017; Kern *et* al., 2019; Meier and Stewart, 2019), but that have paid little attention to *visual* representations of sea ice and the role that maps play in articulating particular visions of the Arctic.

By focussing on the social and cultural contexts of sea-ice science and challenging the objectivity of the resultant knowledge and its representation, the goal of this thesis is not to undermine the broader purpose of sea-ice data products as key tools of knowledge transfer. Instead, the core ambition is to emphasise the importance of thinking critically and reflexively about the entanglements between knowledge, power, and social order, including in science communication (Felt *et al.*, 2017). By critically examining the dominant practices and institutions involved in the satellite remote sensing of sea ice, the aim is to understand how and why particular methodologies have been developed

for acquiring, processing, and reporting satellite observations of sea ice and how this gives rise to *partial ways of knowing* Arctic environments. Examining how scientists produce knowledge about sea ice is important because this knowledge directly affects how the Arctic is perceived, known, and acted upon. Moreover, to recognise that our knowledge of Arctic sea ice always comes from *somewhere* and is shaped and mediated by the circumstances of its production is to recognise that our knowledge is *not inevitable.* In this way, I hope that the outcomes of this thesis provoke new questions about how our knowledge of Arctic sea ice – and of complex environments more broadly – can be made 'better' and more equitable through attending to alternative perspectives and interpretations that are often overlooked in conventional knowledge infrastructures.

1.3.2. Overview of the Thesis

This introductory chapter has aimed to provide some background context to the thesis, highlight the theoretical approach taken, and present the research focus, aim, and objectives. **Chapter 2** provides a more comprehensive overview of the theories, key concepts, and literature that guide the research carried out in this thesis. The chapter elaborates on the concept of social constructivism, outlining the basic assumptions, historical origins, and uses within various sociological approaches to the study of scientific knowledge and critical approaches to cartography. These uses are diverse and, at times, controversial and incongruous. However, social constructivist studies in their various forms provide reasons to be cautious and inquisitive about the *contexts* that shape the production of scientific knowledge. They collectively reject the notion of universal knowledge, challenge the perceived objectivity and neutrality of science, and encourage us to think about how knowledge can be made more equitable and more democratic or enriched and improved by alternative perspectives, values, and experiences.

Chapter 3 outlines the methodological framework of *a social constructivist examination of sea-ice data products*. The chapter introduces and justifies using a mixed-methods research design, informed by integrating insights and techniques from ethnographic and visual research methodologies. The nature of this integrated approach provides a structure for critically examining sea-ice data products and attending to the contexts of their production through three stages of inquiry: 1) a historical review of Arctic sea-ice science; 2) a critical and comparative examination of sea-ice data products; 3) ethnographic fieldwork. The chapter concludes with reflections on researcher positionality, the limitations of the approach, and the methodological implications of the COVID-19 pandemic.

Chapter 4 reviews the historical contexts of Arctic sea-ice science. Through attending to several key periods in the region's complex history and moments of significant scientific and technological change, the chapter explores how scientific knowledge of Arctic sea

ice is entangled with the interests and idealisations of the Arctic that prevail in particular historical and cultural contexts. The chapter reveals how the dominant processes, conventions, actors, and institutions of contemporary sea-ice research are historically contingent and intimately connected to geopolitical anxieties and unequal political and economic capacities.

Chapter 5 examines and compares the dominant assumptions, conventions, and methodologies involved in sensing and classifying Arctic sea ice. The chapter focuses specifically on the practices and technologies involved in producing several sea-ice data products developed by the NSIDC and MET Norway. Each product is addressed in turn, detailing the complex and multifarious processes used to transform satellite observations into meaningful data products. The chapter contends that the inherent uncertainties and limitations of sea-ice observation enable *interpretive flexibility* in producing sea-ice knowledge (Collins and Pinch, 1982; Collins, 1985). It concludes that sea-ice data products are always uncertain and partial approximations.

Chapter 6 presents a two-part critical examination of Arctic sea-ice maps produced by the NSIDC and MET Norway. Firstly, through examining the cartographic techniques and styles of representation, the chapter challenges the authority of sea-ice maps as objective tools of communication, reveals the agency of the mapmaker in the production of knowledge, and contends that sea-ice maps *work beyond their intended purpose* as prescriptive tools. Building on these examinations, an 'alternative mapping of Arctic sea-ice extent' is presented to challenge the inevitability of sea-ice knowledge in past, present, and future contexts. The chapter concludes by calling for a greater reflexivity during the production and dissemination of sea-ice maps.

Chapter 7 expands on the previous chapters to explore the conditions that shape the production and dissemination of sea-ice data products within the context of MET Norway. The chapter describes the *contextual* nature of data products, detailing the situated networks of social and technological arrangements, actors, negotiations, choices, values, and constraints that shape how particular methodologies are developed and sustained within their institutional contexts. It also addresses some notable tensions between scientific authority, institutional visibility, and accuracy and how emerging forms of science communication present new opportunities and challenges for sea-ice reporting, accountability, and credibility.

Finally, the thesis concludes with **Chapter 8**, which draws together the findings from the previous chapters to contemplate how the findings aid our understanding of the sociological nature of sea-ice knowledge. Here, I reiterate a stance that I hope is apparent throughout: that sea-ice data products are useful and important tools for understanding sea-ice variability and the role of sea ice within the broader climate system. However, the products are inherently partial, uncertain, and influenced by the social and cultural

contexts of their production. The concluding chapter considers the importance of recognising the social contingencies of scientific knowledge and how this may lead to new opportunities for embracing alternative perspectives and the pluralities of knowledge interpretation.

2. Theory and Context

2.1. Introduction

This chapter introduces the key theories, concepts, and literatures that guide the research carried out in this PhD thesis. Taken as a whole, the thesis is set out as a sociological study of Arctic sea-ice science, whereby the focus is on understanding how scientific practices are developed and how knowledge about sea ice is formulated and represented. As discussed in Chapter 1, my approach to examining sea-ice science is based on the central assumption that scientific practice can be understood as the product of a complex interplay between nature, science, and the interests of society; and, as such, scientific knowledge cannot be considered independent from the social, political, and cultural contexts in which it is produced. This perspective draws much of its influence from the concept of social constructivism and its complementary uses within the fields of science and technology studies (STS) and critical cartography.

In this chapter, I present an overview of how social constructivism has been developed and used within STS and critical cartography, with a particular emphasis on sociological approaches to the study of science and scientific knowledge. The purpose of this chapter is to establish a general understanding of the core concepts that inform and contextualise this PhD research and indicate where the contributions of this study will hopefully be situated within the broader field of the sociology of scientific knowledge. Bearing in mind the issues introduced in Chapter 1, I illustrate how, and why, a social constructivist approach to the study of sea-ice science can provide important insights into the social and cultural contingency of scientific products of sea ice and emphasise the importance of thinking critically about how scientific practices shape our understandings of the Arctic more generally.

The chapter begins with an overview of social constructivism, laying down the basic assumptions and theoretical departure points for studying how social factors shape the nature of Arctic sea-ice science and its resultant knowledge. Following this, the chapter is broadly split into two parts, focussing on STS and critical cartography, respectively. In Section 2.3, I trace the general history of sociological studies of science from the 1960s to the present day. Here, I review some of the key theoretical and empirical developments through which sociological approaches to scientific knowledge have

made valuable contributions to social constructivism. Particular focus is given to the Strong Programme in the sociology of scientific knowledge (SSK) (Bloor, 1991), the importance of studying science in context, and the idiom of co-production. In Section 2.4, I introduce the critical cartography field, outlining some of the central theoretical developments to illustrate how conceptions of maps have changed from objective and 'truthful' representations to social constructions, and more recently, to post-representational and processual mappings. Additionally, this section reviews some of the recent and parallel developments within critical studies of environmental sensing and visualisation. The chapter concludes by bringing together insights from the two fields to articulate how I use social constructivism to inform my understanding of sea-ice data products, laying a path for the methods chapter that follows.

2.2. An Overview of Social Constructivism

The concept of 'social constructivism' encompasses a wide range of interpretations that vary considerably depending on the contexts in which it is applied (Hacking, 1999; Kukla, 2000). In a general sense, social constructivism refers to a set of ideas about the ways in which our meanings of reality are constructed through social processes and relations (Hacking, 1999). In STS, social constructivism can be loosely defined as a methodological orientation that presupposes that human beings, as social actors, are actively involved in constructing scientific knowledge (Sismondo, 1993; Fuller, 2014). Specifically, it interprets scientific knowledge as the product of a particular set of practices and relations that occur within particular social and cultural contexts (Golinski, 1998).

Social constructivism has been a central premise for various contributions within STS. Although different studies include varying interpretations on the extent to which scientific knowledge is considered a social product, they collectively reject the traditional positivist assumptions of science, which view scientific knowledge to be an objective and unbiased representation of reality. In more modest interpretations of social constructivism, the influence of social factors is limited to aspects such as institutional structures or the identification of research areas and problems (e.g., Merton, 1973). For example, modest social constructivists may point towards the links between political agendas and research funding as evidence for an interest-driven science. In these more modest views, although developments in science cannot be considered wholly independent of the interests of society, social factors are seen to have little bearing on the content or integrity of scientific knowledge (Longino, 1990). This perspective also leaves open the *possibility* for a science where social influences are significantly diminished, if not eliminated.

On the other hand, strong interpretations maintain that the activities and outputs of science are intrinsically and unavoidably social (Fuller, 2014). Crucially, this stronger

position asserts that social factors not only influence the organisation or autonomy of science but play an active role in shaping and legitimising what constitutes knowledge and how it gains its authority (Bloor, 1991). From this perspective, the outputs of science are neither natural nor neutral representations of reality, as their character and persistence rests, at least to some degree, on the social arrangements that exist in a particular time and place (Longino, 1990; Sismondo, 2010). It is this stronger position of social constructivism that underpins the research carried out in this thesis.[3]

Social constructivist texts within STS have proven to be highly controversial. The assertion that scientific knowledge should be viewed as a social construct has provoked heated debates between the 'scientific realists' and the 'constructivists' over the fundamental nature of reality (see Section 2.3.3). From the perspective of realists, the social constructivist outlook has been seen to wholly reject notions of truth, rationality, and the existence of a material reality (e.g., Gross and Levitt, 1994). However, it is essential to highlight that the form of social constructivism used in this study does not necessarily imply that scientific knowledge is merely socially determined or that there is no external reality (Barnes and Bloor, 1982; Golinski, 1998).[4] As Section 2.3.3 details, uses of the social constructivist perspective in STS are generally less concerned with questioning the ontological foundations of knowledge than has been so often claimed. Rather, the central premise is that our *access* to reality – offered by the tools of observation, the techniques of representation, the use of language and discourse, and so forth – is mediated by social factors (Shapin, 1995; Barnes and Bloor, 1996; Golinski, 1998; Hacking, 1999). In this sense, scientific knowledge provides a version of reality that is filtered and conditioned by the collective experiences, perceptions, values, and assumptions that exist within particular historical and cultural contexts. In many cases – sea ice included – that version of reality is derived primarily through the interpretive frameworks and conventions that prevail in Western culture.

The social constructivist perspective of science and scientific knowledge urges us to think critically about the ways in which social and cultural conditions shape how we perceive, understand, and order the world around us (Felt *et al*., 2017). In particular, it draws attention to the issue of *inevitability* and the implications that this has for understanding the entangled relations between power, knowledge, and social order (Hacking, 1999; Jasanoff, 2004a). For Hacking (1999), a fundamental assertion of social constructivism is that our knowledge about a particular phenomenon is not inevitable. The practices through which knowledge is produced are contingent on the complex and

[3] From here onwards, the use of 'social constructivism' will refer to this stronger position unless otherwise stated.

[4] Golinski (1998) notes that social constructivism does offer scope to question the existence of 'reality' from a metaphysical or ontological perspective. Such views reflect an extreme form of idealism in which reality can only exist through human thought and socially constructed meanings. However, this is not the outlook adopted by most practitioners in STS, as such philosophical statements are often received as problematic and self-contradictory.

variable social worlds in which we live. As such, the nature of knowledge is subject to ongoing change or reinterpretation. To deny the inevitability of scientific accounts is to recognise that our knowledge about something could be different. This recognition has significant implications for considering whose values, interests, and perspectives shape the production of scientific knowledge and, in turn, how that knowledge is circulated and put to work in society (Felt, 2017). In particular, it prompts us to examine the ways in which the activities and institutions of science are implicit in reinforcing particular social hierarchies and power imbalances, and critically reflect on whether alternative perspectives and interpretations of knowledge can be gained from outside those dominant structures. These are some of the central ideas that motivate the work carried out in this PhD research.

2.3. The Sociology of Science and Scientific Knowledge

2.3.1. Challenging the Popular Notions of Science and the Emergence of STS

Around the mid-twentieth century, the widely accepted view of science was of a rational, objective, and progressive enterprise that sought to establish general truths about how the world works. In maintaining these core principles, the activities and institutions of science were thought to exist independent of the influence of politics, religion, and other forms of social bias (Daston and Galison, 1992). Such views promote the idea that, if equipped with rational and standardised methods, scientists engaged in their various disciplines, and operating within their closed institutionalised spaces, can observe and represent the world as it exists out there (Popper, 1972; Gregory and Miller, 1998). In other words, they can produce a view of reality unmediated by human values and beliefs: *a view from nowhere* (Nagel, 1986). From this perspective, scientific knowledge can be thought of as a truthful approximation of reality based on direct observation.

Beginning around the 1970s, these positivist ideals of science came under intense scrutiny from a broad range of disciplinary positions, including history, anthropology, and sociology. While they often examined science in different contexts and employed a diverse range of methodological approaches, a common departure point of these emerging critiques of science was that establishing a value-free and objective view of reality was simply unattainable, as social forces are always at play (Bowden, 1995). These critical approaches to the study of science gradually merged in a more organised sense within the field of STS.[5] Broadly speaking, STS gained its prominence during this time as a response to a growing ambivalence around the privileged position of science and technology in Western society (Edge, 1995). Factors driving this ambivalence included a budding dissatisfaction surrounding the positivist values that gave science and

[5] The acronym STS can refer to 'Science and Technology in Society' or 'Science and Technology Studies'. The latter version – the version used in this PhD research – is more commonly used today.

technology their exceptional and authoritative status in modern societies (Sismondo, 2010); the emergence of social movements such as feminism, postcolonialism, and environmentalism that sought to challenge mainstream ideologies (Breyman *et al*., 2017); and a growing concern over the role that science and technology played in reinforcing unequal distributions of power, through their engagements with broader socioeconomic and political matters (Spiegel-Rösing, 1977).

Troubled by the epistemic privilege attached to the scientific method, sociological critiques arose within STS to call for a recognition of science as a socially embedded institution and to argue that the dominant view of scientific objectivity and neutrality was more of an ideological ambition than a reflection of science in practice (Section 2.3.4).[6] Many of these studies maintained that social factors play an active role in influencing the practices and outcomes of science. Scientific knowledge, they argued, was not simply a reflection of reality, but the product of a particular set of localised and value-laden practices. Moreover, in line with growing postmodern critiques, interpretations of knowledge were increasingly understood as complex and heterogeneous: the meanings we attach to statements, theories, and facts are relative to our diverse perspectives and cultural orientations (Lyotard, 1993; McRobbie, 1994; Alvesson, 2004).

A central claim within early sociological studies of science was that scientific knowledge cannot be adequately explained or interpreted without attending to the particular social and material contexts in which it embedded (Shapin, 1995). This prompted a wave of sociological examinations into the character and development of science and the socio-political and cultural contexts in which its activities and outputs are situated. While there are many strands within this broad critique, productive insights have been gained from studies that examined the historical developments of scientific theory and practice (e.g., Kuhn, 1970a; Pickering, 1984; Shapin and Schaeffer, 1985); scientific content and the situatedness of knowledge (e.g., Knorr Cetina, 1981; Latour and Woolgar, 1986; Haraway, 1988; Bloor, 1991); the construction of technological systems (Pinch and Bjiker, 1987); and the broader co-constitutive relations between science, technology, nature, and society (e.g., Jasanoff, 2004a; Latour, 2005). Within these contexts, the social constructivist outlook gathered much of its momentum over the following decades.

2.3.2. Kuhn's Revolutions

A leading figure in the early developments of the sociology of science was Thomas Kuhn, whose seminal book, *The Structure of Scientific Revolutions* (1970a [1962]), transformed the way many think about scientific development. Influenced by Enlightenment ideals of

[6] Here and throughout, I use 'sociological studies' to refer to the various different sociologically-inclined studies of science and scientific practices. This includes the contributions from historians, anthropologists, sociologists, and geographers.

progress, the popular picture of scientific development in the mid-twentieth century was of a linear, cumulative process (Sismondo, 2010). In this view, scientific knowledge builds incrementally through the accumulation of observations, theories, and facts in an ongoing search for the truth (Kuhn, 1970a). Based upon a historical review of scientific activities, Kuhn challenges this philosophy and introduced a distinctly different concept of scientific development.

Kuhn reasons that the process through which scientific knowledge is acquired is not linear. Instead, it occurs in two discontinuous and alternating phases: normal and revolutionary. In the normal phase, science progresses in accordance with a 'paradigm', a term that Kuhn uses to describe a model of scientific activity, characterised by a distinct set of assumptions, theories, working practices, and values that legitimise the work and beliefs of scientists within a particular field (Kuhn, 1970a). Instructed by the paradigm, normal science proceeds to solve problems, describe and interpret phenomena, identify knowledge gaps, and resolve or explain why anomalies occur.

A revolutionary phase occurs when anomalies become too significant or numerous that they can no longer be solved or accounted for according to the methods and logic of the established paradigm (Kuhn, 1970a). This invokes a scientific crisis, a period of extra-ordinary research which is characterised by "[t]he proliferation of competing articulations, the willingness to try anything, the expression of explicit discontent, the recourse to philosophy and to debate over fundamentals" (Kuhn, 1970a: 91). During a crisis, entire models of accepted scientific practice are called into question. In some instances, this may trigger a 'paradigm shift', through which the nature of scientific activity, including its underlying assumptions, values, conceptual framework, and social organisation, can be fundamentally changed. This new paradigm becomes accepted by the scientific community, and science proceeds once again, as normal.

According to Kuhn, the post-revolutionary changes are often so significant that the new paradigm is incommensurable to the old paradigm; that is, the two paradigms cannot be objectively compared or judged against each other because they encompass fundamentally different approaches to scientific problem-solving (Kuhn, 1970a). Additionally, following a paradigmatic shift, the very nature of the problem can also change. In an acute sense, Kuhn pronounces that after a revolution, "the proponents of competing paradigms practice their trades in different worlds" (1970a: 150).

Kuhn's account of episodic scientific development has had many important implications for the sociology of science and the social constructivist perspective. Here, I outline two particularly significant and related aspects: 1) the theory-dependence of observation and incommensurability; and 2) community-driven scientific development.

The notion of the theory-dependence (or theory-ladenness) of observation claims that how we perceive and interpret the world is dependent on particular theoretical

presuppositions and conceptual frameworks (Longino, 1990). This claim is implicit in Kuhn's thesis and relates directly to the incommensurability of paradigms. Kuhn states that each paradigm is characterised by its own distinct set of research standards, theories, and methods against which all scientific activities are measured. In this sense, the paradigm determines how the scientist(s) perceives, observes, and interprets a phenomenon. In doing so, it dictates what is considered to be 'good' or relevant science (Sismondo, 2010). Significantly, if we suppose that Kuhn's notion of incommensurable paradigms is correct and observations can be shown to be theory-dependent, then what is considered to be 'good' or relevant science can *only* be known through the conditions set out by the accepted paradigm that exists within a particular moment in time (Longino, 1990).

Within the sociology of science, the notions of the theory-dependence of observation and incommensurability have encouraged two important assumptions about scientific development: firstly, that there is no theory-independent and objective standard against which to measure scientific progress across different paradigms; and secondly, that scientific knowledge is an interpretation of reality as prescribed by the current paradigm (Barnes, 1982; Longino, 1990). If one accepts these viewpoints, then the prevailing positivist assumptions of scientific knowledge as cumulative, universal, and objective are refuted. Instead, the nature of scientific development emerges as one of non-progressive shifts between different partial and inadequate views of reality (Sismondo, 2010).

For Kuhn's critics, the notions of incommensurable paradigms and non-progressive revolutions were seen to support relativist and irrational interpretations of science (Lakatos and Musgrave, 1970). However, Kuhn describes himself as a firm believer in scientific progress and denied the charges of relativism and irrationality on the assertion that each successive paradigm is always better at problem-solving than its predecessor (Kuhn, 1970a). Kuhn later clarifies his use of 'incommensurability' and uses this to inform an alternative conception of scientific progress to the dominant view noted earlier (see Kuhn, 1970a, 1970b). According to Kuhn, the notion of incommensurability is not always totalising: some concepts or practices may remain pertinent between revolutions, and their persistence can be attributed to their continued value for problem-solving (see also Barnes, 1982; Sismondo, 2010; Bird, 2012). Available resources inform successive paradigms, and new theories, ideas, and methods draw from previous experience. It is in this sense that Kuhn argues for a different conception of scientific progress as *evolutionary*. He contends that thinking about scientific progress in relation to how close a paradigm can approximate some singular, objective 'truth' is problematic. Instead, progress should be thought of as a process through which successive paradigms become better at solving problems in the given scientific environment (Bird, 2012). In other words, they become more *successful*, but not necessarily more 'truthful'.

Whether or not Kuhn's progressive stance is representative of actual scientific development, it is crucial to highlight the emphasis placed on the scientific community's role in shaping the nature of paradigms. Notably, Kuhn implies that the formulation and acceptance of a paradigm, or a particular way of doing science, is fundamentally dependent on the negotiations and consensus of the practising scientists within a specific community (Kuhn, 1970a, 1970b). This implies that the scientific community is actively involved in determining the content and activities of science, and it chooses the nature in which the field develops, albeit based on logical reasoning and shared values (Kuhn, 1970b). For social constructivist readings, in particular, the community-based notion of scientific development has been hugely influential. At the very least, it indicates that science cannot be considered independent from society's influences in the sense that changes in the paradigm are not driven solely by external perturbations but rely on some form of social intervention. It further implies that science does not merely occur in a social context. Rather, the social context actively shapes what 'science' is. The appeal of this view for many sociologists (e.g., Barnes, 1982; Knorr Cetina, 1982; Collins, 1985; Latour and Woolgar, 1986; Bloor, 1991; Pickering, 1991) is the suggestion that science, like many other aspects of culture, is open to varied interpretation and socialisation.

Kuhn's concepts and claims have been used selectively and have been subjected to varying degrees of criticism over the years. Nevertheless, in various commentaries and reviews of the field, Kuhn has been credited for providing the fundamental departure points for thinking about science and scientific knowledge sociologically (see Shapin, 1982; Longino, 1990; Golinski, 1998; Sismondo, 2008, 2010). In particular, the interpretations outlined above encouraged sociologists to start thinking about scientific practices and cultures in more local terms. This prompted a 'new wave' of sociological studies of science that focussed on examining how localised sub-cultures of science and their interactions with the broader social and cultural contexts in which they are situated influence the nature of scientific knowledge (Sismondo 2010).

2.3.3. The Sociology of Scientific Knowledge and the Strong Programme

During the 1960s, David Edge established the Science Studies Unit at the University of Edinburgh. This is thought to be among the first institutionalised spaces of STS, and the work pioneered by its researchers, including David Bloor, Barry Barnes, and Steven Shapin, has been regarded as being hugely influential to the way in which field has developed (Fuller, 2014). In particular, members of the Science Studies Unit made important advances in a new radical, relativist approach to science studies: the sociology of scientific knowledge (SSK). SSK developed the central foundations of social constructivism, and as Hess (1998) notes, SSK and social constructivism are often referred to interchangeably.

The development of SSK in the late 1960s and early 1970s represented a distinctly different approach to the study of science than previous sociological analyses. As Bloor (1991) asserts, early sociological studies of science had primarily attended to the institutional frameworks of science and factors that influence their structure.[7] There had been comparatively little work examining the nature of scientific knowledge and the role that social factors play in shaping the *content* of science. Influenced by Kuhn's paradigms, SSK sought to fill this gap, stressing a need for a greater empirical focus on the practices and conditions that determine what constitutes knowledge and how it is produced and sustained within particular cultural contexts (Bloor, 1991).

The central assertion of SSK is that scientific knowledge should be subject to the same sociological analysis as other knowledge claims. Scholars of SSK interpret science – including its theories, methods, and practices – as fundamentally social and embedded within particular local contexts (Barnes, 1974; Collins, 1974, 1985; Bloor, 1991; Ophir and Shapin, 1991; Pickering, 1991; Shapin, 1995; Barnes *et al*., 1996). This interpretation underpins a further assumption that scientific knowledge becomes truthful, endorsed, and sustained within those contexts. An essential concern of SSK, therefore, is to identify the local and contingent circumstances (social and otherwise) that explain how and why certain 'beliefs' or 'knowledge claims' become (re)produced, institutionalised, and accepted as 'scientific knowledge', whereas others do not (Bloor, 1991). These ideas are central to the Strong Programme in SSK, which Bloor and Barnes chiefly developed during the 1970s and 1980s (Barnes, 1982; Barnes and Bloor, 1982; Bloor, 1991). It is termed 'strong' because it argues the need for all types of knowledge to be subject to sociological inquiry, including sociology itself. It is seen as a reaction to previous 'weak' sociologies of knowledge which tended to limit social explanations to failed knowledge or erroneous beliefs (Ben-David, 1971). In contrast, the Strong Programme reasons that sociological factors are necessary and essential to *all* beliefs or knowledge-claims. It rejects the idea that social contingencies merely undermine the integrity and validity of knowledge, arguing instead that sociological factors influence the very essence of what science is and how scientific knowledge gains its authority (Collins, 1975; Barnes and Bloor, 1982; Bloor, 1991).

Favouring a naturalistic interpretation of science and scientific knowledge, the Strong Programme's central proposition is to dismantle the traditional epistemological distinctions between the objects and methods of the social and natural sciences, through which the latter gain their privileged status (Fuller, 2014). It advocates a move away from thinking about beliefs or knowledge-claims through the distinctions between 'true' or

[7] For example, Robert Merton's analysis concerned the 'norms' or basic values that governed the activities of the general scientific community (Merton, 1973). Merton was less critical of scientific objectivity and rationality; that is, Mertonian sociology contends that the institutional framework of science exists to embody these values and allow science to proceed without being influenced by social factors.

'false', and 'rational' or 'irrational', and towards thinking about the conditions that determine the acceptance and credibility of beliefs (Barnes, 1974; Barnes and Bloor, 1982; Bloor, 1991). As such, knowledge claims, whether they be scientific theories and observations, political ideologies, religious doctrines, or cultural traditions, should all be analysed equally in terms of their explanation. These viewpoints are best articulated through Bloor's four core tenets of SSK:

1. It would be *causal*, that is, concerned with the conditions which bring about beliefs or states of knowledge. Naturally there will be other types of causes apart from social ones which will cooperate in bringing about belief.
2. It would be *impartial* with respect to truth and falsity, rationality or irrationality, success or failure. Both sides of these dichotomies will require explanation.
3. It would be *symmetrical* in its style of explanation. The same types of cause would explain, say, true and false beliefs.
4. It would be *reflexive*. In principle, its patterns of explanation would have to be applicable to sociology itself. (Bloor, 1991: 7, emphasis added)

The Strong Programme's emphasis on social causes and the need to treat all knowledge claims symmetrically and impartially have proven to be particularly controversial ideas for many scientists and philosophers alike. From the outset, critics accused the radically relativist programme of damaging the integrity and validity of science through making simplistic and irrelevant generalisations, over-emphasising a socio-centric view of knowledge formation, and obscuring or even denying the existence of a material world (e.g., Gross and Levitt, 1994; Sokal and Bricmont, 1998; Sokal, 2001; Kochan, 2017). Many of these points of contention were extended to STS more generally and reflected a deepening divide between the realists on the one hand and the 'academic left' on the other.[8] This division came to a head during the so-called 'science wars' that raged in a very public sense during the 1990s and centred around the highly controversial Sokal Affair (Segerstråle, 2000). Within the science wars, those disposed towards relativism were branded as anti-intellectualists, anti-scientists, and radical sceptics; and their claims were widely regarded as objectionable and warranting caution. For many critics, the ideas that sociologists of science offered, namely that scientific knowledge is a social construct and epistemically equivalent to religious beliefs or political ideologies, raised legitimate concerns around the potentially damaging public-policy implications of such thought (Fuller, 2014). For instance, there were concerns that the conclusions of SSK would lead to funding cuts for climate science; increased exposure given to alternative and unorthodox medicines; undermine environmental regulations; and have long-term

[8] The term 'academic left' is commonly used to refer to relativists, social constructivists, postmodernists, and SSK practitioners who are grouped because of their shared pursuit to challenge scientific authority.

consequences for public judgement of scientific issues (Gross and Levitt, 1994). As Lynch (2020) discusses, many of these concerns persist today, and the perspectives encouraged by the Strong Programme have become embroiled in highly contentious debates with regards to post-truth and Left-Right politics (see also Mooney and Sokal, 2007; Sismondo, 2017).

Proponents of the Strong Programme have argued that the hostile stance of many of its critics is primarily based on unfounded claims or misinterpretations of the programme's core principles. In particular, Strong Programmers reject the association between relativism and anti-science claims, arguing that the form of relativism advocated by the programme differs from the stereotype frequently condemned (Bloor, 1991). Three key features define the specific form of relativism implicit in the Strong Programme: 1) the notion that knowledge on a certain topic or phenomenon can vary; 2) that the strength of knowledge claims is dependent on, or relative to, the contexts in which they exist; and 3) it requires a symmetry or equivalence postulate (Barnes and Bloor, 1982). It is variations of the third feature that differentiates between forms of relativism.

Critically, the form of relativism associated with the Strong Programme's symmetry postulate does not state that all beliefs or knowledge claims are equally true or false. It simply argues that all knowledge claims should be analysed equally in terms of the causes of their credibility, regardless of whether or not they are considered true or false, rational or irrational (Bloor, 1991). This is because the same types of causes are present in true and false knowledge claims. The approach can be best understood as a form of methodological relativism, which calls for a neutral examination of all claims to knowledge instead of more extreme, philosophical forms, which question the metaphysical or ontological basis of knowledge (Barnes and Bloor, 1982; Hacking, 1999). Among other proponents of the Strong Programme, Bloor and Barnes contend that it is misinterpretations of this distinction that have given rise to the fiercest critiques.

In various defensive commentaries, Barnes and Bloor have shown a similar dissatisfaction towards attacks on the Strong Programme's views on social determinism (e.g., Bloor, 1991, 2004; Barnes, 2011). For example, Bloor stated: "[t]he strong programme says that the social component is always present and always constitutive of knowledge. It does not say that it is the *only* component, or that it is the component that must necessarily be located as the trigger of any and every change: it can be a background condition" (1991: 166). Comparable reflections were echoed in a more recent essay by Barnes (2011), in which he contends that SSK practitioners have never denied the existence of the natural world. They merely argue that the natural world alone is not a sufficient explanation of scientific accounts of it and that analyses must extend to social dimensions.

Despite the many controversies surrounding the Strong Programme, the perspectives it has advanced have been highly influential to SSK. In particular, the symmetry postulate has become one of the most widely taken up concepts within and beyond the approach and has become an essential foundation of STS (Sismondo, 2010). By disengaging with the traditional epistemological distinctions that give rise to 'true' or 'valid' knowledge, the programme developed a theoretical framework in which social factors are essential to the very nature of knowledge (Shapin, 1995). Not only does this provide the justification for science to be opened up to sociological inquiry and encourage empirical investigations into the local contingencies of knowledge production, but it also opens up the space for 'other' knowledge-producing systems to be taken seriously (Watson-Verran and Turnbull, 1995; Turnbull, 1997, 2000; Philip, 2015).

In the sciences, Western forms of knowledge production are typically privileged over traditional or Indigenous knowledge systems because the latter are perceived to be primitive, entwined with cultural beliefs, unsystematic, and situated within local contexts (Philip, 2015). Consequently, they are not deemed to have the same credibility or authority as their scientific counterparts. For the reasons outlined above, SSK opposes this dichotomy and argues that the long-standing perceptions of Western science as objective, value-free, and authoritative cannot be accepted uncritically. From the perspective of SSK, Western science shares many of the same characteristics as traditional or Indigenous knowledge systems and should be evaluated in the same way. For example, Watson-Verran and Turnbull (1995) contend that: "recognizing the localness of science subsumes many of the previously supposed limitations of other knowledge systems compared with Western science. Though knowledge systems may differ in their epistemologies, methodologies, logics, cognitive structures, or socio-economic contexts, a characteristic they all share is localness" (1995: 116). Thus, viewing different knowledge systems symmetrically enables a greater understanding of why Indigenous knowledge has been (and continues to be) separated from hegemonic views in science.

The Strong Programme's aim has never been to attack or reject science, at least not in any general sense. Instead, it set out to establish a set of methodological imperatives for understanding science as a cultural formation and scientific knowledge as a social product. Although I do not exclusively subscribe to the Strong Programme's tenets in this PhD research, I find it a helpful framework for thinking about how social causes play a role in shaping the nature of Arctic sea-ice data products. By focussing on the causes or determinants through which knowledge becomes accepted and credible, symmetrical research enables a more critical analysis of the entrenched ideas, generalisations, and taken-for-granted assumptions in sea-ice science. Moreover, as the following section will illustrate, examining how knowledge is constructed and what modes of inquiry are involved, without getting caught up in questions over which belief

is more 'rational' or more 'truthful', has been hugely productive for understanding the social and cultural contingency of scientific knowledge about sea ice. Additionally, the perspective offers some valuable departure points for thinking critically about the distinctions, interactions, and exchanges between Western and Indigenous knowledge systems in the Arctic and questioning the appropriateness of the former in Indigenous contexts (Scott, 1996; Nadasdy, 1999; John *et al*., 2004).

2.3.4. Studying Science in Context

The constructivist and relativist perspectives developed within SSK emphasise the social origins of knowledge and assert the importance of studying science in its particular social and cultural contexts. These sentiments are reflected in the following statement by Barnes:

> The culture is far more than the setting for scientific research; it is the research itself. It is not just problems, techniques and existing findings which are culturally specific; so, too, are the modes of perceiving and conceptualising reality, the forms of inference and analogy, and the standards and precedents for judgement and evaluation which are actually employed in the course of research (1982: 10).

Interpretations of this nature have inspired a significant number of historical, sociological, and anthropological studies of science that have attempted to illustrate how socially and culturally specific factors play a role in shaping scientific knowledge production. These studies can be divided into two broad areas of empirical inquiry that reflect the different strands of SSK that materialised in the early 1980s (although it should be noted that the divisions between the strands are not always clear-cut) (Longino, 2002). The first area concerns the broader *macrosocial* factors that are generally thought to exist outside of the scientific community or place of knowledge production. The second emphasises the importance of examining the more localised, *microsocial* factors that exist within the scientific community or place of knowledge production.

Most commonly associated with the Edinburgh School researchers, macrosocial approaches within SSK are primarily concerned with understanding how broader societal conditions affect the values and content of science (Sismondo, 2010). Generally, the macroscale approach focuses on societal interests and structures that are external to the scientific community, such as political ideologies and economic pressures.[9] However, the approach can be extended to internal conditions specific to a particular discipline or subculture of science (Shapin, 1982).

Early macrosocial studies were among the first to apply the Strong Programme's principles of impartiality and symmetry in empirical research (Hess, 1998). At the height

[9] Also known as the 'interest-based' approach.

of the programme's popularity in the late 1970s and early 1980s, sociologists used macroscale approaches to inform meticulous accounts of scientific activities and controversies. Seeking to trace the causal connections between societal conditions and historical debates in science, case studies raised important questions about how social interests and agendas shape the accepted modes of knowledge production, including the dominant methods of scientific practice, the choice of research objectives, the beliefs of the scientific community, and the acceptance and validity of particular theories and intellectual positions.[10]

Through revealing the contingent circumstances affecting scientific research priorities and the evaluation of scientific knowledge, early macrosocial studies of science were seen to reaffirm the central claim of SSK that science cannot be divorced from the social, and is, therefore, amendable to sociological and anthropological examination (see Barnes, 1974). However, a common criticism of the macrosocial approach is that most studies merely suggest the possibility of connections between broader societal structures and scientific knowledge (Hess, 1997). Critics have charged the approach of making *associations* but failing to establish unequivocally how broader interests and agendas translate into science and how they influence the formulation and acceptance of knowledge claims (e.g., Woolgar, 1981). Moreover, as Hess (1997) summarises, the approach has been criticised for offering an overly simplistic view of science and social interests, reducing scientists to passive characters shaped by external forces, and lacking in consideration of the complex contingencies and motivations that affect every day scientific practice.

Nevertheless, the macrosocial approach remains an important method in SSK. Collectively, macrosocial studies have offered a rigorous critique of the traditional epistemology of science and evoked a more in-depth understanding of science as a form of culture, just like any other (Sismondo, 2010). Moreover, as Sismondo (2010) notes, they have helped develop a greater understanding of the broader cultural contexts in which scientific knowledge is situated and how those contexts shape options and choices within scientific research. These are some of the crucial foundations upon which the microsocial approach's detailed and analytical work can build.

The microsocial approach in SSK came about primarily due to the limited ability of macrosocial studies to offer robust insights into how social factors shape the formulation and acceptance of scientific knowledge – addressing this gap called for detailed studies

[10] Some notable examples include: Barnes and Shapin's collection of essays which illustrate how science is interwoven with social and cultural conditions (1979), including a study of a controversy in British genetics whereby different intellectuals positions were shown to align with social class conflicts (MacKenzie and Barnes, 1979); Pickering's study of post-war particle physics, which revealed the active role that scientists play in constructing natural phenomena (1984); and Shapin and Schaffer's historical account of the debate over the validity of Robert Boyle's air-pump experiment in the 1660s, which explored how culturally accepted modes of knowledge production gained their credibility (1985).

of the social conditions *within* the scientific communities. Instead of focussing on how broader societal interests shape the scientific community's values and beliefs, the emphasis was placed on analysing the interactions and activities of scientific actors within the *site of knowledge production.* This focus on the microsocial level of scientific activity reflected a reorganisation of SSK around the prevailing scientific *practices* and *cultures* involved in knowledge production (Knorr Cetina, 1983; Collins, 1985; Pickering, 1992; Schatzki *et al*., 2001).

Although differing in their focus, it is worth noting that the microsocial and macrosocial approaches to SSK can complement each other (Knorr Cetina, 1983). Understanding the broader societal contexts in which scientific research takes place may provide rich insights into why scientific communities hold particular knowledge claims in the first place, why a specific data collection method is considered to be more suitable than others, or how knowledge travels beyond its initial place of production. At the same time, detailed investigations into knowledge production sites may reveal clear linkages and interdependencies between scientific practices and broader societal structures. As Chapter 3 details, the methodology developed and implemented in this PhD research reflects the view that macrosocial and microsocial approaches to studying sea-ice science are complementary, not contradictory.

The microsocial approach favours ethnographic studies of particular scientific cultures, whereby the aim of investigations is to shed light on the activities and interactions that take place during the knowledge production process. This includes detailing the spaces of knowledge production;[11] the tools and techniques adopted by the scientists; the networks and interactions involved in the development, validation, and transfer of knowledge; and the rules, patterns, values, and assumptions about reality upon which knowledge is formulated and sustained (Powell, 2007). In particular, Collins (1981, 1985) underscored the importance of understanding how uniformities are developed and how scientists reach agreement in practice. Collins argued that while ways of seeing and doing can vary between different groups or cultures (scientific or otherwise) that organise themselves around some form of shared endeavour, the very existence of those groups or cultures depends upon uniformities of perception and meaning. These ideas represent the central premise of the Empirical Programme of Relativism (EPOR) (Collins, 1985). EPOR builds upon three main stages: 1) demonstrating that experimental data is open to multiple interpretations (it has *interpretative flexibility*); 2) examining the *closure* mechanisms through which scientists reach agreement on a particular interpretation;

[11] I use the term 'space' here in a broad sense (after Hautala and Jauhianen (2014) and Powell (2007), incorporating material (e.g., physical locations or settings), social (e.g., communicative spaces – interactions between people through discussion, email, journals), and cognitive spaces (e.g., concepts, ideas, mental models of groups or individuals) that all play an essential role in shaping the nature of knowledge and the practices of knowledge production.

and 3) establishing the connections between the closure mechanisms and the broader social and political structures.

Early uses of ethnography in SSK reflected a concerted effort of sociologists and anthropologists to shift the focus of their traditional disciplinary inquiries away from communities and cultures deemed to be more 'primitive', less developed, or less modern than their own (viewed predominantly from the position of white, Western, and male researchers) (Charlesworth *et al.,* 1989). Instead, it was considered both necessary and valuable to apply ethnographic techniques to investigate major institutions and organisations that exercise power and authority in modern society, such as government agencies and scientific institutions. This reorientation in sociological and anthropological focus is what Nader (1972) called 'studying up'.

Latour and Woolgar's *Laboratory Life* (1986 [1979]) is one of the most renowned studies of this kind. The book offers an anthropological account of a neuroendocrinology laboratory at the Salk Institute for Biological Studies, located in La Jolla, California. Over two years, Latour embedded himself in the institute as a researcher, with the chief aim of observing how the routine activities of the practising scientists relate to the construction of scientific facts. In documenting many of the key elements of laboratory life, Latour and Woolgar's comprehensive account illustrates how initial 'chaotic' observations become ordered and accepted as scientific facts. Using Derrida's notion of 'inscription' as an integral process (1977), Latour and Woolgar show how microsocial activities in the laboratory become transformed and manipulated into statements, which then, through key concepts such as networks of meaning, historical exposition, and cycles of credit, emerge as scientific facts.[12] As they describe them, scientific facts do not exist as natural entities out there in the world but rather materialise as a product of the situated processes of communication, negotiation, interaction, and consensus-building (Livnat, 2009). Crucially, however, any references to these production circumstances are removed in the final stages of fact construction. This process of *decontextualisation* has the effect of making knowledge appear objective, and it represents an important mechanism through which locally produced knowledge becomes transferred, validated, and accepted in other settings (Merz, 2006).

Other landmark ethnographic studies of scientific practice include Collins's investigations of British experimental physics laboratories (Collins, 1974, 1985), Knorr Cetina's study of plant biology (Knorr Cetina, 1981), and Traweek's ethnographic account of high energy physicists (Traweek, 1988). These studies are summarised below

[12] The notion of (literary) inscriptions is used to summarise "all traces, spots, points, histograms, recorded numbers, spectra, peaks, and so on" (Latour and Woolgar, 1979: 88). Inscriptions represent the means through which statements are produced and supported.

to offer a glimpse of the breadth of SSK ethnographic inquiry and its value for social constructivism.[13]

Collins's interest in British experimental physics laboratories centred around how scientists conduct, replicate, and draw conclusions from their experiments. The repeatability of scientific observations, or the replicability of scientific methods, is considered the 'touchstone' of modern science and an essential prerequisite to achieving valid and credible knowledge (Collins, 1985). Using the construction and implementation of the 'TEA-laser' as a case study, Collins found that formal channels of information transfer, such as scientific journals or textbooks, were an insufficient explanation of how replication occurs in science and how real and useable knowledge is transferred between scientists (Collins, 1974). His account reveals how localised and highly variable sociological factors, such as overt concealment, personal and biographical characteristics, and tacit knowledge, influence the effective transmission of knowledge and thus inhibit or assist the ability for successful repeatability and replication to occur.

In *Beamtimes and Lifetimes*, Traweek offers a different ethnographic account of high energy physics communities (Traweek, 1988). Based on comparative observations at two national laboratories in the United States and Japan, Traweek presents a detailed interpretation of the material settings, the institutional organisation, and the scientific cultures involved in the construction of knowledge. Paying particular attention to the power structures (cultural, class, and gender) that prevail within the laboratory spaces, Traweek develops an understanding of what it means to be a particle physicist and how this is reflected in the activities and values of the community. She concludes that, despite her observations showing high energy physics as deeply embroiled with broader cultural structures, the communities view their work as unequivocally objective, progressive, and free from human agency.

Similarly, in Knorr-Cetina's *The Manufacture of Knowledge,* the focus is on understanding scientific work in the same way that scientists do (Knorr-Cetina, 1981). The principal argument evident in her account is that scientific inquiry constitutes a context-laden set of localised practices through which scientific knowledge is constructed. She asserts that "nature is not to be found in the laboratory" (Knorr-Cetina, 1981: 4). Instead, the 'nature' that laboratory scientists work with is "preconditioned" or "wholly artificial": the tools and instruments of experimentation are the products of human design and manufacture; books, articles, research notes, graphs, and diagrams are the outputs of human communication; and all substances and source materials are purified, enhanced, selected, standardised, and manipulated by humans during the process of fact

[13] Others prominent studies include Collins and Pinch (1982); Lynch (1985); and Zenzen and Restivo (1982).

construction. Thus, the knowledge created through laboratory processes is knowledge about distinctly unnatural things (Sismondo, 2010).

Although focussing on quite different, contextually specific examples of scientific inquiry, empirical support for social constructivism is one of the most significant and consistent outcomes of SSK ethnographies. In their various interpretations of science, ethnographies have shown that what comes to be constituted and accepted as knowledge is contingent on intrinsically social, locally situated, and context-laden practices and scientists emerge not as passive discoverers or neutral describers of reality but as active creators of knowledge. Moreover, as Knorr-Cetina (1995, 1999) describes, virtually all SSK ethnographies have demonstrated that, although a general methodology may guide scientists, the actual day-to-day practices of science are far less systematic than one might presume. Instead, knowledge production is shown to be characterised by local decision-making processes, continued negotiations between different actors,[14] and idiosyncrasies that exist at a particular time and place but are integral to everyday research (Sismondo, 2010). These processes and routines are what Knorr-Cetina termed 'epistemic cultures', which are "those amalgams of arrangements and mechanisms – bonded through affinity, necessity, and historical coincidence – which, in a given field, make up *how we know what we know*" (Knorr Cetina, 1999: 1). Rather than driven solely by rational, systematic, and technical procedures, scientific work has been shown to involve a great deal of *tinkering*, *interpretive flexibility*, and *indexical reasoning* (Collins, 1981; Knorr Cetina, 1981, 1999; Lynch, 1985, 2019). The consequence of this is that the products of science are *occasioned* (Knorr Cetina, 1981, 1983); that is, the circumstances of their production mark their characteristics and meanings. In summary, what microsocial studies of science have revealed is that "nothing epistemologically special is happening" (Knorr Cetina, 1995: 151) during the production of scientific knowledge. In that sense, it is not distinct from "other" knowledge-producing systems.

2.3.5. The Turn to Technology

The developments within SSK's empirical studies encouraged the field to diversify and extend in new directions. Of particular note is the 'turn to technology' that came about during the mid-1980s (Woolgar, 1991). Many of the principles and concepts developed within SSK seemed equally applicable to technology. Hence, various attempts were

[14] Negotiations are not limited to the practising scientists but also involve a broad range of external agents such as funding agencies, the broader scientific community, and wider social, political, economic groups.

made by historians and sociologists to establish a social constructivist framework for studying technological systems.[15]

Bijker *et al*. (2012) describe three distinct approaches that came to represent the "new" program of the social construction of technological systems (SCOTS): The *social construction of technology* (SCOT), *Large-Scale Technological Systems* (LTS), and *actor-network theory* (ANT). Although these approaches differ in their theoretical and methodological focus, several common traits influenced their initial development (see Bijker *et al*., 2012):

1) The three approaches were supported by the same overarching goal: to incorporate *technology* within the agenda of social studies of science.
2) They all set out to challenge the over-idealised divisions between science and technology, arguing that the boundaries between the science and the technical are far more complex and dynamic than previous studies had implied.
3) All three approaches emphasised the importance of developing theories through detailed empirical investigations.

These traits represent a general constructivist programme for studying technology, whereby the broad aim is to develop an understanding of the relations between science, technology, and society. Where the three approaches differ is to which aspect of society they predominantly focus: SCOT focusses on social groups, LTS on systems, and ANT on networks of human and non-human actants.

Pinch and Bijker (1987) established the first social constructivist approach in the study of technology: SCOT. The principal arguments underpinning SCOT's initial formation were that *both* science and technology are socially constructed cultures and that the boundary between them is, in itself, socially constructed. Contrary to earlier studies of technology that tended to treat science and technology as distinct entities, Pinch and Bijker propose that an integrated social constructivist approach to the study of science *and* technology could provide some productive insights into their interdependencies.

SCOT draws many theoretical and methodological similarities with SSK. Similar to SSK's rejection of positivism, an important starting point for SCOT is a critique of technological determinism. The term 'technological determinism' is commonly used to describe two basic claims about the relations between technology and society (Kline, 2015): firstly, that technology develops autonomously in accordance with an independent, technical logic; and secondly, that technology determines how society develops. Regarding these claims as overly simplistic and politically debilitating, proponents of SCOT argue instead that technologies should be understood as an

[15] Bijker *et al.* (2012) outline 3 meanings of 'technology': 1) physical objects or artefacts; 2) activities or processes; and 3) it can refer to what people *know* and how they act e.g., the *know-how* associated with operating a machine.

outcome of the negotiations and interactions of the particular social contexts in which they are developed (Bijker, 2015).

Drawing significantly from the Strong Programme and EPOR, SCOT calls for the symmetrical and impartial analysis of technological artefacts. Central to this is the notion that social groups are actively involved in shaping the nature of technologies: the social groups define the meanings and problems attached to technologies during their development and, as such, they determine the success or failure of a particular technological artefact. As with scientific knowledge, the same kinds of social explanations are involved in the acceptance or rejection of technologies. For example, using the history of the bicycle as a case study, Pinch and Bijker (1987) present technological development as a non-determined, *multidirectional* process in which the nature of technology is shaped and re-shaped through continued negotiation. The case study stresses the interpretative flexibility of technologies: technological artefacts hold variable meanings, problems, and solutions for different social groups. In the case of the bicycle, different social groups (e.g., women, older men, sports cyclists) are shown to have conflicting technical requirements (e.g., speed, safety, aesthetics), depending on their prevailing socio-cultural norms and values. These different requirements give rise to varying problems and possible solutions, which often extend into legal or moral issues. The example highlights the multiple different directions the developmental process of a technological artefact can follow, illustrating that its design is not inevitable. For Pinch and Bijker, this raises important questions over how and why specific interpretations are selected over others and how *closure* is achieved in practice.

The approach of LTS extends the work of SCOT to include more complex and large-scale technological systems, such as electrical power and rail networks (Hughes, 1983, 1987). Large-scale technological systems are made up of various integrated components, including physical artefacts, such as transmission lines or trains; organisations, such as manufacturing firms or investment banks; and elements that are often considered scientific, such as books, articles, and even research programmes (Hughes, 1987). Hughes describes these systems as "both socially constructed and society shaping" (1987: 45). Each system component is invented, designed, and developed by the system builders who draw upon the necessary economic, political, cultural, and material characteristics to ensure its persistence. These characteristics become embedded in the system's structure, holding the system in place and influencing its societal applications. In turn, large-scale technological systems exert a powerful influence across all levels of society. In this sense, the LTS approach encourages us to view the relationships between science, technology, and society as a 'seamless web' of networks and systems (Hughes, 1983, 1987).

Later work by Callon (1987), Law (1987), and Latour (1987, 2005) extends the idea of a 'seamless web' within the framework of ANT. ANT represents a general social theory

centred on *technoscience* – a term used to stress the entangled relations and causal interdependencies between science, technology, and society (Sismondo, 2010). Although ANT often falls within the broad rubric of SSK and social constructivism, the approach rejects the emphasis placed on the *social*, arguing that what constitutes 'social', 'technical', 'scientific', or 'material' are inherently connected (Hess, 1997). In this sense, it can be understood as a post-humanist theory of knowledge, which Pickering describes as "one that recognizes from the start that the contours of material and human agency reciprocally constitute one another" (2001: 164).

The central proposition of ANT is that *everything* exists in continually shifting and heterogeneous networks of associations between human and non-human actors (Sismondo, 2010). Critically, ANT asserts that all elements of actor-networks are relational; that is, the qualities and properties of objects, ideas, processes, interests and so forth are not innate but are the products of the particular networks in which they are bound (Law, 1999; Latour, 2005). In this framework, the success of science and technology depends upon the relations between actors and their associations engaged in scientific practice. An actor can be understood as anything that influences the production of knowledge, such as scientists, background assumptions, institutional practices, methodologies, instrumentation, and scientific texts (Detel, 2001). According to ANT, all these actors are equally important for how we conceive and interpret knowledge. As such, ANT extends the Strong Programme's principle of symmetry to encompass both human and non-human entities in its analysis.

Within the framework of ANT, Latour developed the notion of *immutable mobile*s (Latour, 1987). An immutable mobile is an object (e.g., a map, a book, a diagram, a photograph), produced through a network, that maintains its shape (physically and functionally) when moving from one location to another. As Latour describes, a map is the perfect example of an immutable mobile; a map is transportable, the land it represents is not. The map gains its status as an immutable mobile through the *network* that surrounds its production. This includes cartographic theory, mapping technologies, ships, navigators, sensing devices, oceans, money, and earlier maps (Law and Mol, 2001). Each of these components plays a vital role in maintaining the configuration of the map and the knowledge it communicates.

Latour argues that the immutability of maps was crucial to how Western scientific knowledge gained its power and authority (Latour, 1987). As cartography became progressively scientific following the Enlightenment, involving the adoption of common principles and standardised procedures (Section 2.4.2), maps increasingly acquired the status of immutable mobiles (Latour, 1987; Kitchin *et al*., 2012). The conventionalised nature of scientific mapping meant that a map produced in a distant land could be deciphered by anyone who shared the same cartographic principles. In this way, the map stabilised knowledge of space and became a crucial "vehicle through which spatial

knowledge can be transported into new contexts" where it can be used to bring about action in the world (Kitchin *et al*., 2012: 18). In other words, maps gained power outside of their place of production as communication tools; they became a method of long-distance control (Law, 1986; Turnbull, 1993). Section 2.4.4 builds on these ideas further within critical cartography.

The turn to technology has drawn attention to the difficulties in separating what constitutes the scientific, the technical, the material, and the social, prompting a more holistic and integrated view of the entangled relations between knowledge and society. The term 'social constructivism' was joined by new terms such as 'co-constructivism', 'co-production', or 'post-constructivism' (Hess, 2001). Adopting these new terms represents a desire to extend beyond SSK's emphasis on social factors to account for the role of non-social and material aspects in the production of knowledge.

2.3.6. Co-production and the Politics of SSK

Since the 1990s, the idiom of co-production has been ubiquitous within STS (Felt, 2017). Taking influence from many of the (social) constructivist insights yielded by SSK and SCOTS, co-production offers a way of conceptualising the entangled relations between science, technology, nature, and society (Jasanoff *et al*., 1995). In short, co-production proposes that "the ways in which we know and represent the world (both nature and society) are inseparable from the ways in which we choose to live in it" (Jasanoff, 2004a: 2). The idiom promotes a systemic understanding of scientific knowledge production, in which scientific knowledge and social order simultaneously shape each other: "[scientific knowledge] both embeds and is embedded in social practices, identities, norms, conventions, discourses, instruments and institutions" (Jasanoff, 2004a: 3).

Co-production focusses our attention on the complex interrelations between knowledge and power, prompting questions about how the production of science and technology is incorporated into state-making practices, and conversely, how the structures and institutions of governance shape knowledge-producing activities (Jasanoff, 2004a). In this sense, the key questions associated with co-production are generally tied to issues of accountability, democracy, and participation in the production and implementation of scientific knowledge (Sismondo, 2008; Harding, 2009; Felt, 2017). It points towards questions such as who actively participates in knowledge production, who decides what constitutes good scientific knowledge for policy action, whose values are included (or excluded) in the framings of scientific and policy issues, and how can science be made more democratic and more accountable to the public?

Co-production has also been an important source of critique for SSK. From the co-productionist viewpoint that knowledge and society are mutually co-constitutive, early SSK investigations have faced criticism for being too uncommitted to the implications of

their findings for scientific and public discourse (Felt, 2017). Various commentators within STS have criticised SSK for demonstrating the social contingencies of knowledge but shying away from its political and cultural implications and responsibilities (e.g., Jasanoff *et al.*, 1995; Jasanoff, 1996; Richards and Ashmore, 1996). Similar criticisms have been aimed at SCOT. For example, Winner (1993) criticised SCOT for explaining how technologies are constructed but failing to present alternative interpretations or critically engage with the consequences of its findings. These critiques were part of a wider discussion during the 1990s that centred around debates about if, and how, the field of SSK should be involved in broader political concerns.

For the most part, debates over the politics of SSK have centred around the methodological principals of symmetry and impartiality that have characterised the field's preoccupation with epistemology.[16] Hess (2001) labels the microsocial studies in SSK as the 'first generation' ethnographies of STS, with their focus predominantly motivated by epistemological concerns. Owing to SSK's commitment to symmetry and impartiality, first-generation analyses tended to remain descriptive and rarely engaged explicitly with the normative implications brought about by constructed knowledge (Richards and Ashmore, 1996; Radder, 1998). For many, this neutral stance was essential to the legitimacy of SSK's claims: the idea that SSK should prescribe alternative interpretations or policy recommendations was considered to be irreconcilable with the field's reflexive and relativist approach to the study of scientific knowledge (Jasanoff, 1996). In a similar vein, although recognising that complete impartiality may not be possible in practice, Collins (1996) argued that striving for a neutral approach to examining knowledge was essential to ensuring that knowledge claims are evaluated based on the merits of their causes, rather than the preconceived biases of the SSK researcher.

Others, by contrast, have claimed that SSK's insistence on neutrality posed various potential political and moral problems. Based on their own research experiences, Scott *et al.* (1990) contended that methodological and social neutrality breaks down in practice, particularly in contemporary scientific controversies that involve matters of public interest. They argued that, through their interactions with research participants in the field, SSK analysts cannot avoid being 'captured' by a particular side of a debate. Similarly, Ashmore (1996) used case studies of specific scientific controversies (the health effects of smoking and the NASA Challenger disaster) to caution against SSK analysts being unwittingly captured by the "wrong side". The concern here is that through their preoccupation with methodological relativism, SSK analysts run the risk of serving ethically questionable or undemocratic political ends.

[16] See *Social Studies of Science*, Volume 26 Issue 2, May 1996.

For others, particularly those who favour the idiom of co-production, SSK's absent engagement with normative issues has been attributed to its relatively narrow and internalist focus. In showing that scientific knowledge is, at least to some degree, shaped by social forces, Jasanoff (1996, 2004a) and Richards (1996) insist that the work of SSK is inherently political and destabilising. Through interrogating the nature of knowledge and the structures that produce and sustain it, SSK opens up scientific practices to critical scrutiny and provides the resources through which the dominant order of society can be questioned. However, the early microsocial accounts of knowledge production rarely addressed the complex interplays between the micro-worlds of scientific practice and broader social and political thought (Wynne, 1996; Jasanoff, 1996, 2004a; Knorr Cetina, 2005). They rarely extended beyond the site(s) of knowledge production to account for how the broader social, cultural, and political structures shape scientific practices or how alternative voices and perspectives may give rise to different interpretations (Winner, 1993; Wynne, 1996). As such, they often lacked the depth and critical insight to prescribe policy recommendations or articulate alternative ways of knowing.

The symmetrical and impartial study of scientific practices should remind us that knowledges are contingent, shaped, and open to alternative interpretations (Law, 1990; Jasanoff, 1996; Richards, 1996). It should help reveal the entangled relations between knowledge and power and the ways through which scientific knowledge reflects and reinforces particular interests and values. For SSK to effectively engage with normative concerns, analyses must extend beyond the place of knowledge production and include a range of perspectives, preferences, and practices that sit outside of the dominant structures (Hess, 2001; Jasanoff, 2008). For Richards (1996), the responsibility of SSK analysts is to ensure that deconstructive critiques of knowledge production are comprehensive and located within their institutional and socio-political contexts. In this sense, they must extend beyond the microscale practices of knowledge production to study knowledge in relation to the broader cultures in which it is embedded (Knorr Cetina, 2005). Moreover, the analysts must be moderated by a reflexive self-awareness of how their own experiences and position in society affect their interpretation of knowledge production and implementation (Wynne, 1996) and a reflexivity to the situatedness of knowledge (Haraway, 1988). It is only then that 'better' and more equitable forms of knowledge can be realised.

More recent studies in STS have used the co-productionist perspective to inform empirical inquiries of scientific knowledge that account for the entangled relations between science, technology, nature, and society. These are often termed 'post-constructivist' approaches or 'second generation' ethnographies (Hess, 2001; Wehling, 2006). These later empirical studies differ from early SSK in that they extend beyond epistemological concerns and into the political and cultural connotations of their findings. As such, later studies have tended to address social problems that are of clear

political significance (e.g., climate science, environmental, gender, ethnicity, class, coloniality, indigeneity); broadened their focus beyond the site(s) of knowledge production and involved multi-sited approaches; and included a variety of different voices and perspectives in their analyses.[17] The foundations of (social) constructivism remain central to their analyses; however, the focus is less directed towards describing knowledge construction processes and more to questioning how knowledge might be constructed in more equitable ways (Hess, 2001; Harding, 2009; Felt *et al.*, 2017 and references within). The issue of constructed knowledge becomes foregrounded in the concepts of power and culture: through systematically addressing and linking micro and macroscale conditions, questioning how science and technology reinforce particular cultural meanings and structural inequalities becomes a central focus (Jasanoff, 2004a; Felt *et al.*, 2017).

2.3.7. STS and Geography

Social constructivist perspectives have gained a foothold in STS because they offer necessary means for critiquing the positivist assumption that scientific knowledge can provide objective, neutral, and authoritative answers to many of society's issues. In contending that the practices, and thus, outcomes of science are unavoidably social, they encourage questions about how social and cultural factors shape scientific knowledge production, who is involved in those production processes, and whose perspectives and voices are marginalised. Geographical scholarship has made important contributions to these debates in recent decades. Broadly, geographers have drawn on and complemented the arguments of STS through critically and reflexively engaging with the social construction of geographical knowledge, examining the spatially situated nature of scientific practice, and addressing ontological and socio-material questions about the agency of human and non-human actants in the production of knowledge (Powell, 2007; Mahoney and Hulme, 2018).

Historical geographers have had particularly influential engagements with the 'spatial turn' in STS, which emphasises the importance of *spatiality* in shaping how scientific knowledge is produced, consumed, and circulated (e.g., Withers 1999, 2002; Livingstone, 2003, 2005). In *Putting Science in its Place*, Livingstone (2003) draws attention to the disparate sites and locations where science is practiced. These sites include conventional places such as laboratories, museums, and workshops, but also cathedrals, ships, coffeehouses, and outdoor spaces. Like the microsocial studies of SSK (Section 2.3.4), Livingstone shows how the *place* of scientific inquiry conditions the nature of scientific activity and its resultant knowledge. Locally situated material resources and cultural

[17] Examples include: Haraway, 1988; Keller, 1995; Watson-Verran and Turnbull, 1995; Shackley and Wynne, 1996; Wynne, 1989, 1992 1996; Espeland, 1998; Lahsen, 2005; Miller and Edwards, 2001; Miller, 2004; Edwards, 2010; Daipha, 2015; Beck *et al.*, 2017; Fox *et al.*, 2017; Powell, 2017.

norms are among the factors shaping knowledge production; for example, the equipment available at a particular site regulates human behaviour and constrains the types of knowledge that can be produced, a site's architecture shapes how practitioners socialise and organise themselves around a shared activity, and each site is characterised by its own set of values, norms, and conventions that influence how (and by whom) scientific practices are carried out. These localised contexts, in turn, are socially defined and shaped by broader cultural norms and activities. Livingstone (2005) further argues that the consumption and circulation of knowledge is geographically contingent: different people interpret knowledge in different ways depending on various cultural, political, and historical conditions.

Along a similar line of critique, other historical geographers have examined the various networks, institutions, and arrangements that are mobilised across various spatial scales in the construction and circulation of knowledge. For example, in examining European knowledge about non-European regions, Arnold (2000), Driver and Yeoh (2000), and Martins (2000) illustrate how conceptions of the 'tropics' during the nineteenth and twentieth centuries emerged through complex interaction between the *in situ* encounters of travelling naturalists (e.g., Humboldt and Darwin), the disciplinary standards and aesthetic conventions attached to European institutions, and the interests and perceptions held by westerners more broadly. These interactions were an important means by which knowledge became accepted and transported across different spatial contexts. In short, the work of historical geographers exemplifies how the credibility of truth-claims is *spatially contingent*, opposing the long-standing ideal that scientific knowledge is 'placeless' and provides a 'view from nowhere' (Nagel, 1986).

Other sub-disciplines of geography have also had productive engagements with STS. Geography, particularly physical geography, has long been recognised as a scientific discipline. Thus, there is a need to critically and reflexively engage with the practices involved in the production of geographical knowledge (Powell, 2007). As Greenhough (2009) reviews, this need has been encouraged and facilitated by changes in the discipline over recent decades. The increasing focus of the social sciences and humanities on culture and critical theory since the 1970s has given way to a growing divide in geography between those who study nature and the environment using scientific modes of inquiry and those who draw from postmodernist, feminist, poststructuralist, and postcolonial debates to (re)interpret the world and the interrelationships between people, place, and the environment. During the 1980s and 1990s, several sub-disciplinary fields, including radical geography, humanistic geography, and feminist geography, emerged under the general guise of *critical geography* to investigate the socially contingent and constructed qualities of geographical knowledge. In particular, there was a growing interest in how *nature* is constructed through scientific inquiry (Whatmore, 2008; Section 2.4).

Early debates over the construction of geographical knowledge about nature centred largely around epistemological questions of representation, language, and discourse (Harley, 1989; Demeritt, 1996; Müller, 2015). In critiquing the positivist ideals underpinning scientific inquiry, Marxist geographers claimed that geographical discourses about the natural world were deficient because they failed to sufficiently capture the interdependencies between the environment and social structures. For example, Harvey (1974) and Peet and Watts (1993) contended that capitalist consumption patterns contribute to many of the environmental issues facing society and the unequal ways in which their impacts are felt. Thus, they argued that to represent environmental problems in an ethically neutral way, geographical knowledge must account for socio-economic relations. Following a similar line of critique, feminist geographers have argued that the physical sciences do not provide objective and value-free accounts of nature; rather, scientific thought and the production of scientific knowledge favours male perspectives. Within this line of critique, studies of the content, theory, methods, and institutionalised spaces of geography found women to be commonly excluded, marginalised, and discriminated against (e.g., Zelinsky, 1973; McDowell and Peake, 1990; Domosh, 1991). As Demeritt (1996) describes, such findings were apparent across the sciences. Thus, the initial agenda of feminist critique was one of equality and reformation (Johnson, 2012); that is, the production of geographical knowledge (and scientific knowledge more generally) could be made more balanced by improving the inclusion and representation of women in scientific disciplines (Harding, 1986; Demeritt, 1996).

Geographers have taken influence from other feminist scholars such as Sandra Harding, Louise Johnson, and Nancy Harstock, who have unpicked objectivity more comprehensively. For example, Harding argues that *all* knowledge is partial and unavoidably social: "[the] products of thought bear the mark of their collective and individual creators, and the creators in turn have been distinctively marked as to gender, class, race, and culture" (Harding, 1986: 15). In recognising that scientific rationality has permeated all aspects of culture, from public thought and action through to the "ways we think about the most intimate details of our private lives" (1986: 16), Harding problematises the very notions of 'objectivity' and 'rationality', arguing that accredited scientific knowledge is rooted in sexist and androcentric biases. This early work has been highly influential to the notion of *strong objectivity*: a term developed by Harding, which suggests that knowledge can be made more equitable through diversifying the values, interests, and assumptions that inform its production (Harding, 2015). Unlike earlier feminist debates, strong objectivity is *transformative* in its agenda; that is, it opposes the conventional positivist notions that objective knowledge can ever be wholly neutral or synonymous with "truthlike".

While recognising that early uses of constructivist arguments by Marxist and feminist geographers offered important critiques of the privilege and authority enjoyed by Western science, Demeritt (1996) argues that they were overly focussed on epistemological concerns and abstract postmodern theories about the (un)truthfulness of scientific *representations* of nature. For Demeritt, they lacked the detailed focus seen in SSK on the scientific *practices* through which observations of nature become shaped, manipulated, and transformed into authoritative knowledge (Section 2.3.4). Moreover, Demeritt contends that the focus on postmodern questions of representation skirted closely to arguably irresolvable meta-physical debates about the nature of reality. Whatmore (2008) voices similar concerns, arguing that early constructivist critiques in geography encouraged crude dichotomies between 'the natural' or 'the social' and 'the realist' or 'the constructivist'. Thus, such critiques were subject to the same criticisms experienced by the Strong Programme (Section 2.3.3).

The need to move beyond the caricatured divisions between the human and the natural, the social and the material, has prompted a shift in geography towards viewing scientific knowledge in more relational and processual terms. As Müller (2015) reviews, calls for the 're-materialisation of geography' have seen geographers increasingly take influence from ANT and the co-production of knowledge (see Sections 2.3.4 and 2.3.5). The focus on socio-material networks put forward by ANT emphasises the equal importance of human and non-human actants in the production of knowledge (Whatmore, 2008). For geographers, recognising the agency of non-human actants (e.g., buildings, pipelines, glaciers), as opposed to thinking about them as passive objects, has offered productive ways for re-thinking the relations between power, politics, and space.[18] Similarly, the notion of co-production exemplifies how our knowledge of the natural world is always culturally situated (Jasanoff, 2004a). For geographers, such perspectives provide the means to question why spatial orders or knowledge claims emerge in particular ways, what holds them together, and how they can be transported across space (Mahony and Hulme, 2018; see Section 2.3.4 on *immutable mobiles*).

Within the last two decades, geographers have contributed to similar debates over the role that sensing practices and technologies play in shaping environmental knowledge. Notable writings within this body of work include Pickles (2004), Dodge and Perkins (2009), Sörlin and Wormbs (2018), Gabrys (2019), and Lehman (2018, 2019). Although focussing on quite different scientific and technological fields, a common argument these studies put forward is that the knowledge produced through sensing practices and technologies is not merely a representation of the environment. Rather, sensing practices and technologies *make* the environment; they shape and structure how the environment

[18] Some notable examples of studies that have taken influence from ANT to illustrate the co-constitutive role of human and non-human actants in shaping spatial orders or knowledge claims include Sundberg (2008), Blok (2010), Collard (2012), Barry (2001, 2013).

is seen, perceived, and understood, and give rise to various possibilities for political and cultural engagement.

More recent geographical scholarship taking influence from STS has developed in the form of *critical physical geography* (CPG). CPG is an emerging body of work that questions how and where physical geographers operate while critically engaging with scientific representations of the world and their role in shaping social and natural systems (e.g., Castree, 2014; Lave *et al*., 2018). As outlined in Lave *et al*. (2018), three core intellectual tenets underpin CPG:

1. Structural power relations and the natural world are deeply intertwined: most landscapes are shaped by human actions and social inequalities.
2. The same power relations inform and govern the scientific practices used to study landscapes: they shape who studies them, what questions are asked, how research is conducted, and how observations are interpreted and represented.
3. The knowledge produced through physical geography significantly impacts people and landscapes.

From the core tenets listed above, there is clear overlap between the theoretical foundations of CPG and STS. In particular, CPG takes scientific knowledge to be inextricably social and it calls for scientific knowledge production to be analysed in its local terms (Lave *et al*., 2018). However, as Lave *et al*. contend the two fields differ markedly in terms of their methodological approaches to studying knowledge production. Generally, practitioners of STS use social science methods to examine scientific practice: science is the *object* of study. In contrast, CPG emphasises the importance of integrating the methods, theories, and insights of physical and human geography in the study of scientific knowledge production. In this sense, physical geography is not simply the object of study, but central to how CPG is practiced.

The need for an integrated approach is underpinned by two key arguments (Lave *et al*., 2018). Firstly, CPG advocates for physical geographers to be more critical about how social and political factors shape their work. Unpicking this argument further, Lave *et al.* acknowledge that physical geography is not an inherently uncritical discipline; that is, physical geographers are critically aware of the complexities of the systems they study, the partial nature of their knowledge claims, and the social and political constraints on day-to-day research activities (e.g., funding priorities, access to technologies, institutional politics). However, CPG contends that physical geography would benefit from a more introspective and reflexive analysis of how social inequalities and power relations shape scientific knowledge construction. Secondly, CPG calls for human geographers to engage more explicitly with the material concerns of the natural sciences. In practice, this requires human geographers to move beyond theory-laden analyses of social processes and towards adopting methods from the physical sciences. Lane *et al.*

(2018) argue that a more integrative approach may help to expose the inherent biases, uncertainties, and power relations present in scientific knowledge production. It also reflects a relational and co-productionist view of the environment: if the environment is co-produced through the entanglements between science, technology, nature, and society, then material concerns cannot be overlooked in sociological studies of physical geography and *vice versa* (Jasanoff, 2004a).

2.4. Critical Cartography

2.4.1. Introduction

> Maps are neither mirrors of nature nor neutral transmitters of universal truths. They are narratives with a purpose, stories with an agenda. They contain silences as well as articulations, secrets as well as knowledge, lies as well as truth. They are biased, partial, and selective. (Short, 2003: 24).

A principal concern in this PhD research is to study how sea-ice data products (maps and other forms of graphical representation) are developed within particular social settings. For centuries, maps have been an essential means for visualising and communicating Arctic sea-ice conditions, and since the introduction of satellites for climate monitoring, the importance of maps has profoundly increased (see Chapter 4). However, like other forms of scientific knowledge, this thesis takes maps to be the product of particular social, cultural, and historical contexts. As such, they cannot be accepted uncritically as objective and neutral representations of Arctic sea-ice conditions. This broadly social constructivist understanding of maps has been developed within the critical cartography literature over recent decades.

The above quote captures many of the fundamental concepts of critical cartography that are central to a critical examination of Arctic sea-ice maps. Critical cartography emerged as an interdisciplinary field during the late 1980s and was part of the broader critique of knowledge production occurring across the humanities and social sciences. In a general sense, the field challenges the perception of maps as objective and neutral representations and questions their relations with broader systems of power and socio-political contexts (Crampton and Krygier, 2006). The field involves both the theoretical critique of maps (e.g., Harley, 1989; Kitchin and Dodge, 2007; Wood and Fels, 2008; Wood, 2010) and the development of alternative, more democratic forms of cartographic practice (e.g., Peluso, 1995; Harmon, 2004). Various theoretical and practical developments within critical cartography have been established. These have offered important insights into the nature of maps, the factors that have shaped their production and distribution, and their role within society.

The following sections outline some of the key theoretical developments that have influenced the approach taken in this thesis. In particular, I draw upon the social

constructivist perspective initiated by Harley (1988a, 1988b, 1989), which argues that maps are socially constructed representations that reflect and reinforce particular social and cultural norms and values. Developing on this, I draw from some of the post-representational approaches that view maps as propositions (e.g., Wood and Fels, 2008) and inscriptions of power (Pickles, 2004). Lastly, I have taken influence from the more recent developments in critical cartography that have argued for a *processual* view of maps, in which maps are actively (re)made and (re)interpreted in relational and contextual terms (Kitchin *et al*., 2012).

2.4.2. Cartographic Positivism

In various scientific contexts, the primary aim of modern cartographic practice is to capture and represent spatial data as accurately as possible.[19] To achieve this aim, the production of maps is guided by scientific techniques and conventions that ensure a certain degree of coherency and objectivity and enable associations to be made between the features on the map and features of the real world (Kitchin *et al*., 2011). Maps produced for scientific purposes are often accepted as objective, apolitical, and value-free descriptions of reality (Wood, 2010; Kitchin *et al.*, 2011). As such, they provide representations of spatial order that are often taken as natural.

The assumptions underpinning modern cartographic practice are part of the broader positivistic tradition that has guided the production of scientific knowledge since the Enlightenment Period (Cosgrove, 2005; Section 2.3.1). Although the recognition of cartography as a formal discipline can be traced back to the nineteenth century, significant shifts towards scientific mapping have predominantly occurred over the last 60 years (Crampton, 2010). As Robinson *et al*. (1977) reviewed, the recognition of cartography as a formal scientific discipline accelerated during the post-war era. Technological innovations, initially in plastics, photogrammetry, and photolithography, and later in the form of electronic devices, computers, and remote sensing applications, greatly improved the capacity to obtain and reproduce observational information with precision. Moreover, the Second World War witnessed an unprecedented demand for maps, resulting in a general recognition of the potential uses of mapping for ongoing military and civilian purposes. Together, these changes prompted the development of formal cartographic principles and theories, through which mapping became increasingly scientific.

Improving the accuracy of mapping was high on the cartographic agenda in the post-war era. Particularly notable contributions to this effort came out of the work of Arthur Robinson (Robinson, 1952; Robinson and Petchenik, 1976; Robinson *et al*., 1995), who

[19] I use the term 'modern' to describe the formal, scientific discipline of cartography that emerged during the nineteenth century.

developed a theory in cartography that characterised maps as formal systems of communication. Within this approach, maps were tools through which 'real world' information could be represented and transmitted to various recipients. The primary aim of the cartographer was to produce efficient and functional maps that placed the needs and preferences of the users at the centre of map design (Robinson and Petchenik, 1976). The use of objective and empirically derived scientific techniques was considered essential to map efficiency and functionality; that is, the design of maps should be guided by logic and reason, not by subjective choices or aesthetic inclinations (Robinson and Petchenik, 1976). In this view, cartography's progress was measured by cartographers' ability to optimise the effectiveness of communication by reducing representational errors and refining map design (Kitchin *et al*., 2012). In other words, through improving technical aspects such as scale, projection, and data classification, maps become increasingly accurate (or 'truthful') representations of the spatial relations they seek to depict (Harley, 1989; Kitchin *et al*., 2012).

By the 1960s and 1970s, the communication theory of cartography became widely adopted within the discipline (Pickles, 2004). One important implication of this functionalist and instrumental approach was the positivist presumption that maps could provide value-free representations if scientific methods are applied (Crampton, 2010). This emphasised the distinctions between 'artistic' and 'scientific' maps (Table 2.1). The former were considered to be prone to subjective and ideological influences and, as such, could not be relied upon as effective and functional forms of communication (Robinson and Petchenik, 1976). Conversely, the use of ordered and coherent techniques by scientific maps came to be seen as the necessary characteristics of 'proper', unbiased, and reliable forms of mapping (Crampton, 2010).

Table 2.1.: Features of 'artistic' and 'scientific' maps. *Source:* Crampton (2010).

"Artistic" Maps	"Scientific" Maps
Aesthetic	Non-aesthetic
Autographic	Anonymous
Imaginative	Factual
Subjective	Objective
Inaccurate	Accurate
Manual	Machine
Old	Modern
Place	Location

2.4.3. The Critical Turn: Maps as Social Constructions and Expressions of Power

Sharing notable parallels with SSK, the emergence of critical cartography during the 1980s prompted the re-evaluation of the positivist epistemology of modern cartographic

practice. Rather than viewing cartography as an objective and neutral pursuit, critical scholars presented an alternative interpretation in which maps are understood as social constructions and expressions of power (Crampton and Krygier, 2006). As this line of critique gained traction, the dominant interest in pursuing accurate forms of mapping through technical refinements was joined by a growing desire to interrogate the role maps play in shaping how space is conceptualised and acted upon in society.

Early developments in this critical perspective are most commonly associated with the influential work of Brian Harley. Harley's critique departed from an understanding of maps as "graphic representations that facilitate a spatial understanding of things, concepts, conditions, processes, or events in the human world" (Harley and Woodward, 1987: xvi). Harley (1988a, 1988b, 1989) contended that maps do not simply communicate reality. Rather, they present a version of reality that reflects and reinforces particular social and cultural norms and values. For Harley (1989), the production of a map involves constructing knowledge through the social processes of interpretation, selection, and styles of representation. Thus, the production inevitability consists of subjective and value-laden decisions about the map's content and design (Harley, 1988a; Monmonier, 2018). Harley argued that the values imbued in maps reflect the perspectives and interests of the mapmaker(s), which, in turn, are shaped by their place in society (Harley, 1988a). It is in this sense that maps are seen as social constructions and expressions of power: "[b]oth in the selectivity of their content and in their signs and styles of representation, maps are a way of conceiving, articulating, and structuring the human world which is biased towards, promoted by, and exerts influence upon a particular set of social relations" (Harley, 1988a: 53).

In contrast to the positivist view of maps as objective and neutral communication tools, the social constructivist critique has developed an understanding of maps as cultural texts laden with conscious and unconscious forms of social bias (Harley, 1989; Turnbull, 1993). Various authors have demonstrated how particular conscious and unconscious biases and ideologies come to be present in maps through the decisions and choices that occur during their production and interpretation (e.g., Harvey, 1988a, 1989; Dodge and Kitchin, 2000; Wood and Fels, 2008; Wood, 1992, 2010). For example, through a structuralist examination of the Official State Highway Map of North Carolina, Wood and Fels (1986) draw attention to the multiple levels of meaning present in maps. Influenced by Barthes' semiotics, they argue that maps have narratives: the codes and conventions used in the map design have a deeper meaning (or a 'second text') that serves the interests, motives, and ideologies of the mapmakers. Others have stressed the experimental freedom that characterises the production of maps: "*a single map is but one of an indefinitely large number of maps that might be produced for the same situation or from the same data*" (Monmonier, 2018: 2). This freedom enables the mapmaker to make

judgements and choices that best represent the desired purpose of the map or the motives of the mapmaker.

Collectively, these critical studies have illustrated that maps are not merely descriptive tools. Rather, they convey spatial relations in a way that inherently embodies and privileges the values and interests of the mapmakers situated within their socio-political and cultural contexts (Turnbull, 1993; Pickles, 2004). Nevertheless, through the use of conventional signs and practices, maps possess the power to produce spatial order in a way that is often taken as *natural*. In a similar vein to the process of *decontextualization* noted in Section 2.3.4, the use of scientific conventions has the effect of making maps appear value-free and objective, simultaneously masking the inherent cultural, political, and ideological interests that they embody (Wood, 1992; Turnbull, 1993).

Through maps, certain 'realities' or ways of seeing the world become naturalised. As a consequence of this, other elements of society are marginalised and silenced. The notion of cartographic silencing (Harley, 1988a, 1988b) is central to the idea that maps are both products and producers of particular power relations. Harley (1988b) describes cartographic silencing as the intentional and unintentional suppression of knowledge that occurs during the production of maps. Silencing can occur at various stages of map production, for example, during data collection and processing, through styles of representation, and during printing and publication (Harley, 1988b). It can occur in purposeful and even sinister ways through which particular aspects of reality are intentionally manipulated, falsified, or censored for strategic and commercial purposes. But silencing can also be an unintended consequence of mapping. As Monmonier (2018) describes, for maps to be useful, they must provide a selective and incomplete representation. This necessitates the deliberate removal or distortion of particular aspects of reality. By using scales, projections, and symbology, scientific maps tend to produce simplified, general, and abstract representations. Although this is necessary to ensure that the map features of interest are readily intelligible, it has the effect of silencing and homogenising real-world complexities (Harley, 1988a). In particular, maps tend to "desocialise" the territory they represent; that is, they produce a view of the world that is socially empty (Harley, 1988a, 1988b). The consequence of this is that it helps remove the "burden of conscience about people in the landscape" (Harley, 1988a: 81). This speaks to the psychological power of maps to shape our perceptions, attitudes, and emotions and how maps can be used to legitimise certain forms of political action and territorial appropriation (Harley, 1988a, 1988b; Bennett *et al*., 2016).

Cartographic silencing is particularly pertinent in relation to maps of the Arctic. As Steinberg *et al.* (2015) illustrate, imaginaries of the Arctic vary considerably between different interest groups and give rise to contesting ideas of how the Arctic is to be known, framed, and lived in the present and future contexts. Depending on one's perspective and experiences, the Arctic may represent a resource frontier to be exploited,

a homeland where people experience their everyday lives, a unique and sensitive environment to be preserved and protected, or simply a space of transit for international commerce. As various studies have shown, maps play an integral role in perpetuating particular imaginaries of the Arctic and subverting others (e.g., Strandsbjerg, 2012; Bruun and Medby, 2014; Bennett *et al*., 2016; Steinberg and Kristoffersen, 2017). For example, through critically examining the different ways that state and Inuit maps articulate the Canadian Arctic, Bennett *et al*. (2016) show how the state uses cartographic practices to define, order, and structure physical space in such a way that marginalises Indigenous communities in terms of economic support, national programmes, and identity. Through binary classifications, straight lines, and distinct boundaries, the living resources, communities, and human experiences of the Arctic are silenced. As Bennett *et al*. illustrate, this has direct geopolitical consequences for how the region is governed and who benefits from that form of governance.

Similarly, Strandsbjerg (2012) draws from Latour's networks (Section 2.3.4) to call for cartographic articulations of the Arctic to be examined as the product of particular networked relations between cartographers, mapping technologies, and physical space. Using this framework, and focussing on the Arctic seabed, Strandsbjerg emphasises the need to critically examine how cartographic practices stabilise and transform complex and unsettled spaces into mapped realities (i.e., how particular articulations of the Arctic emerge through the transformation of complex geophysical features into homogenous categories and simplified icons) (see also Steinberg and Peters, 2015). Relating these ideas to this PhD project, maps of Arctic sea ice use conventional scientific practices that simplify the ocean surface into binary categories with distinct borders: single hues of white, blue, and grey or brown represent sea ice, water, and land, respectively. Through these design features, the complexities and uncertainties of Arctic sea ice are omitted from view. Chapters 5 and 6 critically explores these cartographic features and considers how the scientific practices involved in producing sea-ice data products are shaped and conditioned by the geophysical complexities of the Arctic Ocean.

The fundamental assertion of the social constructivist perspective is that maps are value-laden images that reproduce socially constructed conceptions of the world (Harley, 1988a). With this in mind, Harley sought to replace the positivist epistemology that has dominated cartographic thinking with one rooted in social theory. Influenced by Foucault and Derrida, he proposed that the examination of maps should extend to the mapmakers and their situated contexts using deconstructive analysis (Harley, 1989). Deconstruction calls for the deeper reading of maps as cultural texts, focussing on what elements of reality have been selected, generalised, distorted, or omitted; what codes and conventions have been used to represent spatial relations; why the map was produced, for whom, and by whom; and the deeper meanings and narratives the map speaks to. Such analysis aims to reveal the alternative meanings, hidden agendas, and

intentional and unintentional silences of maps, through which the power embodied in maps can be better understood (Harley, 1989). Such an approach challenges the perceived neutrality of maps and enables a greater appreciation of the social contexts and political circumstances that shape their production and dissemination.

While Harley's work has been hugely influential for developing the foundations of critical cartography, it is widely acknowledged that he did not establish a practical research agenda for translating his theory into practice (Wood, 1993; Crampton, 2001, 2003). Moreover, as the following section will discuss, Harley's deconstructive analysis was seen as an incomplete understanding of Foucault's assertion that power and knowledge are inextricably linked (Foucault, 1991 [1975]).

2.4.4. Beyond Representation

Harley's social constructivist perspective has provided the crucial foundations for challenging the positivist assumptions that underpin modern cartographic practice. It focusses our attention on the social and cultural contingency of mapping and emphasises that reality can be represented in multiple ways and from numerous different perspectives (Crampton, 2001). However, after Harley, various critical cartographers have argued that the approach is limited for two main reasons. Firstly, it views maps as *representations* and gives comparatively little attention to the *active role* maps play in shaping or producing reality (Pickles, 2004; Wood and Fels, 2008; Wood, 1992, 2010). Secondly, in assuming that ideological influences can be addressed through deconstruction, the approach does not challenge the ontological foundations of modern cartographic practice (Kitchin and Dodge, 2007; Kitchin *et al.*, 2012).

Significant steps towards understanding maps as active producers of reality have been established through the readings of Wood and Fels (1986, 2008) and Wood (1992, 2010). Extending the semiotic analysis of the North Carolina State Highway map (Wood and Fels, 1986), Wood and Fels (2008) argue that maps should be understood not as representations but as systems of *propositions*. Their approach draws substantially from SSK's focus on scientific practices (e.g., Latour, 1991; Pickering, 1993; Hacking, 1999), in which maps, like other forms of scientific knowledge, are the consequence of social, linguistic, and practical actions through which the material world is brought into the social world (Turnbull, 1993). Wood and Fels (1986, 2008) claim that everything about a map – including its content, design, accompanying text, and purpose – is an argument that is selected and informed by the values and conventions imposed by the mapmaker. In this sense, maps are "coherent collections of things that we, or at least the mapmakers, hold or hope to be true about the world" (Crampton, 2011: 851). Focussing on maps of the natural world, Wood and Fels illustrate how maps construct ideologies of nature. For example, the nature that exists in maps "is a nature that can be threatened and that can threaten; a nature that can inspire awe and be cuddled; a nature that can be collected

and systematized; a nature that is unknowably remote and underfoot" (Wood and Fels, 2008: xvi). Central to their argument is the notion that a map constructs meaning; the map proposes a particular way of conceptualising nature that incites specific forms of action (Wood, 2010).

Wood and Fels seek to understand cartography as a form of cognitive linguistics, which moves beyond representational concerns and into questions about how maps *construct meaning* and how they gain their authority. To this end, they propose that maps should be examined in terms of their 'paramap', a portmanteau term they use to refer to the perimap and epimap elements of a map (Table 2.2). The aim of scrutinising the paramap is to establish how the design of a map promotes, constrains, and directs the construction of meanings that form the basis of action.

Table 2.2.: Elements of the 'paramap'. *Source*: Wood and Fels (2008).

Paramap	
Perimap	**Epimap**
Titles	Accompanying article(s)
Photographs	Advertisements that refer to the map
Illustrations	Marketing copy
Charts, graphs, timelines	Letters from the editor
Legends, scale bars, north arrows, other standard cartographic elements	Letters to the editor about the map
Callout text, blurbs	Behind the scenes info (how the map was created)
Credits	
Borders, decorative elements	

Similarly, in *A History of Spaces*, Pickles (2004) extends the social constructivist focus beyond concerns with mapping techniques and artefacts and into concerns about how maps *function*. Pickles' critical approach departs from the assumption that maps *create* reality as much as they represent it. He argues for a post-representational examination of maps that focusses on "the work that maps do, how they act to shape our understanding of the world, and how they code that world" (Pickles, 2004: 12). This perspective attends to the ways in which maps inscribe power in the sense that they "provide the very conditions of possibility for the worlds we inhabit and the subjects we become" (Pickles, 2004: 5). Influenced by the approaches adopted in SSK, Pickles contends that the production and interpretation of maps are deeply embedded in social structures, through which particular practices, conventions, and ontologies of cartography become accepted and naturalised. Thus, rather than focus on the map itself, Pickles called for the practices, institutions, and discourses of maps to be examined in terms of their professional, socio-political, cultural, and historical contexts.

More recently, critical focus has been orientated towards the ontological foundations of cartography, and this has prompted increasing calls for maps to be understood as *processes* (e.g., Kitchin and Dodge, 2007; Kitchin *et al*., 2011, 2012; McNeil and Culcasi, 2015). In a processual view, maps are neither representational devices nor static inscriptions of power. Rather, they are dynamic, continuous, and open-ended processes brought into being as a part of wider discourses, practices, and networks of relations (Kitchin and Dodds, 2007). As Kitchin *et al.* (2012) review, developments in this approach have primarily come about due to the failure of earlier critiques to explicitly challenge the ontological underpinnings of cartography. For example, in Harley's approach, 'truthful' representations of reality can be achieved once ideological influences are identified or removed through deconstruction. In this view, ideology is attached to the *subject* of the map and not the map itself. However, this perspective fails to acknowledge that the entanglements between power and knowledge can never be entirely escaped and, as such, maps can never provide wholly truthful representations (Kitchin and Dodds, 2007). Similarly, Kitchin and Dodge (2007) note that in post-representational analyses (Pickles, 2004; Wood and Fels; 2008; Wood, 1992; 2010), maps hold a similar ontological security in that they continue to be understood as a "coherent, stable product – *a* map".

The processual understanding of cartography contends that maps have no ontological security. Rather, the process of mapping is seen as relational, context-dependent, and contingent on wider socio-political, cultural, and economic structures. For Kitchin and Dodge (2007), this means that maps are constantly (re)made, (re)interpreted, and used within different contexts to solve particular relational problems. In other words, the reading of a map relies upon the practices of recognition, interpretation, translation, and communication that differ from one individual or cultural context to the next. As such, the processual perspective calls for maps to be interpreted in relation to the contexts in which mapping occurs. This requires analyses that are "sensitive to capturing and distilling the unfolding and contextual practices of mapping; how mappings are (re)produced through discursive and material practices shaped by personal, social, embodied, political, and economic relations; how sites in which they are embedded matters to their form; how they contextually operate with respect to other discursive media and modes of praxis; and how they perform as actants in the world shaping knowledge and actions" (Kitchin *et al.*, 2012: 494).

2.5. Conclusion: A Social Constructivist Approach to Arctic Sea-Ice Science

The previous sections have outlined some of the significant developments, concepts, and applications of social constructivism within STS and critical cartography. In this section,

I conclude the chapter by articulating how these combined insights from both fields inform the social constructivist approach taken in this PhD research.

This research aims to gain insights into how dynamic and indeterminate geophysical data is acquired, processed, and reported in Arctic sea-ice science. The central focus is to interrogate the ways in which knowledge about Arctic sea-ice conditions is produced through the development of satellite-derived sea-ice data products. Insights from SSK, and STS more broadly, have highlighted how the production of scientific knowledge is shaped and sustained by particular social structures and conditions that vary from one context to another. They have made valuable leaps towards understanding the complex entanglements between knowledge and social order, raising essential questions over accountability, participation, and democracy in science. Complementary approaches in critical cartography have illustrated how, through the processes of selection and styles of representation, maps are social constructs that articulate the world in a way that privileges particular perspectives, values, and interests, while marginalising others. Collectively, these studies provide reason to be cautious and inquisitive about the production, representation, and dissemination of scientific knowledge. They evoke questions about the objectivity and neutrality of science and lead us to inquire about how our knowledge about something could be different.

In adopting a social constructivist framework, this PhD begins with the central assumption that scientific knowledge about sea ice is the product of the complex interplay between science, nature, and society. As such, there is no wholly objective and neutral sea-ice data product. Informed by the Strong Programme in SSK, it contends that social factors are necessary to the very essence of what sea-ice science is and how scientific knowledge about sea ice gains its authority. Sea-ice science is a social endeavour: the acquisition of sea-ice data occurs through technological systems that are developed, coordinated, and sustained by social structures; the processing and manipulation of sea-ice data rely upon arrangements, procedures, and principles that are determined through human practices of negotiation and interpretation; the production of maps and other data product outputs requires judgements and choices to be made about the selection of content, the design elements, and the definitions used in data aggregation; and the dissemination of knowledge relies upon communication systems and wider networks of relations. In short, the success (and power) of sea-ice data products as forms of knowledge is deeply entangled with an interconnected assemblage of social practices. Moreover, as Chapter 1 introduced, although a general methodology guides the production of satellite-derived sea-ice data products, the practices vary from one scientific institution to the next. Consequently, similar to the studies described in Section 2.3.4, scientific knowledge about sea ice can be understood as being produced through socially contingent, locally situated, and context-laden scientific practices.

In line with the (social) constructivist approaches described in this chapter, the view that sea-ice products are in some way shaped by social forces necessitates a critical examination of the practices, discourses, and institutions of knowledge production, as well as the situated contexts in which they are embedded. To this end, this PhD seeks to articulate the production of Arctic sea-ice knowledge through the examination of various sea-ice products within the social and cultural contexts in which they are produced. As Chapter 3 will elaborate, the approach taken in this research attempts to address and link the complex interplays between macroscale and microscale elements of scientific practice to understand how social factors shape the nature of sea-ice science. The macroscale analysis focuses on sea-ice research within its broader historical and societal contexts. The aim here is to understand how these broader contexts shape sea-ice science through questioning, for example, how global climate change discourses inform research objectives and ideologies; why the international community has adopted specific methodologies and conventions; who participates in sea-ice research; and how scientific and technological developments have changed the nature of sea-ice research through time. Microscale investigations build on these insights by attending to the day-to-day working practices involved in producing particular sea-ice data products. The aim here is to gain insights into the epistemic cultures of sea-ice science by examining how scientific knowledge is produced within its localised contexts, focusing mainly on the methods, decisions, and local idiosyncrasies that occur at an institutional level.

The social constructivist framework used in this PhD research recognises that sea-ice data products are useful, necessary, and influential forms of knowledge. Thus, the purpose of this research is not to falsify or undermine that knowledge, nor is it to argue that it is merely socially constructed. Rather, the core argument is that scientific knowledge about sea ice reflects a particular way of observing, processing, and representing complex geophysical data that is shaped by and reinforces the values and perspectives of the specific social contexts in which it is produced. To reinstate the assumptions of social constructivism introduced in Section 2.2, this perspective indicates that our knowledge about sea ice is not inevitable. Thus, situating the research within a sociological perspective provides an opportunity to examine the underlying processes, decisions, and power relations that inform how and why sea-ice science is done in a particular way while recognising that there are multiple ways in which Arctic sea-ice conditions can be known.

The 'turn to technology', the emergence of the idiom of co-production, and the post-representational understandings of cartography are important reminders that knowledge, nature, and society are deeply entangled. As described in this chapter, these approaches stress the contextual and relational nature of knowledge, both in terms of its production and interpretation, and emphasise the importance of reflexive and engaged

critical analysis. Although such perspectives imply that sea-ice knowledge can never be wholly objective and neutral, it does not mean that 'better' and more equitable forms of knowledge cannot be realised. The products examined in this research are socially shaped and society shaping, in the sense that they have direct implications for how the Arctic is understood, framed, and acted upon within wider socio-political and economic contexts. Therefore, a greater understanding of how social and cultural contexts shape the production of sea-ice products may provide valuable departure points for critically examining how sea-ice science may be made more equitable and more democratic or enriched and improved by alternative perspectives, values, and experiences.

3. Studying Sea-Ice Science in Context

3.1. Introduction

The previous chapter outlined the social constructivist perspective of scientific knowledge that underpins the focus of this PhD thesis. This chapter develops this perspective to detail the approach taken to meet the research aim and objectives outlined in Section 1.3.1.

The chapter starts by reiterating some of the theoretical foundations and assumptions that inform the nature of this research. Here, I draw upon the discussions from Section 2.3.6 to indicate how the similarities and differences between constructivist and critical research frameworks are reflected in the methodology developed and implemented in this study. Following this, I introduce the overall research approach, which consists of a mixed-methods design that is predominantly informed by integrating insights and techniques from ethnographic and visual methodologies (Section 3.3). The nature of this integrated approach has provided a structure for critically examining sea-ice data products and attending to the social and cultural contexts in which they are embedded. Three stages of inquiry are subsequently introduced (Section 3.4). These stages include a historical review of Arctic sea-ice science, a critical and comparative examination of sea-ice data products, and ethnographic fieldwork carried out within the Norwegian Meteorological Institute. I detail the focus and purpose of inquiry for each stage, including the specific sea-ice data products, materials, and field sites studied, and the methods and techniques used for data collection and analysis. I conclude the chapter by discussing some of the challenges and limitations that have arisen throughout the research (Section 3.5). This includes an overview of researcher positionality and a summary of the disruptions caused by the COVID-19 pandemic.

3.2. A Social Constructivist Examination of Sea-Ice Data Products

The central assumption underpinning the research aim and objectives is that scientific knowledge cannot be considered independent from the social, political, and cultural contexts in which it is produced (e.g., Knorr Cetina, 1981; Haraway, 1988; Harley, 1988a,

1988b, 1989; Bloor, 1991; Jasanoff, 2004a; Pickles, 2004). In this way, I view sea-ice data products as *cultural artefacts*: they are a source of information that interprets, represents, and communicates sea-ice conditions in a way that reflects and reinforces the perspectives, ideologies, and values of the institutions that develop them. They are data products produced by human subjects and in the context of particular social relations. Consequently, I argue that these products have helped construct and naturalise particular ways of knowing and visualising Arctic sea ice that are not neutral, wholly objective, or inevitable. The focus of this research, then, is to critically examine and compare the institutional practices involved in the production of sea-ice data products to better understand what values, contingencies, biases (conscious and unconscious), and interests, as well as the methods they inform, shape how Arctic sea ice is interpreted and represented in science.

While the approach used in this thesis to investigate sea-ice data products predominantly draws from a social constructivist framework, it is also informed by critical research. Although constructivist and critical research frameworks are informed by similar ontological and epistemological beliefs and often use comparable research approaches and methods, they differ in their intended purpose (Table 3.1). This difference has important implications for the types of questions that have informed the nature of the research undertaken in this thesis. Thus, before outlining the overall approach, it is necessary to briefly consider some of the similarities and differences between constructivist and critical research designs.

As Table 3.1 details, the purpose of constructivist research is to *understand* how people interpret and attach meanings to a phenomenon of interest. By focussing on specific forms of knowledge, artefacts, and practices, the focus is on describing and interpreting how meanings are constructed through the interactions and experiences that occur within particular social and cultural contexts (Merriam and Tisdell, 2015). For example, as illustrated by the early SSK investigations addressed in Chapter 2, (social) constructivist research typically provides detailed and descriptive accounts of the processes and interactions that occur during the production of scientific knowledge. Many focussed on *understanding* and *interpreting* the practices, arrangements, and values involved in the construction of facts, artefacts, or knowledge claims. Notably, the interpretive focus of constructivist research also requires the researcher to attend to how their own social and cultural experiences and values shape the research findings. This is discussed in more detail in Section 3.5.

Critical research extends the constructivist framework further by arguing that knowledge is informed by the social, economic, political, and cultural contexts in which it is produced, and that power relations within these contexts act to privilege some ways of knowing over others (Merriam and Tisdell, 2015). Instead of describing and explaining how knowledge is constructed, the central premise of critical research is to

problematise knowledge by challenging the social conditions and power relations that give rise to particular ways of knowing (Table 3.1). In this way, most forms of critical research are motivated by the desire to bring about change through critiquing existing conditions and challenging conventional forms of knowledge production and distribution (Patton, 2015). As Merriam and Tisdell (2015) note, this does not necessarily require specific changes to occur during the research; however, critical analysis seeks to reveal the unequal power dynamics that prevail in particular contexts in the hope that this will provide an impetus for changes to be made or alternative interpretations to be empowered.

The overall aim of this PhD research aligns more strongly with the purpose of the social constructivist framework. This is reflected by the main focus, which is to gain a deeper *understanding* of the sociological nature of scientific knowledge within the context of Arctic sea-ice science. However, as various authors have cautioned (e.g., Richards, 1996; Jasanoff, 1996, 2004a; Section 2.3.6), interrogating the nature of knowledge production is inherently politically destabilising and inevitably opens up science to critical scrutiny. In this sense, STS researchers have a certain degree of responsibility to critically engage with the political and cultural significance of socially constructed knowledge. As Chapter 2 outlined, questioning the dominant discourses and structures of knowledge production, exposing the conscious and unconscious forms of bias present in particular interpretations and representations, and creating space for alternative voices to be heard, have become increasingly pertinent themes within STS and critical cartography research over recent decades (Crampton, 2010; Felt *et al.*, 2017). To effectively engage with these themes, sociological studies of scientific knowledge have emphasised the importance of attending to the localised contexts of scientific practice and situating these insights within broader socio-political, cultural, and historical structures (e.g., Haraway, 1988; Knorr Cetina, 1999, 2005). Similarly, critical approaches to the study of maps have called for the practices, institutions, and discourses of mapping to be examined in relation to their professional, socio-political, and cultural contexts (e.g., Harley, 1989; Pickles, 2004; Kitchin and Dodge, 2007).

A social constructivist study of Arctic sea-ice data products that is informed by critical research requires an approach that attends to the complexity and situatedness of scientific practice across various scales. It calls for detailed microscale examinations of the methods, discourses, and institutions involved in the production of data products, as well as the macroscale social, cultural, and historical contexts in which their development takes place. Moreover, the recognition that sea-ice knowledge is in some way socially contingent raises essential questions surrounding accountability, democracy, and participation in the production and dissemination of sea-ice data products. Thus, a social constructivist study of sea-ice data products must remain critically aware of how the relations between knowledge and power shape and sustain

the dominant forms of knowledge production and dissemination about environmental changes in the Arctic. In particular, it requires an approach that closely analyses how particular perspectives, experiences, and values inform the nature of sea-ice science and its resultant knowledge. This includes questioning why specific approaches and perspectives have established greater legitimacy than others, how particular representations of sea-ice conditions may favour specific interests and ways of articulating Arctic environmental changes over others, and how alternative discourses and perspectives may give rise to different forms of knowledge. The following section details the general approach developed and implemented in this study to meet these requirements while addressing the overall research aim and objectives.

Table 3.1.: Different research frameworks and their corresponding ontologies, epistemologies, purposes, and types. Modified from Creswell (2013) and Merriam and Tisdell (2015).

Interpretive Framework	*Ontology*	*Epistemology*	*Research Purpose*	*Research Types*
Positivist	Reality is external, objective, and tangible. A singular, universal reality exists "out there". Reality is discoverable.	Reality can be objectively observed, defined, approximated, and described using rational methods. Observations are neutral and value-free.	To define, explain, control, order, predict.	Usually deductive and quantitative forms of analysis e.g., experimental, statistical, numerical modelling.
(Social) constructivist/ Interpretivist/	There is no direct and value-free access to a single, external reality. There are multiple realities and interpretations: the meanings we attach to a phenomenon are context-dependent and reflect our lived experiences and interactions.	Reality is constructed through negotiations and arrangements that reflect particular experiences and ideologies. Knowledge is culturally and historically situated.	To *understand* how meaning is constructed through negotiations and arrangements within particular settings. *Understanding* relies on descriptive and interpretive analysis.	Usually inductive and qualitative forms of analysis, but also quantitative e.g., grounded theory, discourse analysis, ethnography.
Critical	There is no direct and value-free access to a single, external reality. There are multiple realities and interpretations: reality is situated within particular social, political, and cultural contexts. Certain realities are privileged over others.	Reality is constructed through negotiations and arrangements that reflect and reinforce unequal distributions of power. Knowledge is culturally and historically situated.	To *emancipate* or *empower* through critiquing and challenging prevailing conditions, discourses, and power structures.	Usually inductive and qualitative forms of analysis e.g., critical ethnography, engaged analysis, participatory action research.
Transformative/ Postmodern	There is no singular 'Truth' but multiple 'truths', perspectives, interpretations, and voices.	Knowledge is culturally and historically situated. Knowledge reflects power and social relationships in society.	To challenge 'grand narratives' through deconstructing and problematising knowledge. Attends to the plurality of perspectives and voices.	Usually inductive, qualitative, and deconstructive forms of analysis e.g., ethnography, grounded theory, linguistic analysis, participatory analysis.

3.3. Research Approach

As various authors have described, qualitative research is well suited to research inquiries whereby the overall goal is to gain a deeper, contextual understanding of how meanings are constructed and knowledge is produced (e.g., Creswell, 2013; Guest *et al*., 2013; Merriam and Tisdell, 2015). Qualitative research is an umbrella term that encompasses a broad range of definitions and characterisations of research designs. Various authors define qualitative research in different ways: some definitions focus on particular approaches or traditions, such as phenomenology, grounded theory, and ethnography (e.g., Denzin and Lincoln, 1994; Creswell, 2013; Merriam and Tisdell, 2015); whereas other definitions include analytical techniques such as discourse and conversation analysis (e.g., Tesch, 1990; Guest *et al*., 2013). A commonality running through all qualitative research approaches, traditions, and techniques is the emphasis on *observing* and *describing* for the ultimate purpose of understanding how meanings are constructed through lived experiences.

The research carried out in this PhD thesis predominantly integrates insights and techniques from two methodological approaches: ethnography and visual methodologies. Ethnography is a qualitative research approach that explores the shared experiences, perceptions, and knowledges of a culture-sharing group (Wolcott, 2008). Visual methodologies focus on the meanings, discourses, and interpretations associated with visual materials, such as photographs, paintings, videos, and maps (Banks, 2014; Rose, 2016). Rose (2016) notes that visual methodologies are predominantly qualitative because of the emphasis placed on *meaning*. However, quantitative techniques can supplement qualitative research – particularly when statistical aspects of visual images are the focus of inquiry (e.g., content analysis).

The research carried out in this thesis is primarily qualitative, involving a combination of fieldwork and desk-based analysis. It integrates insights and techniques from both ethnographic and visual methodologies to explore the practices involved in the production of sea-ice data products within specific institutional contexts. However, the nature of the research objectives and the numerical foundations of sea-ice data products, necessitates additional insights that can only be gained through quantitative techniques. Specifically, the production of sea-ice data products involves numerous stages of quantitative data manipulation, translation, analysis, selection, and calculation. These processes are challenging to analyse and interpret without working directly with quantitative data. Hence, as Section 3.4 will illustrate, the use of qualitative research methods in conjunction with quantitative methods enables a deeper, hands-on analysis of the processes and conventions involved in the production of sea-ice data products. Moreover, the use of quantitative methods proved to be a vital means for developing

rapport with the sea-ice scientists during the fieldwork components of this study (Section 3.4.5).

The general approaches of ethnography and visual methodologies are discussed below, and the associated methods and materials used in this study are detailed in Section 3.4.

3.3.1. Ethnography

Ethnography can be defined as "the systematic study of culture" (Allard and Anderson, 2005: 833). In broad terms, *culture* refers to the shared experiences, artefacts, perceptions, beliefs, languages, and patterns of behaviour that characterise a social group or community (Fetterman, 2008; Wolcott, 2008). These shared characteristics shape how a particular social group 'makes sense' of the world and attaches *meanings* to a particular phenomenon (Hall, 1997). Such meanings help explain why people behave in a particular way, how people interpret and experience things, and what people know (Spradley, 1980). They may be "explicit or implicit, conscious or unconscious" and can be found in everyday speech, human interactions, texts, images, *scientific methods*, and so on (Rose, 2016: 2). Thus, the central aim of ethnography is to develop in-depth understandings of these shared characteristics and meanings through *thick description* (Geertz, 1973).[20]

The emphasis in ethnographic accounts is on the insiders' *emic* perspectives; that is, ethnographers seek to understand how members of a group see the world and why they behave like they do (Spradley, 1980). In this vein, Traweek identifies four necessary domains of a group's culture that she argues an ethnography must account for:

> The first is *ecology*: the group's means of subsistence, the environment that supports it, the tools and other artifacts used in getting a living from the environment. The second is *social organisation*: how the group structures itself, formally and informally, in order to do work, to form factions, to maintain and resolve conflicts, and to exchange goods and information. The third is *developmental cycle*: how the group transmits to novices the skills, values, and knowledge that constitute a sensible, competent person; the stages of a life and the characteristic attributes of a person at each of those stages. The fourth is *cosmology*: the group's system of knowledge, skills, and beliefs, what is valued and what is denigrated. (1988: 7, emphasis added).

The study of these cultural domains necessitates direct engagement with the group or situation under focus. As such, participant observation represents the primary method associated with ethnographic research. Participant observation typically requires the researcher to actively immerse themselves within the social group under study to gain a

[20] The term 'thick description' encompasses interpretations of the details, nuances, meanings, complexities, motivations, emotions, and networks, which inform social action and behaviour within particular contexts (Ponterotto, 2006).

more in-depth understanding and first-hand experience of the complexities in context (Fetterman, 2008). However, participant observation can entail different levels of involvement, depending on the overall research purpose. Gold (1958) identifies four main roles that characterise the different types of participant observation (Figure 3.1). These roles exist on a continuum that ranges from a complete observer whereby the researcher takes on the role as a passive bystander, to a complete participant whereby the researcher becomes an active member of the community. Participant observation typically involves various methods including direct observations of the social activities and interactions, descriptions of the physical setting, interviews and focus groups with research participants, and document analysis (Fetterman, 2008). While observations are generally obtained *in situ*, interviews and document analysis can be carried out away from the research setting.

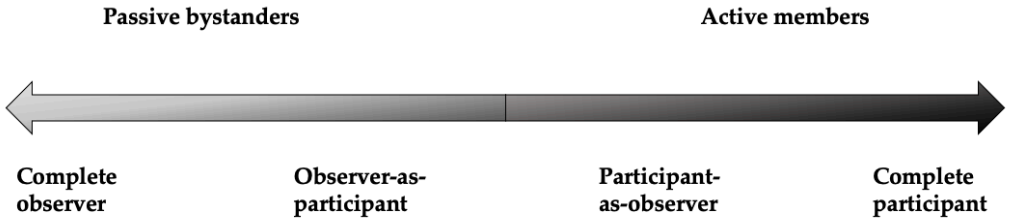


Figure 3.1.: Continuum of participant observation roles.

As Chapter 2 illustrated, the vast majority of SSK's social constructivist insights have been attained through ethnographic inquiry (e.g., Collins, 1975; Latour and Woolgar, 1979; Traweek, 1988). These 'STS ethnographies' (Hess, 2001) involved immersive fieldwork within particular research settings, whereby the main focus was on understanding the practices and cultural contexts of scientific knowledge production. In these accounts, scientific fields were approached like any other cultural formation: the institutions and practices of science were viewed as part of society, and the outputs as relational and situated. Like many forms of ethnographic research, STS ethnographies involved immersive fieldwork over extended periods. Being present over a long duration is important for several reasons: more time generally equates to more detailed and accurate observations; it allows for a more nuanced understanding of the complexities that exist within the community and how these relate to broader social and cultural structures; it enables the researcher to observe and experience how temporal factors affect the activities and interactions of the community; and it provides greater opportunity to assess whether there are discrepancies between what scientists say they do and what they actually do (Fetterman, 2008).[21] While there is no specified minimum time period for ethnographic fieldwork, Walcott (2008) notes that a long-term

[21] A crucial social constructivist argument in STS is that the textbook descriptions of scientific methods are rarely followed stringently. As Haraway puts it: "no practitioner of the high scientific arts would be caught dead *acting on* the textbook versions [of scientific methods]" (1988, emphasis in original).

commitment is usually assumed. Similarly, Fetterman (2008) states that ethnographers should ideally immerse themselves in the communities under study for at least six months.

Although the theoretical focus of this research shares many similarities with STS ethnographies and is highly informed by previous work in this field, the duration of fieldwork was comparatively short: it involved six weeks of immersive research at a scientific institution (Section 3.4.2). With this in mind, I draw attention to the distinction Walcott makes between "*doing ethnography* and *borrowing (some) ethnographic techniques*" (2008: 44, emphasis in original). The former refers to ethnography in its more traditional, anthropological sense, whereby ethnographic fieldwork is characterised by total and prolonged immersion within the community under study, and observations are broad and naturalistic.[22] This form of ethnographic research intends to provide a comprehensive account of the culture under investigation; *an* ethnography is the research *product*, not just a set of methodological procedures. In contrast, the latter phrase refers to ethnography in a methodological sense, whereby ethnographic techniques can offer a "way of looking" at a particular phenomenon within its contexts and with the intent of trying to better understand how it works. In this characterisation, ethnography is the *process*, not necessarily the product of research. In line with this approach, my fieldwork was not intended to provide a thorough ethnographic account of the culture of sea-ice science in a general sense. Rather, the intention was to explore how Arctic sea-ice conditions are interpreted and represented in science by focussing on the processes (social and otherwise) involved in producing particular sea-ice data products, through a study of cultural and scientific practices at one specific institution. While this involves examining how cultural factors shape and inform sea-ice science practice within the institutional contexts, it is the products themselves that are at the heart of the empirical inquiry. Hence, this research has employed ethnographic techniques as a means by which to gain insights into the *aspects of culture* that are relevant in relation to the sea-ice data products under study.

Undoubtedly, a longer duration of immersive fieldwork would have yielded greater insights into the sociological nature of sea-ice data products. Yet, the fieldwork length struck a balance between what was logistically possible given the project's timeframe, and what types of analysis would be most appropriate given the research aim and objectives. Moreover, the duration of fieldwork was unexpectedly shortened by the COVID-19 pandemic, as later sections detail (Section 3.5.3). Immersive fieldwork was used in conjunction with other methods, including interviews and document analysis,

[22] As Guest *et al*. (2013) and Walcott (2008) discuss, contemporary uses of ethnography have diverged from this traditional, anthropological characterisation. Today, ethnography and/or ethnographic techniques can be utilised in a range of disciplinary contexts, and it frequently involves fieldwork of a much shorter duration.

predominantly carried out away from the institutional settings. The data products analysed in this study are openly accessible in online spaces: the final products (digital maps, statistical tables, and graphs), their underlying data, and supplementary documents and data sources can be retrieved and downloaded for analytical and reproductive purposes. Thus, desk-based analysis away from the immediate places of knowledge production has provided an essential means for examining the sociological nature of sea-ice data products together with participant observation.

Moreover, critically analysing the visual aspects of sea-ice data products also constitutes a significant component of this research. This includes exploring how the representational elements of sea-ice data products, such as map symbology and the selection of content, help construct and reinforce particular ways of knowing the Arctic. These compositional and discursive elements require analysis that is challenging to attain through ethnographic techniques alone (Rose, 2016). For this reason, this PhD research integrated techniques and insights from both ethnographic and visual methodologies.

3.3.2. Visual Methodologies

Visual methodologies encompass a range of diverse research methods for analysing and interpreting visual materials (Rose, 2016). Banks (2014) outlines three main categories of visual materials that visual methodologies typically address: visual data produced by the researcher, such as photographs taken during ethnographic research (e.g., Bateson and Mead, 1942); the examination of pre-existing materials, such as historical photographs (e.g., Kirkby, 1997) or maps (e.g., Wood and Fels, 1996, 2008); and materials created collaboratively through exchanges between the researcher and the research participants (Banks, 2014). As various authors have commented (e.g., Bigante, 2010; Bailey and McAtee, 2013; Glaw *et al*., 2017), the use of visual methods can significantly enrich sociological research as it offers a way of analysing non-verbal and non-textual forms of knowledge associated with the phenomenon under study. Therefore, using visual methods alongside more traditional forms of qualitative research, such as observations and interviews, can help capture different kinds of data and access additional levels of meaning.

Maps and other forms of visual imagery are an integral part of contemporary sea-ice science. Many sea-ice data products developed for climate research purposes are rendered in cartographic form and supported by graphical representations, numerical statistics, and textual documentation (Figure 1.1). Visual representations of sea ice are an important means through which sea-ice scientists interpret, predict, and communicate conditions in the Arctic (Grosfeld *et al*., 2016). As such, they have become central to how we understand and 'see' the geography of the Arctic region. A key research objective of this PhD is to critically analyse how sea-ice maps simplify,

consolidate, and represent sea-ice conditions, and visual research methods have been an important means to achieve this.

Critical approaches to visual materials have become increasingly pertinent forms of research across various disciplines in recent decades, including sociology and geography (Bailey and McAtee, 2003; Pickles, 2004; Wood, 2010; Rose, 2016). This growing critical interest in visual materials is rooted in similar theoretical arguments to those developed in STS and critical cartography. Critical approaches take visual materials (including maps) to be broadly socially constructed representations that are shaped and informed by the social, cultural, and historical contexts in which they are produced, disseminated, and consumed (Banks and Zeitlyn, 2015; Rose, 2016). They are never 'merely' reflections of reality but offer a view of the world that is interpreted, displayed, and represented in particular biased and value-laden ways (Rose, 2016). Moreover, the interpretation of visual materials is subjective and changeable. As Hall writes: "there is no single or 'correct' answer to the question, 'What does this image mean?' […] there is no single law which can guarantee that things will have 'one, true meaning', or that meanings won't change over time" (1997: 9).

In *Visual Methodologies*, Gillian Rose (2016) introduces a framework for a critical visual methodology that provides a means through which to understand the meanings implicit in visual materials and examine their role in constituting social relations (Rose, 2016). This framework has been particularly informative for developing my approach to sea-ice maps (and data products more generally). The framework focusses on four *sites* that influence the meanings and social effects associated with visual materials:

1) The site(s) of *production*, referring to the circumstances and conditions through which an image is made.
2) The site of *the image itself*, concerning its content and composition.
3) The site(s) of *circulation*, referring to the dissemination of visual materials.
4) The site(s) of *audiencing*, where the visual materials encounter their viewers or users.

Building on this framework, Rose presents three 'modalities' termed the *technological*, the *compositional*, and the *social*, which provide avenues for a critical understanding of visual materials in relation to the four sites. In defining these three modalities, Rose writes: "The technological concerns the tools and equipment used to make, structure and display an image; the compositional concerns the visual construction, qualities and reception of an image; and the social concerns the social, economic, political and institutional practices and relations that produce, saturate and interpret an image" (2016: 374). Figure 3.2 demonstrates how the sites and modalities of images relate to each other and the type of questions they generate for interpreting visual materials.

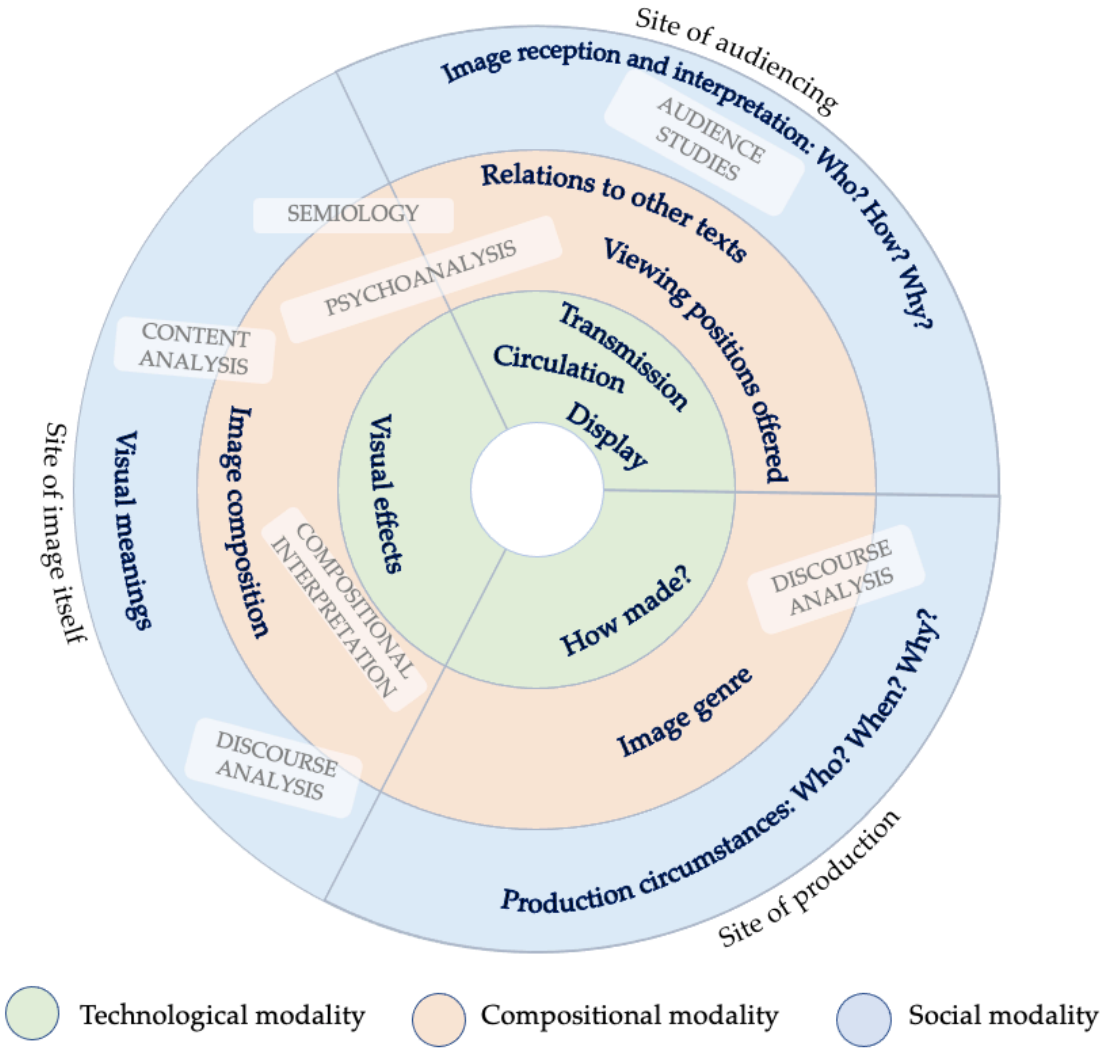


Figure 3.2.: The sites, modalities, research questions (dark blue font), and methods (light grey boxes) for a critical visual methodology framework. Reproduced and modified from Rose (2016).

The research carried out in this PhD is primarily concerned with the site(s) of production: How and where are the sea-ice products produced? What factors (social and otherwise) influence their development? Who produces them and for whom? What is the product's purpose and agenda? What conventions and rules determine how sea-ice data is made meaningful? However, it also pays close attention to the cartographic representations of sea ice and questions how the content and composition of sea-ice maps help to construct particular visions of the Arctic. Similar to the post-representational approaches encouraged by critical cartographers (Section 2.4.4), Rose's framework urges a deeper reading of visual materials that extends beyond the image to account for the *social contexts* and *conditions* that shape their meanings and how they function in society. Thus, attending to these 'sites' using visual methods has involved a close reading of sea-ice data maps and their associated documentation, combining analytical insights from Rose's (2016) compositional interpretation, discourse analysis (Willig, 2014; Rose, 2016), and the deconstructive and post-representational mapping critiques described in

Chapter 2. Rose's critical framework also provides logical justification for integrating ethnographic and visual methodologies to study of sea-ice data products.

3.3.3. Integrating Ethnographic and Visual Methodologies

Critically engaging with the compositional and discursive elements of sea-ice data products through examining specific sea-ice maps and their associated documentation has provided crucial insights into how complex and indeterminate sea-ice data are acquired, processed, and represented in sea-ice science. It has also facilitated a greater understanding of the meanings, discourses, and values embedded in sea-ice data products and the institutions that produce them. The ethnographic components have supplemented these insights by helping to develop a picture of how these products are developed in practice and identify the social contexts and conditions that shape their production and dissemination. Put differently, the close reading and comparative analyses of sea-ice data products sought to understand *what* practices are involved in the acquisition, processing, and reporting of Arctic sea ice and *how* they affect representations of sea ice; the ethnographic components sought insights into *why* these practices exist, *how* they are operationalised in their institutional settings, and *why* they differ between different institutions.

3.4. Methods and Materials

3.4.1. General Overview

Three stages of inquiry were developed to explore the sociological nature of Arctic sea-ice data knowledge using integrated approaches from ethnographic and visual methodologies. The three stages included:

Stage 1: A historical review of Arctic sea-ice science (reported in Chapter 4).

Stage 2: A critical and comparative examination of sea-ice data products (reported in Chapters 5 and 6).

Stage 3: Ethnographic fieldwork (reported in Chapter 7).

Note that the three stages were not explicitly carried out in sequential order. Moreover, the three stages were interactive; that is, insights from each stage were used to inform the direction of the others. The research inquiries have been separated into these stages to reflect the differences in the focus, purpose, and primary techniques employed. Although the stages differ in terms of their focus, when taken together, the intention was to develop a more holistic understanding of the meanings, discourses, and values embedded in sea-ice data products, the epistemic cultures involved in their production, and how the products relate to their broader social, cultural, and historical contexts.

3.4.2. Research Settings and Sea-Ice Data Products

Except for Stage 1, the research has predominantly been carried out within the context of two scientific institutions involved in the development of sea-ice data products: The NSIDC and MET Norway. The research activities consisted of a combination of desk-based analysis of different sea-ice data products and a field visit to the institutional headquarters of MET Norway. A similar field visit to the NSIDC headquarters in Boulder, Colorado was originally planned. However, this was later cancelled due to the ongoing disruptions from the COVID-19 pandemic (Section 3.5.3). That said, the practices and technologies used at the NSIDC to produce sea-ice data products remain a major focus in this research.

The selection of two different institutions enables comparisons to be drawn between the different practices involved in the production of a range of sea-ice data products.[23] This includes comparing the methods, techniques, and conventions used to process and report sea-ice data; the values and interests that inform the research activities and objectives; and the institutional relations with national and international programmes of science. Examining two different institutions also allows for sea-ice data products of the same parameters to be directly compared against each other (e.g., concentration and extent). Focussing on the same parameters yields insights into what methodological differences occur between different institutions, how these differences affect the interpretation and representation of sea-ice data, and perhaps most significantly, why these differences exist in the first place.

The rationale for selecting the NSIDC and MET Norway is multi-faceted. Firstly, the two institutions are highly influential within the international sea-ice science community, each drawing upon a network of specialists to advance understanding of Arctic sea ice. The NSIDC is a United States information centre that "supports research into our world's frozen realms" (NSIDC, 2021). The centre is part of the Cooperative Institute for Research in Environmental Sciences at the University of Colorado, Boulder. Its activities are co-sponsored by the National Aeronautics and Space Administration (NASA), The National Oceanic and Atmospheric Administration (NOAA), and the National Science Foundation (NSF), among other federal agencies. The NSIDC has been at the forefront of cryospheric research for many decades, with its formal origins dating to the First International Geophysical Year in 1957 (Section 4.5.1). Today, the centre is responsible for the processing, archiving, and distribution of geophysical data in support of polar and cryospheric research and hosts a large cohort of prominent experts who have contributed substantially to the international published literature on Arctic sea ice. In particular, the NSIDC's Sea Ice Index serves as a global 'benchmark dataset' for several

[23] Comparative approaches are common in previous sociological studies of scientific knowledge (e.g., Knorr Cetina, 1999; Traweek, 1988).

sea-ice climate indicators, including sea-ice concentration and sea-ice extent (Fetterer *et al*., 2017; WMO, 2020).[24]

Similarly, MET Norway plays a significant role in observing and monitoring Arctic sea-ice conditions within the European climate science community. MET Norway is a state agency working under the Ministry of Climate and Environment, responsible for providing public meteorological services for military and civil purposes. Notably, MET Norway hosts the Ocean and Sea Ice Satellite Application Facility's (OSI SAF) High Latitude Centre (HL) in cooperation with the Danish Meteorological Institute. The OSI SAF HL is controlled by the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) and is responsible for processing and distributing several global sea-ice data products, which are designed to serve a variety of operational users across the EUMETSAT Member States (Figure 3.3). Additionally, MET Norway scientists are directly involved with the production of sea-ice data products for the Copernicus Climate Change Service (C3S). The C3S is committed to providing consistent and authoritative information on the changing state of the world's climate in support of the adaptive and mitigative climate change policies of the European Union (C3S, n.d.). This research focusses on the data products developed by MET Norway scientists on behalf of EUMETSAT OSI SAF and C3S; thus, it is concerned less with MET Norway exclusively, and more with the institution's involvement with OSI SAF and C3S activities.[25]

[24] WMO benchmark datasets for climate indicators are assessed and catalogued based their trustworthiness, ease of user accessibility, and support for global policy makers.
[25] From here onwards, unless explicitly stated otherwise, 'MET Norway' will be used in reference to the research carried out by MET Norway scientists for the purposes of OSI SAF and C3S.

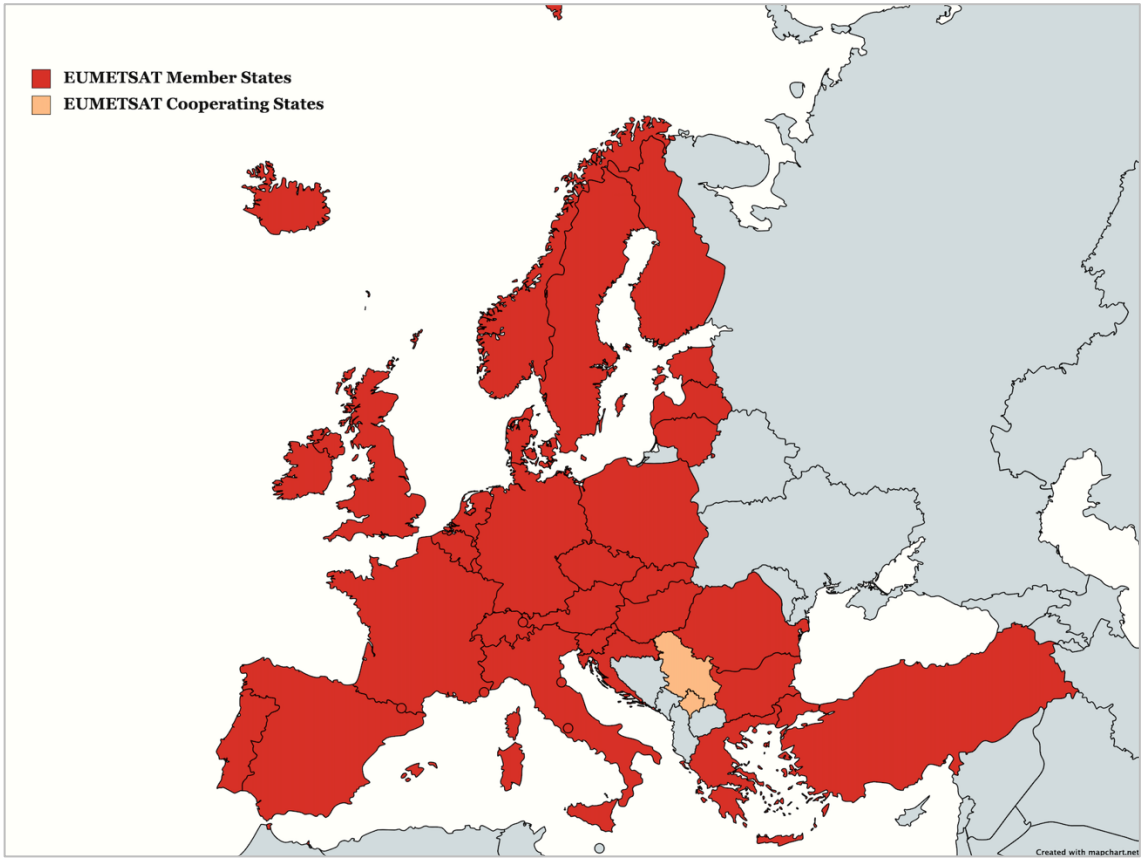


Figure 3.3.: EUMETSAT member and cooperating states.

The second reason for selecting the NSIDC and MET Norway concerns science communication and their role in shaping broader sea-ice knowledge. Due to the influential status of these two institutions in sea-ice research, their associated data products are frequently used in formal communications on global climate conditions, references to their products and associated research scientists regularly appear in national news and media sources, and a quick Google search of 'Arctic sea ice' returns numerous images and articles that directly or indirectly relate to NSIDC and MET Norway sea-ice data products (see Appendix 1).[26] Collectively, these observations imply that the NSIDC and MET Norway hold an authoritative position when it comes to observing, monitoring, and communicating Arctic sea-ice conditions.

The final reason for choosing these specific institutions is that their headquarters are based in different countries and on different continents, meaning that the research activities are informed by different cultural, political, social, and historical landscapes. Moreover, the research outputs of both institutions – including the data products, auxiliary documentation, and associated publications – are predominantly distributed in English. While this has limited the extent of cross-cultural analysis, it has allowed for

[26] The NSIDC has a dedicated webpage for media communications on Arctic sea ice. The webpage provides information for journalists, including details on the important seasonal milestones and their own official press releases that take place throughout the year.

more in-depth comparisons to be made between different data products. That said, non-published communication within the research setting of MET Norway, such as formal and informal verbal conversations and signage, occurred principally in Norwegian. This introduced difficulties during the fieldwork components of this study as it presented obstacles to effective observations. These issues are discussed in more detail in Section 3.5.

At this point, it is worth noting an important distinction between institutes involved in *producing* sea-ice data products and those simply *representing* sea-ice data. The NSIDC and MET Norway scientists are *producers* in the sense that they are involved in the entire production of data products, from the processing of raw satellite data through to the representation and dissemination.

The research has primarily focussed on four sea-ice data products developed by the NSIDC and MET Norway:

- The NSIDC Sea Ice Index, Version 3.0 (NSIDC SII).
- The EUMETSAT OSI SAF Global Sea Ice Concentration Climate Data Record, Version 2 (OSI-450 SIC).
- The C3S Sea Ice Edge Climate Data Record, Version 1 (C3S SIE).
- The C3S Sea Ice Type Climate Data Record, Version 1 (C3S SITy).

These four records are developed using passive microwave satellite data and for the main purpose of monitoring long-term and large-scales changes in Arctic sea-ice cover. The NSIDC SII and the OSI-450 SIC data products are both records of sea-ice concentration calculated on daily timescales. These records are also used to produce calculations of sea-ice extent and area. However, as Chapter 5 details, sea-ice area is generally less reported due to the uncertainties involved in its measurement. The C3S SIE and SITy are *classification* data products that separate the ocean surface into different categories of sea ice. The C3S SIE data product classifies the ocean surface into three types using sea-ice concentration bands: open water (<30%), open ice (30-70%), and closed ice (>70%). The C3S SITy classifies the ocean surface into three classes that represent the dominant stages of sea-ice development: open water (<30%), first-year, and multi-year ice types. A summary of the four data products is provided in Table 3.2.

The following sections provide an overview of the three stages of inquiry and the associated methods used for data collection and analysis.

Table 3.2.: Summary of the four sea-ice data products examined in this thesis.

	NSIDC SII	*OSI-450 SIC*	*C3S SIE*	*C3S SITy*
Ownership and distribution	NSIDC	EUMETSAT OSI SAF	C3S	C3S
Time coverage	March 2005 – present day	January 1979 – December 2015 (Interim product to extend to present day)	January 1979 – December 2015 (Interim product to extend to present day)	January 1979 – December 2015 (Interim product to extend to present day)
Parameters and definition	Sea-ice concentration (%), range 15-100% Sea-ice extent (km^2), based on SIC threshold of 15%	Sea-ice concentration (%), range 0-100% Sea-ice extent (km^2), based on SIC threshold of 15%	Sea-ice edge (%): open water (<30%), open ice (30-70%), closed ice (>70%)	Sea-ice type: open water (<30%), first-year ice, multi-year ice
Year of Inception	2002	2017	2018	2018
Reference	Fetterer *et al*. (2017)	EUMETSAT OSI SAF, (2017); Lavergne *et al*. (2019a)	C3S (2018)	C3S (2018)

3.4.3. Stage 1: A Historical Review of Arctic Sea-Ice Science

A social constructivist perspective of sea-ice science would contend that the contemporary practices and technologies involved in the production of sea-ice data products cannot be fully understood without attending to the historical contexts in which sea-ice science is rooted (Shapin, 1996; Hacking, 1999). Modern science – including its processes, conventions, technologies, actors, institutions, and discourses – are socially situated and historically contingent. The crucial point here is that an "alternative 'successful' science" is always possible (Hacking, 1999: 69). As such, the knowledge gained through scientific practice is not inevitable. Thus, before attending to the specific sea-ice data products, a historical review of Arctic sea-ice science was carried out. This initial stage of the research speaks directly to the first research objective: *to review the history of Arctic sea-ice science and consider how advances in science and technology have influenced the production of scientific knowledge through time and to what extent contemporary Arctic science is a product of political, economic, and cultural frameworks.*

The historical review carried out in this thesis synthesises and builds upon the growing historical work produced by the sea-ice science community and historians of science in recent years (see Chapter 4). The review traces the history of Arctic sea-ice science over the last ~2000 years, with the aim to better understand how and why the practices, technologies, institutions, and discourses of sea-ice science have changed through time and how this has affected the growth of scientific knowledge and ideas about the Arctic. The sorts of questions that motivated this review are: What *technologies* and *practices* were used before satellites? How did these influence the types of knowledge produced about Arctic sea ice? Who were the dominant *actors* involved in historical sea-ice research, and how did this shape the types of knowledge considered to be necessary, credible, and valued? How have societal *interests* in the Arctic Ocean changed through time, and what role has science and technology played in facilitating human encounters with the region? What *conditions* enabled the development and implementation of satellite technologies for sea-ice research purposes, and how did this change our knowledge of Arctic environments?

The historical review has drawn from a variety of secondary sources, including published literature, online databases, institutional webpages, and government policy reports, as well as insights from the latter stages of research. It is by no means intended to be a comprehensive review; however, it helps situate the contemporary practices of sea-ice science within a historical perspective. Moreover, insights from this historical review have helped inform and shape the research carried out in the subsequent stages.

3.4.4. Stage 2: A Critical and Comparative Examination of Sea-Ice Data Products

3.4.4.1. Document Analysis

In sociological research, the term 'document' encompasses various textual and extra-textual materials produced to convey information (Coffey, 2014). The term includes, but is not limited to, 'official' reports, statements, and publications produced to record the activities and actions of an organisation; everyday documents pertaining to internal and external communications (e.g., meeting minutes, emails, notes); and photographs, maps, and advertisements that are often embedded alongside texts. Documents are routinely produced, maintained, archived, and circulated within social contexts (Coffey, 2014). They can be thought of as physical or virtual artefacts created through the activities and practices of a particular social setting or institution; as "the sedimentations of social practices" (May, 2011: 191). Thus, document analysis can be an important mechanism to better understand the practices, interactions, and ideologies that characterise individuals, social settings, or institutions.

The sea-ice data products examined in this thesis encompass various forms of documentation, including visual and statistical elements (e.g., sea-ice maps and graphs),

supplementary documentation (e.g., product user guides and technical reports), and other supporting textual materials and statistical data (e.g., institutional webpages and published literature). Collectively, these documents contain essential information on how sea-ice scientists interpret, process, and represent Arctic sea-ice conditions, as well as the contexts in which sea-ice data products are constructed. Thus, in this research, document analysis has provided an important starting point for understanding the different practices and contexts involved in the data acquisition, processing, and reporting of Arctic sea-ice conditions.

The use of document analysis involved a close reading of sea-ice data products and their associated documentation (Coffey, 2014). A variety of documents were purposefully selected and analysed for each of the sea-ice data products considered, including product user guides and manuals, theoretical background documents, product and user requirement documents, and relevant published literature. A full list of documents and their sources is included in Appendix 3. The analytical focus of document analysis was on describing and comparing the key methodologies used to acquire and process passive microwave observations of Arctic sea ice in the production the different sea-ice data products. This involved paying careful attention to the *context* and the *content* of the documents to extract insights into the retrieval methods and data processing techniques used in the production of data products; the conventions, assumptions, and requirements that shape how sea ice is interpreted, defined, and ordered; and the social, political, and cultural circumstances and conditions in which the data product is constructed. The close reading of documents was largely descriptive and guided by the questions listed in Table 3.3.

Table 3.3.: List of questions guiding document analysis.

Document Analysis

Focus Production: methods, technologies, and systems of data acquisition, interpretation, and translation	- What are the primary variables under focus and how are they defined? - What are underlying data sources? What rules, assumptions, and requirements govern how the data is processed? - What processes, tools, and technologies are used to develop the product? - What is the product's purpose and who are its main users? - Who are the main actors and networks involved in producing the data product? - What additional knowledge informs the production of the product? - What timescales are involved in the production of the product (e.g., temporal frequency)? How long has the product been in production? How have the data products changed over time? - What are the causes of uncertainty and how are they managed?

3.4.4.2. Cartographic Analysis

Building upon the initial descriptive insights gained through document analysis, the next step of the research critically analysed how the different methodologies involved in the construction of sea-ice data products affect how sea ice is represented cartographically. Here, the focus was on critically examining how Arctic sea ice is simplified, generalised, and classified in sea-ice maps; and how these cartographic representations help construct and reinforce particular ways of knowing (or 'seeing') the Arctic in the present and future. Maps of the natural world are necessarily and unavoidably selective: aspects of reality must be generalised, distorted, and excluded for maps to be useful and the features of interest to be readily intelligible (Monmonier, 2018). However, as the deconstructive and post-representational mapping critiques have argued (e.g., Harley, 1989; Pickles, 2004; Wood, 2010), the process of mapping is not neutral or value-free. Maps are the product of conventions, norms, standards, interests, and values embedded within particular social and temporal contexts. Thus, through a critical analysis of sea-ice maps, this research seeks to develop a greater understanding

of the choices, judgements, and interpretations made during their production and how these mapping practices shape how we perceive and understand Arctic sea ice.

My analytical strategy involved closely analysing and interpreting sea-ice maps using compositional interpretation and discourse analysis (Willig, 2014; Rose, 2016). Compositional interpretation is a term devised by Rose (2016) to denote a particular way of looking at and describing images. The approach has been described as a subset of semiotics (Banks, 2014); however, it tends to be more descriptive in its interpretation than more conventional 'semiological' analyses (e.g., Wood and Fels, 2008). The approach pays close attention to the meanings attached to the various elements that make up the map's composition: the use of colour, symbology, spatial arrangement; the content of the map; and the materials on which it is presented.[27] It also considers the map's site(s) of production, particularly when the circumstances of production directly affect how a map is represented (e.g., the technologies and techniques used). In this study, the use of document analysis and ethnographic fieldwork, alongside compositional interpretation has provided an important means for attending to the contexts of sea-ice map production.

Rose defines discourse as the "groups of statements that structure the way a thing is thought, and the way we act on the basis of that thinking" (2016: 187). Discourse analysis is concerned with how texts and images construct and mediate particular realities (Willig, 2014). The goal of discourse analysis is to examine how meanings are produced through *discursive strategies* (or *structures*) and consider their social effects (Willig, 2014). Discursive strategies can be defined as: "the unwritten conventions that operate to produce some kind of authoritative account of the world" (Waitt, 2005: 168). In particular, discourse analysis seeks to deconstruct dominant understandings of world and reveal the silencing of alternative perspectives and knowledge systems (Waitt, 2005). Discourse analysis can be used as a complementary approach to the compositional interpretation of maps by extending the descriptive analysis to consider the performative and constructive properties of the map elements. In other words, how does the selection of content and the design choices of a map give rise to particular way of knowing (Harley, 1989).

In this research, the critical analysis of sea-ice maps adopted a Foucauldian approach to discourse analysis (Waitt, 2005; Rose, 2016). The aim was to tease out the taken-for-granted meanings, assumptions, and practices that shape how Arctic sea ice is simplified, consolidated, and represented cartographically, and consider how these representations help to construct particular visions of the Arctic. It also looked at the *strategies of persuasion* (Gill, 1996); that is, the ways in which sea-ice maps gain their authoritative status as key tools of communication.

[27] The approach can be used for all forms of visual imagery, not just maps (Rose, 2016).

The compositional and discursive analysis of sea-ice maps was guided by the questions listed in Table 3.4.

Table 3.4.: List of questions guiding cartographic analysis.

Cartographic Analysis

Focus Representation: Compositional and discursive elements.	- What elements of reality have been selected, generalised, distorted, or omitted in cartographic representations of sea ice? - How do the elements of the map (e.g., projection, scale, colours, classifications, and symbology) distort and generalise the complexities of Arctic sea ice? - How are geographical regions represented? - What prior knowledge is required to interpret the map? - How does the map gain its authority as an account of Arctic sea-ice conditions? - What conditions of Arctic sea-ice change do they set? (e.g., timing of first ice-free Arctic summer when viewed together with statistical data) - How might these cartographic representations be different?

3.4.4.3. Alternative Mappings of Sea-Ice Extent

As introduced in Chapter 1, sea-ice extent is an important indicator of changes in the spatial and temporal distribution of Arctic sea ice. It is also used to mark the 'ice edge' position by distinguishing between 'ice-covered' and 'open-water' areas. The most used definition of sea-ice extent is based on a 15% sea-ice concentration threshold: areas with concentrations of 15% or less are considered 'open-water', and areas exceeding 15% are considered 'ice-covered'.

In recent years, several studies have questioned the validity of the 15% sea-ice concentration (SIC) threshold used in passive microwave observations to define sea-ice extent and map the 'ice edge' (e.g., Remund and Long, 1999; Partington, 2000; Worby and Comiso, 2004; Ji *et al.*, 2018; Pang *et al.*, 2018). Ji *et al.* (2018) and Remund and Long (1999) conducted statistical analyses that compared different methods for deriving the Arctic sea-ice edge. Both studies indicated that a SIC threshold of ~30% would be more appropriate for sea-ice extent calculations, particularly during the summer months. Other inter-comparison studies have shown that the representativeness of the 15% threshold varies depending on factors such as seasonality and ice characteristics in the

MSIZ (e.g., Partington, 2000), as well as the properties of the passive microwave sensor used in data acquisition (e.g., Meier and Stewart, 2019).

Recently, Matthews *et al*. (2020) used a selection of SIC thresholds (values from 5% to 85%, at increments of 5%) to assess how the threshold choice affected the long-term statistical characteristics of sea-ice extent. While there are lots of uncertainties to account for (e.g., the impact of surface melt), the analysis indicates that changing the threshold significantly impacts sea-ice extent values in two notable ways. Firstly, and perhaps unsurprisingly, higher thresholds yield lower sea-ice extent estimates. In turn, this results in the earlier occurrence of the first ice-free Arctic summer. Additionally, higher thresholds cause the annual sea-ice extent minimums to occur earlier in the year.

Although previous studies provide valuable insights into the statistical effects of the discrepancies and uncertainties in the SIC threshold choice, few consider the *visual* implications of a changing threshold. The final question in Table 3.4 asks: "How might these cartographic representations of sea ice be different?". To explore this further, this study reproduced the ~40-year times-series for Arctic sea-ice extent using monthly sea-ice concentration data obtained from the NSIDC ([NSIDC-0051 dataset], Cavalieri *et al*., 1996). Sea-ice extent statistics and maps were derived using threshold values of 15%, 30%, 50%, and 60%. The choice of alternative thresholds was informed by the need to capture a range of different values while being mindful that there is greater uncertainty in sea-ice retrieval at lower concentrations (Windnagel, 2008).

The data were accessed from the NSIDC website via File Transfer Protocol (FTP) in two different formats: binary (.bin) and network Common Data Form (netCDF).[28] The '.bin' dataset was used to extract sea-ice maps for the four different thresholds using ArcGIS Pro. The data were then processed according to the guidelines stipulated on the NSIDC website and developed upon to reflect the goal of the alternative maps.[29] The maps were subsequently downloaded and presented using an interactive web application developed using the software package R Shiny (Appendix 4). The 'netCDF' dataset was used to extract the accompanying numerical values using Python (Appendix 5).

This reproduction of sea-ice extent maps compliments the critical insights developed through the cartographic analysis (Section 3.4.4.2). In my 'alternative maps', I sought to illustrate how changing the conventional definition of sea-ice extent affects how we visualise Arctic sea-ice change over a range of temporal and spatial scales. Although this

[28] The '.bin' format is associated with the NSIDC-0051 dataset: Sea Ice Concentrations from Nimbus-7 SMMR and DMSP SSM/I-SSMIS Passive Microwave Data, Version 1 (Cavalieri *et al*., 1996). The 'netCDF' format includes the same data as the NSIDC-0051 provided in a different format. It is associated with the NOAA/NSIDC Climate Data Record of Passive Microwave Sea Ice Concentration, Version 3 (Meier *et al*. 2017). The reason for choosing two different formats was for ease of data handling.

[29] The instructions can be found here at https://nsidc.org/support/How-do-I-import-sea-ice-data-binary-data-files-into-ArcGIS. See also Appendix 6.

analysis only concerns one specific and relatively minor change to how sea-ice data is processed and represented, it is scientifically justified. Representing the maps using an interactive web application enables the viewer to compare the visual effects of the range of thresholds for different months of the year and over the full time series (Figure 3.4). The reproduction of the alternative maps is also supported with statistical analyses of sea-ice extent trends over seasonal, annual, and interannual timescales.[30]

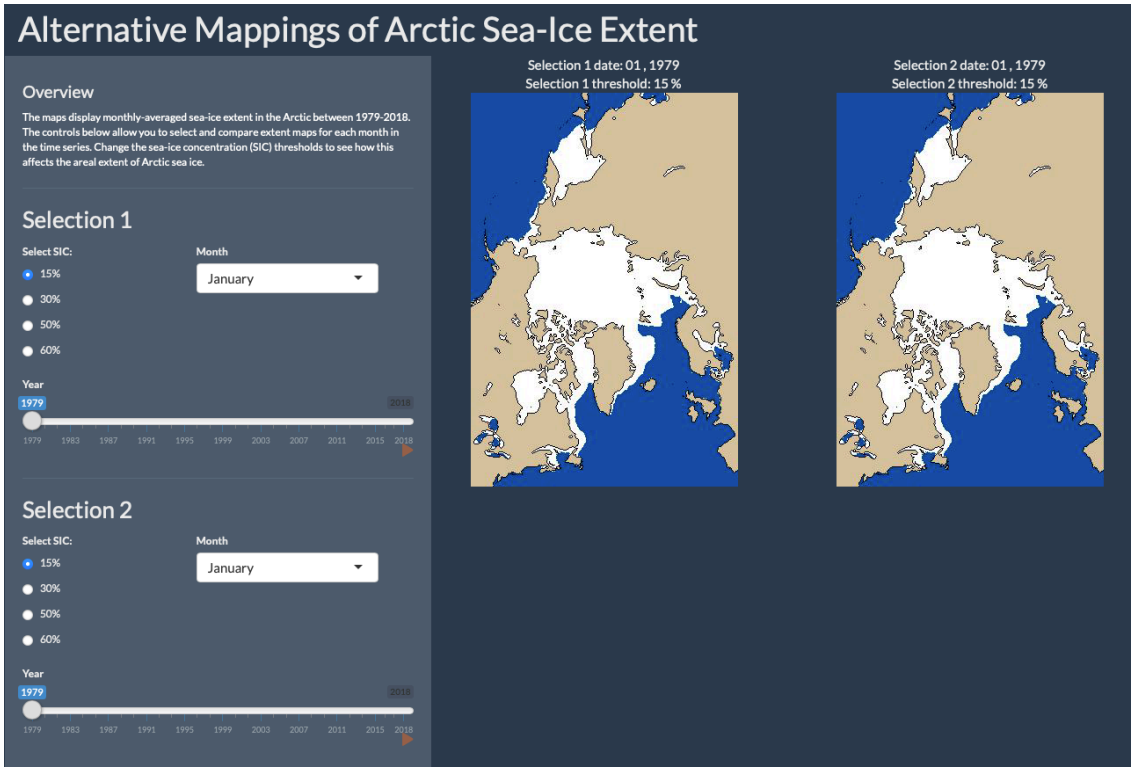


Figure 3.4.: R ShinyApp online web application developed to present the Alternative Mappings of Arctic Sea-Ice Extent. The interface is designed to enable the user to view and compare sea-ice extent maps for different months, using different sea-ice concentration thresholds. The interface can be accessed at: https://alternativemapsofsie.shinyapps.io/Alternative_Mappings/.

3.4.5. Stage 3: Ethnographic Fieldwork

This stage of the research primarily consisted of a six-week fieldwork visit to MET Norway. The main purpose of the fieldwork was to gain a more in-depth and first-hand understanding of how sea-ice data products are developed in their institutional contexts and to identify the social factors, conditions, and idiosyncrasies that shape their production and dissemination. Participant observation represented the primary means of data collection, and this was supplemented by in-depth, semi-structured interviews with sea-ice scientists. The insights gained through ethnographic fieldwork were

[30] Although this analysis used the same data to the NSIDC SII, the sea-ice extent values for a threshold of 15% are not consistent with those reported by the NSIDC. This is due to the manual quality control measures that occur during the production of the NSIDC SII, making their approach subjective and not reproducible. See Chapter 5 for more details.

intended to enhance and substantiate the critical and comparative examinations carried out in Stage 2.

3.4.5.1. Participant Observation: Data Collection

Access and Role

Ethnographic fieldwork was conducted in the Research and Development Department at the MET Norway headquarters in Blindern, Oslo, between February and March 2020. Within this department, sea-ice scientists are directly engaged in developing, processing, and distributing the OSI SAF SIC, the C3S SIE, and the C3S SITy data products. It should be noted that MET Norway's Research and Development Department is not exclusively based at the headquarters in Oslo. The department's operations, particularly in relation to sea-ice monitoring, also extends across their supporting offices in Tromsø and Bergen. Moreover, the production and ongoing development of the data products is shared between MET Norway and the Danish Meteorological Institute. However, as a result of initial discussions held with MET Norway personnel in September 2019, it was decided that due to the climate-orientated focus of my research, the headquarters in Oslo would represent the most suitable location for fieldwork. I was also informed that regular telecom communications would enable contact between the different offices to be maintained during the visit.

During my visit, I assumed a 'participant-as-observer' role within the MET Norway headquarters (Gold, 1958). This role required my continued presence and active involvement in the research activities of MET Norway. For the duration of the visit, I predominantly worked alongside sea-ice scientists carrying out an independent research project comparing the statistical characteristics of the OSI SAF and C3S data products. The general aims and scope of the inter-comparison project were discussed during the initial meetings and through email exchanges before commencing fieldwork. In addition to carrying out this project, I observed the day-to-day working practices of the scientists based in the office where I was placed. The key informants were made aware of the wider purpose and data collection methods of my PhD research through the provision of an information sheet prior to the research taking place (Appendix 7).[31] The information sheet included key details on data use and storage, participant anonymity and confidentiality, and provided the option to withdraw participation at any time during my visit.

Inter-Comparison Project Comparing MET Norway Data Products

For the duration of the fieldwork, I undertook an inter-comparison project on behalf of the MET Norway sea-ice scientists. The project's objective was to analyse and compare

[31] The PhD project was granted ethical approval through the Department of Geography's Research Ethics Committee at Durham University.

monthly-averaged sea-ice concentration estimates calculated using the OSI SAF SIC, C3S SITy, and C3S SIE data products. As noted previously, although the primary data source is broadly consistent across the three data products, there exists some important differences in the product characteristics, data retrieval methods, and processing techniques used. Thus, the inter-comparison project aimed to investigate how the differences between the data products affect the spatial and temporal characteristics of sea-ice concentration and extent, to allow for a better understanding of product uncertainties and systematic biases. Data collection and analysis primarily took place during the research placement, and the project was written up for MET Norway in the months following my return to the UK.[32]

Adopting the role of participant-as-observer generally means that the process of observing is subordinate to the researcher's participation in the day-to-day activities of the group under study (Merriam and Tisdell, 2016). Potential drawbacks of this role include a lack of thorough observations and the possibility of "going native", whereby the researcher becomes too involved in the community under study and loses the important balance between insider (emic) and outsider (etic) perspectives (O'Reilly, 2009a; Marvasti, 2014; Patton, 2015). However, assuming the role of participant-as-observer in this PhD research proved to be highly beneficial for several reasons.

Firstly, working directly with the sea-ice data products provided a more in-depth and first-hand understanding of the different product characteristics, data retrieval methods, and processing techniques used in their development. The project also allowed for a greater understanding of how the complexities and uncertainties of sea ice are managed and translated into meaningful data. It was envisioned that insights gained through this project would directly inform and supplement the qualitative research carried out in Stage 2 and vice versa. Indeed, the insights gained through document analysis before the fieldwork provided necessary background knowledge on the different sea-ice data products.

Secondly, I was informed that this was a project that the sea-ice scientists had hoped to carry out themselves; however, they had been unable to do so due to other research commitments and time constraints. The project catered to the aim and objectives of this PhD research, but it also reflected the interests and needs of the sea-ice scientists in that it constituted a key component of ongoing product development. Regular meetings and informal discussions with key informants shaped how the project progressed. These discussions provided invaluable insights into what aspects of sea-ice research were considered to be important and why. Notably, my participation provided insights into

[32] The full project write-up is included in Appendix 8. The outcomes of this project do not feature explicitly in this thesis; rather, the project provided a means of understanding the data products, limitations, and production circumstances more comprehensively and for developing key data handling techniques.

the range of social and technical factors that shape the decisions and judgements made during the development of the sea-ice data products.

Thirdly, my participation in this project was an important means for building rapport with the scientists. Developing rapport is essential for obtaining effective and high-quality data using participant observation (Marvasti, 2014). Several factors affect rapport: the purpose and topic of the research, the ability to maintain participants' privacy and anonymity, and the degree of similarity between the researcher and the participants (Morgan and Guevara, 2008). As noted in Chapter 2, social constructivist studies of scientific knowledge have long been accused of making simplistic and superficial claims about the practices and outputs of science (e.g., Gross and Levitt, 1994; Sokal and Bricmont, 1998; Sokal, 2001; Kochan, 2017). Thus, carrying out such studies today demands a certain degree of sensitivity and reciprocity during the research process. Directly engaging with the institute's research activities through undertaking the inter-comparison project demonstrated a willingness to understand the (often complex and highly technical) scientific field of sea-ice science and enabled me to give something back through deriving useful results. I do not doubt that my participation in this project positively impacted my interactions with the scientists.

Lastly, this study is an investigation into the sociological nature of *scientific knowledge*. It is not a sociological study of scientists *per se*. Knowledge of the technicalities of sea-ice science is as important as knowledge of the social factors and conditions that shape them. Latour and Woolgar (1979) refer to the balance between the 'technical' and the 'social' as the *observer's dilemma*: to disproportionately focus on sociological factors and disregard the technical, undermines the task at hand and inhibits the ability to see how the two are intimately linked (see also Mulkay, 1974). Therefore, participating in a project on behalf of MET Norway provided a means to focus on both sociological and technical issues.

Direct Observations and Informal Discussions

While carrying out the inter-comparison project, observations were collected of the research setting, the participants, the day-to-day working activities and interactions of the scientists, and my own activities and experiences. As noted previously, the primary aim of conducting ethnographic fieldwork was to develop a more nuanced understanding of the situated and contextual nature of the practices involved in the production and dissemination of sea-ice data products. Thus, the observations were somewhat guided by a set of pre-determined questions that reflected the overall aim and objectives (Appendix 9). However, these questions were not used prescriptively to ensure the process of observing remained flexible and open to new lines of inquiry. In addition to observations, numerous informal discussions with MET Norway scientists occurred over the six weeks. These discussions covered a wide variety of topics,

including the inter-comparison project, general scientific research, the best bakeries in Oslo serving *skoleboller*, and the growing concerns over the COVID-19 outbreak.

Field notes were recorded during the working day to capture and record the observations and exchanges with and between MET Norway scientists. These were initially written as general descriptive notes and "jottings" recorded simultaneously or immediately after the observations and discussions took place (Emerson *et al*., 1995). During the evenings and away from the research setting, the general descriptive notes were developed and expanded upon to include greater detail and reflections on the observations and exchanges (Creswell, 2013). Over the course of the fieldwork, the more detailed notes were used to draw out key themes and develop some initial interpretations.

Interviews

Semi-structured, in-depth interviews were carried out with two research scientists based at MET Norway who are involved in developing the OSI SAF and C3S sea-ice data products. Due to the escalating COVID-19 outbreak (Section 3.5.3), the fieldwork was terminated before the interviews could occur in person. Consequently, the interviews were carried out remotely using the video conferencing software, Zoom, in June 2020. Although there are disadvantages to holding computer-mediated interviews – such as technical issues (e.g., internet connectivity and audio feedback) and the inability to observe non-verbal forms of communication – it introduced a greater flexibility for when the interviews could take place. Moreover, the gap between the fieldwork and the interviews provided valuable time to reflect on the data obtained *in situ* and develop the interview questions accordingly.

The purpose of these interviews was to develop upon and substantiate the insights obtained during the fieldwork and discuss issues or aspects of the data products that remained ambiguous. It also provided the opportunity to identify individual perspectives, values, and experiences, and assess the agreement between individual and institutional ideologies. Following a preliminary analysis of the fieldnotes (Section 3.4.5.2), several key themes emerged from the data. These themes were used to develop interview questions, which guided the conversations (Appendix 10). The interviews lasted between 70-90 minutes, and the audio and video were recorded using Zoom's in-built features.

Prior to the interviews, the research scientists were provided with the aforementioned information sheet and a formal consent form (Appendix 11). Similar to the information

sheet, the consent form included the option to withdraw at any point and detailed the processes to ensure that data would be treated confidentially and anonymously.[33]

3.4.5.2. Participant Observation: Data Analysis

Qualitative data analysis can be understood as the act of interpreting and drawing out meanings from various sources of data. As Crang and Cook (2007) note, ethnographic data sources can often be disparate and variably systematic. The analysis and interpretation of data, too, can occur in more or less systematic ways. For example, ideas and thoughts developed during moments of reflection in the field or initial readings of the data sources are unlikely to follow a formal process. Nevertheless, these initial ideas may become integral to our overall interpretation of the phenomenon under study and are an important element of the creative process of qualitative research (Crang and Cook, 2007). Using systematic procedures can help develop and verify initial ideas while improving the credibility and trustworthiness of the research findings (Braun and Clarke, 2006; Nowell *et al*., 2017).

In this research, the data obtained through participant observation was analysed using thematic analysis. This approach is primarily a descriptive strategy used for analysing, categorising, summarising, and reconstructing data to identify patterns and regularities (Braun and Clarke, 2006; Ayres, 2008). Thematic analysis offers flexibility in its approach, and there are few prescriptions and fixed procedures involved (Braun and Clarke, 2006). The strategy adopted in this research has been informed by the approaches outlined in Creswell (2013) and Nowell *et al*. (2017).

The first step of the analysis involved preparing the data: field notes were collected, converted electronically, and organised chronologically; the interviews were transcribed immediately after the meetings to allow for initial thoughts and reflections to be recorded simultaneously. The process of thematic coding involved reading and re-reading the texts to become familiar with the data; identifying codes, patterns, and key points or phrases of interest; reducing the codes to general themes; and reviewing and comparing themes across the different data sources to establish consistent categories. The identification of codes and themes was informed primarily by my social constructivist approach to scientific knowledge, the overall research aim and objectives, and preliminary interpretations established during the fieldwork and through the previous stages of research.

The analysis was initially conducted using NVivo software; however, due to the enforced homeworking under COVID-19 restrictions, access to NVivo through the University's Remote Access Service was challenging and cumbersome. Therefore, the

[33] Due to the nature of the sea-ice science community, the informants were made aware through the consent form that absolute anonymity may not be achievable.

electronic copies of the data sources were printed, and the analysis was undertaken by hand. To assist with this process, 'code maps' were drawn to help identify linkages, similarities, and causalities between the codes and emerging themes (Cook and Crang, 2007; Figure 3.5).

Figure 3.5.: An example of a code map developed to analyse the data collected during the participant observation carried out at MET Norway.

3.5. Research Challenges and Limitations

3.5.1. Participant Observation

Researchers can face various challenges and issues when carrying out participant observation. Guest *et al*. describe it as one of "the most natural and the most challenging of qualitative data collection methods" (2013: 75). Challenges may include ethical issues, such as consent, access, and anonymity; practical issues, such as researcher safety or global pandemics; and cultural issues, such as language difference. Numerous challenges were faced during fieldwork, some of which have been addressed in the previous sections (e.g., ethics and access). Here, I outline three notable challenges that have directly limited the quality of the data obtained through participant observation. The more general issues such as positionality and generalisability are addressed in the following section.

Firstly, the duration of immersive fieldwork was relatively short. As noted previously, this was partly a reflection of the overall aims and objectives of the research, which favoured the combined use of visual and ethnographic methods, partly due to the constraints of the PhD timeframe (which initially accommodated a second fieldwork visit to the NSIDC), and partly due to the COVID-19 outbreak, which brought an early end to fieldwork. That said, the short duration of the visit limited the quality and quantity of data obtained *in situ.* As such, the data collected only offers a snapshot of the institution's culture and practices at a particular moment in time.

Secondly, the working environment and culture at MET Norway introduced obstacles to effective observations. The office was divided into several smaller individual and dual enclosed offices, making it difficult to interact with scientists during working hours unobtrusively. Moreover, most of the research activities are carried out using computers. Unlike the laboratory processes observed by Knorr Cetina (1999) and Latour and Woolgar (1979), the intricacies involved in constructing computer-mediated knowledge are difficult to observe first-hand. Additionally, the office was made up of scientists working in various strands of meteorology and oceanography, for which sea-ice research constitutes a relatively minor component. A final point to note regarding the physical working environment is that the sixth week of my visit – which unpredictably became my final week – was significantly disrupted by the COVID-19 precautions being introduced.

Lastly, as mentioned in Section 3.4.2, Norwegian was the dominant language spoken in the institution, in which I am not fluent. While (nearly) all researcher-participant dialogue occurred in English, my inability to speak Norwegian limited the opportunities available to observe interactions between scientists.

3.5.2. Positionality and Generalisability

The central argument in this research is that scientific knowledge is intrinsically and unavoidably social: all knowledge is shaped by the social conditions in which it is produced, and its production is informed by particular biases, values, and perspectives. This same argument equally applies to the research carried out in this PhD. The research process and product are inevitably subjective and situated. The research has been mediated by my perspectives, experiences, inherent biases, and expectations as a white, Western, British, educated, cisgender female. All these factors – and many others – have coloured the collection, analysis, and interpretation of data: they have shaped my interest in the topic, the methods and techniques deployed, the questions asked, the exchanges in the field, and the articulation and representation of findings.

Steps have been taken to reduce the influence of preconceived biases and assumptions throughout the research process; for example, using systematic methods of data analysis and adopting a neutral approach to describing the practices (social and otherwise) involved in the construction of sea-ice data products. However, it is important to recognise that the active influence of researcher bias cannot be fully removed from the research process; the outcomes can never be 'untainted' (May, 2011). The consequence of this is that the research carried out in this PhD study may not be generalised or replicable. Moreover, it is impossible to capture all factors that play a role in shaping the acquisition, processing, and reporting of Arctic sea-ice science. The research process involved numerous decisions, judgements, and interpretations about what aspects of sea-ice science I deemed to be important within the logistical and methodological constraints of the project. These choices are inextricably linked to my positionality. Ultimately, this research represents one of an indefinitely large number of approaches that could have been taken to study and interpret the sociological nature of Arctic sea-ice science.

Given the interdisciplinary nature of this PhD research, it is necessary to reflect further on how my previous academic and professional experiences have shaped the research presented in this thesis. Previously, I was trained in the physical sciences, with an undergraduate degree in Physical Geography, a master's degree in Earth Sciences, and industry experience in catastrophe modelling. These experiences instilled in me a positivist epistemology: I was equipped with knowledge and skills to study and interpret earth systems and environmental processes using physical and mathematical principles; I learnt the importance of using rational, repeatable, and replicable scientific methods for achieving valid and legitimate knowledge; and I held the view that objective knowledge about the world is achievable. Throughout this PhD research, these assumptions and preconceived ideas that I once took to be self-evident have been challenged and upended in irrevocable ways and replaced by and large by an interpretivist-constructivist standpoint. While this research adopts a social constructivist

framework, it is valuable to consider how my academic and professional background may have influenced the research process, particularly regarding the interactions that occurred during my fieldwork within a scientific institute.

Ethnographic research seeks to understand and see things from an insider's perspective (see Section 3.3.1). Developing an understanding of an insider's perspective relies upon the researcher's ability to navigate the delicate balance between acting as an empathetic participant and acting as a detached observer (O'Reilly, 2009b; 2012). The intercomparison project carried out during my fieldwork provided the opportunity to participate directly in the scientists' work and assume an insider's role (see Section 3.5.4.1). In this context, my background in the physical sciences proved beneficial. Despite being unfamiliar with the specific data products, processing techniques, and programming software, my prior knowledge and technical experience working with geophysical data enabled me to learn the required skills and carry out the project with relative ease. This provided valuable insights into the characteristics of the data products, as well as the day-to-day working practices of the institute. It also likely hastened the establishment of rapport and supported more candid responses during discussions and interviews. At the same time, however, my familiarity with the concepts and techniques adopted in the physical sciences may have detrimentally affected my ability to articulate and distinguish between insider and outsider perspectives and distance myself from the contexts under observation. Indeed, I often felt more comfortable discussing the technicalities of the intercomparison project than when asking questions about the social contingencies of the data products. In a bid to maintain the necessary distinctions between participant and observer, I dedicated time to maintaining up-to-date observational notes daily and actively engaged with STS literature throughout the fieldwork duration. These acts were essential reminders of the broader research purpose and my dual role as a participant-observer.

3.5.3. Methodological Implications of COVID-19

As implied throughout this chapter, the COVID-19 pandemic has severely disrupted my research project in several ways. In this section, I describe some of the specific implications; although the impacts have primarily been negative, some positive outcomes are important to note.

The COVID-19 outbreak escalated during my research visit to MET Norway. Initially, the duration of the visit was intended to last eight weeks. However, by the sixth week, news that the virus was spreading globally, and at an alarming rate, necessitated the early and immediate termination of my stay. On the morning of Thursday, 12th March, I was informed that MET Norway's operations had moved online, and that remote working would be in place for the foreseeable future. Thus, the necessary course of action was for me to return home with immediate effect. As a result, two to three weeks

of participant observation time were lost, and the remaining project work and interviews were carried out remotely.

Despite the loss of time in the field, the disruption provided time to reflect on my experiences, thoroughly write up the inter-comparison project, and develop questions for the interviews. It also provided interesting insights into the institutional response to broader societal issues. For example, it illustrated how different research activities were prioritised in terms of on-site and remote resourcing (e.g., prioritising access to a VPN) and how online 'spaces' quickly became essential for maintaining research output.

The COVID-19 pandemic subsequently resulted in the cancellation of a second research visit to the NSIDC. The visit was initially planned for Summer 2020 but postponed indefinitely following the restrictions placed on international travel. With time, it became clear that a visit would not be feasible in the PhD timeframe. The second visit represented a significant component of the planned research and was intended to be used as a comparative component. Prior to the COVID-19 outbreak, I had established key informants, and preparations were already underway for me to undertake participant observation. I chose not to carry out interviews remotely with the sea-ice scientists at the NSIDC. While this would likely have provided useful insights into the production of NSIDC sea-ice data products, the value of these interviews would perhaps have been limited due to my inability to build a relationship of rapport and trust over an extended period.

Lastly, the enforced homeworking restrictions introduced delays to productivity and disrupted access to systems, key resources, and crucial support networks.

3.6. Conclusion

In this chapter, I have described the research approach developed and implemented to study the scientific practices involved in the acquisition, processing, and reporting of Arctic sea-ice. I have accounted for the combined use of visual and ethnographic methodologies and outlined the three stages of inquiry that have provided a structure for critically examining sea-ice data products and attending to the social and cultural contexts in which they are embedded. The following chapters present the results and discussion of this study.

4. A History of Scientific Encounters with Arctic Sea Ice

4.1. Introduction

A central contention of this thesis is that the practices and technologies of contemporary science are culturally situated and historically contingent. The processes, conventions, actors, institutions, and discourses that shape what we know and how we come to know are intimately connected to historical periods. As Golinski states: "[p]ractising scientists are continually appropriating the work of their predecessors and orientating themselves in relation to it" (1998: 2). Thus, a key objective of this PhD research is to examine the historical contexts that have shaped and informed the development of the contemporary practices and technologies of sea-ice science.

This chapter presents a historical review of outsiders' understandings of Arctic sea ice over the last ~2000 years. The objective is to develop a greater understanding of the historical entanglements between sea ice, science and technology, and societal interests and consider how changes to the dominant practices of sea-ice science have shaped the growth of scientific knowledge and ideas about the Arctic. Through attending to several key periods in the region's complex history, the following sections illustrate how knowledge of Arctic sea ice has been integral to how the Arctic has been conceptualised, encountered, and acted upon by people who predominantly live outside the region. The chapter describes how perceptions of Arctic sea ice have evolved through time, shifting from an obstacle, a habitat, a military space, to a key component of the climate system. These changing perceptions are interwoven with varying and often contradictory societal interests and idealisations of the Arctic as an uninhabitable space, a resource frontier, a strategic location, and a fragile environment. In turn, the dominant practices and technologies of sea-ice science have changed and adapted to meet the needs of societies within different historical and cultural contexts.

Section 4.2.1 describes how early conceptions of the Arctic as a hostile and uninhabitable space that emerged during Antiquity and the Middle Ages shaped how later generations perceived and engaged with the region. Arctic sea ice represented a boundary of alterity between the known and civilised world and the uninhabitable north for much of this

earlier period. Section 4.2.2 explores how the explosion in mapping practices during the early modern era and the desire for imperial expansion ignited European interest in finding and charting an ice-free passage through the Arctic. Section 4.3 considers how, as the blank spaces on the maps receded, the Arctic was reimagined as a region of great resource potential during the seventeenth to nineteenth centuries, and scientific knowledge of sea ice became wrapped up with commercial and nationalistic interests. Section 4.4 explores how geopolitical competition and anxieties during the Cold War encouraged utilitarian approaches to sea-ice research. Lastly, Section 4.5 examines how the emergence of climate science and the race to conquer space had significant and long-lasting implications for sea-ice research and our understanding of sea ice as an important component of the climate system.

Before beginning, it is essential to recognise the partiality of this historical review. It focusses predominantly on the evolution of Western interests, perspectives, and scientific approaches to Arctic sea ice. There is a distinct lack of Indigenous perspectives throughout; indeed, despite their importance, there is only a brief mention of how Western scientists relied upon the knowledge of Indigenous peoples throughout historical encounters with the Arctic. The partiality of this historical review predominantly reflects the PhD aims and objectives, which seek to understand the practices and technologies that prevail in Western science. However, I hope that by questioning the situated nature of Western sea-ice science, the broader aim of this thesis will complement the wider critical literature demonstrating the value and importance of diversifying Western knowledge systems to include the perspectives, agendas, and interests of those who have long been overlooked.

4.2. Sea Ice as a Barrier

4.2.1. An Arctic Eden (Antiquity to the Middle Ages)

Some of the earliest written descriptions of Arctic sea ice date back nearly two and a half thousand years, to the time of Antiquity (McCannon, 2012). Despite the absence of formal institutions of science, the knowledge and ideas ancient Greek philosophers formulated about the Arctic became the basis of Western geographical thought for the centuries that followed and, in many ways, still influence how the region is perceived today. Thus, an examination of the historical contingencies of sea-ice science cannot disregard this era.

Besides Indigenous peoples who have resided in the Arctic for thousands of years, few had directly encountered the region during ancient times.[34] Ancient Greek knowledge about the Arctic was highly speculative and relied upon fragmented accounts reaching

[34] Archaeologists have found evidence for human occupation north of the Arctic Circle as far back as 30,000 years ago. See McCannon (2012, 2018), Pitulko *et al*. (2016), and Raghavan *et al.* (2014).

the Mediterranean from northern Europe, supplemented with Greek mythology (McGhee, 2006; Cartledge, 2011). Accounts of extreme cold, ice-riddled landscapes, and a midnight sun were intertwined with myths that told of strange beasts, tropical climates, and the exotic paradise of Hyperborea, located 'beyond the north wind' (McGhee, 2006). These descriptions evoked conflicting framings of a mysterious and exceptional, yet hostile region, which instilled a centuries-long desire to uncover what the Arctic encompassed (Bruun and Medby, 2014).

Exploration was vital to making sense of the speculations. Around 330 BC, Pytheas of Massalia, a Greek geographer and astronomer, ventured northwards on what is considered among the most influential exploratory voyages of ancient times (Roller, 2015). Motivated by the desire to advance knowledge of the northern latitudes, as well as to search for valued sources of amber and tin, Pytheas travelled to several countries in northern Europe where he documented observations of natural phenomena and collected ethnographic accounts of the people he met (Mulvaney, 2001; McGhee, 2006; McCannon, 2012). Vestiges of Pytheas's writings were preserved, mostly in the form of second-hand accounts reproduced by scholars such as Strabo and Pliny the Elder (Roller, 2006, 2015). From these accounts, Pytheas is said to have reached and explored much of the north-eastern coastline of Europe, the North Sea, and the British Isles, providing some of the earliest outsider descriptions of these regions (Roller, 2015). After a six-day sail north of the British Isles, Pytheas discovered Thule, an island described in numerous accounts as the land of the 'midnight sun' (McGhee, 2006). To the North of Thule, references made to a 'congealed sea' and a 'sea-lung' have been interpreted as descriptions of pack ice and pancake ice, respectively, suggesting that the voyage may have reached the outer extent of Arctic sea ice (Dodds, 2018).

The fragmented nature of Pytheas's accounts has fuelled speculation over the precise whereabouts of Thule. The descriptions of continuous sunlight, proximity to a frozen sea, and the distance from the British Isles have made Iceland, northern Norway, or southern Greenland plausible locations (Mulvaney, 2001). Although its precise location may never be resolved, Thule came to denote the northern limit of the known and inhabitable world. It represented a remote and mysterious frontier, the position of which was later fixed cartographically at around 63° north (Bravo, 2019). The area north of Thule, beyond the impenetrable icy sea, was widely assumed to be "uninhabited and unimportant" (Bravo, 2019: 43). Such ideas helped foster a boundary of alterity between the civilised southern latitudes and the uninhabitable north. The perceptions of an expansive and hostile Arctic filtered through generations of geographic, scientific, and cultural imagination (Emmerson, 2011; Dodds, 2018; Bravo, 2019).

Throughout the Middle Ages, the legacy of Thule and notions of icy seas, hostility, and paradisal elements remained prevalent in European knowledge of the Arctic (Mulvaney, 2001). Descriptions of sea ice and North Atlantic islands appeared in the accounts of

travellers who set out northwards from northern Europe in search of an Arctic Eden. However, sources of new information about Arctic geography were scarce and unreliable: written texts were subject to exaggeration and influenced strongly by historical myths and biblical stories (McGhee, 2006). Moreover, mapping was not an established practice. Maps were expensive, hand-drawn, and highly subjective representations, which depicted features "according to taste" and where space permitted (Nansen, 1911: 186).[35] The early Middle Ages were, as Nansen describes, "the age of speculation, not observation" (1911: 182).

4.2.2. The Arctic and the Expansion of Early Modern Europe (1500s to 1600s)

The Age of Exploration witnessed a critical turning point in knowledge about Arctic sea ice. The Age of Exploration was a period of early modern European history characterised by extensive maritime travel in search of new territories, geographical knowledge, and commercial prosperity. Pursuing these interests was reflective of, and made possible by, the profound political, societal, and technological changes occurring throughout Europe, which eventually gave rise to the modern international system (Branch, 2013). European interest in the Arctic grew significantly during this period. The Arctic was not seen as a space to conquer in itself, as European economic thinking remained preoccupied with Aristotelian ideas that spaces of civilisation and wealth were concentrated at lower, more temperate latitudes (Emmerson, 2011). However, in Europe's imperial pursuit for global political, economic, and technological dominance, the Arctic was increasingly seen as a region to pass *through* (Markley, 2003). Notions of ice-free passages established a key objective among European nations that came to dominate early scientific interest in the Arctic: to map the Arctic Ocean and find a safe route connecting the East and West.

The map was an indispensable tool in Europe's imperialist expansion. Following major advances in cartography and representational techniques during the late fifteenth and early sixteenth centuries, mapping practices became increasingly popular and widely accessible forms of intellectual inquiry (Branch, 2011, 2013). As Branch (2013) notes, advances in cartography transformed the production and use of maps from a limited practice, primarily constrained to matters of religion or local and regional land itineraries, to a ubiquitous pursuit of information in support of social, political, and economic goals. The significant changes in mapping and its uses materialised out of two key developments: 1) the incorporation of Ptolemaic methods into cartographic practice; 2) developments in mass printing which made it possible for maps to be produced and

[35] Maps during the Middle Ages existed, but they did not build on the same mapping conventions and traditions that underpin modern maps (e.g., coordinate systems). As Branch (2011, 2013) and Wood (2010) note, maps were not a conventional tool for conceptualising space.

distributed widely.[36] As a consequence of these developments, grid-based maps built upon mathematical principles, such as standardisation and quantification, became privileged forms of representation (Pickles, 2004). These developments in early modern cartographic practice had direct implications for how European nations understood and articulated the world around them (Branch, 2013).

An upsurge in the number of nautical charts and global atlases drawn using a coordinate grid of latitude and longitude greatly supported the growth in international trade networks. These were developed first and foremost to define regions in terms of their geographical, social, and political nature and assist navigators searching for new territories and safe travel passages (Branch, 2011). Nevertheless, as critical cartographers contend, rendering territories and oceans cartographically, makes them amenable to state control (e.g., Turnbull, 1996; Harley, 2001; Wood, 2010; Branch, 2011, 2013). Maps emerged as significant – and often highly secretive and censored – artefacts through which states could exercise political authority and order, establish monopolies over trade and shipping, and assert their position within a rapidly modernising international system (Harley, 2001).

Northern European countries were late to develop commercial interests in overseas markets. By the turn of the sixteenth century, most of the global trade networks were controlled by southern European nations, namely Portugal and Spain (Mulvaney, 2001). In a bid to find and exploit alternative access routes to trade in the Far East, many northern countries turned their attention to the Arctic Ocean. At the time, however, knowledge of Arctic Ocean geography was reliant on vague and unsubstantiated information. As McGhee (2006) notes, early maps commonly represented the Arctic territories as vast, ice-riddled, and empty spaces: a *terra incognita* at the top of the world. The lack of direct encounters in the preceding centuries, particularly within the ocean interior, gave way to a great intrigue about what lay beyond the sea ice.

Following accounts of ice-free passages connecting the North Atlantic and Pacific Oceans, early explorers' attempts to transit the Arctic focussed on two infamous routes: the Northeast and the Northwest passages (Mulvaney, 2001). Additionally, with the absence of direct observations, geographers and physicists widely theorised that an open, ice-free polar sea existed at the North Pole, encompassed within an outer belt of sea ice (Craciun, 2010; McCannon, 2018). To curious merchants, the existence of an open sea presented the opportunity for a safer and more accessible trans-Arctic path to global markets. Incentivised by these ideas, this era saw a wave of European explorers,

[36] The translation of Ptomley's Geography into Latin during the 1400s revealed instructions for incorporating a coordinate grid of latitude and longitude into map constructions and an extensive list of cities with assigned geocoordinates. The developments in mass printing meant that maps were commercially viable and affordable for many. These changes resulted in an exponential increase in the production and use of maps.

predominantly from England and the Netherlands, who set out to map the northern territories and chart a navigable sea route through the Arctic Ocean (McCannon, 2018).

Throughout the sixteenth and seventeenth centuries, many futile and often fatal attempts ensued in pursuit of trans-Arctic sea routes. In almost every instance, explorers encountered fierce storms and thick, impassable sea ice, which forced the expeditions to confront an ill-fated dilemma: to turn back and accept defeat or risk the peril of wintering on the ice. The severe and hostile conditions of the Arctic winters, combined with a lack of adequate sustenance and shelter, meant that few explorers could endure a winter on the ice (Mulvaney, 2001). For most, survival quickly became the ultimate objective.

Despite unsuccessfully navigating a safe passage through the Arctic Ocean, exploration during the 1500 and 1600s made some significant and long-lasting contributions to scientific knowledge of the region (McCannon, 2012). Many of the early polar voyages, such as those famously led by Hugh Willoughby (1553), Willem Barentsz (1596), and Henry Hudson (1607), explored and charted previously 'unknown' Arctic coastlines and islands, subsequently opening up new areas for safer navigation (Bravo, 2019).[37] Journals and ship logbooks recovered from these expeditions include descriptions of new-found regions and detailed narratives of the crews' hardships (e.g., Veer *et al*., 1876). Successive voyages brought about new knowledge and a heightened curiosity of the areas that remained out of reach. This was documented by the abundance of maps constructed throughout this era. Many of these maps displayed an animated region, encompassing whirlpools, sea monsters, great rivers, mountain ranges, and a large landmass situated at the geographic North Pole (Figure 4.1).

[37] Single quotes are used to highlight that the 'discovery' of 'new' or 'unknown' lands refers to a Eurocentric history. Undoubtedly, Indigenous peoples will have discovered and explored much of the Arctic long before the era of European exploration.

Figure 4. 1.: Maps of the Arctic produced during the European Age of Exploration: (a) 'Nova Zembla', the newly discovered regions mapped in 1598 by Gerrit de Veer, during the voyages of Willem Barentsz; (b) 'Carta Marina', a map of Scandinavia and its marine environments, 1539; (c) 'Septentrionalium Terrarum descriptio', a map of the Arctic drawn by Gerardus Mercator, 1595. *Source*: Wiki Commons.

In addition to descriptions of landmasses, ship logbooks documented observations of 'ice edge' positions throughout this period. Although highly irregular and infrequent, many of these observations are considered accurate enough to be incorporated into historical sea-ice datasets used in climate research today. One such example is the Arctic Climate System Study (ACSYS) Historical Ice Chart Archive, which extends from 1553 to 2002, and contains 6007 maps (ACSYS, 2003). The ACSYS dataset is used to examine longer-term sea-ice variability and includes observations dating back to Hugh Willoughby's voyage in 1553. Figure 4.2 shows a sample of the digitised sea-ice observations collected during the earlier years of European polar exploration.

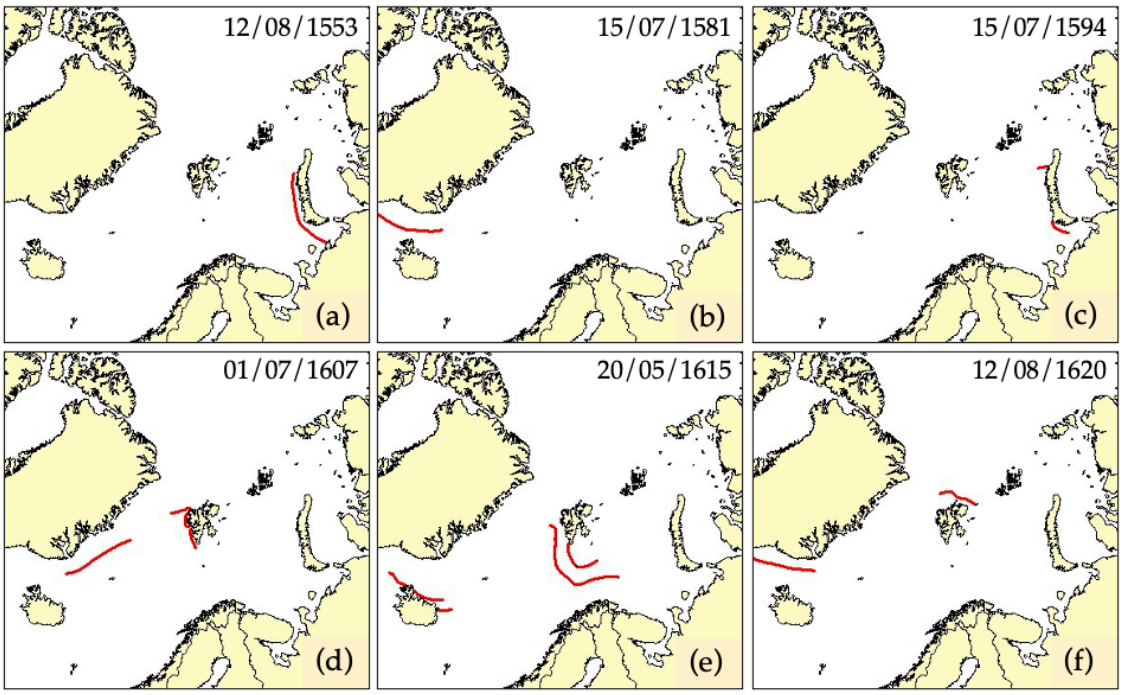


Figure 4.2.: Sample maps from the Arctic Climate System Study (ACSYS) Historical Ice Chart Archive: (a) 12th August 1553; (b) 15th July 1581; (c) 15th July 1594; (d) 1st July 1607; (e) 20th May 1615; (f) 12th August 1620. Red lines depict historical observations regarding the southern limit of sea ice. *Source*: ACSYS (2003).

4.3. Sea Ice as a Habitat and a Resource Frontier

4.3.1. Arctic Whaling (1600s to 1800s)

As the seventeenth century progressed, explorers' interests in the Arctic became less occupied with the search for trans-Arctic sea routes and more with the commercial prospects offered by the region itself (McCannon, 2012). Accounts from many preceding Arctic expeditions noted the abundance of diverse marine life in the northern Arctic waters and near the sea-ice margin (Allen and Keay, 2001; Hacquebord and Avango, 2009). Following reports of seas teeming with fish stocks, seals, and whales, it soon became clear that the Arctic Ocean had more to offer than simply being a place of transit. This was not new knowledge for the indigenous communities who had always relied on the Arctic as a hunting ground; but, to the outsiders discovering these regions for the first time, these animals were seen as a potentially lucrative resource (McGhee, 2006). This new commercial interest in the Arctic necessitated a greater understanding of the spatial distribution and geophysical characteristics of sea ice. Thus, sea-ice science became increasingly important during the subsequent decades.

In attempt to meet the rising demands for oil in European and North American societies, large-scale commercial hunting of whales and walruses occurred in the Arctic throughout the seventeenth to nineteenth centuries, and national trading companies such as Hudson's Bay Company and the Royal Greenland Trading Company were

established (McGhee, 2006). The initial enthusiasm for commercial whaling began in the waters around Spitsbergen following its discovery by Willem Barentsz in 1596. It later extended across the European and North American Arctic coastlines, where trade companies built permanent settlements and whaling stations so that oil could be processed and transported more efficiently to markets elsewhere (Hacquebord and Avango, 2009; Avango *et al.*, 2014). While the broadly unregulated establishment of industrial settlements promoted profitability for European explorers and enabled them to penetrate further inland in search of additional natural resources, it resulted in the wide-scale exploitation and marginalisation of indigenous communities and the surrounding environment (McGhee, 2006; McCannon, 2012).

As Hacquebord and Avango demonstrate, the driving forces behind the growth in commercial whaling were economic *and* geopolitical (Hacquebord and Avango, 2009, 2016; Avango *et al.*, 2014). Under the imperialist ambitions of northern Europe, the large-scale exploitation of Arctic natural resources was seen as a way to extend nations' global influence through expansions in maritime power and territorial control. Informed by continued growth in geographical discoveries, the British and Dutch were soon joined by French, German, Russian, and North American whalers. Trading activities in the Arctic became increasingly characterised by conflict over resources and competition for political influence (see Scoresby, 1820). This was especially notable in the whaling activities in Spitsbergen and along the North American Arctic coastline, where trading companies frequently, and often violently, disputed the control of hunting grounds, and used their land stations as a way of reinforcing the sovereignty claims of the different nations involved.

Crucial to the successes of whaling nations were the scientific activities of navigation and cartography. In their search for marine resources, whaling ships surveyed and mapped large sections of the Nordic Seas and the North American Arctic, recording detailed information on their activities, as well as weather and ocean conditions (Divine and Dick, 2006). As Bockstoce and Botkin (1983) describe, whaling logbooks typically included the following details: date and time, the vessel's geographical position, wind direction and speed, visibility, and sea-ice cover. The position and conditions of sea ice were significant variables affecting whaling activities during this time; often, the northerly limit of commercial whaling correlated with the position of the MSIZ (Polyak *et al.*, 2010; Vacquié-Garcia *et al.*, 2017). The MSIZ is typically defined as the region covered in sea-ice concentrations between 15% and 80% (Rolph *et al.*, 2020). The spatial correlation between whaling activities and the MSIZ can be attributed to two main reasons (Divine and Dick, 2006). Firstly, the MSIZ represents a spatially extensive, highly productive, and sheltered environment – conditions conducive to large clusters of the hunted species of the bowhead whale. Secondly, wooden ships characteristic of this era

were incapable of passing beyond the outer margin of sea ice due to the risks of damage that ice imposed on the vessels and equipment.

There was a duality to how whalers perceived sea ice. On the one hand, the MSIZ was an inviting space inhabited by a profitable resource. On the other hand, it was a dangerous and threatening space that demanded knowledge, vigilance, and skill. Information about the nature of sea ice became a matter of safety *and* commercial interest, prompting whalers operating in the region to begin systematically recording the physical properties of the ice they encountered and mark the position of its extent (Weeks, 1978). Whalers devised terms such as 'grease ice' and 'pancake ice' to describe the conditions and formation of ice in a way that could be easily identified by appearance. These terms were gradually accepted into the reports of the British Admiralty, before being taken up by national and international organisations involved in sea-ice monitoring in the centuries that followed. For example, in 1970, the World Meteorological Organisation (WMO) standardised whalers' sea-ice terminology to be used internationally. Indeed, many institutions practising sea-ice science today (including the NSIDC and MET Norway) commonly use these terms to refer to different ice-types.

Advances in navigational techniques enabled seafarers to measure and record their geographical position with greater accuracy (Sorrenson, 1996). As such, whaling records have proven to be important indicators of longer-term temporal and spatial changes in Arctic sea-ice conditions. Recently, there have been several attempts to compile and examine historical whaling records to analyse long-term sea-ice variability (e.g., Divine and Dick, 2006; Mahoney *et al.*, 2011; Walsh *et al.*, 2017; Figure 4.3). Many of these studies use the data stored in the ACSYS (Section 4.2.2) and Bockstoce and Botkin Historical Sea Ice Data datasets. The Bockstoce and Botkin dataset was compiled in 1983 by John Bockstoce and Daniel Botkin (Bockstoce and Botkin, 1983). It contains over 52,000 daily observations from 1849 to 1914 of which over 23,850 observations include details on sea-ice conditions. Analyses of these observations have provided important insights into the response of sea ice to climate changes on decadal and multidecadal timescales. Significantly, they have revealed that the recent decline in sea-ice cover is unprecedented when situated within this longer-term context (Mahoney *et al.*, 2011).

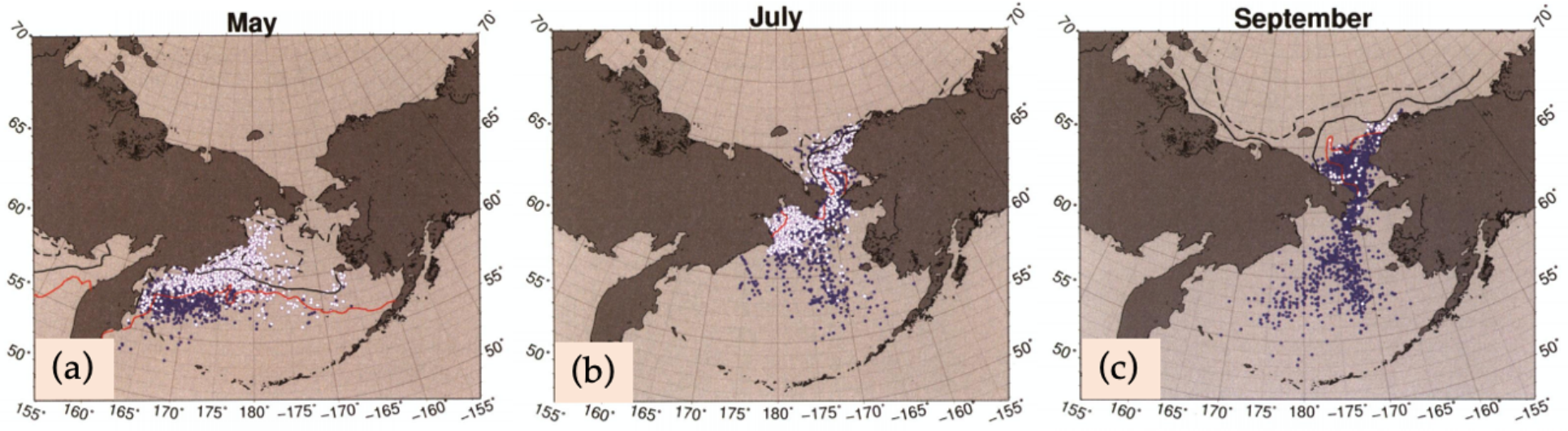


Figure 4.3.: The locations of sea-ice observations made from whaling ships during a) May, b) July, and c) September, in the 1850s.The white dots represent observations of ice conditions, blue dots, where no ice was observed. The red line illustrates the southernmost extent of sea ice, as reported in the U.S. Naval Oceanography Command atlas, 1972-1982. The black solid and black dashed lines represent 20% and 30% sea-ice concentrations, respectively, for the same period. *Source*: Mahoney et al. (2011).

In addition to supporting analyses of long-term sea-ice variability, historical sea-ice records provide useful insights into how different interests and technological capabilities shape definitions of sea-ice cover. For example, in producing a dataset of historical sea-ice records collected between the period of 1750-2002, Divine and Dick (2006) found that whalers cruising in the MSIZ commonly reported sea-ice concentrations between 30-60%, where 30% was considered the maximum limit for safe maritime travel. Consequently, Divine and Dick use the 30% sea-ice concentration to denote the position of the sea-ice edge throughout the dataset. This exemplifies how notions of what constitutes an 'ice edge' are not fixed but depend on the contexts in which sea ice is encountered and the modes of inquiry that are implemented (see Chapter 6).

National governments, trade merchants, and mariners quickly recognised the importance of scientific observations of sea ice in facilitating safer and more extensive commercial and territorial penetration in the Arctic region (Avango *et al.*, 2014). Consequently, maritime exploration became increasingly scientific in the eighteenth and nineteenth centuries (Bravo, 2006; Millar, 2013; Avango *et al.*, 2014). This coincided with a movement towards more rational and progressive ideals of science, for which empirical observation and experience were considered crucial to the credibility of knowledge claims (Golinski, 1998; Bravo, 2006). Although the pursuit of scientific information was primarily driven by commercial and geopolitical interests in the Arctic, knowledge was progressively seen as valuable and useful in its own right (McCannon, 2012). As Bravo discusses, this convergence of values gave rise to a new form of exploration that combined the capitalist enthusiasm for resource utilisation with the search for useful and enlightened geographical knowledge (2006). Whaling expeditions were often supplied with scientific instruments, making the excursions more economically viable and appealing to supporting investors (Bravo, 2006). While this encouraged the information gathered through whaling activities to be collected more systematically, it also exemplified how early Arctic science was explicitly entangled with the broader economic and geopolitical ambitions of Europe's early modern imperial powers (Doel *et al.*, 2014).

4.3.2. Scientific Nationalism and a Frozen Mirage (1700s to 1800s)

The increasing scientific presence in the Arctic during the eighteenth century did much to entrench the region within the political aspirations and nationalist ideologies of northern Europe, the United States, and Russia. Through written accounts and surveys, the Arctic was heralded as "a splendid and unique scientific resource" (Sörlin, 2002: 81), instigating a reassessment of the dominant, long-standing perceptions of the Arctic as a baron, desolate, and uninhabitable region. The Arctic was reimagined as a region of great economic and strategic potential, and, particularly for those nations whose borders extended into the Arctic Circle, it became a significant dimension of their own distinct national identities and nation-building ideals (Auerbach, 1980; Bravo and Sörlin, 2002; Powell, 2008; Friedman, 2011, 2012; Berg, 2013; Sörlin, 2002, 2013). Bravo and Sörlin (2002) illustrate that while the attitudes and strategies used to establish territorial control and economic utility differed between different nations, the use of science proved to be instrumental. The scientific practices of surveying and mapping provided the means of ordering and defining the Arctic regions, and as various authors have commented (e.g., Bravo and Sörlin, 2002; Sörlin, 2002; Wråkberg, 2002; Berg, 2013), such knowledge was subsequently used to legitimise expansionist and utilitarian Arctic politics. Maps obtained through state-funded scientific enterprises became critical tools that anticipated and underpinned political and economic activity in the Arctic. This marked the beginning of a period of great economic, political, and cultural extensions northwards during the nineteenth and twentieth centuries, through which conceptions of the Arctic were transformed from a peripheral frontier, into a complex and globally contested region (Doel *et al*., 2014a).

As explorers travelled further northwards, initially searching for northern sea routes and later to reap the benefits of the region's natural resources, the Arctic gradually became part of the ever-expanding limits of the "known world" (McGhee, 2006: 130). By the nineteenth century, knowledge of the Arctic region had increased significantly through scientific surveys, encounters with indigenous populations (upon which explorers depended - see Eliasson (2002)), and through more frequent, systematic, and longer maritime expeditions. Consequently, early modern maps such as Mercator's were revised to include greater geographical details and extend the cartographic boundaries northwards (Dodds and Nuttall, 2019).

Despite rapid growth in scientific expeditions, large expanses of the Arctic Ocean remained unexplored and unknown. This was in part due to the immense scale of the Arctic region, limitations in technological capacity, and the extreme and often unfavourable environmental and climatic conditions that prevented safe maritime travel. The seasonality, mobility, and indeterminate nature of Arctic sea ice and the lack of distinct boundaries between sea, ice, and land severely challenged the practicalities of

navigation and cartography (Millar, 2013). This undermined the ability of explorers to chart the Arctic coastlines with precision. As Millar (2013) notes, many of the charts of the polar seas collected during the seventeenth and eighteenth centuries contained missing and misrepresentational information. Inaccurate measurements, mapping errors, and incomplete coverage were common characteristics of these earlier charts, which proved to hinder later explorers who were reliant on them for safe passage (Millar, 2013).

Few spaces in the Arctic had evaded the reach of exploration more than the Central Arctic Ocean. The impenetrable nature of sea ice to marine navigation had preserved its allusive qualities. As Craciun writes, the absence of knowledge of what lay beyond the sea ice gave way to a diverse and boundless array of imagined possibilities ranging from "mysterious continents, ice or land bridges joining America and Asia, ice-free passages, temperate utopias, and gateways into the planetary core or into other dimensions" (2010: 693). Drawing from centuries of speculation, these ideas remained prevalent in scientific and literary circles, as without further knowledge, they could not be proved (or disproved) with certainty.

For the expanding British Empire, uncovering what lay beyond the sea ice re-emerged as a key scientific objective during the late-eighteenth and nineteenth centuries. Maritime power and transportation were fundamental to Britain's consolidation of international trade networks and overseas settlements. Therefore, pioneering the Arctic Ocean was seen as an essential means for new possibilities of territorialisation and commerce (Steinberg, 2001; Craciun, 2010; Bruun and Medby, 2014). The desire for control over the Arctic Ocean was bolstered further by the increasing commercial and scientific presence of American, European, and Russian rivals in the Arctic, which invoked a patriotic desire to conquer the region (Weaver, 2015). Consequently, securing an ice-free passage through the Arctic became a crucial naval and "aggressively nationalist" objective during the nineteenth century (Craciun, 2009: 105).

The early decades of the 1800s brought with it the end of the Little Ice Age, a change that marked the end of a centuries-long cooling interval in the Northern Hemisphere (Grove, 2012). Reports from whalers of a reduced sea-ice extent in the Greenland seas sparked enthusiasm amongst the British Admiralty over the increased feasibility of navigating the Northwest Passage (Craciun, 2010). Encouraged by this news, John Barrow, Second Secretary to the Admiralty, initiated a 25-year program of Arctic expeditions that utilised Royal Navy ships for the chief purpose of navigating the Northwest Passage and advancing the latitudinal extent of knowledge northwards. The search for ice-free passages called for a greater necessity to understand and interact with the oceans. As such, the central commercial and geopolitical aspirations of British polar expeditions to secure trans-Arctic trade routes and potentially territorialise new lands were supported by a strong desire to carry out scientific investigations and produce more precise maps

of the Arctic Ocean (Millar, 2013; McCannon, 2018). The ships, strengthened for Arctic travel, were furnished with various scientific instruments, including chronometers, sextants, telescopes, altitude instruments, and thermometers (Ross, 1835). The possession of such instruments enabled ships to chart their geographical position and relate this to valuable measurements of oceanic and atmospheric conditions including ocean currents, depths, and temperatures, as well as sea-ice conditions. As Millar (2013) discusses, the use of precision instruments and accompanying written accounts during these expeditions were important determinants of scientific authority and progress. Thus, their use was seen as a necessity.

The following decades saw several exploratory attempts to find the Northwest Passage and conduct scientific investigations in the Arctic seas. Under the authority of the Admiralty, explorers including John Ross, William Edward Parry, James Clark Ross, and John Franklin travelled along the North American Arctic attempting to locate the Northwest Passage. Each time, the sea ice remained impassable, blocking channels, damaging ships and equipment, and denying Britain's aspirations to conquer the Arctic Ocean (Craciun, 2010). The Northwest Passage proved to be, as Weaver describes it, "a frozen mirage that men pursued" in a failed bid to demonstrate their dominance over nature (2015: 88). Sea ice had the effect of disorienting, immobilising, and debilitating explorers. Expeditions were frequently trapped in the ice and often forced to spend extended periods in the Arctic's extreme conditions, during which many men perished (McGhee, 2006). On failing to navigate the passage successfully, some, including Parry, turned their attention to attaining the North Pole by sledge, only to be halted further by the unforgiving and treacherous conditions on the sea ice (Bravo, 2019).

Despite multiple failures to locate the Northwest Passage or reach the North Pole amidst the ice-choked seas, the British voyages of exploration discovered new lands, mapped great stretches of the coastlines, and collected vast amounts of scientific data (McGhee, 2006; McCannon, 2012). In addition to scientific measurements, explorers' reports contained more general observations on the nature of the Arctic environment and the crews' experiences at sea. Wider public audiences readily subscribed to published narratives from these expeditions, and these accounts became important and popular modes for advancing knowledge of the Arctic region (Emmerson, 2010; Christensen and Nilsson, 2017). As Craciun (2010) and McCannon (2012) note, the stranding of expeditions provided opportunities for explorers to interact with, analyse, and reflect more acutely on the conditions of Arctic sea ice. Such descriptions were circulated through newspapers, paintings, and popular fiction, inspiring and igniting the imaginations of international readers for whom the Arctic represented a distant and fantastical place (Dodds, 2018).

Scientific nationalism intensified throughout the nineteenth century and into the twentieth century (Bravo and Sörlin, 2002). Russia, Norway, Denmark, Sweden, and the

US were amongst other nations competing with Britain to maintain their scientific presence in the Arctic, supporting their attempts to locate a trans-Arctic passage, conquer the North Pole, and penetrate beyond the boundaries of the 'known'. To achieve these geographical milestones and overcome the adversities of the Arctic environment would, as McCannon describes: "symbolize […] the limitless potentialities of Western civilisation in the modern age" (2012: 132). So, nations became fixated not only on accomplishing these objectives, but being the *first* to do so. To be the first to conquer the sea ice was seen as the ultimate demonstration of scientific and political prowess. Consequently, Arctic exploration took on a new character of intense, international rivalry, whereby speed, intelligence, and endurance were amongst the most celebrated qualities (McCannon, 2012; Doel *et al*., 2014a). Under the gaze of a captivated western audience, polar exploration was perceived as a heroic act requiring immense courage and strength. Those who devoted their lives to conquering the hostile Arctic wilderness were met with national admiration and fortune. The scientific achievements of exploration were allied with physical hardship and masculinity: the more dangerous the expedition and the further into the Arctic Ocean it ventured, the greater the interest and support it received from national governments, scientific academies, and the general public (Dick, 2004, Weaver, 2015). Often termed the 'Heroic Age' of exploration (Bravo, 2019), this celebrated period of polar voyaging prevailed until the end of the First World War.

4.3.3. International Collaboration in Sea-Ice Science (1800s to 1900s)

Although media reports, explorers' journals, and historical narratives tended to pertain to the individual ambitions and nationalist elements of polar exploration, the nature of scientific research in the Arctic was becoming increasingly collaborative and institutionalised. In the final quarter of the nineteenth century, political, economic, technological, and societal structures were undergoing significant shifts towards internationalism (Rozwadowski, 2004). Such shifts were both reflected in, and supportive of, the increasingly international character of Arctic sea-ice science, whereby the great and heroic expedition style of Arctic investigation began to give way to shorter, more systematic, and collaborative research trips.

A leading figure in the internationalisation of Arctic sea-ice science was the Austro-Hungarian polar explorer, Karl Weyprecht. Between 1872 and 1874, Weyprecht co-commanded an expedition to the Arctic, during which vast amounts of scientific measurements of Arctic Ocean conditions were obtained (Wood and Overland, 2006). Subsequent data analyses yielded significant insights into the complex and highly variable geophysical properties of Arctic sea ice, as well as the interactions between sea ice, the ocean, and the atmosphere (Weyprecht, 1875). Inspired by these findings, Weyprecht reasoned that further scientific investigations of the Arctic environment

would help resolve many of the fundamental questions of oceanography, meteorology, and geophysics, but that decisive results could only be obtained through coordinated, synoptic, and standardised research efforts across the region (Weyprecht, 1875; Wood and Overland, 2006). Owing to the vast scale of the Arctic and the variability in its conditions over space and time, such operations could not be achieved through the sole efforts of individual institutions or nations engaged in Arctic science (see also Rozwadowski, 2004). Consequently, Weyprecht, amongst other prominent scientists (including Fridtjof Nansen and Adolf Erik Nordenskiöld), advocated strongly for nations to cooperate scientifically in the Arctic. In expressing such ideas, Weyprecht stated:

> The key to many secrets of Nature, the search for which has now been carried on for centuries … is certainly to be sought for near the Poles. But as long as Polar Expeditions are looked upon merely as a sort of international steeple-chase, which is primarily to confer honour upon this flag or the other, and their main object is to exceed by a few miles the latitude reached by a predecessor, those mysteries will remain unsolved. <…> Decisive scientific results can be attained only through a series of synchronous expeditions, whose task it would be to distribute themselves over the Arctic regions, and obtain one year's series of observations made according to the same method. (1875: 33).

In the wake of Weyprecht's observations and recommendations, new international programs of Arctic science began to emerge. The First International Polar Year (IPY) occurred between 1882 and 1883, representing the first major international effort to obtain synchronous observations of geophysical, meteorological, oceanic, and geomagnetic conditions in the Arctic (Wood and Overland, 2006). Eleven nations (inclusive of the Austro-Hungarian Empire, Canada, Denmark, France, Germany, the Netherlands, Norway, Russia, Sweden, the United Kingdom, and the US) established twelve research stations within the Arctic region and additional auxiliary stations located elsewhere (Figure 4.4). The stations used standardised instruments and methods to collect measurements systematically over the course of the programme (Baker, 1982). As Baker (1982) describes, prior discussions between the various nations involved were essential to establishing the logistical characteristics of the programme, including the methods and instruments of observation, the frequency of data collection, and the most suitable localities for research stations. These programme features, as Weyprecht argued, were vital to the identification of spatial and temporal variability in Arctic weather and sea-ice conditions, which, in turn, would provide important insights into the nature of the global climate system (Weyprecht, 1875; Wood and Overland, 2006).

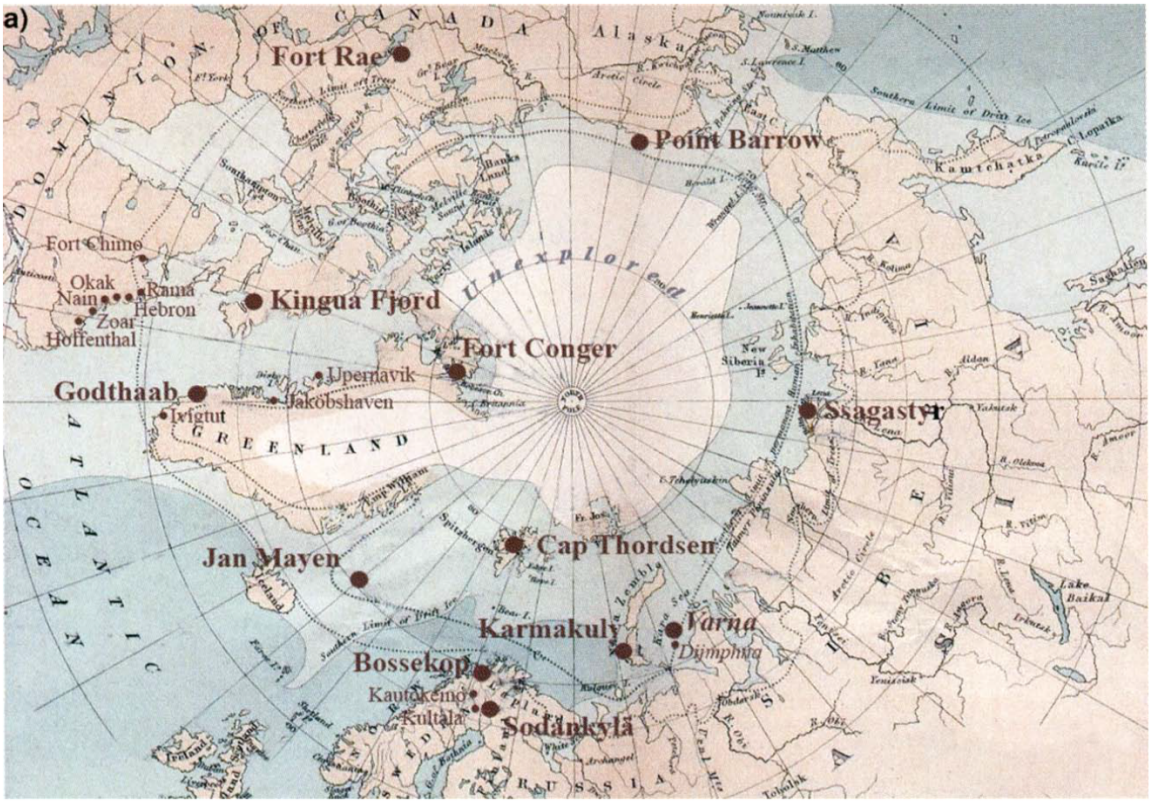


Figure 4.4.: Map of the locations of the principal research stations of the first IPY, 1882-83. Source: Wood and Overland (2006).

For the most part, participating IPY nations adhered to the programme's objectives, and huge amounts of synoptic observations were collected (Baker, 1982). Yet, despite the wealth of scientific information gathered and published following the IPY, few meaningful results were found for the Arctic as a whole (Baker, 1982; Wood and Overland, 2006). This is an outcome that Wood and Overland (2006) have attributed to a lack of coordinated inquiry in the programme's aftermath, meaning that the data were not synthesised and analysed collectively. The published reports included data from individual research stations; while these provided some insights into local and regional conditions, they had little value for understanding the nature of the Arctic climate on a circumpolar scale. Thus, as Wood and Overland state: "[t]he most essential part of the research plan that Weyprecht had envisioned – the synchronous program – was never completed" (2006: 1690).

Rozwadowski (2004) argues that the lack of compelling economic incentives and practical benefits for the participating nations to continue collaborating after the programme had ended contributed to the IPY's failure. In an examination of late nineteenth and early twentieth-century international cooperation in marine and Arctic sciences, Rozwadowski reveals the existence of a complex interplay between internationalist ideals, national interests, and environmental necessity. Using the International Council for the Exploration of the Sea (ICES) as a focal point, Rozwadowski illustrates how a nation's willingness to participate in programmes of international

science during the twentieth century was strongly determined by the political, economic, and societal interests that it would serve. For instance, within the context of ICES, national fisheries increasingly recognised that oceanic conditions such as temperature, currents, and sea-ice cover played an important role in determining the location of fish populations (see also Friedman, 2011). However, the ability to observe and measure such phenomena is significantly undermined by the materially complex nature of the ocean, the features and qualities of which are not confined by national borders (Steinberg and Peters, 2015). In facilitating international cooperation in marine science, ICES was seen as a collaborative means to obtaining a more comprehensive understanding of ocean conditions. In turn, this knowledge would yield direct economic and societal benefits to the involved nations, such as promoting more peaceful, rational, and sustainable exploitation of natural resources (ICES, n.d.; Rozwadowski, 2004). In the case of the IPY, although modelled on ICES, Rozwadowski contends that the direct economic and societal benefits of pan-Arctic research had not been readily identified on a national level, and, consequently, the collaborative research efforts slowly dissolved over the succeeding years. Nevertheless, as Wood and Overland (2006) conclude, despite the limited scientific outcomes of the first IPY, the formation, logistics, and execution of the scientific program played an important role in fostering early collaborative research networks and strategic partnerships in the Arctic. This inspired the organisation of a second IPY in 1932-1933 and the International Geophysical Year (IGY) in 1954-1955.

Another prominent figure in the internationalisation of Arctic sea-ice science was the distinguished Norwegian explorer and scientist Fridtjof Nansen. Despite his celebrated status as a national icon of Norway, Nansen was a devoted internationalist. Nansen held polar exploration in a similar regard to Weyprecht, arguing that "true civilization will not have been reached until all nations see that is it nobler to conquer nature than to conquer each other" (Emmerson, 2011: 17).

In the closing decade of the nineteenth century, Nansen accomplished one of the most ambitious scientific exploits in the Arctic to date. Informed by the earlier atmospheric and oceanic studies of Henrik Mohn, Adolf Erik Nordenskiöld, and Karl Weyprecht, Nansen understood Arctic sea ice to be a floating platform in constant motion in response to wind and ocean currents, with a dominant transpolar drift extending from East Siberia to the Greenland Sea (Nansen 1897; Frolov *et al*., 2006). For Nansen, these currents offered new possibilities for Arctic transit and North Pole discovery and ultimately formed the basic premise of his 1893 expedition.

The technological and practical elements of Nansen's 1893 expedition were unlike any previous scientific ventures in the Arctic. In critiquing the earlier methods of polar voyaging that focussed on journeying over, or through the ice, Nansen argued that "if we pay attention to the actually existent forces of nature, and seek to work *with* and not *against* them, we shall thus find the safest and easiest method of reaching the Pole"

(Nansen, 1897: 17). Harnessing the motion of sea ice in the interest of scientific discovery, Nansen set out to deliberately freeze the expedition's ship, the *Fram*, in the sea ice and drift across the Arctic Ocean. In doing so, the expedition would observe the drift patterns of sea ice, collect valuable geophysical data, and potentially reach the North Pole (McCannon, 2012). To achieve these objectives, the *Fram* was designed using state-of-the-art technology that would enable it to withstand the prolonged pressures of being frozen in the ice; it was well-equipped with some of the most advanced research equipment of the time.

Between September 1893 and August 1896, the *Fram* successfully drifted in the sea ice across the Arctic Ocean, thus validating earlier theories of transpolar drift. Figure 4.5 shows the drift course of the *Fram* expedition, including an on-ice attempt to reach the North Pole on dog-hauled sledges during the winter of 1894-95. Although failing to attain the North Pole, Nansen's voyage reached further north than its predecessors. Moreover, the slow pace of the sea-ice drift provided the ideal conditions for scientific investigations to be carried out. Observations of meteorological, oceanic, astronomical, and magnetic phenomena; Arctic flora and fauna; and the geophysical properties of sea ice were collected extensively and methodically (Nansen, 1897, 1901-1906). As a result, the *Fram* expedition contributed significantly to the knowledge of the Arctic Ocean, with particular regard to the understanding of ocean dynamics and bathymetry (Friedman, 2011). Perhaps most significantly, the expedition's findings concluded that neither a landmass nor an open polar sea existed at the North Pole, bringing an end to centuries of speculation over the geography of the Arctic Ocean (Frolov *et al*., 2006; Dodds, 2018). Instead, the observed patterns of sea-ice drift and the detailed ocean depth and temperature measurements collected throughout the three years revealed two crucial features of Arctic Ocean geography. Firstly, that sea ice extended across most of the ocean throughout much of the year. Secondly, that the seas adjacent to the North Pole were exceptionally deep and characterised by a complex network of currents transporting water to and from the Arctic basin (Nansen 1897, 1901-1906). Nansen recognised the important implications of these findings for understanding broader-scale oceanic circulation and climate patterns. Moreover, his pioneering research methods and subsequent analyses proved fundamental to the development of modern oceanography and climate research (Nansen, 1901-1906; Frolov *et al*., 2006; Friedman, 2011).

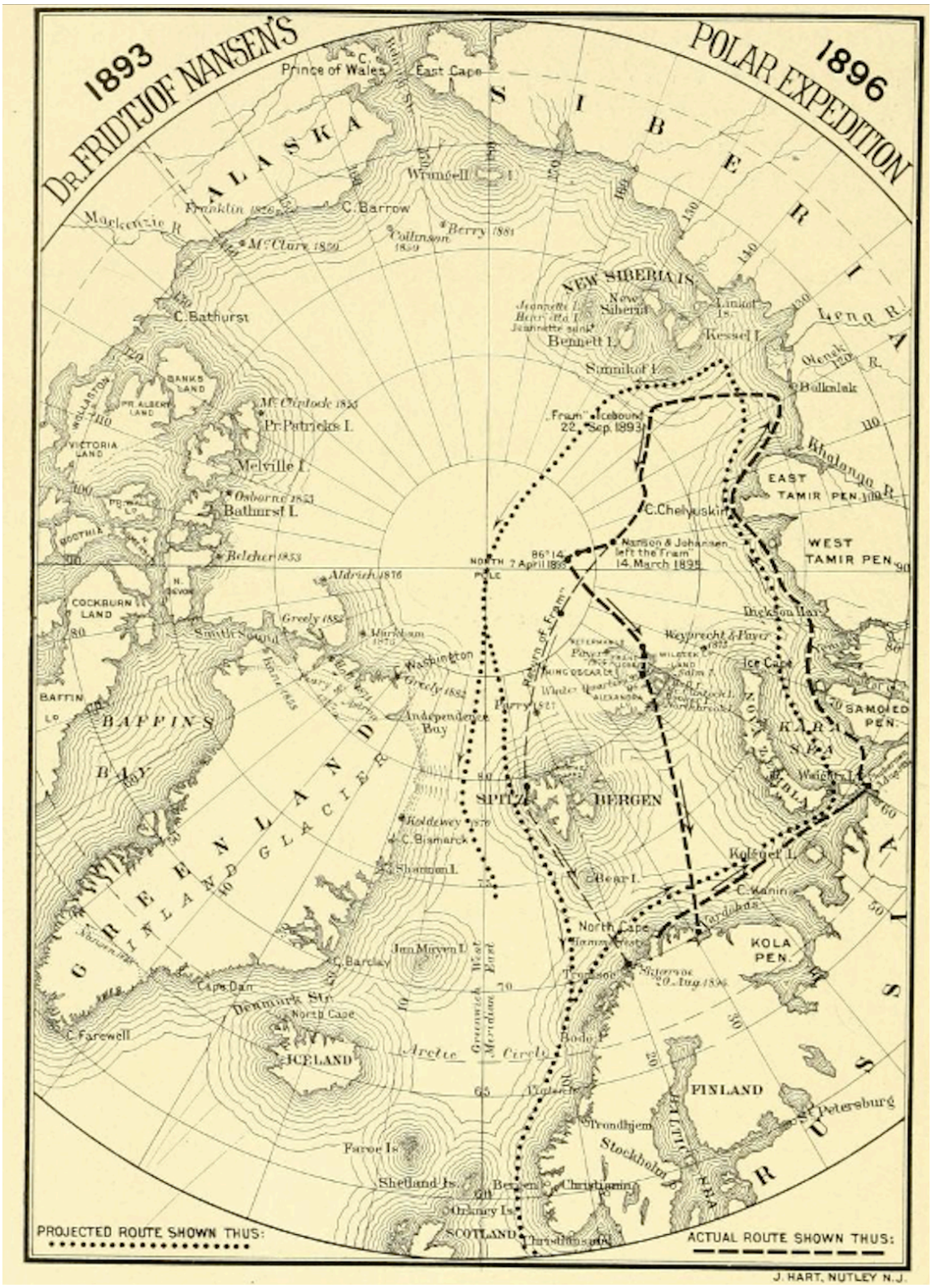


Figure 4.5.: Fram expedition track. On 22nd September 1893, the Fram was frozen into the sea ice off the northwest coast of the New Siberian Islands. From there, the expedition gradually drifted across the central Arctic Ocean, before being released in August 1896. *Source*: Greely (1900).

4.4. Sea Ice as a Military Space

4.4.1. A Soviet Arctic (Late-1800s to Mid-1900s)

In the early decades of the twentieth century, advances in science and technology began to transform the nature of exploration and scientific research in the Arctic. Alongside logistical shifts to more frequent and systematic scientific programmes, shipbuilding, aviation, and communications systems witnessed particularly significant developments. Wooden ships gave way to modern, steel-hulled icebreakers, designed to break through compact sea-ice conditions; investments in aerial transportation produced aircrafts capable of withstanding the Arctic's extreme temperatures; and radio communication was established, greatly enhancing the safety and efficiency of Arctic transit (Ries, 2002; Doel *et al*., 2014a). These technological developments significantly increased the geographical reach of expeditions and assisted in the movement of the supplies and equipment necessary to operate effectively in the region. As Doel *et al*. (2014a) describe, Arctic exploration – whether scientifically, commercially, or politically motivated – was no longer a test of physical endurance and determination. Rather, it was reliant on access to capital investment and modern technologies.

The activities of the Soviet Union largely dominated presence in the Arctic during the first half of the twentieth century. Sitting upon a wealth of geographical knowledge gained through the nation's involvement with the 1882-1883 IPY and the numerous scientific expeditions facilitated by the Russian Academy of Sciences and other state-led institutions during the eighteenth and nineteenth centuries, Soviet Russia saw the Arctic as a central strategic and economic target (Emmerson, 2011; Wråkerg, 2013; Bruno, 2016).[38] Various other Arctic nations shared this ambition, including Sweden, Norway, and Canada, who focussed their political attention on modernising their Arctic territories and competing with sovereignty pressures from neighbouring states (Berg, 2013; Sörlin, 2002, 2013). Arguably, however, few other nations achieved the same degree of domination as the Soviet Union.

To the Soviet Union, the economic and strategic potential that the Russian Arctic's rich array of natural resources, vast open spaces, and sparse population offered was immensurable. Moreover, the Soviets believed that the obstacles of nature, which had proven so historically unwavering, could be overcome through advances in science and technology (Josephson, 2011). Science and technology symbolised development and progress in the Soviet Union and were trusted to hold the solutions through which the Arctic's potentiality could be regulated and conquered for the benefit of the state (Josephson, 2011; Wråkberg, 2013). Inspired by a ruthless vision of resource-led development and supported by the recent technological advances in air, land, and

[38] The Great Northern Expedition during 1730s and 1740s is a notable example of scientific research facilitated by the Russian Academy of Sciences.

maritime travel, the Russian Arctic became the focus of highly ambitious and wide-scale industrialisation, exploitation, and militarisation throughout the 1920s and 1930s. Soviet campaigns rapidly transformed the Arctic's vast geographical spaces into areas for extractive industries, military facilities, labour camps, and transport hubs, all in the pursuit of 'opening-up' the region (Bruno, 2016; Dodds and Nuttall, 2019). Through this rapid landscape transformation, indigenous communities were callously marginalised and dispossessed, and large areas of the Arctic suffered from tremendous environmental destruction and pollution. As many scholars have remarked, the desire for extensive economic and military growth greatly surpassed environmental consciousness. Consequently, the legacy of Soviet expansionism is still visible in the cultural and physical landscape today.

The political and strategic interests in the Arctic strongly influenced the nature of the scientific research that was conducted and the technological developments that were prioritised (Wråkberg, 2013; Doel *et al.*, 2014b). The effective identification, cultivation, and transportation of raw materials and supplies depended on scientific knowledge of the land and seas. For example, the transportation outlets for timber relied on the understanding of river discharge rates that varied seasonally (Josephson, 2011); field inventories were needed to locate and map the distribution of raw materials such as minerals, metals, and forestry (Sörlin, 2013); and maritime transportation called for detailed and up-to-date maps of Arctic sea ice (McCannon 2012). Such knowledge called for systematic studies of the environment and weather conditions. Consequently, as Wråkberg (2013) notes, Soviet-led scientific research in the Arctic during the early half of the twentieth century increasingly focussed on understanding and ordering the environment in a way that served geopolitical and economic interests, namely state-led interventions, resource extraction, and industrialisation (Lajus, 2013; Doel *et al.*, 2014b).

The alliance between science and government interest was particularly apparent in sea-ice research. A central element in the Soviet's Arctic development plans was the desire to chart and secure the Northern Sea Route (NSR): the Russian segment of the Northeast Passage that extends along the coastline from the Bering Strait to the Barents Sea. Soviet planners understood that gaining control over the NSR would open vital shipping lanes and ports along the Arctic coastline, without which the state's Arctic development plans would flounder (Zenzinov, 1944; Dodds and Nuttall, 2019). However, blanks spaces remained on the maps of the Arctic coastlines and islands, and disputes over sovereignty claims prevailed (McCannon, 2018). To mitigate this, the NSR became a major focus of Soviet operations from the 1920s onwards.

To support their political and economic agendas along the NSR, the Soviet Union established Glavsevmorput' (GUSMP) in December 1932.[39] The chief purpose of GUSMP

[39] Also known as the Main Administration of the Northern Sea Route.

was to act as a principal agency for maintaining and coordinating all operations along the NSR and Russian Arctic coastline (McCannon, 2007). This included gaining authority over all ice-breaking activities in the Soviet Union. As McCannon discusses, the establishment of this central authority was seen as the only way to overcome the extremities of the Arctic environment and the difficulties imposed by "bureaucratic over-proliferation" (2007: 401).

The success of GUSMP relied on two key factors: knowledge of Arctic geography and meteorology; and the ability to move safely and efficiently, whether over land, at sea, or in the air (McCannon, 2007). Operating modern icebreakers and small aircraft, the Soviets cruised along stretches of the NSR with new-fangled ease, charting safer waterways through the ice and keeping Russia's northern, ice-bound ports open to shipping for a much greater duration of the year than would otherwise be possible (McCannon, 2007). However, even with the possession of modern technologies, the highly changeable and dynamic nature of sea ice continued to represent a significant hazard to maritime operations. The pervasiveness of sea ice along the Russian Arctic coastline meant that maintaining safe passageways could only be depended on during the summer navigation season, the duration and timing of which varied considerably from one year to the next (anywhere between 70 to 120 days) (Armstrong, 1952). In short, knowledge of the spatial and temporal variability of Arctic sea ice was lacking.

Consequently, scientific knowledge of Arctic sea ice became highly prioritised through state funding and support (Lajus, 2013; Sörlin and Lajus, 2013). Specifically, the ability to *predict* the variability in the behaviour and properties of sea ice was an urgent priority. This focus was reflected in a rapidly increasing scholarship on Arctic sea ice (e.g., Zubov, 1935; Weize, 1923, 1937; Karelin 1940; Laktionov, 1940; Armstrong, 1950, 1954). Moreover, between 1920 and 1940, the Arctic experienced a multi-decadal climatic fluctuation (later termed 'Early Arctic Warming'), which caused pronounced increases in surface air temperatures across large areas of northern Europe (Wood and Overland, 2008). Marked retreats in sea-ice extent occurred, presenting scientists with the idea that sea ice was not a constant feature of the region and that warmer temperatures could be conducive to more prolonged and substantial commercial shipping (Sörlin and Lajus, 2013). This prompted an additional focus on longer-term predictions of sea-ice variability.

Soviet sea-ice research was primarily conducted under the auspices of the Arkticheskiy Nauchno-Issledovatel'skiy Institut (Arctic Institute), founded in 1920 as a department of the Northern Commercial Research Expedition. The Arctic Institute represented the principal polar research institute researching glaciology and sea ice, ice navigation, meteorology, cold adaptation and technology, polar geography, and icebergs (Abramov, 1992; SPRI, 2020). For much of the 1930s, the Arctic Institute operated under the control of GUSMP.

Three broad objectives underwrote the sea-ice research conducted by the Arctic Institute: 1) to observe and report the state of sea-ice conditions; 2) to study the chemical and physical properties of sea ice; and 3) to determine methods of sea-ice forecasting, which relied upon achieving the former two objectives (Laktionov, 1945). Scientific investigations into sea ice were conducted from land, at sea, and by air. With the logistical support from icebreakers and improved overland vehicles, field stations were established along the Russian Arctic coastline and on the Russian Arctic islands. Between 1920 and 1945, the number of Soviet-led research stations in the Arctic increased from five to sixty-two (Armstrong, 1950). The primary objectives of the land-based stations were as follows: to monitor and report variations in the distribution and age of sea-ice cover; ascertain the timing and behaviour of sea-ice formation, growth, break-up, and melting; analyse drift patterns; and investigate the response of sea ice to hydrological and meteorological conditions (Armstrong, 1950).

Observations of sea-ice conditions and investigations into sea-ice behaviour were collected by icebreakers, merchant ships, and scientific expeditions (Armstrong, 1950). Ascertaining the spatial distribution and strength of the ice, particularly in the MSIZ, constituted a major focus of ship-based investigations. The chemical, physical, and mechanical properties of sea ice were studied through periodic ship patrols and carried out according to a set of standardised procedures issued by the Arctic Institute (e.g., Gakkel, 1938; Petrichenko, 1940; Smesov, 1944).

The areal extent and mapping capacity of ship-based observations were significantly improved through support from aircraft. In 1929, the Soviet Union carried out the first airborne ice reconnaissance mission (Armstrong, 1950; McCannon, 2012). While initially used to identify safe waterways ahead of ships operating in the region, Soviet scientists utilised the developments in aviation to systematically patrol and survey the ice-covered waters and coastal features along the Russian Arctic. This greatly expanded the size of the area under investigation and enabled scientists to reach previously unattainable sections of the Arctic Ocean. As the spatial reach increased, so did the need for more detailed and frequent assessments of the ocean surface. From 1941, a fixed programme of airborne ice reconnaissance missions was established to support these needs. Later, following the end of the Second World War, aircrafts equipped with aerial photography were made available for scientific investigation (Armstrong, 1950). Aircraft observations continued in this fashion until the 1970s when satellite technologies took hold (Section 4.5.2).

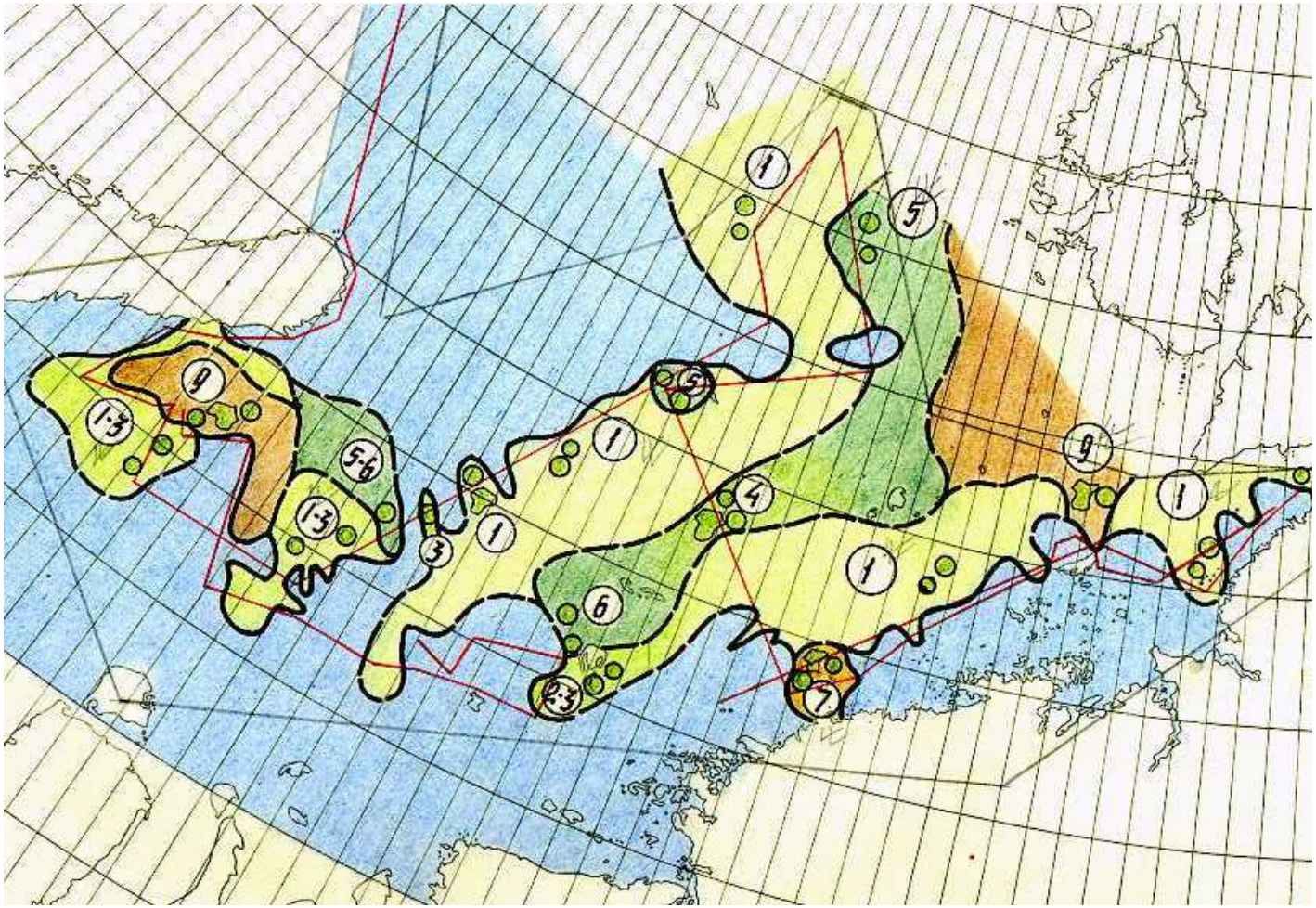


Figure 4.6.: An example ice chart produced by the Arctic Institute and compiled by the NSIDC. The example is from August 1933. Sea ice was classified using standardised national symbology: the white circles and corresponding numbers and colours indicate sea-ice concentration (1 = 10%, 2 = 20% and so on); the adjacent smaller symbols indicate partial concentrations of sea ice and sea-ice development types that differ from dominant conditions. *Source*: ARRI (2007).

From 1933 onwards, the information gained through observations of sea ice was used to develop Arctic Institute sea-ice charts, which have since been compiled and digitised by the NSIDC (Figure 4.6; Smolyanitsky *et al*., 2007). As Mahoney *et al.* (2008) note, these earlier maps depended on highly skilled observers who used various surface features to distinguish between different ice conditions. These features included the colour of the ice, the presence of ridges, cracks, or hummocks, as well as patterns of snow cover (Karelin *et al*., 1946). Maps produced by the Arctic Institute are highly valued in climate studies today due to the detail they include, particularly along the ice edge and for identifying the spatial distribution of different development stages of ice.

During the interwar years, other nations, including Sweden, Norway, and Denmark, were involved in their own sea-ice research programmes, through which they made important contributions to sea-ice knowledge. For example, between 1893 and 1956, the Danish Meteorological Institute (DMI) was engaged in a programme of summer sea ice analysis (Figure 4.7.), and Norwegian scientists made breakthroughs in oceanography and meteorology during the Maud Expedition, 1922-1925 (Sverdup, 1926). However, as Doel *et al*. (2014b) and Sörlin and Lajus (2013) note, the scale and systematic nature of Soviet sea-ice research was largely unrivalled, as few other nations had the political willpower or infrastructural capacity to compete with the Soviet Union's extensive research network. As such, by the late 1930s, Soviet scientists had become world leaders in Arctic sea-ice research. Notable figures included Mikhail Mikhailovich Somov, Nikolay Nikolaevich Zubov, and Vladimir Wiese. These researchers made significant contributions to understanding sea-ice characteristics and variability and the interactive role of sea ice within the broader climate system (Armstrong, 1954; Sörlin and Lajus, 2013).

Studies by Wiese (1923, 1924, 1937) used observations of sea ice to establish correlations between ice conditions in the Arctic and the circulation of warm Atlantic waters into the Barents Sea. Developing on this idea, Wiese illustrated how atmospheric conditions – namely the position of the Icelandic air pressure minimum – could be used as a proxy in forecasting the distribution and variability of sea-ice cover. Similar investigations by Zubov and Somov established important connections between the spatial variability of sea ice and the Gulf Stream (Zubov, 1935; Somov, 1941). They also revealed key insights into the characteristics and driving forces of Arctic sea-ice drift (Zubov and Somov, 1940). These findings proved significant to understanding the cyclical nature of sea-ice cover and were used to inform sea-ice forecasts, which the Arctic Institute had begun issuing on long (seasonal) and short (daily – weekly) timescales (Armstrong, 1954). However, according to Armstrong (1954), these forecasts were based upon sparse observations and were too generalised for accurate and practical navigational purposes. The scientific community increasingly recognised that more detailed, comprehensive investigations into local conditions were needed to improve predictions. As such, issued

forecasts were to be used as a general guide and practised with caution. Despite failing to achieve a reliable method of sea-ice prediction, the progress achieved by the Soviet scientists highlighted the necessity of including oceanographic and meteorological observations in sea-ice prediction and significantly advanced scientific knowledge of Arctic environments (Sörlin and Lajus, 2013). Moreover, it highlighted the importance of studying Arctic sea ice as a key component within the broader climate system.

It should be emphasised that although national strategic and economic interests heavily influenced the sea-ice research conducted by the Soviet Union in the first half of the twentieth century, the scientists themselves remained part of the wider international research network. This network was founded largely through the activities of the first IPY. As Lajus and Sörlin have shown, international collaboration in the form of data sharing, joint expeditions, and the circulation of ideas were characteristic of Arctic research in the interwar years, and Soviet science was no exception (Lajus, 2013; Sörlin and Lajus, 2013; Lajus and Sörlin, 2014). These collaborative links were particularly apparent between Soviet and Scandinavian oceanographers and glaciologists, such as Harald Ulrik Sverdrup and Hans Ahlmann who became notable international figures of Arctic science (Bones, 2013; Lajus, 2013). Many of the interactions played out through the preparation and fulfilment of the second IPY programme (1932-1933). The second IPY called for the active participation and collaboration of meteorologists, glaciologists, oceanographers, and radio scientists alike, who relied on the use of the polar research stations distributed throughout the Arctic (see Kimball, 1931 and Fleming, 1932). In fact, as Lajus and Sörlin (2014) contend, many of the collaborative links between Soviet and western scientists managed to prevail into the 1940s and 1950s, despite the political restraints imposed by the Cold War.

Figure 4.7.: An example of a sea-ice chart 'The State of the ice in the Arctic Seas', compiled by the Danish Meteorological Institute for June 1924. *Source*: Walsh et al. (2017).

4.4.2. The Cold War on Ice (Mid-1900s)

The geopolitical significance of Arctic sea ice grew significantly following the end of World War Two. Amidst rising geopolitical tensions between the Soviet Union and the Western allies, the Arctic was reconceptualised as a critical space for national military strategy (Doel *et al.*, 2014b). Following advances in transportation, communication systems, and instruments of warfare, geographical proximity between the United States and the Soviet Union was a major cause for concern and a key driving force behind the desire to occupy the Arctic for strategic purposes (Dodds and Nuttall, 2019). The meagre 85 km distance separating the leading antagonists placed the Arctic Ocean and the Bering Strait central in military planning and surveillance. This had radical effects on the nature of Arctic sea-ice science and knowledge infrastructures that emerged in the early Cold War years.

Under President Truman's leadership, US military preoccupation with the Arctic regions was considered integral to effective national security (Leffler, 1984). This included gaining control over Arctic air space and establishing military and scientific bases in strategically important locations, such as Greenland and Alaska (Leffler, 1984; Hummel, 2005; Doel *et al.*, 2014b). However, the dominance of the Soviet Union's continued scientific presence in the Arctic exacerbated the anxieties of the United States (Doel *et al*., 2014b). Moreover, as Doel *et al*. (2014b) notes, Soviet research in the Arctic became increasingly insular and secretive in the post-war era, prompting increased concern from Western onlookers. The US feared the level of knowledge the Soviets possessed on Arctic environments would undermine their efforts to contain Soviet expansion in western Europe. Consequently, US strategists made substantial investments into Arctic science during the late 1940s and 1950s. This included establishing several research programmes tasked with advancing knowledge of polar environments, with a particular focus on how they could affect, or be incorporated into, military strategy (Doel, 2003; Doel *et al.*, 2014b).

Understanding Arctic sea ice was a primary concern of the US military forces. Due to its thick and widespread distribution, sea ice was perceived as a restrictive force that set the limits on terrestrial and marine mobility (Sörlin and Lajus, 2013). To US Navy and Army operations, sea ice's dynamic and unpredictable nature was costly and dangerous. This prompted the need for a formal program of systematic sea-ice observation and forecasting, obtained through ice reconnaissance flights, drift stations, and later, submarine cruises (Bates, 1955; Rothrock and Wensnahan, 2007).

In 1955 alone, the American Arctic was surveyed through over 500,000 miles of aerial reconnaissance carried out through collaboration between the U.S. Navy, the U.S. Air Force (USAF), the U.S. Corps of Engineers, theatre commands, and several Canadian activities (Bates, 1955). The information obtained through these observations was used

in the preparation of hundreds of short and long-term ice forecasts and the development of several publications and ice charts published by the U.S. Navy Hydrographic Office (NHO) (Bates, 1956). In addition, the NHO detailed standardised techniques for ice reconnaissance and maintained records of the U.S. Navy's areal coverage (Bates, 1956). This collection included the development of oceanographic atlases for the Northern Hemisphere, in which sea-ice classes were distinguished by type (sea, land-fast, or pack) and by their navigability for different vessel types (icebreakers, reinforced vessels, or unreinforced vessels).[40]

Simultaneously, inspired by the Soviet's use of drift stations, the US military began thinking about sea ice as a potential platform for territorial occupancy. Vast expanses of compact ice floes, as well as huge masses of thick, floating ice (termed 'ice islands'), were considered as potential military-scientific spaces for research stations, transportation, storage, and aircraft landing (Koenig *et al.,* 1952; Weeks, 1959). Fletcher (1950) and Koenig *et al. (*1952) describe the efforts of the USAF to identify and track the drift and evolution of several ice islands using reconnaissance flights during the late 1940s. Through regular observations and radar photography (Figure 4.8), the USAF identified surface features of the ice islands and concluded that they were relatively stable and unchanging (and thus, occupiable) on yearly timescales.[41] The notion that sea ice could be used as an extension of the land intensified scientific research into its geophysical and chemical properties. Research into sea-ice thickness, tensile strength, mechanics, surface roughness and variability, and salinity was of great interest (e.g., Assur, 1960; Kingery, 1963; Reed, 1958; Weeks and Lee, 1958), and gradually, ice became the *location*, as well as the focus of investigations.

[40] An example of an NHO oceanographic atlas for the Northern Hemisphere can be found here: https://research.mysticseaport.org/item/l0999014/.
[41] See Bruun and Steinberg (2019) for a critical examination of how the US military's perception and construction of the T-3 ice island as a territory challenged hegemonic conceptions of *territory*.

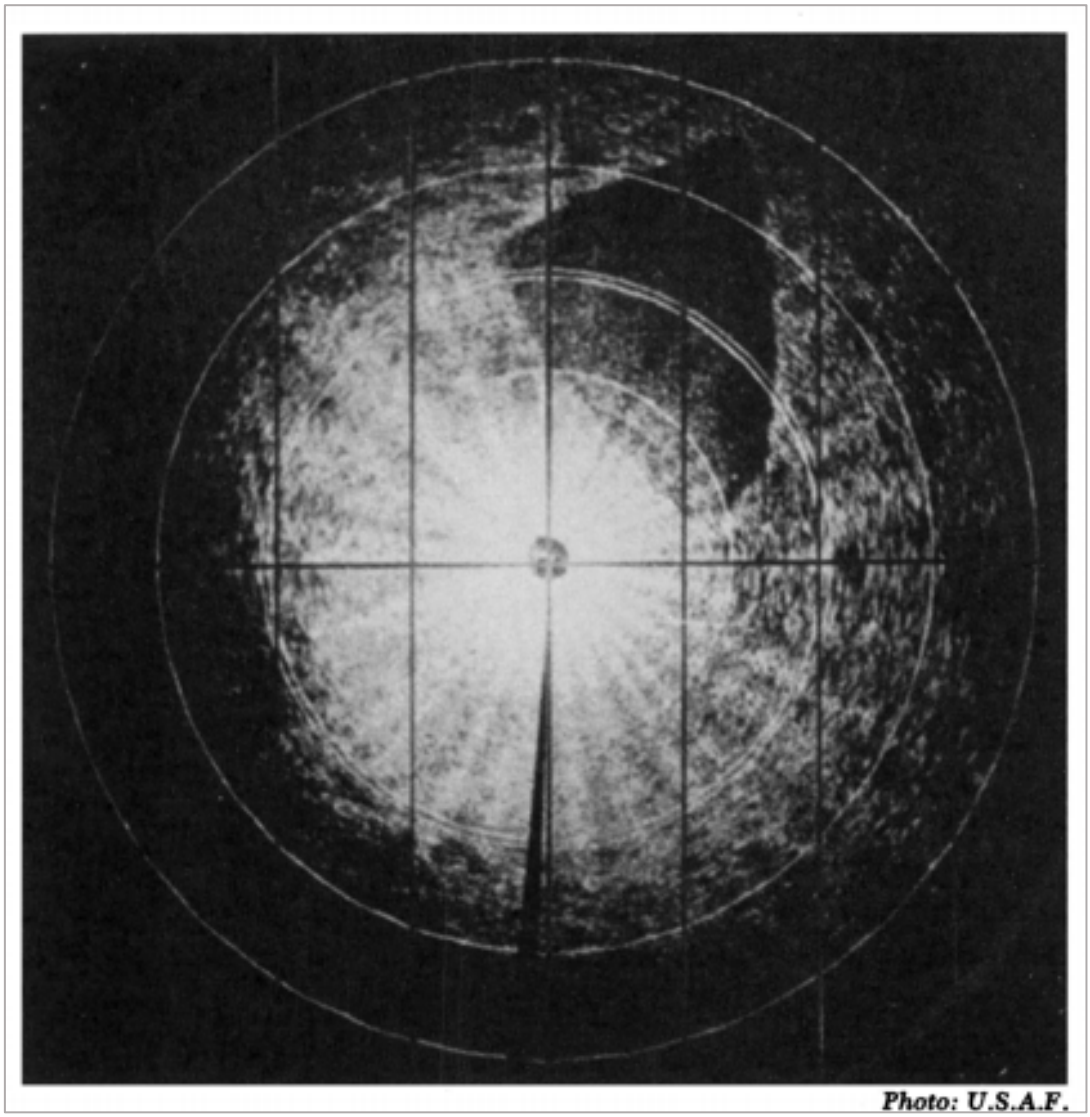


Figure 4.8.: Radar imagery of the T1 ice island (dark angular area, top right), captured during reconnaissance flights of the U.S. Air Force, January 1952. This image was captured on 14th August 1946, approximately 300 miles north of Point Barrow, Alaska. The area of the T1 ice island exceeded 200 square miles. *Source*: Koenig et al. (1952).

By the late 1940s, most sea-ice investigations were carried out by research organisations and universities and sponsored through military patronage (Doel, 2003; Doel *et al.*, 2014b). In 1947, the U.S. Navy initiated the Arctic Research Laboratory (ARL) in Barrow, Alaska, which sought to provide "basic scientific investigations of physical and biological phenomena related to the Arctic environment" (Shelesnyak, 1948: 97).[42] This included scientific programmes on ice islands and sea ice, through which research stations were established *on* the ice (Reed, 1969). Drift stations named Arctic Research Laboratory Ice Stations (ARLIS, I-IV) were used to support ARL's investigations into oceanographic and meteorological conditions, including under-water acoustics, marine biology, seismology, and sea-ice mechanics (ONR, 1963). Similarly, in 1949, the U.S. Army Corps of Engineers founded the Snow, Ice, and Permafrost Research

[42] ARL later became the Naval Arctic Research Lab (NARL) in 1967.

Establishment (SIPRE), tasked with conducting extensive investigations into the geophysical properties of snow, sea ice, land ice, and the frozen ground.[43] SIPRE's operations were motivated by the rationale that "[m]any of the problems encountered in the development of arctic regions arise from the characteristics of the earth's layer or sublayer of snow, ice, and permafrost" (SIPRE, 1950: 1). SIPRE contended that a better understanding of these characteristics would help reduce the issues faced in Arctic warfare, construction, transportation, communications, and civilian activities.

SIPRE's research into sea ice was intimately tied with engineering problems in cold regions and sought information that could inform the development of technologies and infrastructures to overcome the difficulties imposed by the Arctic's 'deviating' environment (SIPRE, 1950). Other organisations operating under similar motives included the Air Force Cambridge Research Laboratories (est. 1945) and Canada's Defence Research Northern Laboratory (est. 1947). Despite often approaching sea-ice environments from different institutional and disciplinary positions, these organisations regularly collaborated to fulfil a common objective: *to gain a more advanced understanding of the environmental conditions under which the North American military forces could operate effectively* (e.g., Weeks, 1959*)*. This motivation is reflected in the titles of many technical reports and research papers that emerged during this period, some examples of which are included in Table 4.1.

Table 4.1.: Sample of research papers from the US scientific activities in the Arctic during the 1950s and 1960s.

Title	*Author(s)*	*Affiliation*
'Composition of sea ice and its tensile strength'	Assur (1960)	SIPRE
'Explosions in the ice'	Livingston (1960)	SIPRE
'Ice cap access route Narssarssuaq, Greenland: location and engineering evaluation'	Leighty and Poulin (1960)	SIPRE
'Observations on the Physical Properties of Sea-Ice at Hopedale, Labrador'	Weeks and Lee (1958)	SIPRE, AFCRL, NHO

Scientific research that served Cold War strategic interests benefitted substantially from military investments. Doel (2003) argues that the intensity of this alliance shaped the disciplinary evolution of the physical environmental sciences in the US during the post-war era (see also Weart, 2008 and McCannon, 2012). The military and strategic need for

[43] SIPRE was reconstituted in 1961 as the Cold Regions Research and Engineering Laboratory (CRREL).

knowledge on cold-weather environments, particularly for engineering and prediction purposes, elevated the importance of geophysics, oceanography, glaciology, atmospheric science, and terrestrial magnetism. Military patronage flowed into these fields and created new institutional spaces for them to flourish, while other environmental and social sciences received comparatively minimal support. As well as providing financial and logistical backing, Doel contends that the military's commitment to the physical environmental sciences changed their intellectual nature (see Forman, 1985). The desire to understand, predict, and even control environments revealed a "utilitarian and operational definition of environmental research" that became a characteristic feature of environmental sciences (Doel, 2003: 636). As the reports noted in Table 4.1 suggest, this directly influenced the character and purpose of Arctic science, including the questions asked and valued, the tools used, and the methods implemented.

The utilitarian and operational approach to Arctic science and technology was strengthened further by developing new methods of scientific inquiry. Following significant advances in computational technology during World War Two, environmental science and technology during the mid-twentieth century saw a shift towards more quantified, modelled, and deductive analytical methods (Barnes, 2008). This reflected an emerging belief that numerical approaches to environmental problems, characteristic of the methods adopted in geophysics, had stronger epistemological claims to knowledge truths than more traditional inductive and observational analyses (Doel, 2003; Lynch, 2006). Further encouraged by a cultural enthusiasm for technology (Doel, 2003), calculable knowledge derived through computer-programmable methods, such as statistics and mathematical modelling, was increasingly favoured over qualitative and descriptive forms. This epistemological shift profoundly changed the nature of scientific research that emerged from the 1950s onward. Hey *et al*. (2009) describe the widespread adoption of computational techniques within various scientific disciplines as the *fourth paradigm of science* (after Kuhn, 1970a).

The high demands for predictive knowledge about the climate during the Cold War, both for civilian and strategic purposes, encouraged the pursuit of new technologically driven approaches to meteorological research (Harper, 2008). As Edwards (2010) details, one of the earliest applications of the digital computer was in numerical weather prediction (NWP) in 1950. Constructed upon coordinate grid systems, NWP utilised mathematical models of the atmosphere and oceans to simulate current and near-future conditions. This swiftly led to the development of global climate models (GCMs) which sought more comprehensive and longer-term simulations of various climate system components, including sea-ice cover (Edwards, 2010). The macroscopic and numerical approach to the climate system that GCMs afforded transformed how information about Arctic sea ice was collected, analysed, and represented in the decades that followed.

4.5. Sea Ice as an Indicator and an Amplifier of Climate Change

4.5.1. The Emergence of Climate Science (Mid-1900s)

From the mid-twentieth century onwards, the notion that sea ice was intimately connected to broader climatic regimes began to take hold. Indeed, the pioneering efforts of Nansen, Weyprecht, and Wieze, among many others in the preceding decades (Section 4.3.3), had established foundational links between sea-ice variability and oceanic and atmospheric processes. These early ideas were enhanced due to the increased attention directed towards Arctic environments during the Cold War, which greatly improved the scientific and technological means through which sea ice could be observed, and significant patterns could be identified. Evidence collected from various fields, including oceanography, glaciology, and meteorology, yielded a wealth of new knowledge about the climate in which sea ice emerged as an integral component (Weart, 2008; Sörlin and Lajus, 2013). Significantly, the expanding collection of synoptic and systematic observations, obtained through national and international programmes of science, indicated that Arctic sea ice experienced cyclical variability in response to changes in atmospheric and oceanic conditions across short and long-term timescales (Crane, 1981). From this enhanced understanding, the dominant, longstanding perception of sea ice as an obstacle was joined by a new realisation: sea ice is an *indicator* and an *amplifier* of global climate change.

During the 1950s, when interest in climate change was mounting, understanding the connections between the sea ice, the ocean, and the atmosphere became a major focus of scientific research. Knowledge of these connections was considered essential to regional scale sea-ice and weather prediction, upon which ensuing Cold War operations relied (Doel *et al.*, 2014b). In addition to the practical, short-term need for knowledge of sea-ice variability, the mid-twentieth century saw a growing body of research seeking to understand and predict the workings of the global climate system over longer-term timescales.[44] Within this body of work, scientists were accumulating evidence of glacial and sea ice retreat across the Northern Hemisphere (e.g., Brooks, 1949; Ahlmann, 1953), examining the influence of increasing concentrations of carbon dioxide on temperature (e.g., Callendar, 1938, 1958; Plass, 1956; Revelle and Suess, 1957), and investigating energy and carbon exchanges between the atmosphere and the oceans (e.g., Bolin, 1960; Suess, 1953). While the findings emerging from these investigations were deeply complex, incomplete, and even contradictory at times (Sörlin, 2009, 2011; Sörlin and

[44] Broadly, this research falls within the field of climate science. Influenced significantly by Cold War strategic interests and the rise of digital computers, climate science emerged as an institutionalised field during the second half of the twentieth century. In many ways, the strategic need to understand the climate for short-term prediction gave climate scientists the platform to investigate long-term, large-scale climate change. See Edwards (2010); Harper (2008); and Weart (2008).

Lane, 2018), the common message they told was of a gradually warming climate, the footprints of which were most notable in the Arctic.

The cause or duration of the warming was not fully understood. Some of the more prevalent theories from earlier decades attributed warming to variations in solar insolation (e.g., Hoyle and Lyttleton, 1939), increasing concentrations of CO2 (natural or anthropogenic) (e.g., Callendar, 1938; Plass, 1956), and volcanic emissions (e.g., Humphreys, 1913). Yet, due to limitations in observation and experimentation, these theories lacked evidence and conviction. Nevertheless, scientists were beginning to warn of the possible risks that climate change could have on human populations and the environment (Weart, 2008). Concern was growing over the potential of melting ice caps to raise sea levels, and scientists like Gilbert Plass warned that the temperature rise from the accumulation of atmospheric CO2 "may be so large in several centuries that it will present a serious problem to future generations" (Plass, 1956: 315).

The US was the forerunner in attending to the questions of climate science. Determining the causes and effects of climate change was a top priority of scientists working at a growing number of university departments and research institutions, such as Scripps Institution of Oceanography (est. 1903), the Geophysical Fluid Dynamics Laboratory (GFDL, est. 1955), the National Center for Atmospheric Research (NCAR, est. 1960), and the Cooperative Institute for Research in Environmental Sciences (CIRES, est. 1967). Backed by substantial federal investments and access to the latest innovations in science and technology, these institutions sought answers to the complex problems of the climate system through pioneering computer modelling in climate change investigations (e.g., Manabe *et al*., 1965). Elsewhere in parts of Europe and Asia, new programmes of climate research were also being initiated. However, it was not until the turn of the century that they became as influential as their US counterparts (Edwards, 2010).

By necessity, climate science demands an interdisciplinary and international approach. Due to the interconnectedness of the climate system and its ignorance of national borders, a comprehensive understanding requires simultaneous inputs globally and from a wide range of disciplines. Despite climate change being low on the 1957-1958 IGY research agenda, the need for an open and international network of data sharing and storage were a chief recognition of the IGY organising committee and a main legacy of the programme (Korsmo, 2010). The World Data Center (WDC) system was established in 1957 to meet these needs: the US and the Soviet Union hosted two primary centres, and a third was jointly led by international committees such the WMO, Japan, Australia, and several countries in western Europe (Korsmo, 2010). Notably, the WDC-A for Glaciology represents the formal origins of the NSIDC, which emerged in 1976 following changes to the location, management, and organisational structure of the centre (NSIDC, n.d.). The WDCs were principally established as safe and accessible repositories of the scientific data obtained by the IGY nations (CSAGI, 1959). This was seen as an immediate

necessity of the forthcoming IGY programme and for maintaining important interdisciplinary and international science networks beyond the programme's completion. The use of digital infrastructures in climate studies, such as computer models, requires vast quantities of data to be transmitted, manipulated, and stored with ease (Edwards, 2010). Therefore, the formation of dedicated institutions and WDCs undoubtedly played a significant role in facilitating a *global* framework of climate science.

The innovations in technology and the institutional changes in climate science, significantly expanded the scope of analyses of ice-ocean-atmosphere interactions. In the 1960s and 1970s, the theoretical and model-based literature on the role of Arctic sea ice in the climate swelled rapidly. Of particular interest were the effects of sea ice on surface albedo (e.g., Langleben, 1966, 1968, 1969), ocean-atmosphere energy exchanges (e.g., Maykut and Untersteiner, 1971; Maykut, 1978), and ocean density stratification during processes of freeze and thaw (e.g., Walsh, 1983). Supported by GCMs and observations from research stations and ice reconnaissance missions (e.g., ARLIS), many of these feedbacks were reasonably well quantified (see Crane, 1981). Through initial investigations, sea ice emerged as an influential component of the climate system. In particular, the high albedo of sea ice and its insulating effect on the underlying water were shown to have profound impacts on regional and hemispheric climate dynamics (Makyut 1986). Specifically, the models emphasised that sea-ice extent, concentration, thickness, and type (first year and multi-year ice) were significant variables affecting energy exchange between the ocean and the atmosphere and the poleward temperature gradient (Crane, 1981). Similarly, GCMs predicted significant declines in sea-ice cover in response to CO2-induced temperature increases (Parkinson and Kellogg, 1979; Manabe and Souffer, 1980). This sparked concern that future sea-ice loss would have substantial implications for ocean-atmosphere heat exchange and large-scale climate dynamics, leading to international calls for observations of seasonal, interannual, and decadal monitoring of sea-ice cover (GARP, 1975).

Despite the apparent significance of the correlations found between Arctic sea ice and broader climatic processes, the models could not capture the precise nature of ice-ocean-atmosphere interactions (Crane, 1981). The uncertainties caused by the highly localised and changeable nature of sea-ice characteristics and the complexities of climate feedback mechanisms, were compounded by a short and punctuated observational record. Direct observations were notably lacking beyond perennially ice-covered regions of the Arctic Ocean; the more seasonal and dynamically active areas of sea-ice cover, such as the MSIZ, were poorly accounted for in early investigations (Makyut, 1986). An improved understanding demanded a more comprehensive database of sea-ice observations. Fortunately, in the coming years, Earth Observation capacities were about to be transformed through developments in satellite remote sensing technology.

4.5.2. The Satellite Era: Breaking the Polar Observational Barrier (1950s Onwards)

The beginnings of the satellite era materialised during the IGY of 1957-58. A core focus of the IGY programme was to develop scientific instrumentation and technologies for the study of the Earth in a more holistic manner (Bulkeley, 1991). This included high-profile research efforts into the possibility of launching satellites to study and monitor the state of the Earth's atmosphere and surface features. On October 4th, 1957, following intense state-sponsored research and development, the Soviet Union launched the first satellite: Sputnik 1. Developed principally to test the viability of placing a satellite into Earth orbit and obtain scientific measurements, Sputnik's successful orbit was celebrated as a monumental feat of engineering and a turning point in the history of humankind (NASA, 2017). The launch marked the beginning of a scientific and technological revolution, which over time, transformed how humanity understood the world and its place within it (Wormbs, 2013).

Beyond its scientific purpose, the triumph of Sputnik was seen as a highly political and symbolic display of the Soviet's power on the world stage (McDougall, 1985). Against a backdrop of open international hostilities, Sputnik's launch exacerbated the security concerns of western powers and encouraged the US to react through their own programme of spaceborne exploration. At a time when US leaders valued prestige and perceptions as much as actual military force, the seismic scientific and technological accomplishments of the Soviet Union in space constituted a major threat to national security and reputation (McDougall, 1985; Bulkeley, 1991; Launius, 2010). A preliminary statement issued by the U.S. National Security Council (NSC) in June 1958 echoed these sentiments. The statement emphasised that urgent research into the various potentials of satellite technology would help position the US as "the recognised leader in the over-all development and exploitation of outer space for scientific, military, and political purposes" (NSC, 1958: 18). As highlighted by the NSC, the potential uses of satellites included communication, scientific research, reconnaissance, and military applications.

On October 1st, 1958, the U.S. National Aeronautics and Space Administration (NASA) was established to facilitate scientific and technological developments in space exploration. At its core, NASA is an open and independent civilian agency responsible for providing leadership on all space activity, except where military operations, weapons systems, and defence are associated (McDougall, 1985). As defined by the 'National Aeronautics and Space Act of 1958', NASA's chief objectives include: expanding knowledge of atmospheric and space phenomena, the improvement of space vehicles and instrumentation, preserving the US position as a leader in space science and technology, international cooperation in the peaceful pursuit of space-related activities and resultant applications, and optimising the use of US scientific and engineering resources (PSAC, 1958). Those activities of a direct military nature fell to the U.S.

Department of Defense (DoD) control, who later initiated their own weather satellite programme in parallel: the Defense Meteorological Satellite Program (DMSP). This division between military and non-military space operations was immediately problematic. McDougall (1985) outlines that the separation between scientific and military operations was increasingly blurred during the Cold War. Consequently, it was almost impossible to develop a depoliticised programme of space exploration. Nevertheless, the institutional distinction and the open, civilian focus of NASA were fundamental to preserving internationally peaceful and cooperative activities in space.

The scientific opportunities afforded by the developments in satellite technology were broad and of international interest. Recognising the huge demand for data in weather forecasting and climate science, meteorological and geophysical applications were among the earliest scientific objectives formulated by NASA (PSAC, 1958). Despite no direct mention in the early documentation on NASA objectives and activities (e.g., Logsdon *et al*., 1995), through developments in spaceborne meteorological and geophysical research, sea-ice observation reaped the benefits in the decades that followed.

Within two years of its infancy, NASA initiated TIROS (Television Infrared Observation Satellite), an experimental programme developed to test the usefulness of satellites in environmental studies of the Earth (NASA, 2016). In particular, the experimental programme sought to investigate the design features of the spacecraft instrumentation, orbital regime, and data processing systems. The TIROS programme made important steps towards developing an effective system of meteorological satellites. Its resulting imagery provided key insights into atmospheric conditions and large-scale weather patterns, which proved immensely valuable for weather forecasts worldwide (NASA, 2016). Studies using TIROS photography also demonstrated the applicability of satellites for ice reconnaissance (e.g., Wark *et al*., 1962). Through comparisons with aerial photographs and visual observations, Wark *et al*. (1962) used satellite photographs to identify and interpret sea-ice characteristics in the Gulf of St. Lawrence, including sea-ice type, distribution, and cover (Figure 4.9).

The initial applications of TIROS imagery, particularly for sea-ice observations, were severely limited. Firstly, due to the nature of satellite photography and infrared imagery, the identification of surface characteristics was limited by the prevalence of clouds and daylight hours (Tedesco, 2015). Additionally, the low Earth orbit and space orientation

of the TIROS satellites permitted only partial coverage of the Earth (NASA, 2016). As a result, the polar regions were omitted from view.

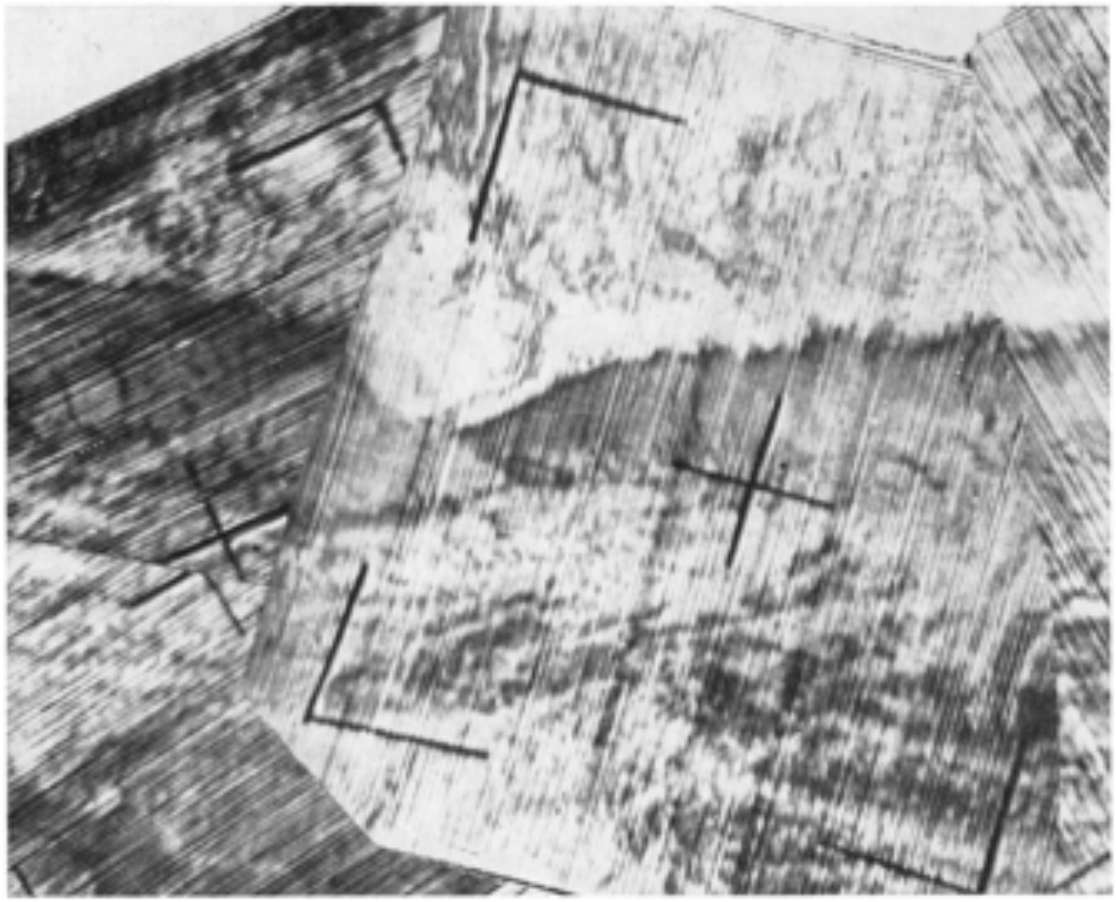


Figure 4.9.: TIROS 2 photographs of sea ice, Natashquan Point area, January 1961. The outer black lines in the corners of the images correspond to approximately 10-15 miles. *Source*: Wark et al. (1962).

In 1964, NASA launched a second-generation of Earth Observation satellites: the Nimbus series. Building on many of the limitations identified in TIROS, Nimbus encompassed seven satellites, launched between 1964 and 1978. The primary objective of Nimbus was to develop a fully integrated, operational system of Earth Observation satellites in support of an improved practical and modelled understanding of atmospheric processes and variability (GSFC, 1962). This involved developing satellites to obtain consistent measurements of the Earth's atmosphere, oceans, and surface features and sophisticated ground data acquisition and processing systems to ensure the timely transmission of data to users worldwide (Press, 1962). It was expected that meteorologists and atmospheric scientists working at national meteorological institutes would constitute the main users of Nimbus data. However, over time, developing a consistent global observing system would prove invaluable for a much broader range of scientific fields.

For many reasons, Nimbus was a huge success. A significant advance in the Nimbus system beyond the TIROS satellite was shifting to a polar orbit and an Earth-oriented

configuration (Press, 1962). This alteration permitted complete global coverage of the Earth daily. This change would revolutionise our understanding of the world and pave the way for future satellite observing systems. In line with a growing recognition of the interconnectedness of the climate system, observing and mapping the global distribution of snow and ice cover were among some of the key objectives, alongside cloud-cover, atmospheric pressure, hurricane tracking, sea-surface temperatures, and carbon exchanges (Albert, 1962). Global observations of these parameters were considered essential to making accurate predictions of weather forecasts and climate predictions (Sabatini, 1972). For the first time, the synoptic and all-encompassing view of Nimbus satellites provided new techniques to fulfil many of these observational needs.

The Nimbus programme also supported the US's desire to become a world leader in space science and technology. In part, this can be explained by the immense logistical challenges associated with satellite remote sensing systems. Satellite remote sensing is an immensely data-intensive endeavour and produces remarkably different data types than other observation methods (Edwards, 2010). As with all subsequent satellites programmes, Nimbus demanded an extensive ground system network of communications, command facilities, and data centres (Stelter, 1962). In the long run, national developments in computational technology (e.g., algorithms, automation, software) and telecommunications would provide improved platforms and facilities for the more efficient acquisition, analysis, and application of global satellite data (Edwards, 2010). However, particularly in the early satellite years, these data processing activities were extremely costly and infrastructurally demanding (Press, 1962; Hey *et al.*, 2009). For many smaller nations, the political and economic ramifications of these challenges, such as inaccessibility of adequate computing systems and profitability issues, hindered the establishment of necessary research institutions and facilities around satellite remote sensing (Røberg and Collett, 2004; Wormbs, 2013). Consequently, for many decades, the US's specialised centres and dedicated institutions enjoyed hegemony over Earth Observation satellites.[45] Still, it should be noted that, while the US was a leader in space exploration, smaller nations (mainly European countries) actively cooperated with NASA from its beginnings and made significant contributions to scientific research and technological innovations (Røberg and Collett, 2004).

The Nimbus series became the principal research and development platform of the US for satellite remote sensing. Each successive mission generated new information about the Earth's systems and highlighted the drawbacks of the various instruments and operating systems.[46] Notably, the sensors used on the early Nimbus satellites were

[45] These included NASA's Goddard Space Flight Center (GSFC); National Oceanic and Atmospheric Administration (NOAA); U.S. Weather Bureau's National Weather Satellite Center (NWSC); National Space Science Data Center (NSSDC); NSIDC; and NCAR.
[46] See the Nimbus (1-7) User Guides, available from the NASA Technical Reports Server, for more information on mission developments: https://ntrs.nasa.gov/.

limited to infrared and visible wavelengths. While these satellites benefited greatly from the Nimbus programme's improved spatial and temporal coverage, including observations over the polar regions, surface characterisation in the early missions was severely limited by cloud cover and daylight times. The high prevalence of regional cloud cover in the Arctic represented a significant challenge for measuring the distribution of sea-ice cover.

The major turning point for sea-ice observations occurred in the early 1970s, following the launch of Nimbus-5. Advances in electromagnetic imaging technologies made it possible for passive microwave radiometers (PMRs) to be incorporated on the Nimbus satellites (Sabatini, 1972). In contrast to visible and infrared systems, PMRs can acquire surface information irrespective of atmospheric conditions such as cloud cover and solar illumination (Tedesco, 2015). Accordingly, the inclusion of PMRs enabled a more complete and consistent record of surface phenomena, including sea-ice cover, snow distribution, and soil moisture (Wilheit, 1972; Gloersen and Hardis, 1978). Particularly for the scientists involved in monitoring Arctic sea ice, the adoption of microwave instruments was seen as an exciting and invigorating development in observing capabilities (Parkinson *et al*., 1987).

For a detailed outline of the processes involved in passive microwave remote sensing of sea ice, see Chapter 5. The important point to note here is that PMRs do not directly measure the properties of sea ice; rather, they measure the microwave radiation naturally emitted from the surface. Different surface types emit different signatures of microwave radiation (brightness temperatures), depending on factors such as their physical and chemical composition and surface temperature (Eppler *et al.*, 1992). With an understanding of the physics of electromagnetic radiation, the different signatures of microwave radiation can be used to differentiate between areas of sea-ice cover, open water, and land.

Compared to alternative methods of sea-ice observation, including aerial reconnaissance, ships, land stations, and submarines, the introduction of PMRs represented a fundamentally different approach to sea ice, both practically and epistemically. Monitoring sea-ice characteristics no longer depended on scientific expeditions *to* the Arctic, whether for *in situ* measurements or descriptive observations from the ground, air, or sea. Instead, they relied upon the treatment of sea ice as an abstract and calculable unit, the characteristics of which can be estimated through empirically-derived assumptions and digital manipulation (Gloersen *et al*., 1992). In practice, such theoretical approaches enabled analysts to remotely study and predict the conditions of sea ice from offices situated thousands of miles away from the Arctic.

The implications of satellite microwave radiometry for understanding the conditions and variability of sea ice and its role within the broader climate system would prove

hugely significant. As noted earlier, studies into ice-ocean-atmosphere interactions throughout the 1960s and 1970s highlighted the need for more comprehensive datasets of sea ice extent, concentration, thickness, and type. In 1972, following the launch of an experimental PMR (the Electronically Scanning Microwave Radiometer (ESMR)) on Nimbus-5, it was clear that these instruments could provide valuable observations of these variables in support of investigations into the global climate system (except thickness observations) (Parkinson *et al*., 1987). However, due to initial issues around instrumental sensitivity and technical problems, the observations obtained using the ESMR were plagued with data gaps and uncertainties (Gloersen *et al.*, 1992).

By the launch of Nimbus-7 in October 1978, substantial developments in microwave instrumentation in the form of the Scanning Multichannel Microwave Radiometer (SMMR) enabled a near-constant bi-diurnal coverage of Arctic sea-ice extent and concentration. Although of a relatively poor spatial resolution (see Chapter 5), no such consistent, spatially extensive data were available from other means of sea-ice observation – a statement that remains broadly true today. The data acquired from SMMR observations included radiation measurements compiled every two days, from which monthly-averaged sea-ice concentration and extent could be derived (Figure 4.10). The initial SMMR datasets were processed by the Goddard Space Flight Centre (GSFC) and archived and distributed by the NSIDC.

Over time, PMR observations supplied the datasets necessary to analyse regional, seasonal, and inter-annual variability in Arctic sea ice. Motivated primarily by the importance of sea ice for climatological applications, early studies used these datasets for the following purposes: to provide a comprehensive picture of sea-ice variability in the Arctic, detect meaningful connections with broader atmospheric and oceanic phenomena, and examine different algorithmic approaches to data interpretation (e.g., Cavallieri and Zwally, 1985; Parkinson and Cavalieri, 1989; Gloersen *et al*., 1992, 1993). The dominant picture arising from these data showed a strong seasonality across the Arctic and significant variability between regions of the Arctic Ocean. Over the full SMMR record (October 1987 to August 1987), there was a statistical hint of overall sea-ice decline; however, the time series was too short and too variable for concrete conclusions to be reached (Gloersen *et al.*, 1992).

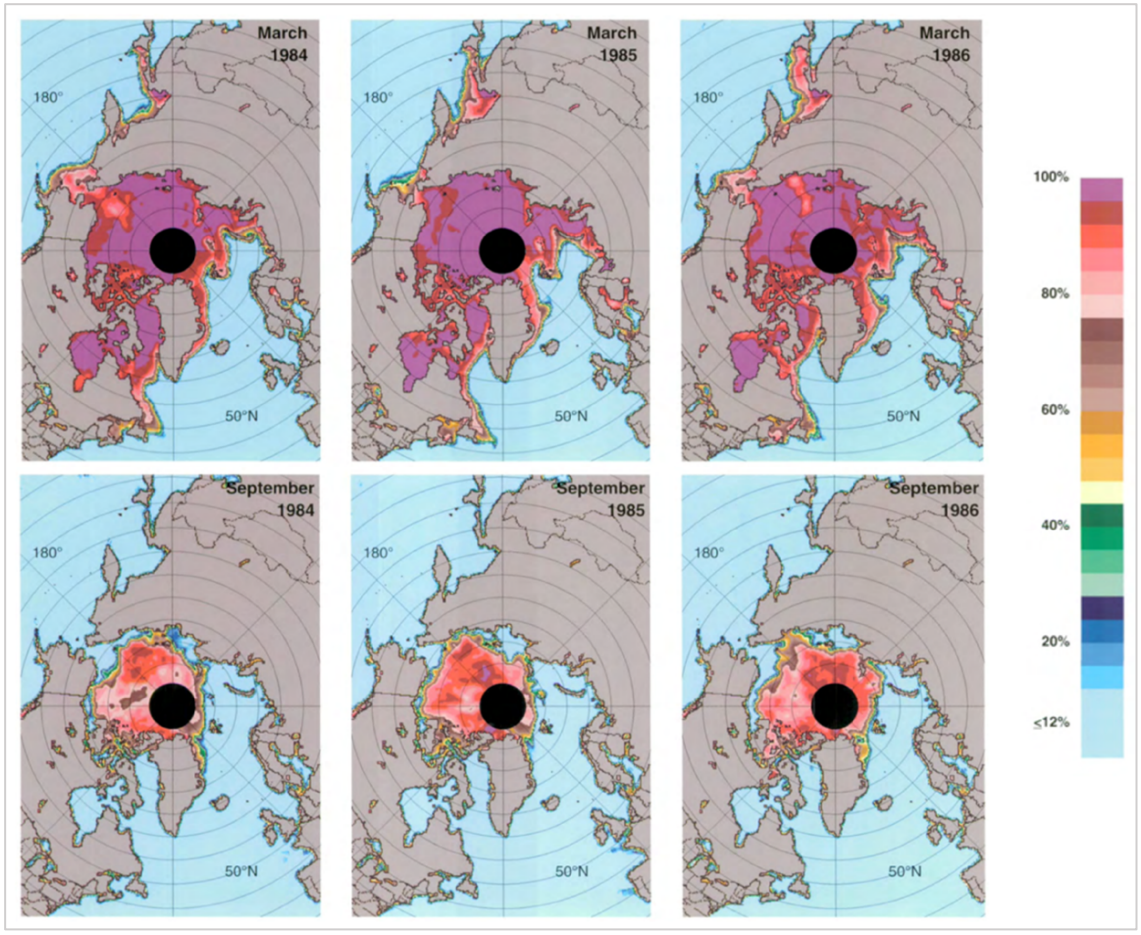


Figure 4.10.: Example average-monthly sea-ice concentration maps, derived from Nimbus-7 SMMR imagery for March and September 1984-86. *Source*: Gloersen et al. (1992).

During this same period, international concerns over the state of the climate system were increasing. In 1990, the IPCC's First Assessment Report (FAR) stated with certainty that atmospheric concentrations of CO2 were increasing, and this would significantly affect Earth systems through increased global temperatures (IPCC, 1990). The polar regions were predicted to see the greatest increase in temperature; however, the nature of climate warming was uncertain in terms of its timing, magnitude, and spatial patterns.

Acknowledging the many uncertainties in their predictions, the IPCC FAR called for internationally coordinated research efforts to advance our understanding of the climate system through improved observational and modelling capabilities. Systematic long-term observations of the climate system were imperative to understanding and parameterising the key drivers of change. These requirements resonated at the Second World Climate Conference in 1990, an event which made important steps towards initiating multilateral action against climate change (SWCC, 1990). These steps resulted in establishing the United Nations Framework Convention on Climate Change (UNFCC) and a Global Climate Observing System (GCOS) in 1992. Through supporting national and international programmes to meet climate observational needs, GCOS was established to "provide comprehensive information on the total climate system,

involving a multi-disciplinary range of physical, chemical and biological properties and atmospheric, oceanic, hydrologic, cryospheric and terrestrial processes" (GCOS, 1992; SWCC, 1990). GCOS underscored the importance of ongoing international and cooperative measurements of Arctic sea-ice cover variables, including extent, concentration, and type.

As time passed and the satellite data series grew, unmistakeable trends in sea-ice variability began to emerge on longer-term timescales. By the mid-to-late-1990s, a statistically significant declining trend in overall Arctic sea-ice extent was apparent in the now 20-year-long record (Gloersen *et al*., 1993, 1999; Parkinson *et al*., 1999). Other studies also revealed substantial reductions in the areal cover of multiyear ice, indicating a possible regime shift in sea-ice type (e.g., Johannessen *et al*., 1999). However, as Serrezze (2018) summarises, regional and interannual variability in response to poorly constrained atmospheric and oceanic processes continued to complicate the trends. That sea ice would play a role in climate change was certain, but exactly how and when was unclear.

Over the last two decades, sea-ice science has broadly progressed along the same lines of inquiry. Evidence accumulated from a range of scientific disciplines across the Arctic has unanimously shown that the region is warming faster than the global average (Overland *et al*., 2018). New PMR sensors have been launched to continue monitoring large-scale changes in sea-ice conditions (Appendix 2). With time, the continuous, daily PMR observations of Arctic sea ice have documented significant and long-term downward trends in sea-ice cover, shifts in the seasonality of sea ice, and changes in sea-ice composition (e.g., Meier *et al*., 2007; Cavalieri and Parkinson, 2012). In particular, through satellite data and statistical trends, the unprecedented decline in sea-ice extent has come to represent one of the most visible and compelling indicators of climate change (Serrezze, 2018; Figure 4.11).

The synoptic and all-encompassing view of the Earth that satellites permit has enabled sea-ice decline and variability trends to be viewed and understood within a broader *global* context (Wormbs, 2013). Consequently, the Arctic has emerged at the forefront of global climate change discussions: it has caught the attention of scientists, politicians, commercial stakeholders, and the general public, both within and beyond the Arctic region (IPCC, 2018, 2021; WMO 2021). Driving this recent surge of international attention is a growing recognition that significant and ongoing declines in Arctic sea ice have the potential to elicit profound and far-reaching climate, ecological, and societal consequences (Overland *et al*., 2018).

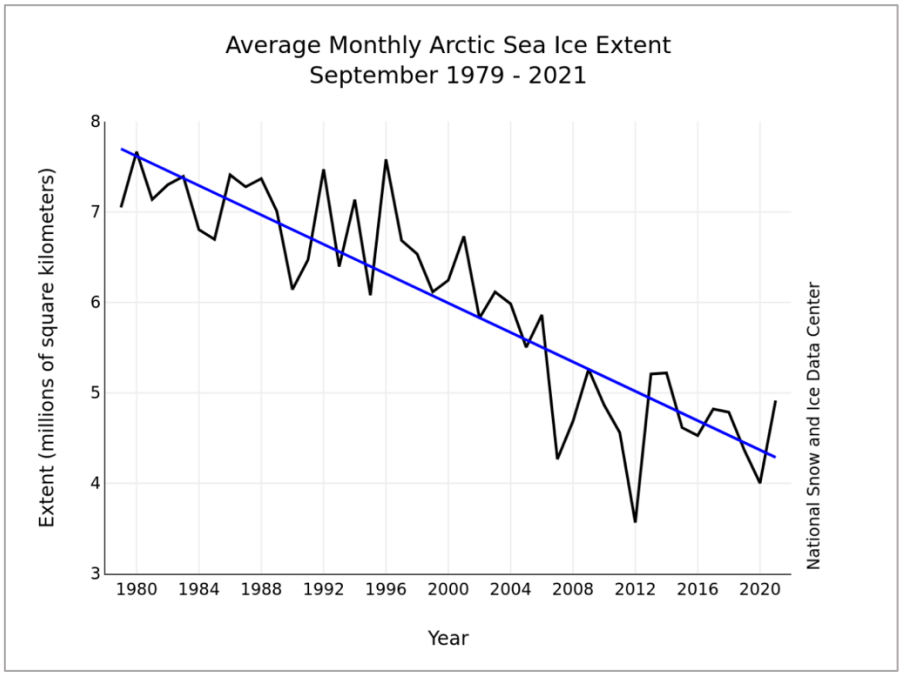


Figure 4.11.: Monthly September sea-ice extent, 1979-2021. *Source:* Image courtesy of the National Snow and Ice Data Center, University of Colorado, Boulder.

Recent years have seen the emergence of new forms of international and interdisciplinary research activities which strive to understand and mitigate against the local, regional, and global consequences of sustained sea-ice decline.[47] PMR observations continue to represent a vital source of sea-ice data for many of these activities, and scientists and research institutes worldwide rely upon this consistent 40-year time series for investigation. As technology has advanced, new forms of higher resolution satellite sensors have been developed to complement this record and facilitate additional observational needs to be met (e.g., thickness). Additionally, developments in infrastructure and computation have enabled data to be processed, manipulated, and disseminated in more efficient and sophisticated ways.

4.6. Conclusion

This chapter has presented a review of the history of Western encounters with Arctic sea ice. It has sought to place contemporary sea-ice science within a broader historical context and demonstrate how the practices, discourses, technologies, and actors of science have emerged to inform our understanding of the region today and the methods through which it is studied.

Throughout the region's complex history, different interests, environmental factors, and developments in science and technology have converged in producing knowledge about

[47] Some examples: MOSAiC (Multidisciplinary drifting Observatory for the Study of Arctic Climate); ESA CCI (European Space Agency Climate Change Initiative); CAO (Changing Arctic Ocean); ELOKA (Exchange for Local Observations and Knowledge of the Arctic).

the Arctic. Varying societal, geopolitical, strategic, and economic interests have incited countless encounters with Arctic sea ice. As this chapter has outlined, science and technology have played a vital role in facilitating those encounters. Science and technology have changed and adapted to overcome the challenges of the Arctic environment and serve the knowledge requirements of various stakeholders across both national and international scales within different historical and cultural contexts. In doing so, they have also influenced how the Arctic is perceived, known, and acted upon.

The climatic importance of Arctic sea ice is at the forefront of current scientific and political concerns. The notion that '*what happens in the Arctic, does not stay in the Arctic'* is frequently voiced through scientific reports, media stories, conferences, and political assemblies. It is used to warn that the implications of continued sea-ice loss for the climate system will be significant and far-reaching. Accordingly, scientific discourses about Arctic sea ice are predominantly global and future-orientated. Research objectives are primarily concerned with uncovering what the future Arctic Ocean will look like, how sea-ice environments will continue to evolve and change, and what impact these changes will have on global systems, both natural and human. The dominant scientific narrative emerging from recent decades is that the scale and pace of Arctic sea-ice melt are unprecedented and potentially irreversible (Overland *et al*., 2018). The observed changes in sea-ice conditions have been directly linked to anthropogenic climate change and serve as a clear reminder of the hegemonic role that humans have played in influencing Earth systems and material elements (IPCC, 2021). Viewing the region through this global perspective gives way to a perception of an Arctic that is fragile and in need of scientific, political, and environmental cooperation from a broad range of national and international actors (Doel *et al*., 2014a).

This chapter has demonstrated that to understand these contemporary and future framings of Arctic sea ice, there is a need to attend to the historical contexts of sea-ice science and encounters with the Arctic. How Arctic sea ice has been perceived, understood, and monitored in the past, and by whom, has important implications for how it is observed, measured, and represented today. For many scholars, the acumination of global geopolitical, economic, and scientific interest in response to unparalleled environmental transformation represents the emergence of a 'new' Arctic (e.g., Doel *et al*., 2014a). This is an Arctic we have come to understand as a place of global significance, where a broad range of diverse interests and concerns come together to form a highly complex and interconnected region. As this chapter has shown, this global perspective of a fragile, interconnected Arctic has a relatively short history. Such notions materialised most compellingly during the latter half of the twentieth century, reflecting a convergence of environmental changes, growing societal concerns over climate change, and new developments in science and technology (namely satellites and climate

models) and their associated epistemological shifts towards synoptic, quantitative, and data-driven observations (Edwards, 2010).

Although they were not developed explicitly for this purpose, the introduction of satellites was a technological breakthrough for sea-ice science and essential to the emergence of a global systems perspective of Arctic environmental change. Likened to a paradigm shift in science (Kuhn 1970a; Jasanoff, 2004b), the global view satellites offer transformed our knowledge of the Arctic, including the challenges and opportunities related to future change and how these might be addressed. In this way, satellite observations have come to be seen as part of a global solution to the problem of sea-ice decline (e.g., GCOS, 2018). However, this chapter has shown that satellite technologies and their resulting knowledge and representations are deeply entangled with society. International competition and anxieties, political and economic capacities, and international objectives of science played a significant role in supporting the rapid development and success of satellite technologies, particularly during the Cold War era and the decades that followed. That is not to say that without these driving forces, satellites would not have developed. Such a view would be too simplistic. However, the developments in satellite technologies illustrate how the nature of contemporary sea-ice science is contingent on a particular set of intersecting geopolitical, economic, institutional, and environmental conditions that prevail within historical and cultural contexts. These conditions have shaped and informed the dominant conventions, actors, institutions, and discourses that define what we know and how we come to know. Consequently, as Chapters 5 and 6 explore, through constraining how sea ice is sensed, classified, and represented, satellites and their associated knowledge infrastructures have helped construct particular partial and situated ways of knowing the Arctic in contemporary and future contexts.

5. Sensing and Classifying Arctic Sea Ice

5.1. Introduction

Today, ongoing and consistent monitoring of the spatial and temporal distribution of sea-ice cover is a central focus of sea-ice research. Passive microwave satellite remote sensing technologies are the primary means through which information about Arctic (and Antarctic) sea-ice cover is acquired in contemporary sea-ice science. For climate science applications, these technologies are preferable over field-based and other remote sensing methods for several reasons:

- They enable large-scale coverage of the Arctic Ocean without the need for direct physical contact.
- They have a high temporal resolution, offering a near-complete coverage of the Arctic Ocean at least once per day.[48]
- They acquire surface characteristics irrespective of the amount of cloud cover and solar illumination.
- They offer a near-continuous record of data since the 1970s.

The improved observational capabilities afforded by these technologies have enabled scientists – predominantly based in the US and Europe – to develop consistent, comprehensive, and homogenised sea-ice data products that document the long-term and large-scale variability in Arctic sea-ice cover. Through the production of data products, passive microwave observations of sea ice are acquired, processed, analysed, and consolidated for use by the scientific community, policymakers, industry, and the public. In the form of numerical values, images, and maps, these products have captured and displayed long-term trends, enabling scientists to detect changes in sea-ice cover on a scale that would be difficult if not impossible to comprehend by other means. In this way, sea-ice data products are directly involved in generating and communicating evidence for climate change. They have helped facilitate the shift towards understanding

[48] The satellites are near-polar orbiting satellites; they do not pass directly over the North and South Poles due to the orientation of their orbital paths.

sea ice as an integral feature of the global climate system and the Arctic as a region that demands urgent attention and action from various stakeholders (IPCC, 2019).

However, as discussed in Chapter 1, recent work from within the sea-ice community has focussed attention on the inconsistencies in the practices of passive microwave sea-ice parameter retrieval between different data products and scientific institutions (e.g., Ivanova *et al*., 2015; Meier and Stewart, 2019). These inconsistencies raise a shared concern: different processing methods can result in significant disagreements on the absolute values of the spatial and temporal distribution of ice cover in the Arctic. Inconsistencies in absolute values, in turn, hamper our ability to effectively predict and prepare for the implications of ongoing and future sea-ice decline. Thus, a significant focus within the sea-ice community is on identifying, quantifying, and reducing the inconsistencies in sea-ice retrieval.

From a sociological perspective, the divergence in scientific practices emphasises the multiplicity of potential interpretations and meanings that can emerge from satellite-borne observations of sea ice. This indicates that sea-ice data products are not mere representations of Arctic sea-ice conditions. Instead, they represent a specific way of observing, interpreting, and classifying complex geophysical conditions through which knowledge about the Arctic takes shape. This raises important questions about who is making those interpretations and how different meanings are constructed through the interactions between sea ice, sensing technologies, and social practices.

To explore these issues, this chapter presents a comparative examination of the contemporary scientific practices involved in sensing and classifying Arctic sea-ice data. In line with the analytical approach outlined in Section 3.4.4, the chapter focusses on the practices involved in constructing four passive microwave satellite-derived sea-ice data products developed by the NSIDC and MET Norway: the NSIDC SII v3.0, the OSI-450 SIC v2.0, the C3S SIE v1.0, and the C3S SITy v1.0.[49] These products are some of the many examples of how scientists acquire and translate satellite-derived observations into meaningful and quantifiable parameters of sea ice. In the context of this PhD research, the products have provided an essential means for exploring how the complexities and indeterminacies of Arctic sea ice are interpreted, processed, simplified, and consolidated through scientific practices and how these practices differ between institutions. The purpose of this chapter is to better understand the conventions and techniques that shape how sea-ice knowledge is produced in Western science. In other words, this chapter is an attempt at opening the *black box* to better understand how scientists construct knowledge about sea ice.

[49] Sea-ice research is a continuously evolving field. Specific data product methodologies regularly undergo changes in their processing methods and techniques and new versions are published periodically. The descriptions in this chapter are based upon examinations carried out during the period of October 2018 through July 2021.

The chapter is separated into two main sections. Section 5.2 begins with a description of the general principles involved in passive microwave satellite remote sensing of sea ice. This includes the sensing technologies used to measure the surface characteristics, the data-processing procedures used to transform satellite observations into sea-ice parameters, and the assumptions and uncertainties inherent in the techniques commonly used throughout the sea-ice science community. Section 5.3 builds on this to detail how the general principles are adopted, modified, and extended by the NSIDC and MET Norway in constructing the four sea-ice data products. The focus here is on the different retrieval methods and data processing techniques used in the production of data products; the conventions, assumptions, and requirements that shape how sea ice is interpreted, translated, defined, and ordered; the main actors and networks involved in the construction of the product; and the products' intended purposes, applications, and users. The chapter concludes with a discussion of some of the main differences in how the products are constructed.

5.2. Sensing Sea Ice

In passive microwave remote sensing, the retrieval of sea-ice parameters is not based on direct measurements of the geophysical properties of sea ice. Rather, it is based on observations of the interaction between electromagnetic microwave radiation and Earth surface materials from which the characteristics of sea-ice cover can be estimated (Tedesco, 2015). Achieving meaningful and quantifiable information about sea ice using passive microwave systems involves a complex process of transformation: radiation data is remotely acquired from the surface using satellite sensors and subsequently interpreted and transformed into geophysical parameters of sea ice using empirically-derived algorithms. These algorithms use algebraic calculations that combine electromagnetic radiation theory, observations of the Arctic Ocean (*in situ*, airborne, and satellite), and various assumptions about radiation physics and the physical and chemical properties of sea ice, the ocean, and the atmosphere (Carsey, 1992; Tedesco, 2015). The transformation process is informed by general principles common to most sea-ice climate data products of *ice cover* parameters, such as concentration, extent, and type (Section 1.2.1).[50] These principles are integral to the feasibility of remote sensing applications for monitoring sea-ice cover; they govern how sea-ice scientists gain access to, classify, and stabilise the complexities of Arctic sea ice. Thus, an analysis of the scientific practices involved in constructing sea-ice data products must begin with an understanding of the general principles of passive microwave remote sensing.

[50] Other parameters such as sea-ice thickness are based on different sensing technologies and use different approaches.

5.2.1. Passive Microwave Radiation and the Electromagnetic Spectrum

As Tedesco (2015) details, the interaction between electromagnetic radiation and Earth surface materials differs depending on the physical and chemical properties of the material, such as temperature and phase state (gas, liquid, or solid), as well as the frequency of the electromagnetic radiation. Different surface materials absorb, transmit, or reflect varying amounts of incident electromagnetic radiation, and this amount denotes the *emissivity* of a material. Emissivity (ε) is defined as the ratio between the amount of energy radiated from a material and the energy radiated from a blackbody at the same temperature. By definition, a blackbody is an idealised, hypothetical object that absorbs all incident radiation, making it a perfect emitter when in thermal equilibrium (ε = 1). Objects and materials on the Earth's surface are not blackbodies; meaning, they absorb (and emit) a *fraction* of incident radiation and reflect or transmit the remainder (ε = <1). Measurements of the amount of radiation emitted at different electromagnetic frequencies can be used to derive information about the geophysical properties of the surface under observation.

Passive microwave satellite sensors obtain measurements of the radiation naturally emitted by the Earth's surface across the microwave portion of the electromagnetic spectrum (Figure 5.1). The microwave portion has a frequency range of approximately 0.3 to 300 gigahertz (GHz); however, most passive microwave sensors used in sea-ice science operate at approximately 5 to 100 GHz frequencies. Following the success of the SMMR sensor onboard the Nimbus-7 satellite (Section 4.5.2), several passive microwave sensors have been used onboard satellites to measure and monitor Arctic sea ice. Details of the sensors and their associated characteristics are listed in Appendix 2.

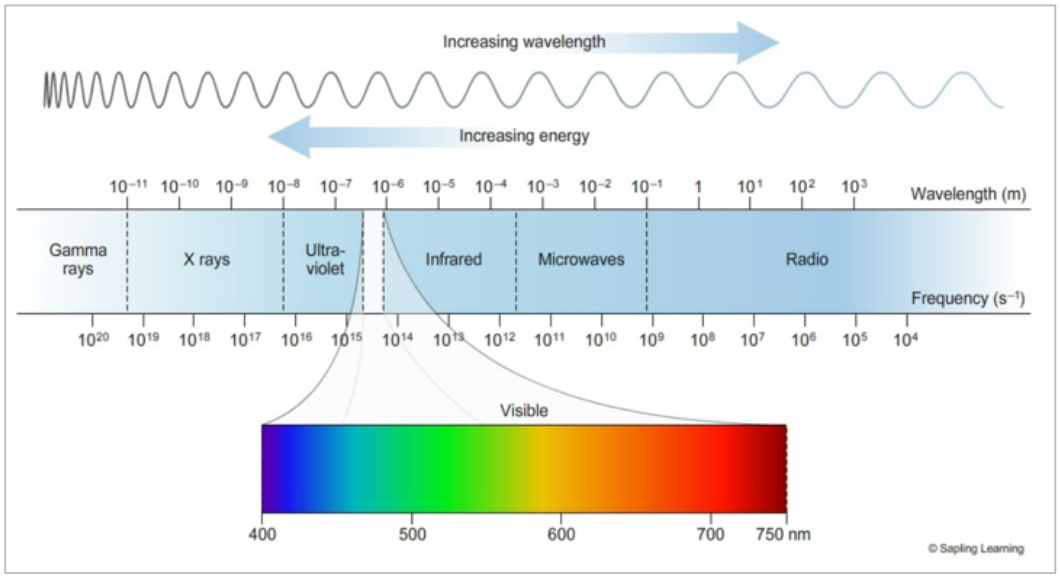


Figure 5.1.: Electromagnetic spectrum. *Source*: https://sites.google.com/site/chempendix/em-spectrum.

The radiation measured by the sensors is not pure measurements of surface-level emission: atmospheric components such as oxygen, water vapour, clouds, and precipitation alter the amount of radiation reaching the sensors through emission, absorption, and attenuation (Meier, 2005). These components complicate the radiation signal reaching the sensor and inhibit the interpretation of surface characteristics. However, the relatively dry atmosphere in the polar regions is highly transmissive, particularly at the operating frequencies used in sea-ice observations (Figure 5.2). The radiation signals reaching the sensor are less affected by atmospheric interference than in lower latitudinal areas. Water vapour and oxygen still affect some operating frequencies, particularly at the higher frequency channels, such as 85.5 and 91.7 GHz (Figure 5.2). In observations of sea ice, the impact of these components can be reduced through additional data processing steps and by comparing retrievals at multiple frequency channels (Section 5.3).

The amount of microwave radiation measured by the sensors at the different frequencies is usually referred to as the *brightness temperature* (TB). Across the microwave range, brightness temperature is a function of the emissivity and the physical temperature of the surface being measured (Tedesco, 2015). It can be expressed quantitatively using the Rayleigh-Jeans Law:

$$T_B = \varepsilon * Ts$$

Equation 1

where T_B is brightness temp (measured in units of Kelvin), ε is emissivity (0-1), and Ts is physical temperature.

Brightness temperature is defined as "the physical temperature of an object, if it were a blackbody at a given *frequency* and *polarization*" (Meier and Markus, 2015: 252, emphasis added). According to this definition, in addition to frequency, the polarisation of electromagnetic radiation is an important factor in interpreting surface-level information using passive microwave observations. The polarisation of microwaves relates to the theory that electromagnetic waves can be described by electric and magnetic field components, which are orientated perpendicularly to each other and the direction of wave propagation (Figure 5.3). Polarisation describes the oscillation direction of the electric field component, otherwise known as the *plane of polarisation*. The example shown in Figure 5.3 shows an electromagnetic wave with a strict vertical polarisation, meaning the electric field component only oscillates up and down. However, electromagnetic waves emitted by objects and materials on the Earth's surface are rarely confined to a singular plane: components of the electric field oscillate in variable directions that remain perpendicular to the direction of wave propagation. The

direction(s) of oscillation is(are) influenced by the chemical and physical properties of the material.

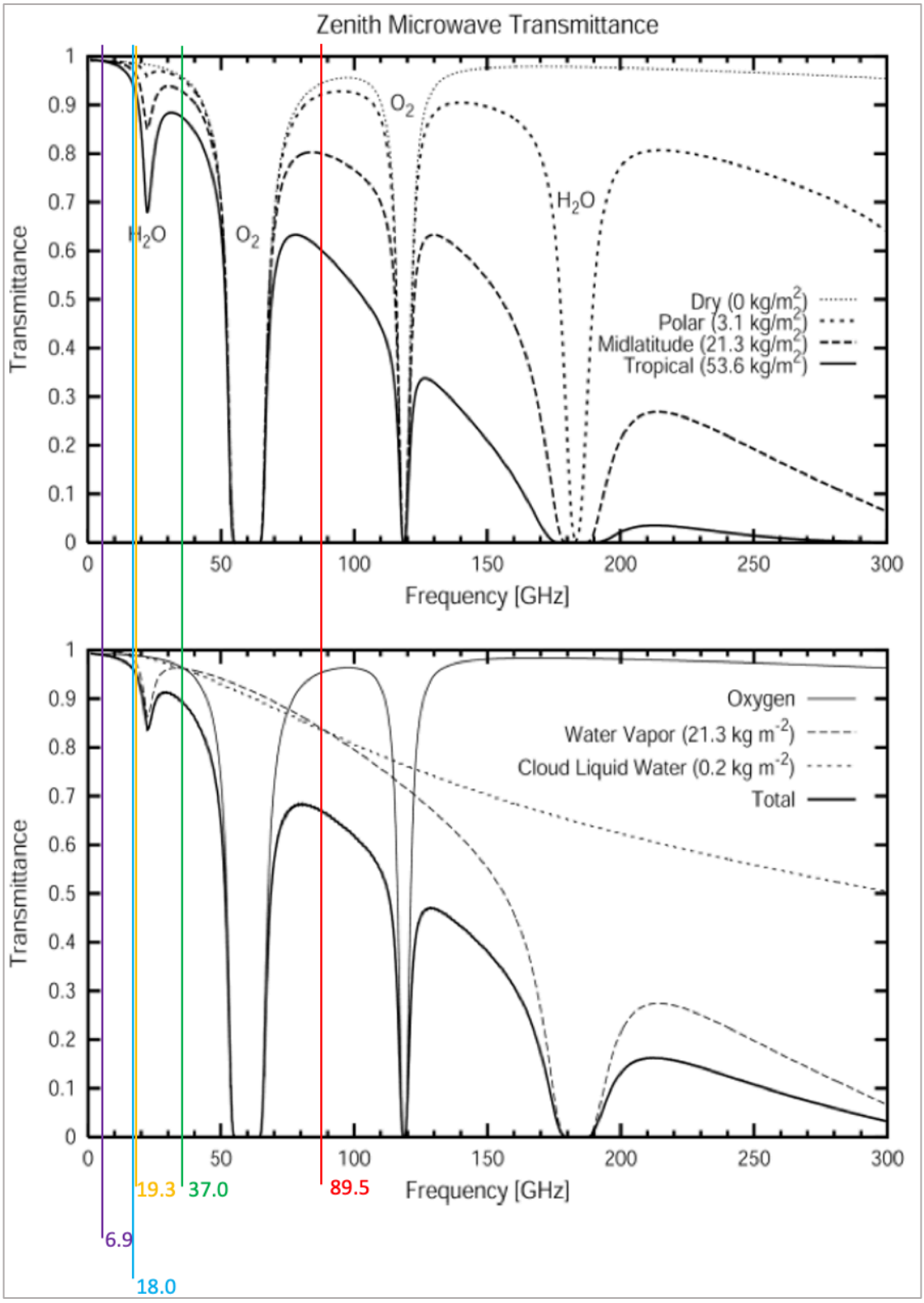


Figure 5.2.: Typical atmospheric transmissivity of the atmosphere at different humidity levels (dry, polar, midlatitude, and tropical) and microwave frequencies. The typical operating frequencies used in sea-ice retrieval are indicated on the graph: from left to right, 6.9 GHz (purple), 18.0 GHz (blue), 19.3 GHz (yellow), 37.0 GHz (green), 89.5 GHz (red). *Source:* Petty (2006) - modified to indicate the position of the operating frequencies.

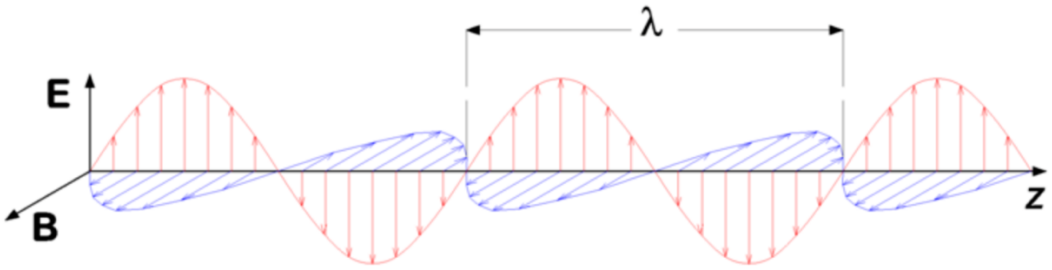


Figure 5.3.: A vertically polarised electromagnetic wave. The electric field component (E) is shown in red to be oscillating vertically; the magnetic component (B) is shown in blue to be oscillating at right angles to the electric component. The direction of wave propagation (z) is perpendicular to the electric and magnetic field components. *Source:* P.wormer, CC BY-SA 3.0, Wikimedia Commons, https://commons.wikimedia.org/wiki/File:Electromagnetic_wave.png.

The amount of energy (brightness temperature) measured at various combinations of frequency and polarisation can provide different and complementary information about the observed surface characteristics (Gloersen *et al.*, 1999). Consequently, most passive microwave sensors used in sea-ice retrieval are designed to acquire measurements at various frequency channels and horizontal and vertical polarisations (Appendix 2). Figure 5.4 provides an example of the different brightness temperatures captured over the Arctic Ocean at horizontal and vertical polarisations for the same frequency channel. Therefore, knowledge of the radiation properties of Arctic Ocean surfaces can be used alongside these measurements the determine sea-ice cover.

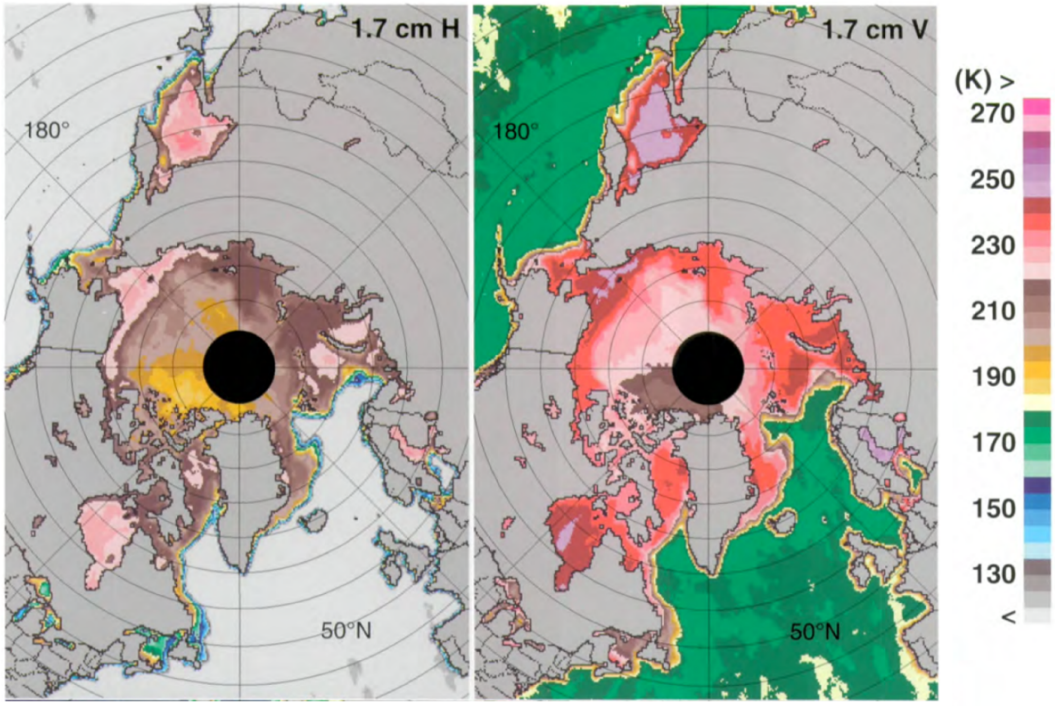


Figure 5.4.: An example of the different brightness temperatures captured using the Nimbus-7 SMMR sensor at a 1.7 cm microwave wavelength (approximately 18 GHz frequency) for different polarisations. Horizontally polarised brightness temperatures are shown on the left, vertically polarised on the right. This example is from average monthly data obtained for February 1979. *Source:* Gloersen et al. (1999).

5.2.2. Microwave Radiation Properties of Sea Ice

Extensive research has been carried out to ascertain the passive microwave radiation signatures of sea ice and open water using integrated observations from ground-, aircraft-, and satellite-based sensors (e.g., Gloersen *et al*., 1973; Svendsen *et al*., 1987; Eppler *et al*., 1992). Through these investigations, the emissivity signatures of different ice types have been shown to vary substantially across the operating frequencies and dual polarisations of microwave radiation. The main factors driving this variability include differences in the presence and distribution of brine and gas within the ice, surface roughness, snow cover, and phase state (Meier and Markus, 2015).

Observations have established three dominant emissivity signatures from the Arctic Ocean: first-year ice, multi-year ice, and open water (Eppler *et al*., 1992). *First-year ice* is defined as sea ice of no more than one year's growth, and *multi-year ice* is defined as sea ice that has survived at least one melt season (WMO, 2014). The radiation properties of these ice types are of particular importance as they provide the theoretical basis for discriminating between sea ice and open water, ascertaining the spatial distribution of different ice types, and determining sea-ice concentration using passive microwave technologies. Table 5.1 lists the typical microwave emissivity signatures of sea ice and open water that are generally accepted throughout the sea-ice community and have been used to derive long-term and large-scale records of sea-ice cover for many decades.

Table 5.1.: Typical emissivity signatures for different ice types in the Arctic, measured at various microwave frequencies and vertical and horizontal polarisations. Water, first-year ice, and multi-year ice are highlighted in colours that correspond to Figure 5.5. Note that the absolute values carry less weight individually; rather, it is the relative differences that form the basis of sea-ice retrieval calculations. *Source:* Eppler et al. (1992).

Ice type	Pol.	4.9	6.7	10	18.7	21	37	90	94
Water	V	0.505 (0.015)	0.513 (0.015)	0.532 (0.015)	0.570 (0.033)	0.617 (0.015)	0.662 (0.029)	0.792 (0.019)	0.753 [0.026]
	H	0.253 (0.015)		0.295 (0.020)	0.332 (0.018)	0.332 (0.018)	0.392 (0.015)	0.528 (0.022)	0.488 [0.050]
New	V	0.560		0.568	0.623		0.703	0.850	
	H	0.280		0.315	0.368		0.417	0.573	
Nilas (dark)	V			0.705	0.760		0.810	0.885	
	H		0.580	0.613	0.678		0.769	0.846	
Nilas (gray)	V		0.775	0.813	0.837		0.880	0.915	
	H		0.720	0.765	0.800		0.840	0.880	
Nilas (light)	V			0.910	0.950		0.960	0.955	
	H			0.850	0.890		0.930	0.925	
Densely packed 3-cm-thick pancakes	V	0.740	0.750	0.748	0.811	0.826	0.868	0.893	
	H	0.595		0.638	0.700	0.715	0.761	0.780	
First-year ice	V	0.935 [0.010]	0.900 (0.020)	0.924 (0.036)	0.941 (0.019)	0.960 (0.019)	0.955 (0.015)	0.926 (0.045)	0.934 (0.015)
	H	0.850 [0.065]	0.840 (0.025)	0.876 (0.021)	0.888 (0.019)	0.910 (0.020)	0.913 (0.013)	0.886 (0.031)	0.895 (0.009)
Dry multiyear	V	0.926 [0.037]	0.925 (0.020)	0.890 (0.035)	0.850 (0.068)	0.787 [0.080]	0.764 (0.079)	0.680 (0.105)	0.566 [0.061]
	H	0.865 [0.049]	0.820 (0.030)	0.817 (0.075)	0.780 (0.080)	0.635 [0.125]	0.706 (0.115)	0.650 (0.011)	0.535 [0.061]
Flooded multiyear	V			0.910 (0.056)	0.942 (0.036)		0.953 (0.015)	0.902 (0.062)	
	H			0.858 (0.080)	0.912 (0.050)		0.927 (0.040)	0.867 (0.068)	
Frozen melt pond	V		0.910 [0.050]	0.913 [0.039]	0.969 [0.030]		0.970 [0.017]	0.876 [0.069]	
	H		0.813 [0.069]	0.814 [0.061]	0.877 [0.037]		0.885 [0.036]	0.818 [0.093]	
Summer melting	V	0.945 [0.018]	0.944 [0.020]	0.960 (0.018)	0.960 (0.020)	0.960 [0.006]	0.970 (0.010)	0.953 (0.010)	0.960 (0.010)
	H	0.820 [0.020]	0.870 [0.025]	0.890 (0.025)	0.890 (0.025)	0.910 [0.012]	0.933 (0.015)	0.920 (0.020)	0.933 (0.015)
Summer frozen surface crust (extreme case)	V	0.955		0.965	0.960	0.950	0.898	0.728	
	H	0.923		0.933	0.920	0.900	0.833	0.678	

( ) = standard deviation of pooled numbers extracted from the literature, rather than individual measurements.
[ ] = standard deviation when only one source was available; numbers are missing if tolerances were not given.
This table was compiled by using data from Comiso et al. [1989], Grenfell [1986, 1992], Grenfell and Comiso [1986], Grenfell and Lohanick [1985], Lohanick and Grenfell [1986], Mätzler [1986], Mätzler et al. [1985], The Norsex Group [1983], Onstott et al. [1987], and Svendsen et al. [1987].

Figure 5.5 provides an illustration of typical first-year ice, multi-year ice, and open water emissivity signatures captured at different microwave frequencies and polarisations. Figure 5.6 depicts these emissivity characteristics schematically in relation to the key physical and chemical properties of first-year and multi-year ice types.

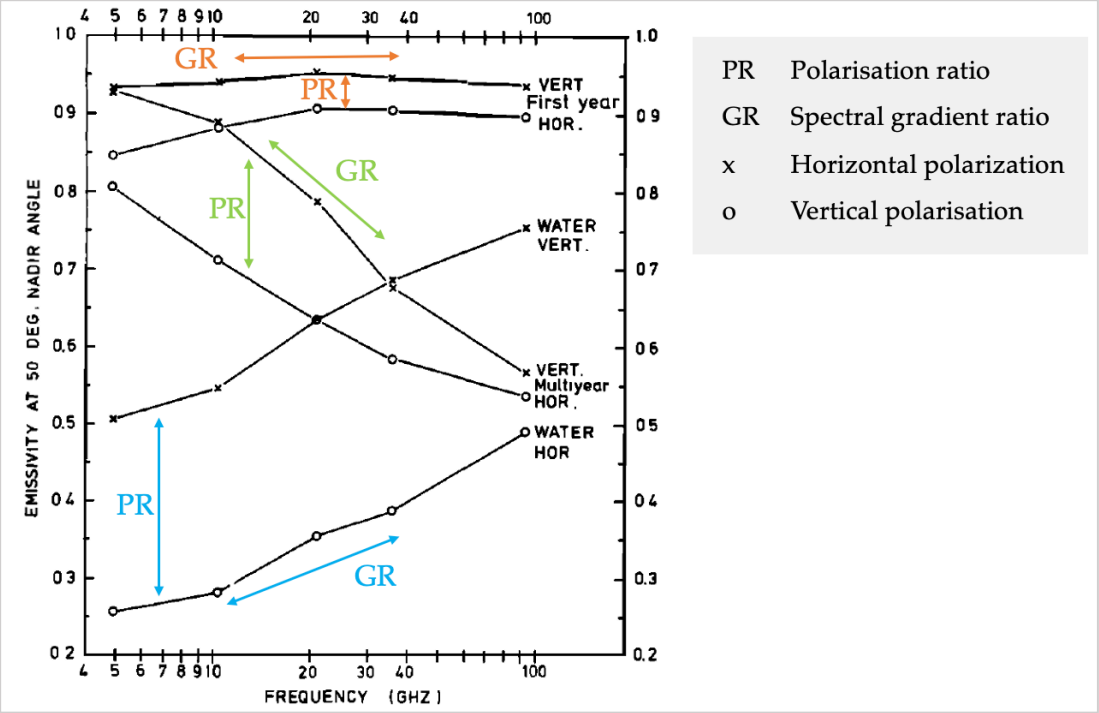


Figure 5.5.: Typical emissivity signatures of first-year ice, multi-year ice, and open water obtained at various microwave frequencies and vertical and horizontal polarisations. The emissivity signatures were measured during the Norwegian Remote Sensing Experiment (NORSEX) in 1979. See text for definitions of PR and GR. *Source:* Svendsen et al. (1983) - modified to illustrate the polarisation (PR), the spectral gradient ratios (GR), and include a key.

Figure 5.5 shows that, generally, open water has a lower emissivity than first-year and multi-year ice and is characterised by strong polarisation (Meier and Markus, 2015). This results in a high *polarisation ratio*, which is defined as the difference between the amount of radiation (brightness temperatures) observed at horizontal and vertical polarisations (Comiso *et al*., 1997). In contrast, first-year ice has a high emissivity due to the relatively large presence of highly absorbent brine pockets that become trapped within the ice during its development (Eppler *et al*. 1992; Figure 5.6a).[51] The amount of radiation emitted from first-year ice is similar across the operating frequencies. This results in a low *spectral gradient ratio* (GR), defined as the difference in emissivity between frequencies (Comiso *et al*., 1997). Characteristically, first-year ice is also cold and dry, resulting in weak polarisation across all frequencies (Hallikainen and Winebrenner, 1992).

Multi-year ice exhibits greater variation in emissivity across the frequency range and between polarisations. The emissivity is high at lower frequencies and gradually reduces as the frequency increases, resulting in a high GR (Figure 5.5). Eppler *et al*. (1992) describe several factors that cause this observed variability compared to first-year signatures.

[51] Brine pockets typically have very high saline concentrations. They are highly absorbent of incident radiation and act as a *lossy medium* at the operating microwave frequencies used in sea-ice retrieval. The physical properties of brine pockets and their implications for passive microwave remote sensing are detailed in Tucker *et al*. (1992).

These include changes to the surface characteristics (e.g., the formation of hummocks, fractures, ridges, and melt ponds) and chemical composition of ice, and variability in the density and wetness of snow cover.

Differences in the salinity of first-year and multi-year ice is a particularly significant driver of emissivity variability (Meier and Markus, 2015). As Tucker *et al*. (1992) describe, sea-ice salinity gradually reduces over time, particularly in the upper layers of ice, as brine pockets are expelled and drained through pressure and gravity. During the summer, the process of brine removal is enhanced as meltwater collects on the surface and subsequently percolates through the ice, replacing the highly absorbent brine pockets with air bubbles and voids that scatter a higher fraction of incident radiation (Figure 5.6b). As a result, multi-year ice is typically characterised by lower salinity concentrations and lower brightness temperatures than newly formed ice, particularly in the freeboard section (Figure 5.6c). The significant differentiation in emissivity across the frequency range occurs due to differences in microwave penetration depths: lower frequencies penetrate deeper into the ice than higher frequencies (Hallikainen and Winebrenner, 1992; Figure 5.6c). Thus, lower frequencies reach parts of the ice where saline concentrations remain high, yielding emissivity measurements similar to first-year ice. In contrast, the emissivity is much lower at higher frequencies, reflecting the reduced salinity and increased radiation scattering in the shallower layers (Eppler *et al*., 1992).

Variability in the density and wetness of snow cover can differentially alter the passive microwave signal of sea ice throughout the year (Eppler *et al*., 1992). During the winter, dry snow is highly penetrable, particularly at lower frequencies (Figure 5.6a). As snow begins to melt in response to warming temperatures during the spring and summer months, snow cover becomes increasingly absorbent and exhibits a high emissivity signature. This can significantly reduce the accuracy of surface characterisation as it has the effect of making multi-year ice appear like first-year ice. This similarity can be seen in Table 5.1 through comparing the emissivity of 'Dry multiyear' and 'Flooded multiyear' ice types. Increased meltwater presence can have a similar effect (Section 5.2.4).

To summarise the key differences in the emissivity signatures of first-year ice, multi-year ice, and open water in the Arctic:

- First-year ice has *high emissivity* across all frequencies and a *low polarisation ratio*.
- The emissivity of multi-year ice decreases with increasing frequency, resulting in a *high gradient ratio*.
- Water has a *low emissivity*, particularly in the lower frequencies.
- Water has a significantly higher *polarisation ratio* compared to first-year and multi-year ice types.

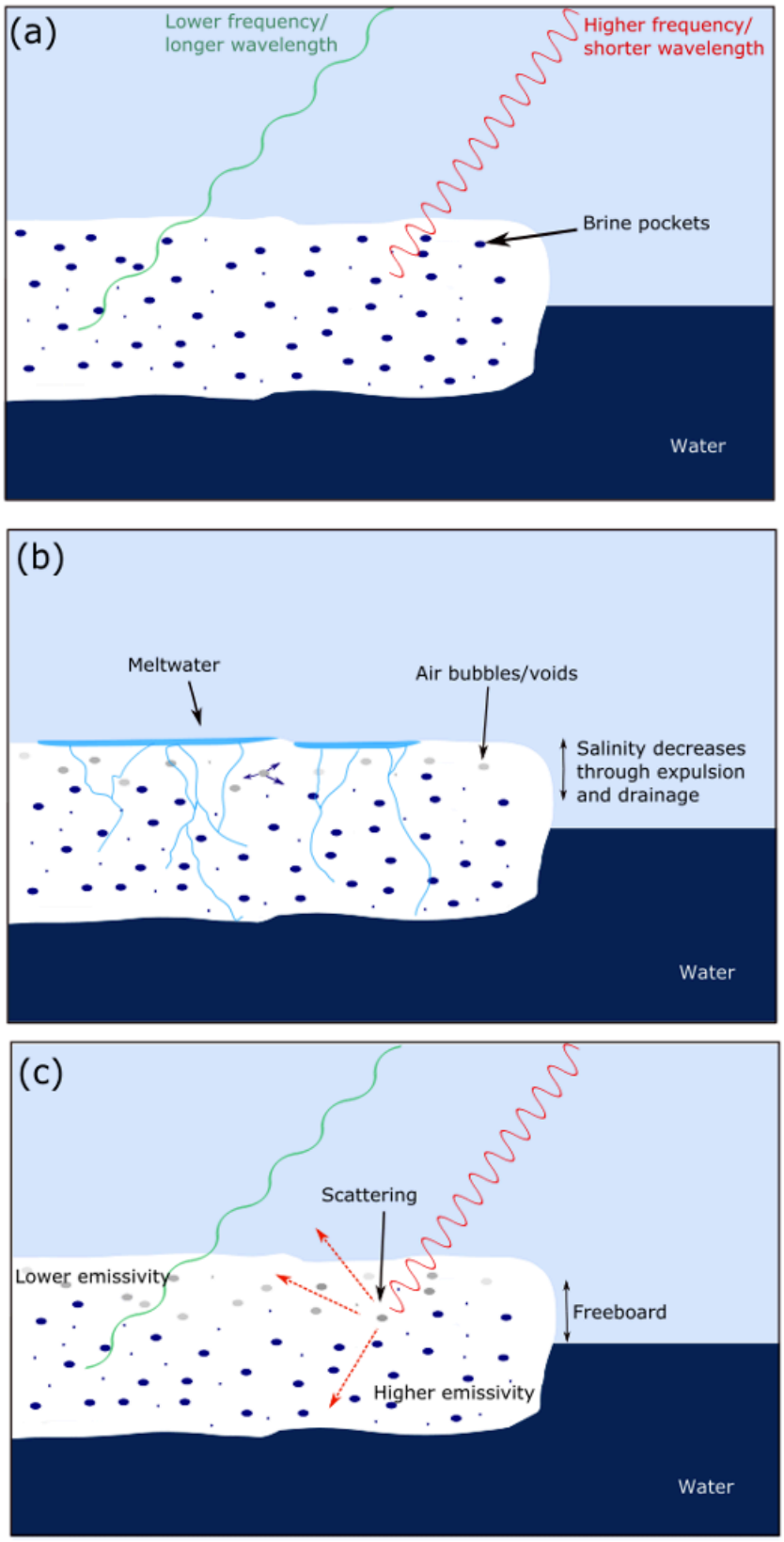


Figure 5.6.: A schematic diagram depicting the typical emissivity characteristics of first-year and multi-year sea-ice types in relation to their changing physical and chemical properties throughout the year: (a) first-year ice during the winter; (b) the increased presence of meltwater and the process of brine removal during the summer; (c) multi-year ice following the removal brine. See text for a full description of how these characteristics affect the emissivity of sea ice.

5.2.3. The Transformation of Radiation Data into Sea-Ice Parameters

The differing emissivity signatures of first-year ice, multi-year ice, and open water form the theoretical basis of algorithms used to transform radiation data into meaningful and quantifiable sea-ice parameters. Various research groups and institutions have developed different algorithms to facilitate this transformation; for example, Pedersen *et al*. (2017) list more than thirty different algorithms used to retrieve sea-ice concentration. Some of the more widely known sea-ice concentration algorithms include the NASA Team (Cavalieri *et al*., 1984), Bootstrap (Comiso, 1986), and Bristol (Smith, 1996).

The multitude of existing algorithms used in sea-ice research reflects differences in the methodologies adopted by different research groups and institutions – some of the main discrepancies and associated reasons are discussed in Sections 5.3 and 5.4 and throughout Chapter 7. While the algorithms differ in their approach, all essentially share a common assumption: the brightness temperature measured by the satellite sensor is predominantly comprised of a combination of microwave emissions from open water and first-year and multi-year sea-ice types (Meier and Stewart, 2019). Algorithms exploit the brightness temperatures observed at various microwave frequency channels and polarisations that tend to cluster around the three dominant signatures of open water and the two ice types. These brightness temperature clusters are used to establish 'tie-points', representing the typical brightness temperatures and sea-ice concentrations of the three surface types (Figure 5.7). For example, in calculations of sea-ice concentration, the tie-points of first-year ice and multi-year ice are assumed to represent sea-ice concentrations of 100%, and the tie-points of open water represent sea-ice concentrations of 0%. Most algorithms adopt these assumptions and use some form of algebraic equation to approximate intermediate sea-ice concentrations for all brightness temperature values that fall between these tie-point ranges (Section 5.3).

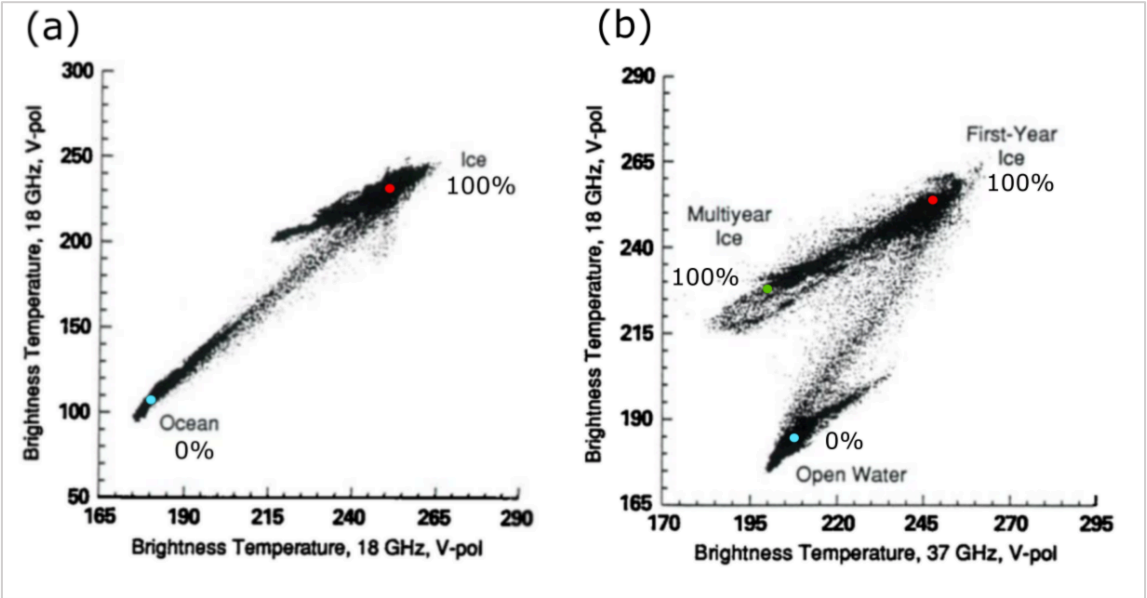


Figure 5.7.: Example brightness temperature scatterplots obtained by the DMSP SSM/I satellite-sensor over the Arctic Ocean on 11th March 1988. The plots illustrate the emissivity of sea ice and open water as a function of microwave polarisation and frequency: (a) brightness temperatures at 18 GHz vertical and horizontal polarisations; (b) brightness temperatures at 18 GHz and 37 GHz vertical polarisations. Example tie-points are illustrated by the coloured points: (a) ice (red) and open water (blue); (b) first-year ice (red), multi-year ice (green), and open water (blue). *Source: Eppler et al. (1992) - modified to include example tie-points and corresponding percentage sea-ice concentrations*. (Note there is an error in the original source of Figure 5.7a.: the y-axis should read "18 GHz, H-pol").

5.2.4. Uncertainties, Observational Constraints, and Unwanted Signals

Research into the changing spatial and temporal distribution of Arctic sea ice benefits significantly from the comprehensive and consistent coverage afforded by passive microwave satellite sensors. However, there are numerous drawbacks to this observation method that introduce uncertainties and ambiguities into sea-ice parameterisation. As acknowledged in the scientific literature, two of the main limitations – spatial resolution and atmospheric and oceanic influence – are described here. Section 5.3 details some of the steps taken to reduce their effects during the production of sea-ice data products.

A major source of uncertainty in the passive microwave satellite remote sensing of sea ice is the coarse spatial resolution. Spatial resolution refers to the level of surface detail retrieved during observation (Tedesco, 2015). For satellite observations, this is defined by the sensor's *footprint* (or *field of view*): the maximum area of the surface that the sensor can capture at any given moment. When passing over the Arctic Ocean, the brightness temperatures captured by the sensor are used to interpret the surface type within the sensor's footprint. The size of the footprint is inversely proportional to the microwave frequency and the diameter of the sensor antenna: the lower the frequency (and thus, lower energy) and smaller the sensor, the larger the footprint required (Pedersen *et al.*, 2017). Microwave energy is characteristically low, and the satellite sensors have

relatively small diameters ranging from 0.66-0.79 m (Appendix 2). As such, passive microwave sensors require large footprints to capture sufficient energy for surface characterisation (Meier and Markus, 2015). The required footprint size varies significantly depending on the sensor and channel frequency. As the table listed in Appendix 2 details, the spatial resolution of the sensors varies from approximately ~3150 km^2 at lower frequencies to ~224 km^2 at higher frequencies.[52] Generally, higher frequency channels are associated with considerably finer spatial resolutions. However, the brightness temperatures retrieved at these high-frequency channels are subject to greater atmospheric interference (see Figure 5.2), resulting in less accurate approximations of sea-ice parameters. As such, many data products do not use these higher channels in their calculations. As Section 5.3 will show, the choice and utilisation of different frequency channels in sea-ice observations involves navigating a delicate tension between accuracy and spatial resolution.

Due to their coarse spatial resolution, when a passive microwave sensor 'senses' the surface, it measures the integrated brightness temperatures over a large surface area (e.g., 1140 km^2 at 37.0 GHz). These integrated signals provide observations that generalise, simplify, and may obscure surface-level characteristics. Smaller-scale features of the Arctic Ocean, such as leads, polynyas, and localised variability – particularly towards the 'ice edge' – are lost in the integrated signal (Gloersen *et al*., 1999; Meier, 2005; Meier and Markus, 2015). Coastal boundaries are also difficult to locate accurately because the emissivity signatures of land, sea ice, and open water are blurred in the overall signal. The blurring of land and ocean boundaries is of particular concern because significant land areas can appear in the signal as *ice* and are included in calculations of sea-ice cover (Parkinson *et al*., 1987). This error is commonly referred to as 'land contamination' or 'land-to-ocean spillover'.

Similarly, although first-year and multi-year ice appear in the signal as the dominant surface types, the overall composition of Arctic sea ice is highly complex and heterogeneous. First-year and multi-year ice occur alongside various other sea-ice types representing differing sea-ice development stages, such as frazil ice, grease ice, nilas, pancake ice, and young ice (WMO, 2014; Figure 5.8). These ice types are typically younger, more ephemeral, and more disaggregated than first-year and multi-year ice; their compositions tend to be more variable in their water content, phase state, and salinity (Gloersen *et al*., 1999). These qualities give rise to brightness temperatures signatures that are generally less distinct and identifiable – particularly at coarser spatial resolutions. As such, their spatial distribution and extent cannot be approximated

[52] Newer instruments (e.g., AMSR-E and AMSR2) have smaller footprint sizes for the same frequency channels due to their larger antenna diameters (Appendix 2). As a result, they can resolve the surface to a greater level of detail (~ 5 – 25 km). However, these instruments have only operated since 2002 and therefore have limited use in long-term trend analysis.

unambiguously using passive microwave technologies. Nevertheless, these less dominant ice types contribute to the total amount of sea-ice cover in the Arctic. They, therefore, play a role in modulating energy exchanges between the ocean and the atmosphere and how much incoming solar radiation is reflected or absorbed by the Earth's surface. Thus, the inability to observe the spatial distribution and variability of these features using current passive microwave technologies inherently limits our understanding of global climate change.

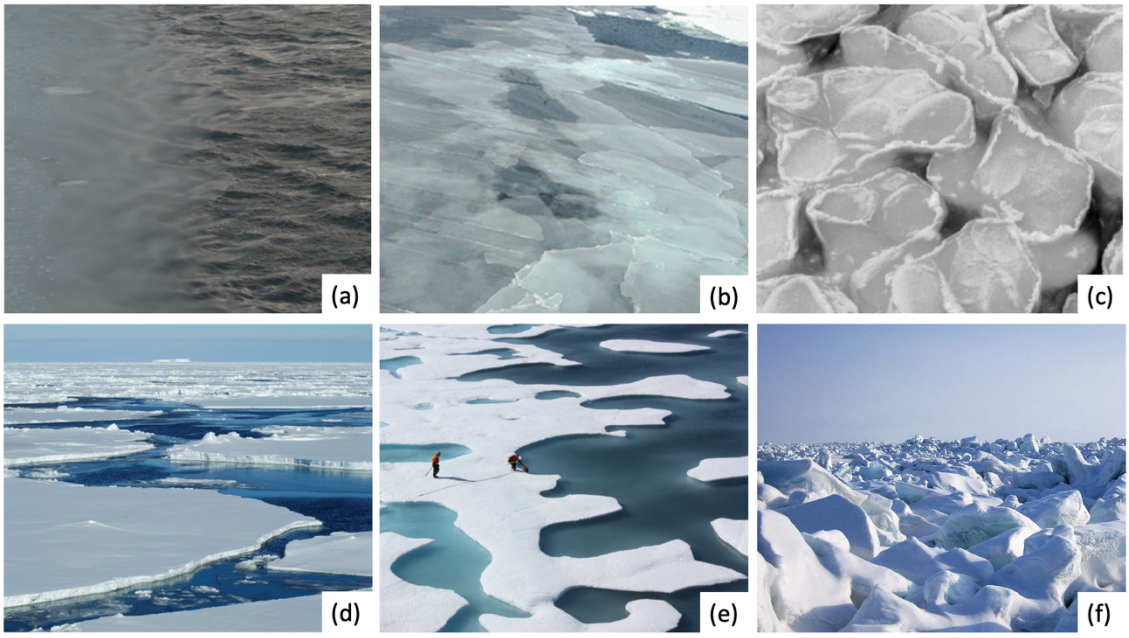


Figure 5.8.: Different development stages of sea ice: (a) grease ice, (b) nilas ice, (c) pancake ice, (d) pack ice, (e) meltwater ponds on the pack ice, and (f) hummocks. *Source:* (a), (c), (e), and (f) Wikicomms; (b) https://earthobservatory.nasa.gov/features/SeaIce; (d) https://www.britannica.com/science/pack-ice#/media/1/437835/146382.

The accuracy of sea-ice retrieval can be further hindered by the sensitivity of first-year and multi-year brightness temperature signatures to atmospheric and oceanic interference. As previously noted, the radiation signals at higher frequency channels are more sensitive to water vapour and oxygen. Various oceanic features, such as sea-surface roughness and sea-surface temperatures, can also complicate the signals and threaten the accuracy of the transformation process (Meier and Markus, 2015). These effects are most apparent towards the marginal sea-ice zones and in areas of low sea-ice concentration. Snow cover and meltwater on the surface can degrade the emissivity signature of the underlying ice, particularly during the summer months (Meier, 2005; Kern *et al.*, 2020). Collectively, these features represent unwanted signals that attenuate, falsify, contaminate, and replicate the brightness temperatures of Arctic sea ice, making it difficult to differentiate between ice types and accurately determine their spatial distribution. Steps can be taken to limit the effects of some of these uncertainties and ambiguities on approximations of sea-ice cover (Section 5.3); however, they cannot be removed completely.

5.3. Classifying Sea Ice: Constructing Sea-Ice Data Products

The general principles (and limitations) described in the previous section are common to the four sea-ice climate data products examined in this study: they represent the fundamental starting point for obtaining practical and quantifiable records of sea-ice cover parameters. The NSIDC SII, the OSI-450 SIC, the C3S SIE, and the C3S SITy data products are constructed according to established methodologies that govern how the initial passive microwave observations are selected, processed, and transformed into meaningful and ordered knowledge about Arctic sea ice. Although the specific methodologies differ, their construction follows a processing sequence that is broadly consistent across the products (Table 5.2). The processing sequence begins with the acquisition and manipulation of the raw brightness temperature data. This initial processing typically involves translating raw radiation measurements into calibrated, geolocated, and error-corrected brightness temperature datasets (e.g., Wentz, 1988, 2010). Following initial processing brightness temperatures are reprojected onto uniform daily averaged gridded fields, the resolution of which depends on the spatial resolution of the channel frequencies used. The next step involves transforming the processed and reprojected brightness temperatures into sea-ice parameters using algorithms that exploit the signatures of first-year ice, multi-year ice, and open water. At this point, additional procedures are implemented to remove or reduce atmospheric and oceanic influences and correct for false sea-ice signals. Lastly, the transformed data are used to produce final data values, statistical plots, and maps to calculate and analyse the spatial and temporal distribution of sea-ice parameters.

The conversion to gridded fields is a particularly crucial step in the parameterisation of sea ice properties and is integral to producing consistent data products for several reasons. Firstly, using a standard spatial grid allows for estimations of sea-ice parameters to be compared between different products that use different methodologies or data sources. This is an essential part of data product validation (e.g., Ivanova *et al.*, 2014; Section 5.4). Secondly, the various sensors used over the satellite record are technically inconsistent: they have different footprint sizes, temporal resolutions, visit times, and operating frequencies (Appendix 2). These differences can significantly impact observed brightness temperatures, and thus, sea-ice parameter retrieval (e.g., Comiso *et al.*, 1999).[53] Mapping the data onto a common grid represents one of the many techniques used to reduce the influence of inconsistencies in sensor characteristics (NSIDC-GSFC, 2020). Lastly, as the following sections illustrate, the procedures and definitions used to calculate parameters of sea-ice cover and map their temporal and

[53] The effects of sensor differences on sea-ice concentration retrieval were also analysed in this PhD research as part of the intercomparison study carried out during participant observation at MET Norway. See Appendix 8.

spatial distribution are fundamentally dependent on the use of gridded fields with consistent grid-cell areas.

The following sections describe how the general principles and processing sequence are adopted, modified, and extended to construct the NSIDC SII, the OSI-450 SIC, the C3S SIE, and the C3S SITy data products. Each product is addressed in turn, detailing the general features and purpose, data processing methods, intended functions and applications, and the institutions and networks involved in its production.

Table 5.2.: The general processing sequence common to the four sea-ice data products. Note that the exact order of these stages is not wholly consistent across the products. For example, in producing the MET Norway products, the reprojection to uniform grids occurs after the brightness temperatures are transformed into sea-ice parameters (Section 5.3.2.4 and 5.3.3.5).

***Stage 1:** Acquisition*	Acquisition of raw brightness temperature measurements using passive microwave satellite remote sensors.
***Stage 2:** Initial processing*	Initial processing, calibration, geolocation, and error correction of raw brightness temperature data.
***Stage 3:** Conversion, reprojection, and averaging*	Corrected brightness temperature data are converted to consistent satellite swath formats and reprojected to uniform daily average gridded fields.
***Stage 4:** Transformation*	The processed and reprojected brightness temperature data are transformed into sea-ice parameters.
***Stage 5:** Additional processing and final formatting*	Production and formatting of data values, statistical plots, and visual imagery for calculate and analyse the spatial and temporal distribution of sea-ice parameters.

5.3.1. NSIDC SII

5.3.1.1. Overview

Developed in 1999 and first published by the NSIDC in 2002, the NSIDC SII is the most established of the four products in operation. The product was initially developed in cooperation with NOAA's National Geophysical Data Center and financially supported by NOAA's National Environmental Satellite, Data, and Information Service. The product was developed as a means for graphically representing satellite-derived observations of sea-ice concentration, extent, and area in response to the growing demands for measurements of key parameters of sea-ice cover during the 1990s (Section 4.5). Specifically, it was envisioned that the NSIDC SII would provide easy-to-use information on the spatial and temporal variability of these parameters, using input sea-ice concentration data derived from other pre-existing datasets. In this sense, the NSIDC SII was not intended to be a data product in its own right; rather, it was designed as a

website that would "repackage" and communicate the observations of other datasets in a way that is accessible and understandable to a wide variety of audiences (Fetterer and Knowles, 2004). However, to achieve a consistent time series drawn from multiple data sources, it was necessary to include additional processing steps. As a result, the NSIDC SII became an official sea-ice data product in 2008, with its independent documentation and processing methodology (Windnagel, 2008).

Today, the NSIDC SII is a consistent and up-to-date source of daily and monthly sea-ice concentration, extent, and area data, dating from November 1978 to the present. The product's stated purpose is to provide "a quick look at Arctic- and Antarctic-wide changes in sea ice" (NSIDC Sea Ice Index, n.d.), with the main application being long-term analysis of trends in sea-ice cover. According to the user guide, scientific researchers and the "scientifically inclined general public" represent the intended users (Windnagel, 2021: 52). The product includes data values and visual images of daily and monthly sea-ice concentration, extent, and area: maps depict average daily and monthly spatial distributions and monthly anomalies and trends in concentration and extent; statistical graphs show long-term trends in sea-ice extent; text files store daily and monthly extent and area values in numerical format (Figure 5.9). These outputs are published and archived on the NSIDC SII website and updated daily, usually with a delay of one day.[54] The data values and visual images are presented in an interactive format: users can 'freely' view, animate, compare, and download the data via a simple interface and file transfer protocol.[55] The website also includes documentation that outlines the input data sources, processing chains, uncertainties, and guidance for using the product. In addition to the NSIDC SII website, the product outputs are regularly posted and referenced on the NSIDC Arctic Sea Ice News and Analysis (ASINA) website.[56] This is a separate site established in 2006 by the NSIDC Science Communications team in response to the increasing media attention directed towards the NSIDC's alarming research outputs (Windnagel, 2021). ASINA's website includes detailed interpretations of the NSIDC SII observations and other NSIDC data products.

[54] NSIDC SII website: https://nsidc.org/data/seaice_index
[55] The use of inverted commas is to indicate that while the product may be freely available to the user, there are substantial financial costs involved in its production (e.g., the cost of the construction, launch, and maintenance of satellites and sensors; the cost of developing ground networks to receive and distribute satellite data; the cost of research grants to cover the work of scientists; the cost of processing software).
[56] ASINA website: https://nsidc.org/arcticseaicenews/

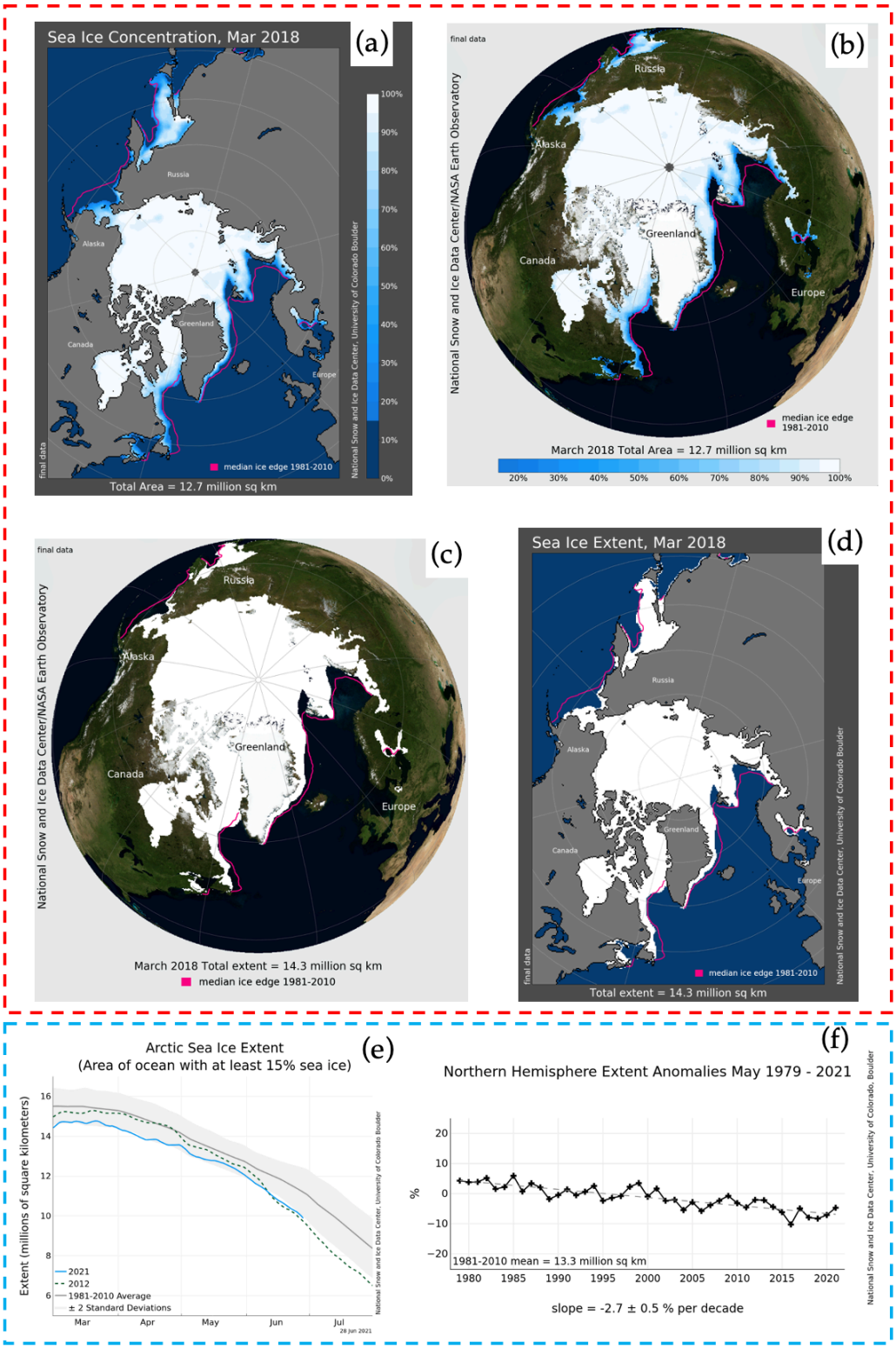


Figure 5.9.: NSIDC SII example outputs. The images enclosed within the red-dashed line show monthly data for March 2018. The two images along the top show sea-ice concentration data displayed in (a) map and (b) GeoTiff ('Blue Marble') formats; the bottom two images show sea-ice extent in (c) GeoTiff ('Blue Marble') and (d) map formats. The data plots enclosed within the blue-dashed line show sea-ice extent data: (e) provides a snapshot of extent changes for the most recent four months, against the climatological average (1981-2010) and the record annual sea-ice minimum (2012); (f) shows monthly extent anomalies plotted as a percentage difference of a particular month and the mean for that month based on the climatological dataset (1981-2010). *Source:* Compiled from Fetterer *et al.* (2017).

5.3.1.2. Data Sources, Contributors, and Processing Sequence

The NSIDC SII is developed using sea-ice concentration datasets derived from passive microwave brightness temperature observations obtained by the SMMR, SSM/I, and SSMIS sensors (Appendix 2). The sea-ice concentration data is not processed as part of the NSIDC SII but exists in separate datasets used for other additional applications.

The NSIDC SII is divided into two subsets of sea-ice data: *near-real-time* and *final*. The *near-real-time* subset includes the most recent available sea-ice concentration data, created using the *Near-Real-Time DMSP SSMIS Daily Polar Gridded Sea Ice Concentrations* (NRTSI) dataset (Maslanik and Stroeve, 1999). The *final* subset includes all sea-ice concentration data from the beginning of the SMMR record to approximately six to eighteen months before the present, created using the *Sea Ice Concentrations from Nimbus-7 SMMR and DMSP SSM/I-SSMIS Passive Microwave Data* dataset (GSFC SIC) (Cavalieri *et al*., 1996). The product is divided into these two subsets because the final GSFC SIC includes additional quality control measures to improve the accuracy of sea-ice concentration retrieval. However, this additional processing results in a latency period of approximately one year; therefore, the NRTSI is an interim dataset developed at the NSIDC to "fill the gap" before the final GSFC SIC becomes available (Windnagel, 2021: 2). The production of the NRTSI dataset seeks to replicate the GSFC SIC processing as close as possible. For this reason, this thesis only considers the processes specific to the final GSFC SIC subset of the NSIDC SII.

The GSFC SIC's production and processing and its subsequent input into the NSIDC SII, builds upon a long-term collaboration between the NSIDC and NASA's Goddard Space Flight Center (GSFC). Headquartered in Greenbelt, Maryland, the GSFC represents a major space research laboratory developed by NASA in 1959 to support the agency's scientific and technological operations. Given the dominant role that NASA played in initiating and facilitating the use of satellites in sea-ice research (see Section 4.5.1), the GSFC has been significantly involved in developing the methodologies of passive microwave sea-ice retrieval since its inception. Since 1983, the NSIDC has represented the primary institute for archiving and managing passive microwave sea-ice data, and several prominent NSIDC scientists have worked with researchers at the GSFC to develop the techniques of data processing and reporting. These collaborative links are indicated throughout the supporting documentation (Appendix 3).

Over the full-time series, the division of data responsibilities in relation to the general processing sequence (Table 5.2) varies between the NSIDC and the GSFC and includes additional support from elsewhere. This division is illustrated in Figure 5.10 and described below. For the SMMR data (October 1978 to August 1987), the GSFC is responsible for the entire process of sea-ice concentration retrieval, from the initial processing, error-correction, and reprojection of the raw brightness temperatures

through to their transformation into sea-ice concentration data (Gloersen *et al*., 1992). Following the transition from NASA's Nimbus-7 satellite to Department of Defense DMSP satellites (August 1987 onwards), the sea-ice concentration data processing responsibilities have become less exclusive to the GSFC. The initial processing of the raw brightness temperatures is carried out by Remote Sensing Systems (RSS), a private research company based in Santa Rosa, California. Founded in 1974, RSS describes itself as a "world leader in processing and analyzing microwave data collected by satellite microwave sensors" (RSS, n.d.). Full details of RSS's processing and calibration steps can be found in Wentz (1988, 2010). For this study's purposes, the key point is that the initial processing converts the raw radiation data into *homogenised* and *consistent* long-term records of brightness temperature data. RSS distributes the processed brightness temperature data to the NSIDC (among many other research institutes for use in ocean-climate analysis), where it is subsequently converted into consistent swath formats and reprojected onto Polar Stereographic spatial grids of daily average brightness temperature values (Meier *et al*., 2019). The grid cell resolution is 12.5 x 12.5 km for the higher frequencies (85.5 and 91.7 GHz) and 25 x 25 km for all other frequencies. The GSFC remains responsible for transforming the brightness temperatures into sea-ice concentration data, which becomes the main input data source of the NSIDC SII (NSIDC-GSFC, 2020).

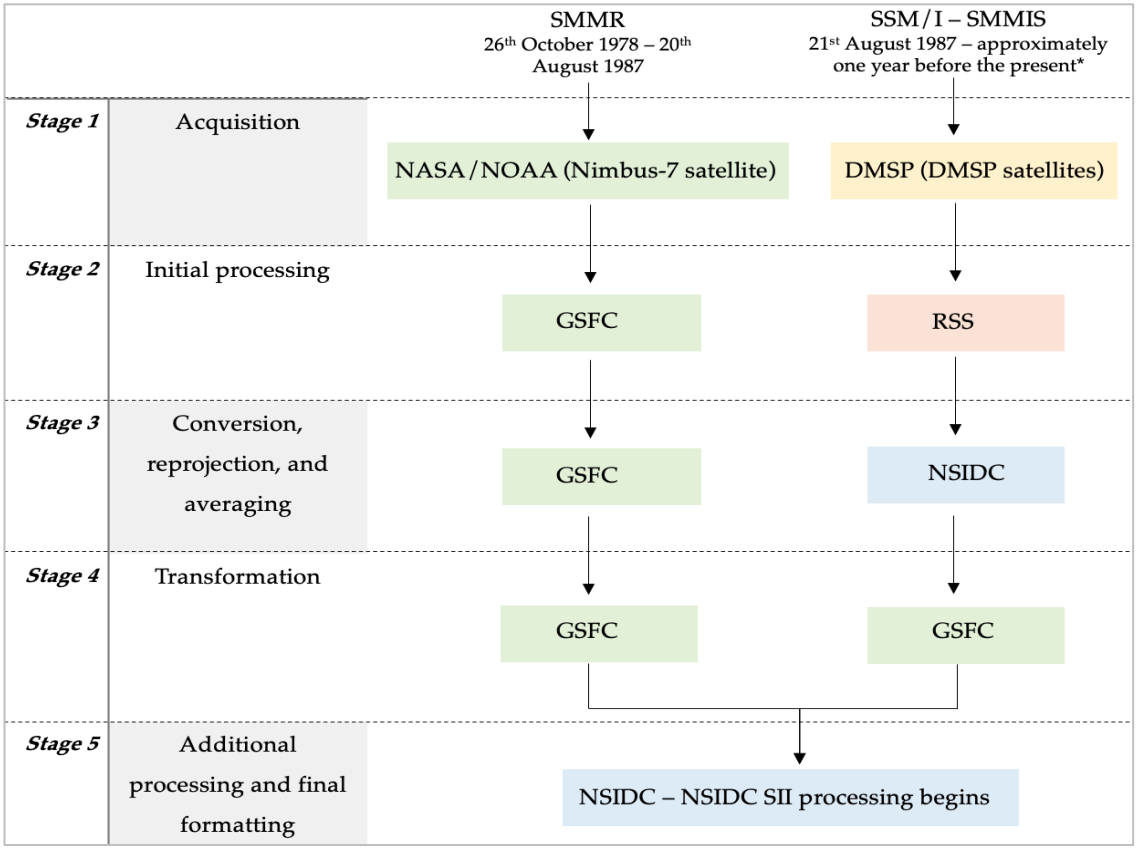


Figure 5.10.: GSFC dataset processing sequence and main contributors (Table 5.2). *This is applicable for the GSFC subset only; the NRTSI subset is produced solely by researchers at the NSIDC.

5.3.1.3. Sea-Ice Retrieval Algorithm

The GSFC SIC used in the construction of the NSIDC SII is derived using the NASA Team algorithm (Cavalieri *et al*., 1984). This algorithm was first developed during the 1980s by researchers in the Oceans and Ice Branch of the Laboratory for Hydrospheric Processes at the GSFC. A summary of the algorithm is described below. For complete explanations, see Cavalieri *et al*. (1984, 1999).

The NASA Team algorithm begins with the fundamental assumption that the observed brightness temperature can be expressed as the sum of the contributions of first-year ice, multi-year ice, and open water:

$$T_B = T_{BW}C_W + T_{BIF}C_{IF} + T_{BIM}C_{IM}$$

Equation 2

where T_{BW}, T_{BIF}, and T_{BIM} are brightness temperatures for open water, first-year ice, and multi-year ice, respectively, and C_W, C_{IF}, and C_{IM} are the corresponding sea-ice concentrations.

The observed differences in the polarisation and gradient ratios of first-year ice, multi-year ice, and open water brightness temperatures constitute the theoretical basis of retrieving sea-ice concentrations using the NASA Team algorithm (Section 5.2.2). The algorithm uses the two brightness temperature ratios between three horizontally (h) and vertically (v) polarised frequency channels: 19v, 19h, and 37v GHz. The brightness temperature ratios between these channels are expressed as follows:

$$PR(19) = [T_B(19v) - T_B(19h)] / [T_B(19v) + T_B(19h)]$$

Equation 3

$$GR(37v/19v) = [T_B(37v) - T_B(19v)] / [T_B(37v) + T_B(19v)]$$

Equation 4

where PR is polarisation ratio, GR is spectral gradient ratio, h is horizontal polarisation, v is vertical polarisation, and T_B is brightness temperature. Note that for the SMMR period, the algorithm uses 18 GHz (vertical and horizontal) instead of 19 GHz. Table 5.3 lists the specific satellites, sensors, frequency channels, and corresponding sampling grid cell resolution used by the NASA Team algorithm.

Table 5.3.: The frequency channels and corresponding sampling grid cell resolution used by the NASA Team algorithm.

Satellite - Sensor	Operating Period	Operating Frequencies Used by NASA Team Algorithm (GHz)	Sampling Grid Cell Resolution
NIMBUS-7 – SMMR	26th October 1978 – 20th August 1987	18.0 (v, h)	25 x 25 km
		37.0 (v)	25 x 25 km
DMSP-F08 – SSM/I	21st August 1987 – 18th December 1991	19.0 (v, h)	25 x 25 km
		37.0 (v)	25 x 25 km
DMSP-F11 – SSM/I	19th December 1991 – 29th September 1995	19.0 (v, h)	25 x 25 km
		37.0 (v)	25 x 25 km
DMSP-F13 – SSM/I	30th September 1995 – 31st December 2007	19.0 (v, h)	25 x 25 km
		37.0 (v)	25 x 25 km
DMSP-F17 – SSMIS	1st January 2008 – 31st December 2017	19.0 (v, h)	25 x 25 km
		37.0 (v)	25 x 25 km
DMSP-F18 – SSMIS	1st January 2018 – present	19.0 (v, h)	25 x 25 km
		37.0 (v)	25 x 25 km

Like the brightness temperature clusters seen in Figure 5.7, scatterplots of the polarisation and gradient ratios for the 19 (or 18) and 37 GHz channels tend to cluster around three values, representing the typical radiation properties of first-year ice, multi-year ice, and open water (Figure 5.11). In Figure 5.11, the line connecting first-year ice (FYI) and multi-year ice (MYI) clusters represents 100% sea-ice concentration, and the open water point represents 0% sea-ice concentration. The distance between the open water point and the FYI-MYI line is a linear measure of sea-ice concentration (NSIDC, 2021b). The PR-GR distributions are used to establish a unique set of nine *fixed* brightness temperature tie-points representing average sea-ice concentrations for the three surface types measured using the three different channels. By combining these tie-points with Equations 2-4, sea-ice concentrations can be calculated for all brightness temperature observations.

The algorithm also uses gradient ratios at 19, 22, and 37 GHz vertically polarised channels to derive a *weather filter* (Figure 5.11). This weather filter is used to remove all measurements assumed to be weather-related *spurious* sea-ice concentrations in areas of open water or low ice concentrations (Cavalieri *et al*., 1999). As noted in Section 5.2.1,

atmospheric and oceanic features such as water vapour and sea-surface roughness can mimic the brightness temperatures of sea ice and significantly increase the extent of sea-ice cover. The 22 GHz channel is used because it sits further up the water vapour line (Figure 5.2) and is thus better suited for detecting the influence of water vapour than the 19 and 37 GHz channels. All measurements that meet the criteria set in Table 5.4 are set to 0% sea-ice concentration to reduce these effects. In practice, this tends to remove all areas covered in sea ice of less than 15% concentration (NSIDC, 2021b).

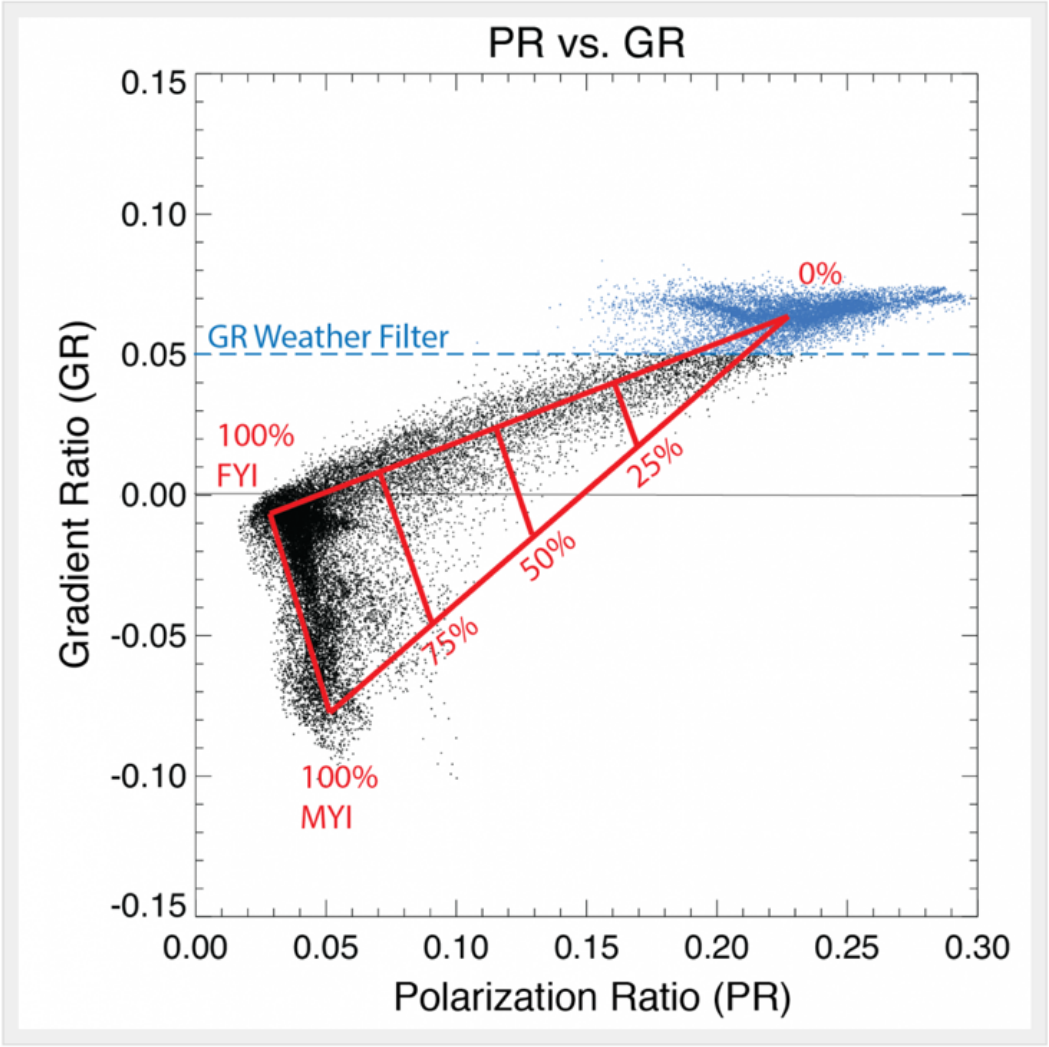


Figure 5.11.: Example polarisation and gradient ratios for brightness temperatures obtained from 28th February 2018 using the DMSP-F18 SSMIS satellite-sensor. The red triangle identifies and connects the brightness temperature clusters for first-year ice, multi-year ice, and open water. Using these clusters, intermediate sea-ice concentrations can be derived, as shown by the lines for 75%, 50%, and 25%. The blue areas represent an applied weather filter used to remove spurious ice in areas of open water and the marginal sea-ice zone. *Source:* NSIDC (2021b).

Table 5.4.: Gradient ratios used in the application of a weather filter. *Source:* NSIDC (2021b).

Sensor	Weather Filter Criteria
SMMR	GR(37/19) > 0.07
SSM/I	GR(37/19) > 0.05 and/or GR(22/19) > 0.045
SSMIS	GR(37/19) > 0.053

Notably, the brightness temperature tie-points used by the NASA Team algorithm are not consistent across the different satellite-sensor periods. As described in Cavalieri *et al*. (1997), the main reason for this inconsistency is the changing characteristics of the sensors and their host satellites. With each successive mission, the differences in the frequency channels, visit times, and orbiting altitudes (Appendix 2), bias the radiation signals measured by the sensors. This, in turn, gives rise to different clusters and average brightness temperature values. As Figure 5.12 shows, a significant jump in brightness temperatures occurs following the transition from the Nimbus-7 SMMR sensor to the DMSP-F8 SSM/I sensor and the corresponding shift from the 18 to 19 GHz frequency channel.[57] This is primarily because the 19 GHz channel is more affected by atmospheric water vapour than the 18 GHz channel (Cavalieri *et al.*, 1999; Section 5.2.1). Additionally, there are minor differences between the brightness temperatures measured by later satellite-sensors due to differences in the orbital characteristics of the successive DMSP satellites.

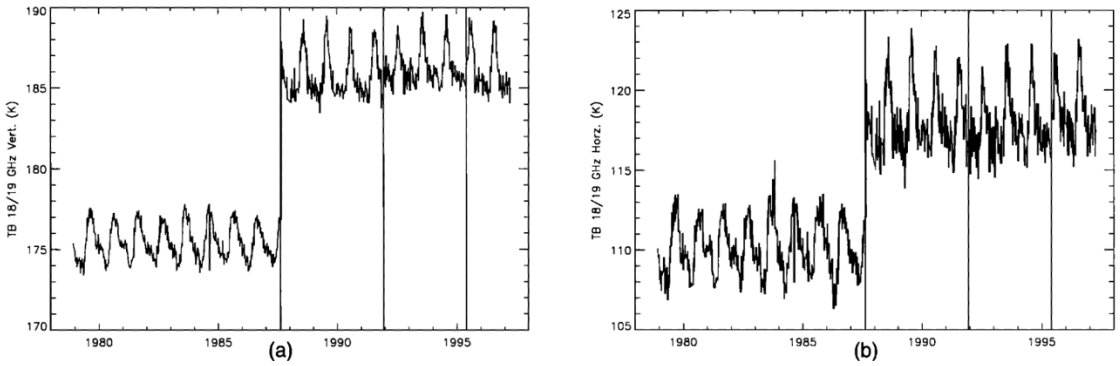


Figure 5.12.: Time series showing the jump in brightness temperatures obtained at 18/19 GHz vertically (a) and horizontally (b) polarised channels following the switch from the SMMR to SSM/IS sensor in 1987. *Source:* Cavalieri et al. (1999).

The difference in the brightness temperatures measured by each satellite-sensor is problematic because it results in marked changes in sea-ice concentration estimates (Cavalieri *et al.*, 1999). Thus, as detailed in Cavalieri *et al.* (1999), to reduce these effects on sea-ice concentration retrieval, each satellite-sensor has a unique set of fixed tie-points

[57] Similar examples can also be seen in the intercomparison project carried out during fieldwork, Appendix 8.

derived and adjusted using linear regression relationships between the brightness temperatures observed during periods when the satellite-sensor periods overlap. Additionally, the open water tie-points are "subjectively fine-tuned" to further reduce the inconsistencies (Cavalieri *et al.*, 1999: 15,810). This fine-tuning process involves manually changing the tie-point values to meet the desired temporal consistency between satellite-sensors. Full details of the adjustment processes and lists of the tie-points are provided in Cavalieri *et al.* (1997, 1999, 2011). The crucial point to note is that in the adjustment of tie-points, the desire for temporal consistency outweighs the importance attached to accurate retrieval. The following statement reflects this: "we obtain a self-consistent time series, not necessarily one that has the highest absolute accuracy in terms of ice concentration" (Cavalieri et al. 1999: 15,810).

The NASA Team algorithm represents one of the longest-used techniques of passive microwave sea-ice concentration retrieval. However, as various studies and validation exercises have highlighted, several notable uncertainties and limitations are associated with this algorithm (e.g., Steffen and Schweiger, 1991; Cavalieri *et al*., 1992; Partington *et al.*, 2003; Meier, 2005). Firstly, the use of *fixed* tie-points for each satellite-sensor period neglects the temporal and spatial variation in surface-type brightness temperatures (Steffen and Schweiger, 1991). Atmospheric and oceanic factors, physical temperature, meltwater, sporadic and ephemeral ice types, and surface-level composition changes can affect the brightness temperatures at varying degrees throughout the year (Steffen and Maslanik, 1988; Steffen and Schweiger, 1991; Anderson *et al*., 2007). Moreover, these features have significant spatial variability. As such, the representativeness of using fixed tie-points for determining actual surface-level conditions is variable through space and time. Secondly, the overlapping periods between satellite-sensors is short: typically, less than one month, when the desired period is approximately one year (Cavalieri et al. 1999). The limited observational data for determining the sensitivity of brightness temperatures to changes in satellite-sensor characteristics means that the linear relationships used in tie-point adjustments are based on greater assumptions and are less able to account for spatial and seasonal variability (Cavalieri *et al*., 1997, 1999). Lastly, the frequency channels used by the algorithm (18/19 and 37 GHz) have relatively poor spatial resolutions (see Section 5.2.4). As such, the surface-level features cannot be resolved finer than ~30 km.

The main consequence of these limitations is that the NASA Team algorithm performs poorly where ephemeral ice types are dominant, the ice concentration is low, and meltwater is more prevalent, particularly during the summer months. Generally, the accuracy of the total sea-ice concentration derived using the NASA Team algorithm is cited as being within +/- 5% during the winter and +/- 15% during the summer (NSIDC-GSFC, 2020). However, these uncertainty values are not indicative of the Arctic as a whole; the actual uncertainty varies significantly spatially and temporally due to

atmospheric and oceanic contamination and technical sources of error (e.g., sensor drift). For example, as Fetterer (2002) reviews, comparisons of passive microwave sea-ice concentrations against manual sea-ice charts produced by the U.S. National Ice Centre and the Canadian Ice Services can yield regional differences in sea-ice area by up to 30 to 40 percent during the melt season. These differences generally reduce significantly during the winter as the sea ice becomes drier and more compact.

5.3.1.4. Additional Sea-Ice Concentration Processing

Before the GSFC SIC can be inputted into the NSIDC SII, several additional processing steps occur. These include filling in missing data gaps and correcting for land-to-ocean spillover and residual weather-related effects.

Over the forty-year time series, data gaps are common (see Cavalieri *et al.*, 1999). They can occur on a small scale, whereby individual pixels scattered across the grid are missing data, primarily due to aggregation errors that arise during the reprojection to spatial grids. They can also occur over much larger areas due to gaps between the orbital swaths or poor scans. These larger spatial gaps tend to occur on daily timescales and are more prevalent with increasing distance from the pole. Data gaps such as these are filled using spatial and temporal linear interpolation schemes: the sea-ice concentration of a missing grid cell is estimated using the values of the surrounding grid cells. In other words, this procedure constructs missing data using the assumption that the variability of surface characteristics is minimal between adjacent grid cells.

Occasionally, data gaps can be more significant, affecting large areas over weeks to months. For example, between 3rd December 1987 and 12th January 1988, the time series is punctuated by a continuous data gap across the Arctic Ocean due to satellite glitches (Windnagel, 2021).[58] This data gap is too significant for interpolation techniques to be applied and, as such, it remains in the record as missing data. Similarly, the near-polar orbit of the satellites results in a circular sector of missing data centred over the North Pole. The size of this data gap (referred to as the 'Arctic Pole Hole') varies between sensors with areas ranging from 0.029 - 1.19 million km^2 (Appendix 2).

Due to the coarse spatial resolution of the frequency channels used by the algorithm, the accuracy of the GSFC SIC suffers from land-to-ocean spillover (Section 5.2.4). This effect is more apparent during the summer months when the sea ice retreats from the coastline and the emissivity signatures become less distinct. As detailed in the GSFC SIC User Guide (NSIDC-GSFC, 2020), two combined and automated correction methods are used to reduce this land-to-ocean spillover. Firstly, a land mask is used to classify terrestrial areas and filter out any false signatures inland. Secondly, a matrix is applied to the dataset to classify each grid cell into five classes: land, shore, nearshore, offshore, and

[58] This data gap is apparent for all observations from the SSM/I sensor during this period.

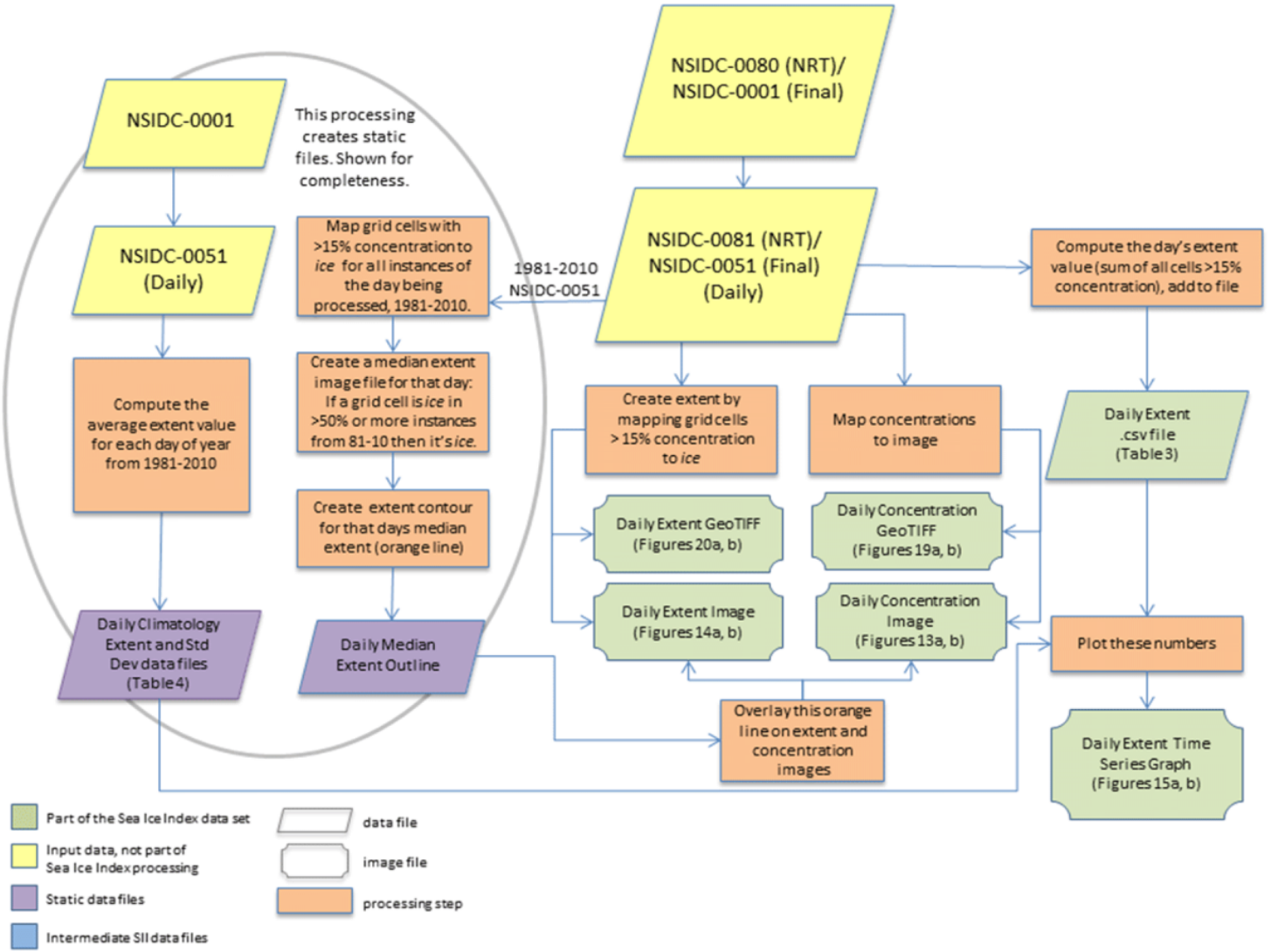
non-coastal ocean. The correction method assumes that, during the summer, most coastlines are free of sea ice. Therefore, using the classifications matrix and an additional matrix of minimum monthly sea-ice concentrations, sea ice identified in grid cells within the close vicinity of a coastline is presumed to be false sea-ice signals and set to 0% sea-ice concentration. The correction method is considered a "rough approximation" of false sea-ice signals along the coastlines, and it substantially reduces spurious ice concentrations on a large scale (Cavalieri *et al*., 1997: 8).

The weather filter applied by the NASA Team algorithm removes much of the influence of weather-related features in the marginal sea-ice zone and open water areas. However, some residual weather effects may remain, causing the brightness temperatures of open water to appear like sea ice. To correct this, 'valid ice masks' are applied to the dataset (NSIDC-GSFC, 2020). These masks are based on monthly climatological sea surface temperature (SST) measurements obtained from the NOAA Ocean Atlas (Levitus and Boyer, 1994). The correction uses a cut-off brightness temperature value to identify grid cells containing 'invalid ice': for the northern hemisphere, grid cells, where the monthly SST brightness temperatures exceed 278 K, are set to 0% sea-ice concentration for that month.

The final processing step involves manually correcting the dataset for grid cells that contain "clearly erroneous sea ice concentration values" that have not been removed through the previous correction methods (NSIDC-GSFC, 2020: 17). These grid cells are identified by visual inspection and tend to be situated in regions or latitudes where sea-ice cover is not plausible. This process is subjective; as such, exact replications of the same dataset may not be achievable.

5.3.1.5. NSIDC SII Processing

Once the above processing steps have been carried out, the GSFC SIC is distributed to the NSIDC for input into the NSIDC SII. Daily and monthly average data are provided on Polar Stereographic projected grids, with a grid cell resolution of 25 km. It is important to note that the grid cell resolution used is *nominally* 25 km (625 km^2). The actual size of each grid cell varies slightly due to the curvature of the Earth and the characteristics of the Polar Stereographic projection: across the whole grid domain, the grid cell areas range from 382 km^2 to 664 km^2 (Windnagel, 2021). This variation must be accounted for during the calculation of sea-ice parameter values. The NSIDC uses the sea-ice concentration data to produce data values and visual images of sea-ice concentration, extent, and area according to the processing chains shown in Figure 5.13. In an effort to streamline the production of the NSIDC SII, all processing has been carried out automatically using Python since January 2017.



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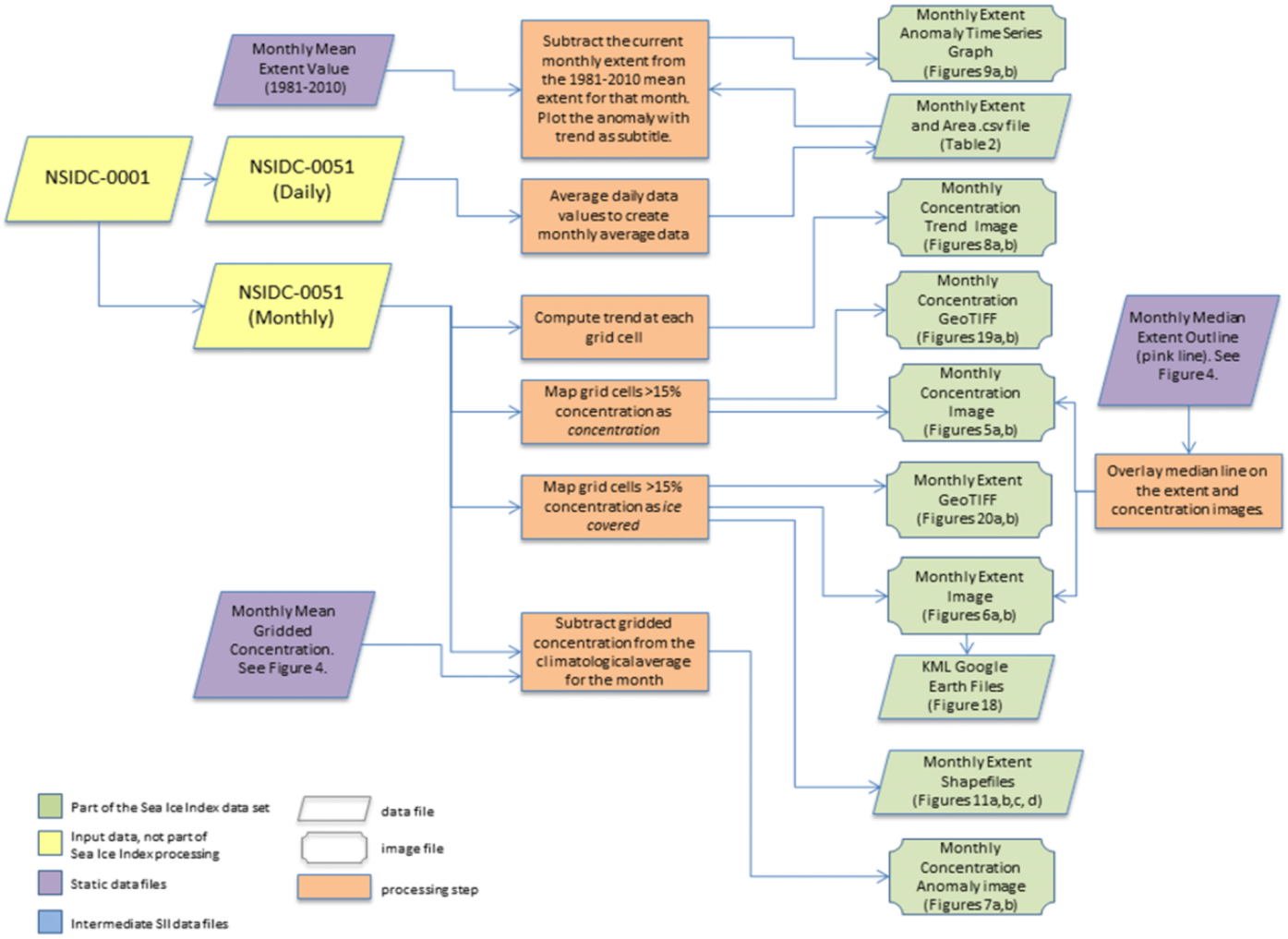


Figure 5.13.: NSIDC SII processing chains for the final GSFC subset of the product. Daily processing chain (previous page) and monthly processing chain (above). Monthly data is calculated by averaging the daily values for a given month. *Source:* Windnagel (2008).

The NSIDC SII produces gridded sea-ice concentration maps using the GSFC daily and monthly sea-ice concentrations for each day and month of the year. In these maps, each 625 km^2 grid cell across the Arctic Ocean is colour-coded in graded shades from dark blue to white, representing the transitioning sea-ice concentrations from open water (<15%) to closed pack ice (100%). Partly due to the reasons already described (e.g., weather-related effects in the marginal sea-ice zone), the NSIDC considers grid cells with sea-ice concentrations below 15% to be too uncertain to include in the data product (Windnagel, 2021). Therefore, a sea-ice concentration threshold of 15% is used, whereby all grid cells with values less than 15% are re-classified as open water. This definition is also used to mark the 'ice edge' and provides a distinct and immediate transition from ice to open water. Chapter 6 discusses the origins of this threshold and critically explores some of the implications of its use.

The gridded sea-ice concentrations are used to calculate sea-ice extent and area values and produce maps of sea-ice extent. Calculations of sea-ice area are relatively straightforward: the sea-ice concentration of each grid cell that meets the 15% threshold is multiplied by the grid-cell area. These values are summed together to get total sea-ice area values for the Arctic Ocean. Notably, the Arctic Pole Hole is not included in area calculations because the sensors cannot capture observations of this area. Calculations of sea-ice extent are similar to sea-ice area, except the sea-ice concentration values in each grid cell are not used beyond the application of the 15% threshold. As noted previously in Section 1.2, sea-ice extent is a binary measure of sea-ice conditions that orders grid cells into two categories: *ice-covered* or *ice-free*. For the NSIDC SII, a grid cell is considered ice-covered if the sea-ice concentration meets the required 15% threshold and ice-free if it falls below it. Maps of sea-ice extent illustrate the spatial distribution of ice-covered and ice-free areas by colouring all ice-covered grids white and all ice-free areas dark blue. Hemispheric-wide sea-ice extent values are calculated by summing the *total* area of all grid cells with sea-ice concentrations of 15% and above. The Arctic Pole Hole area is assumed to be covered in sea-ice concentrations of 15% and above and is therefore included in sea-ice extent estimates. However, as Chapter 6 will explore, the accuracy of this assumption is disputable.

The NSIDC SII User Guide calls for users to be vigilant around using several product outputs (Windnagel, 2021). Firstly, it urges caution about the representativeness of the monthly sea-ice concentration images and their associated trends. To calculate the monthly sea-ice concentration values, daily sea-ice concentrations for each grid cell are averaged, and the spatial and temporal variability is conflated. This means that the day-to-day variability, particularly in the marginal sea-ice zone, could be much more significant than the monthly averages allude to. Secondly, it stresses that all outputs – especially sea-ice extent values and daily measurements – are intended to be viewed in the context of the full-time series and less as individual images or values. In other words,

greater importance is attached to the *trends* than the absolute values or individual images. This is primarily due to the uncertainties and limitations of passive microwave sea-ice concentration retrieval and the "somewhat arbitrary" nature of using a 15% threshold to define the 'ice edge' (Windnagel, 2021: 17). Lastly, the NSIDC are less inclined to report sea-ice area as a quantitative measure of long-term Arctic sea-ice cover. The main reasons for this are twofold. Firstly, the varying area of the Arctic Pole Hole with each sensor creates a discontinuity in the dataset, reducing the (highly valued) temporal consistency. Secondly, the reduced accuracy of the NASA Team algorithm in the presence of meltwater or lower sea-ice concentrations introduces significant uncertainties in calculating sea-ice area, particularly during the summer. While they state that sea-ice area can be a useful measure of sea-ice cover, it requires greater background knowledge and additional information on the real-time conditions at the surface. This suggests that sea-ice area is not befitting the NSIDC SII's primary purpose of providing "a quick look" at Arctic sea-ice conditions.

5.3.2. OSI-450 SIC v2.0

5.3.2.1. Overview

The OSI-450 SIC data product is a long-term record of daily sea-ice concentration data, deriving estimates from brightness temperatures obtained using the SMMR, SSM/I, and SSMIS passive microwave sensors. The product was first released by OSI SAF in early 2017 and covers the period from January 1979 to December 2015. Known formally as the 'OSI SAF Global Sea Ice Concentration Climate Data Record, Version 2', the OSI-450 SIC is a fully reprocessed version of an earlier OSI SAF sea-ice concentration data product: OSI-409. The original version was first developed in 2006 through collaborative research carried out between OSI SAF, the UK Met Office, and the NSIDC, for the primary purpose of providing continuous observations of sea-ice concentration in the Arctic and the Antarctic, in support of the international calls for the ongoing monitoring of key parameters of sea-ice cover (Tonboe *et al.*, 2017; GCOS, 1992, 2018). The OSI-450 SIC represents an enhanced version of the original sea-ice concentration product with improved data processing methods, namely, an improved sea-ice retrieval algorithm and processing chain (Lavergne *et al.*, 2019a, 2019b; Sørensen *et al.*, 2021).

The initial development of the OSI-450 SIC was an outcome of ongoing research and development at OSI SAF and a collaboration between OSI SAF and the European Space Agency Sea Ice Climate Change Initiative (SICCI). OSI SAF sought to develop a data product that would improve the accuracy of sea-ice concentration retrieval and provide detailed and quantified information on the uncertainties and limitations involved (Lavergne *et al.*, 2019b). Between 2013 and 2018, as part of a series of SICCI projects, comprehensive evaluations and intercomparisons were undertaken between several sea-ice concentration retrieval algorithms (e.g., Ivanova *et al.*, 2015). These studies

contributed to the growing literature revealing stark differences in estimates of sea-ice concentration, area, and extent (e.g., Ivanova *et al*., 2014; Comiso *et al*., 2017), highlighting some of the shortfalls of existing methodologies, including those implemented in the NSIDC SII. Following their investigations, SICCI developed an improved algorithm for sea-ice concentration retrieval: the SICCI2. SICCI granted OSI SAF the use of the new algorithm to develop the OSI-450 SIC in exchange for SICCI's use of the OSI SAF processing software to produce a complementary climate data record.

As discussed in detail later (Section 5.4), modifying the methodologies of pre-existing and operational sea-ice data products can be problematic. Implementing new techniques, such as different algorithms, may significantly alter the consistency of sea-ice data records by changing the way satellite observations are selected, manipulated, and transformed into meaningful data. This partly explains why, in order for OSI SAF to take advantage of emerging developments in sea-ice and satellite research and technology, the production of a new and independent version of the sea-ice concentration data product was necessary. The previous version is archived on the website and is used to assess the relative improvements of the OSI-450 SIC product (Kreiner *et al*., 2019a).

The OSI-450 SIC is less tailored to the general public than the NSIDC SII: the primary stated users of OSI SAF data products are considered to be National Meteorological Services and oceanic and climate research agencies (OSI SAF, 2021). These users exploit the data for various applications, including marine forecasts and input into climate models for assimilative and predictive purposes. Additional users may include economic, political, and environmental stakeholders, such as government agencies, coastal engineers, fisheries, and offshore industries for use in planning. As Chapter 7 will detail further, the diversity of users is an important factor shaping the nature of product development.

The OSI-450 SIC data is archived on a dedicated webpage within the EUMETSAT OSI SAF website.[59] Through this webpage, users can 'freely' access and download the data files and images via an FTP server, access supporting documentation, and view and compare data via a 'quick look' interactive interface (Figure 5.14). Where time coverage overlaps, the interactive interface also enables users to compare the OSI-450 SIC with other OSI SAF data products for relevant parameters such as sea-ice drift, sea and ice surface temperatures, and sea-ice type. In addition to providing standalone sea-ice concentration data, the OSI-450 SIC is used to produce the OSI SAF Sea Ice Index.[60] The

[59] Product website: https://osi-saf.eumetsat.int/products/osi-450.
[60] OSI SAF Sea Ice Index webpage: https://osi-saf.eumetsat.int/products/osi-420. At the time of writing (July 2021), the OSI SAF Sea Ice Index has a 'demonstrational status'; that is, it has not been integrated fully into the OSI SAF product portfolio. In the months following my fieldwork, the Sea Ice Index was redeveloped to improve the accessibility and design of the visual data outputs.

OSI SAF Sea Ice Index is a climate indicator of sea-ice cover and uses the OSI-450 SIC to produce graphs and data files of long-term trends in daily and monthly sea-ice extent and area (Figure 5.15). Sea-ice extent and area values are calculated using the same 15% sea-ice concentration threshold described in Section 5.3.1.5 making them comparable with the NSIDC SII.

The OSI-450 SIC has the status of a 'released' data product meaning the end date of the product has already passed. Like the NSIDC SII, OSI SAF produces an interim 'operational' sea-ice concentration data product (OSI-430-b) to extend the record from December 2015 to the present day.[61] To ensure homogeneity, the production of the interim sea-ice concentration data product mirrors that of the OSI-450 data product. As such, it is not explicitly examined in this PhD research.

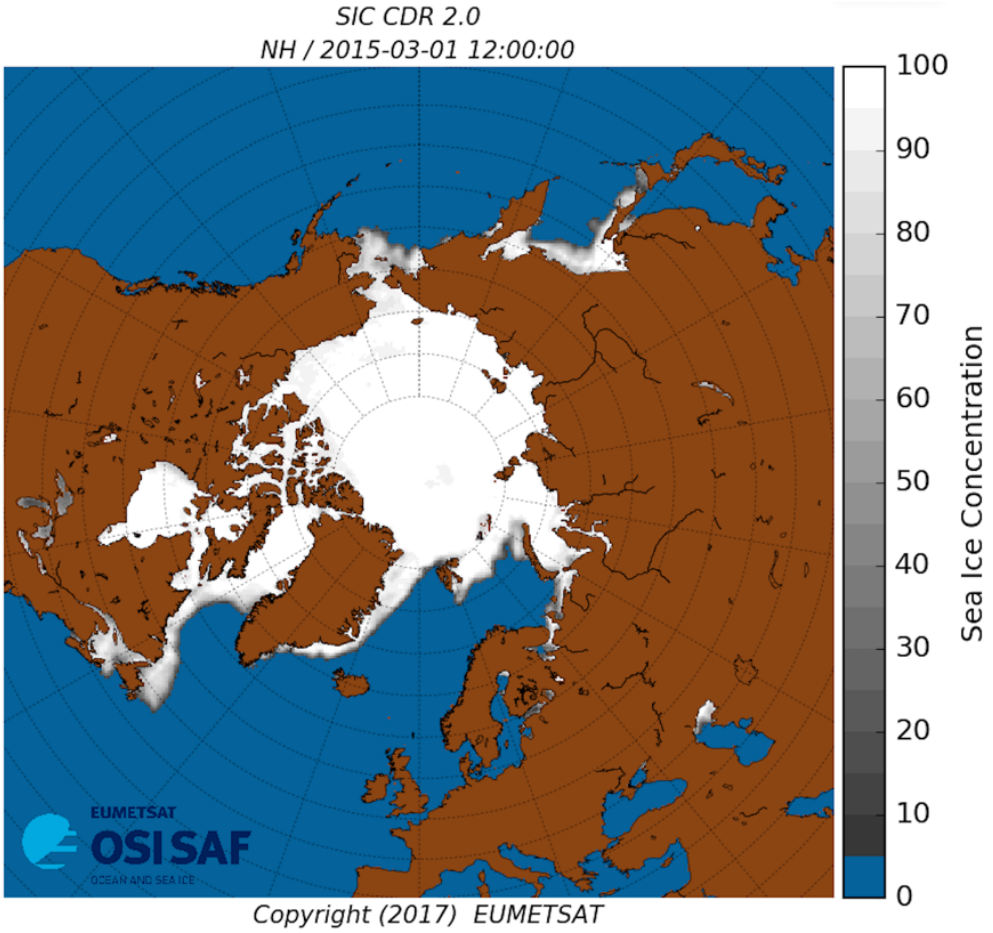


Figure 5.14.: Example sea-ice concentration image derived using the OSI-450 SIC data product. *Source:* EUMETSAT Ocean and Sea Ice Satellite Application Facility, Global sea ice concentration climate data record 1979-2015 (v2.0, 2017), OSI-450, doi: 10.15770/EUM_SAF_OSI_0008, (Data extracted from OSI SAF FTP server/EUMETSAT Data Center: 1979-2021, Northern Hemisphere, accessed 2021-07-02).

[61] The interim product has a latency period of ~16 days.

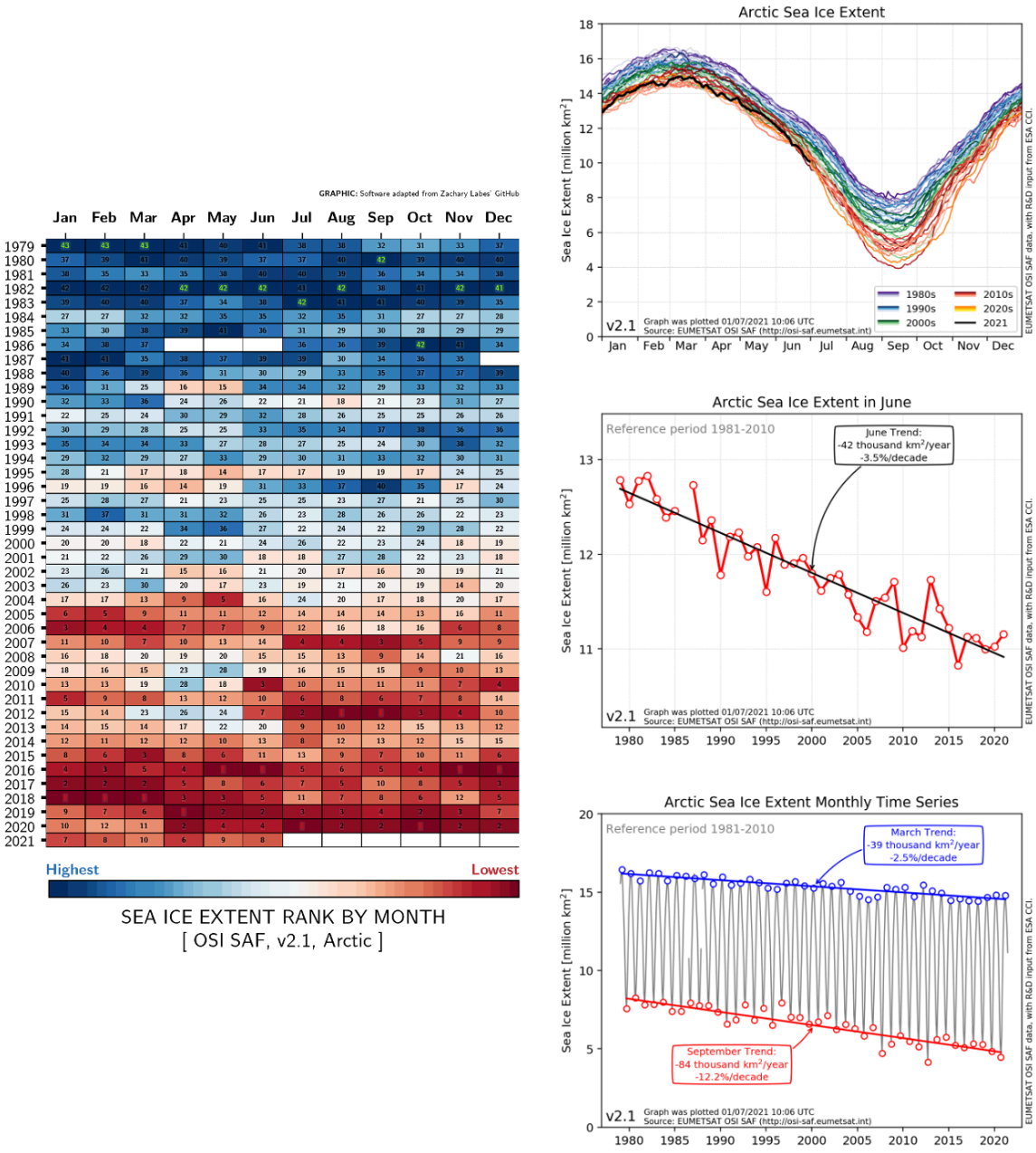


Figure 5.15.: Example sea-ice extent and area data outputs from the OSI SAF Sea Ice Index v2.1. *Source:* compiled from EUMETSAT Ocean and Sea Ice Satellite Application Facility, Sea ice index 1979-onwards (v2.1, 2020), OSI-420, Data extracted from OSI SAF FTP server: 1979-2021, Northern Hemisphere, accessed 2021-07-02.

5.3.2.2. Data Sources, Contributors, and Processing Sequence

Although the OSI-450 SIC differs from the original sea-ice concentration data product (OSI-409) in terms of its algorithm and processing sequence, the foundational principles and methodologies prevail. As outlined in Tonboe *et al.* (2016: 2), these include the following key aims:

1) Find algorithms with low sensitivities to atmospheric and surface emissivity variability.
2) Correct the brightness temperatures for the properties that can be quantified.

3) Calibrate the algorithms to the actual ice and water signatures using dynamical tie-points.
4) Quantify the residual uncertainties.

As the above aims demonstrate, the production of the OSI-450 SIC is motivated by the desire to construct an accurate sea-ice concentration product *and* quantify the uncertainties and limitations involved (Lavergne *et al*., 2019b). The emphasis on uncertainty quantification is apparent at every processing step and reflects a focus on assisting users in making informed judgments about the accuracy of different sea-ice estimates (see Chapter 7 for more discussion on this).

The production of the OSI-450 SIC is primarily carried out by members of OSI SAF and includes input from SICCI, the EUMETSAT Climate Monitoring Satellite Application Facility (CM SAF), and the European Centre for Medium-Range Weather Forecasts (ECMWF). The division of data processing responsibilities in relation to the general processing sequence (Table 5.2) is illustrated in Figure 5.16 and described below. The product user manual includes a figure of a data-processing chain comprised of four levels (Figure 5.17). There are clear similarities between the various levels illustrated in Figure 5.17 and Stages 3-5 of the general processing sequence listed in Table 5.2. However, to avoid confusion and maintain consistency with the terminology used by OSI SAF, the processing steps will be described below in relation to the 'Levels' outlined in Figure 5.17.

While there is no apparent acknowledgment in the documentation, the OSI SAF data processing chain and associated terminology resembles the 'data-processing levels' used in NASA's Earth Observing System Data and Information System data products (Table 5.5). This suggests the presence of broader set of technical standards that guide the processing earth-observation data.

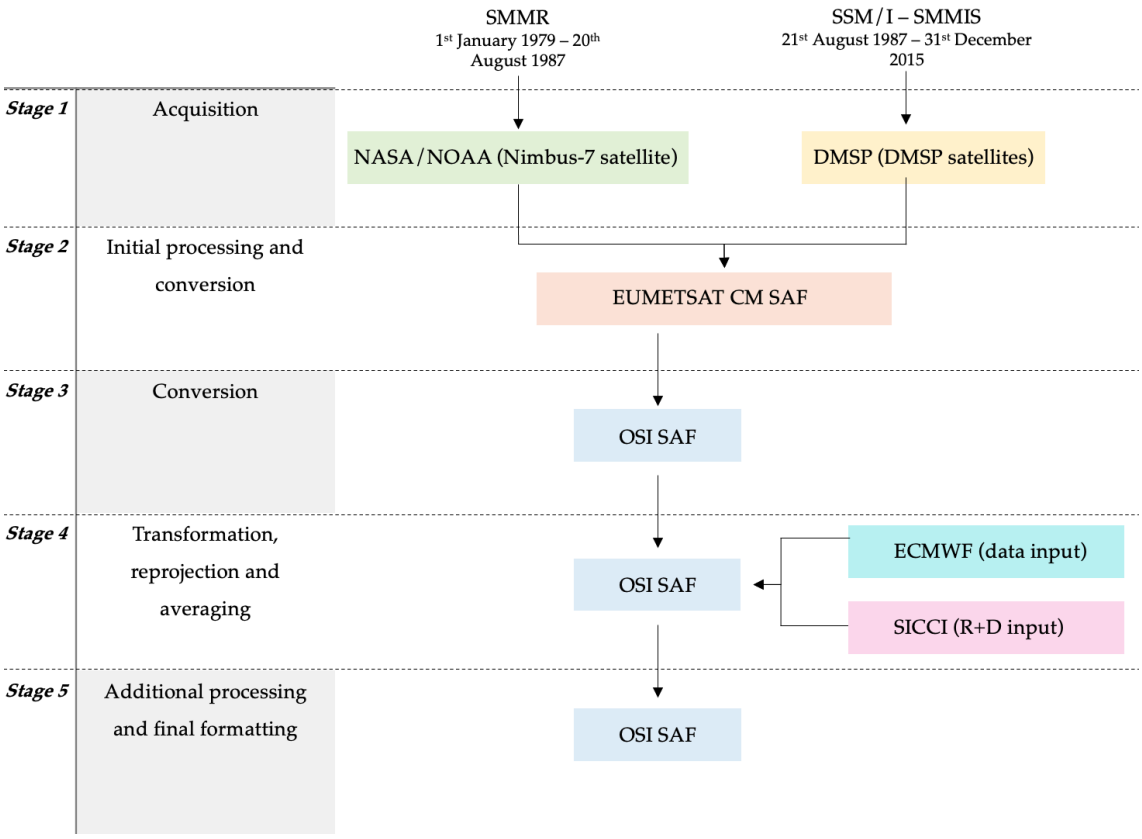


Figure 5.16.: OSI-450 SIC processing sequence and main contributors.

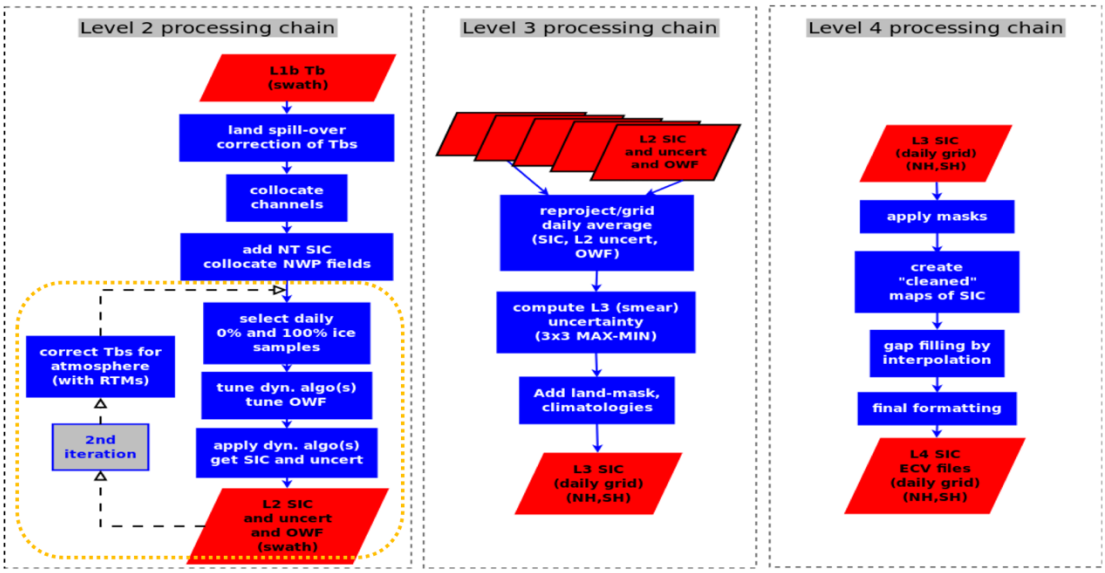


Figure 5.17.: OSI-450 SIC Level 1-4 processing chains. *Source:* Sørensen et al. (2021) - modified to indicate the main processes involved in transforming brightness temperatures into sea-ice parameters (enclosed within yellow dotted line).

Data Level	Description
Level 0	Reconstructed, unprocessed instrument and payload data at full resolution, with any and all communications artifacts (e.g., synchronization frames, communications headers, duplicate data) removed. (In most cases, NASA's EOS Data and Operations System [EDOS] provides these data to the Distributed Active Archive Centers [DAACs] as production data sets for processing by the Science Data Processing Segment [SDPS] or by one of the Science Investigator-led Processing System [SIPS] to produce higher-level products.)
Level 1A	Reconstructed, unprocessed instrument data at full resolution, time-referenced, and annotated with ancillary information, including radiometric and geometric calibration coefficients and georeferencing parameters (e.g., platform ephemeris) computed and appended but not applied to Level 0 data.
Level 1B	Level 1A data that have been processed to sensor units (not all instruments have Level 1B source data).
Level 2	Derived geophysical variables at the same resolution and location as Level 1 source data.
Level 3	Variables mapped on uniform space-time grid scales, usually with some completeness and consistency.
Level 4	Model output or results from analyses of lower-level data (e.g., variables derived from multiple measurements).

Table 5.5.: NASA's Earth Observing System Data and Information System data processing levels. *Source:* https://earthdata.nasa.gov/collaborate/open-data-services-and-software/data-information-policy/data-levels.

5.3.2.3. Pre-Processing of Brightness Temperatures (Levels 1 and 2 Processing)

Consistent with the NSIDC SII, the initial input data source of the OSI-450 SIC is brightness temperatures obtained from the SMMR sensor onboard the Nimbus-7 satellite and the SSM/I and SSMIS sensors onboard a series of DMSP satellites. CM SAF, a facility that sits parallel to OSI SAF within EUMETSAT's satellite application facilities network, carries out the initial processing of the raw brightness temperatures. CM SAF's primary mission is to develop, archive, and distribute high-quality satellite-derived products and services for climate monitoring applications (CMSAF, n.d.). The raw radiation data are initially processed by CM SAF and distributed in a Fundamental Climate Data Record (FCDR) of Microwave Imager Radiances.[62] The processing carried out by CM SAF is similar to that carried out by RSS during the production of the NSIDC SII: raw radiance data is decoded and translated into filtered, error-corrected, geolocated, and calibrated brightness temperatures. Full details of CM SAF's processing and calibration steps can be found in Fennig *et al.* (2020).

Following initial processing, the brightness temperatures are distributed to OSI SAF for use in their sea-ice data products. The brightness temperatures enter the OSI-450 SIC processing chain as Level 1b data and subsequently undergo two further pre-

[62] The U.S. National Research Council committee defines FCDRs as: "a time series of measurements of sufficient length, consistency, and continuity to determine climate variability and change" (NRC, 2004: 1).

transformation processing steps: land-to-ocean spillover correction and data collocation (Figure 5.17). In contrast to the approach taken in the GSFC SIC (Section 5.3.1.3), the timing of the land-to-ocean spillover correction differs: it occurs *before* sea-ice concentrations have been derived and reprojected, not after. OSI SAF recognised limitations with the GSFC approach (Sørensen *et al.*, 2021), likely because the reprojected sea-ice concentrations have gone through additional stages of data aggregation, and uncertainties have accrued. To avoid this, OSI SAF corrects the influence of land-to-ocean spillover at footprint level for each frequency channel used. The correction is based on a method detailed in Maaß and Kaleschke (2010), which builds upon the basic assumption that the brightness temperatures measured for each sensor footprint can be separated into 'land' and 'sea' contributions using additional high-resolution shoreline data. The brightness temperature signals of footprints adjacent to the coastline, which exhibit a land contribution, are corrected.

Following the land-to-ocean spillover correction, the brightness temperatures are collocated in preparation for the transformation into sea-ice concentration data and subsequent processing steps. The transformation and subsequent processing (Levels 2 to 4 in Figure 5.17) are carried out by OSI SAF, with research and development input from SICCI and additional data input from ECMWF.

5.3.2.4. Sea-Ice Retrieval Algorithm (Level 2 Processing)

The OSI-450 SIC uses a *hybrid* algorithm to derive sea-ice concentration estimates from the observed brightness temperature data. The algorithm, SICCI2, is hybrid because it combines two other sea-ice concentration algorithms: the Bootstrap frequency mode (BFM) (Comiso, 1995) and the Bristol (Smith, 1996). The reason for combining these two algorithms is that they each perform well at respective ends of the sea-ice concentration range: the BFM performs particularly well in areas of low sea-ice concentration and the BRI in areas of high sea-ice concentration. These relative performance characteristics were identified during the SICCI projects (e.g., Ivanova *et al*., 2015), which ultimately led to their selection in developing the SICCI2. Summaries of the three algorithms are provided below. For full explanations of the BFM see Comiso (1995), for the Bristol see Smith (1996), and for the SICCI2 see Lavergne *et al*. (2019a, 2019b) and Sørensen *et al.* (2021).

The Bootstrap algorithm was developed during the 1980s by the same team of GSFC-researchers behind the NASA Team algorithm. It uses brightness temperature observations obtained at two frequency channels: 19v (18v for SMMR), 37v, and 37h GHz. Brightness temperatures observed at these frequency channels exhibit the familiar distribution seen previously: they cluster around the typical signatures for first-year ice, multi-year ice, and open water (Figure 5.18). The Bootstrap algorithm is separated into two modes - the *polarisation* mode and the *frequency* mode – which use these clusters to

estimate sea-ice concentrations (Comiso, 1995). The polarisation mode compares the brightness temperature clusters measured at the same frequency (37 GHz), but in different polarisations. This mode, shown by the example in Figure 5.18a, is best applied to areas of higher concentrations within the ice pack where atmospheric and oceanic influence is less apparent. The relatively higher resolution associated with 37 GHz means that the tie-points for first-year ice and multi-year ice, and the line between them (A-D), can be established with greater certainty. The frequency mode (BFM) compares the brightness temperature clusters obtained at different frequencies for the same polarisation (18v/19v and 37v GHz). This mode, shown by the example in Figure 5.18b, is less sensitive to atmospheric and oceanic noise because it uses the lower frequency channel, making it better suited for areas of lower sea-ice concentrations and towards the 'ice-edge'. However, the lower sensitivity to noise comes at the expense of coarser spatial resolution (Section 5.2.4).

Both modes use the same geometric principles to approximate sea-ice concentrations. As shown in Figure 5.18, most observations tend to cluster along the lines A-D and O-D, where A represents the tie-point for first-year ice, D represents the tie-point for multi-year ice, and O represents the tie-point for open water. The Bootstrap algorithm builds upon the assumption that large areas of the central Arctic Ocean are covered in 100% sea-ice concentration during the winter (Comiso *et al*., 1997). This assumption is based on the strongly correlated clusters of brightness temperature observations along the line A-D, which is assumed to represent areas of 100% sea-ice concentration. To calculate sea-ice concentrations between 0-100%, the algorithm employs linear interpolation using isolines that run parallel to line A-D representing constant sea-ice concentration values. The approach is illustrated using the example in Figure 5.18c, whereby the sea-ice concentration of a brightness temperature observation, *T*, is equal to the ratio of the distance between T-O, and O-I, with I representing the point of intersection along the 100% sea-ice concentration line.

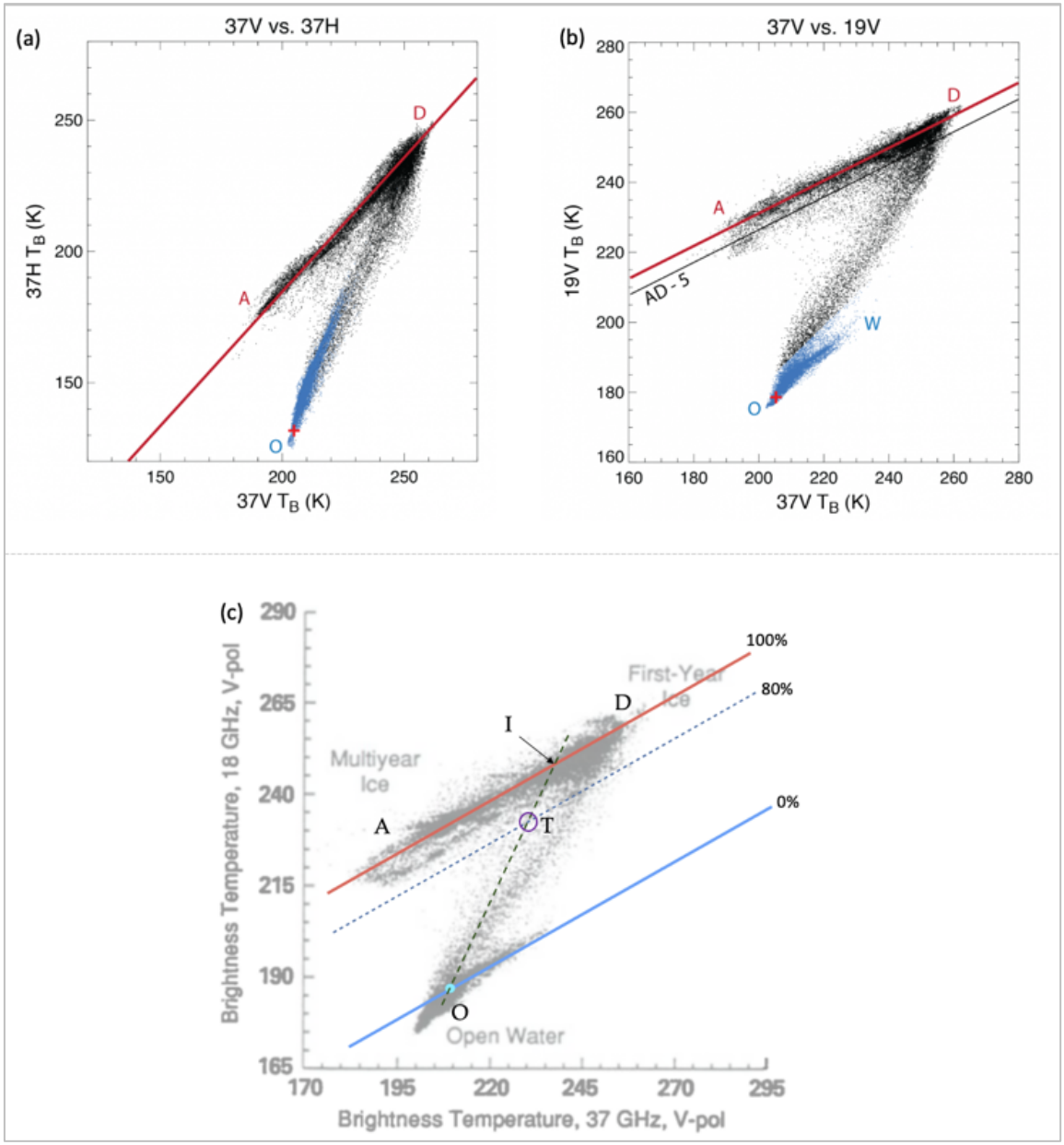


Figure 5.18.: (a) Bootstrap polarisation mode for brightness temperatures captured at 37v and 37h GHs. (b) Bootstrap frequency mode for example brightness temperatures captured at 37v and 19h GHz. (c) An illustration of the geometric approach used to calculate sea-ice concentration - see text for explanation. In these images, the red line (A-D) connecting the tie-points for first-year and multi-year ice represents 100% sea-ice concentration, O and W represent open water (0% sea-ice concentration). *Source:* (a) and (b) - NSIDC, 2021b; (c) – Eppler *et al.* (1992) – modified to illustrate the geometric approach.

The Bristol algorithm is theoretically similar to the Bootstrap algorithm and has been described as a generalisation of the two Bootstrap modes (Smith, 1996). Pedersen *et al.* (2017) note that it was developed to reduce the discontinuity in sea-ice concentrations due to the different Bootstrap modes. The Bristol algorithm uses cluster analysis of brightness temperatures obtained at the same frequency channels (19v, 37v, and 37h). However, rather than comparing the channels independently based on their frequency or polarisation characteristics, the algorithm combines the modes into one using a three-dimensional approach and principal component analysis (Figure 5.19). The Bristol

algorithm uses a fixed geometrical relationship (or *fixed data projection plane*) between closed-ice (A-D) and open water (H) within that three-dimensional space to derive sea-ice concentrations. Smith (1996) originally selected this data plane because it offered the largest range of open water to closed ice signatures (Lavergne *et al*., 2019b).

The SICCI2 algorithm combines the Bristol and BFM algorithms to take advantage of the relative performance characteristics noted above and achieve more accurate retrievals across the sea-ice concentration range. The algorithms are combined to produce hybrid sea-ice concentration values using linear weighted averages of the two outcomes (Lavergne *et al*., 2019b). This can be expressed as follows:

$$\begin{cases} w_{ow} = 1; & \text{for } B_{ow} < 0.7 \\ w_{ow} = 0; & \text{for } B_{ow} > 0.9 \\ w_{ow} = 1 - \dfrac{B_{ow} - 0.7}{0.2} & \text{for } B_{ow} \in [0.7; 0.9] \end{cases}$$

$$\mathrm{SIC}_{\mathrm{hybrid}} = w_{OW} \times B_{OW} + (1 - w_{OW}) \times B_{C}$$

Equation 5

where w_{OW} and B_{OW} are the weight and output for sea-ice concentration from the 'best open water' algorithm, and B_{CI} is the output for sea-ice concentration from the 'best closed ice' algorithm.

As well as using hybrid retrieval mechanisms that achieve a good level of accuracy across the sea-ice concentration range, the SICCI2 algorithm has a distinct advantage of being a *dynamic algorithm*. Sea-ice retrieval algorithms are characterised as dynamic if at least one of the following features is not fixed: 1) the brightness temperature tie-points used to represent average values for first-year ice, multi-year ice, and open water, and 2) the equation used to compute sea-ice concentration – the SICCI2 benefits from both features.

The SICCI2 is described as a "hybrid, self-tuning, self-optimizing sea-ice concentration algorithm" (Lavergne *et al*., 2019b: 54). In other words, using representative samples for 0% and 100% sea-ice concentration data derived from a daily-updated training dataset, the algorithmic tie-points and equations are tuned to best represent the brightness temperature measured at a particular moment in time. In contrast to the NASA Team algorithm that only updates tie-points following changes to the satellite-sensors (Section 5.3.1.3), the SICCI2 tie-points for open water and closed ice types are dynamically tuned *daily*. Once the tie-points have been selected, the SICCI2 uses a similar three-dimensional approach to the BRI algorithm to calculate sea-ice concentration. However, rather than using a fixed data projection plane connecting the closed-ice line (A-D) with open water (H), the algorithm is optimised by rotating the projection plane around the closed-ice

line within the three-dimensional space (Figure 5.19a). The aim here is to exploit the different brightness temperature signatures for open water and closed ice obtained at different frequencies and polarisations and combine this to achieve a more accurate picture of sea-ice concentration. From the training dataset, the optimisation process produces two *optimal planes* with corresponding rotation angles that best capture the distribution of open water and closed ice samples and ultimately define the SICCI2 algorithm (Figure 5.19b). Observed brightness temperatures are subsequently projected to each plane and transformed into two sets of sea-ice concentration values using a geometric approach resembling Figure 5.18. The final, combined sea-ice concentration values are achieved by using Equation 5.

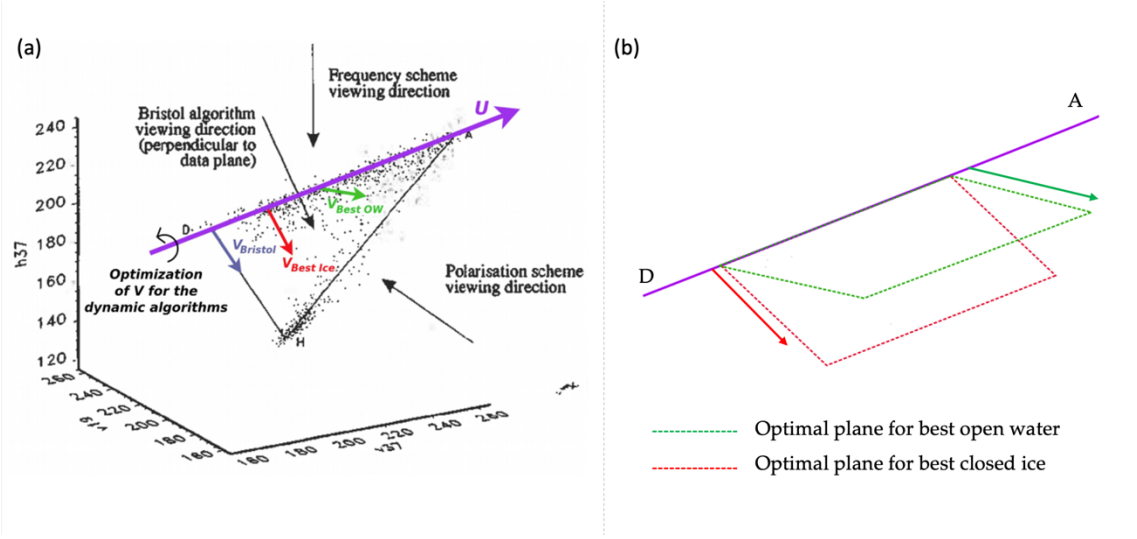


Figure 5.19.: (a) A 3D representation of the SICCI2 algorithm showing the projected brightness temperatures for 37v, 37h, and 19v GHz channels. Clusters are identifiable for open water (H) and along the closed-ice line (A-D). The black parts of the diagram represent the original figure from Smith (1996) for the Bristol algorithm, which has been edited using the colours to show the SICCI2. The red arrow represents the best vector for calculating higher sea-ice concentrations, the green arrow represents the best vector used for calculating lower sea-ice concentrations, and the purple arrow (U) represents the direction used to define the vectors for best ice and open water. The angles between the vectors for best ice and open water and U are used to produce two optimal planes. (b) A simplified representation of the two optimal planes for best open water and best closed ice sea-ice calculations. *Source*: (a) Lavergne *et al.* (2019b).

The rationale behind this self-optimising, dynamic approach is that the algorithm can be adapted to capture the temporal and spatial variability in brightness temperature measurements. This variability may be caused by atmospheric and oceanic factors, heterogeneities in surface-level composition, differences in satellite-sensor characteristics, and seasonal and interannual variability in sea-ice cover (Steffen and Maslanik, 1988; Anderson *et al.*, 2007). The dynamic approach helps produce a more representative and consistent record of brightness temperatures and, thus, sea-ice concentration.

During the transformation process at Level 2, the brightness temperatures undergo a correction for atmospheric influence. This correction involves using a *radiative transfer model* (RTM) combined with numerical weather prediction data for the surface and the atmosphere, derived from the ECMWF ERA-Interim reanalysis (Dee *et al*., 2011). The OSI-450 SIC uses the RTM model developed by RSS and described in Wentz (1983, 1997). The RTM model works by simulating the brightness temperature emitted from an ice-covered surface during different atmospheric states, using sea-ice concentration data and ERA-Interim data for several key parameters, including wind speed, air temperature, and water vapour.[63] The purpose of these simulations is to estimate and remove the unwanted radiation contributions of the atmosphere that contaminate the brightness temperatures from sea ice.

In addition to the RTM-atmospheric correction, the SICCI2 uses an open-water filter to remove spurious sea ice in areas of open water or low ice concentrations. The open-water filter is essentially the same correction process as the weather filter used by the NASA Team algorithm (Cavalieri *et al*., 1999); however, OSI SAF/SICCI consider the name 'open-water filter' to be more representative of what the process achieves. There are two other notable differences between the correction process used by the NASA Team and SICCI2 algorithms (Lavergne *et al.*, 2019a). Firstly, the SICCI2 only uses gradient ratios at 19 and 37 GHz and not 22 GHz (Table 5.4). The main reason for this is that the RTM-correction method is thought to sufficiently detect the noise observed at the 22 GHz channel that occurs mainly from the influence of water vapour. Secondly, the open-water filter used in the SICC2 benefits from the dynamic tuning of the algorithm and as such, the open-water filter thresholds are not fixed.

Despite using an open-water filter in their processing, OSI SAF stress caution around their use, particularly filters that use fixed thresholds (Lavergne *et al*., 2019a). The reason for this is that although they have been shown to remove spurious ice effectively, open-water filters inevitably remove true ice signals (Ivanova *et al*., 2015). Both approaches used by the NSIDC and OSI SAF result in true ice signals being erroneously removed in areas of low concentration: the NASA Team filter tends to classify all areas with sea-ice concentrations of <15% as open water (Section 5.3.1.3); the OSI-450 SIC filter often removes areas covered in sea ice of <10% concentration.

The final processing step of Level 2 involves calculating the uncertainties associated with the transformation process. Where possible, the OSI-450 SIC provides estimates of the inherent SICCI2 algorithm uncertainties for each sea-ice concentration value. The main sources of these uncertainties include sensor noise and the residual effects from the atmosphere and the ocean that have not been identified or removed through the

[63] The ERA-Interim dataset contains 3-hourly estimates of these parameters available throughout the OSI-450 SIC time coverage.

correction procedures. These remaining uncertainties are estimated using the standard deviation of 0% and 100% measurements when applied to the training data for open water and closed ice samples. While this approach successfully identifies and estimates some of the uncertainties, the effects of atmospheric and oceanic influence cannot be fully accounted for. Moreover, the degradation of sea-ice brightness temperatures due to meltwater increases the level of uncertainty in the OSI-450 SIC during the summer.

5.3.2.5. Additional Sea-Ice Concentration Processing (Levels 3 and 4 Processing)

Once the sea-ice concentration has been derived and the algorithm uncertainties estimated, the data is reprojected and averaged to uniform gridded fields (Level 3 processing; Figure 5.16). Sea-ice concentrations are projected onto Equal-Area Scalable Earth 2 (EASE2) grids with a grid cell resolution of 25 km.

The process of reprojecting and averaging the data to grid cells introduces additional uncertainties, often called 'smearing uncertainties' or 'representativeness errors' (Tonboe *et al*., 2016; Lavergne *et al*., 2019b). These uncertainties arise for two key reasons: 1) the grid cell resolution is finer than the spatial resolution of the sensor footprints; 2) the frequency channels have different footprints meaning they sense different areas of the surface. Smearing uncertainties are most apparent around the 'ice edge' where the surface characteristics of adjacent footprints are more variable. It should be noted that such uncertainties are problematic for all passive microwave data products of sea ice whereby satellite data is reprojected to gridded fields. However, due to apparent differences in principles and intended purposes, not all data products provide information on the effects of data smearing (e.g., the NSIDC SII does not provide an indication of smearing uncertainties). As described in Section 5.3.2.1, providing quantitative information of the different sources of uncertainty is central to the production of the OSI-450 SIC product. As such, OSI SAF provide estimations of smearing uncertainties using a smearing model. The compares the sea-ice concentration outputs against a reference dataset obtained using a higher-resolution (1 km) sensor: the Moderate Resolution Imaging Spectroradiometer (MODIS) (Tonboe *et al*., 2016). This dataset is regarded as the "truth" on the basis that it provides "a realistic spatial distribution of ice at the right scale for input to the model and as a reference for comparison" (Tonboe *et al*., 2016: 11).

Before the final OSI-450 SIC data values and maps are produced, several additional processing steps occur. These include filling data gaps using spatial and temporal interpolation and applying masks for land and maximum sea-ice extent. Data gaps arise in the OSI-450 SIC record for much the same reason as the NSIDC SII. These data gaps are filled in the OSI-450 SIC using spatial and temporal linear interpolation schemes using the values of the surrounding grid cells on preceding and succeeding days. Similar to the NSIDC SII, a land mask is applied to the dataset to distinguish between land and

ocean-covered areas. The land mask used in the OSI-450 SIC is based on the Operational Sea Surface Temperature and Sea Ice Analysis (OSTIA) mask (Donlon *et al.*, 2012). OSI SAF adjust the mask to fit the 25 km grid resolution and ensure consistency with the masks used by the NSIDC in several of their sea-ice climate data records (including the NSIDC SSI). The mask application typically sees all grid cells with a land fraction of <30% set to ocean (open water or ice-covered). The OSI-450 SIC also uses a maximum sea-ice extent limit to remove residual false ice signals in open water areas. This limit is based on a sea-ice climatology developed by researchers at the NSIDC (Meier *et al.*, 2015) and derived from the National Ice Center Arctic Sea Ice Charts and Climatologies dataset. The climatology is used to indicate the outer extent of where sea ice could exist, based on past data (i.e., the extent of valid ice). OSI SAF modifies the NSIDC climatology by manually changing the grid cells using additional input from higher resolution ice charts developed by the US National Ice Center, Canadian Ice Service, and Norwegian Ice Service (Lavergne *et al.*, 2019b). In practice, the climatology works by excluding all areas that do not meet the required criteria: for at least 25% of the years from 1979 to 2015, the sea-ice concentration exceeded 40% (Lavergne *et al.*, 2019a). An additional buffer zone of 150 km is used to extend the climatology outwards.

The final sea-ice concentration data is provided in Network Common Data Format version 4 (NetCDF) with accompanying maps (PNG images) for each available day. Each NetCDF file contains the gridded data featuring the six key variables listed and described in Table 5.6. Unlike the NSIDC SII, which excludes areas below 15% sea-ice concentration, the OSI-450 SIC includes sea-ice concentration values that range from 0-100%. This means that there is no specified 'ice edge' definition in the OSI-450 SIC. However, when used to calculate sea-ice extent in OSI SAF's Sea Ice Index, a 15% threshold is used.

Table 5.6.: List and descriptions of the key variables included in the final OSI-450 SIC data product.

Variable	*Description*
Main sea-ice concentration	Fully filtered sea-ice concentration values, corrected for atmospheric influence and open-water filters
Raw sea-ice concentration	Unfiltered and uncorrected sea-ice concentration values
Algorithm uncertainty	The estimated error associated with the transformation of radiation data into geophysical variables
Smearing uncertainty	The estimated error associated with the reprojection and averaging of data to uniform gridded fields
Total uncertainty	The estimated combined error of the algorithm and smearing uncertainty
Status flag	Provides an indication of the processing steps involved in the derivation of a particular sea-ice concentration value (e.g., if that value is a result of gap-filling)

5.3.3. C3S SIE v1.0 and SITy v1.0

5.3.3.1. Overview

C3S is an information service provided by the Copernicus Earth Observation Programme of the European Union and implemented by ECMWF. C3S is committed to providing consistent and authoritative information on the changing state of the world's climate in support of the adaptive and mitigative climate change policies of the European Union. As part of this effort, C3S maintains a Climate Data Store that archives and distributes a wide range of 'freely' available data products, applications, software tools, and supporting documentation that enable users to explore and interact with data for key climate indicators.[64] The C3S products are developed by researchers at MET Norway on behalf of ECMWF C3S to support these objectives.

The C3S SIE and SITy are daily sea-ice classification climate data products that separate the ocean surface into discrete sea-ice classes using brightness temperature data measured by passive microwave sensors. The SIE product classifies the ocean surface into three types using sea-ice concentration data: open water (< 30%), open ice (30 – 70 %), and closed ice (> 70 %). The concentration thresholds used to classify the surface types are derived from the World Meteorological Organisation's Ice Chart Colour Code

[64] C3S Climate Data Store website: https://cds.climate.copernicus.eu/#!/home

Standard and are recognised internationally as the standard practice for operational ice charts (WMO, 2014). The SITy product classifies the ocean surface into three discrete classes representing the dominant development stages of ice: open water, first-year ice, and multi-year ice types. The definition for open water regions is consistent with the C3S SIE (areas with a sea-ice concentration <30%). Although the main parameters of interest in the C3S SIE and SITy differ from the previous sea-ice concentration products, their construction builds upon the same basic principles described in Section 5.2. Examples of the two product outputs are shown in Figure 5.20.

The two products are produced using the same processing methods and sequence, with broadly consistent data sources, algorithms, and data formats. As such, they are described together in this section and referred to collectively as the 'C3S products'.

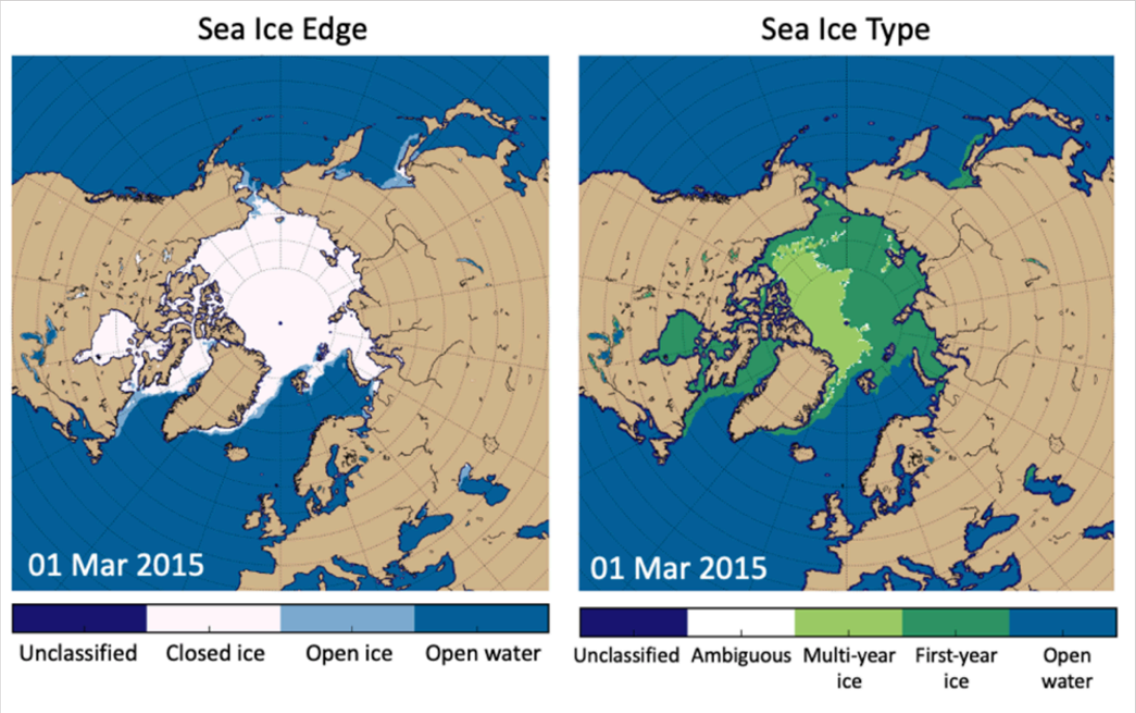


Figure 5.20.: Example images for the C3S SIE (left) and SITy (right) data products. *Source:* https://cds.climate.copernicus.eu/cdsapp#!/dataset/satellite-sea-ice-edge-type?tab=overview.

The C3S products were first released by C3S in the summer of 2018 and cover the period from January 1979 to December 2015. The products' aims are to provide consistent, long-term data to monitor and assess the variability in sea-ice cover characteristics over recent decades and support projections of future changes in Arctic sea ice. Accordingly, climate and ocean modellers are considered to be the primary user groups of the two products (DMI, 2020). That said, studies carried out by GCOS have identified a large and diverse user community that require long-term sea-ice classification data for a variety of scientific, environmental, commercial, and political applications (GCOS, 2011, 2015,

2016). Chapter 7 explores how different user requirements shape and inform the production of these products.

The C3S products are archived on a dedicated webpage within the C3S Climate Data Store website.[65] Through this webpage, users can 'freely' access and download the data files in NetCDF format, access supporting documentation, and use the data to create online applications through the Climate Data Store programming interface. Unlike the previous data products, there is no 'quick-look' option for viewing the C3S products in 'ready-made' images and maps. However, the programming interface allows users to retrieve the data of interest, make calculations, and produce graphs, maps, and other visual outputs. The interface is designed with a range of users in mind, including students, researchers, and software developers; though, it stresses the need for basic knowledge of Python and access to the internet. The open-source nature of these products (and climate data products more generally) is discussed further in later chapters: Chapter 6 explores how the lack of 'ready-made' data outputs grants users greater flexibility in the design of maps and images; Chapter 7 probes how issues around accessibility (e.g., digital inequalities) influence the circulation of climate change knowledge and the democratisation of science.

Similar to the OSI-450 SIC and the NSIDC SII, C3S also releases interim data products extending the sea-ice edge and type records to the present day.[66] As before, the practices involved in the production of the interim products are consistent with the C3S products. Thus, they are not explicitly examined in this PhD research.

5.3.3.2. Data Sources, Contributors, and Processing Sequence

The basic principles and processing methods implemented in the C3S products originate from the *operational near-real-time (NRT)* sea-ice edge (OSI-402) and sea-ice type products (OSI-403), developed and distributed by OSI SAF (Aaboe *et al*., 2018a). The climate and operational NRT versions of the SIE and SITy products share many similarities: they focus on the same parameters with consistent definitions, they use the same algorithms and processing chains, and their outputs are comparable in design. However, several notable differences make them distinct product types. Some of the main differences are listed in Table 5.7. For a full overview, see the C3S SIE and SITy Product User Guide and Specification document (Aaboe *et al*., 2019).

[65] See note 64.
[66] With a 16-day latency period.

Table 5.7.: Main differences between the climate and operational NRT versions of the SIE and SITy data products.

Feature	*Climate Data Products (C3S SIE and SITy)*	*Operational NRT Data Products (OSI-402 and OSI-403)*
Ownership and distribution	ECMWF C3S	EUMETSAT OSI SAF
Purpose	Provide a long-term consistent record	Provide accurate and timely data on the state of sea-ice cover
Time coverage	January 1979 – December 2015 (Interim product to extend to present day)	March 2005 – present day
Satellite data source	Passive microwave radiometers	Passive and active microwave radiometers
Year of Inception	2018	2014

The fundamental difference between the climate and operational NRT versions is the purpose of the products. As noted previously, the fundamental purpose of climate data products is to provide a temporally consistent record. This requires using consistent data sources, processing methods, principles, and correction techniques across the full-time series. In contrast, for operational NRT products, the primary purpose is to obtain accurate data in a timely manner. This often involves supplementing the long-term passive microwave data record with additional sources from shorter-term and higher resolution sensing instruments. Accordingly, the operational OSI-402 and OSI-403 products include data obtained using active microwave scatterometer instruments and more recent passive microwave radiometers with higher resolution footprints (e.g., AMSR2). Whereas the climate versions only use passive microwave data obtained from the SMMR, SSM/I, and SSMIS. Thus, despite having consistent principles and broadly similar processing methods, the difference in data sourcing results in different outputs between the climate and operational versions of the SIE and SITy products (Aaboe *et al*., 2019).

Researchers at MET Norway produce the C3S products using the OSI SAF processing framework and systems. The division of data processing responsibilities in relation to the general processing sequence (Table 5.2) is illustrated in Figure 5.21 and described below. As with the OSI-450 SIC, the C3S SIE and SITy Product User Guide includes a figure of a data-processing chain comprised of data-processing levels (Figure 5.22). The processes involved at each level are described in the following sections. Notably, many of the processes are consistent with the OSI-450 SIC – particularly the correction methods and the order of the processing sequence. An important difference to note is that for the OSI-450 SIC product, the core scientific work is implemented during the transformation process at Level 2. In contrast, the core processing of the C3S products occurs at Level 3, following the reprojection and averaging the daily gridded fields (Figure 5.22).

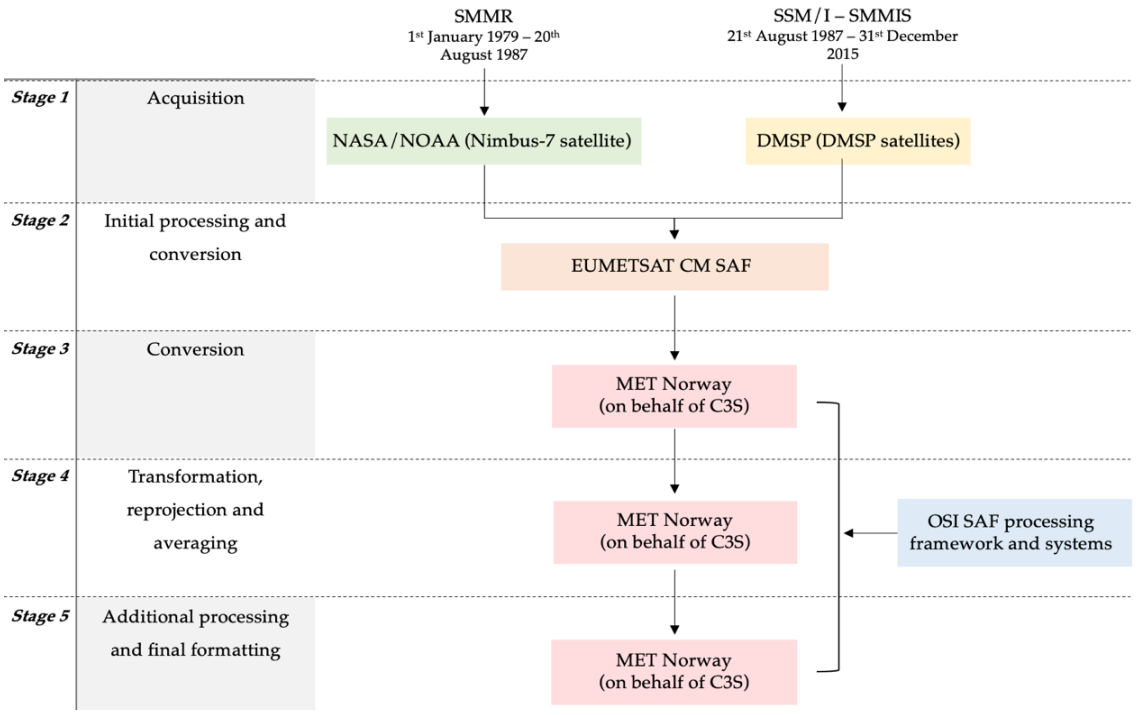


Figure 5.21.: C3S SIE and SITy processing sequence and main contributors.

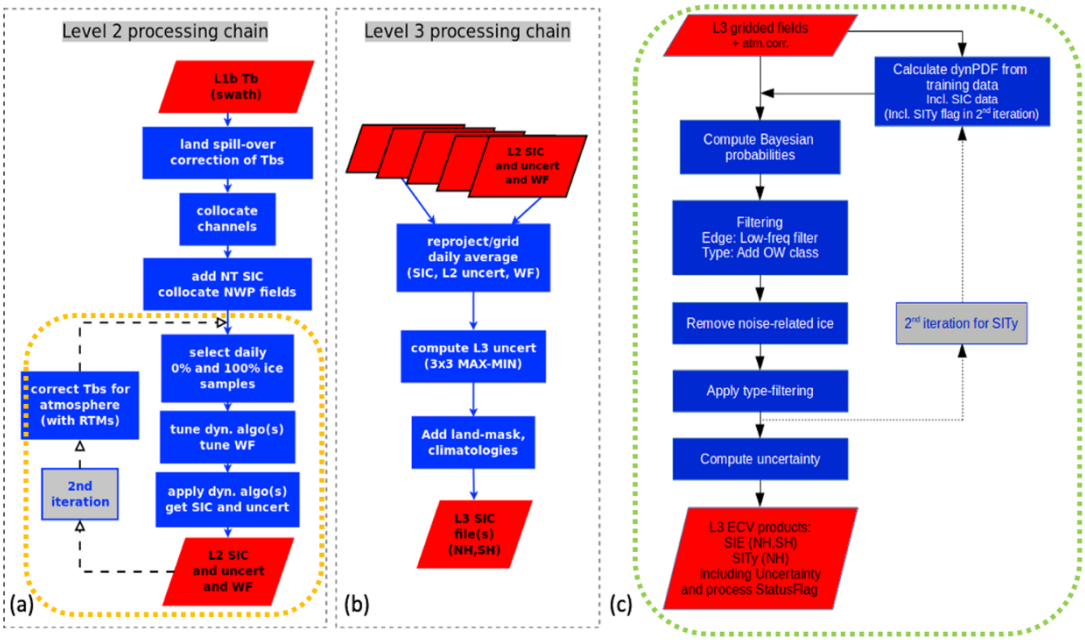


Figure 5.22.: OSI-450 SIC Level 1-4 processing chains. *Source:* Aaboe *et al.* (2018) - modified to indicate the main processes involved in transforming brightness temperatures into sea-ice parameters (enclosed within yellow dotted line) and the core classification work (enclosed within green dotted line).

5.3.3.3. Pre-Processing of Brightness Temperatures (Levels 1 and 2 Processing)

The C3S products use brightness temperatures obtained from the SMMR, SSM/I, and SSMIS sensors to categorise the ocean surface into different sea-ice classes and open water. The initial processing of brightness temperature data, including error correction and geolocation, the land-to-ocean spillover correction, and data collocation, is consistent with the OSI-450 SIC product, as described previously.

5.3.3.4. Sea-Ice Retrieval Algorithm (Level 2 Processing)

The theoretical basis of the sea-ice retrieval algorithm used in the development of the C3S products resembles that of the NASA Team algorithm (Section 5.3.1.3). The approach assumes that the observed brightness temperatures are primarily comprised of contributions from first-year ice, multi-year ice, and open water (Equation 2). Using brightness temperature observations obtained at swath level, the algorithm derives a set of classification parameters based on the brightness ratios between three horizontally (h) and vertically (v) polarised frequency channels: 19v, 19h, 37v, 90v, and 90h GHz. The brightness temperature ratios between these channels are expressed using Equations 3 and 4 and the following for the higher frequency channel:

$$PRn90 = [T_B(n90v) - T_B(n90h)]/[T_B(n90v) + T_B(n90h)]$$

Equation 6

where PR is polarisation ratio, GR is spectral gradient ratio, h is horizontal polarisation, v is vertical polarisation, and T_B is brightness temperature.

The specific frequency channels used to calculate the classification parameters vary across the observational period (Table 5.8). The C3S products use higher frequencies than the NSIDC SII and the OSI-450 SIC: 85.5 GHz is used for the SSM/I period and 91.655 GHz for the SMMIS period. As previously described (Section 5.2.4), these higher frequency channels benefit from higher spatial resolutions, which means that the sensors can resolve greater details at the surface, and the data is sampled at finer grid cell resolutions. However, the brightness temperatures captured at these higher frequency channels are subject to greater atmospheric influence. To help reduce this effect, the brightness temperatures are corrected for atmospheric influence using the ERA-Interim dataset and the algorithm is dynamically tuned to produce a weather filter to remove spurious sea-ice signals. These correction procedures are consistent with those used in the production of the OSI-450 SIC (see Section 5.3.2.3). However, unlike the OSI-450 processing chain, the weather filter is not applied to the C3S products until the final processing stages during Level 3 (see below).

Table 5.8.: The satellite-sensors, frequency channels, and corresponding sampling grid cell resolution used to produce the C3S SIE and SITy. All frequencies are captured at vertical and horizontal polarisations. *The 85.5 GHz channel was not used during the DMSP-F08 satellite mission (July 1987 – December 1991) due to a technological malfunction.

Sensor	***Operating Frequencies (GHz)***	***Sampling Grid Cell Resolution (km)***
SMMR	18.0	25 x 25
(October 1978 – August 1987)	37.0	25 x 25
SSM/I	19.35	25 x 25
(July 1987 – July 2006)	37.0	25 x 25
	85.5*	12.5 x 12.5
SSMIS	19.35	25 x 25
(November 2005 – December 2015)	37.0	25 x 25
	91.655	12.5 x 12.5

5.3.3.5. Classifying the Ocean Surface (Level 3)

Once the sea-ice classification parameters have been derived using the brightness temperature ratios, the data are projected and averaged to uniform gridded fields. The C3S products are projected onto Equal-Area Scalable Earth 2 (EASE-Grid 2.0) grids with grid cell resolutions of 12.5 km and 25 km.

The main classification of the products follows the data projection. Gridded data fields are classified into different ocean surface types using a Bayesian approach which calculates the *probability of occurrence* of the most likely surface type within each grid cell. This classification method was first developed in 2005 to produce operational products (Aaboe *et al*., 2018a). The approach is summarised here, and a full explanation is provided in Aaboe *et al*. (2018b).

The Bayesian approach relies on prior knowledge of surface conditions and the relationship between the measured classification parameters and different surface classes. Training datasets are established for each distinct surface class and are used to provide information on how the corresponding brightness temperatures behave over a given period (15 days). The training datasets for that given period are updated daily and are derived from additional input data sources. The C3S SIE uses sea-ice concentration data from the OSI-450 SIC product to develop a training dataset of typical brightness temperatures for three main surface classes of open water (< 30%), open ice (30 – 70 %), and closed ice (> 70 %). The C3S SITy uses a training dataset of typical brightness temperatures for specific target areas in the Arctic Ocean that are thought to be

dominated by multi-year ice and first-year ice, respectively. The C3S SITy also uses the open water classification from the SIE product to derive the 'ice edge' (<30% sea-ice concentration).

The Bayesian approach statistically compares the measured classification parameters against the training datasets to establish Bayesian probabilities (i.e., the most likely surface class) for each grid cell in the SIE and SITy datasets. For each grid cell, the probability of each possible class type sums up to 100%: the final classification is defined by the surface type with the highest Bayesian probability. In addition to identifying the most likely surface type at each grid cell, the Bayesian method indicates the statistical uncertainty of the classification: the higher the calculated probability of surface type, the lower the uncertainty in the resulting classification for each grid point, and *vice versa*. For example, for a SITy grid cell, whereby there are two possible surface types, a 100% probability represents the highest *certainty*, and a 50% probability represents the highest *uncertainty*.

5.3.3.6. Additional Sea-Ice Concentration Processing (Level 3 Processing)

Before the final C3S products are released, several additional processing steps occur. Firstly, a mask is applied to remove erroneous sea ice in areas where it is improbable to be present. This correction method uses the same climatological maximum and buffer zone as the OSI-450 SIC described previously (Section 5.3.2.5). All grid cells that fall outside of this maximum extent are classified as open water. Secondly, the weather filter derived during the retrieval of the classification parameters is applied to remove spurious sea ice that is likely caused by atmospherically influenced brightness temperatures towards the 'ice edge'. Thirdly, grids cells are flagged if the measured ERA-Interim air temperature at 2 m height exceeds 5°C. This is because warm air temperatures introduce errors in the classification of sea-ice types (Tonboe *et al*., 2016). Flagging the pixels that may be affected by warm air temperatures is a way of communicating the associated uncertainties to users and enabling them to make informed judgements. Fourthly, regional ice-type masks are developed to ensure that areas where multi-year ice does not occur are not erroneously classified during the process. Lastly, ambiguous ice classes are introduced into the C3S SITy product to identify grid cells, whereby the classification is too uncertain to be relied on. Ambiguous ice classes are based on the following criteria:

1) Spatial ambiguity – the Bayesian probability of a specific ice class is <75%.
2) Temporal ambiguity – between 1st May and 30th September, all ice-cover is classified as ambiguous.

The leading cause of the temporal ambiguity is meltwater on the surface, which prevents accurate differentiation between first-year and multi-year ice using passive microwave

technologies (Aaboe *et al.*, 2018b). Thus, without supplementing the passive microwave record with additional input data sources as is done in the operational product, the C3S SITy represents an unreliable record of Arctic sea-ice type for nearly half the year. Although using the additional data sources implemented in the operational product would improve the accuracy of the C3S SITy, it would undermine its temporal consistency. Thus, the decision to classify large areas of the Arctic Ocean as ambiguous ice during the summer exemplifies how temporal consistency is the most important factor shaping the product's development.

The final C3S data are provided as NetCDF data files for each available day. The NetCDF files for each product contain the gridded data featuring three key variables listed and described in Table 5.9.

Table 5.9.: List and descriptions of the key variables included in the final C3S data products.

Variable	*Product*	*Description*
Sea-ice edge	SIE	Five variables of surface class based on sea-ice concentration thresholds: land, open water <30%, open ice 30-70%, closed ice >70%, unclassified.
Sea-ice type	SITy	Six variables of surface class on sea-ice types: land, open water <30%, first-year ice, multi-year ice, ambiguous, unclassified.
Uncertainty	SIE and SITy	The estimated error associated with each grid cell – based on Bayesian probability.
Status flag	SIE and SITy	Provides an indication of the processing steps involved in the derivation of a particular classification (e.g., if a grid cell has been set to open water using maximum sea-ice climatology)

5.4. Conclusion: Uncertainties, the Absence of 'Truth', and Interpretive Flexibility

Developing temporally consistent and homogenous records of sea-ice cover is the ultimate motivation underpinning the production of sea-ice data products derived using passive microwave satellite observations. However, as this chapter illustrates, producing consistent and long-term data products from passive microwave observations of sea ice is a complex and multifarious process that involves many uncertainties and assumptions. As Section 5.2 outlines, passive microwave satellite sensors do not directly measure sea ice. Rather, they capture microwave radiation data, from which surface characteristics can be estimated through complex transformation

processes. These processes involve several stages of data selection, conversion, and simplification, and the resulting outputs are often general approximations of surface conditions. Between the four products examined in Section 5.3, the general processes are comparable: the products all begin with the same source of radiation data and employ the same basic principles and technological systems for generating long-term and consistent datasets. These practices are vital to ensuring that practical spatial information can be deciphered from the satellite observations and related to other ocean-climate data products (e.g., ocean and atmospheric temperature). However, differences exist in what aspects of the satellite observations are selected and how they are processed and transformed into ordered and meaningful knowledge about sea ice. Table 5.10 summarises some of the main differences between the methodologies of the four products.

Many of the differences in the methodologies reflect different ways of dealing with the inherent uncertainties and limitations of passive microwave satellite remote sensing. The main sources of uncertainty include atmospheric and oceanic interference and coarse spatial resolutions (Section 5.2.4). These features represent unwanted signals and technical limitations that reduce the accuracy and consistency of sea-ice data products and place constraints on what can be observed. As Section 5.2.1 describes, the initial selection of the frequency channels and polarisations used in the algorithms determine what aspects of the surface are 'seen' during the production of each data product. This, in turn, can significantly alter estimates of total sea-ice cover and its spatial and temporal distribution. The choice of frequency channel also has a significant bearing on the uncertainties introduced into the knowledge production process (Section 5.2.4). At lower frequencies, the brightness temperatures are less contaminated by the atmosphere but have poorer spatial resolution. While this means that the signal observed within the sensor footprint can be attributed to first-year ice, multi-year ice, and open water with greater certainty, the heterogeneity at the surface is more obscured and the estimations more generalised. This introduces significant uncertainties in sea-ice retrieval, particularly in coastal locations and around the 'ice edge', where the boundaries between different surface types fall within the footprint being observed. In contrast, higher frequencies resolve the surface variability at a greater level of detail, but this comes at the expense of accurate sea-ice parameterisation due to greater atmospheric interference.

Table 5.10.: The main methodological differences of the NSIDC SII, OSI-450 SIC, and C3S SIE and SITy data products.

Processing Method	***NSIDC SII***	***OSI-450 SIC v2.0***	***C3S SIE v1.0 and SITy v1.0***
Product Inception	2004 (input sea-ice concentration dataset, 1992)	2017 (original version, 2006)	2018 (operational NRT versions, 2014)
Frequency Channels and Polarisation	18.0 (v, h); 19.0 (v, h); 37.0 (v)	18.0 (v); 19.0 (v); 37.0 (v, h)	18.0 (v); 18.0 (v); 37.0 (v, h); 85.5 (v, h); 91.6 (v, h)
Algorithm	NASA Team	SICCI2	PR/GR and Bayesian
Algorithm Principle	PR/GR	Cluster analysis: combined polarisation and frequency modes	PR/GR and Bayesian
Tie-Point Selection and Adjustment	Fixed	Dynamic	Dynamic
Open Water Filter/Weather Filter	GR(37/19) and or GR (22/19), Fixed	GR(37/19), Dynamic	GR(37/19), Dynamic
Atmospheric Correction of Brightness Temperatures	No	Yes – Numerical weather prediction data, RTM ERA-Interim reanalysis data	Yes – Numerical weather prediction data, RTM ERA-Interim reanalysis data
Gap-Filling	Yes – spatial and temporal interpolation	Yes – spatial and temporal interpolation	No
Land-To-Ocean Spillover	Yes – procedure applied to reprojected SIC	Yes – procedure applied to brightness temperatures at swath level	Yes – procedure applied to brightness temperatures at swath level
Valid Ice Mask	Yes – based on NOAA Ocean Atlas SSTs	Yes – based on NSIDC climatology modified with higher resolution operational ice charts from US National Ice Center, Canadian Ice Service, and Norwegian Ice Service	Yes – based on NSIDC climatology modified with higher resolution operational ice charts from US National Ice Center, Canadian Ice Service, and Norwegian Ice Service
Manual Correction to Remove Spurious Ice	Yes	No	No
Projection	25 km Polar Stereographic	25 km EASE2	12 km and 25 km EASE2
Ice Edge	15% sea-ice concentration	0% sea-ice concentration	30% sea-ice concentration
Intended Users (Primary)	Climate scientists and general public	Climate scientists	Climate scientists

Navigating the tension between spatial resolution and accuracy strongly shapes the methodologies of the four data products examined here. The NSIDC SII, OSI-450 SIC, and C3S SIE and SITy are developed using different algorithms that approach sea-ice retrieval differently. The main differences include the choice of frequency channels and polarisations, the algorithmic principles, and the selection and adjustment of tie-points (Table 5.10). These differences cause variable spatial resolutions and atmospheric sensitivities among the products and require scientists to implement various procedures to remove or reduce their effects on sea-ice retrieval. Although their implementation and associated methods vary by product, the different procedures represent attempts to make the data products more 'truth-like' and representative of actual sea-ice conditions. These include using statistical and empirical correction methods to estimate and reduce the influence of the atmosphere, developing dynamic tie-points to capture spatial and temporal variability in surface emission, applying filters and masks to provide clearer boundaries between the ocean and the land, and manual processing to remove apparent errors.

Scientists' attempts to construct data products that are more 'truth-like' are impeded by a significant challenge: *the absence of 'truthful' data.* In remote sensing, 'ground truth data' refers to the *in situ* measurements obtained using instrumentation located directly at the source of interest. These measurements are important for validating and verifying remotely-sensed observations against actual features and materials at the surface, calibrating remote sensing techniques to reduce errors, and assessing atmospheric interference. Measurements of surface-level conditions obtained from ships and on-ice expeditions are an important source of ground-truthing data for spaceborne observations of sea ice. However, due to the Arctic's extreme weather, long periods of darkness, and the exceptionally mobile and expansive nature of sea ice, ground truth data obtained through these means are spatially and temporally sparse (Meier and Stewart, 2019).

Measurements acquired using higher-resolution sensors and other forms of remote sensing (e.g., aerial photography) are commonly used to supplement ground truth data by providing approximations of surface-level characteristics on a more frequent basis than is available by *in situ* methods. Alternative data sources can also be used to estimate the influence of atmospheric and oceanic components on observed brightness temperatures. Indeed, the four data products examined here rely on external, higher-resolution data sources to validate their outputs and correct uncertainties and errors throughout their production. For example, the OSI-450 SIC and C3S data products use numerical weather prediction data (ERA-Interim reanalysis data) to correct for atmospheric interference; OSI-450 SIC uses high-resolution cloud-free images (MODIS) to assess smearing uncertainties; the NSIDC uses sea-surface temperature data (NOAA Ocean Atlas) to delineate areas of 'valid ice' cover; and all four data products are

validated against operational sea-ice charts produced by national ice centres such as the U.S. National Ice Center (Fetterer, 2002; Kreiner *et al.* 2019a, 2019b). However, while these higher resolution datasets are often considered closer approximations of reality, they are still just that: *approximations.* They, too, are characterised by various uncertainties and assumptions and involve several stages of data aggregation, simplification, and manipulation.

There is broader debate to be had about the 'truthfulness' of ground-truth data and other higher resolution datasets used to validate passive microwave observations of sea ice. Even if ground-level data were more readily available, questions may be asked about how those measurements are obtained, how they are aggregated spatially and temporally, and how they are subsequently scaled up and compared against satellite data. More fundamentally, it provokes questions about how sea-ice conditions are visually determined at ground level. What does 20% sea-ice concentration 'look' like and how does that differ to 10%, 30%, or 40%?

Many of these problems are made more apparent through observational programmes such as Ice Watch: a data network developed at the Geographic Information Network of Alaska and coordinated by MET Norway. Ice Watch encourages and facilitates the standardised collection of ship-based visual observations of sea ice through providing the protocols and software for ships operating in the polar regions to record information on the concentration, morphology, and characteristics of sea ice (Hutchings *et al*., 2020). Although a thorough examination of this programme is beyond the scope of this thesis, a brief analysis of the stipulated methodology offers interesting insights into the subjectivities and drawbacks involved in obtaining visual observations of sea-ice cover. Based on the 'Ice Watch Manual' provided on the website (Hutchings *et al*., 2020), the process of observing ice from ships can be summarised as follows:

1. The preferred location to observe sea-ice conditions is from the ship's bridge or upper deck with a 360° view.
2. If multiple people are observing at the same time, observations should be compared at the time of recording.
3. New observers should be paired with more experienced observers for training and to ensure consistency in observations throughout the voyage.
4. The consistency and quality of observations will be checked by a 'watch leader'. Where possible, the watch leader should routinely observe the ships RADAR and navigational data.
5. Observations of the sea-ice conditions (e.g., concentration, type, thickness, and floe size) should be collected every hour, on the hour, while the ship is moving at approximately 3 nautical miles per hour. Observations are to be recorded over a distance of 1 nautical mile for a duration of 10 minutes. The observations are

recorded using the support software tool, ASSIST (Arctic Shipborne Sea Ice Standardization Tool).

6. Observations of sea-ice concentration is a compulsory data input; all others are supplementary. Sea-ice concentration is recorded in fractions of tenths and observers are provided with photographs and images such as those shown in Figure 5.23 to guide their observations.

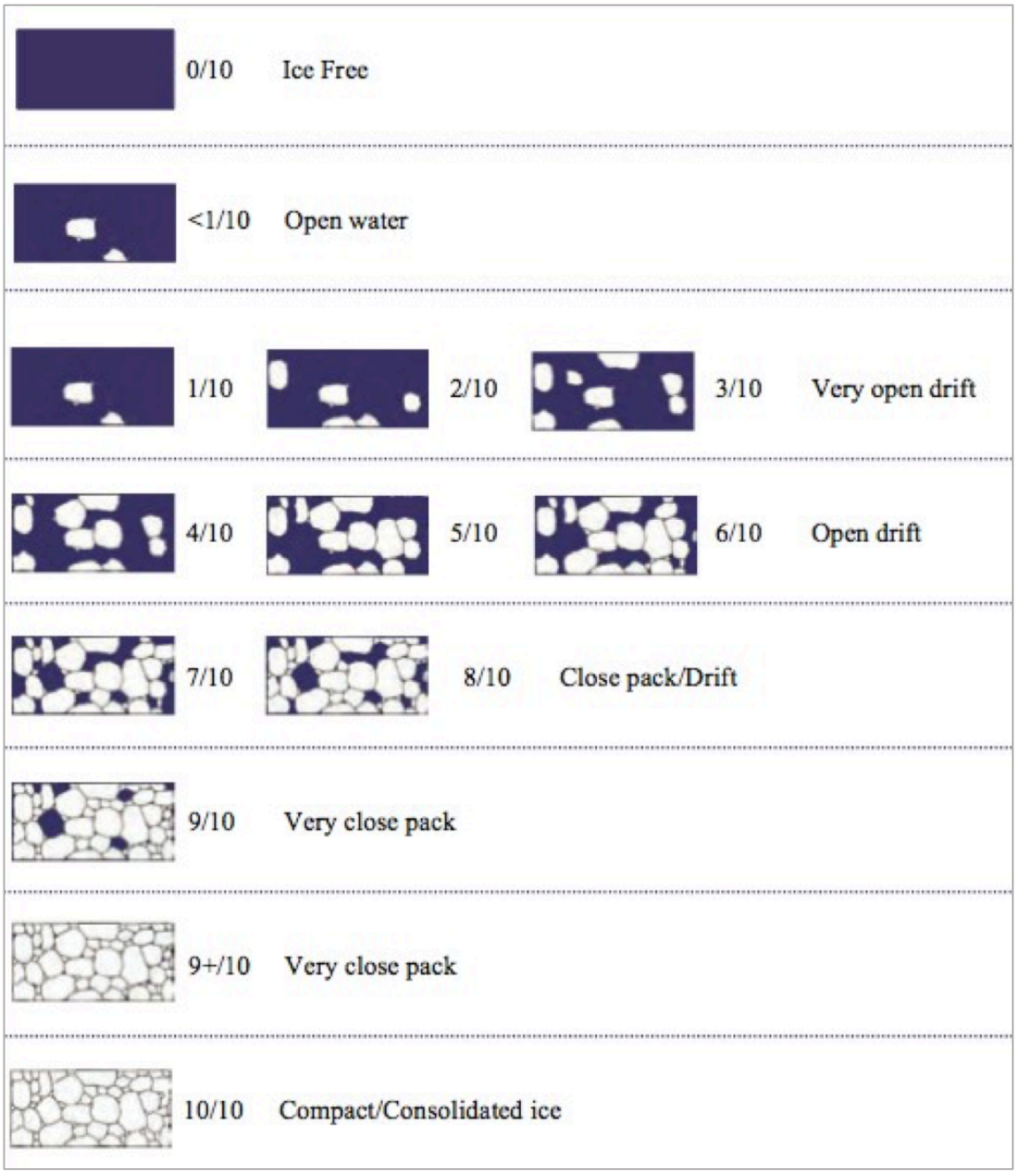


Figure 5.23.: Example images of ice cover fractions. *Source*: Hutchings *et al*. (2020), reproduced from the Canadian Ice Service's Manual of Standard Procedures for Observing and Reporting Ice Conditions (MANICE).

Ultimately, the stipulated methodology of Ice Watch indicates that the characterisation of sea-ice cover using ship-based methods is highly subjective. It comes down to the observer's discretion and relies upon a 'trained eye' and tacit knowledge.

Similarly, a 'trained eye' is central to the production of the U.S. National Ice Center operational ice charts, which are used to validate passive microwave observations. Figure 5.24 shows an example of an operational sea-ice chart produced by the U.S. National Ice Center. Such charts are produced using a variety of data sources: higher resolution synthetic aperture radar imagery is the preferred data type; other satellite, aerial, and ship observations are also used to improve the spatial and temporal coverage. The production of these ice charts typically requires sea-ice analysts to visually identify and manually characterise the ocean surface into different sea-ice types and concentrations, using Geographic Information System ESRI ArcMap software. During a field visit to MET Norway, I observed analysts producing similar charts for the Norwegian Ice Service (Figure 5.25). Through observing analysts digitally hand-tracing the 'boundaries' of the different categories of sea ice, it became apparent that experience, a 'trained eye', and tacit knowledge undoubtedly play a role in determining how the Arctic Ocean is classified into discrete surface categories. This prompts questions over the repeatability and reproducibility of sea-ice charts and their validity as more 'truthful' representations of sea-ice conditions.

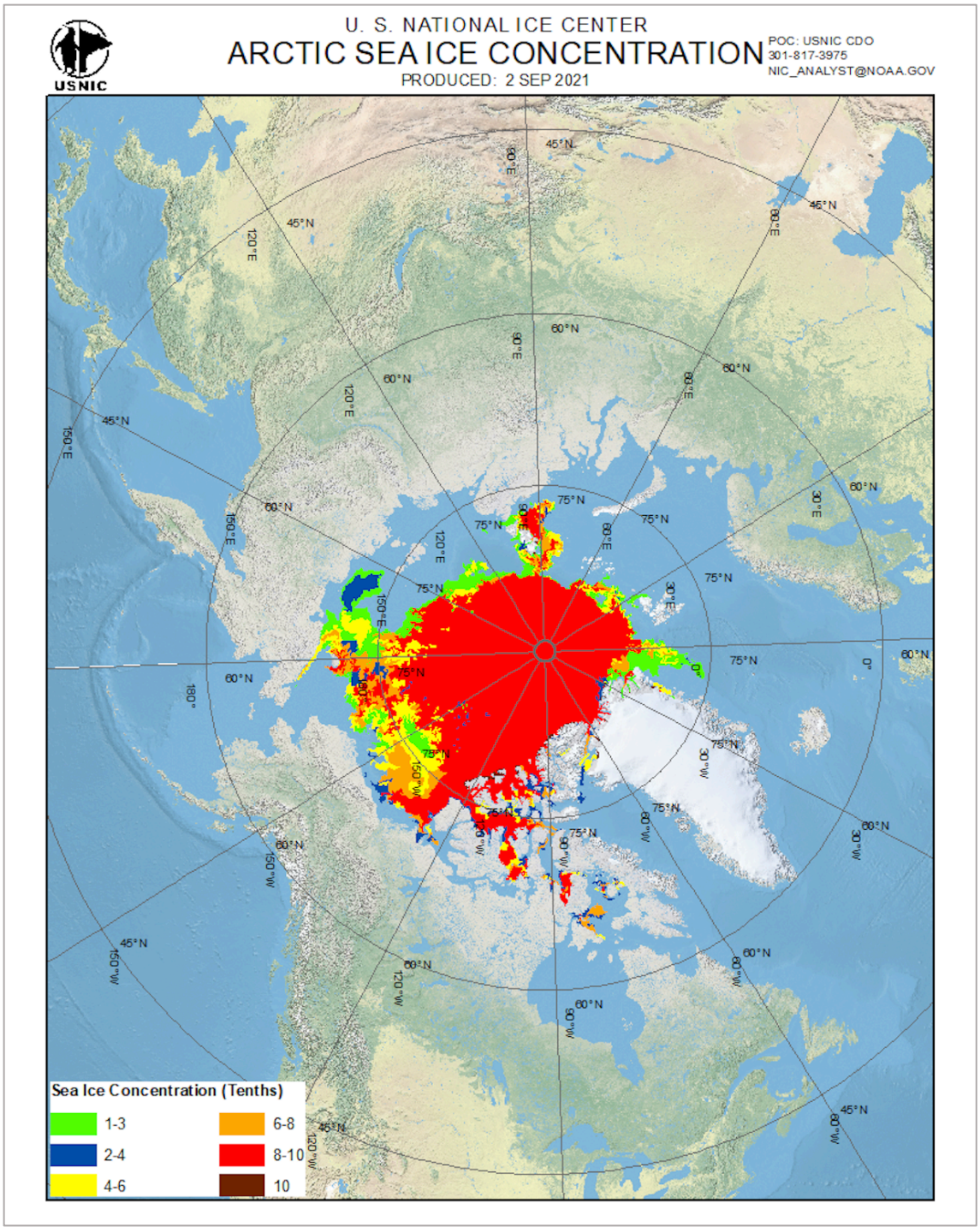


Figure 5.24.: Example U.S. National Ice Center sea-ice chart, produced for 2nd September 2021. *Source:* https://usicecenter.gov/Products.

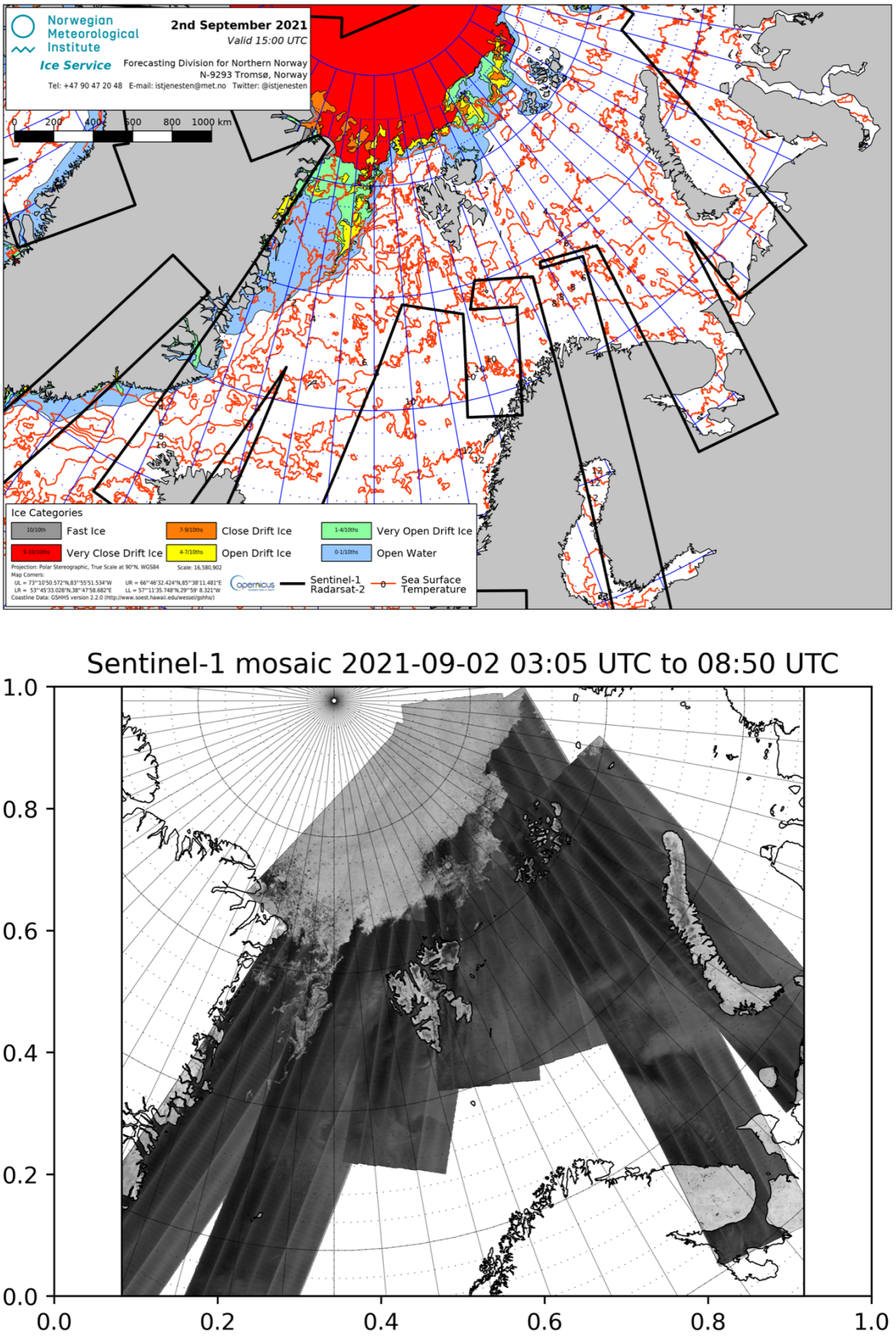


Figure 5.25.: Example Norwegian Ice Service sea-ice chart, produced for 2nd September 2021 (top). Underlying Seninel-1 data used in the production of the ice chart (bottom). *Source:* https://cryo.met.no.

The absence of 'truthful' data means that there is no definitive way of assessing the absolute accuracy of passive microwave satellite observations of sea ice – at least not within the confines of contemporary science and technology. In short, there is no single, universal account of Arctic sea-ice conditions against which the products can be compared. This has facilitated the development of different methodologies used to acquire, process, and represent passive microwave observations of sea ice; to use Collins' words, it has enabled a certain degree of *interpretative flexibility* in producing sea-ice knowledge (Collins and Pinch, 1982; Collins, 1985). The four products examined in this chapter represent different approaches to producing consistent records and managing the uncertainties and limitations of passive microwave sea-ice retrieval. As Chapter 7 explores in more detail, the development of these different approaches may be described as being *contextual* and *relational*. They are contextual in the sense that the methods and procedures implemented in each product reflect the decisions and choices made by the scientists working within their institutional and broader social contexts. These decisions and choices are informed by the products' purpose and requirements, the networks that collaborate in their production, and the scientific knowledge and technical capabilities available at their time of inception. The approaches are relational in the sense that, in the absence of 'truthful' data, their viability and trustworthiness is strongly shaped by how well data products perform relative to each other (e.g., Ivanova *et al.*, 2014; Meier and Stewart, 2019).

In many respects, the methodologies developed by GSFC and NSIDC researchers and implemented in the NSIDC SII have become 'benchmark' approaches in contemporary sea-ice science. This is made evident in the OSI SAF and C3S documentation, which frequently states the need to achieve consistency and comparability with NSIDC procedures, as well as the WMO's formal recognition of the NSIDC SII as a 'benchmark dataset' (WMO, 2019). However, many of the processes applied in the NSIDC SII are rooted in historical contexts; for example, the algorithmic principles and correction procedures were developed over thirty years ago using the scientific and technical know-how available at that time (Cavalieri *et al.*, 1984). While the earlier inception of the GSFC SIC (Table 5.10) and the prestige attached to GSFC and the NSIDC have likely helped the NSIDC SII establish greater authority and credibility within and beyond the sea-ice science community, the value attached to temporal consistency may have had a constraining effect on the product's development.

Over the years, data product validation exercises and intercomparison studies have highlighted the uncertainties and biases present in the NASA Team algorithm (e.g., Steffen and Schweiger, 1991; Cavalieri *et al.*, 1992; Meier, 2005; Ivanova *et al.*, 2014; see Section 5.3.1.3). Such studies are an essential part of scientific progress by helping scientists to identify how the methodologies of sea-ice retrieval can be improved. For example, the deficiencies identified in the NASA Team algorithm motivated the

development of an enhanced version: NASA Team 2 (Markus and Cavalieri, 2000). However, as this chapter has illustrated, even minor changes to the methodologies can have significant implications for the consistency of sea-ice retrieval estimates. This, in turn, reduces the applicability of a data product for climate research purposes. As Chapter 7 will explore further, changing a product's methodology can also have detrimental consequences for the perceived trustworthiness and reliability of a particular approach or dataset. Thus, while minor revisions may be manageable and are often a necessity (e.g., changes to the sensor characteristics), it appears that the NSIDC SII is limited in how much it can adapt and progress in light of more recent developments in scientific research and longer-term changes in the geophysical characteristics at the surface. This sentiment is echoed in the GSFC SIC and NSIDC SII documentation where it is openly acknowledged that the need to maintain consistency in sea-ice retrieval mechanisms is valued more than accuracy (Section 5.3.1).

Following rigorous validation exercises and peer review (Chapter 7), new products can be developed that take advantage of the most up-to-date understanding of passive microwave sea-ice retrieval. For example, through a collaboration with NOAA, the NSIDC have developed an additional sea-ice concentration climate data record that improves upon the limitations of the NSIDC SII to provide more accurate depictions of long-term sea-ice conditions (Meier *et al*., 2017). Similarly, the more recently developed OSI-450 SIC and C3S data products described in this chapter have benefited from the evolution of scientific knowledge and technical capabilities. A notable example of this is the use of dynamic brightness temperature tie-points that are more representative of the spatial and temporal variability in surface characteristics. However, as implied by their comparative use and circulation within and beyond the scientific community, newer products are less established and are yet to achieve the same prestigious reputation enjoyed by the NSIDC SII. This suggests that the success of a sea-ice data product as a reliable and trustworthy form of knowledge is not directly determined by how accurately it depicts sea-ice characteristics. Rather, the success of a sea-ice data product is contingent on social factors such as institutional credibility, the operating duration of the product, and the ease at which data can be accessed and used in different contexts. Chapter 7 will return to these factors in more detail with a particular focus on how *institutional visibility* shapes scientific inquiry.

Examining the four data products developed by the NSIDC and MET Norway reveals how the contemporary scientific practices of acquiring, processing, and reporting Arctic sea-ice conditions vary between different institutions and data products. This chapter has shown that, due to the inherent limitations and uncertainties, the value attached to temporal consistency, and the absence of 'truthful' data, the sea-ice knowledge gained through passive microwave satellite remote sensing is always partial and uncertain. Consequently, sea-ice data products are not mere representations of reality. Instead, they

provide particular ways of interpreting and knowing the Arctic Ocean that are dependent on the situated arrangements and interactions between sea ice, technologies, and people that prevail in specific cultural contexts and at particular moments in time. Chapter 7 explores these situated arrangements and interactions more explicitly in relation to MET Norway's operations. The coarse resolution of the sensors means that even subtle differences in the methodologies can have significant implications for how the surface is interpreted. These uncertainties and limitations are widely acknowledged by sea-ice scientists who emphasise caution around using absolute values of sea-ice parameters outside of the products' intended purpose. However, as Chapter 1 detailed, individual data values and images are regularly circulated outside of the longer time-series and away from their supporting documentation. As such, the uncertainties, assumptions, and complex procedures that underpin their production are harder to deduce and the products appear as authoritative accounts of Arctic sea-ice conditions. The following chapter builds on these discussions and the examinations presented here to critically examine the implications of the different methodologies for how Arctic sea ice is represented cartographically.

6. Visualising Arctic Sea Ice: A Critical Examination of Sea-Ice Maps

6.1. Introduction

Maps have long played an essential analytical and communicative role in Western scientific encounters with Arctic sea ice (see Chapter 4). Since the introduction of satellites in sea-ice research during the 1970s, scientific maps have become a standard form of data visualisation and a principal tool through which scientists interpret and report satellite observations of sea ice. As the previous chapter details, converting satellite data into mapped form is an essential step in producing the NSIDC SII, OSI-450 SIC, and C3S SIE and SITy sea-ice data products. The mapping of data enables scientists to document and monitor changes in the distribution in Arctic sea-ice cover over various spatial and temporal scales and make important inferences about future sea-ice conditions (e.g., Cavalieri and Parkinson, 2012; Stroeve *et al*., 2012a; Stroeve and Notz, 2018). The use of maps also enables scientists to translate and communicate complex research in a way that can be easily understood by diverse audiences (Christensen and Nilsson, 2017).

Due to the near-continuous and large-scale coverage that passive microwave sensors permit, the lack of alternative means of observation, and the ease at which they can be accessed, reproduced, extracted, and translated into various contexts, the NSIDC SII, OSI-450 SIC, and C3S SIE and SITy sea-ice maps have emerged as authoritative accounts of Arctic sea-ice conditions. This authoritative position is reflected in the normative role these products play in supporting leading climate organisations to overcome challenges in climate research and inform appropriate mitigative and adaptive policies (GCOS, 2015, 2016, 2018). It is also reflected in their frequent circulation in high-level scientific reports and national and international news outlets (Appendix 1). Through these various means of communication, these maps shape the knowledge and perceptions of scientists, policymakers, commercial stakeholders, and the general public. For many, scientific maps of sea-ice cover have become powerful and visually compelling indicators of

climate change. By rendering the Arctic Ocean cartographically on daily and monthly timescales, these maps enable viewers to *visualise* the rate and scale of sea-ice changes in ways that are difficult to comprehend via other forms of communication. Consequently, the image of melting ice has become "a pervasive and nearly predictable icon of climate change, signalling catastrophe and global meltdown" (Gabrys and Yusoff, 2012: 2).

However, these sea-ice maps are not simply a reflection of surface conditions, nor are they a depiction of unmediated satellite observations. Rather, they are an essential part of knowledge construction; they are a means through which scientific knowledge claims about sea-ice cover take shape. As Chapter 5 illustrated, the generation of sea-ice data products is a complex and multifaceted process: it involves a myriad of technical procedures that select, transform, manipulate, and refine the data to derive meaning and meet the purpose of the products. Moreover, these processes differ between products and institutions, reflecting different ways of interpreting data and managing the uncertainties and limitations of passive microwave technologies. The resultant maps invariably facilitate an understanding of the Arctic Ocean that is partial and simplified. To be useful, maps must be selective, and mapmakers must choose what to show and how to show it. However, these selective choices have direct and often unintended socio-political, economic, and cultural consequences (Pickles, 2004; Wood, 2010). Yet, when these maps are widely circulated, the complex and contingent processes of knowledge production are hidden from view: the products are *decontextualised* (Latour and Woolgar, 1979). They emerge as seemingly objective and authoritative accounts that naturalise particular ways of measuring, representing, and knowing the Arctic.

In this thesis, I contend that the mapped visions of the Arctic that the four sea-ice data products provide cannot be accepted uncritically as wholly objective, apolitical, and unmediated representations of Arctic sea ice. Moreover, I argue that sea-ice scientists are not passive observers of reality but *active creators* of knowledge. Building on the examinations provided in Chapter 5, this chapter presents the results of a compositional and discourse analysis of the cartographic representations of the Arctic Ocean that the four products represent. In line with the approach outlined in Chapter 3, the following sections critically analyse how the cartographic techniques used to represent the satellite data shape how we perceive and understand Arctic sea ice. Moreover, the chapter questions how the use of specific conventions of sea-ice research has broader implications for our knowledge of the changing Arctic environment.

The chapter is separated into two main sections. Firstly, Section 6.2 explores how the sea-ice data products provide a view of the Arctic that embeds and is embedded in the values and judgements of the mapmakers situated within particular social and cultural contexts. Through examining specific cartographic techniques (e.g., projection, orientation, data selection, symbology), this section reveals the agency of the mapmakers in the production of knowledge, challenges the authority of sea-ice maps as objective

tools of communication, and considers the extra functions that the maps serve. Section 6.3 presents the results of an 'alternative mapping of Arctic sea-ice extent'. By reproducing the NSIDC's forty-year sea-ice extent record using a different definition to delineate the 'ice edge', this section challenges the inevitability of our knowledge of Arctic sea-ice variability in past, present, and future contexts. The overall aim of this chapter is to encourage greater consideration and reflexivity around the unintended socio-political and cultural implications of mapping practices used to communicate scientific knowledge.

6.2. The Cartographic Composition and Discourse of Arctic Sea Ice

The examinations presented in this section are based on the maps shown in Figures 6.1-6.3. These maps are representative examples selected from each of the four sea-ice data products showing sea-ice conditions for March 2015. However, the arguments developed in this chapter apply to the full time series.

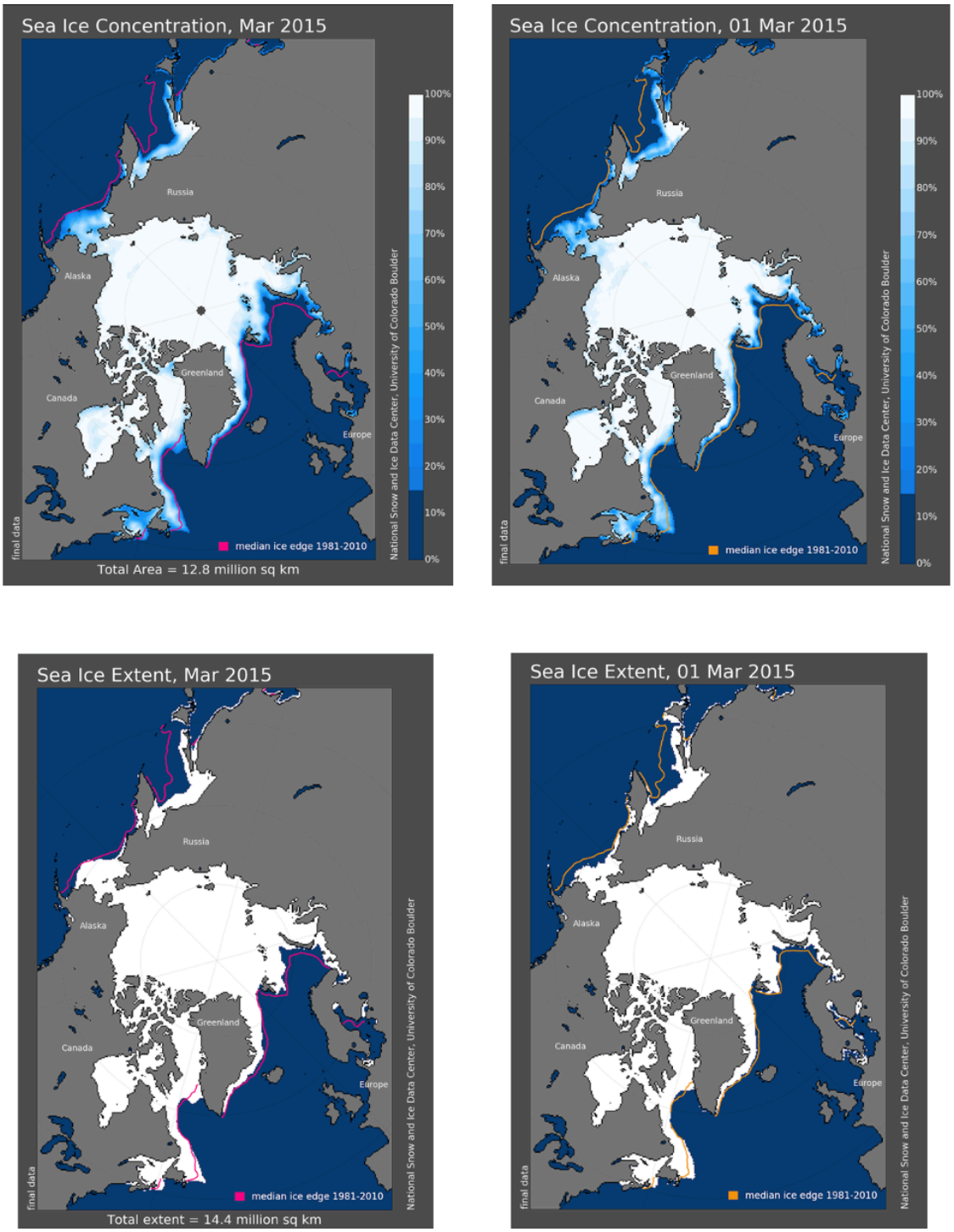


Figure 6.1.: NSIDC SII maps. Monthly sea-ice concentration map for March 2015 (top left); daily sea-ice concentration map for March 2015 (top right); monthly sea-ice extent map for March 2015 (bottom left); daily sea-ice extent map for 1st March 2015 (bottom right). *Source*: Fetterer *et al.* (2017).

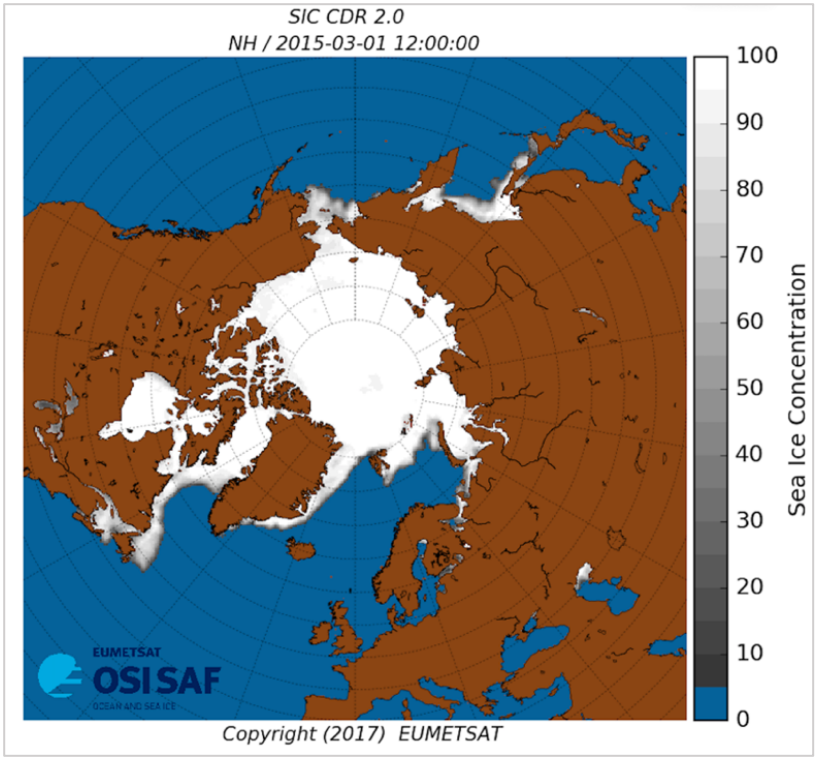


Figure 6.2.: OSI-450 SIC daily sea-ice concentration for 1st March 2015. *Source:* EUMETSAT Ocean and Sea Ice Satellite Application Facility, Global sea ice concentration climate data record 1979-2015 (v2.0, 2017), OSI-450, doi: 10.15770/EUM_SAF_OSI_0008, (Data extracted from OSI SAF FTP server/EUMETSAT Data Center: 1979-2021, Northern Hemisphere, accessed 2021-07-02).

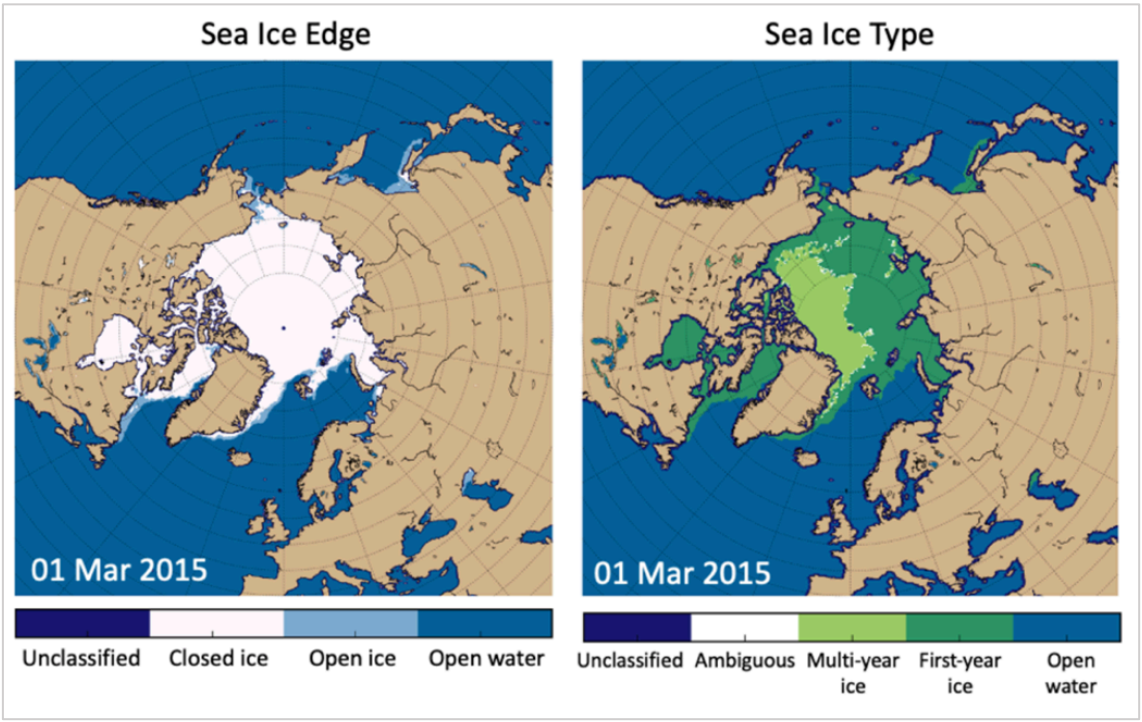


Figure 6.3.: C3S SIE daily sea-ice edge map for 1st March 2015 (left); C3S SITy daily sea-ice type map for 1st March 2015 (right). The maps for the C3S data products are not presented in 'ready-made' form (see Section 5.3.3.1). The examples provided here are taken directly from the product's website, suggesting that these represent the intended map design. OSI SAF's operational versions of the two data products (see Section 5.3.3.2) use the same design, further supporting this suggestion. *Source*:
https://cds.climate.copernicus.eu/cdsapp#!/dataset/satellite-sea-ice-edge-type?tab=overview.

6.2.1. Map Projection

Map geometry has a significant influence on how we perceive space. As Harley writes: "[t]he geometrical structure of maps – their graphic design in relation to the location on which they are centred or the projection which determines their transformational relationship to the earth – is an element which can magnify the political impact of an image even where no conscious distortion is intended" (1988a: 66). The geometry of a map can accentuate or reduce the size of regions, centralise or peripheralise places, and maintain or warp the shape of countries. Although some geometric conventions are more dominant than others (e.g., north-up orientation), the projection and orientation of maps are not fixed nor objective, but a choice made by the mapmakers. This choice inevitably shapes how we view the world and whose perspectives and interests are privileged or marginalised.

Map projection is a fundamental technique of cartography. It is the means by which the Earth's curved surface is systematically transformed onto a flat, two-dimensional plane. A major challenge in cartography is that this process of transformation always induces distortion: there is no way of mapping spherical data to a flat surface while preserving spatial relationships. As Snyder (1997) describes, many hundreds of map projections have developed over the last two thousand years in attempts to map the Earth onto flat surfaces accurately. Yet, all projections inevitably distort areas, shapes, distances, directions, or combinations of these properties.

The nature and amount of distortion vary by projection method and type. The more popular projection methods used today are generally classified as 'conical', 'azimuthal', or 'cylindrical', depending on the projection surface and method used. Different map projection types seek to eliminate or reduce the properties of spatial distortion:

- *Equal-area* projections are designed to preserve the area of the displayed features but do so at the expense of shape, angle, and direction.
- *Conformal* projections significantly distort area but maintain local shapes and angles.
- *Equidistant* projections preserve distances but only between a restricted set of locations.
- *True-direction* projections show accurate directions between specific points but distort shape and area.

In most instances, mapmakers can tailor projections to meet specific requirements depending on the function of the map. The size of the region being mapped also influences the amount of distortion (Monmonier, 2018). Due to the Earth's curvature, distortion tends to be amplified in maps that represent space on hemispheric or global scales. For example, on several world map projections, such as the Mercator's,

distortions to the shape or size of landmasses can be easily identified. On maps depicting more limited areas, such as town or city-level, distortion may be much harder to deduce.

In sea-ice research, area-preserving projections are typically valued more than those that maintain shape, angle, and relative distances. This is because the *area* is the fundamental property being monitored in studies of sea-ice cover. The choice of map projection varies between the NSIDC SII, OSI-450 SIC, and C3S data products. The NSIDC SII uses the NSIDC Polar Stereographic projection, and the OSI-450 SIC and C3S data products use the Equal-Area Scalable Earth Grid 2.0 (EASE-Grid 2.0). These are two of the more commonly used projections in sea-ice research because they provide minimal distortion to area and shape in the Arctic Ocean.

The polar stereographic projection used in the NSIDC SII is developed using an azimuthal projection method. When used in the Arctic, this method places the North Pole at the centre of the map and transforms regions in the Northern Hemisphere from a South Pole perspective (Figure 6.4a). Polar stereographic azimuthal projections are conformal, meaning that local shapes and angles are represented accurately. However, area and distance are increasingly distorted with decreasing proximity to the *tangent* (or 'true point of contact' between the sphere and the surface). In standard polar stereographic projections, the *tangent* is usually defined by a single point placed at 90° N (Figure 6.4a). At this point, the spatial properties are accurately represented.

Significantly, although the North Pole is positioned at the centre in the NSIDC SII maps, the NSIDC's Polar Stereographic projection has been tailored so that the true point of contact is defined by a *secant line* placed at 70° N (Figure 6.4b). GSFC and NSIDC researchers have used this tailored projection for over 30 years (see Gloersen *et al*., 1992). It was developed to reflect the typical location of the MSIZ and reduce the effect of areal distortion on sea-ice retrievals in regions of lower sea-ice concentration, where uncertainties are already greater (Section 5.3.1.3). With increasing distance from the secant line, the accuracy of spatial properties significantly reduces, resulting in areal distortions of approximately 6% at the North Pole and up to 31% towards the outer edges of the rectangular grid (NSIDC, 2021c). As noted in Section 5.3.1.5, statistical analyses of sea-ice concentration, area, and extent require these areal distortions to be accounted for using an additional data processing tool provided on the NSIDC website.

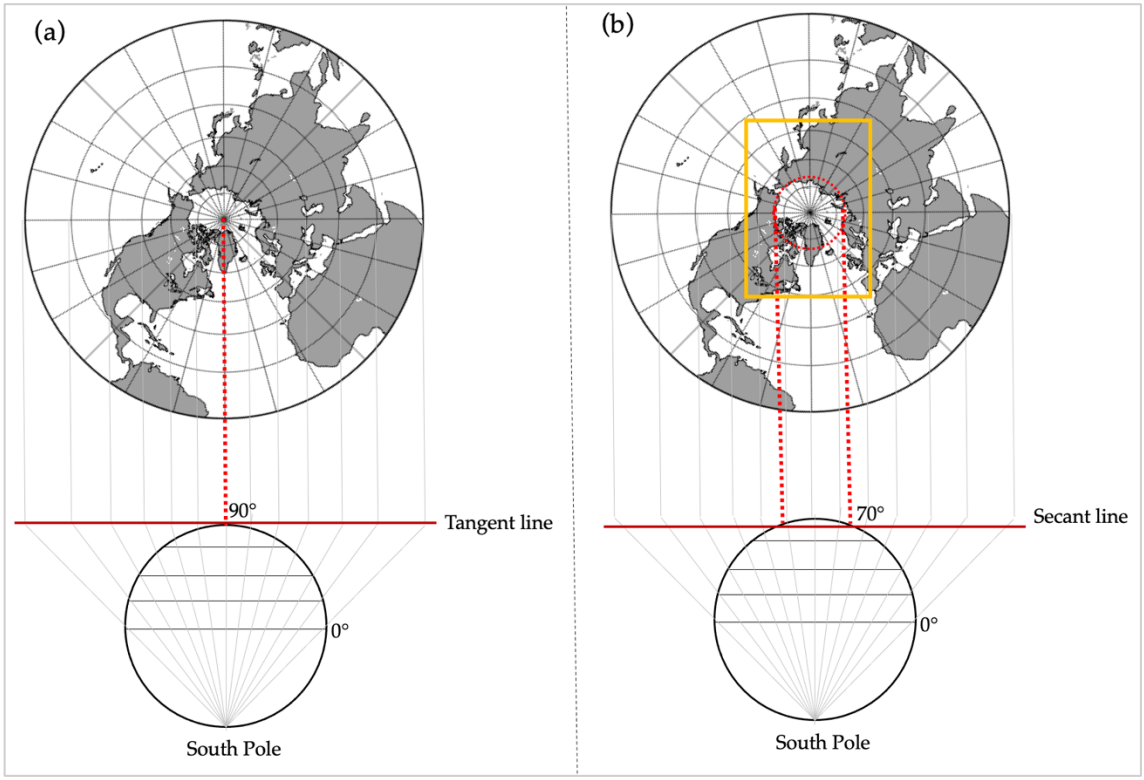


Figure 6.4.: Polar stereographic projection types: (a) standard polar stereographic projection; (b) NSIDC's tailored polar stereographic projection. The red dotted lines indicate the point(s) on the map where the spatial properties are accurately represented. The corner latitude and longitude positions are (latitude, longitude clockwise from top-left): 30.98,168.35; 31.37, 102.34; 34.35, 350.03; 33.92, 279.26.

The tailored projection used by the NSIDC to better represent conditions in the MSIZ prompts questions about its ongoing validity. As sea ice continues to decline, studies have revealed changes to the geometry and location of the MSIZ over recent decades. For example, Rolph *et al*. (2020) show how the location of the MSIZ is increasingly shifting northwards, with average latitudes during July and September typically falling between 74° and 83° N. This suggests that the current method of projecting the data using a secant line at 70° N may not be as applicable as it once was. It is unlikely that changing the position of the secant line by a few degrees' latitude would have a noticeable effect on the cartographic representation of sea ice. However, the tailored definition clearly demonstrates the mapmakers' agency in portraying the Arctic in a particular way that is driven by situated interests.

The EASE-Grid 2.0 used in the OSI-450 SIC and C3S data products is also based on a polar azimuthal projection method but preserves areas rather than shapes. It is defined by four equal-area projection types: two polar azimuthal equal-area projections, a global cylindrical equal-area projection, and a lower and mid latitudinal cylindrical equal-area projection (Figure 6.5). Although equal-area map projections have existed since at least the eighteenth century, the EASE-Grid 2.0 originates from a collaboration between NOAA and NASA during the early 1990s. EASE-Grids were explicitly designed for

passive microwave satellite observations in the polar regions. They provided an easier and more versatile alternative to other pre-existing grids used to project satellite-derived geophysical phenomena (Brodzik *et al.*, 2012). It is not clear whether these pre-existing, less-versatile grids included the NSIDC Polar Stereographic projection. However, a notable difference between the two projection types is that the area of each grid cell is accurate in EASE-Grids and does not require re-adjustment at varying latitudes. This makes the EASE-Grids more convenient for spatial analysis and it increases the transferability and comparability of the data products. As such, they have been applied in numerous remotely sensed and *in situ* datasets of various parameters, including an assortment of sea-ice data products, permafrost distribution, soil moisture, and snow cover.[67]

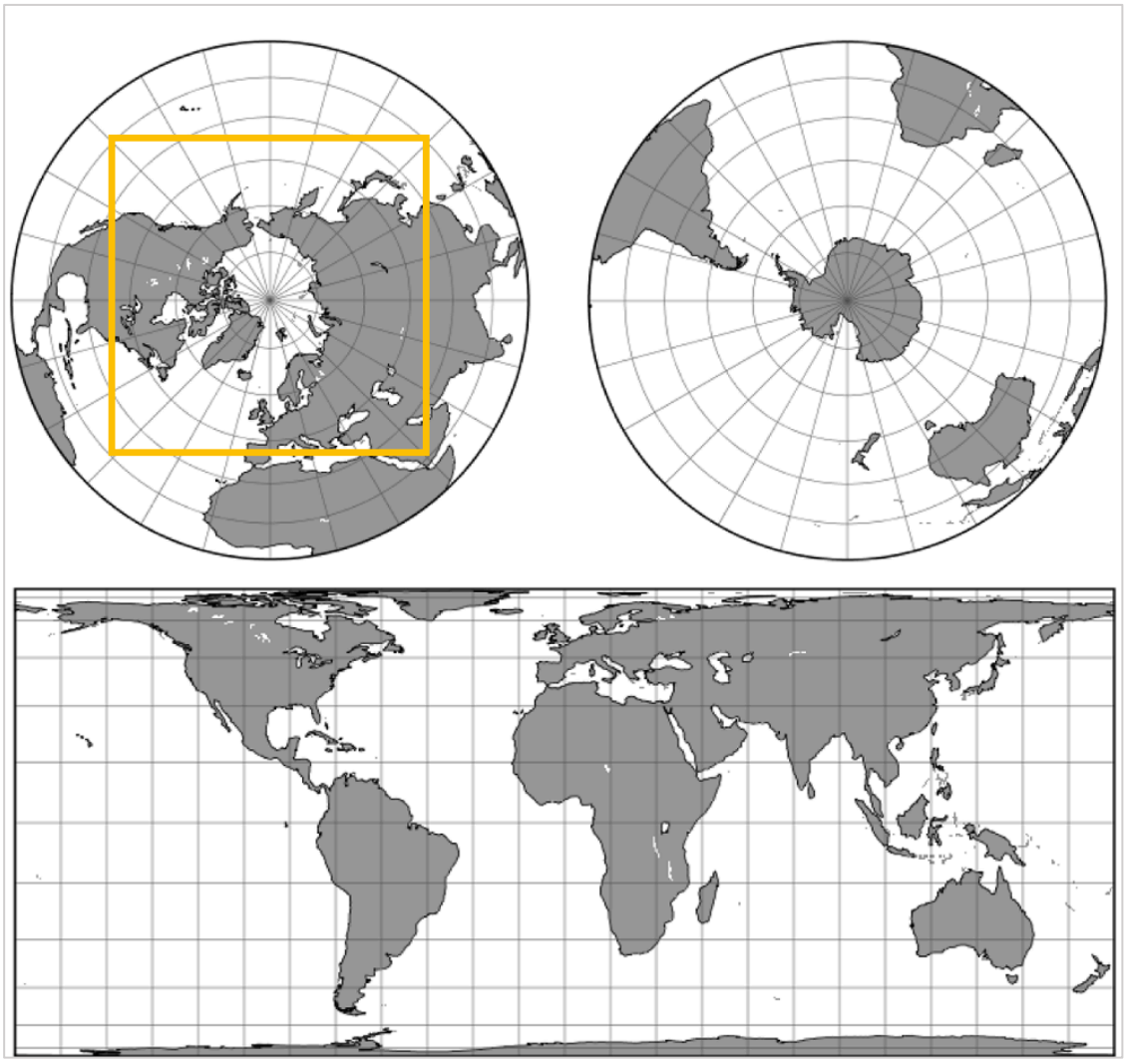


Figure 6.5.: The different projection types that define the EASE-Grid 2.0: a polar azimuthal equal-area centred on the North Pole (top left) and South Pole (top right), and a cylindrical equal-area grid (bottom). The yellow box shows the spatial coverage of the OSI-450 and C3S grids.

[67] For examples, see: https://nsidc.org/data/ease/data_summaries.html.

The OSI-450 SIC and C3S data products are mapped using an azimuthal equal-area projection centred on the North Pole. This projection accurately represents the area of displayed features but distorts their shape with increasing distance from the centre. However, between latitudes of 70-90° N – the approximate region of sea-ice cover – shape distortion is minimal. The preservation of area across the map makes the EASE-Grid 2.0 particularly versatile for sea-ice research: it can be altered to include an infinite number of grid cell resolutions, depending on the spatial resolution and data coverage. This means that sea-ice data sampled at a particular grid resolution can be easily scaled and compared against data sampled at different resolutions.[68]

In the two projection types, the distortions are most significant at lower latitudes: for the NSIDC SII, the area of surrounding landmasses increases radially; for the other three products, the shapes become increasingly stretched. The NSIDC SII also suffers areal distortion at the centre. However, it is difficult to clearly identify these features when visually examining and comparing the various sea-ice maps (Figures 6.1-6.3). The shape of the map frames, the limited regional coverage of the maps, and the omission of national borders (see Section 6.3.2.2) help lessen noticeable distortions. At the hemispherical scale (Figures 6.4 and 6.5), however, the spatial inaccuracies become more apparent.

6.2.2. Map Orientation

Although geometrically dissimilar, the two polar projections used in the NSIDC SII, OSI-450 SIC, and C3S data products present a comparable view of the Arctic whereby north is placed at the centre of the maps. This way of viewing the Arctic differs from the conventional north-up orientation that characterises many world map projections that have become ubiquitous in everyday life. For example, features are almost always orientated with north at the top in Google Maps, atlases, and decorative maps. Ptolemy is often credited as being one of the first to use and popularise the north-up orientation, and it became common practice during the sixteenth century following three interconnected developments: the translation of Ptolemaic methods into cartographic practice; the adoption of magnetic compasses by European navigators; and the publication of Mercator's world map in 1569 (Ashworth, 2019) (Section 4.2.2). Although it is customary today, there is no explicit rule dictating which way a map should be orientated.

In conventional north-up maps, the Arctic region is often partially shown and depicted running along the top of the frame. This way of representing the region can encourage perceptions of the Arctic as a distant and peripheral region, a frontier at the edge of the

[68] For the intercomparison project carried out during the fieldwork (Appendix 8), I compared data at 12.5km^2 and 25 km^2 mapped using the EASE-Grid 2.0. The comparisons involved a simple scaling calculation as opposed to reprojecting the data.

world (Steinberg *et al*., 2015). Indeed, notions of 'looking north', the 'High North', the 'Far North', and the 'Arctic frontier' have become central to many national imaginaries of the Arctic and shaped understandings of its political, geographical, and cultural nature (Dodds, 2010; Steinberg *et al*., 2015; Bennett *et al*., 2016). North-up maps – particularly historical north-up maps – have played a central role in cementing these perspectives (Chapter 4).

In the sea-ice maps, the Arctic moves from the periphery to the centre (Figures 6.1-6.3). The Arctic Ocean is represented in its entirety and is enclosed by the landmasses of the Northern Hemisphere. The cartographic distances between Russia, North America, and Europe are lessened, and the region is depicted as a more interconnected and international space. By visibly emphasising the proximity of the northern continents to the Arctic Ocean and each other, it can be argued that these maps encourage discourses of the Arctic as a space of unity and collective engagement and emphasises that sea-ice decline is a global issue (Wormbs, 2013; Steinberg *et al*., 2015; Lindberg, 2019).

The map geometries differ most notably in their choice of longitude that defines the central meridian and east-west orientation. While there is no fixed approach, many world and polar map projections use the prime meridian to define the "true" centre.[69] The prime meridian is an imaginary line fixed at 0° longitude. It is based on the meridian of the Royal Observatory in Greenwich and became internationally recognised as the universal reference point for organising space in 1884 (Withers, 2017). Due to its international recognition, using the prime meridian to define a map's centre is often taken as neutral. The evolution of the United Nations emblem is a famous example of the perceived neutrality associated with this orientation in polar maps. Produced in 1945 for the United Nations Conference on International Organisation hosted in San Francisco, the original emblem depicted a world map using a polar azimuthal equidistant projection centred on -90° E. However, due to the unequal prominence this orientation gave to North America, the emblem was later revised to 0° to provide a more neutral portrayal (Biddiscombe, 2020).

The OSI-450 SIC and C3S maps are orientated around the prime meridian at 0° (Figure 6.2-6.3). Although it is often regarded as neutral, it can be argued that this orientation promotes a Eurocentric view of the Arctic. The North Atlantic, most of Europe (including Norway), and Greenland are prominent and shown in the familiar north-up configuration, albeit with slight tilting. The shape-preserving qualities of the EASE-Grid 2.0 projection at higher latitudes mean that these regions can be easily identified. In

[69] Several examples can be found on the following websites: Arctic Centre, https://www.arcticcentre.org/EN/arcticregion/Maps; British Antarctic Survey, https://www.bas.ac.uk/data/our-data/maps/topographic-maps/antarctica-and-the-arctic/; The Centre for Borders Research, https://www.durham.ac.uk/research/institutes-and-centres/ibru-borders-research/maps-and-publications/maps/arctic-maps-series/.

contrast, large parts of Russia, Northern Asia, and North America are represented 'upside-down' or heavily tilted and positioned above the North Pole. These arrangements are less familiar in conventional practice. Thus, orientating the map at 0° provides a view of the Arctic that favours the perspective of viewers situated in Europe. In this way, it can be seen to foreground the northerly-directed interests and geopolitical objectives of European nations. In particular, this orientation emphasises the close proximity of northern European nations such as Norway, Sweden, and Finland to the Arctic and reinforces their authority as Arctic States.

There is a need to critically contemplate the historical origins of the prime meridian more generally. The dominance of centring maps on the prime meridian, at least in Western cartographic practice, means its use is rarely problematised, and we often accept it as natural. However, as Withers (2017) describes, the history of how the prime meridian became fixed was by no means inevitable but the product of long and complex political and scientific debate. During the nineteenth century, in an increasingly globalised world, the need to establish a single regulatory line was considered imperative for numerous commercial and socio-political applications. Yet, deriving a wholly neutral reference point was considered impractical, and the lack of robust scientific rationale meant choosing "one line to rule the world" (Withers, 2017: 5) was highly contentious and contingent. Ultimately, the decision to settle on the Greenwich meridian reflected the interests of nations with political authority, scientific superiority, and power. As Warf (2019) writes, this system that has become so central to modern cartography was established on the back of the capitalist and colonial interests and ideologies of Western nations who sought a standardised method for organising space and projecting power. This came at the expense of individual national practices, cultural heterogeneities, and alternative worldviews.

The NSIDC SII maps are orientated around -45° E (Figure 6.1). Similar to the EASE-Grid 2.0, the conformal nature of the Polar Stereographic projection maintains the shapes of landforms. However, in contrast to the OSI-450 SIC and C3S maps, the modified orientation shifts North America eastwards and reduces the region's tilt around the North Pole. As a result, North America assumes a more prominent position in relation to the Arctic and its familiar north-up configuration becomes more identifiable compared to the conventional 0° longitude.

The use of a -45° E orientation in polar maps appears to be exclusive to those that use the NSIDC Polar Stereographic projection grid. As with the tailored latitudinal point of contact, this orientation dates to some of the earliest analyses carried out as part of the GSFC-NSIDC network (Figure 6.6). While early reports explain how the general projection method was established geometrically (e.g., Parkinson, 1987; Gloersen *et al*., 1992), there is no apparent reason for using this particular longitude. At first thought, it

seems plausible that the orientation was selected to best represent the data within the rectangular coverage of the grid; however, Figure 6.6 refutes this.

Why do the NSIDC not use the more conventional orientation at 0°? Is it because the configuration of North America becomes less identifiable, and thus, less familiar to US audiences? Is it a way of promoting institutional authority and distinctiveness through adopting their own conventions? Is there a more technical and scientific justification? The supplementary documentation provides no obvious answers to these questions. However, it does imply that a significant reason for the ongoing use of the NSIDC Polar Stereographic projection and associated orientation is the need to maintain temporal consistency in how the sea-ice data are represented (NSIDC, 2021c). Regardless of the reasons, the GSFC and NSIDC have developed and popularised a way of looking at the Arctic that favours the worldviews and interests of North America and parts of Western Europe.

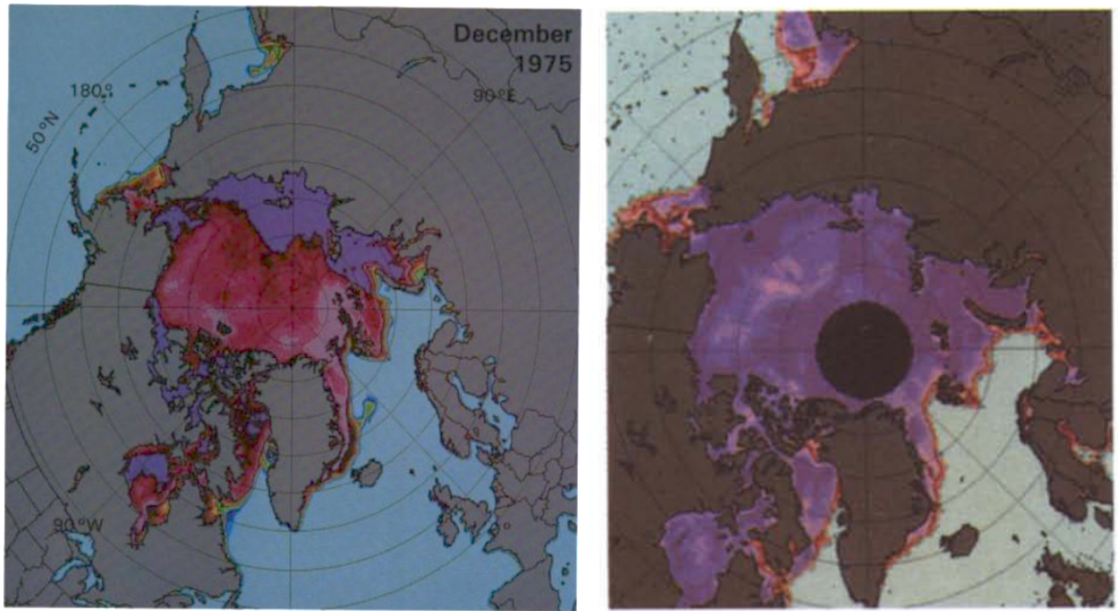


Figure 6.6.: Examples of early sea-ice concentration maps produced by GSFC researchers and archived by the NSIDC: average-monthly sea-ice for December 1975 captured using the Nimbus-5 ESMR sensor (left) and January 1980 capturing using the Nimbus-7 SMMR (right). Both images have been produced using the same projection method and -45° E orientation as the NSIDC Polar Stereographic projection; however, the grid shape and size is not consistent. *Sources:* left - Parkinson *et al.,* (1987); right – Cavalieri and Zwally (1985).

The ethnocentrically biased perspectives that the NSIDC, OSI-450, and C3S data products provide become more apparent when the orientations are altered. Figure 6.7 provides sea-ice concentration maps with central meridians at 45°, 90°, and 180° E. Given my positionality as a Western researcher, as the central meridian moves from 0°, the maps' orientation becomes less familiar, and the shapes of Greenland and Europe become less recognisable. Instead, the perspectives and viewpoints of Eastern Europe, Russia, the Bering Strait, and even Japan and China become more prominent. For the

NSIDC SII in particular, this suggests that the "quick-look" reading that these maps seek to facilitate (Section 5.3.1.1.) is not equally experienced but contingent on the viewers' social and cultural contexts.

Critically, while details of the maps' projection and orientation are documented, the maps themselves do not refer to the projection methods, the nature and degree of spatial distortion, or focal points used. Thus, when the maps are circulated individually and away from the supporting documentation, these viewpoints are taken as natural, and the authoring role of the mapmaker disappears. Moreover, there is no reflexive discussion within the documentation about the potential biases and partialities that the projections and orientations may promote. Indeed, the NSIDC SII user guide states that the projection and spatial coverage of the maps is "simply a convenient pictorial representation" of the data (Windnagel, 2021: 36), implying a lack of awareness of the potential biases these views of the Arctic permit. It suggests that the representational choices are driven by pragmatic and functional concerns, with less consideration for their (unintended) socio-political and cultural consequences.

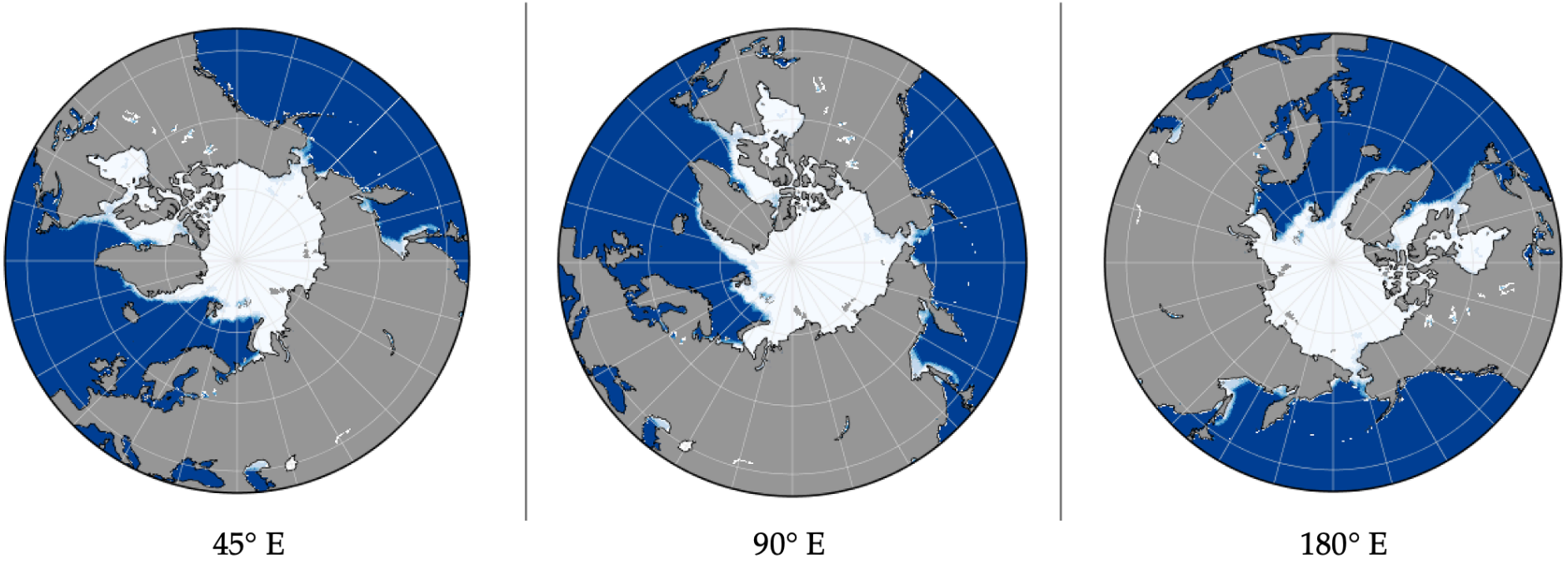


Figure 6.7.: Sea-ice concentration maps orientated at 45°, 90°, and 180° E. These maps are produced using the OSI-450 SIC data but the same biases are present in the NSIDC SII and C3S data products.

6.2.3. Selection, Symbology, and Silences

6.2.3.1. Map Content and Purpose

The NSIDC SII, OSI-450 SIC, and C3S sea-ice maps are produced to represent the areal properties of different sea-ice cover characteristics in the Arctic:

- The NSIDC sea-ice concentration depicts daily and monthly concentration (Figure 6.1).
- The NSIDC sea-ice extent depicts daily and monthly extent (Figure 6.1).
- The OSI-450 SIC shows daily sea-ice concentration (Figure 6.2).
- The C3S SIE classifies the ocean surface into different concentration bands using daily sea-ice concentration data (Figure 6.3).
- The C3S SITy displays the daily distribution of first-year and multi-year ice types (Figure 6.3).

In each instance, the variable and time period being shown is indicated by the supplementary text located above or within the map frame. However, there is no direct mention of the Arctic, and the viewer is left to identify the maps' location by other means. The NSIDC SII maps include a select number of place names, including Greenland, Europe, Russia, Alaska, and Canada. These are likely used to signal the map's location and support the viewers' "quick-look" interpretation; though, it is not clear why this particular combination of continents, countries, and US states is used. The OSI-450 SIC and C3S maps do not include place names; however, the OSI-450 SIC title includes 'NH' to indicate the Northern Hemispheric focus. Beyond these limited toponymic practices, identifying the location and scale of the maps relies upon prior knowledge, familiarity with the map projection and orientation, or reference to the supporting documentation and product webpages.

The maps provide highly simplified representations of the Arctic region. Across all five maps, the gridded data is separated into the elemental surface types of land, ocean, lakes, sea ice, and missing or unclassified data. *Colour* is the primary means through which these different surface types are symbolised. All maps use contrasting colours to distinguish between land, water, and sea-ice covered areas and focus the viewers' attention on the sea ice. Although the exact hues are not consistent between the NSIDC, OSI SAF, and C3S, the maps use colours commonly associated with the surface types they represent: the water-covered areas are depicted in blues; the land is depicted in neutral greys or browns akin to rock or soil; the ice-covered waters predominantly depicted in bright white. The exception to this trend is the C3S SITy map, whereby the sea ice is shown in two different shades of green, reflecting differences in first-year and multi-year ice types.

Table 6.1.: Map characteristics and variables of the four sea-ice data products.

Data Product	*Grid Resolution*	*Grid Domain*	*Number of Individual Grid Cells*	*Variables (Total Number of Mappable Surface Types)*
NSIDC Sea-Ice Extent	25 x 25 km	304 x 448	136,192	- Land (1) - Lake (1) - Open water (1) - Fully ice-covered (1) - Missing data (1)
C3S SIE	25 x 25 km 12.5 x 12.5 km	432 x 432 864 x 864	186,624 746,496	- Land (1) - Lake (1) - Open water (1) - Open ice (1) - Closed ice (1) - Missing data (1)
C3S SITy	25 x 25 km 12.5 x 12.5 km	432 x 432 864 x 864	186,624 746,496	- Land (1) - Lake (1) - Open water (1) - Multi-year ice (1) - First-year ice (1) - Ambiguous (1) - Missing data (1)
NSIDC Sea-Ice Concentration	25 x 25 km	304 x 448	136,192	- Land (1) - Lake (1) - Open water (1) - Sea-ice concentration (17: 5% increments between 15-100%) - Missing data (1)
OSI-450 SIC	25 x 25 km	432 x 432	186,624	- Land (1) - Lake (1) - Open water (1) - Sea-ice concentration (20: 5% increments between 0-100%) - Missing data (1)

Depending on the parameter, the maps use colour in two different ways to represent sea ice. For the NSIDC sea-ice extent and C3S maps, whereby grid cells can be classified into a limited number of discrete sea-ice variables (Table 6.1), single block colours are used to *distinguish* between surface types. Sea-ice extent is a binary definition that classifies the ocean surface as either *fully* ice-covered or open water, depending on whether the sea-ice concentration in a particular grid cell exceeds the 15% threshold (Section 5.3.1.5). For areas representing the ocean surface, each mapped grid cell in the NSIDC sea-ice extent map is assigned a value of '0' (open water) or '1' (ice-covered) and subsequently coloured in single shades of dark blue and bright white, respectively. The C3S SIE data product uses a similar threshold approach to divide grid cells into three discrete classes of open water shown in dark blue (<30%), open ice shown in light blue (30-70%), and closed ice shown in bright white (>70%). Likewise, the C3S SITy product is characterised by three main surface types: open water shown in dark blue (<30%), multi-year ice represented in light green, and first-year ice in dark green.

Notably, while the definitions used to classify the grid cells into the discrete boundaries is provided in the supporting documentation for NSIDC sea-ice extent and C3S maps, there is no indication of these definitions on the individual maps. The C3S maps include a legend signifying the meaning of each colour but with no explanation of how the different classes have been established. Besides a title, the NSIDC sea-ice extent map does not include any descriptive information on the definition of sea-ice extent. Consequently, when viewing the maps in isolation, the different classifications emerge as objective representations of what exists *out there*. The processes of selection, aggregation, and interpolation described in Chapter 5 are unseen.

For the NSIDC and OSI-450 sea-ice concentration maps, grid cells can be assigned a much broader range of values (Table 6.1). Rather than using block colours, colour gradients are used to indicate changes in the *intensity* of sea-ice concentration. The NSIDC map uses a colour gradient from white to dark blue to depict intermediate concentrations between 15% and 100%. A colour bar is included on the side of the map's frame to indicate that the represented changes in sea-ice concentration occur in increments of 5%. Similarly, the OSI-450 SIC map represents changes in sea-ice concentration between 0% and 100%, at 5% increments using a colour gradient from white to dark grey. Like the NSIDC map, this is indicated by a colour bar located on the right side of the map frame.

The use of colour gradients in the two sea-ice concentration maps is limited. Due to the small scale of the maps, the inability to zoom in on their features, and the subtle changes in hue, visually identifying incremental steps in sea-ice concentration is difficult. This has the effect of blurring the boundary between closed ice and open water over an indiscernible area; as such, there is no way of visually identifying intermediate sea-ice concentrations when looking at these maps alone. That said, the NSIDC user guide states

that small scale changes in sea-ice concentration are "probably not significant" (Windnagel, 2021: 9). This statement reinforces that the maps are intended to be viewed collectively as part of a time series, and that variability in sea-ice concentration is to be interpreted on seasonal, interannual, and decadal timescales. In other words, the individual sea-ice concentration maps carry little weight unless they are viewed comparatively.

The importance of time and the value attached to *trends* is strengthened in the NSIDC SII maps by including median sea-ice edge lines. These lines – shown in orange on the daily maps and pink on the monthly maps – represent the median sea-ice extent over the period 1981 to 2010 (Figure 6.1). The purpose of this line is to provide a "quick visual comparison" between the mapped conditions and what is 'typical' for that particular day or month over the longer-term period (Windnagel, 2021: 10). It is a symbolic reminder of the speed at which sea-ice conditions are changing over time.

6.2.2.2. Working Beyond Purpose

The use of common colour associations in maps of the environment (e.g., blue water, brown terrain, white ice) can aid the effective interpretation of a map and eliminate the need for additional explanatory elements such as legends or supplementary text (Monmonier, 2018). While their simplicity is immediately evident, by mimicking colours that can be observed in nature, the NSIDC, OSI-450, and C3S sea-ice maps appear as less abstract and more realistic representations of the Arctic region. Such practice helps the maps achieve a certain degree of objectivity and a heightened sense of *cartographic realism*. This has the effect of distancing the final maps from the complex and contingent transformation processes that underpin their production; it enables the viewer to make an immediate connection between the satellite data and the real-world surface being mapped. Indeed, the power that these colour associations hold in shaping our interpretations is more evident when alternative colour schemes are used (Figure 6.8).

The NSIDC, OSI-450, and C3S maps are produced using digital mapping software programs (e.g., Python) with built-in and default colour palettes. Significantly, due to the underlying data format (Section 5.3), these programs do not implicitly know which gridded data values correspond to 'ice', 'water', 'land', or 'lakes'. Thus, customising the colour schemes to reflect conventional colour associations and delineate the boundaries between different surface types is a deliberate and conscious intervention by the mapmakers.

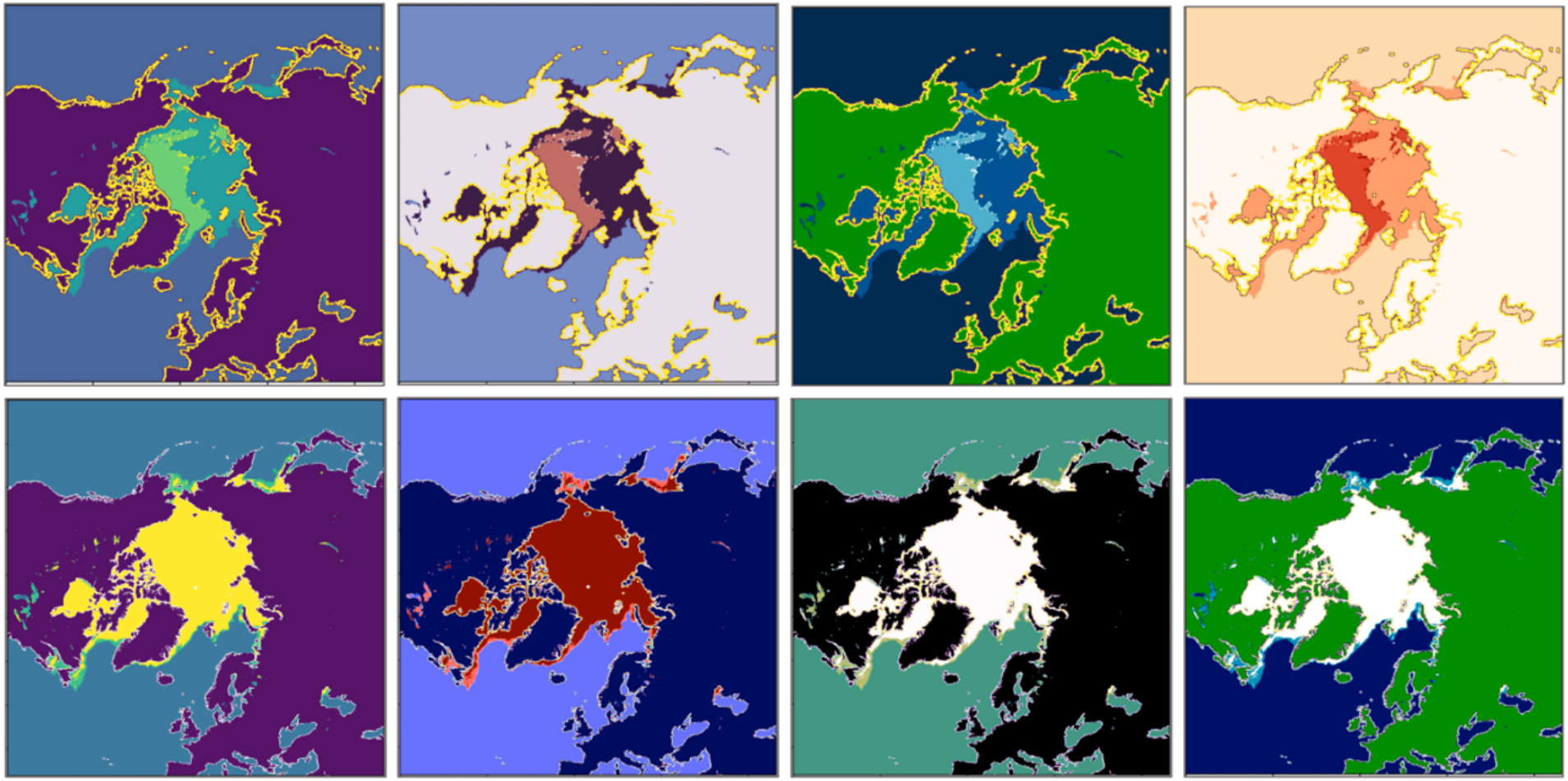


Figure 6.8.: Examples of C3S SITy (top) and SIE (bottom) maps produced in the Python programming software, PyCharm, using a selection of pre-defined colour palettes. The two far-left schemes are default.

The use of single block colours and simple gradients is predominantly a reflection of the products' purpose. Each map is designed to provide a quick visual interpretation of a specific sea-ice parameter that plays an important role in the climate system. For these purposes, the simple colour schemes, conventional colour associations, and the distinct lack of other symbolic elements are highly effective: they draw the viewers' attention to the feature of interest and removes extraneous details. However, as previously noted, these products do not exist solely within the scientific realm. These maps are not simply records of sea-ice parameters but selective interpretations of the Arctic, which shape and constrain broader understandings of the region in the present and future. In this sense, the maps *work beyond their intended purposes*.

Besides the inclusion of major lakes (e.g., Lake Baikal in Russia and the Great Lakes of North America), variations in the topography, ecology, geology, and vegetation are omitted in the maps. There are no national borders, few – if any – place names, and no indication of social infrastructures, communities, and lived experiences. Perhaps more significantly, the Arctic, North Pacific, and North Atlantic Oceans are represented as a single, homogenous unit without labels and with no variation in temperature, depth, or currents – features that have a vital influence on the characteristics of sea-ice cover (Comiso *et al*, 2008). The names of regional Arctic seas are not included, despite being crucial to the regional analyses carried out using the sea-ice data products (e.g., Gloersen *et al.*, 1991; Parkinson and Cavalieri, 2008). The expansive area of bright white (or green in the C3S SITy maps) gives the impression that the Arctic Ocean is dominated by ice and little else.

Additionally, through the use of bright white colour, discrete boundaries, and temporal lines, the maps "propose the existence" of measurable and clearly defined 'ice edges' (Wood, 2010: 44). Using sea-ice concentration as the fundamental unit of measure, the maps construct and fix boundaries between the open ocean and ice-covered waters that do not exist in reality, at least not in a distinct, linear, and uncontested form (Steinberg and Kristoffersen, 2017). The need to delineate the Arctic Ocean into distinct surface types of sea ice, open water, and different sea-ice types reflects the dominant interests of various stakeholders including scientists seeking to quantify the effects of sea ice on the climate system; environmentalists seeking to quantify the rate of change; insurers seeking to quantify risk; and policymakers seeking to implement and justify rules and regulations (see Section 7.4.1). However, it is evident from Chapter 5 that, even within the context of ocean-climate science, what constitutes an 'ice edge' is variable and contingent. Depending on the parameter under study and the scientific methodologies used to transform the satellite data, the 'ice edge' may be defined using sea-ice concentration thresholds at 0% (the OSI-450 SIC), 15% (the NSIDC SII), or 30% (the C3S SIE and SITy). Yet, due to the limitations and uncertainties of passive microwave satellite technologies – namely, the poor spatial resolution of the sensors and the influence of

atmospheric and oceanic factors on sea-ice concentration retrieval – these definitive lines will never be more than approximations. Even when consistent thresholds are used between products, for example, during sea-ice extent analyses, the actual mapped location of the 'ice edge' is not consistent due to the methodological differences outlined in Chapter 5.

The issue of defining an 'ice edge' extends beyond differences in institutional definitions and technological limitations. As Steinberg *et al*. (2020) argue, the indeterminate and dynamic nature of sea ice complicates attempts to define and quantify its spatial properties. The edge of the sea ice is not characterised by a simple and static boundary between ice and water; rather, it is a zone of transition that can extend over several tens of kilometres and is in constant motion due to wind and ocean currents. Within this zone, sea ice exists in many different material forms and many diverse geophysical, biological, chemical, and social interactions and interchanges take place (Steinberg and Kristoffersen, 2017). The presence and ephemeral nature of sea ice govern terrestrial and marine habitats (Derocher *et al*., 2004; Stirling and Parkinson, 2006), affect spatial patterns of biological productivity (Grebmeier *et al*., 2006), and directly influence local, regional, and global climatic regimes (Chapin *et al*., 2012; Overland *et al*., 2018). Arctic sea ice is also an integral part of human life, particularly among Indigenous communities for whom sea ice is central to their livelihoods, well-being, and sense of belonging (Durkalec *et al*., 2015). Economic and political interest has grown substantially in recent decades owing to the growing prospects for resource extraction (USGS, 2017), ambiguities over sovereignty and sea ice law (Dittmer *et al*., 2011; Baker and Mooney, 2012; Shake *et al*., 2014; Steinberg and Kristoffersen, 2017), and the opening of new trade networks (Stephenson *et al*., 2018), in response to diminishing sea-ice cover. Thus, formally defining an 'ice edge' is complicated by the various and often conflicting functions sea ice serves. As Steinberg and Kristoffersen write: "the same area of sea ice may be a hazard to a ship, a highway for a dog sled or snowmobile and a place of refuge for a polar bear" (2017: 629). Across these different contexts, sea ice may simultaneously represent a barrier to movement, a facilitator of movement, or a habitat below, above, or within the ice. Moreover, as Chapter 4 detailed, the functions that Arctic sea ice serves are deeply entangled with societal interests and idealisations that prevail in particular cultural and historical contexts. Ultimately, what constitutes an 'ice edge' varies depending on the circumstances in which sea ice is encountered. However, through the representational techniques used in the sea-ice maps, these diverse circumstances and functions become silenced. The 'ice edge' and boundaries between surface types are defined and stabilised (temporally and spatially) according to the needs, values, and ideologies of ocean-climate scientists working within their particular institutional and social contexts.

The issue in contention is not whether the definitions and representational techniques are appropriate for ocean-climate research purposes (although, as Section 6.3 explores, the validity of conventional definitions is debatable). Indeed, the methods involved in producing the sea-ice data products build upon several decades of intensive scientific research and consensus, and the importance of these maps for capturing the scale and pace of climate change is hard to refute. The key point is that these sea-ice maps are expressions of the Arctic Ocean in geophysical terms: they represent *a version* of the world that is neatly ordered into abstract and quantifiable units that can be systematically monitored. Critically, however, these selective and partial visions of the Arctic have become normalised through their wider circulation. As various others have argued (e.g., Strandsbjerg, 2012; Bennett *et al*., 2016; Steinberg and Kristoffersen, 2017), the power of maps to produce and communicate knowledge of space is particularly prominent in the Arctic because very few people inhabit or experience this space directly. Thus, for many, these partial, selective, and technical cartographic realities of the Arctic are the only realities known.

Without delving into the supporting documentation or examining the maps with a critical eye, the partiality of these sea-ice maps and the mediating role of the scientists is not immediately evident. The maps' objectivity and the neutral role of the scientists is upheld further by the privileged status afforded to satellite technologies as tools of observation. Often termed the "eyes in the sky" (Wormbs, 2013), satellites are seen as a means by which to objectively survey the world and achieve an exceptional perspective that cannot be obtained by other means (Cosgrove, 1994; Parks, 2005). The use of projection, orientation, scale, and colours reminds us that the sea-ice maps have been produced from data obtained at a distance. The cartographic techniques and the discourse surrounding the technological prowess of satellites helps instil the notion that the sea-ice maps offer an unmediated view of the Arctic Ocean. This apparent unmediated viewing is strengthened further in the NSIDC SII maps through the supplementary provision of the sea-ice extent and concentration data mapped onto NASA's Blue Marble images (Figure 6.9). This form of data visualisation makes the image appear like photographs captured from an exceptional position. It persuades the viewer of the unparalleled ability of satellites to objectively observe "everything from nowhere" (Haraway, 1988: 581).

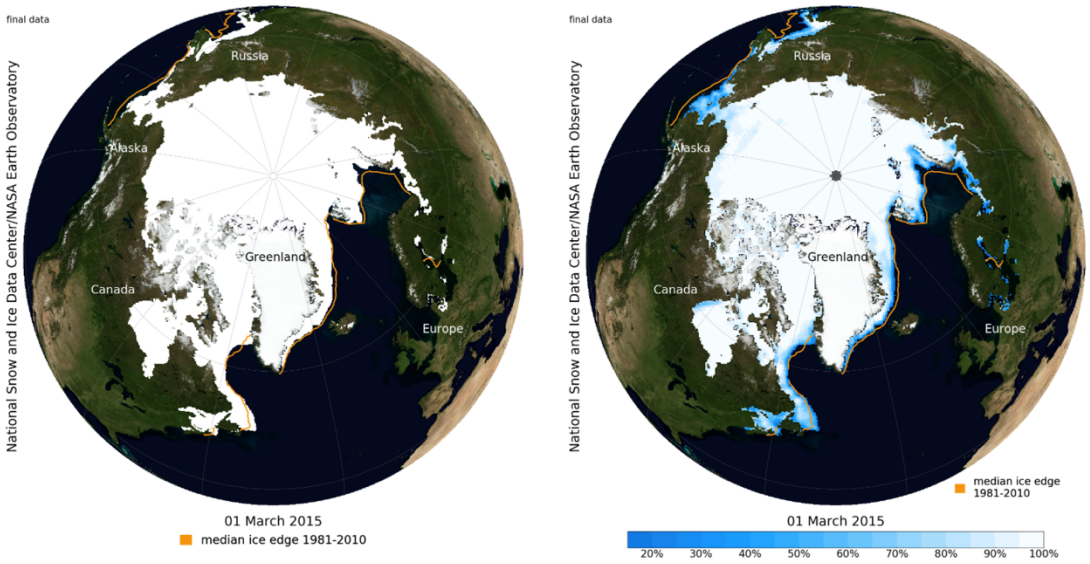


Figure 6.9.: NSIDC SII sea-ice extent and sea-ice concentration data mapped onto NASA's Blue Marble images. *Source:* Fetterer *et al.,* (2017).

The simplicity and selectivity of the sea-ice maps may be desirable for their intended uses and users (see Chapter 7 for a discussion on user requirements). The desocialisation of the Arctic region reflects an attempt to preserve a distance between science and politics and between natural and social matters. It is a way of maintaining the impression of disembodied scientific objectivity and neutrality – features that this thesis contends are unattainable ideals. At the same time, the removal of humanistic elements in sea-ice maps may inadvertently perpetuate misconceptions about sea-ice decline and promote feelings of complacency around climate change action. Articulating the Arctic Ocean in geophysical terms silences many of the socio-political, economic, and cultural challenges and interests associated with sea-ice decline. These omissions speak to several misconceptions and dominant discourses about the Arctic as *the last frontier*, a vast, desolate, and uninhabited wilderness waiting to be intervened by onlookers situated outside of the region (Doel *et al*., 2014; Steinberg *et al*., 2015). As Wormbs (2018) contends, such scientific images promote a narrative of a current and future Arctic that marginalises human agency and frames sea-ice decline as an environmental issue. Sea-ice decline does not just signal an environmental response to warming temperatures. It reflects changes occurring across all scales and facets of life; it is as much a matter of socio-political, economic, and cultural concern as it is environmental.

The simplicity and scale of the maps also reinforces the framing of sea-ice decline as a global phenomenon requiring political action on an international scale (see Section 4.5.2). Such perceptions and understandings of Arctic sea ice as a central component in the global climate system are prevalent in scientific and media discourses about climate change (Christensen, 2013; Christensen *et al*., 2013; Christensen and Nilsson, 2017). While this can help foster international collaboration and responsibility, it can be argued that

this comes at the expense of more local discourses and lived experiences, which are often at odds with the impersonal and minimalistic representations of science (Jasanoff, 2010; Brüggemann and Rödder, 2020; Eriksen, 2020).

Many of the local discourses and diverse meanings of sea ice have been highlighted through the *Siku-Inuit-Hila* (Sea Ice-People-Weather) project that ran from 2006 through 2010 (Gearheard *et al.*, 2013). *Siku-Inuit-Hila* was a multi-disciplinary and multi-cultural project that brought together social and physical scientists and members of Indigenous communities in Barrow, Alaska; Kangiqtugaapik (Clyde River), Nunavut; and Qaanaaq, Greenland. By sharing ideas, knowledge, skills, and experiences relating to sea ice, the purpose of the project was to develop a greater understanding of the dynamics of the relationships between sea ice and humans in the Arctic. Many of the study outcomes are presented in *The Meaning of Ice (*Gearheard *et al.*, 2013) – a rich collection of descriptions, photographs, artwork, illustrations, maps, glossaries, and stories documented through collaborations between scientists and Indigenous communities. The collection provides comprehensive insights into the dimensions of life in the Arctic, the diverse role that sea ice plays in shaping livelihoods, and the various meanings that people attach to sea ice. Notably, the knowledge presented in this collection is often at odds with simplistic, standardised, and impersonal scientific representations; instead, it is diverse, subjective, evocative, and personal.

Similar criticisms have been aimed at other climate change discourses and visualisations (e.g., Nocke *et al.*, 2008; Schneider, 2012; Schneider and Nocke, 2014). For example, Schneider and Nocke (2014) argue that using simplistic colours, highly conventionalised graphs, and elementary symbols to represent environmental features in IPCC reports can create a view of climate change that feels too unfamiliar and disconnected from our everyday lives to initiate practical responses. This has prompted calls for the impersonal, reductionist, and universalist forms of scientific representation to be joined by alternative forms of visual communication that better account for the multiplicity of voices, perspectives, and subjectivities that make up the human dimensions of climate change (Jasanoff and Martello, 2004; Schneider and Nocke, 2014; Wormbs, 2018; Hahn and Berkers, 2021).

6.3. Alternative Mappings of Arctic Sea Ice

6.3.1. Sea-Ice Extent and the Conventional 'Ice Edge'

For ocean-climate science applications, sea-ice extent is among the most important and widely used indicators of the spatial and temporal evolution of Arctic sea-ice cover. As previously noted, sea-ice extent is a measurement of the total area of the Arctic Ocean covered in a significant amount of sea ice. Usually, it is defined using a 15% sea-ice concentration threshold, meaning all grid cells covered in more than 15% sea ice are included in extent calculations (Figure 6.10).

The use of a 15% sea-ice concentration threshold to mark the maximum extent of Arctic sea ice became accepted practice following the NASA DMSP SSM/I Validation Program carried out during March 1988 and described in Cavalieri *et al*. (1991). The validation exercise involved a series of coordinated aircraft flights deployed to obtain sea-ice observations over the Bering, Beaufort, and Chukchi Seas. These higher-resolution observations were compared against sea-ice concentration data obtained via passive microwave sensors and transformed using the NASA Team algorithm. The main objectives of these comparisons were to assess the accuracy of the algorithm and to determine an appropriate passive microwave concentration threshold for defining and mapping the 'ice edge'. The 15% sea-ice concentration band was found to correspond well with the location of the outer edges of sea-ice cover identified from the air. However, as Cavalieri *et al*. (1991) acknowledged when explaining the methodology, choosing a 15% sea-ice concentration threshold was somewhat arbitrary due to the disaggregated nature of the sea-ice edge.

The use of this threshold is crucial to the framing of discourse around Arctic sea-ice decline. For over thirty years, the 15% threshold has dominated our understanding of Arctic sea-ice cover: its use has determined the absolute quantities of sea ice, where the edge is located, and what types of sea ice are included within this definition (i.e., closed or ephemeral). It is also crucial to informing our understanding of potential Arctic futures; for example, speculations about when the Arctic Ocean will experience the first ice-free summer are dependent on the threshold used to define sea-ice extent (Notz and Stroeve, 2018). Consequently, the choice of threshold has significant environmental, socio-political, and cultural implications. As discussed in the previous section, by using a threshold to fix the ice edge in space and time, certain human and non-human encounters with sea ice are made real, possible, and thus regulable, whereas others are marginalised. In other words, it operates as a "more-than-scientific reference" (Gabrys and Yusoff, 2011: 6).

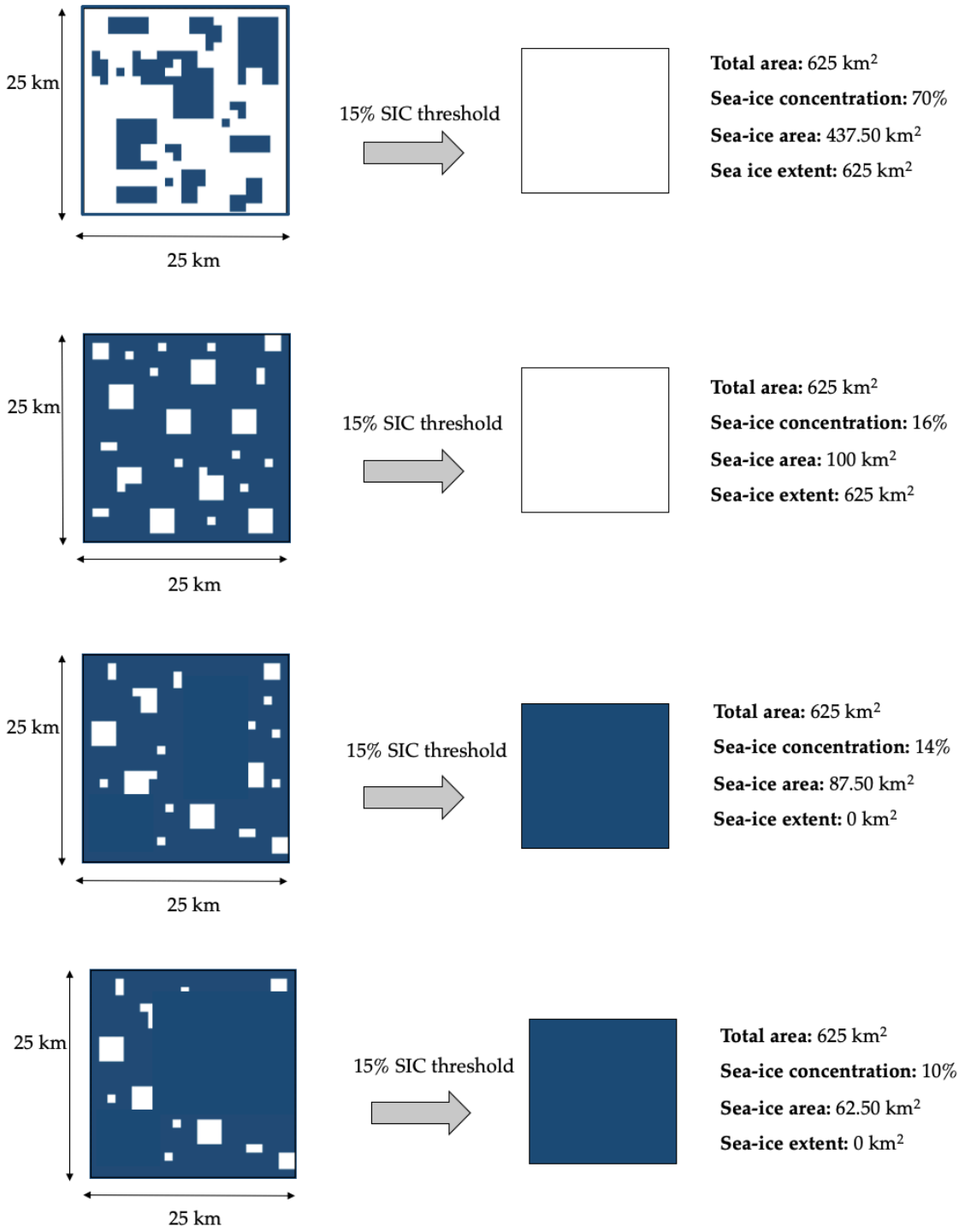


Figure 6.10.: Derivation of sea-ice extent based on a 15% sea-ice concentration threshold, illustrated at grid cell level with a spatial resolution of 25 km x 25 km.

Due to variations in the seasonal regimes of sea ice, such as increased summer melt and changing characteristics of sea ice in the MSIZ, recent research has illustrated that the 15% sea-ice concentration threshold may not be particularly representative of the 'ice edge' position (e.g., Remund and Long, 1999; Partington, 2000; Worby and Comiso, 2004; Ji *et al.*, 2018; Pang *et al.*, 2018; see Section 3.4.4.3). Other studies have examined the implications of using different thresholds on sea-ice extent trends (e.g., Matthews *et al.*, 2020), finding that while long-term trends are consistent, higher thresholds

unsurprisingly alter the timing of the annual minimum and yield earlier estimates of the first ice-free summer. While these studies have highlighted important uncertainties and biases in sea-ice concentration retrieval, they have predominantly focussed on the statistical implications of using different thresholds, with little consideration for how they might affect the cartographic representations of Arctic sea-ice extent.

This section presents the results of the alternative sea-ice extent analysis described in Section 3.4.4.3. Monthly sea-ice extent maps and statistics have been reproduced from the NSIDC SII record using a variety of sea-ice concentration thresholds (15%, 30%, 50%, and 60%). The following sub-sections detail some of the notable visual and statistical implications of changing the sea-ice concentration threshold. The statistical results are intended to be viewed simultaneously with the online web application in order for the reader to observe how using a different threshold affects cartographic representations of Arctic sea ice.[70] The purpose of the following analyses is to highlight how our knowledge of Arctic sea-ice variability in past, present, and future contexts is not inevitable, but shaped by conventions that are somewhat arbitrary, partial, and open to dispute.

It should be noted that the absolute values for each threshold are indicative and that there are additional processing methods that have not been implemented (e.g., manual processing to remove spurious ice). As such, the absolute values calculated using the conventional 15% sea-ice concentration threshold may differ from the NSIDC's reported values.

6.3.2. Results and Discussion

6.3.2.1. Overall Trends

The monthly-averaged Arctic sea-ice extent values for 15%, 30%, 50%, and 60% sea-ice concentration thresholds are displayed in Figure 6.11. Across the full 1979-2019 time series, long-term sea-ice extent trends between the various threshold concentrations exhibit notable yet mostly unsurprising differences. At higher thresholds, the total area of the Arctic Ocean covered in sea ice reduces. From Figure 6.11, the long-term trends appear comparable on seasonal, interannual, and decadal timescales, and the long-term decline is apparent during the typical winter maximum (March) and summer minimum (September).

[70] The web application can be found at the following address: https://alternativemapsofsie.shinyapps.io/Alternative_Mappings/. The application is best viewed using a laptop or desktop computer.

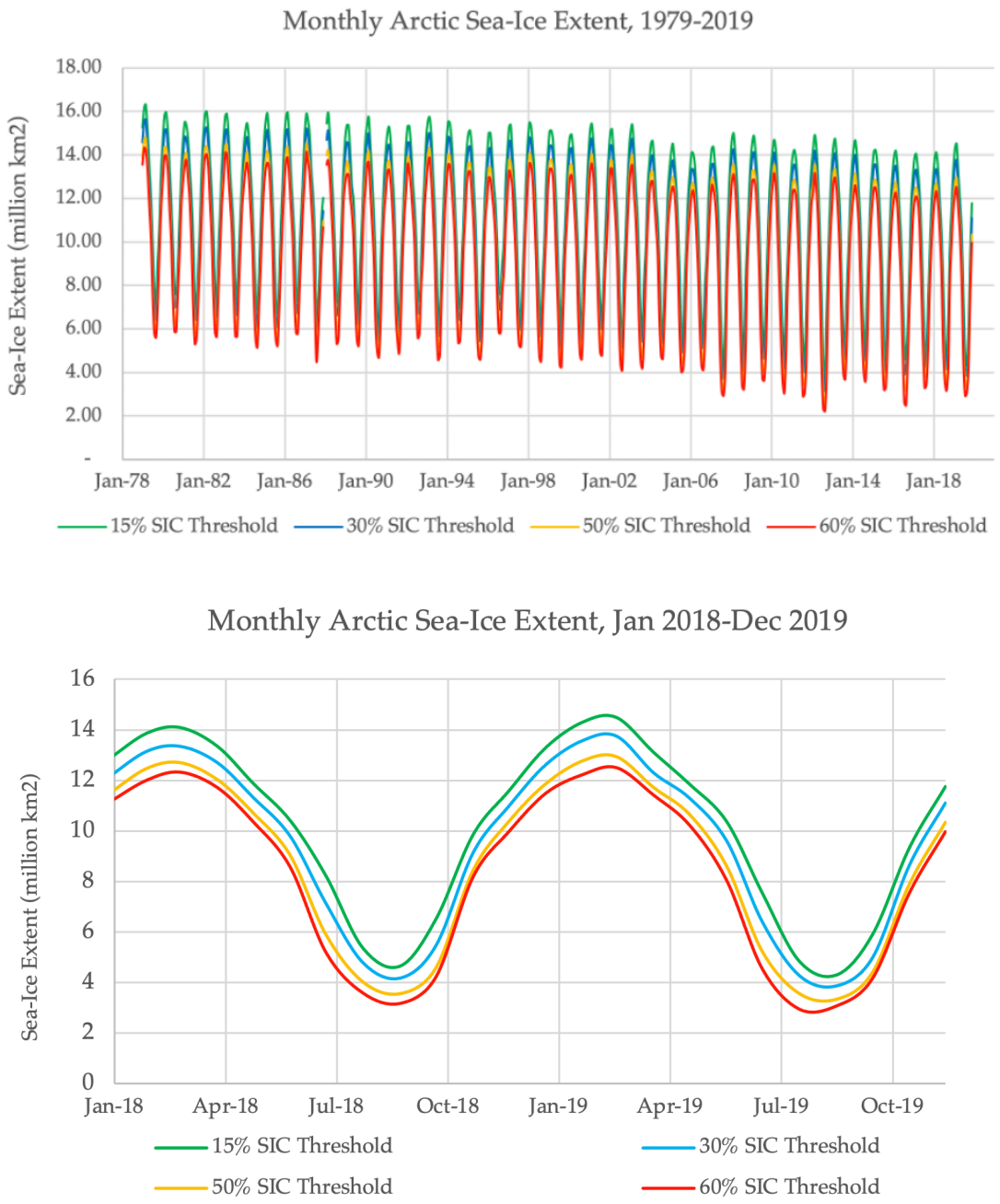


Figure 6.11.: The top graph shows monthly Arctic sea-ice extents from 1979 to 2019, calculated using sea-ice concentration thresholds of 15%, 30%, 50%, and 60%. The lower graph shows two seasonal cycles to aid comparisons.

When viewing the percentage differences between the thresholds (Figure 6.12), there is greater variability in sea-ice extent values, with differences ranging from ~4% to ~50%. Notably, the percentage differences between sea-ice extents calculated at the conventional 15% sea-ice concentration threshold and those calculated at higher thresholds seem to have become more variable and severe in recent years, as illustrated in Figure 6.12 by the increasing redness of the monthly grid cells. This suggests that, at higher thresholds, the 'ice edges' have begun retreat and break-up more extensively than in previous decades.

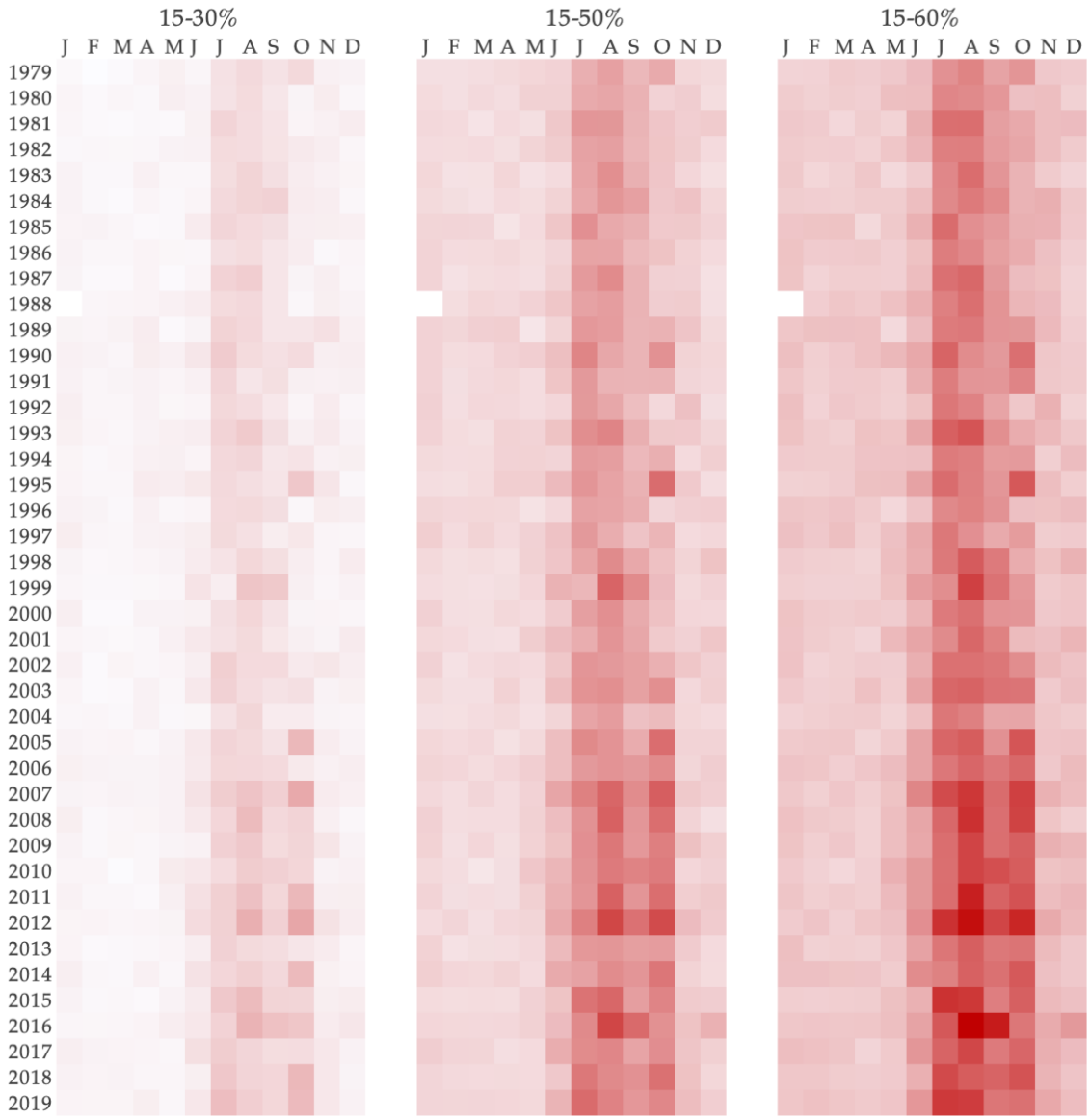


Figure 6.12.: Monthly differences between sea-ice extent values calculated using sea-ice concentration thresholds 30%, 50%, and 60% and the conventional 15% threshold. The darker the red cells, the more severe the differences are. Corresponding percentage values are. Corresponding percentage values are provided in Appendix 12.

Looking at the sea-ice extent maps, the use of different thresholds results in significant changes in the spatial distribution of sea ice. At higher thresholds, the expansive area of bright white visibly reduces in size across all months and thresholds and becomes increasingly punctuated with open water gaps during the summer (Figure 6.13). Sea-ice cover is less extensive around coastal locations, particularly along the western and eastern fringes of the Russian Arctic coastline, the Canadian Archipelago, and the Eastern coast of Greenland.

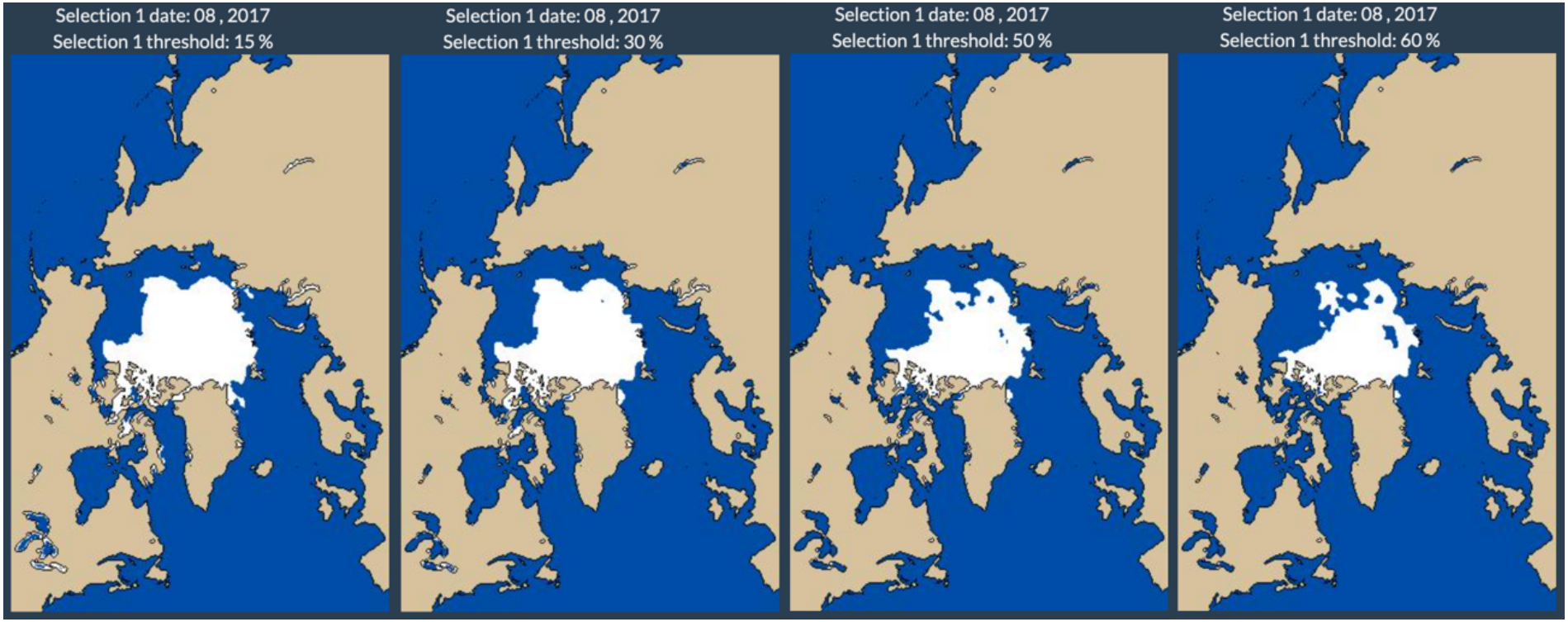


Figure 6.13.: Monthly sea-ice extent maps for August 2017, produced using sea-ice concentration thresholds of 15%, 30%, 50%, and 60%.

6.3.2.2. Monthly Variability

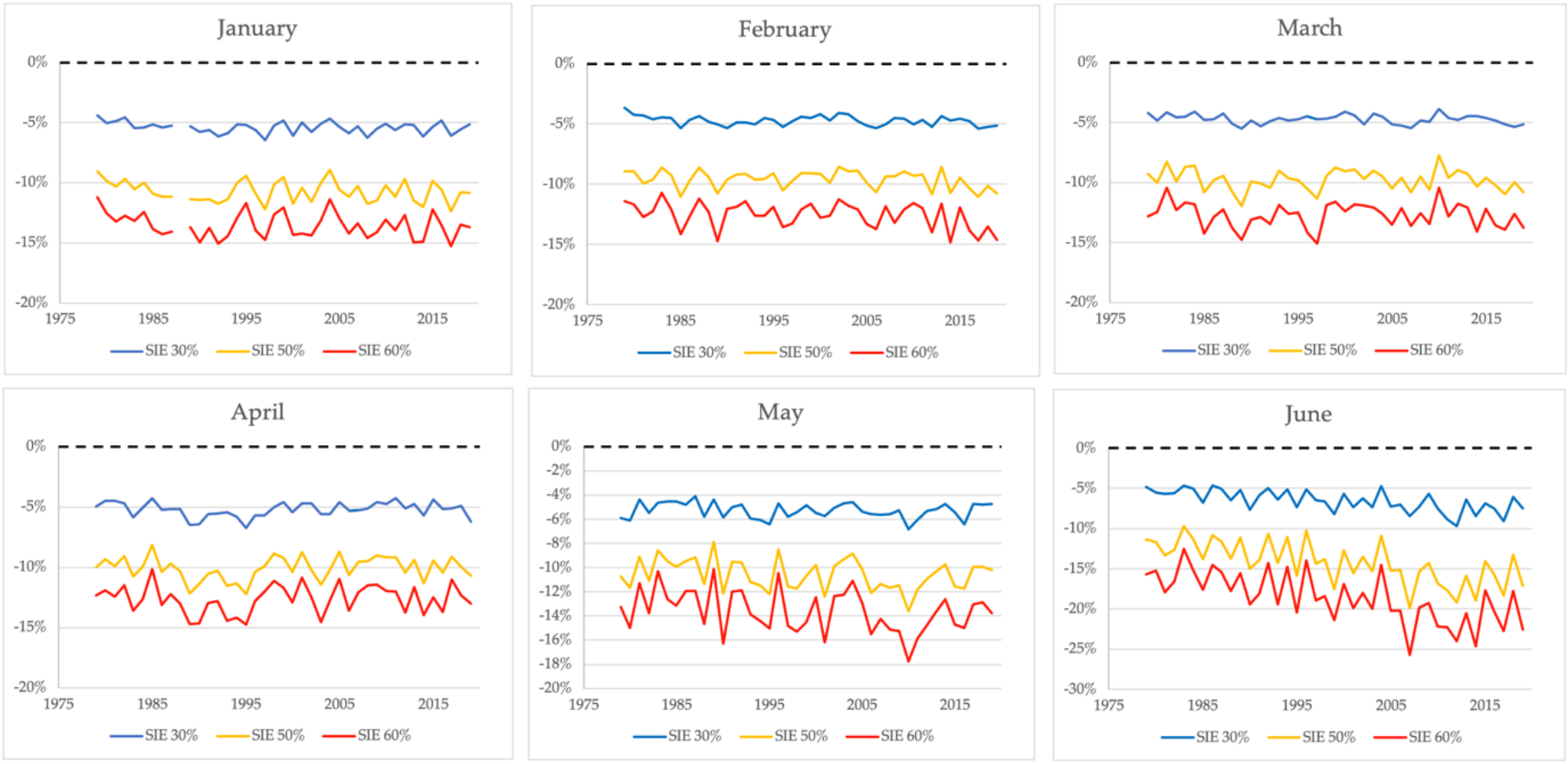
Monthly-averaged sea-ice extent differences for all months are included in Figure 6.14 On monthly timescales, the differences between sea-ice concentration thresholds are more apparent. Across all months, higher thresholds yield lower sea-ice extent values. The differences are most significant and variable from June through October, and the largest discrepancies occur within more recent decades (Table 6.2).

The statistical differences on monthly timescales reflect the more general changes to sea-ice cover that have occurred in recent decades. Based on long-term analysis of passive microwave trends and earlier records from the 1950s onwards, research has shown that melt seasons are becoming longer and starting earlier in the year (e.g., Serreze *et al*., 2007; Stroeve *et al*., 2012b). The results presented in this study imply that these shifts in the timing and duration of the seasonal thaw are more apparent at higher thresholds.

Table 6.2.: The top ten dates where the different thresholds yield the greatest differences in monthly sea-ice extent values.

		Sea-Ice Extent (million km2)				*Percentage Differences*		
Rank	*Date*	*15%*	*30%*	*50%*	*60%*	*15-30%*	*15-50%*	*15-60%*
1	Aug-16	5.34	4.42	3.33	2.62	-17%	-38%	-51%
2	Aug-12	4.52	3.70	2.82	2.34	-18%	-38%	-48%
3	Sep-16	4.60	3.93	3.18	2.50	-15%	-31%	-46%
4	Aug-11	5.30	4.51	3.57	2.92	-15%	-33%	-45%
5	Oct-12	6.82	5.48	4.31	3.83	-20%	-37%	-44%
6	Aug-08	5.80	4.88	3.90	3.38	-16%	-33%	-42%
7	Jul-12	7.54	6.66	5.52	4.41	-12%	-27%	-42%
8	Jul-15	8.40	7.28	5.94	4.91	-13%	-29%	-42%
9	Aug-07	5.19	4.46	3.54	3.09	-14%	-32%	-41%
10	Aug-15	5.39	4.54	3.69	3.21	-16%	-32%	-40%

The greatest discrepancy occurs in August 2016, with differences in sea-ice extent values of up to 2.7 million km^2 (~51%). As Figure 6.15 shows, changing the threshold has the most prominent influence on the 'ice edge' location in the East Siberian and Chukchi Seas, and Central Arctic Ocean. At lower thresholds, large parts of these regions are shown to have significant ice coverage. At higher thresholds, the 'ice edge' shifts northwards away from these regions and they are represented in the maps as far more open and almost completely 'ice-free' during the summer. Similar spatial patterns are visible during the summer months throughout much of the record.



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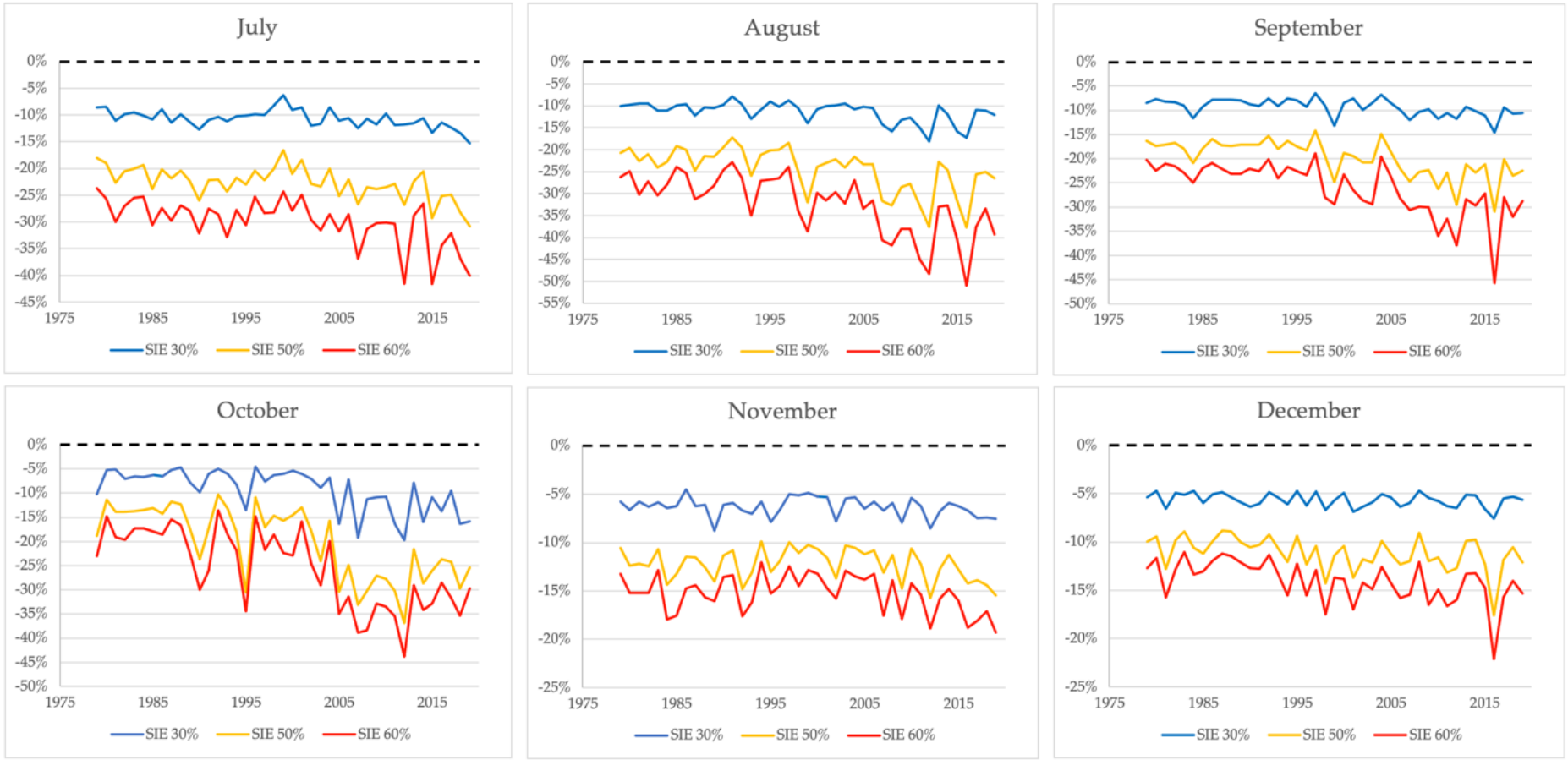


Figure 6.14.: Differences in monthly-averaged sea-ice extent values calculated using 15%, 30%, 50%, and 60% sea-ice concentration thresholds, for each month of the year between 1979 and 2019. The black dashed baseline represents the 15% threshold. The differences in sea-ice extent values between 15% and 30% are shown in blue, 15% and 50% in yellow, and 15% and 60% in red.

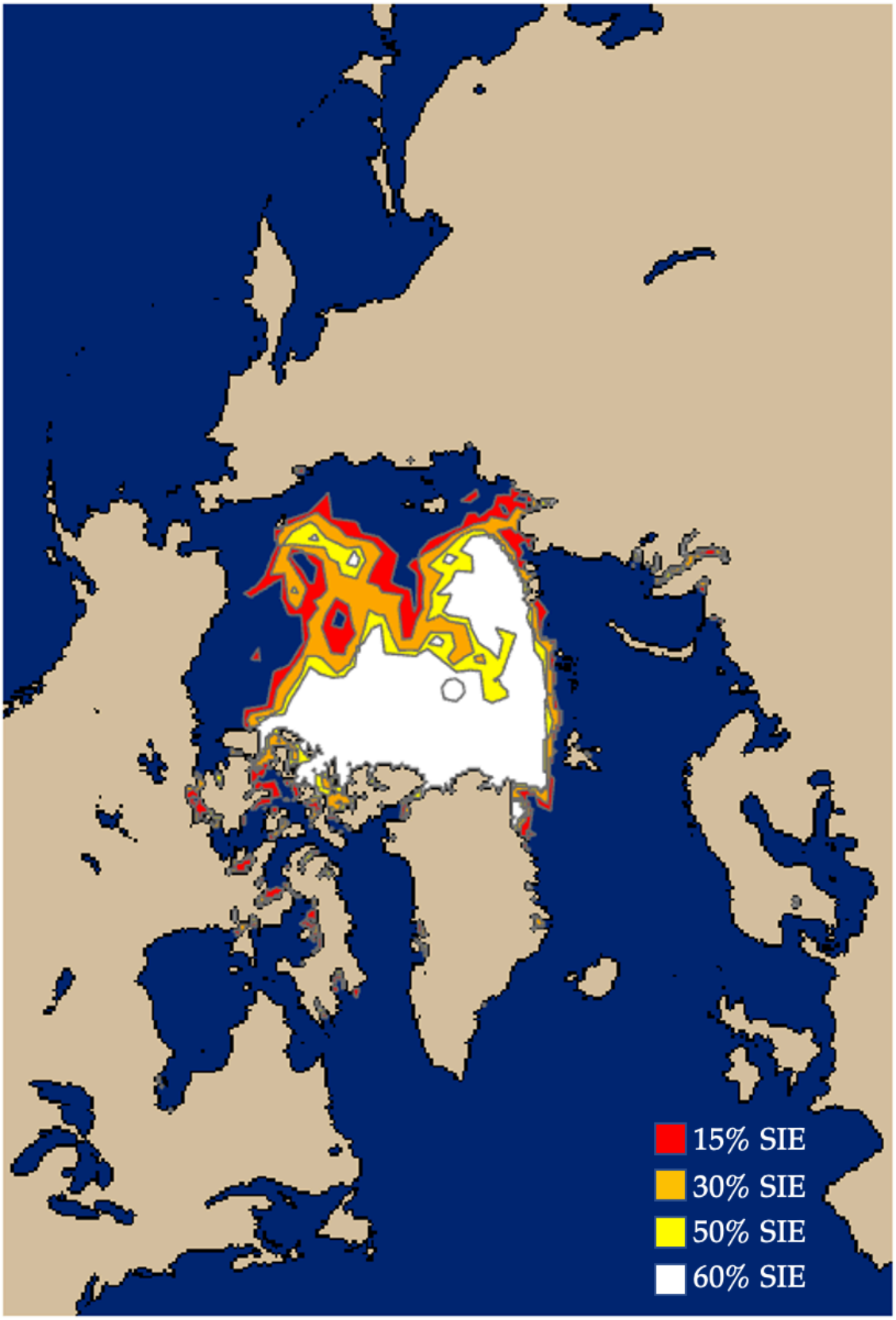


Figure 6.15.: Monthly sea-ice extent map showing the different locations of the sea-ice edges derived using sea-ice extent thresholds at 15%, 30%, 50%, and 60% for August 2016.

Comparing the different 'ice edges' associated with the various thresholds reveals how important threshold choice is in shaping the potential opportunities and risks that sea-ice decline may provide (Figure 6.16). The maps of sea-ice extent produced using higher thresholds construct visions of a more open and ice-free Arctic. In some instances, particularly during earlier years of the record, summer sea-ice extents mapped using the conventional 15% threshold extend across the Arctic Ocean from North America to Russia. This creates a seemingly continuous and homogenous unit of ice joining the two landmasses and blocking the Arctic sea routes for most of the year. In contrast, at higher thresholds, the Northern Sea Route and Northwest Passage are seemingly open and ice-free. These representations favour the interests of strategic and commercial prospectors as maritime activities appear more logistically and economically viable.

Ships operating in the Arctic region tend to rely upon higher resolution ice charts for navigational safety and seasonal forecasts for short-term planning and decision making (Stephenson and Pincus, 2017). Thus, as independent records, passive microwave observations of sea ice tend to be less applicable for short-term navigational purposes. However, seasonal forecasts are based on various data sources, including passive microwave observations of sea-ice extent defined using the conventional 15% threshold. Using probabilistic and coupled ice-ocean atmospheric models, seasonal and decadal forecasts increasingly rely on passive microwave observations of sea-ice extent to predict the future spatial and temporal distribution of Arctic sea ice (e.g., Stroeve *et al.*, 2012a; Stephenson *et al.*, 2018; Andersson *et al.*, 2021). These predictions are used to inform the planning and investments in energy, security, and environmental policy (Stephenson and Pincus, 2018).

Several studies have shown that the validity of the 15% sea-ice concentration threshold as an indicator of the 'ice edge' position is increasingly uncertain during the summer due to the disaggregated nature of the MSIZ, surface meltwater, and limitations in passive microwave technologies (e.g., Remund and Long, 1999; Partington, 2000; Wormby and Comiso, 2004; Ji *et al.*, 2018; Pang *et al.*, 2018; Meier and Stewart, 2019). Critically, if the 15% threshold is becoming less valid, then predictions of future sea-ice conditions and the associated opportunities and risks they pose are becoming more uncertain. This exemplifies how the choice of threshold is not just a scientific convention used to monitor changes in sea ice for ocean-climate research purposes. By fixing a continuous boundary between 'ice-covered' and open water areas, it shapes and constrains the socio-political, economic, and cultural implications of changes in Arctic sea ice. In the context of maritime activities, it is an indicator of the 'openness' of the Arctic Ocean.

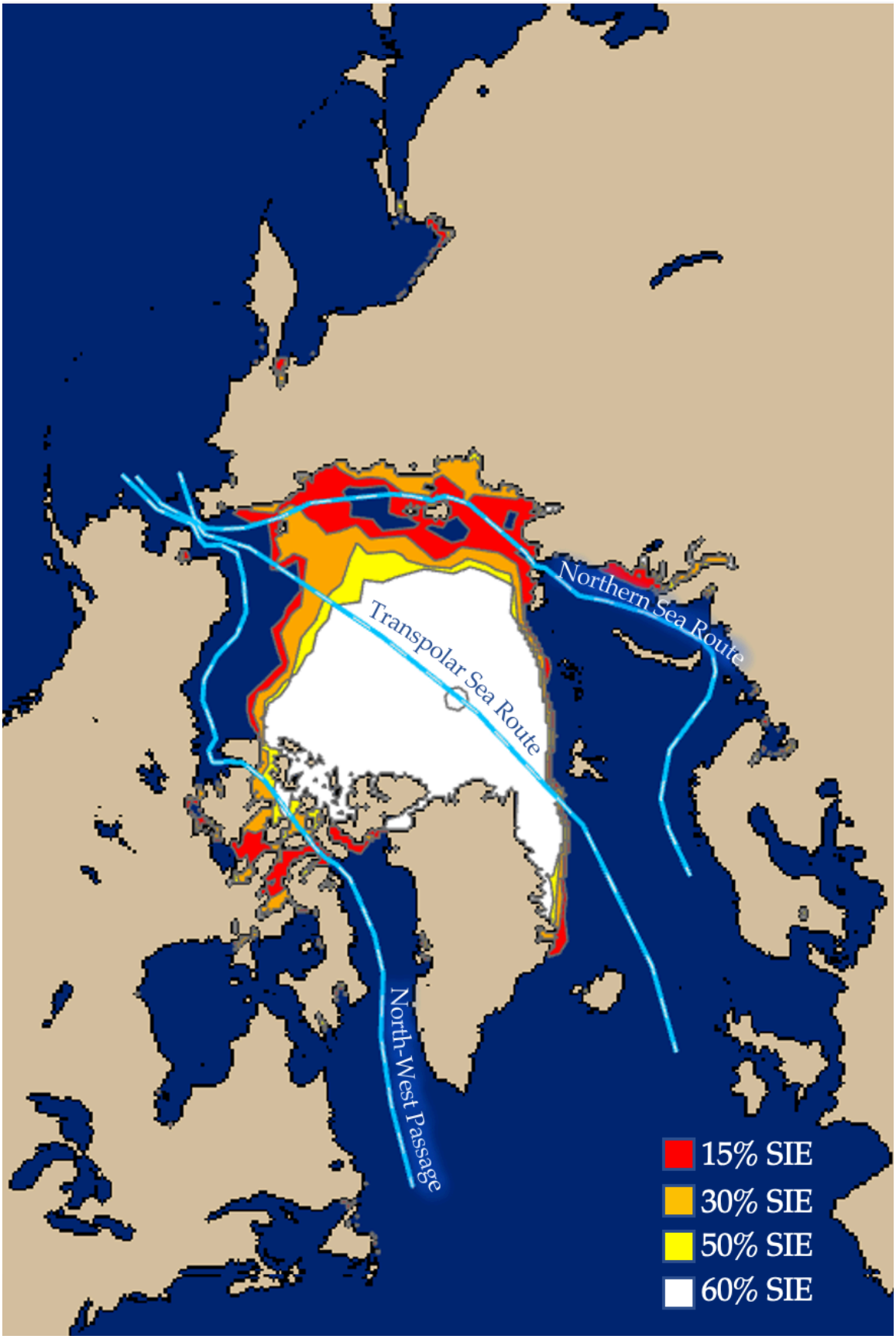


Figure 6.16.: An example sea-ice extent map whereby the different 'ice edges' either permit or block maritime travel along the sea routes. The sea-ice data is monthly average for October 2012.

The spatial differences in mapped sea-ice extent also highlight issues regarding the Arctic Pole Hole. As described in Section 5.3.1.4, data gaps occur at the North Pole due to the near-polar orbit of the satellites. It is generally assumed that this area is covered in sea-ice concentrations exceeding 15%; therefore, it is automatically classified as 'ice-covered' and included in calculations of sea-ice extent. However, the assumption that the Pole Hole meets the threshold concentration can no longer be relied upon at higher thresholds. Figure 6.17 shows a map for September 2016, whereby the Arctic Pole Hole intersects with the 60% sea-ice concentration boundary. While it is highly unlikely that 60% sea-ice concentration threshold would be adopted as a definition for sea-ice extent, it highlights the possibility that the current assumptions and ways of managing the Pole Hole data gap using the conventional 15% threshold may not be valid in the future as sea-ice continues to retreat.

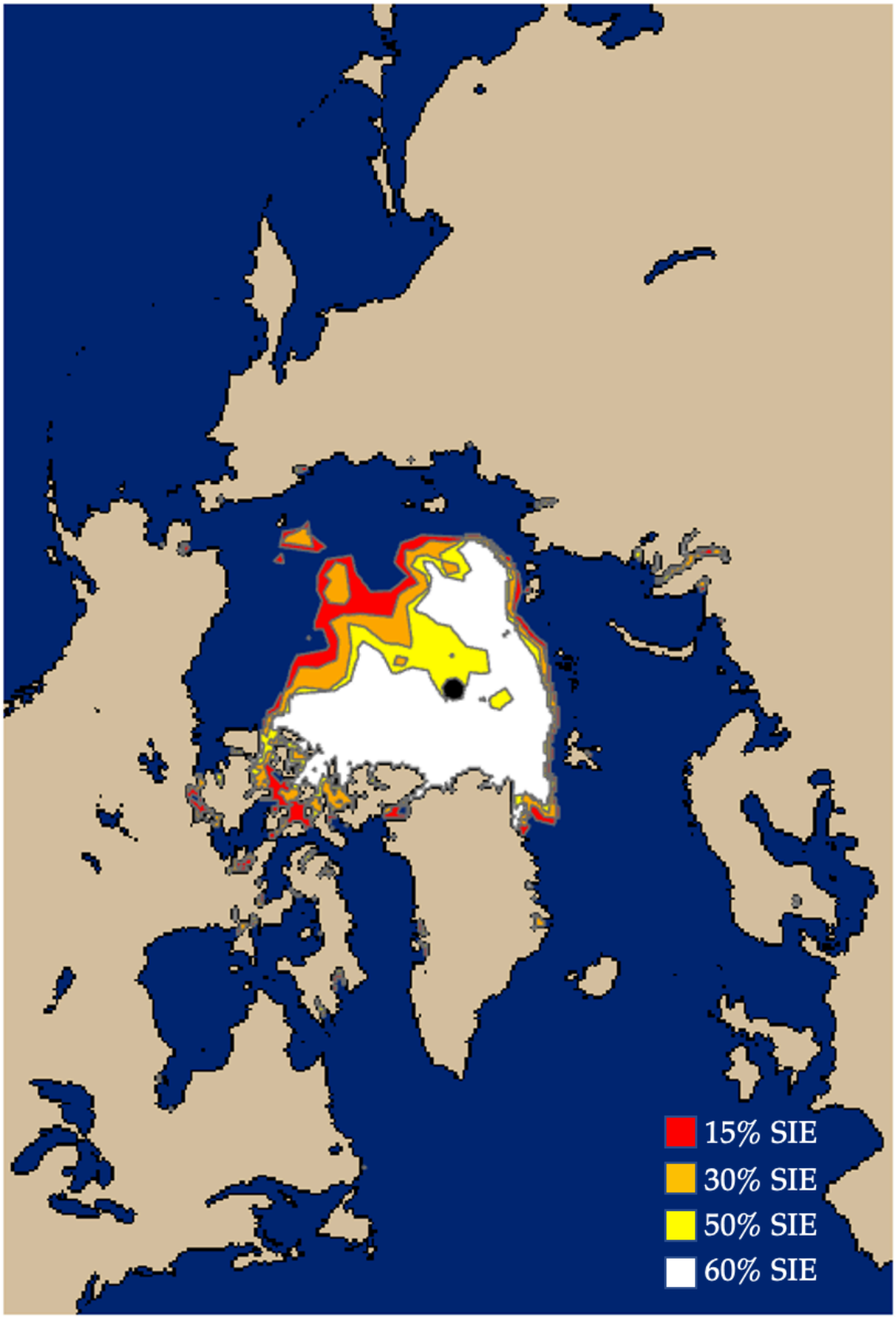


Figure 6.17.: Monthly sea-ice extent map showing the different locations of the 'sea-ice edges' derived using sea-ice extent thresholds at 15%, 30%, 50%, and 60% for September 2016. The Arctic Pole Hole is shown to intercept the 'ice edge' boundary for the 60% sea-ice concentration threshold.

6.3.2.3. Seasonal Extremes and the Timing of the First Ice-Free Summer

The annual maximum and minimum extent values are important indicators in long-term trends in Arctic sea-ice variability. The sea-ice minimum receives widespread attention from within and beyond the scientific community, as it represents a crucial marker of the pace of sea-ice decline and a reminder that we are moving ever closer to an *ice-free summer*. High-level scientific reports and the media stories commonly focus on the annual sea-ice minimum (e.g., IPCC, 2019, 2021; WMO, 2020), the sea-ice community closely analyses September sea-ice cover (e.g., Parkinson and Cavalieri, 2008; Stroeve *et al.*, 2012b; Notz and Strove, 2018), and in the preceding months, collaborative networks between scientific institutions, citizen scientists, and stakeholders seek to provide estimates on September sea-ice extents (e.g., the Sea Ice Prediction Network's Sea Ice Outlook, formed in 2008).

Statistical comparisons of March and September reveal similarities in sea-ice extent for the different thresholds (Figure 6.18). As expected, the absolute values are lower at higher thresholds, but the general trends are comparable across the full time series. A notable exception to this is September 2016, whereby the higher thresholds yield significantly lower sea-ice extents: for the 60% SIC threshold, total ice coverage is ~2.1 million km² (~46%) lower than the conventional threshold. This difference is more prominent when comparing the percentage differences (see Figure 6.14).

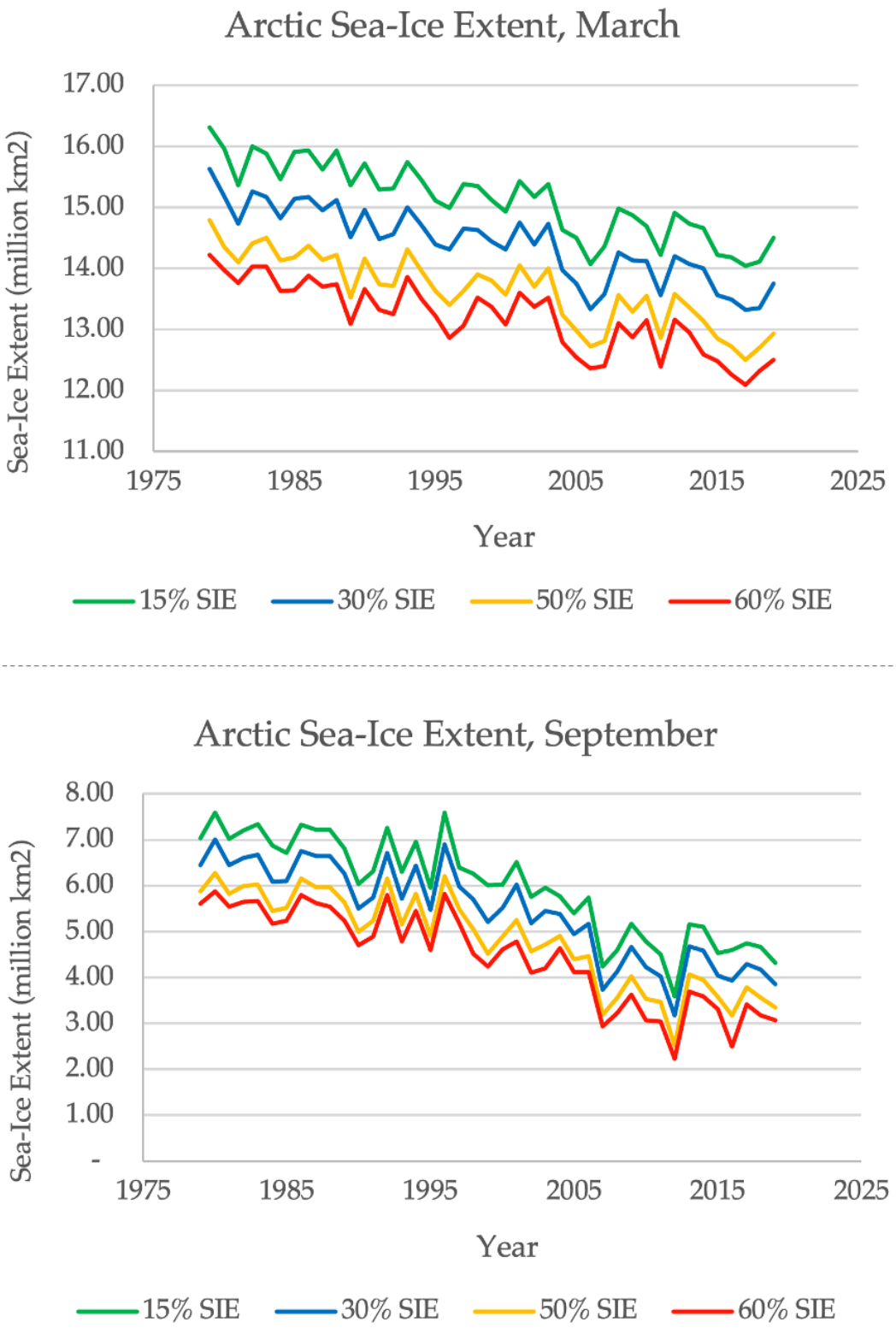


Figure 6.18.: Sea-ice extent trends for March and September between 1979 and 2019, calculated using sea-ice concentration thresholds at 15%, 30%, 50%, and 60%.

Looking at the sea-ice maps, the changing thresholds in March give rise to very similar representations of Arctic sea ice. Due to the large spatial coverage of ice and the more compact conditions that are characteristic of winter sea ice, the position of the sea-ice boundary is not too dissimilar. In contrast, the effects of the different thresholds on the spatial distribution of sea ice are far easier to detect for September. The total area represented in white reduces in size, the general shape changes, and the homogenous area of bright white includes a greater number of blue inclusions representing open water areas.

One of the more notable results of this comparison study is the effect of threshold changes on the timing of the first ice-free summer. The notion that the Arctic is moving towards ice-free summers is widely accepted within the scientific community. While many uncertainties are involved, most models predict that the first ice-free summer will occur before the end of the century, if not significantly earlier (Overland *et al*., 2018). In a recent study by Notz and SIMIP Community (2020), all modelled scenarios predicted the occurrence of ice-free summers *before 2050* (see also the IPCC, 2021). Note that 'ice-free' does not actually mean zero ice in absolute terms: 'ice-free' is defined by a total sea-ice extent of, or less than, 1 million km^2. The reason for this is that fast ice types and isolated areas of sea-ice cover will likely prevail among island groups such as the Canadian Archipelago long after the main pack ice in the Central Arctic Ocean has disappeared.

Using a simple linear extrapolation method, the September sea-ice extent trends were used to estimate the timing of the first ice-free summer. As Figure 6.19 shows, higher thresholds will experience ice-free summers several years before the conventional 15% definition: the first ice-free summer will occur in 2059 using the 15% threshold, 2055 using the 30% threshold, 2048 using the 50% threshold, and 2043 using the 60% threshold. While this exercise is a highly simplified way to forecast future variability in Arctic sea ice, it illustrates the importance of thresholds for shaping our understanding of future scenarios. More sophisticated analyses often use a variety of statistical approaches to produce a composite estimate of future ice-free summers (e.g., Matthews *et al*., 2020) or modelled simulations whereby other climatic components are accounted for (e.g., Notz and Stroeve, 2018; Notz and SIMIP Community, 2020). However, in these scenarios, sea-ice extent trends calculated using the conventional 15% threshold are often the primary data source for sea ice.

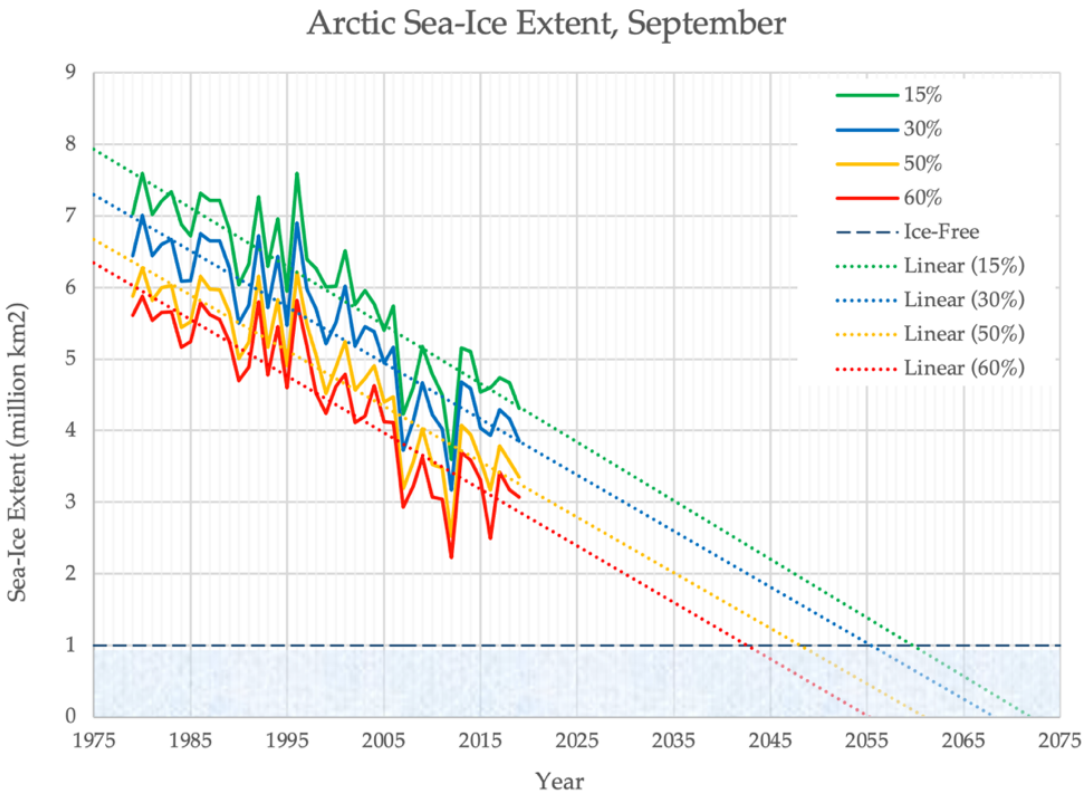


Figure 6.19.: The different timings of the first ice-free summer based on the sea-ice extent trends for September between 1979 and 2019, calculated using sea-ice concentration thresholds at 15%, 30%, 50%, and 60%.

A second notable implication of changing the thresholds is the effect it has on the timing of the annual minimum. As previously noted, September is usually the month when sea-ice cover retreats to its lowest extent. However, across the full time series, the number of instances whereby the summer minimum occurs in August increases at higher thresholds. At 15% and 30% thresholds, there is only one year when sea-ice extents are lower in August than September – in both instances, this occurs in 1987. At 50%, there are three years when sea-ice extents are lower in August than September, and at 60%, there are twelve years when the annual minimum occurs in August. Figure 6.20 illustrates how, at higher thresholds, the differences between August and September sea-ice extent values reduce significantly.

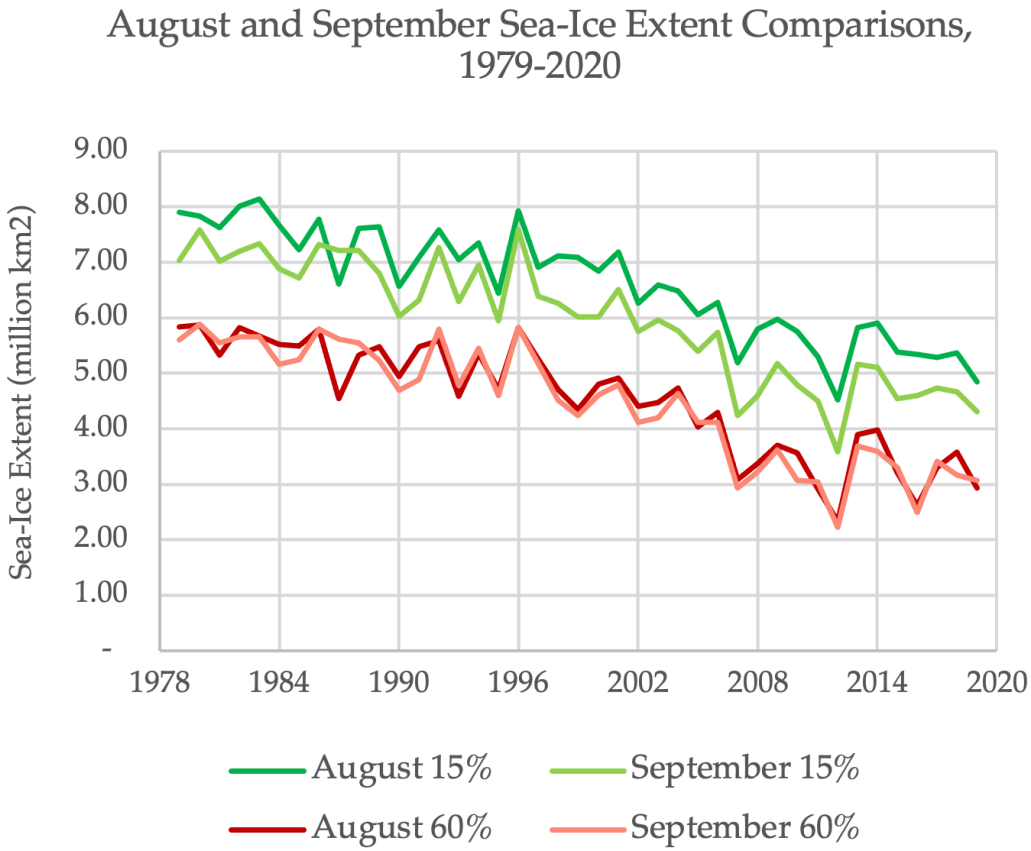


Figure 6.20.: Sea-ice extent trends for August and September between 1979 and 2019, calculated using sea-ice concentration thresholds at 15%, 30%, 50%, and 60%.

Matthews *et al*. (2020) found a similar pattern whereby the occurrence of an August annual minimum was increasingly likely at higher thresholds. In their intercomparison study, a higher 85% sea-ice concentration threshold yielded twenty-four out of thirty-nine years where the annual minimum occurred in August. They suggest two possible explanations for the earlier occurrence of the sea-ice extent minimum. Firstly, higher concentration bands generally coincide with higher latitudes where temperatures are colder. Thus, the instances where the minimum occurs in August may reflect colder September conditions, which resulted in the earlier freeze-up of the more compact ice. Secondly, the shift in seasonality may reflect the inaccuracies in passive microwave sea-ice concentration retrieval. During August, meltwater pools are more prevalent on the sea-ice surface. These may be causing low sea-ice concentration biases due to the inability of passive microwave technologies to accurately isolate and account for the emissivity signature of surface meltwater.

Significantly, the shift in seasonality has a marginal effect on the timing of the first ice-free summer. Repeating the same extrapolation method with sea-ice extent trends for August, the first ice-free summer for the 60% sea-ice concentration threshold occurs in 2041, 2 years before the first ice-free summer experienced in September for the same threshold. For all other thresholds, ice-free Augusts occur later than in September.

6.4. Conclusion: Towards a More Reflexive Sea-Ice Science?

Through critically examining sea-ice maps associated with the NSIDC, OSI-450, and C3S data products, this chapter has explored how the maps provide a view of the Arctic that embeds and is embedded in the values and judgements of the mapmakers situated within particular social and cultural contexts. Sea-ice maps derived from passive microwave satellite observations invariably facilitate an understanding of the Arctic Ocean that is partial, uncertain, and contestable. They are developed to systematically monitor and communicate the spatial distribution of *specific sea-ice parameters* that play a crucial role in the global climate system. They are expressions of the Arctic Ocean in geophysical terms. They are intended to inform and provide a quick visual interpretation of specific sea-ice conditions through their highly selective and simple design.

Although they are made predominantly for ocean-climate research applications, once they enter the public sphere and become detached from their scientific context, the maps work on many different and often unintended levels – they *work beyond their intended purpose.* Through the processes of acquisition, selection, aggregation, and styles of representation, the sea-ice maps articulate the Arctic Ocean in a way that is necessarily partial. The limitations of contemporary satellite technologies mean that localised features and more ephemeral ice-types fall outside of what is observable, representable, and thus, knowable. By classifying the ocean surface into abstract and quantifiable units, the complex, dynamic, and contestable nature of sea ice becomes silenced. The diverse functions and interests that sea ice serves are rendered imperceptible by static and uniform boundaries and arbitrary definitions. The homogenous use of colour perpetuates an understanding of the region as a vast, lifeless, and empty space. In short, the maps give rise to particular understandings of the Arctic, while marginalising and silencing others.

The prevalence of scientific sea-ice maps in contemporary society makes them powerful tools of knowledge production and transfer, particularly as few people will ever go to the Arctic, and even fewer will directly encounter sea ice. Through their wide circulation, these maps emerge as seemingly objective and authoritative accounts that naturalise particular ways of knowing the Arctic, and the complex and contingent processes of knowledge production are not visible. The surrounding documentation is thorough, and both institutions are transparent about the processes and assumptions involved in producing the data products. Transparency is considered a vital requirement of 'state-of-the-art' climate data records; it allows users to make informed decisions about the validity and applicability of different data products (GCOS, 2016). At several points in the products' supporting documentation, the NSIDC, OSI SAF, and C3S acknowledge the many uncertainties involved in passive microwave sea-ice retrieval and stress the importance of viewing the individual data values and images within their longer-term

context. However, beyond acknowledging that absolute data values may not be replicable due to manual processing, many of these limitations and uncertainties are technical in nature. There is little reflexive discussion about how individual, institutional, and broader cultural conditions shape the production of knowledge. Perhaps more significantly, there is a distinct lack of consideration about the (un)intended social effects of sea-ice data products. Indeed, as the following chapter will discuss, the desire for scientists to maintain a distance between the processes of knowledge *production* and the socio-political *application* of that knowledge appears to be an important characteristic in contemporary sea-ice science. Scientists deal with objective facts; it is up to politicians and decision makers to decide what to do that knowledge.

Is there a need for powerful institutions such as the NSIDC and MET Norway to alter how they represent long-term changes in sea ice? Should sea-ice maps include greater detail on the diverse ecological, political, and cultural elements of the Arctic? Perhaps greater inclusivity can be achieved by enabling viewers to re-orientate the maps to reflect their social and cultural backgrounds and experiences. At the very least, there needs to be greater reflexivity about the situated nature of scientific knowledge and the unintended socio-political and cultural implications of sea-ice maps *from within* the sea-ice community. There needs to be a greater recognition that these maps are not simply representations of specific Arctic sea-ice parameters; they are prescriptive tools that influence how the Arctic is known and thus acted upon in present and future contexts.

7. Sea-Ice Science in a Socio-Cultural Context

7.1. Introduction

The previous chapters have shown how, although collectively guided by fundamental principles and drawing from the same data sources, the methods, procedures, design, and outputs of sea-ice data products are not consistent between different products and institutions – even those developed for the same sea-ice parameter. This variation implies that scientific knowledge of sea ice is not wholly objective or neutral; rather, its character and persistence is contingent, at least to some degree, on the situated contexts in which the products are constructed. Drawing from document analysis, in-depth interviews, and experiences in the field, this chapter expands on the previous discussions to explore the conditions (social and otherwise) that shape the production and dissemination of sea-ice data products within the context of MET Norway. The emphasis in this chapter is less on the specific processes and techniques of knowledge construction or the styles of representation; indeed, that was the chief focus of Chapter 5 and Chapter 6. Instead, this chapter is concerned more with the situatedness of scientific practices and the conditions or presuppositions that influence how certain types of knowledge come to be accepted as valuable and credible. In other words, the chapter seeks to better understand the arrangements and interactions that influence how and why particular methodologies are developed, sustained, and operationalised in their institutional settings, how the products are used and applied, and how they relate to different knowledge producers and broader societal contexts.

Section 7.2 explores the various actors, interactive networks, requirements, and constraints that play a role in shaping how sea-ice data products are made. Particular focus is given to following key themes: the role that MET Norway plays in supporting European programmes of climate-related research through its involvement in EUMETSAT and C3S research programmes; the top-level requirements that govern the overarching objectives and agendas of contemporary sea-ice research; the constitutive role of product users in shaping the content and design of sea-ice data products; and the evolutionary nature of data product development. Section 7.3 discusses how the

reporting of key climate indicators, such as sea-ice extent, is perceived as an important determinant of institutional visibility and credibility. It also highlights some notable tensions between visibility, scientific authority, and accuracy, and how emerging forms of science communication present new opportunities and challenges for the nature of sea-ice reporting. Section 7.4 examines how broader political agendas and technological developments shape the production and dissemination of sea-ice knowledge through focussing on two significant events: the recent political disputes over the defining and mapping of the 'ice edge' as part of the Norwegian Government's Barents Sea Management Plan; and the imminent termination of the U.S. DMSP satellite programme.

The primary focus of this chapter is the contexts that shape the production and dissemination of the OSI-450 SIC and C3S data products because the fieldwork focussed predominantly on the teams developing and working with these products. However, encounters in the field occurred with a broad range of actors working in various branches and applications of satellite remote sensing, oceanography, and meteorology, and between different regional offices of MET Norway. As such, the scope of this chapter is often more general: many of the observations, interpretations, and discussions are not necessarily limited to specific data products but concern the contexts that shape knowledge production and dissemination within the institute more broadly.

7.2. Product Development: Requirements, Evolution, and Users

7.2.1. MET Norway and Climate Research

MET Norway is a state-funded agency working under the Norwegian Ministry of Climate and Environment. Headquartered in Oslo, MET Norway also has regional offices in Bergen and Tromsø, and support stations throughout the country. Across the three main offices, MET Norway's operations are divided into five departments: 1) Forecasting, 2) Observation and Climate, 3) the Development Centre for Weather and Forecasting, 4) Information Technology, and 5) Research and Development. Through the work carried out in these departments, MET Norway is responsible for providing public meteorological services for civil and military purposes. This includes preparing weather forecasts, monitoring the climate, and conducting research and development work to develop new systems and improve existing products and services. The primary objective underpinning all these operations is "to ensure that authorities, industry, institutions and the general public are best able to protect life and property, plan ahead and protect the environment" (MET Norway, n.d.).

The impetus for a national meteorological institute in Norway can largely be traced to the 'Great Storm of 1854', during an early phase of the Crimean War (Lindgrén and Neumann, 1980). An unusually intense Atlantic storm hit Balaklava port on 14th November and resulted in significant damage and loss among Allied forces (Britain,

France, and the Ottoman Empire). The effects of the storm prompted many European countries to focus efforts on developing synoptic weather forecasting to mitigate against future storms. Owing to its vast Atlantic-facing coastline, Norway had a particular interest in improving weather forecasts, and a meteorological institute was established in 1866 to facilitate this.[71] Since its establishment, MET Norway has figured prominently in international climate research, particularly in the polar regions and in relation to Arctic sea ice (Bones, 2007; Lajus, 2013; Sörlin, 2011, 2013). Indeed, Fridtjof Nansen's ground-breaking oceanographic and meteorological work in the Arctic Ocean was strongly influenced by the institute's founding director, Henrik Mohn, who developed an initial theory of polar drift during the 1870s (see Section 4.3.3). Henrik Mohn also played a pivotal role in shaping Norway's involvement in the first IPY, 1882-1883 (Bones, 2007).

The systematic and large-scale monitoring of the climate system is considered fundamental to supporting stakeholders, policymakers, and the public to make informed decisions about climate change mitigation and adaptation on global, national, regional, and local scales. In recent decades, MET Norway has become increasingly involved in international climate research through collaborating on several European programmes, including the European Ocean and Sea Ice Satellite Application Facility (OSI SAF), the European Space Agency Climate Change Initiative (ESA CCI), and the Copernicus Climate Change Service (C3S).[72] Through these programmes, MET Norway researchers are directly involved in producing and disseminating consistent sea-ice data products, including the OSI-450 SIC and C3S SIE and SITy.

The OSI-450 SIC and C3S data products are generated within two separate institutional frameworks, and each draws from several different research organisations (Figures 7.1 and 7.2; see also Sections 5.3.2.2 and 5.3.3.2). The OSI-450 SIC is produced through collaboration between MET Norway and the Danish Meteorological Institute (DMI) as part of the OSI SAF research programme; the C3S products are produced by MET Norway researchers on behalf of Copernicus for the C3S programme. Despite these institutional distinctions, all three products are underpinned by a consistent research objective: to support prominent international actors such as the World Meteorological Organisation and the Global Climate Observing System (GCOS) in the continued, systematic, and collaborative monitoring of the climate system. In this respect, the OSI SAF and C3S research programmes and their respective data products are complementary to each other, and there is some sharing of expertise, data, and processing systems.

[71] *Meteorology in Norway*. *Nature* 101, 26–27 (1918). https://doi.org/10.1038
[72] Although not a member of the European Union, MET Norway is actively involved in numerous EU science initiatives.

The scientists working at research institutes like MET Norway are the fundamental actors responsible for generating knowledge of sea ice. Their role is to process, translate, interpret, and represent knowledge of sea ice through generating and disseminating data products. However, individual scientists have little autonomy over their characteristics and design. Situated within their specific institutional arrangements, the day-to-day research of the sea-ice scientists is strongly shaped and informed by interests, requirements, and constraints that primarily exist external to the place of production. Many of these are addressed in the following sections.

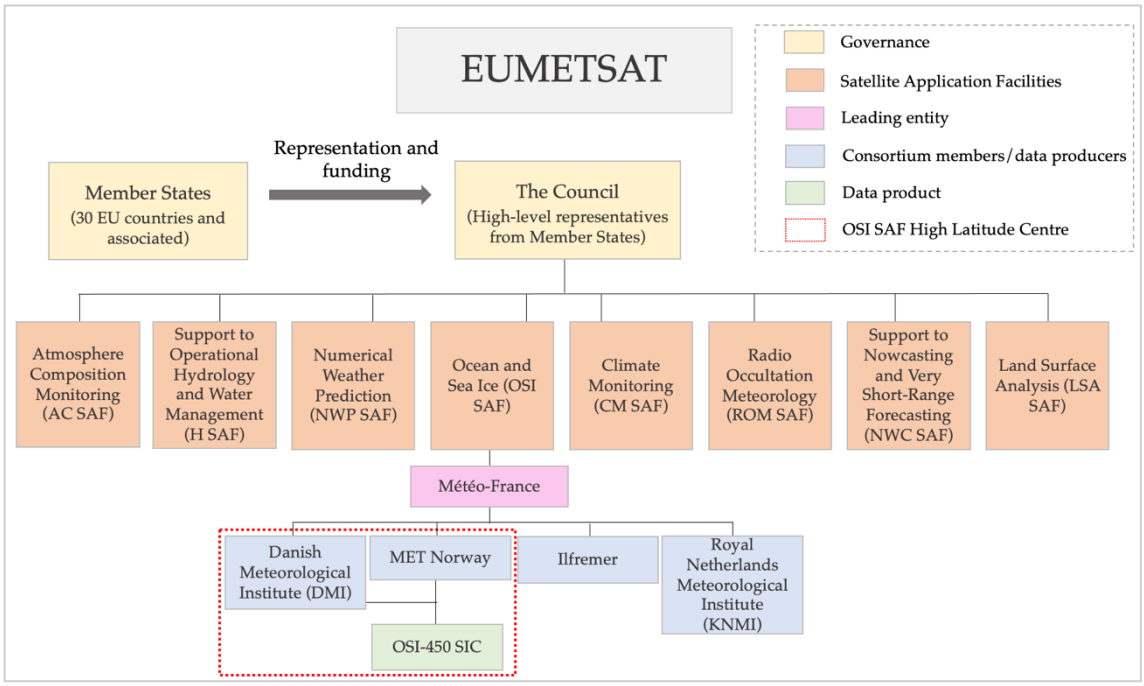


Figure 7.1.: Institutional framework supporting the OSI-450 SIC data product.

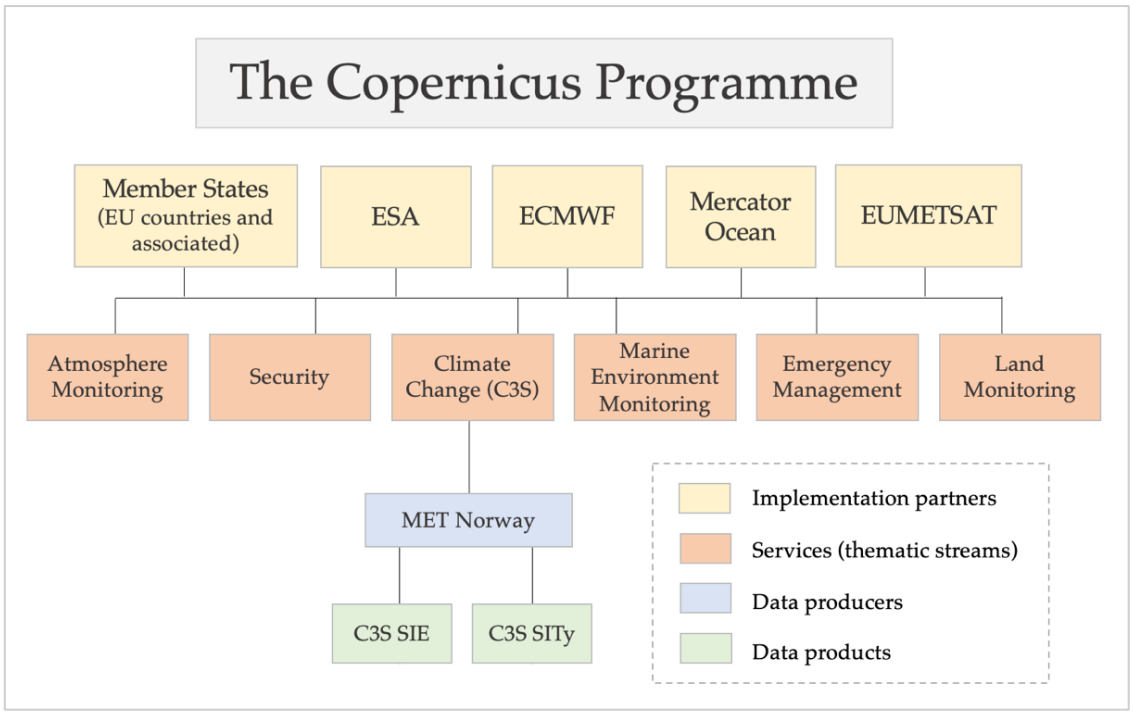


Figure 7.2.: Institutional framework supporting the C3S data products.

7.2.2. Top-Level Requirements

The top-level requirements governing the nature of climate-related sea-ice research carried out at MET Norway come from GCOS. Formally established in 1992 following calls for improved climate system monitoring, GCOS is an international and interdisciplinary framework supporting the provision of comprehensive information on various atmospheric, oceanic, hydrologic, cryospheric, and terrestrial properties and processes (GCOS, 1992; see Section 4.5.2). GCOS strives to meet two interrelated objectives: 1) ensure that the information needed to address climate-related issues is being obtained; and 2) that this information is made freely available and accessible to users. Notably, GCOS does not make direct observations or generate data products. Instead, the organisation provides the operational framework and guidance to support and improve pre-existing national and international Earth Observation systems, research agencies and programmes, and scientific and technical facilities (including national meteorological services).

Working in close partnership with the IPCC and the UNFCCC, GCOS regularly assesses the observations needed to understand current and future changes in the climate system. A significant element of this work has been the establishment of Essential Climate Variables (ECVs): a list of 54 physical, chemical, or biological variables or groups of linked variables that play an important role in the climate system.[73] The systematic observation and continued monitoring of ECVs are considered essential to developing

[73] The corresponding website for GCOS ECVs is: https://gcos.wmo.int/en/essential-climate-variables.

appropriate mitigative and adaptive responses to climate change, assessing the risks and causes of climate events, and predicting future changes.[74] Through identifying and establishing these global observational needs, major scientific bodies, like GCOS and the UNFCCC, have come to represent what Martello and Jasanoff term, "knowledge brokers for the world" who have taken on the role of accruing "universally acceptable facts, ideas, and messages about phenomena" (2004: 7).

Sea ice has been defined as an ECV due to its essential role in influencing the surface albedo and modulating atmospheric and oceanic exchanges (Thomas, 2017). GCOS underscores several key sea-ice parameters, including concentration, extent, edge, and thickness, and calls for data producers to prioritise their observation and monitoring. The prioritisation of these parameters over others is based on three main criteria: the *relevance* of a parameter for characterising climate system variability; the *feasibility* of a parameter in terms of scientific and technological capacity; and the *cost-effectiveness* of producing datasets of a specific parameter.

The NSIDC, OSI SAF, and C3S are among the leading research programmes tasked with producing and maintaining long-term sea-ice data products that meet GCOS requirements. Alongside the NSIDC SII and the NOAA-NSIDC CDR, the OSI-450 SIC data product represents the primary source for sea-ice concentration and extent data; the C3S SIE is the primary source for sea-ice edge data (GCOS, 2021). While sea-ice type has not been identified as an independent ECV of sea ice, knowledge of the distribution of first-year and multi-year ice types is important for several other ECVs, including concentration and thickness (DMI, 2020). Thus, the C3S SITy data product represents a valued source of climate information.

The concept of ECVs has the strongest influence on MET Norway's involvement in climate-related sea-ice research. GCOS stipulates which sea-ice parameters are considered valuable knowledge, and thus, which data products should be given priority in terms of funding and resources. They also provide target requirements on the frequency, resolution, and accuracy of ECV data products (Table 7.1).[75] These requirements establish the general data product characteristics that data producers should aim to achieve over a ten-year timeframe.

[74] Ten basic principles established by the Conference of Parties (COP) and the UNFCCC at the COP-5 climate conference in November 1999 guide the monitoring of these variables: https://gcos.wmo.int/en/essential-climate-variables/about/gcos-monitoring-principles.
[75] These requirements are set out in the GCOS Implementation Needs Plan (GCOS-200), published in 2016 (GCOS, 2016). An updated plan is set to be published in 2022.

Table 7.1.: GCOS ECV target requirements for sea-ice concentration, extent, and edge parameters (GCOS, 2016).

Sea-Ice Parameter	*Temporal Frequency*	*Spatial Resolution*	*Accuracy*	*Stability (per decade)*[76]
Sea-Ice Concentration	Weekly	1-15 km	5% ice area fraction	5%
Sea-Ice Extent/Edge	Weekly	1-5 km	5 km	Unspecified

For MET Norway researchers working with the OSI-450 SIC and C3S sea-ice data products, the needs of GCOS were described as "the mother of all requirements" (Interview, 16th June 2020). GCOS requirements filter down through the OSI SAF and C3S research programmes, take on more specific characteristics, and govern the day-to-day research carried out by the various data producers and consortium partners (Figures 7.1 and 7.2). Table 7.2 lists some of the more specific targets imposed by OSI SAF and C3S research programmes, which comply with and extend the GCOS requirements.

[76] Changing satellite sensors can alter the consistency of sea-ice retrieval and cause data values to drift. *Stability* indicates the amount of drift that is considered acceptable for the product to remain of high-quality.

Table 7.2.: EUMETSAT OSI SAF and Copernicus C3S data product requirements. *Source:* ESA (2020) and DMI (2020).

EUMETSAT OSI SAF	*Copernicus C3S*
General data product characteristics: global coverage (NH and SH); multi-decadal temporal coverage; extends to present time; maintain temporal consistency. **Ancillary documentation:** maintain documentation on all data processing systems, including algorithms and software; provide detailed documentation on the algorithmic principles, product user guides, and validation reports. **Data accessibility:** provide data products in widely accepted standard formats (e.g., NetCDF). **Validation and quality control:** continuously and automatically monitor the quality and performance of data products using higher resolution ice charts from regional ice centres; uncertainty information is to be provided at grid-cell level; interpolation methods should be used to improve retrieval in coastal locations.	**General data product characteristics:** global coverage (NH and SH); multi-decadal temporal coverage; extends to present time; temporal consistency; continually updated on minimum of monthly basis. **Data source:** use multi-sensor data source where possible; use Copernicus satellite data where possible and appropriate. **Data producer**: have technical capacity, partnerships, and infrastructure necessary to support CDR development and delivery. **Ancillary documentation:** provide detailed information on uncertainties; include quality flags and masks; rich and standardised meta-data on products; include information on data quality and performance; provide detailed documentation on the algorithmic principles and product user guides; include detailed information on processing chains and traceability of data products. **Data accessibility**: provide data products in widely accepted standard formats (e.g., NetCDF). **Product evolution**: where possible, use pre-existing product processing chains and adapt or upgrade them. **User support**: implement a dedicated user support system. **Validation and quality control:** routinely monitor the quality and performance of data products.

7.2.3. The Constitutive Role of Users

With the growing demand for climate system observations in support of mitigative and adaptive climate change policies and stakeholder decision-making, data providers are increasingly encouraged to generate high-quality products that are accessible and meet the needs of different user communities. Findlater *et al*. (2021) characterise this as a shift in user-producer relations away from the more traditional *supply-driven* approaches of climate science, whereby data producers predominantly take on the role of informers and users as passive consumers, towards a *user-driven* approach, whereby users have a constitutive role in shaping the research agendas and outputs (see also Jeuring *et al*., 2020).

My encounters in the field revealed how incorporating the preferences and interests of users is of utmost importance in the production and dissemination of the OSI-450 SIC and C3S data products. For instance, when carrying out the intercomparison project described in Section 3.4.5.1 of Chapter 3, early meetings emphasised the need to establish an objective that would consider the interests of OSI SAF, C3S, and the users (Appendix 8). Data producers engage in an ongoing dialogue with users through surveys, formal reviews, and more informal discussions at conferences and in online spaces. Through this dialogue, users play a significant role in shaping the nature of sea-ice data products. They affect the content of the data products by stipulating specific requirements for the spatial and temporal coverage and resolution, stability, and precision of measurements. They influence the design and format of product outputs, including the projection of the maps and representation of data. They also have an important say regarding the frequency and timeliness of product reporting.

The primary users of the OSI-450 SIC and C3S data products are the climate research community. In particular, the products are an essential data source for climate model development, validation, data assimilation, and long-term trend analysis (DMI, 2020; OSI SAF, 2021). Notably, however, the climate research community is diverse with a broad range of requirements, experience, and interests. Scientists must find ways to reconcile these differences when producing and disseminating sea-ice data products.

The scientists distinguish between two broad categories of users: 'expert' and 'non-expert'. This characterisation is derived primarily from the outcomes of various sea-ice user requirement surveys carried out by ESA CCI (see ESA CCI, 2020), which sought to discern and differentiate between various user needs. This characterisation is used by MET Norway scientists in their overall understanding of user groups, as was evidenced during interviews and discussions in the field.

Expert users typically include scientists involved in other climate-related research programmes who have a deeper and more intricate understanding of the product uncertainties, limitations, and specificities. They are generally familiar with the various

data-processing levels that characterise the OSI SAF and C3S data processing chains and are knowledgeable of the methods and data handling steps involved (see Sections 5.3.2.2 and 5.3.3.2). As one MET Norway research scientist explained, "They want to use the uncertainties to look at the [status] flags. They are really the ones challenging us to improve" (Interview, 16th June 2020). Expert users typically use sea-ice data within numerical modelling applications and require detailed information on the uncertainties and limitations surrounding sea-ice data retrieval.

In contrast, non-expert users represent a broader array of researchers who are predominantly interested in 'quick-look' data product outputs (e.g., maps, graphs, and numerical values). Generally, non-expert users tend to have a more superficial interest in the data products and are less concerned with having a detailed understanding of the uncertainties and various data-processing steps involved in their production. As one research scientist said, "[They] just want a white colour for sea ice and a blue colour for ocean. That is what they need… They don't want to understand [uncertainty]; they don't want to open the documentation and understand why there is noise" (Interview, 16th June 2020). In many instances, sea ice represents a secondary variable in non-expert analyses; for instance, maps of sea-ice cover may be used in oceanographic studies of sea-surface temperatures to provide a simple, binary distinction between ocean and ice-covered areas.

Catering for the needs of expert and non-expert users involves striking a balance between applicability, accuracy, and transparency. Most non-expert users want a simple indicator; they want a data product that is 'clean', whereby the data producers have removed or filtered out the noisy signals caused by atmospheric and oceanic interference. During an interview, a research scientist mentioned that the inclusion of noise may even be perceived as a negative reflection of data quality and cause users to seek alternative data sources such as the NSIDC. Many of the correction procedures described in Chapter 5, such as the open-water filters, valid ice masks, and interpolation, are largely used to make the products more suitable for non-expert users.

For expert users, the heavily filtered products are less desirable. Correction techniques used to mask out the noise involve various assumptions and can introduce subjectivities into the knowledge production process. Thus, the expert user seeks full transparency in how the data has been transformed from the raw satellite observations into useable and simplified outputs. Expert users want detailed information about the specific causes of uncertainty, the processing steps involved at each stage, and how the correction procedures have changed the data. In instances where a correction procedure alters the consistency of data processing (e.g., using temporal interpolation to fill in gaps caused by a temporary satellite outage), expert users often prefer to manage the remaining inconsistencies themselves (see ESA CCI, 2020).

To accommodate the contrasting needs of expert and non-expert users, the OSI-450 SIC and C3S data products are presented in their final, filtered, and simplistic formats but are supplemented with detailed information about uncertainties and the data-processing steps involved in deriving each value or classification. This information is included in each data file through status flags and uncertainty estimates at grid-cell level, and all processing steps and algorithmic principles are detailed in the supplementary documentation (Sections 7.2.2 and 7.2.3). The OSI-450 SIC product goes a step further. It is designed so that expert users can reverse some of the data aggregation and filtering steps by having greater access to raw sea-ice concentration values (Lavergne *et al*., 2019; see also Section 5.3.2.5).

There is a notable tension between the needs of users and the interests and research focus of OSI SAF scientists working with the OSI-450 SIC data product. The scientists consider themselves, first and foremost, remote sensing scientists. Their main interest is in the individual satellite observations and the sea-ice retrievals at Level 2. Level 2 data refers to sea-ice concentrations calculated at swath level that have not been projected or converted to uniform grids and have been subject to less manipulation and aggregation (see Sections 5.3.2.2 and 5.3.3.2). The requirements of expert users align most closely with this focus. However, as the following interview extract reflects, there is still a disconnect that has important implications for data product accuracy:

> As remote sensing scientists, we are really interested in the individual observations from the satellites. We work close to the satellite data – that is our focus. […] But nobody can use that. So, we have to take the step to produce the daily maps […] and in the end, people just want to have the indicator. They want to have the time series. […] We are being pulled by the users to prepare something that they can use. […] At the same time, we are trying to get the users to come play with us, more towards the data. Because we know that, as soon as we aggregate, we are lowering the quality somehow. (Interview, 16th June 2020).

The generation of uniform gridded maps and outputs is an important step in making data products applicable for different users' needs. Indeed, EASE-2.0 grids were primarily adopted because they offered a more convenient and user-friendly means of spatial analysis (Section 6.2.1). However, such processes involve several additional stages of data refinement, aggregation, and averaging, through which the data become less representative of the initial observations.

Consequently, a longer-term research goal of sea-ice scientists is to encourage users to move away from using the data in the aggregated and filtered formats and towards working with the retrievals at Level 2. This represents a new area of sea-ice research, and there are resources and research grants available for establishing projects that encourage this transition. One such example is the 'Sea Ice Retrievals and data Assimilation in

Norway' (SIRANO) project.[77] SIRANO is a research and development project running from 2020-2024, carried out through a collaboration between MET Norway and the Arctic University of Norway (UiT) and funded by the Research Council of Norway. Part of the project's aim is to help facilitate the shift from Level 3 and Level 4 maps towards Level 2 data by demonstrating the advantages for applications, such as sea-ice forecasting. At present, however, most users, particularly non-experts, lack the capacity to use Level 2 data. As one respondent indicated, it requires different processing software, and many users are often not familiar with the advantages of using data that has been subject to fewer stages of data processing. Thus, despite being less representative than the unfiltered and uncorrected retrievals, the production of gridded sea-ice data products is likely to continue for the foreseeable future.

Like Pinch and Bijker's (1987) study of technological artefacts (Section 2.3.5), the significance of user requirements implies that the success of data products is strongly determined by the users' values, interests, and knowledge. That user requirements are variable indicates that product design and the nature of development is not inevitable but (re)shaped through continued negotiations. In the OSI SAF programme, the negotiations between the scientists and users are notably formal. Once identified, OSI SAF conducts systematic reviews of user requirements and assesses whether they should (or can) be implemented. These reviews are formally led by EUMETSAT, and expert users from institutes such as ECMWF or Copernicus are asked to provide feedback on the proposed requirements. In some cases, due to technological, algorithmic, and more general socio-political constraints (e.g., financial costs), user requirements cannot be incorporated into data products. For instance, the interviewed research scientists stated that all users want sea-ice data products with a higher spatial and temporal resolution. These needs cannot be met with current technologies because they are beyond the observational capabilities of the satellites. In other instances, an approved requirement becomes part of the developmental process and the focus of research. I was informed that this style of negotiation is quite unique to OSI SAF. Other research programmes have a dialogue with users "but there is no formality and there is no pressure [to interactively engage]" (Interview, 16th June 2020).

7.2.4. Product Evolution and the Niche Effect of Algorithms

When developing a sea-ice data product, the particular methods, techniques, and design features are chosen depending on the intended purpose and requirements. The OSI-450 SIC and C3S data products are primarily generated for ocean-climate research applications. Accordingly, the chief goal is to develop a methodology that consistently retrieves sea-ice data over the full satellite record.

[77] More information can be found on the project's website: https://cryo.met.no/en/sirano.

Today, however, scientists rarely develop a methodology from scratch. The nature of product development was described in an interview as being "evolutionary". Where possible, new products and product versions build on pre-existing methodologies and adapt or improve them to reflect the latest scientific research, technological capabilities, and stipulated requirements. In this way, the OSI-450 SIC product is based on the earlier OSI SAF sea-ice concentration product: the OSI-409. The two products are methodologically similar and are guided by the same developmental principles; however, the OSI-450 SIC represents an improved version with an updated retrieval algorithm and processing methods (see Section 5.3.2.2.). Similarly, the C3S data products are based on the OSI SAF operational near-real time versions, modified to improve their temporal consistency for climate research (see Section 5.3.3.2.).

In a broader sense, the methodologies underpinning all three sea-ice data products have directly evolved from the early years of passive microwave satellite remote sensing. For example, the algorithmic principles of the OSI-450 SIC and C3S data products are, in many ways, modifications of the Bootstrap and NASA-Team algorithms developed by the GSFC during the 1980s. More generally, the products all employ the same fundamental principles, suffer similar technological limitations caused by the coarse resolution of the satellites and atmospheric and oceanic interference, and use comparable procedures to reduce errors.

Despite having similar origins and facing common problems, however, there is no single or predetermined direction in which products develop and evolve. The day-to-day research activities of the scientists largely focus on refining methodologies through identifying areas of weakness and developing and testing new techniques to improve the accuracy and applicability of sea-ice data products. Yet, each product has a distinct methodology, is characterised by different strengths and weaknesses, and is governed by varying top-level and user requirements.

Between different data products, the choice of sea-ice retrieval algorithm is perhaps the most influential factor shaping the nature of product evolution. As Chapter 5 outlined, the various products employ algorithms that approach sea-ice retrieval differently: the choice of frequency channels and polarisations is inconsistent, the algorithmic principles vary, and the representative brightness temperature tie-points are static or dynamic (see Table 5.10). These differences shape what elements of the Arctic Ocean are 'seen' and thus known; they also give rise to different strengths and weaknesses that influence which elements of the products are prioritised in terms of ongoing research and development.

The choice of algorithm is contingent on the research objectives, developmental objectives, social arrangements, and technological infrastructures that sustain the products. For example, the 'developmental philosophy' (to use a respondent's term) underpinning the OSI-450 SIC data product is to improve the accuracy of sea-ice

concentration retrieval throughout the whole 0-100% range to assess (and quantify) the fractional coverage of sea ice. This philosophy reflects the broader requirements of GCOS, the structure of EUMETSAT, and the needs of users. Achieving high-quality sea-ice concentration retrieval across the whole Arctic Ocean throughout the year is the ultimate objective, and so the day-to-day research focuses on "making high-scale refinements", concentrating on the "finer details", and "detecting the small-scale factors" that cause deficiencies at grid-cell level (Fieldnotes, 12th March 2020). The self-tuning, self-optimising SICCI2 algorithm was chosen over other algorithms because it improves the accuracy of sea-ice concentration retrieval spatially and temporally across the full range of concentrations (Lavergne *et al*., 2019; see Section 5.3.2.4). Yet, the development of this particular hybrid algorithm depended upon a collaboration between OSI SAF and ESA SICCI scientists who shared a similar understanding and outlook on how sea-ice retrieval could be improved. In turn, this relied on securing necessary funds and resources to develop the algorithm, assess its suitability, and implement it within the product methodology. In other words, through experimentation and negotiation, the collaborating scientists reached a consensus on how the product should evolve. Other data producers (e.g., NSIDC or JAXA) use different algorithms and associated methods and procedures that reflect their own research objectives, focus, and social arrangements and constraints. Hence, other products evolve in different directions.

A consequence of the niche effect of algorithms is that it limits the scope for external input and creates an insular working culture. As one scientist stated: "the limitation is that we cannot really take any input from the outside because there is no way we can change our processing systems to incorporate that" (Interview, 16th June 2020). Product evolution is constrained according to the strengths and weaknesses associated with each algorithm. This means that new approaches or scientific and technological breakthroughs that arise in the broader sea-ice community cannot be implemented unless they are directly related to the pre-existing methodology or algorithmic branch. Adopting disconnected methods or procedures may risk disrupting the stability of the product and cause significant differences in sea-ice retrieval. This, in turn, may undermine the product's credibility as a reliable data source.

The niche and *multidirectional* evolution of data products resembles Kuhn's revolutions and the theory-dependence of observation (Kuhn, 1970a; Longino, 1990; Chapter 2: Section 2.3.2). Sea-ice scientists are working in their institutional networks to solve problems and improve the accuracy of sea-ice data retrieval. While the practices of sea-ice science are guided by the same fundamental principles, theoretical presuppositions, and technological constraints, the exact direction of development is governed by the choice of algorithm, the stipulated requirements of each data product, and the negotiations between collaborating scientists. This implies that satellite observations of

sea ice are always interpreted, processed, and reported within the context of a specific methodological framework. This framework restricts how the scientists perceive, process, translate, and represent sea-ice conditions: it sets the standards for inquiry; determines what is 'good' and valued knowledge; and regulates the focus of ongoing product development. It also places restrictions on who participates in scientific practice and whose values, perspectives, and interests are accounted for in the production and dissemination of sea-ice knowledge. In short, it indicates that the knowledge of Arctic sea-ice conditions that these products provide is shaped by particular networks of social and technological arrangements, negotiations, choices, values, and constraints that exist within specific institutional spaces.

7.2.5. Networks of Authority and Knowledge Geographies

Although external input is restricted in how sea-ice data products evolve, each product methodology draws upon a vast network of ideas, methods, theories, resources, and expertise situated in different places and from different moments in time. The sea-ice data products are also interdisciplinary, integrating the expertise of oceanographers, meteorologists, physicists, mathematicians, and increasingly – as processing systems become more automated – computer scientists.

The notion that contemporary data products build upon several decades of collaborative and international research may be seen as an important defence of valid, credible, and progressive science. Such a perspective implies that sea-ice science steadily progresses through the sharing of ideas, expertise, and technologies, and our knowledge of Arctic sea ice improves with time. For Latour (1987), the vastness of networks mobilised during knowledge production significantly influences scientific authority. Focussing on scientific articles and technical documents, Latour argues that the number of authors and referenced texts help persuade the reader of the strength of a knowledge claim: to challenge a knowledge claim is to challenge all others engaged within that network.

To explore these ideas further, Figure 7.3 provides an indication of the networks of authority that sustain the OSI-450 SIC and C3S data products. Taking influence from Latour (1987) and the 'knowledge geographies' of Felt *et al.* (2017), the figure maps the institutional affiliations of the data producers and the authors referenced in the associated documentation at the time of publication.

The maps illustrate the collaborative and international nature of sea-ice data products. Although the products are predominantly produced and disseminated at MET Norway, the networks involved in their production go far beyond the national scale. The references to previous work throughout the documentation provide an indication of the various institutions that have influenced (directly or indirectly) the production and dissemination of the data products. This suggests that the data products mobilise a much

wider network of people and authority than the small group of researchers responsible for the day-to-day processing.

The OSI-450 SIC data product is influenced by 78 institutions located in 19 countries. With some crossover, the C3S data products reference 25 institutions located in 11 countries. These include scientific and technological research institutes, government agencies, and university departments (Appendix 13). Based on the dates of publication, the timing of these affiliations range from 1925-2021 for the OSI-450 SIC data product and 1977-2019 for the C3S data products.

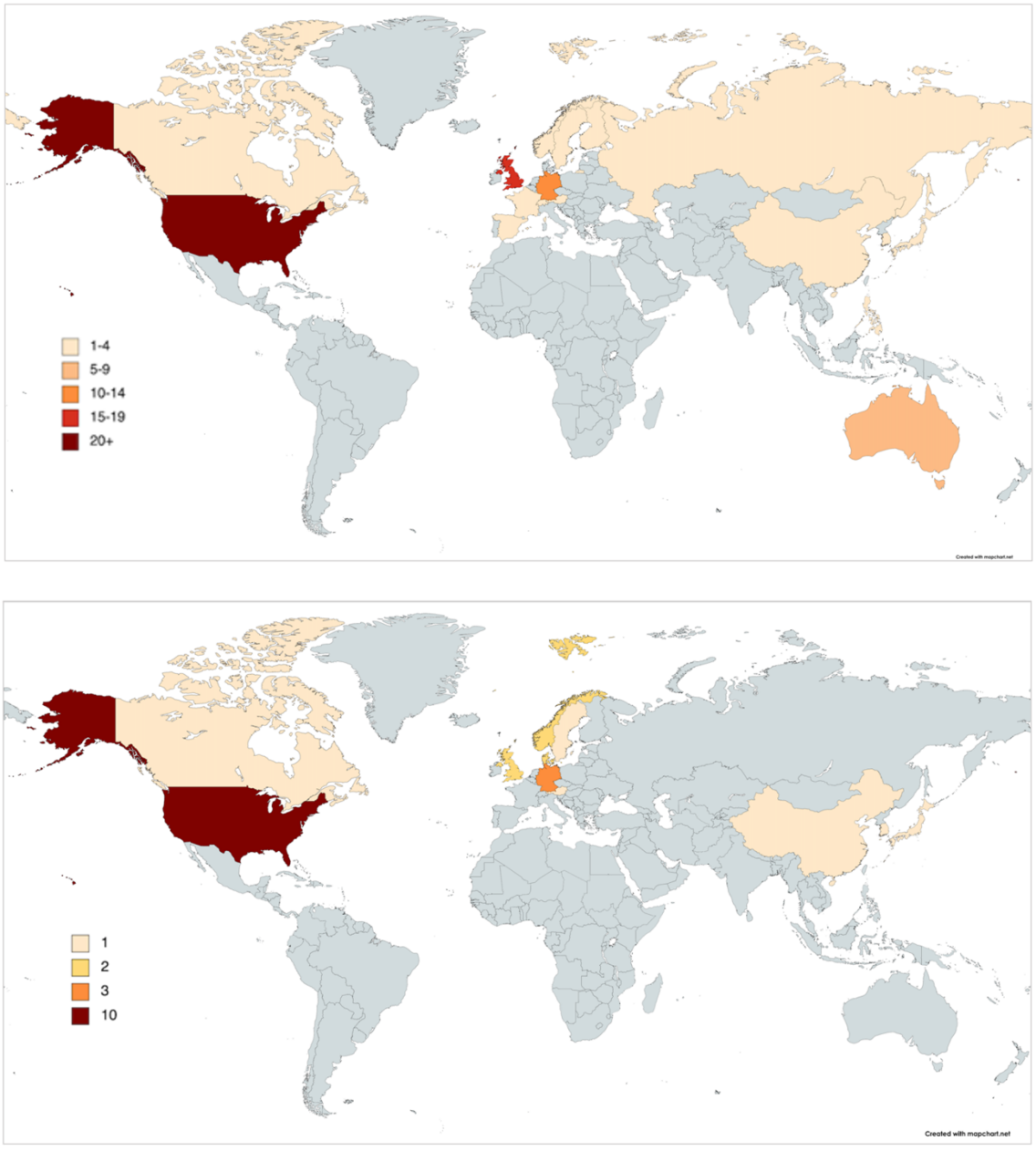


Figure 7.3.: Knowledge geographies of the OSI-450 SIC (top) and C3S data products (below), based on the institutional affiliations of the authors referenced in the associated documentation. For the OSI-450 SIC, this included Lavergne *et al*. (2019a, 2019b) and Sørensen *et al*. (2021). For the C3S data products, this included Aaboe *et al*. (2018b, 2019).

While the international and interdisciplinary nature of these networks may have an important influence on the credibility of the data products, it also invites critical reflection. A fundamental argument advanced in STS is that knowledge always comes from *somewhere;* it is always marked by the socio-cultural circumstances of its production and privileges particular perspectives, values, and interests, while marginalising others. Given the normative role that the OSI-450 SIC and C3S data products play in influencing global climate change knowledge and policies, it is important to critically reflect on *where* the networks of authority are located.

The maps shown in Figure 7.3 illustrate that although the products draw upon international collaboration, they are not truly *global*. The institutions involved in the production of the data products are predominantly located in Western countries. In both maps, the US and European countries dominate the institutional geographies, making up nearly 80% of the institutions in the OSI-450 SIC and 84% in the C3S products. The US and UK combined represent nearly 50% of the institutional affiliations in both products, with the former being the dominant location.

The mapped institutions indicate that the practices of contemporary sea-ice science have an uneven geographical distribution. The maps show how Western approaches to scientific knowledge dominate contemporary sea-ice science. The expertise, ideas, norms, and theories used to shape the development and evolution of the sea-ice data products predominantly come from nations with the financial and material resources to invest in research and development (Table 7.3). Moreover, northern European countries and the US played a dominant role in shaping the history of Arctic sea-ice science through defining what types of information were legitimate and worthy of focus (Chapter 4). US institutions, in particular, have benefitted most substantially from historical investments in satellite technologies and climate science. As Chapter 4 discusses, these investments were inextricably linked to geopolitical and strategic interests.

It is essential to stress that these maps merely indicate the knowledge geographies underpinning the OSI-450 SIC and C3S data products. The complexities of knowledge production and the dispersion of authority are far more intricate than these maps can capture. Mapping the institutions on a national scale overlooks regional differences and inequalities, which, in turn, influence access and participation. Individual knowledge geographies are also far more comprehensive and nuanced than can be ascertained through institutional affiliations alone: each author is influenced by their own experiences, knowledge, cultural backgrounds, and political orientations (Felt *et al*., 2017). Moreover, as Latour (1987) notes, references to other texts may be included to indicate affiliations that have had no bearing on the nature of scientific practice or the resultant knowledge. In a similar vein, it is unlikely that all influences will have been captured by the reference lists consulted. For example, the collaborative relations

between the scientists and users are not captured here. However, it offers a starting point for thinking critically about how our knowledge of sea ice is tied to uneven distributions of power and wealth.

Table 7.3.: Gross domestic spending on research and development in 2019. This includes all research and development activities carried out by resident companies, research institutes, universities, and government laboratories. *Source:* OECD, https://data.oecd.org/rd/gross-domestic-spending-on-r-d.htm#indicator-chart.

Country	*Total value (millions of US dollars)*	*% of GDP*
United States	612, 714	3.07
China (People's Rep.)	514, 798	2.24
Japan	171, 854	3.20
Germany	132, 511	3.19
Korea	100, 055	4.64
France	64, 053	2.20
United Kingdom	51, 702	1.76
Taiwan	42, 966	3.49
Russia	39, 201	1.04
Italy	34, 254	1.47

7.3. Credibility, Visibility, and Knowledge Dissemination

7.3.1. Sea-Ice Indicators and the Importance of Institutional Visibility

The validity of a proposition, observation, or knowledge claim is an indication of its 'truthfulness'. Credibility is the quality of being trusted or believed it. As Shapin writes: "[t]he credibility and the validity of a proposition ought to be one and the same" (1995: 255-256). In other words, the credibility and trustworthiness of a knowledge claim should correlate directly with how truthful it is shown to be. However, in satellite observations of sea ice, this correlation is problematic. Due to the absence of 'truthful' data, the credibility of a sea-ice data product cannot be ascertained through questions about validity alone because there is no way of knowing exactly how much sea ice is present at the time of observation (see Section 5.4). Consequently, the acceptance of a sea-ice data product as a credible form of knowledge can be characterised as being relational; that is, it largely depends on how well it performs relative to the outputs of other data producers.

Ascertaining the relational quality of data products occurs in two notable ways. Firstly, through validation and intercomparison studies, data products are directly compared to higher resolution observations, *in situ* data, or other coarse resolution passive microwave data products (e.g., Ivanova *et al*., 2014, 2015; Kern *et al*., 2019; Meier and Stewart, 2019). These studies provide an indication of the plausible range of sea-ice cover values, and the accuracy (or validity) of a data product is assessed relative to this range, although, as Chapter 5 discussed, alternative, higher resolution data sources also have limitations. Secondly, social factors, such as institutional reputation, appear to be a significant determinant of data product credibility. In this sense, the more reputable institutions influence how the broader sea-ice community produces and disseminates research.

The maps and graphical representations of sea-ice concentration and extent are frequently used in scientific and non-scientific applications as indicators of the scale and rate of change occurring in the Arctic. However, the maps and data graphs were described as being "down the line" from the interests and work of the remote sensing scientists (Interview, 16th June 2020). In addition to meeting the requirements of GCOS and product users, a major reason for reporting these indicators in such formats is that they are considered a crucial vehicle for capturing the attention of other scientists, policymakers, and the public and for competing with leading institutions like the NSIDC as a reputable knowledge provider (see Section 6.2). As one research scientist stated, "[We] are working on sea-ice extent and sea-ice area just for the visibility. Nobody will look at or be interested in [the] maps if [we] don't have a sea-ice extent or sea-ice area indicator to say that [we] exist" (Interview, 16th June 2020). This implies that the reporting of these indicators influences the apparent credibility of MET Norway as a data provider. Achieving credibility matters because it presents new opportunities for research funding and collaboration.

EUMETSAT, the main funders of OSI SAF, are particularly interested in gaining visibility in the broad field of Earth Observation. One way of achieving this within sea-ice research is to produce comparable outputs to the NSIDC. The NSIDC SII is a more established and internationally recognised sea-ice data product than those produced by OSI SAF. In particular, despite not knowing for certain how accurately the product performs, the NSIDC SII has become a benchmark indicator for sea-ice extent and is widely used in scientific and non-scientific applications. Consequently, for an organisation that relies upon EUMETSAT for funding, achieving similar sea-ice extent estimates to the NSIDC is highly regarded by OSI SAF scientists. To converge with the NSIDC's outputs shows that EU institutions are of a similar level of maturity to the US and can be depended on as an alternative source of sea-ice knowledge. Moreover, providing a scientific consensus on the state of Arctic sea-ice conditions from disparate data producers is perceived as a powerful indicator of the strength of scientific claims.

A recent example of a notable convergence is the inclusion of OSI SAF sea-ice extent data alongside the NSIDC in the 'WMO Statement on the Status of the Global Climate in 2019' (WMO, 2020; Figure 7.4). Published during my fieldwork, I was informed that OSI SAF's representation in this high-level report was both a novel occurrence and a valued achievement. Since 1993, the WMO has been issuing annual statements on the state of the global climate, with reports featuring sea-ice extent from 1999 onwards. Between 1999 and 2007, the primary data provider was the Hadley Centre, located at the UK MET Office. Following the publication of the NSIDC SII, the NSIDC took over this role as the sole provider of sea-ice data. Thus, the inclusion of OSI SAF data in the 2020 report is significant. It is seen as a means of strengthening the visibility of OSI SAF on an international scale and strengthening their authority as a source of knowledge. It also demonstrates to EUMETSAT that the OSI-450 SIC is a viable allocation of research funding. Indeed, the association between institutional visibility and continued financial support is reflected in one scientist's following statement: "if we want to survive, we need visibility" (Interview, 16th June 2020). OSI SAF's data was also included in the most recent WMO statement alongside the NSIDC's data (WMO 2021).

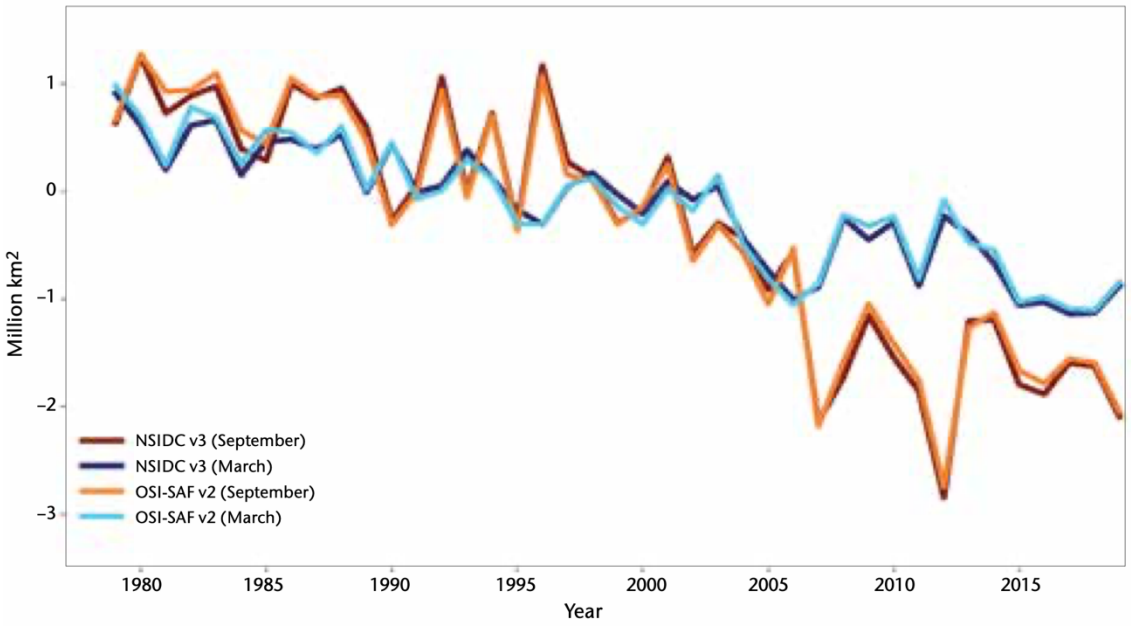


Figure 7.4.: Monthly Arctic sea-ice extent anomalies for September (red and orange) and March (blues), 1979-2019, relative to 1981-2010 averages. The graph shows data produced by NSIDC and OSI SAF and reported in the 'WMO Statement on the State of the Global Climate in 2019'. *Source*: WMO, 2020.

Despite the value attached to achieving convergence, there is a notable tension between institutional visibility, credibility, and accuracy. Validation studies have highlighted limitations in the sea-ice concentration retrievals associated with the NSIDC SII, especially when compared to more recent products such as the OSI-450 SIC or the NOAA-NSIDC CDR (Meier et al., 2014, 2017; Ivanova *et al.*, 2015; Kern *et al.*, 2019; Meier and Stewart, 2019). There are two conceivable explanations for the NSIDC SII's relative

limitations in sea-ice concentration retrieval. Firstly, as discussed in Chapter 5, the age of the product and the value attached to maintaining temporal consistency likely have a constraining factor on how much it can evolve and implement new methods and techniques (e.g., using dynamic tie-points to capture greater spatial and temporal variability in brightness temperatures). Products like the OSI-450 SIC, released since the NSIDC SII's initial publication in 2002, have benefitted from these advances. Secondly, as alluded to through conversations with MET Norway scientists, the ubiquity of the NSIDC SII as a sea-ice extent indicator may mean that its developmental focus has been on establishing an accurate and representative edge at 15% sea-ice concentrations, rather than improving the retrieval accuracy at higher concentrations.

It can be argued that the NSIDC SII has earned its credibility not solely on the grounds of validity assessments but through other social arrangements and structures. Factors such as the age of the product, institutional reputation and power, collaborative relations with other powerful institutions like NASA and NOAA, and the dominance of US-funded satellites have likely bolstered the NSIDC's authoritative position and supported the product's legitimacy as a source of sea-ice knowledge. Moreover, as Chapter 6 argued, the design, composition, and ubiquity of the sea-ice maps play an important role in persuading the viewer of the products' apparent objectivity and truthfulness. With this in mind, OSI SAF's interest in achieving convergence with the NSIDC SII prompts an essential question about how a balance between institutional visibility and accuracy is achieved in practice. The following interview extracts explore this question further in relation to the WMO reports noted above:

> *Interviewer*: Given that the developmental philosophy [of OSI SAF] is getting sea-ice concentration as accurate as possible […] and that for EUMETSAT, getting a convergence in sea-ice extent with the NSIDC's Sea Ice Index is a valued achievement […] is there a contradiction between achieving – or aspiring to achieve – accuracy and achieving convergence?
>
> *Interviewee*: Yes […] I see the contradiction. In that case [the WMO 2020 report], EUMETSAT is very interested in visibility. It is not just the plot. It is correct that if the plot was showing disagreement, then it [OSI SAF's data] probably would not be in that high-level report. The high-level report is really to show all the sources of evidence […]. For example, [the report] also has the surface air temperature, and here you have 5-6 different sources all showing the same thing. They are all shown because *that's* the important message. So, we don't aim for consistency for the sea-ice extent, but it is good that they are consistent.
>
> The validation papers (e.g., Kern *et al.*, 2019) […] show that there might be an inconsistency in the sea-ice extent: a small minor one that does not contradict the message of less ice in the Arctic. We actually challenge the NSIDC, and we want to show that on the sea-ice concentration values, scientists should really look at the sea-

> ice concentration data and check other sources. […] But we are still so young at OSI SAF that we also just want any visibility and this WMO report was really good to have.

These extracts indicate that OSI SAF would not sacrifice the accuracy of the sea-ice concentration retrieval to converge with the NSIDC SII. OSI SAF are not explicitly aiming for convergence, and it was recognised that doing so could be interpreted as contradictory. Rather, the visibility that the WMO report offers is a valued means through which the users of sea-ice data products become aware of the work being carried out by OSI SAF. It was noted by a research scientist that the differences between the OSI-450 SIC and the NSIDC SII are in the "tiny details" and that the vital message to convey in high-level reports is the consistency in long-term observations (Interview, 16th June 2020). At the same time, OSI SAF is acutely aware of the many limitations and uncertainties of passive microwave technologies. They present themselves as a challenger to the NSIDC and encourage scientists and data users to see beyond individual data sources and consider their varying strengths and weaknesses and relative uncertainties. This outlook reflects foundational principles that underpin OSI SAF's methodology, namely, the emphasis on providing a transparent characterisation of uncertainties and errors to enable users to make informed judgements about the accuracy of different sea-ice products (see Section 5.3.2.2).

Additionally, the previous chapter illustrates the contestable nature of defining an 'ice edge' using binary thresholds. When asked about the representativeness of the 15% sea-ice concentration definition for sea-ice extent, scientists generally responded with a similar sentiment: the 15% threshold is *the* accepted method for deriving extent and while recognising the issues around its continued use, developing and implementing new thresholds to improve the representativeness of sea-ice extent is not seen as a particularly advantageous use of time or resources. Moreover, changing the definition could significantly alter the trends in sea-ice cover and undermine temporal consistency (see Section 6.3). This may initiate broader questions and concerns over the credibility of scientific research.

Discussions about sea-ice extent were often met with ambivalence around its suitability as an indicator of long-term changes in sea-ice conditions. In recent years, the growing number of intercomparison studies focussing on the differences in retrieved sea-ice extent values between institutions have shed light on some important biases and limitations around its use (see Section 6.3.1). In light of this increased focus, there are concerns around how the differences in absolute values may become more problematic for the sea-ice community, particularly regarding public perceptions of uncertainty and scientific credibility.

Despite the dominant and widespread use of sea-ice extent, a major focus of current work within the international sea-ice community is to improve sea-ice area and have this

become a primary indicator. However, sea-ice area is much more sensitive to the uncertainties and limitations caused by the poor spatial resolution of the sensors and the effects of atmospheric and oceanic interference on brightness temperature measurements (Section 5.2). This means that absolute values of sea-ice area are more uncertain and give rise to greater discrepancies between institutions (i.e., sea-ice area increases relative uncertainties). Moreover, the Pole Hole introduces complications for sea-ice area calculations because there is no way of knowing the actual concentration of sea ice covering this area. That said, the area of the Pole Hole has reduced with each successive satellite mission (Appendix 2). As Section 7.4.2 details, this trend is set to continue, making the use of sea-ice area potentially more feasible in the future.

Despite current limitations, the use of sea-ice area is becoming more popular, especially in climate modelling applications and among expert users. For example, in the IPCC AR6, sea-ice area is the main indicator used to assess changes in Arctic sea-ice cover (IPCC, 2021). The report states: "we assess changes in sea-ice area (the actual area of the ocean covered by sea ice) rather than sea-ice extent, because sea-ice area is geophysically more relevant and not grid-dependent" (Fox-Kemper *et al*., 2021: 44).[78] This shifting focus was described as a characteristic of the "new generation" of climate scientists (Interview, 16th June 2020). It indicates a significant change in the direction of sea-ice research and implies that the partial and simplistic view that sea-ice extent provides is no longer regarded as an adequate indicator of sea-ice conditions.

The shifting focus onto sea-ice area does not necessarily mean that sea-ice extent reporting will stop. Sea-ice extent represents one of the longest and most consistent climate data records. Moreover, sea-ice extent is used to mark the 'ice edge' in many world atlases and non-scientific maps, reflecting its role as a "more-than-scientific reference" (Gabrys and Yusoff, 2011: 6). However, the movement towards reporting sea-ice area may have significant implications for our understanding of the Arctic in current and future contexts and how we respond. As Section 6.3 argued, the use of sea-ice extent has played a crucial role in framing discourse around Arctic sea-ice decline. While satellite limitations will still introduce ambiguities in the data, sea-ice area is a less arbitrary measure of sea-ice cover. It produces a more spatially and temporally nuanced understanding of sea-ice conditions.

Moreover, the shift to using area may invoke changes to the structural relations of the broader sea-ice community. Sea-ice area calculations demand a sea-ice concentration product that is highly consistent throughout the year and on pan-Arctic scales. Notably, OSI SAF's developmental focus on improving sea-ice concentration retrievals by attending to the "finer details" may improve the credibility of the OSI-450 SIC product,

[78] The IPCC Six Assessment Report has been approved and accepted; however, at the time of writing (October 2021), it remains subject to final copy-editing and layout.

and OSI SAF may become a more dominant and reputable source of sea-ice data in the future.

7.3.2. Participation, Communication, and Accountability

Our ability to mitigate and adapt in the face of climate change relies on the accurate, reliable, and accessible communication of scientific research. As such, the importance of scientific knowledge transfer has increased in recent decades, and there is greater pressure for research institutes to disseminate their results beyond the scientific community and engage in public dialogue (Grosfeld *et al*., 2016). This need is also reflected in one of the fundamental requirements of GCOS: to provide freely available and accessible data (Section 7.2.2).

For the most part, OSI SAF and C3S disseminate their products on dedicated websites, whereby users can 'freely' access, download, use, and redistribute the data. The storing and reporting of data products in open online spaces enables knowledge to be accessed and shared more extensively and quickly than conventional, and often more restricted channels (e.g., scientific journals). However, there is an important difference in how the OSI SAF and C3S data products are disseminated, which affects their relative accessibility. As noted in Chapter 5, the OSI-450 SIC data product is presented in a 'quick-look' format, enabling users to view and compare maps and data values. Thus, although it is designed with climate researchers in mind, the 'quick-look' format of data outputs makes the product more accessible to a wider audience.

In contrast, although the C3S products are 'freely' available for access and use, they are not presented in a 'quick-look' format. Retrieving the information of interest requires users to process the data using the Climate Data Store interface, and this relies upon some prior knowledge and experience of data programming software, such as Python. Consequently, the products tend to remain within scientific circles.

In addition to the presented format of the data products, the type of sea-ice parameter also influences research dissemination. As noted in the previous section, sea-ice concentration and extent (and increasingly area) are widely reported indicators of changes in Arctic sea-ice conditions. They tend to receive greater attention in public spheres than parameters such as sea-ice type. In recent years, Arctic sea-ice decline has drawn the attention of scientific, socio-political, and commercial stakeholders alike, and reports of sea-ice concentration and extent have featured extensively in the media (Christensen *et al*., 2013; Christensen and Nilsson, 2017; Appendix 1). Such coverage is a vital component of scientific knowledge dissemination and forms a crucial link between scientists, policymakers, and the public.

Due to differences in institutional maturity, media reports on Arctic sea-ice concentration and extent tend to focus on the NSIDC's outputs disproportionately.

Accordingly, the NSIDC has established a website dedicated to providing regular news updates on the state of sea-ice conditions and managing journalistic queries.[79] OSI SAF's products receive comparatively limited media attention. A major communication outlet for OSI SAF's research has been through a monthly bulletin on the state of the climate produced by Copernicus C3S and reported online.[80] Scientists remarked on how this formal and independently managed communication outlet reduces the pressure to engage with the media, and there is generally a less formal dialogue or information exchange with journalists. Indeed, as one respondent stated: "[OSI SAF] are still outside or below [the media's] radar… we don't feel the pressure to be in the media with sea-ice change because [we] know it's taken care of [in] Europe by C3S" (Interview, 16th June 2020).

At the same time, social media networks such as Twitter have become widely used tools for science communication and public engagement (López-Goñi and Sánchez-Angulo, 2017). Many scientific journals, institutions, and prominent research scientists have a Twitter account and use it for various purposes, such as communicating research outputs, promoting opportunities, generating research ideas, discussing key problems, and developing international social networks. Indeed, virtually all the institutions I have researched and individuals I have interacted with as part of this PhD study use Twitter in these ways.

Twitter can be a highly effective and beneficial form of science communication. The platform can offer more accessible ways to communicate complex research and engage with a wider public audience than more traditional communication outlets (López-Goñi and Sánchez-Angulo, 2017). It can also encourage public participation and help lessen the gap between researchers, policymakers, the media, and the public.

For MET Norway scientists, Twitter represents a useful avenue to public reporting and engagement. It improves the visibility of their research activities and enables an informal and interactive dialogue between scientists, journalists, and the public. That said, the scientists stressed a need to be cautious around how scientific information is presented on Twitter. Due to the restricted character limit of 'Tweets' (280 characters, as of 2018), Twitter enables the dissemination of content-low and fast-paced information. Visual data, such as sea-ice maps and graphs, are particularly amenable to this still style of knowledge dissemination because they are designed to enable a 'quick-look' identification of sea-ice conditions. However, important details about the broader context of the data products are often omitted. Posts may include URL links to the product's website or details on who has produced the data, but vital information about

[79] The website is the Arctic Sea Ice News and Analysis (ASINA), introduced in Section 5.3.1.1.
[80] The Copernicus C3S Climate Bulletin website can be found at the following address: https://climate.copernicus.eu/climate-bulletins.

the inherent uncertainties, limitations, and complexities of passive microwave satellite remote sensing requires the user to engage more comprehensively.

When disseminating research beyond scientific circles, the scientists expressed specific concerns over the loss of context, particularly with reporting absolute values of key indicators such as sea-ice extent or classification products whereby the 'ice edge' definition differs from the conventional 15% sea-ice concentration (e.g., C3S products). While long-term trends in sea-ice cover are generally consistent between different data producers, absolute values vary due to differences in data product methodologies. Differences between the reported extent values can be in the hundreds of thousands of km^2. For example, in September 2021, the NSIDC reported a monthly average sea-ice extent value of 4.9 million km^2 compared to OSI SAF's reported value of 5.59 million km^2. Without prior knowledge of why they occur (Chapter 5), the extent of these differences may be problematically received. As such, the scientists focus on reporting trends rather than absolute values. This is reflected in the following statement: "In terms of the absolute level, [we] are still not confident in communicating. What is important is the trends [and] as long as people are focussed on the trends, we are safe" (Interview, 16th June 2020).

Concerns over the loss of context underscore the importance of the transparent approach taken by the OSI SAF and C3S programmes. The supplementary documentation that includes guidelines for using the data and detailed explanations about how the products have been produced are vital for enabling users to make informed choices. However, as some scientists acknowledged, there is no guarantee that this information will be considered, particularly by those who come to the data through content-low sources like Twitter. Thus, for many, the products are often accessed, viewed, used, and redistributed with little context about their development.

In addition to the loss of context, the open-access nature of contemporary sea-ice science, alongside the increased dissemination through the media and social media outlets, has exposed scientific research to new forms of public scrutiny. Sea-ice science is fallible: it is characterised by many uncertainties, assumptions, and technological limitations, and errors and gaps in sea-ice reporting are not uncommon (Chapter 5). However, this fallibility is often misinterpreted as inaccurate or 'bad' science and erroneous reporting of sea-ice conditions occurs in a far more public way than it did previously. This can have significant consequences for public trust in scientific knowledge.

A recent example of such public erroneous sea-ice reporting occurred in February 2021. Due to a fault at a ground processing station that resulted in a data outage between February 19th-22nd, the NSIDC incorrectly reported the NSIDC SII data. Notably, the reliance on automated systems means that sea-ice maps and other forms of representation are instantaneously published on the NSIDC's website following data processing. Before an explanation was provided on February 26th, images such as Figure

7.5 circulated on Twitter and other online forums, prompting concerned responses from a diverse audience.[81] These included initial expressions of concern that sea-ice was experiencing a drastic and sudden decline; questions over the reliability of satellites as a source of data and the credibility of the NSIDC's outputs; and claims from climate change denialists stating that the images served as evidence for the conspirative nature of climate science. Alongside these concerns were reassurances that data gaps or errors happen, and this reported drop in sea-ice extent was likely due to a processing error. A selection of quotes is provided in Appendix 14 to illustrate the breadth of responses in online spaces.

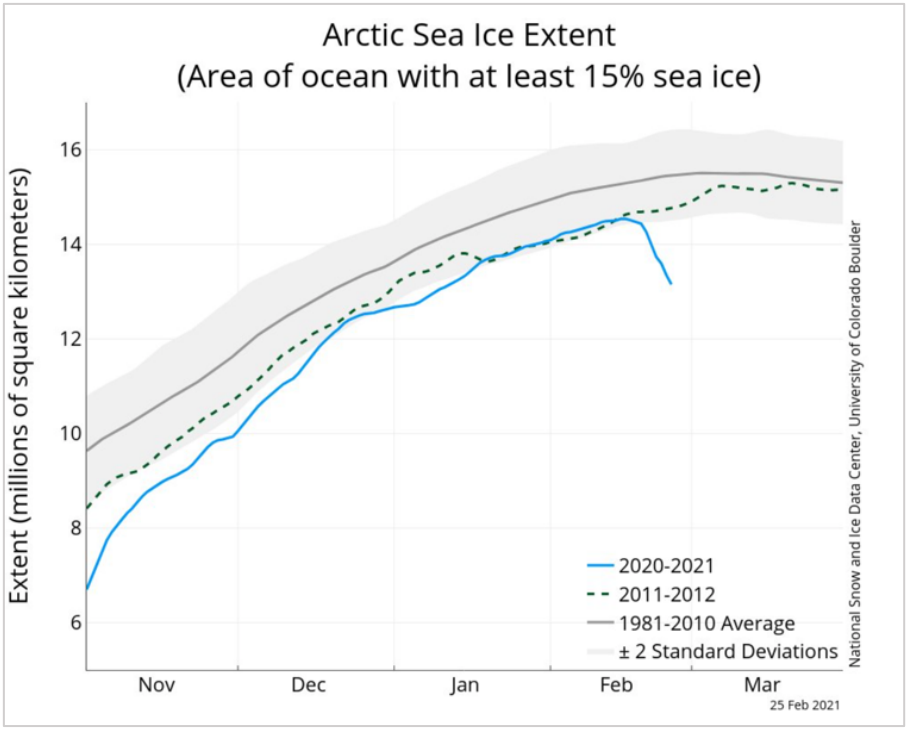


Figure 7.5.: NSIDC's erroneous reporting of Arctic sea-ice extent on 25th February 2021. The sharp decline of the blue line during mid-February occurred due to a data gap. *Source:* https://nsidc.org/arcticseaicenews/.

For MET Norway scientists, the potential for misinterpretation and increased public scrutiny necessitates care about how information is disseminated. Although the scientists can indicate how the products *should* be used through user guides and other supplementary documentation, once the products are disseminated, they have little control over how they are actually used. Instead, the users are responsible for applying or interpreting the research findings. This means that as sea-ice data products are increasingly circulated in the public realm, they are open to varying (mis)interpretations

[81] The NSIDC Tweeted an official response on 25th February 2021: *"For those following sea ice extent & concentration on our site: sea ice processing is currently having problems. Daily Sea Ice Index/Arctic Sea Ice News & Analysis values after February 19 are erroneous. We are investigating the issue and will correct it as soon as possible."* On 26th February 2021, they also Tweeted: *"If you've been following sea ice numbers, you may have noticed a gap in data from 2/19 to 2/22. Unfortunately, these data are missing and unrecoverable due to a problem that occurred at the ground station during planned maintenance. We apologize for any inconvenience."*

and can be (mis)used or abused in ways that may undermine their intended message. This has prompted discussions about how uncertainty information can be better reported in sea-ice data products. One possible solution is to bring the uncertainty values to the foreground by including them on the reported sea-ice maps or data graphs. However, there is concern that this would invoke further misinterpretations and negative perceptions, partly due to the inability to verify observations with certainty (see Section 5.4).

The potential for misinterpretation also prompts questions about accountability in the dissemination of sea-ice research. My encounters in the field and document analysis imply a separation between knowledge *production* and knowledge *application*. The scientists are generally responsible for acquiring, interpreting, and presenting the data, and their focus is on maximising productivity through optimising data processing methods. The scientists generally have less involvement with the "downstream" applications of science, and "non-scientific" tasks such as report writing and administration – tasks which are more recurrent with MET Norway's increasing involvement with EU-funded projects – were regarded as disruptive to "scientific productivity" (Fieldnotes, 6th February 2020). This suggests that the role or primary motivation of sea-ice scientists engaging in knowledge dissemination is to inform and raise awareness through reporting high-quality, evidence-based, and accurate information. The exchange is monologic, and the public are largely cast as passive receivers; for instance, one scientist stated that their involvement on Twitter was less about achieving "a better product" and more about *informing* the public (Interview, 16th June 2020).

The problem with separating the production and application of knowledge in this linear way is that it often fails to account for the complex and heterogeneous nature of knowledge interpretation (Irwin and Brynne, 1996; Kappel and Holmen, 2019). It reduces the complexities of knowledge interpretation to an issue of *use* versus *misuse* (see Haraway, 1988), as opposed to recognising that there is no single way in which knowledge is interpreted. This becomes particularly salient in the public communication of scientific knowledge. While public understanding of sea-ice science is not a focus in this thesis, it suffices to say that the knowledge presented to the public will always be interpreted and understood according to individual experiences, socio-economic status, cultural backgrounds, educational attainment, and political orientations (Livingstone, 2005; Sismondo, 2010).

Similarly, the open-source nature of data products and the 'free' availability of computer processing software, such as Python, widen the scope of participation in sea-ice research. As one scientist remarked: "[T]ools are developed open source and are available [not only] for professionals and other research scientists" (Interview, 16th June 2020). In previous decades, sea-ice research was carried out exclusively by specialised institutions

that could invest in the necessary computing power and software tools for data processing. The dissemination of research was also restricted: data was stored and circulated via CD-ROMs, and scientific reports represented the main outlet for communication (see Gloersen *et al*., 1992). Thus, the shift towards transparent and open data processing and availability is seen to be democratising sea-ice research: "everyone can process the satellite data – it is not a specialised process" (Interview, 16th June 2020). For MET Norway scientists, this further underscores the importance of accuracy in their data and data processing methods. However, it also points to a broader issue regarding digital cultures and climate communications (see Boykoff, 2019, 2020). While the shift towards open-source and online dissemination inevitably increases access and participation, it risks exacerbating inequalities of power and access. As Boykoff (2019) notes, knowledge about climate change exists by and large in the digital sphere. Paradoxically, those who are most at risk of the effects of climate change are often the same people who are least likely to participate in these digital spaces.

7.4. Politics and Sea-Ice Science

7.4.1. The Barents Sea Management Plan: Politicising the 'Ice Edge'

Following directly on from the previous section, maintaining a perceived separation between science and politics is often seen as imperative for producing objective, credible, and legitimate knowledge (Bay-Larsen *et al*., 2020). It follows that scientists should remain separate from the political domain until a consensus has been achieved to avoid scientific conclusions being influenced or corrupted by subjective biases. In discussions, I was informed that the scientists at MET Norway must manoeuvre carefully to avoid being embroiled in political disputes (Fieldnotes, 13th February 2020). This manoeuvring involves trying to be "as objective as possible" through maintaining a distance between scientific activities and social applications, taking care in how "to visualise the data" in various forms of representation, and adopting a transparent approach through the provision of detailed documentation on the limitations and uncertainties of data products (Interview, 18th June 2020). However, with the Arctic featuring ever more centrally in debates about climate change and geopolitics, maintaining a (perceived) separation is challenging.

In early 2020, during my placement at MET Norway, a live debate was occurring in the Norwegian Government over defining the southern border of the MSIZ – the 'ice edge' (or 'iskant' in Norwegian) – and locating its geographical position. This debate was highly publicised and regularly featured in online news reports throughout my visit.[82]

[82] Some example English language news reports can be found at the following addresses: https://www.newsinenglish.no/2020/02/13/norway-on-edge-over-the-ice-edge/; https://www.highnorthnews.com/en/struggle-over-ice-edge-decides-future-norways-oil; https://www.highnorthnews.com/en/norwegian-battle-over-ice-edge-starts-week.

As a region of great biological importance, the need for a formal definition of an 'ice edge' in the Barents Sea represents an attempt to balance the sustainable development of emerging industries, such as resource extraction, with concerns over the environmental vulnerability of the MSIZ (Norwegian Ministry of Climate and Environment, 2020). However, within political circles and between politicians and scientific experts, there lacks a consensus on the precise whereabouts of this region.

Many of the disagreements that played out in March 2020 reflected the different opinions of stakeholders positioned at opposing ends of the political spectrum over how the vulnerable region should be regulated. Situated on the far right, the Progress Party, which until two months earlier had been part of the Høyre (Right) Party-led coalition government, called for a dynamic edge that would simultaneously open the region to petroleum activities while maintaining environmental protection. Centre-right parties within the coalition government that was in place in March 2020, including the Liberal Party, called for a more cautious, southerly reaching edge to protect a larger proportion of the MSIZ, a position that was shared as well by non-governing parties further to the left including the Green Party (Berglund, 2020).

The Norwegian Government sought advice from several expert institutions on defining the edge and demarcating a zone of vulnerability. These included: the Norwegian Polar Institute (NPI), the Norwegian Institute of Marine Research, and the Norwegian Petroleum Directorate. Between these different groups, perspectives on how to define the 'ice-edge' differ. The NPI is Norway's primary institution for environmental monitoring, mapping, and management-orientated research in the Arctic. Based on substantial research into the biological productivity and diversity in the MSIZ, the NPI recommended a definition based on a sea-ice frequency of 0.5%.[83] Sea-ice frequency measures the percentage of ice-covered days for a given month over the last 30 years, whereby 'ice-covered' constitutes sea-ice concentrations of 15% or more (Itkin *et al*., 2014). A 0.5% frequency indicates that a given area was covered in at least 15% sea-ice concentration for approximately five days in a particular month over the last 30 years. All the environmentalists, climatologists, and oceanographers consulted by the government supported this definition (Berglund, 2020). Conversely, industry stakeholders proposed a more northerly positioned 'ice edge' defined using a 30% sea-ice frequency. Compared to the more cautious approach, this higher frequency would

[83] Two major scientific reports contributed to the cautious definition put forward by the NPI. In 2018, several Norwegian institutions, including the NPI, MET Norway, the Norwegian Environment Agency, and the Norwegian Directorate for Fisheries, contributed to a special report on the value and vulnerability of Norwegian seas (available at: https://www.miljodirektoratet.no/globalassets/publikasjoner/m1303/m1303.pdf). In 2019, the NPI produced an independent report on the values and vulnerability of the marginal sea-ice zone (available at: https://brage.npolar.no/npolar-xmlui/handle/11250/2563226?locale-attribute=en.

give rise to differences in area of over 150 km² and position the 'ice edge' in a more favourable location for petroleum activities.

After several weeks of debate, in April 2020, the Norwegian Government settled on an 'ice edge' defined using a 15% sea-ice frequency (Norwegian Ministry of Climate and Environment, 2020). For the government, this was seen as a compromising definition; for many others, it was seen to favour the interests of the petroleum industry and ignore the advice of scientific experts, not least because the 15% frequency line fell just northward of all previously issued licences, meaning that no previously permitted petroleum activities would need to be rescinded (Berglund, 2020). Figure 7.6 illustrates the two 'ice edge' positions derived using the different definitions of sea-ice frequency (0.5% and 15%).

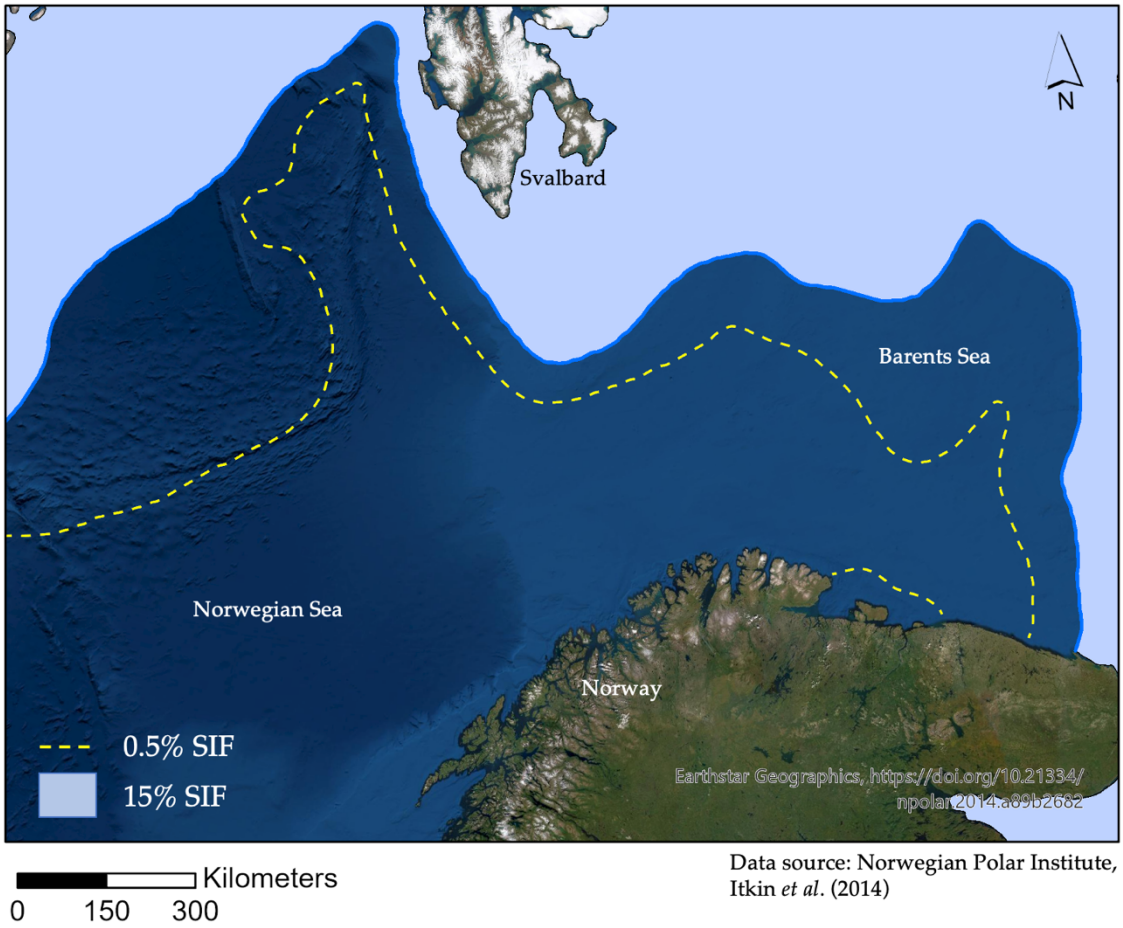


Figure 7.6.: Sea-ice frequency used to mark the 'ice edge' in the Barents Sea. The map shows two different definitions (0.5% and 15%) for April for 1988-2017.

The debate over the Barents Sea 'ice edge' reflects a broader question about whether sea ice is an appropriate proxy for ecosystem vulnerability in the MSIZ. In a report published in 2018, the NPI highlighted the lack of spatial difference in vulnerability across the zone (von Quillfeldt, 2018). They found that, due to the dynamic and variable nature of the physical, chemical, and biological properties of the MSIZ, it was not possible to delineate zones of differential variability using sea ice as a proxy indicator. An important

implication of this finding is that vulnerability is not directly determined by the concentration of sea ice or proximity to the main ice pack. Thus, changes in the spatial and temporal distribution of sea-ice cover do not correlate with changes to ecosystem vulnerability.

Notably, the NPI's sea-ice frequency dataset is based on passive microwave sea-ice extent data derived using the NOAA-NSIDC sea-ice concentration climate record (Itkin *et al.*, 2014; Meier *et al.*, 2014, 2017). This raises important questions about the uncertainties involved in using a coarse resolution dataset as a basis for demarcating the 'ice edge'. Indeed, as Meier and Stewart (2019) have shown, mapped positions of the 'ice edge' can vary between passive microwave data products by as much as 75 km (based on 15% sea-ice extent). These differences are perhaps less problematic for large-scale and long-term trend analysis, but their application in this political context is questionable.

Similarly, following the critical discussions included in Chapter 6, passive microwave observations of sea ice render the Arctic Ocean in geophysical terms. The fundamental principles underpinning the calculation of sea-ice concentration and extent are based on microwave emissivity signatures that have little correlation with environmental vulnerability (Chapter 5: Section 5.2). Although not directly involved in the Barents Sea Management Plan debates, MET Norway scientists shared a similar disdain with the political focus on sea ice for demarcating zones of vulnerability. For one scientist I spoke to, the use of indicators such as sea-ice concentration and extent within these political contexts is misleading and problematic. This sentiment is reflected in the following interview extract:

> The sea-ice limit was only a cover for the biological cycles. […] What is important is the biota, or the life there. […] The sea-ice concentration data was in the end, much more an illustration: it's very visual. But since the sea ice is retreating in the Barents Sea, there will be less sea ice in the future and you can't really use it as an argument for not going there. Sea-ice is retreating but that doesn't mean that the ecosystems are moving necessarily […] The sea ice is moving but what you actually want to protect doesn't move at the same time. (Interview, 16th June 2020).

Fixing the 'ice edge' within the Barents Sea Management Plan is an example of how passive microwave observations of sea-ice cover can be used outside of their intended purposes to support and legitimise policies. In this highly publicised debate, sea-ice concentration and extent have become crudely mired in debates about environmental protection, whereby other indicators would be better suited. Within this context, it is important to emphasise the power associated with the visual dimension of mapped sea-ice cover. Due to the inevitability of future declines in sea-ice cover, the mapped location of an 'ice edge' will likely shift northwards with time. Thus, continuing to use sea-ice cover as a proxy for ecosystem vulnerability will increase the area open for petroleum

activities and have major environmental consequences. Ultimately, in this process of (re)mapping a sea-ice boundary, sea-ice cover has become a "strategic pawn in political disputes involving strong conflicts of interest" (Bay-Larsen *et al*., 2021: 169).

The Barents Sea Management Plan reflects an example of where the 'ice edge' has become a veil used to advance political and economic interests in what exists below the surface. However, it is important not to interpret this simply as a misguided *application* of sea-ice cover. Regardless of their intended purpose, the very act of producing maps of sea-ice cover is political because it gives rise to particular understandings or ways of representing the Arctic, which in turn affects how it can be known, imagined, and acted upon. As Chapter 6 contended, the geophysical framings of the Arctic Ocean that the scientific products of sea-ice cover provide help reinforce and encourage the notion that complex, heterogeneous, and contested ice-covered areas can be classified into distinct and quantifiable units. Thus, by mapping these spaces, it can be argued that sea-ice scientists play an active role in making them visible, knowable, and useable for different political interests and agendas, albeit unintentionally.

7.4.2. Ageing Satellites and a New Era of Satellite Observation

Since the 1970s, the satellite-sensors used in sea-ice research have been predominantly owned by the US as part of the NASA, NOAA, and U.S. Department of Defense satellite programmes. Currently, scientists and research institutes worldwide, including MET Norway and the NSIDC, rely on a record of passive microwave observations retrieved using the SMMR, SSM/I, and SSMIS instruments flown onboard the Nimbus-7 and DMSP satellites (Appendix 2). Other passive microwave satellite-sensor options are available for retrieving observations of sea-ice cover. The WMO maintains a list of past, present, and future environmental satellite missions, instruments, and other related information, which includes eighteen different passive microwave radiometers operating between 1978 and 2046 that either provide, or have the potential to provide, measurements of sea-ice cover.[84] These include instruments owned and operated by the Japanese Aerospace Exploration Agency (JAXA), the China Meteorological Administration (CMA), and the Russian Federal Space Agency (Roscosmos) (Table 7.4). However, the duration and consistency of the passive microwave observations retrieved using SMMR, SSM/I, and SSMIS instruments, and thus, their value for long-term climate monitoring, are largely unrivalled.

[84] The list can be viewed online via the 'Observing Systems Capability Analysis and Review Tool' (OSCAR): https://space.oscar.wmo.int/spacecapabilities.

Table 7.4.: Timelines of passive microwave satellite remote sensing instruments that provide, or have to potential to provide, observations of sea-ice cover. The information is sourced from the WMO's 'Observing Systems Capability Analysis and Review Tool'. (Details of the providing agency acronyms are listed in the accompanying 'List of Abbreviations'.)

Instrument	Satellite	Providing Agency	1970s	1980s	1990s	2000s	2010s	2020s	2030s	2040s
AMSR	ADEOS-2	JAXA	Japan							
AMSR2	GCOM-W	JAXA								
AMSR-3	GOSAT-GW	JAXA								
AMSR-E	EOS Aqua	JAXA								
CIMR	CIMR	ESA, EC, & EUMETSAT	Europe							
MWI (MetOp-SG)	EPS Second Generation	ESA & EUMETSAT								
MTVZA	Meteor-3M	Roscosmos	Russia							
MTVZA-GY	Meteor-M Series	Roscosmos								
MTVZA-GY-MP	Meteor-MP Series	Roscosmos								
MTVZA-OK (MW)	Okean Operational-1	NSAU	Ukraine							
MWRI	Feng-Yun-3 Series	CMA	China							
MWRI-RM	Feng-Yun-3 Series	CMA								
MWRI (HY-2)	Hai Yang 2	NSOAS								
GMI (Core)	GPM	NASA	USA							
WindSat	Coriolis	DoD								
SMMR	Nimbus-7	NASA								
SSM/I	DMSP-F Series	DoD								
SSMIS	DMSP-F Series	DoD								

The SSMIS instruments flown onboard the DMSP F-17 and F-18 satellites continue to be the primary data source underpinning many climate data records of sea-ice cover, including those analysed in this PhD research. However, these satellite instruments have extended far beyond their expected operation time of approximately 5 years (Witze, 2017; Table 7.4). The intended successor to the F-18 satellite, the DMSP F-19, failed prematurely in 2016 following a communications failure (Gruss, 2016). The Department of Defense constructed the DMSP F-20 satellite during the 1990s for use in Earth Observation; however, the U.S. Congress voted to defund and dismantle the satellite due to concerns over the cost of storage, launch, and maintenance (Gruss, 2015).[85] At present, the US have no confirmed plans to launch a replacement satellite programme on the same scale as the DMSP. This is primarily due to budget constraints and a shift in focus away from large-scale weather satellite missions and towards small-scale programmes that centre on cybersecurity and information technology (Werner, 2018).

The European Space Agency is planning the launch of the second generation of meteorological operational satellites (Metop-SG) in the mid-2020s (Kramer, 2022). Building directly on the passive microwave sensors flown as part of the DMSP satellite missions, the Metop-SG series will include a new microwave imager (MWI), which is expected to extend the sea-ice cover record into the future. However, this instrument is set to be launched onboard the Metop-SG-B1 satellite no earlier than January 2025, presenting the possibility of a data gap in the passive microwave record.

In the months leading up to my fieldwork, the sea-ice community expressed concern that the ageing US satellite-sensors might disrupt the long-term consistency of sea-ice data products and compromise future ocean-climate research (Gerland *et al.*, 2019). This potential disruption has prompted institutes working with passive microwave sensing instruments to assess alternative data sources to ensure that, if the satellites were to perish imminently, the long-term consistency of the passive microwave record is maintained. This has included attempts to merge passive microwave data with observations obtained through other means, such as visible or active microwave systems (DMI, 2020). However, merging passive microwave data with other visible or active data sources will undoubtedly affect the temporal consistency of the data products and alter the nature of the resultant knowledge, as they observe different surface properties. Additional efforts have been made to compare and combine the retrievals from overlapping passive microwave sensors (e.g., Du *et al.*, 2014; Gao *et al.*, 2020). For instance, the NSIDC is working on incorporating retrievals from JAXA's AMSR-E and AMSR2 instruments into their sea-ice concentration records (e.g., Markus *et al.*, 2018). However, differences between the AMSR-E and AMSR2 and the SMMR, SSM/I, and SSMIS sensors, in terms of their design characteristics and spatial resolution (Appendix

[85] The DMSP F-20 has since been repurposed as a museum piece in the Schriever Space Complex at the LA Air Force Base.

2), demand careful cross-calibration and cross-comparison to ensure that inter-sensor biases do not undermine the consistency of the data. Moreover, the current AMSR2 sensor, operating since August 2012, has now also extended beyond its expected operating period of five years.

The potential for the imminent loss of US satellites has encouraged negotiations between experts over the possible transition to Chinese satellites as a replacement data source (Witze, 2017). Running in parallel to the DoD and JAXA instruments, CMA operate a series of satellites (Feng-Yun-3) with passive microwave radiometers onboard (MWRI). These instruments share similar characteristics to the SSMIS sensor; therefore, they have the potential to become the primary source of passive microwave observations following the termination of the DMSP programme. However, initial intercomparison and validation studies have shown significant disparities between the sea-ice observations derived using the MWRI and other international passive microwave instruments and data products (Hao *et al*., 2021). Reducing these disparities is a significant focus of contemporary research, and recent studies have indicated that through using different sea-ice retrieval algorithms, correction methods, and inter-sensor calibration techniques, the comparative accuracy of MWRI sea-ice retrieval can be significantly improved (e.g., Chen *et al*., 2021; Hao *et al*., 2021; Shi *et al*., 2021).

In addition to the uncertainties and biases that inter-sensor differences introduce, it is worth considering how international relations may compromise the access, distribution, and use of data obtained by Chinese satellites. In particular, owing to their collaborative links with NASA's GSFC, the incorporation of data from CMA satellites has the potential to introduce political obstacles for the NSIDC (Witze, 2017). In 2011, the U.S. Congress passed a law (the Wolf Amendment) restricting NASA scientists from using government funds to directly engage or cooperate with Chinese scientists (Foust, 2019). While this does not explicitly prevent data sharing *per se*, it may complicate matters and increase the precarity of the NSIDC's potential future reliance on Chinese satellites as a fundamental data source. For EU institutions like MET Norway, the potential transition to using Chinese satellites is less fraught. The relationship between Europe and China in space-related scientific research is seemingly more open and cooperative. For example, ESA and the Chinese National Space Agency have a history of collaboration in space activities, and there are plans in place for ongoing cooperation in the coming years (Jones, 2021). Indeed, CMA satellite data have been made available to OSI SAF due to collaborative agreements between EUMETSAT and CMA (DMI, 2020).

Alongside China, Europe is likely to become a major player in passive microwave satellite data provision. This shift is expected to be of great benefit to European institutions involved in space-related research. Shortly after the commencement of the Metop-SG series, a partnership between ESA, EUMETSAT, and the European Commission will see the launch of the Copernicus Sentinel Expansion Missions from

2028 (Table 7.4), which will include a cutting-edge passive microwave sensor: the Copernicus Imaging Microwave Radiometer (CIMR). As outlined in the mission documentation (ESA, 2020), the launch of CIMR specifically concerns improving the observations of Arctic sea-ice conditions to support the establishment and implementation of EU policies to reduce the societal impacts of changes in the Arctic. The CIMR sensor represents a far more advanced instrument than any of its predecessors (ESA, 2020). The sensor is characterised by a much larger antenna (>5 metres), which will vastly improve the spatial resolution of the data (~5 – 50 km depending on the frequency channel). The swath width is significantly wider at >1900 km, thus providing more extensive coverage and eliminating the data holes at the poles. The sensor will also obtain data at lower frequency channels, which are less affected by atmospheric and oceanic interference. In short, due to these various characteristics, CIMR will significantly improve the accuracy of space-borne observations of sea ice. As such, CIMR is colloquially referred to as "the Game-changer" (Lavergne, 2018).

The launch of CIMR is expected to cause a transformational change in the nature and distribution of satellite data; as such, it generated excitement among the scientists with whom I interacted. For European institutes, the CIMR mission is expected to offer many advantages. These include improving the security and reliability of passive microwave data for scientific and operational applications; increasing European autonomy and independence from other non-European data providers, such as China, USA, and Japan; advancing the technical capacity and skills of European agencies in space science and technology; and elevating Europe's status within the Earth Observation community (ESA, 2020). The launch of CIMR also reflects a significant cultural shift in sea-ice research. As one research scientist proclaimed:

> The US dominance on the satellite front is disappearing. It is going away. In a few years' time, everybody will have to use either Chinese or European satellites. […] [The CIMR instrument will represent] the best satellite system in the world and [for the first time in history] it is in Europe, no more in the US. That is a shift, which is good for us in Europe.

As Chapter 4 illustrated, the US has largely controlled the development and implementation of satellites fitted with passive microwave instruments for several decades. For the NSIDC, the hegemony enjoyed by US institutions over Earth-observation satellites has likely played an important role in shaping the institute's authority and credibility within the international community. Only time will tell if the termination of the DMSP satellites, the launch of CIMR, and the shift to alternative data sources will alter the prominence of the NSIDC as a world leader in satellite-derived sea-ice research. Relatedly, the elimination of the Pole Hole will likely hasten the shift towards reporting sea-ice area as a key indicator, instead of sea-ice extent. A potential implication of this is that the authority and credibility of other sea-ice concentration data

products (e.g., the OSI-450 SIC or the NOAA-NSIDC CDR) may be elevated beyond the NSIDC SII as a global reference dataset.

Although the launch of CIMR is likely to affect the nature and distribution of satellite observations on a macroscale, its impact on MET Norway's sea-ice operations is not straightforward. As Section 7.2.1 described, the funding structures that support the satellite operations and the associated scientific research carried out as part of the OSI SAF and the C3S programmes are convoluted and largely disparate. Although there is some transfer of knowledge and processing applications, these programmes run parallel and remain independent. At present, all four products use the same passive microwave data acquired using the DMSP satellites. However, following the future termination of these satellites, the OSI SAF and C3S products may diverge in their data sources: the OSI-450 SIC product will likely use data acquired by EUMETSAT's planned Metop-SG missions, whereas the C3S products are expected to benefit directly from CIMR. This potential divergence in future data sources further illustrates how our knowledge of sea ice is not a simple representation or passive observation of nature. Instead, it is fundamentally dependent on the available material, technological, and cultural resources that exist in a particular context at a particular moment in time.

7.3. Conclusion

The settings in which the sea-ice data products are developed and disseminated has important consequences for what types of knowledge are generated, who participates, and how the products are used to inform policy and decision-making. Accordingly, the focus of this chapter has been on exploring some of the situated contexts in which the OSI-450 SIC and C3S sea-ice data products are embedded and how these contexts influence key issues such as scientific authority, accountability, and participation in contemporary sea-ice research.

The OSI-450 SIC and C3S sea-ice data products represent valued sources of knowledge on the state of Arctic sea-ice cover. Produced first and foremost for the climate research community, they contribute to our understanding of the climate system and help inform the development of mitigative and adaptive responses to climate change. While the scientists are responsible for the day-to-day operations, the production and dissemination of data products draw upon networks of social and technological arrangements, negotiations, choices, values, and constraints that extend across various local, regional, and international scales.

Top-level requirements reflect the needs of the international climate research community. These are stipulated by GCOS, filter down through respective institutional structures, and govern what elements of sea ice should be prioritised in terms of funding and resources. The international sea-ice community strongly influences the nature of

data product development and evolution by imposing conventions, standardised methods, and theories that influence the types of knowledge produced and reported. On a more local scale, user-producer interactions play a constitutive role in shaping the content and format of the sea-ice data products through specifying the necessary characteristics of a *useful* product.

The vastness of the collaborative, international, and interdisciplinary networks sustaining the data products may help to improve their perceived robustness and credibility. However, these networks are not *global*. Critically reflecting on the institutional affiliations underpinning the production of the data products reveals how the prevailing conventions, theoretical presuppositions, and conceptual frameworks shaping contemporary sea-ice research are rooted in Western institutional networks. These networks influence the allocation of research funding, shape what is considered valid and legitimate knowledge, set standards that enable communication and collaboration, and encourage an idealised distinction between production and use and between *science* and *politics*.

The pressure to engage beyond the scientific community has increased the prevalence of open and online forms of research dissemination. These channels offer new opportunities and challenges for sea-ice research. On the one hand, they enable knowledge to be transferred to wider audiences and provide greater opportunities and spaces for scientists, users, policymakers, and the public to engage in sea-ice research interactively. From a critical perspective, this may provide more spaces for alternative perspectives and interests to be brought to the fore and encourage greater reflexivity in producing and disseminating sea-ice knowledge. On the other hand, the openness exposes sea-ice science to greater public scrutiny and increases the potential for research to be mobilised in unintended ways.

The focus on users has shown how sea-ice data products have variable meanings and applications. The term 'users' reflects a diverse community characterised by a broad range of requirements, experiences, and interests. Due to the complex and heterogeneous nature of knowledge interpretation, these meanings and characteristics become more variable when the data products are disseminated beyond the scientific realm. For scientists, the potential for varied (mis)interpretations underscores the importance of producing high-quality and objective data products and maintaining transparency in how data are acquired, processed, and translated. This enables users to make informed decisions in the face of complex and uncertain sea-ice data. However, as this chapter argues, this focus maintains a separation between *production* and *application*, which may have problematic implications for accountability. Moreover, the increasing online focus of research dissemination risks exacerbating inequalities in knowledge accessibility due to unequal access to digital infrastructures and variation in scientific and computer literacy.

Sea-ice data products are produced in the name of society: they are generated to improve our understanding of the climate system and to aid the development of mitigative or adaptive responses in the face of climate change. Thus, arguably, the scientists and authoritative institutions such as MET Norway and the NSIDC have a social responsibility to become more thoroughly and reflexively engaged in how their outputs are received and used. This engagement requires more than opposing unintended uses, maintaining transparency, or engaging in a user-producer dialogue (Section 7.2.3). It requires scientists – or perhaps dedicated and trained science communicators – to assume greater accountability for the pluralistic interpretations of their work in broader society. As others have pointed out elsewhere (e.g., Bird, 2014; Hackett *et al*., 2017; Stilgoe and Guston, 2017; Findlater *et al*., 2021), a greater engagement with the "downstream" applications of knowledge may be necessary to achieve more socially and ethically robust knowledge. This may involve greater interactive engagements with the public through public outreach and education or explicitly identifying and addressing the potential legal, social, ethical, and political issues that sea-ice data products and their associated limitations may give rise to.

8. Conclusions

8.1. Introduction

The aim of this thesis has been to gain insights into how knowledge about Arctic sea ice is produced and disseminated in contemporary sea-ice research. Informed by social constructivist arguments developed within STS and critical cartography, this thesis has sought to better understand how the interactions between sea ice, sensing technologies, and social practices influence our knowledge of Arctic sea ice. Specifically, the focus has been on understanding the dominant scientific practices and technologies used in the satellite remote sensing of sea ice for climate research purposes. Four sea-ice data products generated by the NSIDC and MET Norway – two leading scientific institutes in sea-ice research – have been at the centre of analytical inquiry. Using integrated methods from ethnographic and visual methodologies, this research has examined these products in terms of their underlying practices and technologies, institutional settings, and the broader socio-cultural, political, and historical contexts in which they are embedded.

This chapter concludes the thesis by synthesising the main outcomes and implications of the study. The chapter begins by reiterating the motivation behind this thesis and purpose of carrying out this research. The conclusions of the previous four chapters are then summarised in relation to the initial aim and objectives introduced in Chapter 1. Following this, the chapter considers some of the study's implications and outlines potential avenues for further research.

8.2. Summary of the Research Purpose and Findings

The increasing levels of interest directed towards the Arctic and the global implications of Arctic sea-ice decline were the primary motivation of the work carried out in this thesis. Accurate and timely knowledge of the spatial and temporal variability in Arctic sea-ice conditions is needed to inform public and policy decision-making in present and future contexts. Sea-ice data products derived from satellite observations are widely used to report knowledge of sea-ice conditions to vast audiences. They play an important role in shaping our understanding of Arctic sea ice in the context of the broader climate system. However, due to the complexities of Arctic sea ice and the challenges involved

in its observation, measurement, and visualisation, the knowledge these products communicate is limited.

The fundamental assumption underpinning this thesis is that scientific practice can be understood as a complex interplay between science, nature, and the interests of society. Consequently, scientific knowledge cannot be considered independent from the social, political, and cultural contexts in which it is produced. This assumption is predominantly informed by the concept of social constructivism and its various uses within the fields of STS and critical cartography. Situated within this perspective, the research began by contending that the limitations and discrepancies involved in the satellite remote sensing of Arctic sea ice necessitate an examination from sociological and critical perspectives. The institutional differences in how sea-ice data products are developed indicate the multiple interpretations and meanings that can emerge from satellite observations of sea ice. These differences suggest that the scientific practices underpinning the data products are *socially shaped*, and the resultant knowledge these products communicate is not wholly objective or unmediated. The wide circulation of sea-ice data products and their ubiquity in broader climate change discourse means that these data products directly affect how the Arctic is perceived, known, and acted upon. Consequently, the discrepancies in scientific practice, the mechanisms through which sea ice is simplified, consolidated, and represented, and the social contingencies of scientific knowledge of sea ice demand critical reflection. These issues formed the basis of the research presented in the previous chapters.

The empirical chapters began with a review of the history of Arctic sea-ice science (Chapter 4). By attending to several key periods in the region's complex history, this initial review sought insights into how the relations between science, technology, and societal interests have shaped our knowledge of Arctic sea ice through time. The findings demonstrate how the practices of sea-ice science are deeply entangled with societal interests and idealisations of the Arctic region that prevail within particular socio-cultural and historical contexts. These entanglements have shaped what aspects of the Arctic Ocean have been the focus of scientific research, how science and technology have developed to facilitate varying encounters and, ultimately, what types of knowledge have been produced and for whom.

The emergence of passive microwave satellite sensors during the 1970s was a technological breakthrough in sea-ice research that transformed the types of knowledge produced. It enabled scientists to observe and monitor Arctic sea-ice conditions on a frequency and scale that was previously unattainable and identify important feedbacks between sea ice and the climate system. The use of satellites has also facilitated and encouraged a global systems perspective of the Arctic as a fragile region needing scientific, political, and environmental cooperation from a broad range of national and international actors.

The historical review illustrated how various political, economic, and cultural factors encouraged the rapid development and success of satellites in sea-ice research, particularly in the US. These included epistemological shifts to more deductive and quantitative modes of scientific inquiry, a cultural enthusiasm for computational technologies, geopolitical anxieties that sparked military investments in geophysics and space research and technology, and the implementation of a global framework for synoptic observations of the climate system (Doel, 2003; Edwards, 2010). As a result of these developments, the large-scale and long-term monitoring of Arctic sea ice in geophysical terms has come to dominate how the Arctic Ocean is perceived, known, and acted upon in scientific and socio-political contexts. These developments also influenced which nations are at the forefront of contemporary sea-ice research. Due to the extensive infrastructural and computational demands of satellite remote sensing, those who have authority today – namely US and European institutes – are predominantly those who historically had the political and economic capacities to invest in the acquisition and processing of satellite observations. Consequently, although the research is carried as part of a *global* knowledge infrastructure, contemporary sea-ice science is predominantly a Western pursuit, rooted in Western conventions, frameworks, values, and institutions.

In the critical and comparative examinations of Chapters 5 and 6, the focus turned to the specificities of the sea-ice data products and their underlying methodologies. Chapter 5 explored how scientists construct meaningful knowledge about sea ice and represent it on maps; with a particular focus on the retrieval methods, data processing techniques, and the conventions and assumptions that shape how satellite observations are interpreted, translated, defined, and ordered in the production of data products. The chapter reveals how, due to the dominance of geophysical and quantitative approaches to sea-ice data retrieval, coupled with the inherent limitations of satellite technologies and the complexities of sea ice, the data products always provide uncertain and partial accounts. Small-scale features and localised variability are not resolved, and the lack of ground-truth data limits the extent to which the validity (accuracy) of observations can be assessed. The discrepancies in scientific practices reflect differences in how institutions select, interpret, classify, and correct satellite observations. This supports the notion that each data product provides a particular way of knowing sea ice in the Arctic Ocean that is dependent on the situated arrangements and interactions between sea ice, sensing technologies, and the people that prevail in specific institutional contexts.

Critically, as this research has shown, the complex and multifarious processes of knowledge production are not visible in the final data product outputs. To use Latour and Woolgar's term (1979), through maps and other forms of visual and numerical representation, the data products are *decontextualised*: the processes of transformation are rendered invisible, and the products appear objective and unmediated, and thus, as transferrable in various contexts. A central contention running through this thesis is that

the perceived objectivity and neutrality of data products gives them the power to persuade the viewer of the credibility and veracity of the knowledge they communicate. This argument is substantiated in Chapter 6 through compositional and discourse analyses of sea-ice maps.

Through critically examining their underlying cartographic techniques and styles of representation, Chapter 6 contended that sea-ice maps derived from passive microwave satellite observations *work beyond their intended purpose.* Maps are central to sea-ice research: mapping data is an essential data processing step in generating data products, and maps enable scientists to document, monitor, and communicate trends in sea-ice variability. The utility of all maps relies on processes of selection. Yet, these processes are always subjective and often have unintended socio-political and cultural implications (Pickles, 2004; Wood, 2010). The maps examined in this thesis are expressions of the Arctic Ocean in geophysical terms. They are intended to inform and provide a quick visual interpretation of *specific sea-ice parameters*. However, these maps subvert and silence many of the broader societal and ecological functions that sea ice serve(s). The crucial argument this chapter makes is that, while they may have useful applications in ocean-climate research, these maps do not exist exclusively within the scientific realm. Through their wide circulation, styles of representation, and the privilege attached to satellite technologies, these conventional scientific representations appear as seemingly objective and authoritative accounts of what exists *out there*. Yet, as Chapters 5 and 6 have shown, they simplify Arctic environments, contribute to the prevailing and often reductionist discourses of the Arctic as a vast, lifeless, and empty space, and ultimately influence how the region is known and acted upon in present and future contexts.

Building on the previous discussions, Chapter 7 examined the institutional contexts in which the data products are generated and disseminated. Drawing from ethnographic fieldwork at MET Norway, the chapter explored how and why particular methodologies are developed, sustained, and operationalised in their institutional settings; how the products are used and applied; and how they relate to different knowledge producers and broader societal contexts. The chapter demonstrated how the scientists' methodologies draw upon networks of social and technological arrangements, negotiations, choices, values, and constraints that extend far beyond the local place of knowledge production. For instance, top-level requirements from intergovernmental climate science institutions govern what elements of Arctic sea ice should be prioritised in their observation and they set the target standards for accuracy and consistency, user-producer relations inform the characteristics and design of data products, and negotiations between scientists at various institutes shape how the data products develop. Due to the difficulties of assessing the absolute accuracy of satellite observations, the credibility of data products is shown to be *relational*: data product

accuracy is assessed in relative terms, and their trustworthiness is strongly shaped by social factors, such as institutional visibility and reputation, and the duration of the data product. In other words, these social factors provide some explanation for the success of certain methodologies for measuring, interpreting, and knowing the Arctic.

Finally, Chapter 7 described how shifts towards more open forms of scientific knowledge dissemination present new opportunities and challenges for sea-ice reporting. The inherent uncertainties and limitations of sea-ice data products demand caution in how they are reported to avoid the damaging effects that misinterpretations have on credibility. However, the chapter argued that the desire of scientific institutions to maintain an idealised separation between knowledge *production* and *application* and between *science* and *politics* risks overlooking important differences in how broader society interprets knowledge.

8.3. Research Implications

The above findings demonstrate some of the ways in which the practices of contemporary sea-ice research are inextricably linked to the social and cultural contexts in which they are carried out. The main implication of these findings is that scientific knowledge of sea ice reflects and reinforces particular values, perspectives, interests, and concerns about changing Arctic environments. Indeed, this research has shown that the character and persistence of data products are shaped by the ongoing processes of communication, negotiation, interaction, and consensus-building that occur within particular institutional contexts. Drawing on the collaborative networks mobilised in the generation of data products, scientists working at these research institutes influence how sea ice is measured, classified, and ordered. They make choices and judgements about how the complexities of sea ice are managed and translated into useful information. In doing so, scientists, situated within specific socio-cultural and historical contexts, play an active role in defining the problems and potential solutions that changes in Arctic sea ice present. This indicates that what counts as useful and authoritative knowledge is socially contingent, variable, and open to change.

The ways in which knowledge of Arctic sea ice is produced and disseminated have consequences for how we perceive, understand, and govern the region. The sea-ice data products examined in this study are produced and disseminated as part of a global effort to understand and communicate environmental change and mitigate against the effects of current and future climate change. Scientific institutes like the NSIDC and MET Norway represent leading authorities on the state of Arctic sea-ice conditions, and scientists, policymakers, and the public look to them as a source of knowledge. Over the course of this research, it became increasingly apparent that sea-ice scientists recognise, discuss, and openly report the uncertainties and limitations involved in passive microwave satellite observations. There is no pretence that sea-ice data products are

infallible representations of sea-ice conditions. On the contrary, in conversations and throughout the supporting documentation, the uncertainties and limitations are laid bare, and caution is stressed around the dissemination and application of these products. Indeed, maintaining transparency in how the data products are constructed is an essential characteristic of contemporary sea-ice research and a necessary means of establishing trust between scientists and users. However, the uncertainties and limitations discussed in the sea-ice community are predominantly technical in nature and often not represented in the data products. Gaps in our understanding are attributed to scientific and technological limitations, such as the coarse resolution of sensors or the inability of algorithms to detect oceanic and atmospheric influences. Through intercomparison studies and ongoing developments, the broad focus of the sea-ice community is on identifying and reducing these gaps in the pursuit of high-quality and accurate data products. These observations imply that contemporary sea-ice science is underpinned by the positivist belief that an objective view of the Arctic Ocean is attainable.

As is the case with climate science more broadly, uncertainties, disagreements, or ambiguities in scientific findings challenge the translation of knowledge into policy action as it can prompt questions over the veracity of scientific claims and present multiple problems and potential solutions. As Oreskes *et al*. (2019) discuss, this leads scientists to actively seek *univocality* in climate science reporting. Yet, this can lead to underestimating or underdetermining the implications of climate change because scientific consensus is not synonymous with truth (Hulme, 2009; Oreskes *et al*., 2019). Similarly, the relational nature through which sea-ice data products gain credibility and the ongoing efforts to identify and eliminate biases through intercomparison studies imply that the sea-ice community are committed to achieving a *singular*, consensus-driven knowledge of Arctic sea-ice conditions. Achieving *univocality* rests on the positivist assumption that science can provide an objective and neutral *view from nowhere* (Nagel, 1986). However, as the research presented in this thesis has shown, sea-ice science is not wholly objective and neutral but socially contingent. This implies that the methodologies, research objectives, actors, institutions, and discourses of contemporary sea-ice research are not inevitable and that our understanding of Arctic sea ice could be different.

Moreover, as this PhD study has contended, the value attached to quantitative, technical, and geophysical approaches to measuring and mapping Arctic sea ice fail to adequately capture the complex socio-cultural and political dimensions of the Arctic. By homogenising complex environments and reducing the diverse meanings into static lines, uniform boundaries, and arbitrary definitions, contemporary sea-ice data products shape and structure what aspects of the Arctic are seen, known, and knowable. These outcomes align with a growing body of STS research which has shown how the social

and epistemic authority of climate science, the privilege attached to geophysical approaches, the prevalence of Western scientific knowledge systems, and the entanglements between knowledge and power structures are characteristic of the production of knowledge in climate science more broadly (e.g., Shackley *et al*., 1998; Jasanoff, 2004; Beck *et al*., 2017; Lehman, 2019; Findlater *et al*., 2021; Lahsen and Turnhout, 2021). As Findlater *et al*. (2021) and Lahsen and Turnhout (2021) recently discuss, these characteristics present challenges for achieving sustainable and democratic policy responses to climate change because they exclude the diverse perspectives and meanings that fall outside of the dominant norms, structures, and institutions.

Given the normative role sea-ice data products play in shaping our understanding of the global climate system and societal responses to current and future changes, this thesis argues that there is a need for greater recognition of how societal influences shape sea-ice science. There is a need for a more transparent and reflexive understanding of the situated nature of scientific knowledge and the unintended socio-political and cultural implications of sea-ice data products *from within* the sea-ice community. However, at present, it appears that sea-ice scientists predominantly view societal and political interests as problematic influences that undermine the validity and credibility of scientific knowledge and introduce subjective biases. This commitment to maintaining a perceived separation between science and politics likely places limits on the extent to which scientists would enter open discussions about the social contingency of their outputs because a loss of credibility has implications for institutional authority, research funding, and opportunities for collaboration (see also Lahsen and Turnhout, 2021). This implies a lack of awareness of the assertion that social constructivist studies have endeavoured to show since their beginnings: that sociological factors do not undermine the integrity or validity of science but are essential to *all* knowledge claims (Collins, 1975; Barnes and Bloor, 1982; Bloor, 1991; Haraway, 1988).

To reiterate a point that I hope is clear throughout this thesis: the recognition that our knowledge of Arctic sea ice is socially contingent should not discredit that knowledge, nor should it provide the impetus for conspiracy theorists or climate change denialists to argue against the reality of sea-ice decline. However, it should encourage the importance of recognising the multiplicity of interpretation and human responses to environmental change (see Jasanoff, 2004b; Lahsen and Turnhout, 2021). Attempts to speak with one global voice and the desire to maintain an idealised separation between science and politics risk reinforcing particular social hierarchies and power imbalances and undermining our ability to effectively respond to the implications of sea-ice decline. Questioning how social dimensions shape the dominant practices, institutions, and conventions of sea-ice science provides opportunities for reflecting on how diverse ways

of seeing and knowing can support more democratic and socially responsible forms of scientific practice.

8.4. Avenues for Further Research

With the above findings and implications in mind, there are multiple directions in which this research could progress in the future. This final section outlines some of these potential avenues.

As outlined in the methodology (Chapter 3), the timeline of this PhD study coincided with the outbreak of the COVID-19 pandemic. The pandemic severely disrupted the research project in various ways, including the cancellation of a second comparative research trip to the NSIDC. While document analysis has provided important insights into how the data products are generated, a field visit would have undoubtedly provided a more nuanced understanding. Thus, one of the more direct and supplementary avenues for further research is to carry out a comparative ethnographic study at the NSIDC to develop further insights into the contingencies of their sea-ice data products. This would provide important indications of how the institutional contexts that shape the methodologies compare to those of MET Norway.

Similarly, there is scope to examine other institutes that play a role in contemporary sea-ice research. In particular, it would be interesting to examine how sea-ice knowledge is produced in institutes outside of Europe and the US; for example, the Arctic and Antarctic Research Institute (AARI) in St. Petersburg, Russia or the Japanese Aerospace Exploration Agency (JAXA) in Tokyo, Japan. Such examinations would provide opportunities for greater cross-cultural examinations.

In addition to focussing on the institutional contexts, the constitutive role of users in shaping the development and evolution of data products invites further examination. As Chapter 7 detailed, continued negotiations between the scientists and users influence the design and format of product outputs. Thus, future work may further examine *who* the users are and how their requirements are shaped by their own situated experiences, perspectives, and interests.

More broadly, there is scope to shift the focus away from the circumstances shaping how knowledge of Arctic sea ice is *produced*. A common critique of early sociological and constructivist studies of scientific knowledge is that, while providing detailed insights into the social contingencies shaping the construction of knowledge, many focussed too narrowly on the circumstances of knowledge *production* (Winner, 1993; Wynne, 1996; Jasanoff, 1996, 2004). Few extended beyond the site(s) and conditions of knowledge production to account for how alternative voices and perspectives may give rise to different interpretations (see Chapter 2: Section 2.3.6). Arguably, the research presented in this thesis may be subject to a similar critique. Although the findings have

demonstrated the contingent nature of contemporary sea-ice science, the focus has predominantly been on understanding the circumstances of knowledge production with little consideration for the diverse ways in which the data products are applied and interpreted within and beyond the scientific community.

While this may be seen as a limitation of the study, it also provides avenues for further research. For instance, it would be valuable to gain insights into the role that sea-ice data products play in shaping understandings of the Arctic in public and policy arenas. Indeed, in personal conversations outside of academia, I have frequently faced misconceived ideas about the Arctic as a "people-less place", featuring "nothing but ice". Thus, rather than simply theorising how sea-ice data products shape knowledge as Chapter 6 sought to do, engaging more directly with public perceptions may provide further critical insights into the power that these data products have and *how* they *work beyond their intended purpose.*

Similarly, there has been little attention on the perspectives and values of the social groups that sit outside of the dominant knowledge infrastructures of contemporary sea-ice science. In other words, this thesis has stopped short of exploring alternative ways in which our knowledge of sea ice could have emerged. For instance, given their powerful role in shaping our understanding of Arctic sea ice, there is scope to explore how local and Indigenous perspectives may improve the knowledge generated and represented in satellite-derived sea-ice data products.

Various studies in recent years have considered how Indigenous perspectives on sea ice can improve and substantiate scientific research (e.g., Meier *et al*., 2006; Huntington *et al*., 2009; Eicken, 2010; Gearheard *et al*., 2013). For example, Eicken (2010) outlines how sea-ice scientists – namely those engaging in geophysical and biological research – can learn from local and Indigenous knowledge. Eicken contends that local and Indigenous perspectives can enhance scientific knowledge of sea ice in various areas of engagement. These include informing the selection of study sights for analysing sea-ice variability, identifying rare events or significant changes in sea-ice characteristics, recording subtle and long-term changes in the climate, and providing more comprehensive and holistic perspectives on sea ice. In satellite remote sensing applications, local and Indigenous knowledge can complement assessments of sea-ice cover variability by providing more intimate insights into small-scale features and conditions that current satellite technologies cannot effectively capture (Meier *et al*., 2006). In these instances, local and Indigenous knowledge is seen as a means to supplement and substantiate scientific data, mainly where knowledge gaps arise due to observational limitations. In other words, the nature of scientific knowledge production remains essentially unchanged.

The examinations presented in this thesis offer a critical starting point for interrogating whose voices, perspectives, and knowledges are not accounted for in the practices,

infrastructures, and institutional networks of contemporary sea-ice data products. Such insights may support a shift towards a more reflexive and transparent sea-ice science that recognises the value of critically reflecting on the social dimensions of scientific practice and the diverse meanings and functions of sea ice. Such critique should not detract from the overall purpose of the sea-ice research products. Rather, it should explore how alternative perspectives and ways of knowing can encourage new ways of producing, representing, and disseminating more democratic, legitimate, and socially responsible knowledge of Arctic sea ice.

Appendices

Appendix 1: References to and applications of the data products

Examples where NSIDC, OSI SAF, and C3S data products have been used or referred to in high-level scientific reports, English language media and online magazines, non-scientific applications, or as the basis for reporting by other scientific institutions.

High-level scientific reports:

Intergovernmental Panel on Climate Change (IPCC)

- Satellite observations of sea ice were too limited to provide detailed analyses in the IPCC First Assessment Report published in 1990. Trends began to appear in the years that followed. However, the individuals referenced in this early report for their work on sea-ice analyses were directly involved in the development of the methodologies still used today (e.g., Gloersen and Campbell, 1988). See Chapter 7, https://www.ipcc.ch/report/ar1/wg1/.
- In the IPCC Second Assessment Report published in 1995, data on sea-ice cover were still too short to ascertain key trends. Time series of sea-ice extent were first included in this report, based on the Nimbus-7 SMMR passive microwave data: https://www.ipcc.ch/report/ar2/wg1/.
- Chapter 2 of the IPCC Third Assessment Report, *Climate Change 2001: The Physical Science Basis,* includes time series of the sea-ice concentration data that forms the basis of the NSIDC SII (e.g., Cavalieri *et al*., 1997): https://www.ipcc.ch/report/ar3/wg1/. Similar data are included in Chapter 4 of the IPCC Forth Assessment Report, *Climate Change 2007: The Physical Science Basis*: https://www.ipcc.ch/report/ar4/wg1/.
- Chapter 4 of the IPCC Fifth Assessment Report, *Climate Change 2013: The Physical Science Basis,* includes two hemispheric polar projection visualisations of the cryosphere, situated on the Arctic and Antarctica (page 322). The sea-ice cover data shown on the projection are sourced from the NSIDC: https://www.ipcc.ch/reports/?rp=ar5.
- The 2019 IPCC Special Report on the Ocean and Cryosphere in a Changing Climate includes data and results from several studies that have intercompared several sea-ice data products, including the NSIDC and the EUMETSAT OSI SAF data products: https://www.ipcc.ch/srocc/chapter/chapter-3-2/.
- Chapter 9 of the 2021 IPCC Sixth Assessment Report, *Climate Change 2021: The Physical Science Basis,* includes assessments of Arctic sea-ice variability based on various sea-ice data products including the NSIDC SII and the EUMETSAT OSI-450 SIC: https://www.ipcc.ch/report/ar6/wg1/. These are used to project future trends up to 2054.

World Meteorological Organisation

- NSIDC sea-ice extent data used in the WMO Statement on the State of the Global Climate in 2006: https://library.wmo.int/doc_num.php?explnum_id=7689.
- NSIDC sea-ice extent data and maps used in the WMO Statement on the State of the Global Climate in 2007: https://library.wmo.int/doc_num.php?explnum_id=3457.
- NSIDC sea-ice extent data and maps used in the WMO Statement on the State of the Global Climate in 2008: https://library.wmo.int/doc_num.php?explnum_id=3461.
- NSIDC sea-ice extent data and maps used in the WMO Statement on the State of the Global Climate in 2009: https://library.wmo.int/doc_num.php?explnum_id=3462.
- NSIDC sea-ice extent data and timeseries used in the WMO Statement on the State of the Global Climate in 2010: https://library.wmo.int/doc_num.php?explnum_id=7739.
- NSIDC sea-ice extent data and timeseries used in the WMO Statement on the State of the Global Climate in 2011: https://library.wmo.int/doc_num.php?explnum_id=3463.
- NSIDC sea-ice extent data, timeseries, and maps used in the WMO Statement on the State of the Global Climate in 2012: https://library.wmo.int/doc_num.php?explnum_id=7809.
- NSIDC sea-ice extent data and timeseries used in the WMO Statement on the State of the Global Climate in 2013: https://library.wmo.int/doc_num.php?explnum_id=7862.
- NSIDC sea-ice extent data and timeseries used in the WMO Statement on the State of the Global Climate in 2014: https://library.wmo.int/doc_num.php?explnum_id=7907.
- NSIDC sea-ice extent data and timeseries used in the WMO Statement on the State of the Global Climate in 2015: https://library.wmo.int/doc_num.php?explnum_id=7931.
- NSIDC sea-ice extent data and timeseries used in the WMO Statement on the State of the Global Climate in 2016: https://library.wmo.int/doc_num.php?explnum_id=3414.
- NSIDC sea-ice extent data and timeseries used in the WMO Statement on the State of the Global Climate in 2017: https://library.wmo.int/doc_num.php?explnum_id=4453.
- NSIDC sea-ice extent data and C3S sea-ice concentration maps (based on OSI SAF data) used in the WMO Statement on the State of the Global Climate in 2018: https://library.wmo.int/doc_num.php?explnum_id=5789.
- Comparative time series of NSIDC and OSI SAF sea-ice extent data used in the WMO Statement on the State of the Global Climate in 2019: https://library.wmo.int/doc_num.php?explnum_id=10211.
- Comparative time series of NSIDC and OSI SAF sea-ice extent data used in the WMO Statement on the State of the Global Climate in 2020: https://library.wmo.int/doc_num.php?explnum_id=10618.

Other scientific and non-scientific sources that use NSIDC, OSI SAF, or C3S data (as opposed to directly analysing sea-ice observations):

The Arctic Centre

- Maps of the Arctic region are based on the NSIDC SII sea-ice extent: https://www.arcticcentre.org/EN/arcticregion/Maps/Sea-Ice

The UK Met Office

- Climate Dashboard reports of sea-ice extent are based on the NSIDC SII and the OSI-450 SIC data product: https://climate.metoffice.cloud/sea_ice.html

National Geographic

- World Maps use NSIDC SII sea-ice extent data to mark the position of the 'ice edge': https://www.natgeomaps.com/wall-maps.

Polar Portal

- Animated sea-ice concentration maps and extent time series based on the OSI-450 SIC data: http://polarportal.dk/en/sea-ice-and-icebergs/sea-ice-extent0/

C3S ERA-Interim

- This dataset includes maps and graphs that are produced using sea-ice data from a variety of data sources, including OSI SAF and the NSIDC: https://climate.copernicus.eu/monthly-sea-ice-maps

Example reports of Arctic sea ice in the media and online magazines that make reference to the data products or include maps and graphs (based on selection from Google searches of "Arctic sea ice"):

The Guardian

- https://www.theguardian.com/world/2006/may/15/antarctica.environment
- https://www.theguardian.com/environment/2019/jun/07/oceans-demise-the-end-of-the-arctic-as-we-know-it
- https://www.theguardian.com/world/2020/apr/21/ice-free-arctic-summers-now-very-likely-even-with-climate-action
- https://www.theguardian.com/environment/2020/dec/02/humanity-is-waging-war-on-nature-says-un-secretary-general-antonio-guterres
- https://www.theguardian.com/environment/2021/nov/01/the-climate-crisis-explained-in-10-charts

High North News

- https://www.highnorthnews.com/en/closer-look-sea-ice-situation-barents-sea
- https://www.highnorthnews.com/en/late-forming-chukchi-sea-ice-continues-unprecedented-trend

New York Times

- https://www.nytimes.com/2007/05/01/us/01climate.html?searchResultPosition=10
- https://www.nytimes.com/interactive/2017/09/22/climate/arctic-sea-ice-shrinking-trend-watch.html
- https://www.nytimes.com/interactive/2018/03/23/climate/arctic-ice-maximum.html
- https://www.nytimes.com/2021/09/22/climate/arctic-sea-minimum.html

New Scientist

- https://www.newscientist.com/article/2300385-extreme-lack-of-sea-ice-in-hudson-bay-puts-polar-bears-under-pressure/
- https://www.newscientist.com/article/2279764-some-arctic-sea-ice-is-thinning-twice-as-fast-as-previously-thought/

- https://www.newscientist.com/article/2118093-global-sea-ice-is-at-lowest-level-ever-recorded/
- https://www.newscientist.com/article/2163204-record-low-arctic-ice-linked-to-freak-weather-in-us-europe/

BBC

- https://www.bbc.co.uk/news/science-environment-31976749
- https://www.bbc.co.uk/news/business-45527531
- https://www.bbc.co.uk/news/science-environment-54211760
- https://www.bbc.co.uk/news/science-environment-57650226

The Independent

- https://www.independent.co.uk/climate-change/news/arctic-sea-ice-siberia-temperature-climate-change-b1723810.html
- https://www.independent.co.uk/climate-change/news/arctic-sea-ice-level-climate-change-global-warming-siberia-b1345792.html

National Geographic

- https://www.nationalgeographic.com/science/article/arctic-summer-sea-ice-could-be-gone-by-2035

Appendix 2: List of Satellite-Sensors and Associated Characteristics

Satellite (Space Agency)	*Sensor (Providing Agency)*	*Nationality of Satellite/ Sensor*	*Operating Period*	*Operating Frequency (GHz), Polarisation (v, h), and Corresponding Footprint (km)*	*Temporal Frequency*	*Swath Width*	*Sensor Aperture Diameter (m)*	*Pole Hole Area (million km²)*	*Equator Crossing Time (Local Time)*	*Nominal Orbiting Altitude*
Nimbus-7 (NASA)	SMMR (NASA)	USA/USA	26th October 1978 – 20th August 1987	6.6 (v, h), 148 x 95 10.7 (v, h), 91 x 59 18.0 (v, h), 55 x 41 21.0 (v, h), 46 x 30 37.0 (v, h), 27 x 18	Bi-diurnal	783 km	0.79 m	1.19	12:00 (descending)	955 km
DMSP-F08 (DoD, NOAA)	SSM/I (DoD)	USA/USA	9th July 1987 – 18th December 1991	19.3 (v, h), 70 x 45 22.2 (v), 60 x 40 37.0 (v, h), 38 x 30 85.5 (v, h), 16 x 14	Daily	1400 km	0.79 m	0.31	06:10 (descending)	860 km
DMSP-F10 (DoD, NOAA)	SSM/I (DoD)	USA/USA	7th January 1991 – 13th November 1997	19.3 (v, h), 70 x 45 22.2 (v), 60 x 40 37.0 (v, h), 38 x 30 85.5 (v, h), 16 x 14	Daily	1400 km	0.79 m	0.31	07:30 (descending)	790 km
DMSP-F11 (DoD, NOAA)	SSM/I (DoD)	USA/USA	28th November 1991 – 31st December 1999	19.3 (v, h), 70 x 45 22.2 (v), 60 x 40 37.0 (v, h), 38 x 30 85.5 (v, h), 16 x 14	Daily	1400 km	0.79 m	0.31	05:00 (descending)	830 km

DMSP-F13 (DoD, NOAA)	SSM/I (DoD)	USA/USA	3rd May 1995 – 31st December 2008	19.3 (v, h), 70 x 45 22.2 (v), 60 x 40 37.0 (v, h), 38 x 30 85.5 (v, h), 16 x 14	Daily	1400 km	0.79 m	0.31	05:51 (descending)	850 km
DMSP-F14 (DoD, NOAA)	SSM/I (DoD)	USA/USA	7th May 1997 – 23rd August 2008	19.3 (v, h), 70 x 45 22.2 (v), 60 x 40 37.0 (v, h), 38 x 30 85.5 (v, h), 16 x 14	Daily	1400 km	0.79 m	0.31	17:00 (ascending)	850 km
DMSP-F15 (DoD, NOAA)	SSMIS (DoD)	USA/USA	28th February 2000 – 31st July 2006	19.3 (v, h), 70 x 45 22.2 (v), 70 x 40 37.0 (v, h), 38 x 30 91.7 (v, h), 16 x 13	Daily	1500 km	0.66 m	0.029	14:50 (ascending)	850 km
DMSP-F16 (DoD, NOAA)	SSMIS (DoD)	USA/USA	1st November 2005 – 31st December 2015	19.3 (v, h), 70 x 45 22.2 (v), 70 x 40 37.0 (v, h), 38 x 30 91.7 (v, h), 16 x 13	Daily	1700 km	0.66 m	0.029	06:20 (ascending)	850 km
DMSP-F17 (DoD, NOAA)	SSMIS (DoD)	USA/USA	14th December 2006 – 31st December 2017	19.3 (v, h), 70 x 45 22.2 (v), 70 x 40 37.0 (v, h), 38 x 30 91.7 (v, h), 16 x 13	Daily	1700 km	0.66 m	0.029	06:40 (ascending)	850 km
DMSP-F18 (DoD, NOAA)	SSMIS (DoD)	USA/USA	8th March 2010 – present	19.3 (v, h), 70 x 45 22.2 (v), 70 x 40 37.0 (v, h), 38 x 30 91.7 (v, h), 16 x 13	Daily	1700 km	0.66 m	0.029	04:50 (descending)	850 km

EOS Aqua (NASA)	AMSR-E (JAXA)	USA/Japan	1st June 2002 – 3rd October 2010	6.9 (v, h), 75 x 43 10.65 (v, h), 51 x 29 18.7 (v, h), 27 x 16 23.8 (v, h), 32 x 18 36.5 (v, h), 14 x 8 89.0 (v, h), 6 x 4	Daily	1445 km	1.6 m	01:30 (ascending)	705 km
GCOM W1 (JAXA)	AMSR2 (JAXA)	Japan/Japan	23rd July 2012 – 31st May 2017	6.9 (v, h), 62 x 35 7.3 (v, h), 58 x 34 10.65 (v, h), 42 x 24 18.7 (v, h), 22 x 14 36.5 (v, h), 12 x 7 89.0 (v, h), 5 x 3	Daily	1450 km	2 m	13:30 (ascending)	700 km

Notes:

- The exact operating times used vary – different data products used different data
- The AMSR-E and AMSR2 tend not to be used in the long-term climate data records because they only begin in 2002.

Appendix 3: List of Documents Analysed

								Data Product		
Document Name	**Document Type**	**Document Source**	**Original Publication Date**	**Document Updated Regularly (Y/N)**	**Date of Version Analysed**	**Document Version**	**Document Reference**	**NSIDC SII**	**OSI-450 SIC**	**C3S SITy**	**C3S SIE**
Sea Ice Index, Version 3: User Guide	Technical Document	NSIDC	2008	Y	2021	-	Windnagel, 2008	*			
Sea Ice Concentrations from Nimbus-7 SMMR and DMSP SSM/I-SSMIS Passive Microwave Data, Version 1: User Guide	Technical Document	NSIDC	2019	Y	2020	-	NSIDC-GSFC, 2020	*			
NASA Technical Memorandum 104647 Arctic and Antarctic Sea Ice Concentrations from Multichannel Passive-Microwave Satellite Data Sets: October 1978 - September 1995 User's Guide	Technical Memorandum	NASA GSFC	1997	n.a.	1997	-	Cavalieri et al., 1997	*			
Sea Ice Index	Online Webpage	NSIDC	n.d.	Y	n.d.	-	NSIDC Sea Ice Index, n.d.	*			

Knowledge Base: Descriptions of and Differences between the NASA Team and Bootstrap Algorithms	Online Webpage	NSIDC	n.d.	N	2021	-	NSIDC, 2021b	*	*	*	*
Sea Ice Index: Interpretation Resources for Sea Ice Trends and Anomalies	Technical Document	NSIDC	2002	N	2002	-	Fetterer, 2002	*			
DMSP SSM/I-SSMIS Daily Polar Gridded Brightness Temperatures, Version 5, User Guide	Technical Document	NSIDC	2019	Y	2019	-	Meier et al., 2019	*			
Version 2 of the EUMETSAT OSI SAF and ESA CCI sea-ice concentration climate data records	Journal Publication	The Cryosphere	2019	n.a.	2019	-	Lavergne et al., 2019b		*		
Global Sea Ice Concentration Climate Data Record Product User Manual	Technical Document	OSI SAF	2017	Y	2021	2.1	Sørensen et al., 2021		*		
Algorithm Theoretical Basis Document for the OSI SAF Global Sea Ice Concentration Climate Data Record	Technical Document	OSI SAF	2016	Y	2019	1.2	Lavergne et al., 2019a		*		

Product User Guide and Specification: Sea Ice Edge and Sea Ice Type Climate Data Records	Technical Document	ECMWF Copernicus Report	2018	Y	2019	1.3	Aaboe et al., 2019			*	*
Algorithm Theoretical Basis Document: Sea Ice Edge and Sea Ice Type Climate Data Records	Technical Document	ECMWF Copernicus Report	2013	Y	2018	2.2	Aaboe et al., 2018b			*	*
Global Sea-ice edge and Type, Product User's Manual	Technical Document	OSI SAF	2015	Y	2018	2.3	Aaboe et al., 2018a			*	*
CCI+ Sea Ice ECV User Requirements Document (URD)	Technical Document	ESA sea Ice CCI+	2019	Y	2020	2.0	ESA, 2020	*	*	*	
Target Requirements and Gap Analysis Document, Sea Ice	Technical Document	ECMWF Copernicus Report	2018	Y	2020	4.0	Kreiner et al. 2019c	*	*	*	
Global Sea Ice Concentration climate data record (SMMR/SSMI/SSMIS)	Online Webpage	OSI SAF	n.d.	Y	2021	-	OSI SAF, n.d.	*			
Global Sea Ice Type	Online Webpage	OSI SAF	n.d.	Y	2021	-	OSI SAF, n.d.			*	
Global Sea Ice Edge	Online Webpage	OSI SAF	n.d.	Y	2021	-	OSI SAF, n.d.				*

Sea ice edge and type daily gridded data from 1979 to present derived from satellite observations	Online Webpage	C3S	n.d.	Y	2021	-	C3S, n.d.			*	*
The EUMETSAT Sea Ice Concentration Climate Data Record	Journal Publication	The Cryosphere	2016	n.a.	2016	-	Tonboe et al. 2016		*		
Global Sea Ice Concentration Climate Data Record Validation Report, OSI-450 and OSI-430-b	Technical Document	OSI SAF	2017	Y	2019	1.1	Kreiner et al. 2019a		*		
OSI SAF Continuous Development and Operations Phase Product Requirement Document	Technical Document	OSI SAF	2017	Y	2021	1.8	OSI SAF, 2021		*	*	*
C3S Product Quality Assessment Report Sea Ice Edge and Type	Technical Document	ECMWF Copernicus Report	2018	Y	2019	1.2	Kreiner et al. 2019b			*	*

Appendix 4: R-Shiny Code

```
library(shiny)
library(datasets)
library(shinythemes)

rm(list=ls())
setwd(" ") #insert your directory filepath

ui <- fluidPage(theme = shinytheme("superhero"),
        headerPanel("Alternative Mappings of Arctic Sea-Ice Extent"),
        sidebarLayout(
          #position = "right",
          sidebarPanel(
            strong("Overview"),
            p(""),

            helpText("The maps display monthly-averaged sea-ice extent in the Arctic between 1979-2018. The controls below allow you to select and compare extent graphs for each month in the time series. Change the sea-ice concentration (SIC) thresholds to see how this affects the areal extent of Arctic sea ice."),

            p(""),

            "----------------------------------------------------------------",
            p(""),

            #SELECTION 1
            strong("Selection 1"),

            selectInput(inputId = "threshold_1",
                label = "Select SIC Threshold",
                choices = list("15%" = "15",
                           "30%" = "30",
                           "50%" = "50",
                           "60%" = "60"),
                selected = "15"),

            selectInput(inputId = "month_1",
                label = "Month",
                choices = list("January" = "01",
                           "February" = "02",
                           "March" = "03",
                           "April" = "04",
                           "May" = "05",
                           "June" = "06",
                           "July" = "07",
                           "August" = "08",
                           "September" = "09",
                           "October" = "10",
                           "November" = "11",
                           "December" = "12"),
                selected = "01"),

            sliderInput(inputId = "year_1",
                label = "Year",
                min = 1979,
                max = 2018,
                value = 1979,
                step = 1,
                sep = "",
                animate = animationOptions(interval = 700,
```

```
                                playButton = icon("play", "fa-1x"),
                                pauseButton = icon("pause", "fa-1x"))),

        "-----------------------------------------------------------------",
        p(""),

        #SELECTION 2

        strong("Selection 2"),

        selectInput(inputId = "threshold_2",
                label = "Select SIC Threshold",
                choices = list("15%" = "15",
                        "30%" = "30",
                        "50%" = "50",
                        "60%" = "60"),
                selected = "15"),

        selectInput(inputId = "month_2",
                label = "Month",
                choices = list("January" = "01",
                        "February" = "02",
                        "March" = "03",
                        "April" = "04",
                        "May" = "05",
                        "June" = "06",
                        "July" = "07",
                        "August" = "08",
                        "September" = "09",
                        "October" = "10",
                        "November" = "11",
                        "December" = "12"),
                selected = "01"),

        sliderInput(inputId = "year_2",
                label = "Year",
                min = 1979,
                max = 2018,
                value = 1979,
                step = 1,
                sep = "",
                animate = animationOptions(interval = 700,
                                playButton = icon("play","fa-1x"),
                                pauseButton = icon("pause", "fa-1x"))),

        helpText(""),
        helpText("data obtained from NSIDC")),

    mainPanel(

        column(4, align = "center",
            textOutput(outputId = "selected_SIC_1_date"),
            textOutput(outputId = "selected_SIC_1"),

            imageOutput(outputId = "selected_SIC_Map_1")),

        column(6, align = "center",
            textOutput(outputId = "selected_SIC_2_date"),
            textOutput(outputId = "selected_SIC_2"),
            imageOutput(outputId = "selected_SIC_Map_2"))
    )

))
```

```
server <- function(input, output, session) {

   output$selected_SIC_1_date <- renderText({
      paste("Selection 1 date: ", input$month_1, ",", input$year_1)
   })
      output$selected_SIC_1 <- renderText({
      paste("Selection 1 threshold: ", input$threshold_1, "%")
   })

   ##show single image
   #  output$selected_SIC_Map <- renderImage({
   #    list(src = "Reclassify_15_nt_201802_f.jpg", contentType = "image/jpg")
   #  }, deleteFile = FALSE)

   #select by month and year
   output$selected_SIC_Map_1 <- renderImage({
      filename <- normalizePath(file.path(".",
                                paste("Reclassify_",    input$threshold_1,    "_nt_",    input$year_1,
input$month_1,"_f.jpg", sep = "" )))
      list(src = filename,
           alt = paste("Image number", input$month_1))
   }, deleteFile = FALSE)

   output$selected_SIC_2_date <- renderText({
      paste("Selection 2 date: ", input$month_2, ",", input$year_2)
   })

   output$selected_SIC_2 <- renderText({
      paste("Selection 2 threshold: ", input$threshold_2, "%")
   })

   output$selected_SIC_Map_2 <- renderImage({
      filename <- normalizePath(file.path(".",
                                paste("Reclassify_",    input$threshold_2,    "_nt_",    input$year_2,
input$month_2,"_f.jpg", sep = "" )))
      list(src = filename,
           alt = paste("Image number", input$month_2))
   }, deleteFile = FALSE)

}

shinyApp(ui = ui, server = server)

#  selectInput(inputId = "year_test",
#            label = "Year_test",
#           choices = list("1978",
#                          "1979",
#                         "1980",
#                         "1981",
#                        "1982",
#                       "1983",
#                      "1984",
#                     "1985",
#                    "1986",
#                   "1988",
#                    "1987",
#                  "1989",
#                 "1990",
#                "1991",
#               "1992",
#              "1993",
#             "1995",
```

```
#           "1994",
#         "1996",
#          "1997",
#        "1998",
#       "1999",
#      "2000",
#     "2001",
#                 "2002",
#                "2003",
#               "2004",
#               "2005",
#              "2006",
#               "2007",
#               "2008",
#                "2009",
#                 "2010",
#                    "2011",
#                "2012",
#                "2013",
#                "2014",
#               "2015",
#                "2016",
#                 "2017",
#                  "2018"),
#    selected = "2018"),
```

Appendix 5: Python Code

```
import glob
import netCDF4
from netCDF4 import num2date
import numpy as np

# data and source
list_of_files = glob.glob('insert data file name/*.nc', recursive=True)
number_files = len(list_of_files)
print('Number of months (check) = ', number_files)
area_file = '<filelocationname>/psn25area_v3.dat'

# file and variables
for f in list_of_files:
    nc = netCDF4.Dataset(f)
 #    print(nc.variables.keys())

# accessing variables
    sic = nc.variables['goddard_nt_seaice_conc_monthly'][0, :]
 #    print(sic.sum())
 #    print(sic.shape)
 #    print(sic)
 #    print(Date_ice_conc, sic.count())

    time = nc.variables['time']
#     print(time)

# formatting date
    timedim = time.dimensions[0]
  #   print('name of time dimension = %s' % timedim)
    dates = num2date(time[:], time.units)
    Date_ice_conc = [date.strftime('%Y-%m-%d') for date in dates[:10]]

# accounting for projection distortion, reading area file as 4-byt integer scaled by 1000
    area = np.fromfile(area_file, dtype=np.uint32)
    area = area.reshape((sic.shape), order='F').astype('float') / 1000

    pixel_area = 625

# SIE without accounting for area distortion

    SIE = (sic > 0.15) * pixel_area
 #    print(Date_ice_conc, 'SIE:', SIE.sum(), 'km2')


# SIE accounting for area distortion
    SIE_AREA = np.multiply((sic > 0.15), area)
 #    print(Date_ice_conc, 'SIE_AREA:', SIE_AREA.sum(), 'km2', 'need to add pole hole')


    print(Date_ice_conc, 'SIE', SIE.sum(), 'SIE_AREA:', SIE_AREA.sum(), 'km2', 'need to add pole hole')
```

Appendix 6: Producing NSIDC Alternative Maps in ArcPRO

The following instructions provide guidance for producing the alternative NSIDC SII maps in ArcPRO, using '.bin' data files.

1. Access and download the data from the NSIDC website:

i. The 'Sea Ice Concentrations from Nimbus-7 SMMR and DMSP SSM/I-SSMIS Passive Microwave Data, Version 1' can be found at the following link: https://nsidc.org/data/NSIDC-0051.

ii. Download the data: 'final-gsfc/' → 'north/' → 'monthly/' https://daacdata.apps.nsidc.org/pub/DATASETS/nsidc0051_gsfc_nasateam_seaice/final-gsfc/north/monthly/.

iii. Save the '.bin' files to a folder, and change file extension to '.bil'. E.g., nt_200901_f17_nrt_n.bin → nt_200901_f17_nrt_n.bil

For ease of data handling, the data was separated and processed separately by year. In the folder, there should be 12 individual data files for each month.

nt_200901_f17_nrt_n.bil
nt_200902_f17_nrt_n.bil
nt_200903_f17_nrt_n.bil
nt_200904_f17_nrt_n.bil
nt_200905_f17_nrt_n.bil
nt_200906_f17_nrt_n.bil
nt_200907_f17_nrt_n.bil
nt_200908_f17_nrt_n.bil
nt_200909_f17_nrt_n.bil
nt_200910_f17_nrt_n.bil
nt_200911_f17_nrt_n.bil
nt_200912_f17_nrt_n.bil

2. In notes (or other text editor), create a header file with the following content:

nrows 448
ncols 304
nbands 1
nbits 8
layout bil
byteorder I
skipbytes 300
ulxmap -3837500
ulymap 5837500
xdim 25000
ydim 25000

Save in same folder, with the same name, except with '.hdr' file extension for *each data file*.

3. Covert '.bil' file to ESRI compatible grid format:

In ArcGIS Pro, open ArcToolbox.

ArcToolbox → Conversion Tools → To Raster → Raster to Other Format (multiple).

In the dialogue box that opens, select your '.bil' file(s) as the Input Raster(s). In the Output Workspace field, select the location to store the new data file. Choose TIFF as the output raster format. Click OK. The program will use your '.hdr' file to define your input raster and create a new, ESRI-compatible file.

Run.

4. Define the Projection of the '.tif' files.

In **ArcToolbox**, go to **Data Management Tools → Projections and Transformations → Define Projection**.

In the dialogue box that opens, choose the file you created in step 3 as the **Input Dataset or Feature Class**.

Select **Projected Coordinate Systems → Polar → NSIDC Sea Ice Polar Stereographic**

Run.

5. Convert raster to %.

The data files have a range of values between 0-254, corresponding to the following surface types:

0-250 = sea-ice concentrations

251 = data gaps

252 = unused

253 = coastline

254 = landmask

255 = missing

To convert these values to %, divide scaled data by 2.5 using ArcToolbox.

ArcToolbox → Spatial Analyst → Map Algebra → Raster Calculator

Save as new Output Raster.

Run.

6. Reclassify the data.

The files should now have a range of values between 0-101.6, corresponding to the following:

0-100 = sea-ice concentrations

100.4 = data gaps

100.8 = unused

101.2 = coastline

101.6 = landmask

102 = missing

To reclassify the data into distinct threshold boundaries, use Spatial Analyst in ArcToolbox.

ArcToolbox → Spatial Analyst → Reclass → Reclassify

Select Input Raster, reclassify the data values using the desired sea-ice concentration threshold.

For example, for a threshold of 15%, use the 'Start' and 'End' dialogue box as follows:

Start	End	New
0	15	1

15	100	2
100.4	100.4	3
100.8	100.8	4
101.2	101.2	5
101.6	101.6	6
102	102	7

Run.

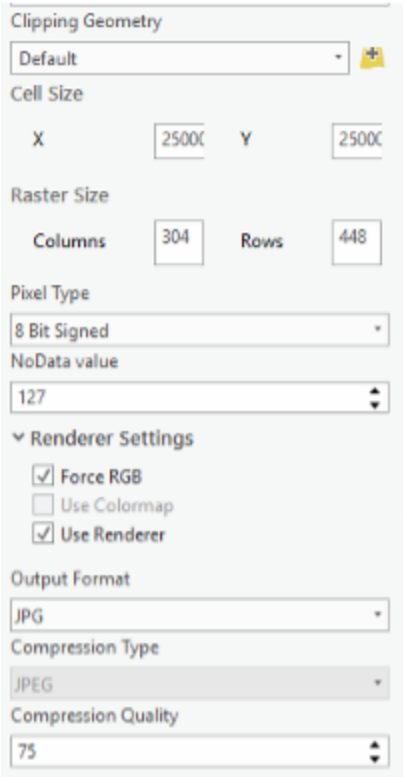
Change symbology to represent the surface categories with colour of choice.

Repeat for additional thresholds.

7. Export the maps as JPG.

Select the file, click export raster. Export to JPG using desired output settings.

For example:



Appendix 7: Information Sheet

Research information sheet for the project titled, "Measurement, Knowledge, and Representation of Arctic Sea Ice"

Researcher:	Laura Seddon, PhD Candidate
Department/University:	Department of Geography, Durham University, UK
Organisation:	Durham Arctic Research Centre for Training and Interdisciplinary Collaboration (DurhamARCTIC)
Funding Body:	The Leverhulme Trust
Type of Research:	Participant Observation
Host Institution:	MET Norway
Period of Research:	3rd February – 27th March 2020

Research Purpose

The purpose of the above research project is to critically examine the ways in which Arctic sea ice is measured, defined, and reported through sea-ice data products. The project studies how data derived primarily from passive microwave remote sensing methods is aggregated and used to classify the region for the purposes of operational sea-ice monitoring and climate research.

An additional aim is to gain a more in-depth and comprehensive insight into the research contexts in which sea-ice science is conducted. Such insights will inform a better understanding of the day-to-day practices and decisions that are involved in the production of sea-ice maps and data products, that are subsequently used to inform numerous different user groups of sea-ice conditions in the Arctic, across various timescales.

Data collection and methods

In order to achieve the above aims, this study uses participant observation as the primary method of research. Throughout the dates specified above, the researcher will be undertaking a placement at MET Norway, working alongside sea-ice scientists engaged in the analysis and reporting of remotely sensed sea-ice conditions in the Arctic. The researcher will work on a project that compares the sea-ice conditions derived using two different sea-ice data products in order to determine the presence of systematic biases or uncertainties, as well as to understand what processes, decisions, and assumptions inform the development of the sea-ice products and data sets.

In addition to working on a project, the researcher will be collecting information on the research setting at MET Norway. Information will be gathered through various formal and informal means. Informal methods of data collection will include conversations and general observations of the scientific activities that occur on a day-to-day basis. On a more formal basis, the researcher will conduct interviews and group discussions with various sea-ice scientists.

The means through which this information will be recorded during the visit will include:

- Direct observation
- Note-taking
- Audio recordings (for interviews and focus groups only)

In the case of interviews and focus groups, additional informed consent will be obtained from participants at the time of the interview or focus group.

Information Use, Anonymity, and Confidentiality

The information collected during the placement will be used to inform the researcher's PhD thesis and associated means of research dissemination, including presentations and posters at conferences, and publication of research findings in academic journals and online resources. Where possible, every effort will be taken to ensure that the anonymity and confidentiality of all scientists is maintained throughout the research project; data will be collected, stored, and handled in anonymous form. All personal information collected will be treated as confidential information and remain anonymous unless disclosure is specifically requested by the researcher, and permission is granted by the participant.

In cases where absolute anonymity may not be achievable (for example due to the scientist's involvement with a particular scientific activity or organisation), the scientist will be made aware of how this information will be used to inform the research, and offered the opportunity to withdraw at any time they choose to do so.

All of the information obtained during the research placement will be stored securely on a password protected computer, and paper notes will be placed in locked storage. Such provisions shall be maintained until the completion of the PhD. All data shall be kept for no longer than is needed for the purpose of the research.

Withdrawal

If you do not wish to be a part of this study or wish to withdraw from the research at any stage, you are free to do so. Please inform the researcher using the below contact details. In either case, any personal information relating to the scientist in question will not be used to inform the study, and in the latter case, any information already obtained will be destroyed, where practical.

If you have any questions relating to this research, please contact the researcher at the following email address: laura.seddon@durham.ac.uk.

Appendix 8: MET Norway Intercomparison Project

An inter-comparison study of Arctic sea-ice extent derived using the EUMETSAT OSI SAF and C3S Sea Ice Concentration, Sea Ice Type, and Sea Ice Edge climate data records

Laura J Seddon

Department of Geography, Durham University, UK

13th May 2020

This project was completed as part of a research visit to the Norwegian Meteorological Institute, Oslo, between February and March 2020. Note that at the time of investigating, the L4 product is 'in progress'.

Intercomparison Report List of Acronyms

ATDB	Algorithm Theoretical Basis Document
C3S	Copernicus Climate Change Service
CDR	Climate Data Record
CDS	Climate Data Store
DMSP	Defence Meteorological Satellite Program
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
NASA	National Aeronautics and Space Administration
NSIDC	National Snow and Ice Data Center
OSI SAF	Ocean and Sea Ice Satellite Application Facility
PUM	Product User Manual
SIC	Sea Ice Concentration
SIE	Sea Ice Edge
SITy	Sea Ice Type
SMMR	Scanning Multichannel Microwave Radiometer
SMM/I	Special Sensor Microwave/Imager
SMMIS	Special Sensor Microwave Imager/Sounder

1. Introduction

Over the past forty years, Arctic sea-ice variability has been monitored using passive microwave remote sensing systems. Based on this long-term record, observations have revealed rapid declining trends in sea-ice cover in response to warming atmospheric and oceanic temperatures, and increasing concentrations of greenhouse gases (Stroeve *et al*., 2012). Owing to its interactive and amplifying role within the earth's climate, significant and ongoing changes in the distribution of Arctic sea ice have the potential to elicit profound and far-reaching climate, ecological, and societal consequences. Therefore, the provision of consistent, accurate, and reliable observations of sea-ice variability is an essential requirement of the sea-ice research community (WMO, 2016).

The Copernicus Climate Change Service (C3S) is committed to providing consistent and authoritative information on the changing state of the world's climate, in support of the adaptive and mitigative climate change policies of the European Union. To support the C3S objectives, scientists at the Norwegian Meteorological Institute (MET Norway) use passive microwave observations of sea ice to develop and distribute several sea-ice climate data records (CDRs) for the C3S climate data store (CDS). Sea-ice CDRs aim to provide information to monitor and assess variability over recent decades, as well as support projections of future changes in Arctic sea ice.

For the period of 1979 to 2015, MET Norway scientists produce daily and monthly gridded CDRs for various essential sea-ice parameters, including sea-ice concentration, edge, and type. The sea-ice concentration (SIC) CDR provides information on the fractional coverage of sea ice in the Arctic. The sea-ice edge (SIE) and sea-ice type (SITy) CDRs use sea-ice concentration data, along with additional information on ocean surface conditions, to classify areas into distinct categories based on the dominant surface types. In addition to providing essential information on the fractional cover of sea ice and the distribution of dominant sea-ice types, the SIC, SITy, and SIE CDRs can be used to calculate sea-ice extent. As a measurement of the total area of a region covered in a significant concentration of sea ice (usually 15%), sea-ice extent is a key indicator of the spatial and temporal evolution of sea-ice cover in the Arctic. Sea-ice extent is also used to mark the position of the ice-edge by distinguishing between ice-covered and open water areas. This distinction has important implications for virtually all applications of sea-ice products and datasets.

For the SIC, SITy, and SIE CDRs, the primary data source is passive microwave brightness temperature (Tb) measurements, retrieved using a series of microwave radiometers, operating since the late 1970s. Details of the passive microwave instrumental records and their associated satellite missions are provided in Table 1. The calculation of sea-ice parameters using this data exploits the observed variability in the microwave emissivity of different surface types, arising from different factors such as surface roughness and temperature (Gloersen *et al*., 1973). The contrasting brightness temperature (Tb) signatures between different surfaces provides the theoretical basis for estimating sea-ice

concentrations and distinguishing between open water, ice, and different ice types (Eppler *et al*., 1992).

Although the primary data source is broadly consistent across the CDRs for sea-ice concentration, edge, and type, there exists some important differences in product characteristics and data retrieval methods. The most significant differences include:

- the imaging channels used in the acquisition of Tb data;
- the algorithmic processes used in the calculation of sea-ice parameters;
- the grid resolutions to which the data are mapped; and
- the thresholds used to delineate the ice-edge.

Section 2 provides a more detailed overview of the products' characteristics and differences. As various inter-comparison studies have illustrated (e.g. Comiso *et al.*, 2017; Ivanova *et al.*, 2014; Meier and Stewart, 2019), variations in retrieval methods and data processing techniques between sea-ice data products can have a large impact on the relative estimates of sea-ice concentration and extent. This undermines the consistency and comparability of climate data records and hinders future projections of Arctic sea-ice variability.

With the product differences in mind, this report details an inter-comparison study that analyses and compares monthly-averaged sea-ice extent estimates calculated using the SIC, SITy, and SIE CDRs. Sea-ice extent is compared on seasonal, interannual, and decadal timescales, as well as across different spatial regions. The aim is to provide insights into how the use of different retrieval methods and processing techniques affects the statistical characteristics of Arctic sea-ice extent. The focus on sea-ice extent as a comparative parameter is an effective way of evaluating and comparing sea-ice concentration retrieval across the three different data records. Such analysis will allow for a better understanding of uncertainties and biases in sea-ice concentration and extent calculations. This knowledge is essential for all sea-ice data applications and for continued product development.

Table 1: Details of the passive microwave sensors used in the OSI SAF CDRs

Sensor	Satellite(s)	Operating times
Scanning Multi-channel Microwave Radiometer (SMMR)	NASA Nimbus-7	Oct 1978 – Aug 1987
Special Sensor Microwave Imager (SSM/I)	DMSP F8	Jul 1987 – Dec 1991
	DMSP F10	Jan 1991 – Nov 1997
	DMSP F11	Jan 1992 – Dec 1999
	DMSP F13	May 1995 – Dec 2008
	DMSP F14	May 1997 – Aug 2008
	DMSP F15	Feb 2000 – Jul 2006
Special Sensor Microwave Imager/Sounder (SSMIS)	DMSP F16	Nov 2005 – Dec 2013
	DMSP F17	Dec 2006 – Dec 2015
	DMSP F18	Mar 2010 – Dec 2015

2. Data and Methods

This inter-comparison study evaluates and compares monthly-averaged sea-ice extent estimates calculated using three sea-ice products: sea-ice concentration, edge, and type. The sea-ice edge and type products are produced on behalf of C3S, whereas, the sea-ice concentration product is produced by the EUMETSAT Ocean and Sea Ice Satellite Application Facility (OSI SAF). The records are formally referred to as the EUMETSAT OSI SAF Global Sea Ice Concentration CDR, OSI-450 v2.0 (SIC); the Sea Ice Edge C3S CDR (SIE); and the Sea Ice Type C3S CDR (SITy). The key characteristics of the CDRs used in this study are provided in Table 2 and summarised in this section. Note that this study only considers sea-ice coverage for the northern hemisphere.

2.1. Global Sea-Ice Concentration Climate Date Record, OSI-450 v2.0

The SIC CDR is a long-term climate record that provides a consistent time series of daily averaged sea-ice concentrations obtained from passive microwave observations of Tb data. In addition to providing information on the fractional coverage of sea ice, the CDR is the primary dataset used in the OSI-SAF daily and monthly reports of sea-ice extent.

The passive microwave data used to compute sea-ice concentration is obtained from a series of microwave radiometers, operating from 1978 to present. These instruments include the Scanning Multichannel Microwave Radiometer (SMMR), the Special Sensor Microwave/Imager (SSM/I), and the Special Sensor Microwave Imager/Sounder (SSMIS). An overview of the passive microwave instrumental records used in the processing of the SIC CDR is provided in Table 2. The Tb data acquired using these instruments is explicitly corrected for atmospheric influence using numerical weather prediction (NWP) data from the European Centre for Medium-Range Weather Forecasts (ECMWF).

Sea-ice concentrations are calculated from the Tb data using a specific set of data processing methods. The data processing chain for the SIC CDR can be divided into three main elements: Level 1 and 2, Level 3, and Level 4. Figure 1 outlines the main processing stages, and they are briefly summarised below. A more comprehensive overview of these processing steps and the science underpinning them is provided in the SIC Algorithm Theoretical Basis Document (ATBD) (Lavergne *et al.*, 2019a). See also Lavergne *et al*. (2019b).

The first stages, Level 1 and 2, involve the processing steps applied to the original swath data, without data averaging or gridding. During Level 1 processing, Tbs are corrected for land influence using a land spill-over algorithm (Maas and Kaleschke, 2010), and the data is collocated. The steps in Level 2 involve the implementation of key scientific processes. These include the dynamic tuning of tie-points and algorithms, the tuning of the open water filter, the correction for atmospheric influence using a Radiative Transfer Model (RTM) function (Dee *et al*., 2011), and the computation of sea-ice concentration and algorithm uncertainties. The SIC CDR uses the hybrid algorithm SICCI2 to calculate sea-ice concentration from atmospherically corrected Tb data. The SICCI2 is comprised of the Bootstrap algorithm (Comiso, 1986; Comiso *et al*., 1997) and the Bristol algorithm (Smith, 1996). The characteristics and scientific basis of the SICCI2 are described in detail in Section 3.2 of the ATBD document.

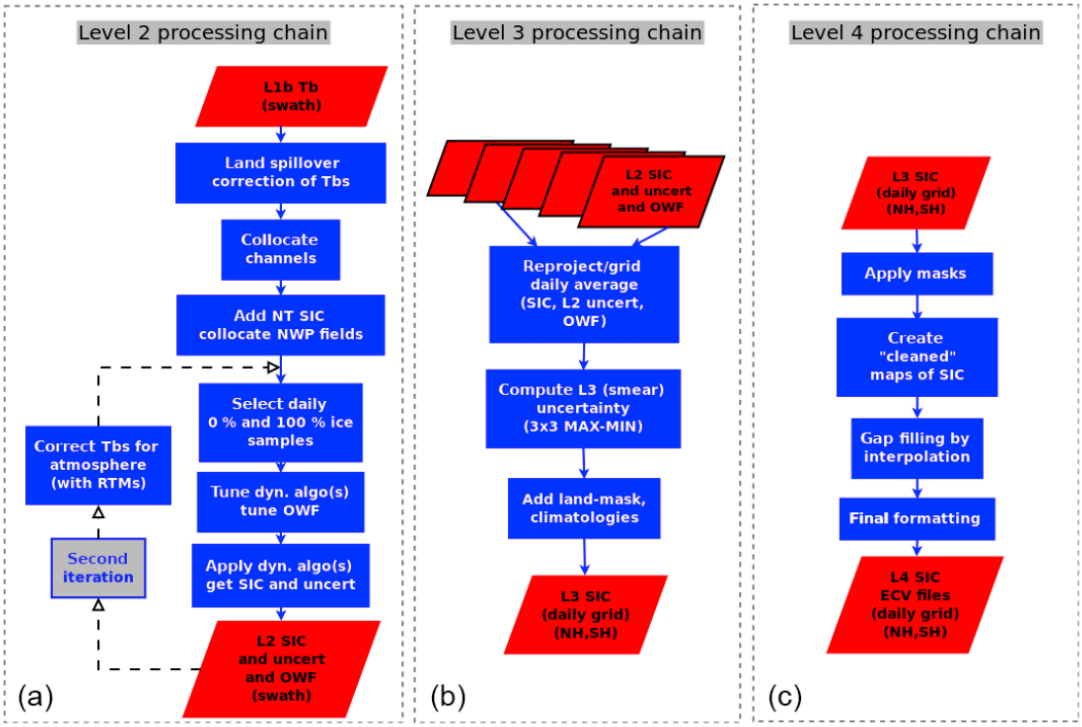


Figure 1: The three main stages of the SIC CDR processing chain (Sørensen et al., 2019)

Level 3 processing involves the application of swath data to daily gridded fields, the calculation of smearing and gridding uncertainties, and the preparation of masks for land and sea-ice climatology. For the SIC CDR, output grids are produced with a grid resolution of 25 km. Gridding is applied to all areas with data coverage, including the coastal zone, and for all variables that may be of interest. This includes output grids for sea-ice concentration estimates using both corrected and uncorrected Tbs. However, for the purpose of this study, only corrected sea-ice concentration estimates have been used.

The final stage, Level 4, involves the spatial and temporal interpolation for areas of missing data, as well as the application of land and climatology masks. The sea-ice climatology used in the SIC CDR is based on an edited version of the climatology produced for the National Snow and Ice Data Center (NSIDC) Sea-Ice Concentration CDR. The NSIDC climatology data is subsequently edited manually by OSI SAF using comparative information from Canadian and Norwegian ice charts (Sørensen *et al.*, 2019).

Following the completion of Level 4 processing, final daily SIC datasets are presented on a Lambert Azimuthal Equal Area polar projection (also known as Equal Area Scalable Earth 2 (EASE2)), with a grid cell resolution of 25 x 25 km.

Table 2: Overview of the CDR characteristics. *Note that the 85.5 GHz channel was not used from the SSM/I sensor during the operating time of the DMSP-F8.

CDR	Primary input data (sensor: frequency, GHz, polarisation)	Other input data	Grid resolution and projection	Parameter description	Parameter definition	Reference
SIC CDR v2.0	SMMR: 18V, 37V, 37H SSM/I: 19.35V, 37V, 37H SSMIS: 19.35V, 37V, 37H	NWP for atmospheric correction	25 km x 25 km, Lambert azimuthal equal-area (EASE2)	Fractional area of sea-ice cover.	Sea-ice concentration percentage range: 0 – 100%	Lavergne *et al*., 2019
SITy CDR L3 & L4	SMMR: 18V, 18H, 37V, 37H SSM/I: 19.35V, 19.35H, 37V, 37H, 85.5V*, 85.5H* SSMIS: 19.35V, 19.35H, 37V, 37H, 91.65V, 91.65H	NWP for atmospheric correction	25 km x 25 km, Lambert azimuthal equal-area (EASE2)	Dominant surface type: *open water, first-year ice, multiyear ice.*	Sea-ice concentration thresholds: Open water <30% FYI >30% MYI >30%	Aaboe, 2018b, 2018c
SIE CDR L4	SMMR: 18V, 18H, 37V, 37H SSM/I: 19.35V, 19.35H, 37V, 37H, 85.5V*, 85.5H* SSMIS: 19.35V, 19.35H, 37V, 37H, 91.65V, 91.65H	NWP for atmospheric correction	12.5 km x 12.5 km, Lambert azimuthal equal-area (EASE2)	Dominant surface type: *open water, open ice, closed ice.*	Sea-ice concentration thresholds: Open water <30% Open ice 30 – 70% Closed ice >70%	Aaboe, 2018b, 2018c

2.2. Sea Ice Edge and Type CDRs

The CDRs for SIE and SITy are processed using broadly the same algorithm system, processing chain, and data format. They are both described in this section.

The SIE CDR and the SITy CDR are sea-ice classification products that separate the ocean surface into discrete sea-ice classes. The basic principles and definitions implemented in the SIE C3S and the SITy C3S CDRs are generally consistent with the operational near-real-time sea-ice edge and sea-ice type products, developed by OSI SAF and described in the corresponding product user manuals (Aaboe *et al.*, 2018a). Since 2009, the operational products include data obtained using active microwave scatterometer instruments (Advanced SCATterometer (ASCAT)). The CDRs only use passive microwave data in order to provide consistent and long-term records.

To differentiate between areas of sea ice, open water, and different surface types, the CDRs primarily use atmospherically corrected Tb data obtained from the ~40-year passive microwave record. An overview of the passive microwave instrumental records used in the processing is provided in Table 2. Note that throughout the operating periods of the three passive microwave sensors, the SITy and SIE CDRs incorporate higher and lower frequencies, as well as different polarisations to the SIC CDR. A particularly notable difference occurs from 1991 onwards when the SITy and SIE CDRs begin to incorporate data obtained at higher frequencies (85.5 GHz from the SSM/I sensor and 91.65 GHz from the SSMIS). In comparison, 37 GHz is the highest frequency used in the SIC CDR throughout the time series. These differences have important implications for the computation of sea-ice concentration and type, as they affect how the Tb data is retrieved and interpreted in the data processing chains.

The SIE CDR uses atmospherically corrected Tb data and sea-ice concentration data to identify three main classes of ocean surface type: open water (< 30 %), open ice (30 – 70 %), and closed ice (> 70 %). The concentration thresholds used to classify the surface types are derived from the World Meteorological Organisation's Ice Chart Colour Code Standard (WMO, 2014) and are recognised internationally as the standard practice for operational ice charts.

The SITy CDR classifies ocean surface data into three discrete types that represent the dominant development stage of ice: open water (<30%), first-year ice (≥30%), and multiyear ice (≥30%). The definition for open water regions is consistent with the SIE CDR (areas with a sea-ice concentration <30%). The latter two classes, first-year and multiyear ice describe the dominant stage of sea-ice development within a particular region. First-year ice is defined as seasonal sea ice that has formed following the preceding melt season, whereas multiyear ice is sea ice that has endured at least one melt season. Differences in the physical and chemical composition of first-year and multiyear ice, give rise to variations in measured microwave emissivity at different frequency channels and polarizations (Comiso, 1983). The algorithms used to distinguish between surface classes in the SIE and SITy CDRs exploit these differences in measured microwave emissivity.

The initial data processing steps used in the development of the SIE and SITy CDRs are consistent with those used in Levels 1, 2, and 3 processing of the SIC CDR v2.0, as detailed in Section 2.1. However, there are some important distinctions between the two processing chains as illustrated in Figure 2, and briefly summarised below. A thorough description of these processing steps can be found in the CS3 Algorithm Theoretical Basis Document (ATBD) and the Product User Guide and Specification for SIE and SITy (Aaboe, 2018b, 2018c).

Once the original swath data has been pre-processed and corrected for atmospheric influence (Level 1 and 2 processing), the SIE and SITy data is applied to gridded daily fields (Level 3). Similarly to the SIC CDR, daily gridded fields are applied to all areas with data coverage, including the coastal zone and for all variables that may be of interest. This includes the classification parameters used to distinguish between Tb signatures, sea-ice concentration estimates, and weather filters.

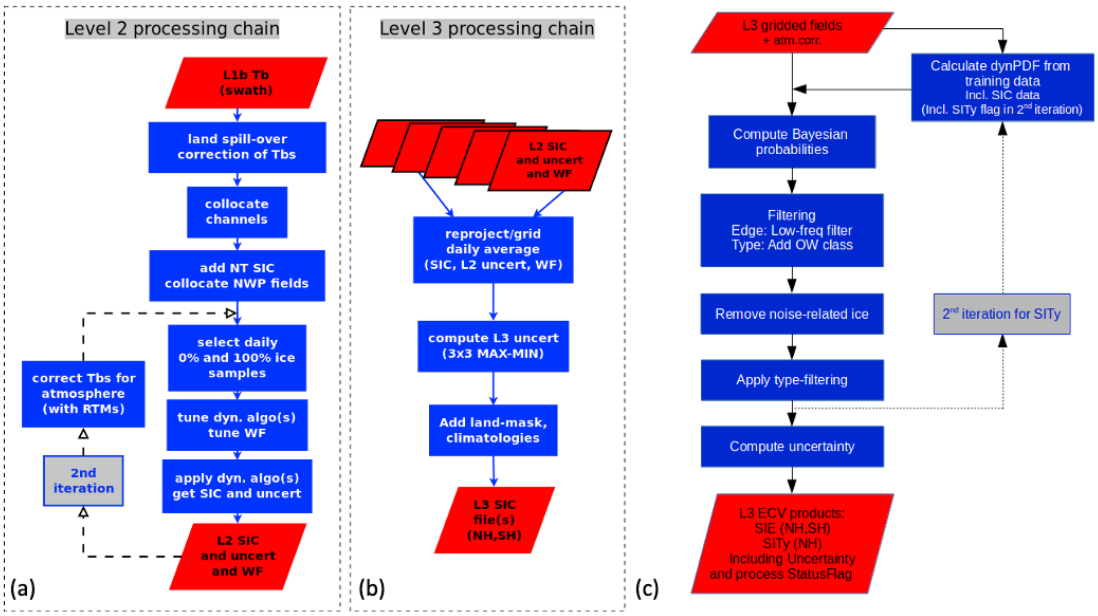


Figure 2: The three main stages of the SIE and SITy CDR processing chain (Aaboe, 2018c)

The main classification of sea-ice edge and type variables occurs once the data is applied to gridded daily fields. It is this step that distinguishes the processing chains of the SIE and SITy CDRs from the SIC CDR. Gridded data fields are classified into sea-ice types using a Bayesian approach which calculates the probability of occurrence of the most likely surface type within each grid point. This classification method relies on prior knowledge of surface conditions, as well as the relationship between measured parameters (atmospherically corrected Tbs) and different surface classes (Aaboe *et al.*, 2018a). The final classification of each grid point is defined by the surface type with the highest Bayesian probability. In addition to identifying the most likely surface type at each grid point, the Bayesian method provides an indication of the statistical uncertainty of the classification; the higher the calculated probability of surface type, the lower the uncertainty in the resulting classification

for each grid point, and vice versa. The final step in Level 3 processing involves the filtering and adjustment of classifications that are suspicious or obviously incorrect.

Following the completion of Level 3 processing, the final daily-averaged estimates of sea-ice edge and sea-ice type data are presented on Lambert Azimuthal Equal Area polar projections, with grid resolutions of 12.5 km and 25 km, respectively.

This study uses two different versions of the SITy CDR: SITy_L3 and SITy_L4. For both versions of the data record, the processing methods and data formats are consistent, however, the L4 version uses temporal and spatial interpolation to fill in gaps where satellite data is missing. For the SIE CDR, only the L4 version is used.

2.3. CDR comparisons

This study seeks to examine how different product characteristics and data retrieval methods implemented in the C3S CDRs for sea-ice concentration, edge, and type, impact monthly sea-ice extent trends in the Arctic. Several comparative analyses are performed which compare the SIE and SITy monthly sea-ice extent estimates against the SIC CDR v2.0. For each dataset, the monthly sea-ice extent values are given as averages of the daily sea-ice concentration, type, and edge values.

A summary of each of the comparisons is provided in Table 3 below and the results are detailed in Section 3.

Table 3: Overview of the comparisons between the SIC, SITy, and SIE CDRs.

Comparison	Data Record 1	Data Record 2
C1	SIC CDR v2.0	SITy CDR L3
C2	SIC CDR v2.0	SITy CDR L4
C3	SITy CDR L4	SIE CDR L4

The distinction between ice-covered and open water areas is an essential element of sea-ice CDRs, particularly when reporting sea-ice extent. However, between the three CDRs considered in this study, the definition used to delineate the sea-ice edge is not consistent. As noted previously, the SIC CDR is the primary dataset used in the OSI SAF daily and monthly reports of sea-ice extent values. As is standard practice in climate studies (e.g. Gloersen *et al*., 1993; Parkinson and Cavalieri, 2008), OSI SAF reports sea-ice extent using a 15% sea-ice concentration threshold. Grid cells with a sea-ice concentration over 15% are classified as ice-covered areas and those below 15% are classified as open water areas. In comparison, in the SIE and SITy CDRs, the ice-edge is marked by a sea-ice concentration threshold of approximately 30%.

To directly compare sea-ice extent and concentration retrieval between the three different products, sea-ice extent is computed from the SIC CDR using a concentration threshold of

30%, to ensure consistency with the SIE and SITy CDRs. For the SIC CDR, sea-ice extent is computed by summing the area of all grid cells with a concentration >30%. For the SIE and SITy CDR, sea-ice extent is computed by summing the total area of the ocean surface classified as open ice and closed ice, or first-year ice and multiyear ice, respectively. Ambiguous ice types are also included in the SITy extent calculations.

Pan-Arctic estimates of monthly-averaged sea-ice extent are compared over the full 1979 - 2015 time series (where data is available for both CDRs). In addition to providing comparisons at hemispheric scale, sea-ice extent values were considered regionally, to assess any spatial variation between the records. The gridded fields were quartered as shown in Figure 3. Note that the labels of each division do not reflect official territorial divisions, rather they have been assigned according to the dominant coastline or ocean for ease of description.

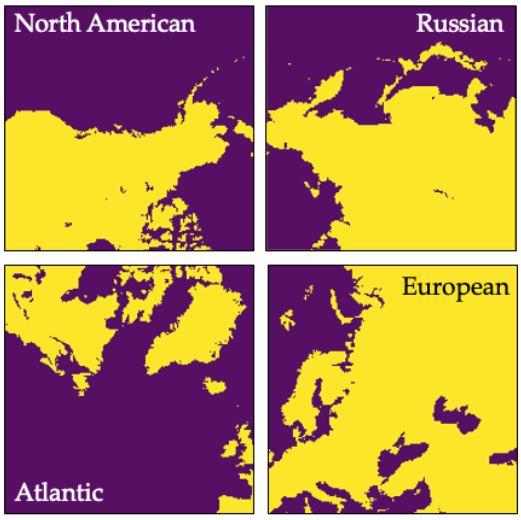


Figure 3: Quarterly divisions of the Arctic region for spatial analysis of sea-ice extent trends.

Due to the differences in grid resolution between the SIE CDR (12.5 km) and SIC CDR (25 km), in addition to the differences mentioned above, the two data records are not directly compared to each other. The discrepancies in grid resolution are likely to result in significant differences in sea-ice extent estimates between the two data sets. The effect of grid resolution on extent estimates is expected to inhibit the ability to assess the impacts on sea-ice extent calculation caused by other factors, such as the choice of imaging channels (frequency and polarisation). To consider the impact that grid resolution has on sea-ice concentration and extent retrieval in isolation, the SIE_L4 CDR is compared against the SITy_L4 CDR (see Section 3.3).

3. Results

The results of comparisons 1-3 are detailed in this section. Monthly averaged sea-ice extent values are reported in units of 10^6 km^2 (millions of square kilometres) throughout. Data is provided for the period of 1979 to 2015, with the exception of April and May 1986, for which passive microwave satellite data is not available.

3.1 Comparison 1

3.1.1. Comparison of SIC and SITy_L3 sea-ice extent

Monthly-averaged Arctic sea-ice extent time series for the SIC and the SITy_L3 data records are displayed in Figure 4.

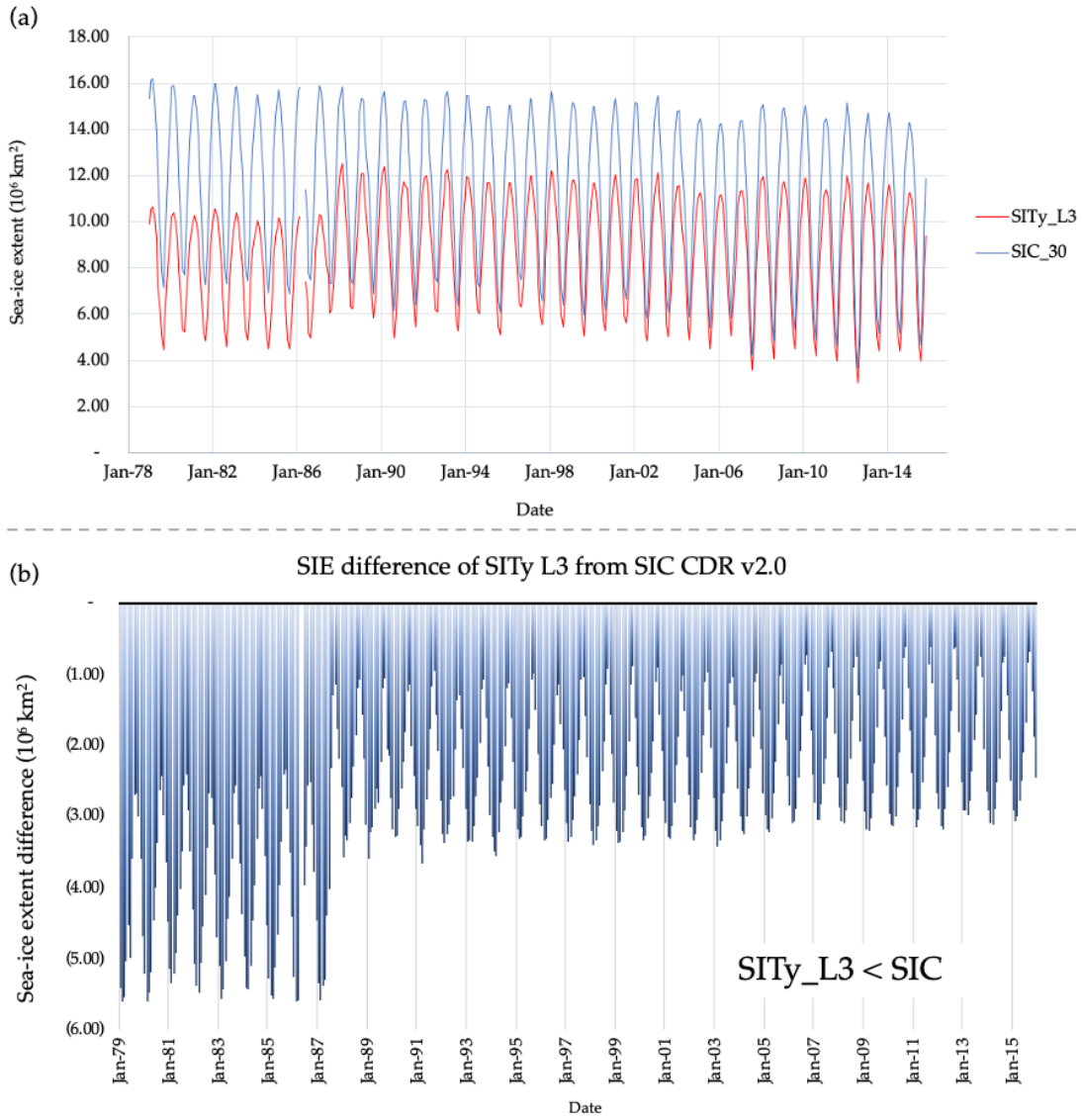


Figure 4: (a) Monthly-averaged sea-ice extent time series from the SITy_L3 and SIC CDRs, 1979-2015; (b) sea-ice extent difference (SIC – SITy_L3).

Overall, the SIC and SITy_L3 sea-ice extents show some consistency between 1979 and 2015 (Figure 4a). For both data sets, there are consistent seasonal and interannual signatures, a long-term negative trend in sea-ice extents, and consistent timing of the sea-ice minima and maxima. Despite these similarities in the trend characteristics, the sea-ice extent values for the SITy_L3 are significantly lower than those calculated using the SIC CDR, throughout the time series. The differences between the data records are most significant during the winter and between 1979 and 1987.

Figure 4b shows the considerable disparity in sea-ice extent estimates between the two CDRs. Over the full time period, the sea-ice extent estimates for the SITy_L3 are, on average, ~2.7 x

10^6 km^2 (~23%) lower than the SIC CDR. Though, there is a definite shift in the severity of the differences after July 1987. Between 1979 and 1987, the SITy_L3 provides significantly lower extents (averaging at ~9% lower) than those calculated from July 1987 onwards. The smaller SITy_L3 extents retrieved during the earlier period accentuate the disparities between the two CDRs, resulting in differences of up to ~5 x 10^6 km^2 (~41%) and averaging at ~4 x 10^6 km^2 (~34%). After July 1987, the SITy_L3 provides higher extent values, and the differences between the data records reduce substantially to an average of ~2.3 x 10^6 km^2 (~20%).

Looking in more detail at the seasonal trends (Figure 5), the general shape and seasonal characteristics of the time series for March and September sea-ice extents are comparable for the SITy_L3 and SIC CDRs, except for the period preceding July 1987. Of particular note, is the similarities in seasonal variability between March and September sea-ice extents, with March extents averaging at ~57% higher than September extents for the SIT_L3 CDR, and ~59% for the SIC CDR (Figure 5 a-b). Additionally, the two CDRs exhibit similar degrees of severity in the long-term trends for March and September.

The differences in sea-ice extent values between the SITy_L3 and SIC times series are apparent in both seasons but are more significant during March (Figure 5 c-d). Excluding the period leading up to July 1987, the average difference in March sea-ice extents between SITy_L3 and SIC CDRs is ~3.3 x 10^6 km^2 (~22%), whereas the average difference in September is lower at ~0.9 x 10^6 km^2 (~16%). While there is some apparent interannual variability in sea-ice extent differences for both March and September, the overall trends for the two datasets are very similar from July 1987 onwards. Prior to July 1987 however, the CDRs exhibit greater variability in both seasons.

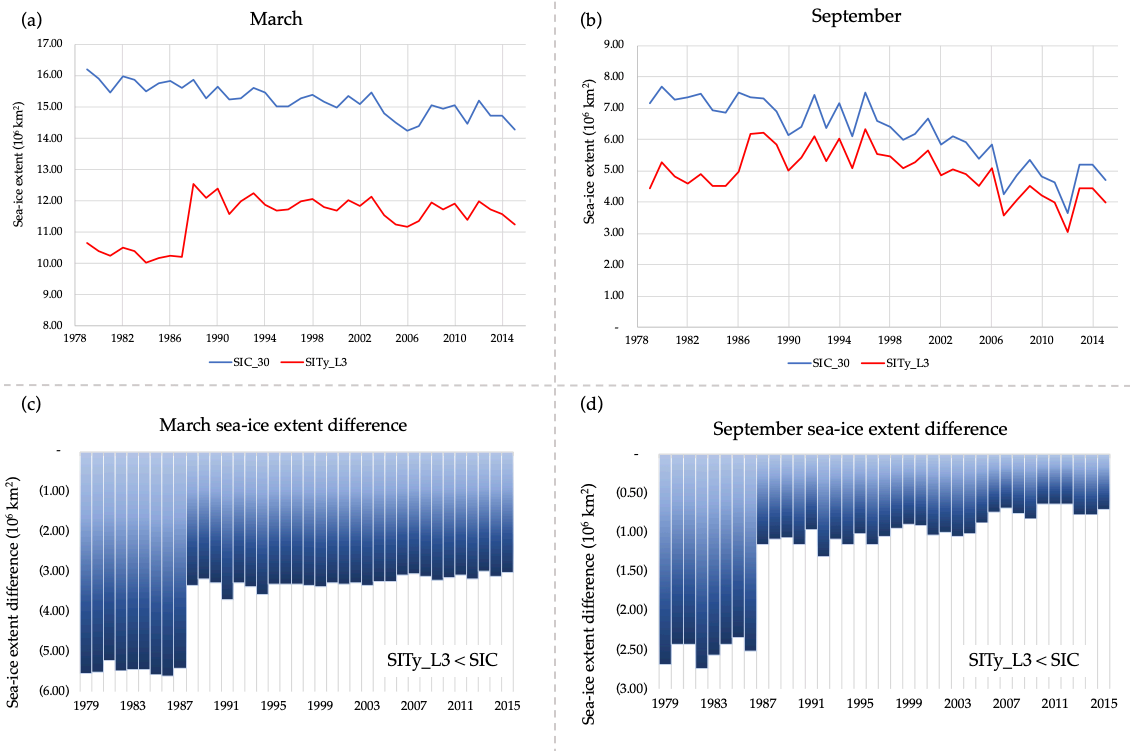


Figure 5: (a) March sea-ice extent time series for the SITy_L3 and SIC CDRs, 1979-2015; (b) September sea-ice extent time series for the SITy_L3 and SIC CDRs, 1979-2015; (c) March sea-ice extent differences, 1979-2015; (d) September sea-ice extent differences, 1979-2015. The baseline in (c) and (d) is the SIC sea-ice extent values.

The clear step-change in the SITy_L3 time series following July 1987 coincides with the launch of the SSM/I sensor. Changes to the sensor properties used in the retrieval of Tb data therefore had a marked impact on the classification of surface characteristics in the SITy_L3 dataset.

A significant proportion of the observed disagreement between the SITy_L3 and SIC CDRs can be attributed to differences in the total area of masked or unclassified data in the gridded datasets. Masked regions include areas over land, as well as ocean regions positioned outside of the maximum sea-ice climatology. Unclassified areas include missing data and areas near the coastline. Figure 6 provides two examples of daily gridded data files from the SITy_L3 and SIC CDRs, whereby only the unclassified data and masked areas, are represented. As illustrated by the data plots, the total area of masked or unclassified regions is visibly more extensive in the SITy_L3 data file than the SIC data file (~61.3 x 10^6 km^2 compared to ~55.5 x 10^6 km^2), indicating that the SITy_L3 data filters out large areas of the ocean surface. This is largely because the SITy and SIE L3 CDRs do not use spatial and temporal interpolation to fill in grid points of missing data. The effect of this is most notable in narrower coastal regions and around island groups, such as the Canadian Archipelago, Severnaya Zemlya, and Svalbard.

It is highly probable that the extensive area of masked and unclassified regions in the SITy_L3 CDR is a primary cause of the discrepancies in sea-ice extent between the two datasets. The false representation of surface types, particularly in coastal locations, is likely

to result in large areas of "true" ice being unaccounted for in sea-ice concentration and extent calculations. This effect would explain why the observed differences are more significant during the winter/spring months when sea ice is generally more widespread across the Arctic.

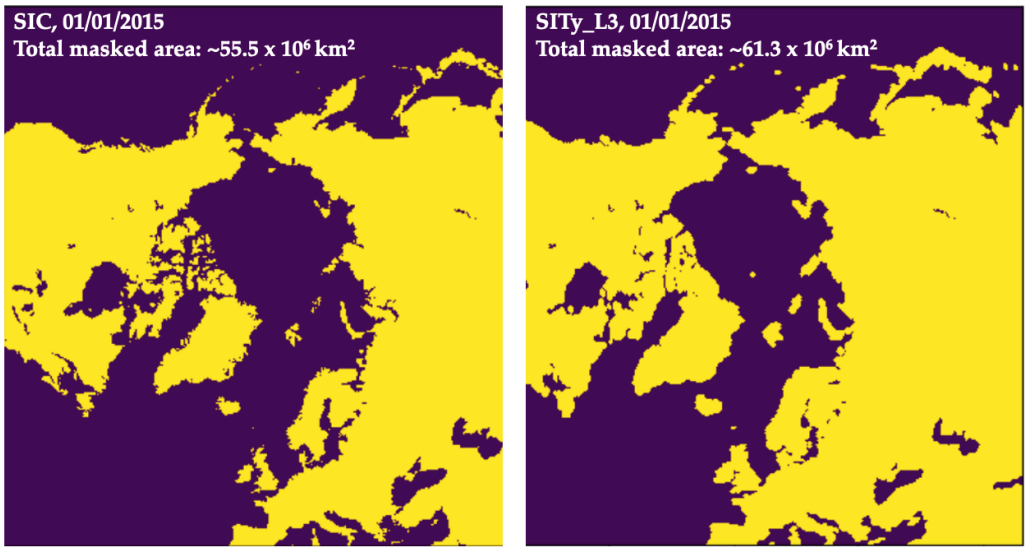


Figure 6: Maps showing the total daily masked area (yellow) for a SIC (left) and SITy_L3 (right) data file, 01/01/2015.

3.1.2 Comparison of SIC and SITy_L3 sea-ice extent using consistent masks

To further investigate the impact of the relative proportions of masked and unclassified data on the inter-record differences, sea-ice extents for the SIC CDR were re-calculated using the masked regions from the SITy_L3. A masked array encompassing all unclassified and masked data was produced for each SITy_L3 data file, and applied to the corresponding SIC data file, prior to calculating daily sea-ice extent values. Through this analysis, the influence of invalid and missing data is removed, thus, allowing for a more direct comparison of sea-ice concentration retrieval between the two processing chains.

Pan-Arctic scale

Using consistent masks for the SITy and SIC CDRs greatly improves the agreement between the extent estimates at 30% sea-ice concentration (Figure 7). With a few exceptions, most of which occur before July 1987, the extent values are very similar throughout the time series. This improved agreement confirms that much of the earlier differences observed between the datasets are attributable to inconsistencies in the masked data.

The step-change in the data series after July 1987 is still present, however, with the earlier time period now showing notably lower extent values for both datasets (approximately 2 x 10^6 km^2). The shift in extent values in both datasets occurs due to inconsistencies in the total area of the SITy_L3 masked data associated with the different satellite sensors (see Appendix A). During the operating period of the SMMR sensor, the SITy_L3 data files are characterised by significantly larger areas of masked or unclassified data. A substantial reduction in the masked area, by approximately 2 x 10^6 km^2, occurs in July 1987, coinciding with the transition

to the SSM/I sensor. While there is some minor variability on seasonal and interannual timescales, the dataset maintains the lower masked areas throughout the remainder of the time series. These differences correspond closely with the variability exhibited in the sea-ice extent values from the SITy_L3 and SIC CDRs (Figure 7).

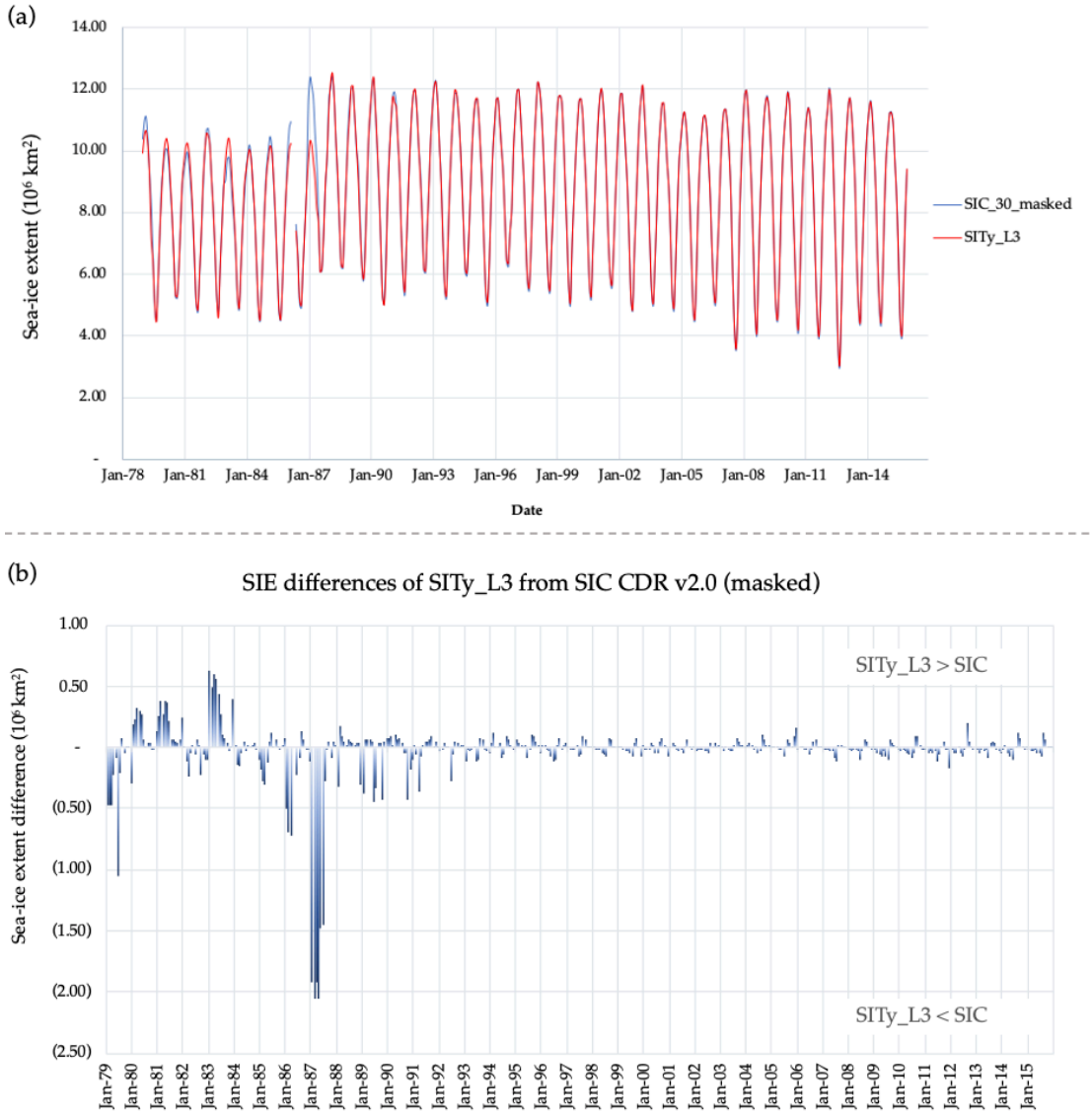


Figure 7: (a) Monthly-averaged sea-ice extent time series from the SITy_L3 and SIC (masked) CDRs, 1979-2015; (b) sea-ice extent difference (SIC – SITy_L3).

Overall, the differences in sea-ice extent values between the two datasets have significantly reduced following the application of consistent masks (Figure 7b). Excluding the period prior to July 1987, the differences are consistently below 0.5 x 10^6 km², and average at <0.05 x 10^6 km² (<1%). The largest discrepancies continue to arise during the operating time of the SMMR sensor, between 1979 and 1987. During this period, the differences average at ~0.27 x 10^6 km² (~2.8%). A particularly notable difference occurs in the winter/spring of 1987, during which the SITy extents are approximately 2 x 10^6 km² (16%) lower than those calculated using the SIC CDR, from January through June.

In addition to the pronounced variability before 1987, further inter-record variation occurs between 1987 and 1991, during the operating time of the SSM/I-F8 sensor. During this period, sea-ice extents are more variable for both records, and the differences between the extent values are more significant, albeit less severe than the earlier SMMR period. This is particularly apparent during the months when the SITy_L3 extents fall below the SIC CDR. After 1991, the two records become more aligned and exhibit less deviation on seasonal and interannual timescales.

The March and September time series exhibit a similar temporal variability (Figure 8). Before 1991, the March and September sea-ice extents for both CDRs exhibit greater interannual variability and are incompatible with the longer-term trends. These characteristics are more pronounced in March. In contrast, from 1992 onwards, March and September extents exhibit less variability, and the SITy_L3 and the SIC CDRs show strong agreement. For March, SITy_L3 extents are generally marginally lower than those calculated using the SIC CDR (<1%), and for September, the reverse is apparent. Monthly-averaged sea-ice extent distributions for all months show a similar distribution to those detailed above and are included in Appendix B.

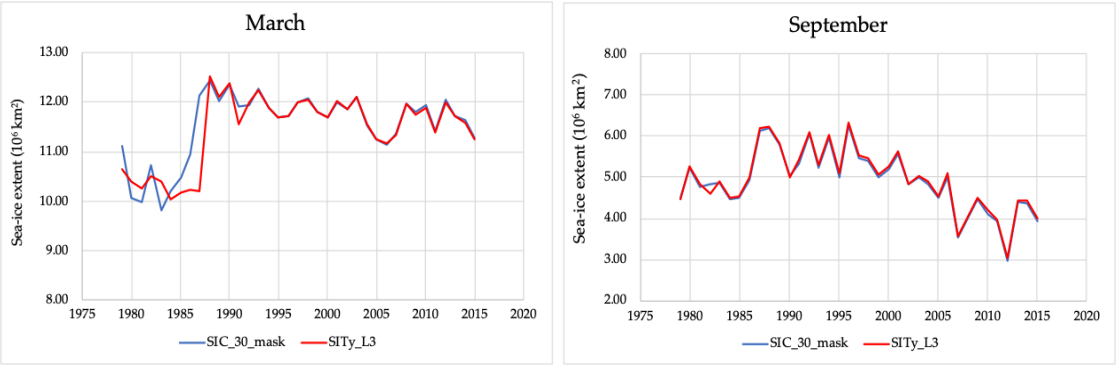


Figure 8: SITy_L3 and SIC monthly-averaged sea-ice extent time series for March and September, 1979-2015.

The variability in the sea-ice extent differences between the three periods (1979-1987, 1987-1991, and 1992 onwards), correlates strongly with changes to the satellite data inputs (Table 1), confirming that the changes in the sensor properties had a measurable impact on the relative estimates of sea-ice concentration. The improved inter-record agreement shown after 1991 can be explained by the incorporation of Tb data obtained at higher frequency channels in the processing of the SITy CDR (85.5 GHz from the SSM/I sensor and 91.65 GHz from the SSMIS).

Looking in more detail, Figure 9 demonstrates how the three distinct time periods (1979-1987, 1987-1991, and 1992-2015) affect the percentage differences in sea-ice extent between the two datasets, on an annual basis. The two earlier periods exhibit substantial interannual and seasonal variability in extent differences (Figures 9a - c), particularly during the winter and spring months. In contrast, from 1992 onwards, sea-ice extents align much more closely across all months and exhibit a clearer seasonal pattern in their differences, with some

periods when the SITy_L3 extents exceed the SIC extents, and other periods when the reverse is true (Figure 9d).

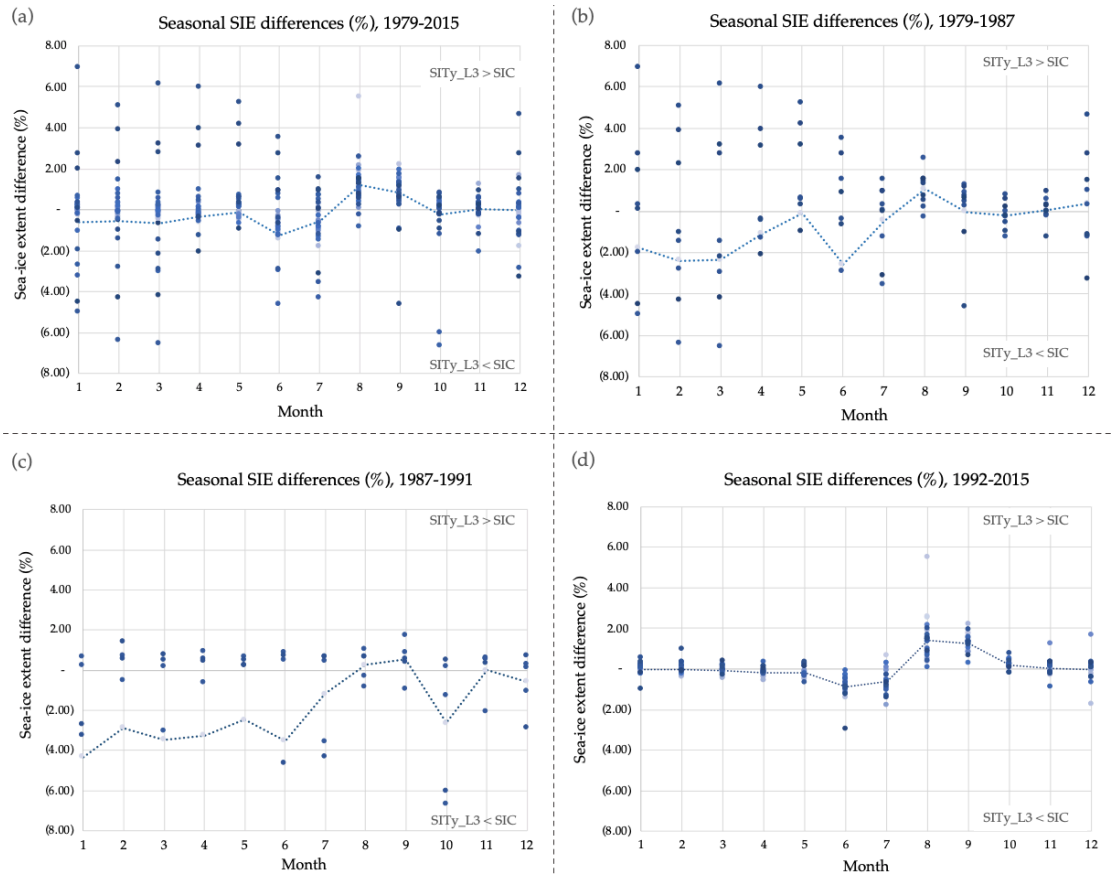


Figure 9: Monthly extent differences (%) for: (a) the full time series, 1979-2015; (b) SMMR operating period, 1979-1987; (c) SSM/I F8 operating period, 1987-1991; (d) SSM/I F10-F15 and SSMIS operating periods, 1992-2015.

By focussing on a 3-year period between 2001-2004, Figure 10 examines the seasonal nature of the differences in more detail. Despite only minor variability in the sea-ice extent differences (ranging from approximately -0.05 to +0.12 x 10^6 km^2), a seasonal pattern is apparent. Generally, the greatest agreement between the two datasets occurs between the late autumn and early spring (October – April), with the SITy_L3 extent fluctuating just above or below the baseline. After reaching the winter maximum, the SITy extents gradually fall slightly below the SIC CDR extents during the spring and summer, before rapidly increasing again during August and September.

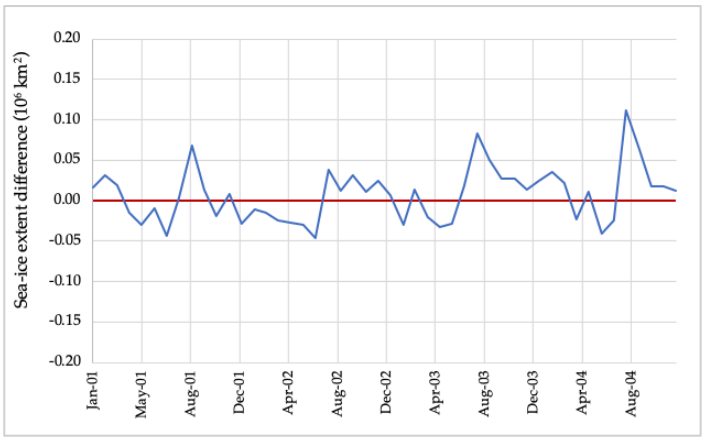


Figure 10: Seasonal variability in extent differences between the SITy_L3 and the SIC (masked) CDRs, 2001-2004. The baseline is the SIC extent values.

The seasonal pattern in sea-ice extent differences after 1991, may be explained by differences in how the retrieval methods and processing chains of the SITy_L3 and SIC CDRs interpret and manage changes to sea-ice surface conditions throughout the year. For most years, the largest inconsistencies in sea-ice extents tend to occur during the late summer, when melt ponds, surface water, and unconsolidated ice are prevalent features. As discussed in Meier *et al*. (2015), these characteristics pose challenges to the passive microwave retrieval of sea-ice concentration, as they can alter the microwave emission of the surface to appear more like open water (Eppler *et al*., 1992). This can result in an underestimation of sea-ice concentration (Ivanova et al., 2015; Kern *et al.*, 2016). The pronounced differences in SITy_L3 and SIC extents during the late summer, suggests that the two CDRs vary in their sensitivity to surface melting, which in turn, has an impact on the relative estimates of sea-ice concentration and extent.

Spatial distribution of sea-ice extent

Sea-ice extent estimates were compared using the quarterly divisions noted in Section 2.3, to consider how the differences in SITy_L3 and masked SIC extents vary spatially.

Annual-averaged sea-ice extent time series for each quarter are presented in Figure 11. Overall, the SITy_L3 and the SIC extents show strong agreement in their extent values, across all four spatial divisions. The temporal variability associated with changes to the satellite sensors are apparent in all regions. Prior to 1992, the extent trends are more variable and inconsistent, and the SITy_L3 and SIC extent values are generally lower and less compatible throughout the year. After 1991, the records exhibit similar temporal trends, with clear seasonal signatures and consistent interannual variability.

The time series for March and September show similar temporal patterns in extent agreement for all four divisions (Figure 12). Similarly to the distributions shown in Figure 8, the variability and inconsistency between the data records before 1992 are much more significant in March, than September. This is more apparent in the Russian and Atlantic segments (Figure 12b and c).

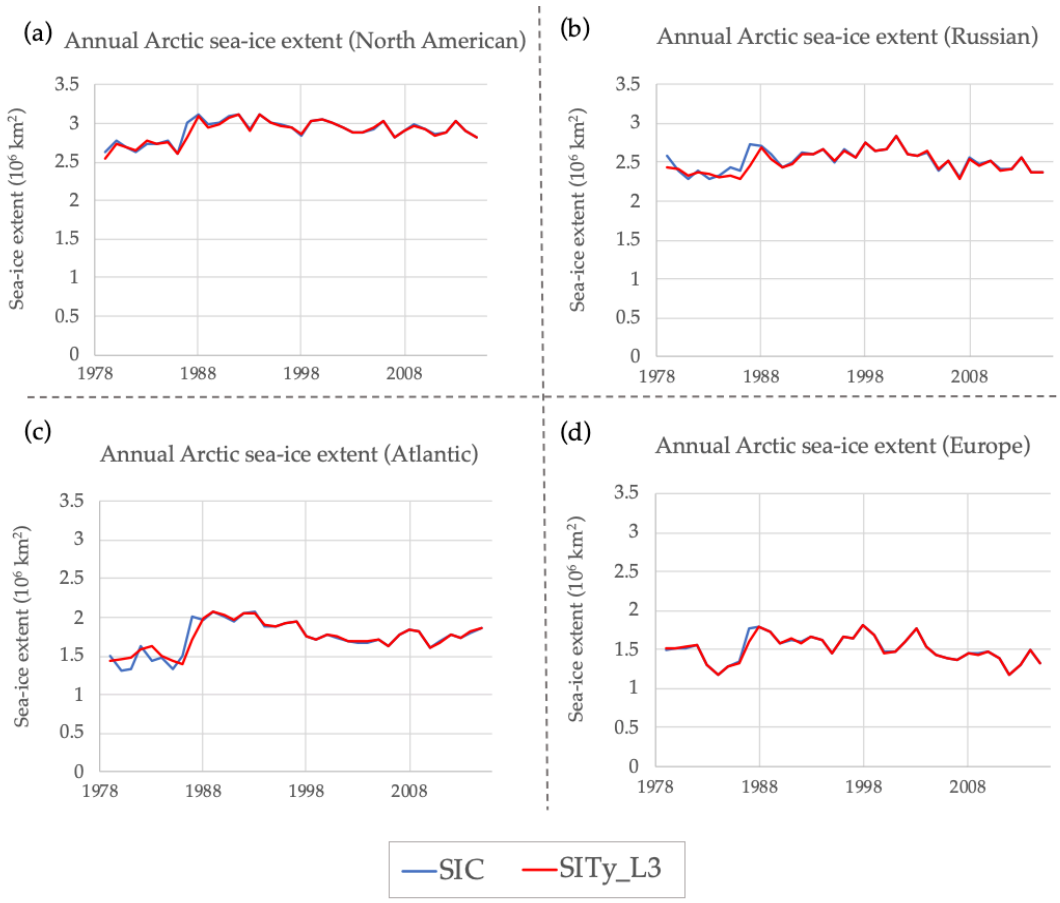


Figure 11: Regional average annual SIC and SITy_L3 sea-ice extent time series for: (a) North American, (b) Russian, (c) Atlantic, (d) European divisions, 1979-2015.

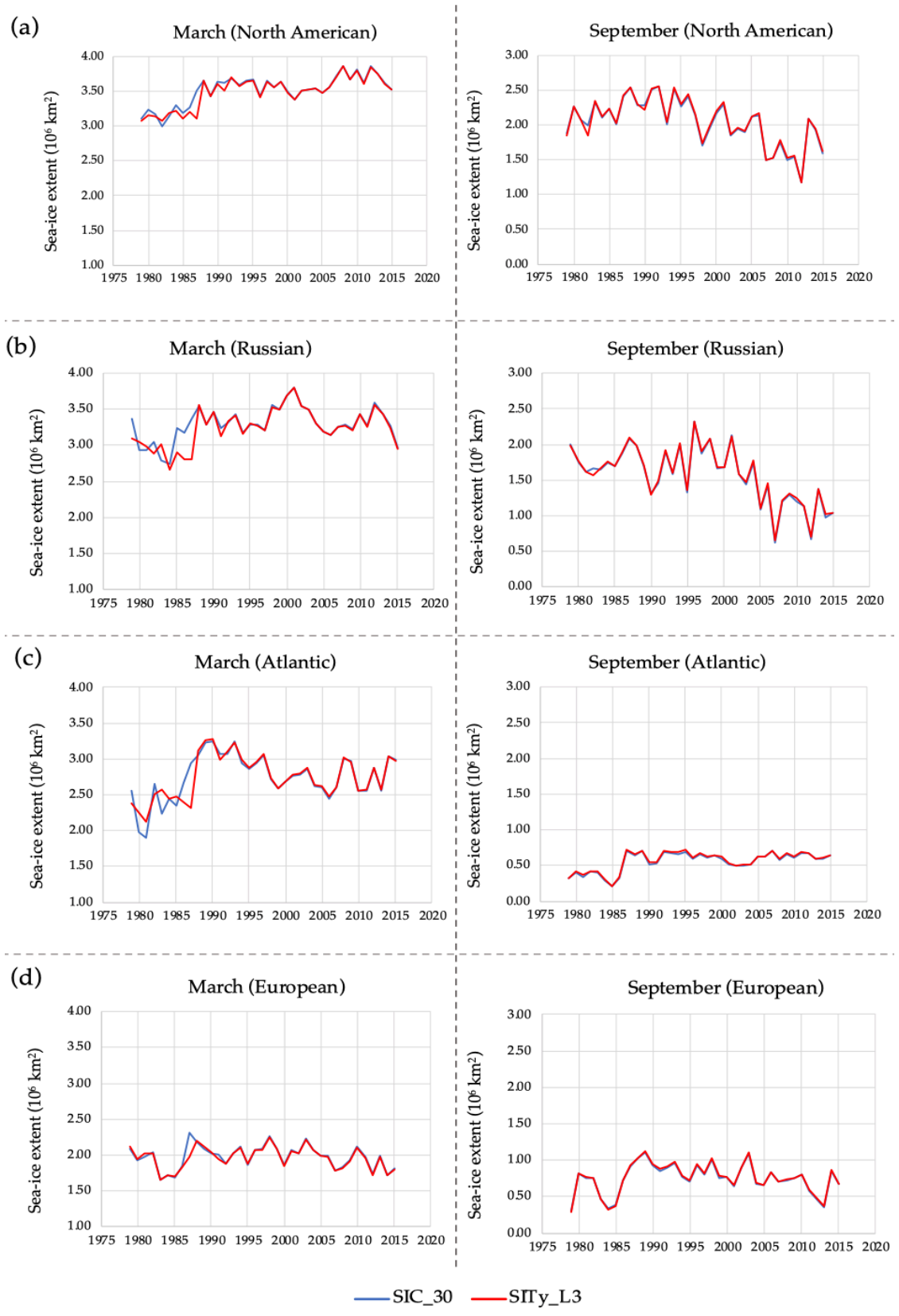


Figure 12: March and September SIC and SITy_L3 sea-ice extent time series for: (a) North American, (b) Russian, (c) Atlantic, and (d) European divisions, 1979-2015.

The differences in extent values for each quarter show a similar temporal pattern to that of the pan-Arctic scale comparison (Figure 13). In each instance, the differences in SITy_L3 and SIC extents are more significant and variable before 1992, after which, they become more

aligned and exhibit an apparent seasonal expression. Excluding the years before 1991, when SITy_L3 extents are noticeably different to the SIC, the inter-record extent differences are consistently below ~0.13 x 10^6 km^2 and average at ~0.01 x 10^6 km^2 (<1%) across all divisions.

In addition to these general patterns, the pronounced difference in extents for winter/spring 1987 features prominently in each of the time series, whereby the SITy_L3 yields considerably lower extents than the SIC.

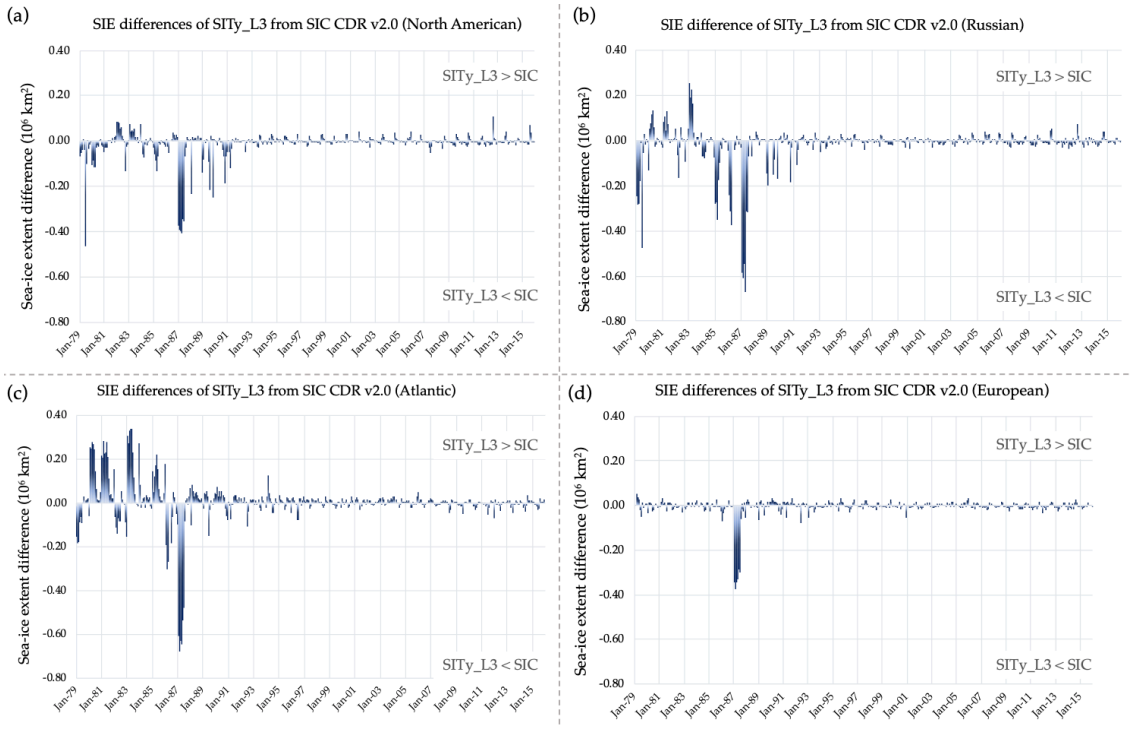


Figure 13: Sea-ice extent differences between the SITy_L3 and the SIC (masked) CDRs, 1979-2015, for: (a) North American, (b) Russian, (c) Atlantic, and (d) European divisions. The baseline is the SIC extent values.

Although mostly similar, there is some spatial variability in the agreement between the SITy_L3 and SIC extents. The European division exhibits the highest similarities in extent values across the time series; except for the spring/summer 1987, the differences remain within ~ 0.08 x 10^6 km^2 (~ 5%) and average at less than ~0.01 x 10^6 km^2 (< 1%) (Figure 13d). With a few exceptions towards the latter end of the time series, the Russian, North American, and Atlantic divisions yield similar agreement to the European division after 1991 (Figure 13a-c). However, the differences in these divisions are more significant and variable throughout the earlier SMMR and SSM/I F8 operating periods, particularly in the late spring and early summer months. The inter-record disagreement exhibited prior to 1991 is most pronounced in the Atlantic division. As shown by Figure 13c, for a large part of the SMMR period, SITy_L3 extents in the Atlantic division differ substantially to those calculated from the SIC, with differences of up to ~ 0.68 x 10^6 km^2 (~ 23%).

The pronounced disagreement in the Atlantic division during the SMMR and SSM/I F8 periods may be explained by the presence of relatively low sea-ice concentrations in the Greenland and Labrador seas, as well as the proximity to extensive areas of open water (see

Ivanova *et al*., 2014). Passive microwave retrievals over regions of low sea-ice concentrations are subject to greater amounts of atmospheric interference than regions with more consolidated sea ice, which may explain the spatial variability in the sea-ice extent estimates. The extension of sea ice throughout the Canadian Archipelago and along the eastern and western flanks of Greenland, gives rise to a significant amount of coastal ice and a large ice margin in the Atlantic division. These features increase the variability of surface Tb signatures, which in turn, can impede the accurate detection of surface conditions using passive microwave data. With these phenomena in mind, the pronounced inter-record differences in the Atlantic division and during the spring/summer months are likely attributable to the differences in how the SITy_L3 and SIC retrieval methods interpret and manage variations in surface and atmospheric emissivity.

3.2 Comparison 2

3.2.1 Comparison of SIC and SITy_L4 sea-ice extent using consistent masks

Temporal consistency in the methods of data retrieval and processing is an essential characteristic of climate data records. As well as providing a dependable dataset to analyse sea-ice variability in recent decades, a reliable and consistent long-term data record is essential to the assessments of historical and future change (Kern *et al*., 2019). However, as shown in the previous comparison, the significant change in the total area of SITy_L3 masked data between pre- and post- 1987, results in substantial inconsistencies in the long-term data records of sea-ice extent.

The SITy C3S CDR L4 (SITy L4) represents an updated version of the SITy data record. While the SITy_L4 record maintains the same retrieval methods and data processing techniques as the SITy_L3, a vital element of the update is the use of interpolation methods to fill in the gaps of missing data. In the SITy L4 record, the total area of unclassified or masked data is reduced to a consistent area of 61.29×10^6 km^2 throughout the full time series (Figure 14). The use of spatial and temporal interpolation effectively increases the total area of the ocean surface that is included in the computations of sea-ice concentration and surface type classification. As Figure 14 shows, the effect of reducing the area of unclassified data is most notable during the SMMR period.

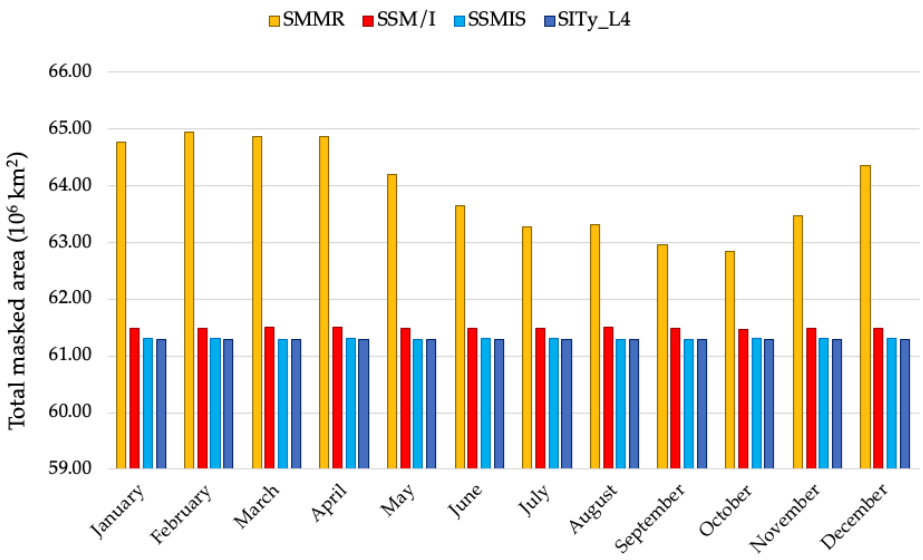


Figure 14: Comparison of the total masked area between SITy_L3 and SITy_L4 data files. The figures for the SMMR, SSM/I, and SSMIS operating periods are representative samples of SITy_L3 data files from 1984, 2002, and 2015, respectively.

To examine how the use of interpolation methods affects the long-term sea-ice extent trends, the SITy_L4 is compared against the SIC CDR. To ensure consistency in the total area considered, monthly sea-ice extent values were re-calculated from the daily SIC data files, using the masked arrays from the corresponding SITy_L4 data files.

Pan-Arctic scale

With the application of consistent masks, the SIC and SITy_L4 records show strong agreement in extents across the period of 1979-2015 (Figure 15). The long-term trends, the timing of the seasonal maximum and minimum sea-ice cover, and interannual variability are consistent between datasets (Figure 15a). In contrast to the SITy_L3 and SIC comparison, the significantly lower extents before 1987 are no longer apparent in either data series. This further confirms that the earlier temporal shift in extent variability experienced in both records after 1987 (Figure 7), is attributable to differences in the total area of masked and unclassified data. From 1987 onwards, the SITy L4 record yields very similar extents to the SITy_L3, due to the similarities in the total area of masked data.

The improved consistency and agreement are apparent for both seasons, as shown by the average March and September sea-ice extent trends (Figure 16). The time series for each month show similar agreement in extent differences, plots of which are provided in Appendix C.

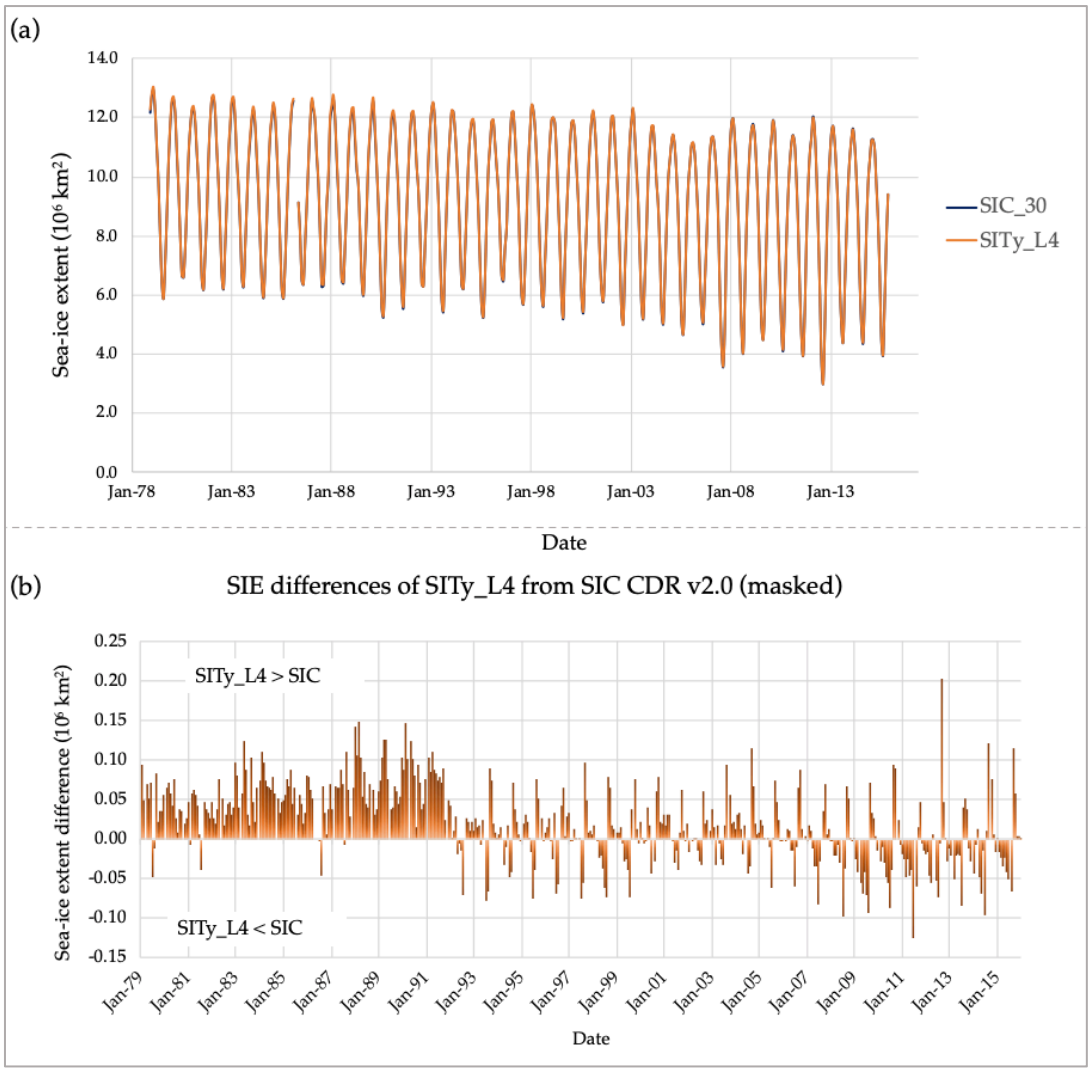


Figure 15: (a) Monthly-averaged sea-ice extent time series from the SITy_L4 and SIC (masked) CDRs, 1979-2015; (b) sea-ice extent difference (SIC – SITy_L4).

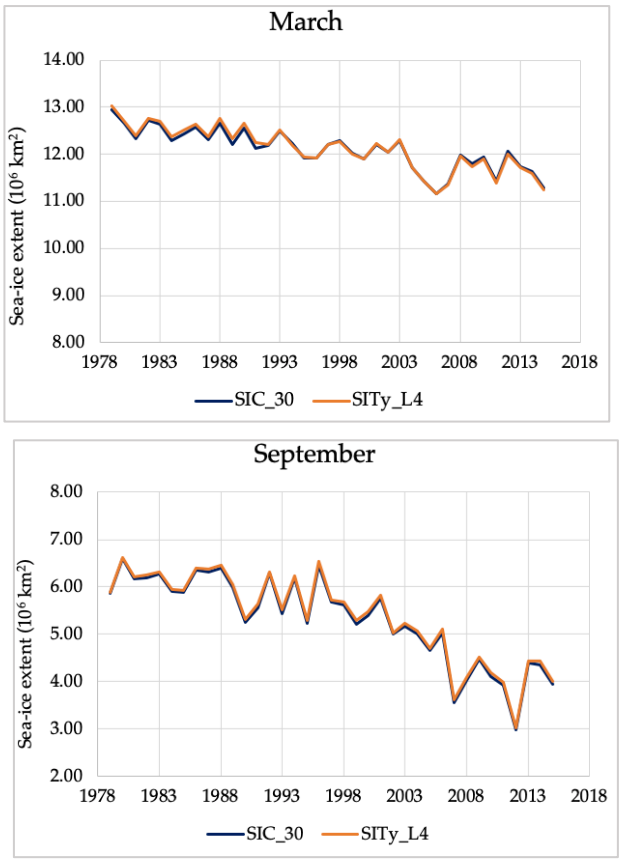


Figure 16: SITy_L4 and SIC monthly-averaged sea-ice extent time series for March and September, 1979-2015.

The differences between the two datasets are marginal across the time series (Figure 15b). With the exception of August 2012, when the SITy_L4 extent is ~0.2 x 10^6 km^2 (~5.5%) higher than the SIC, the extent differences are consistently less than ~0.15 x 10^6 km^2 (~3%) and average at below ~0.04 x 10^6 km^2 (<0.5%). Yet, despite the increasing temporal consistency of sea-ice extent values for both CDRs, as well as a reduction in their differences, a clear change in the long-term pattern remains apparent after 1991. For the majority of the SMMR and the SSM/I-F8 operating times, the SITy_L4 yields higher sea-ice extent values than the SIC CDR. The differences in this earlier period vary over seasonal and interannual timescales, with the largest differences typically occurring in the late summer (August and September). Following the transition to the SSM/I-F10 in 1991, the extent differences begin displaying the same seasonal cyclicity as discussed in Section 3.1.2 (Figure 9), whereby the SITy extents fluctuate above and below the SIC, depending on the time of year. Changes to the frequency channels available between sensors, as well as inconsistencies in the channels used by the CDRs, is the primary cause of this shift in the temporal pattern of extent differences.

In addition to the change around 1991, the differences in extent values appear to increase slightly towards the latter end of the time series. This evident for both positive and negative differences. Similarly to the earlier transition, this variability could be explained by differences in retrieval channels between the SSM/I and the SSMIS sensor, following the changeover in 2005 (Table 1). Changes in the surface characteristics and seasonal regimes of

the sea ice over time could also be affecting the relative detection of sea-ice concentration between the data records. The declining trends in sea-ice concentration and extent measured over the modern satellite record, have been accompanied by a reduction in sea-ice thickness and volume (Kwok and Rothrock, 2009; Kwok 2018;), as well as an increase in the length of the summer melt season (Markus et al., 2009). These changes are likely to be increasing the variability in the measured Tb signatures, which in turn, alters the interpretation of surface characteristics between the different input data and processing chains of the SIC and SITy CDRs.

Spatial distribution of sea-ice extent

Annual-averaged SITy_L4 and SIC sea-ice extents for the Russian, North American, Atlantic, and European divisions are displayed in Figure 17. Following the application of revised data masks, the divisions show an increase in the agreement between the two datasets across the full period, and the step-change in the trends after 1987 is no longer apparent. The improved temporal consistency and agreement in the datasets are also apparent in time series for March and September (Appendix D).

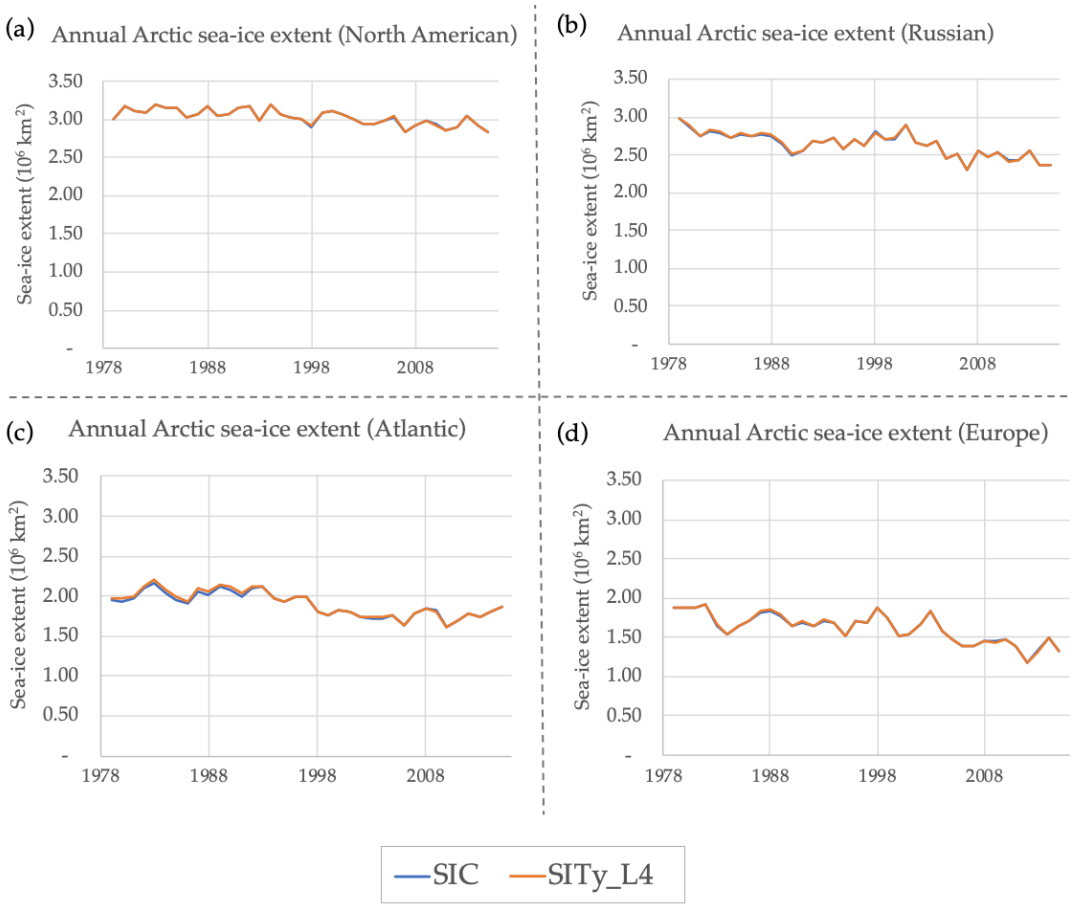


Figure 17: Regional average annual SIC and SITy_L4 sea-ice extent time series for: (a) North American, (b) Russian, (c) Atlantic, (d) European divisions, 1979-2015.

The differences in the extent values for each division are displayed in Figure 18. Similarly to the pan-Arctic scale comparison, the temporal shift in extent differences following the

transition to the SMM/I-F10 sensor in 1991, is apparent in each division. However, across all divisions, the variability and severity in the extent differences prior to 1991 have reduced significantly following the update to the SITy data record. From 1991 onwards, the extent differences correlate strongly with the plots for the SIC and SITy_L3 comparisons (Figure 13).

For the majority of the time series, the divergence in the CDRs is minimal. The variability in sea-ice extent differences after 1991, is relatively consistent for the European division, with the SITy_L4 extents fluctuating above and below those of the SIC, in line with the seasonal pattern discussed in Section 3.1.2. In the Russian and North American divisions, the differences begin to increase towards the latter end of the time series, particularly during the late summer. Given the greater quantity of sea ice present in these regions, in comparison to the European and Atlantic divisions, it is likely that these divisions are contributing most to the increase in extent differences visible on a pan-Arctic scale.

The greatest differences between the CDRs continue to occur in the Atlantic division. Here, the variability during the operating times of the SMMR and SMM/I F08 sensors is more severe than the other three divisions, with the SITy_L4 extents exceeding those of the SIC by up to ~8.5%. After the transition to the F10 sensor in 1991, the Atlantic assumes the same seasonal pattern as the other three divisions. However, the differences between the CDRs are marginally more significant throughout. The potential reasons for this are noted in Section 3.1.2.

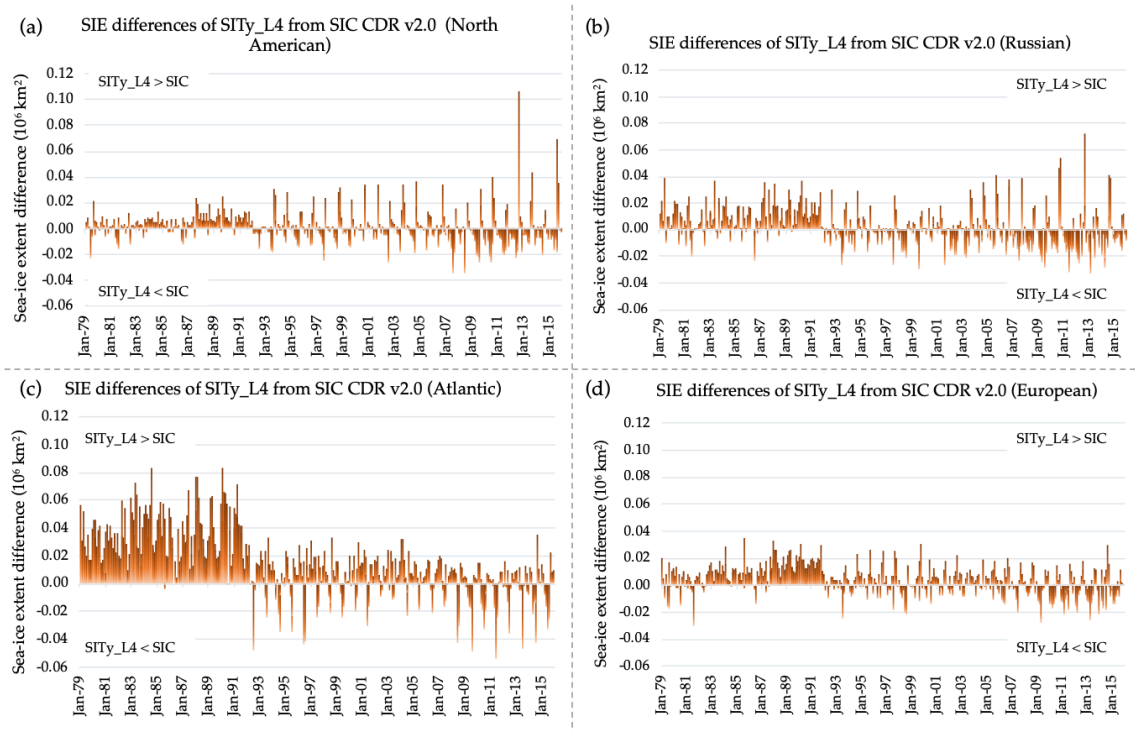


Figure 18: Sea-ice extent differences between the SITy_L3 and the SIC (masked) CDRs, 1979-2015, for: (a) North American, (b) Russian, (c) Atlantic, and (d) European divisions. The baseline is the SIC extent values.

3.3. Comparison 3

3.3.1. Comparison of SIE_L4 and SITy_L4 sea-ice extent

The SIE CDR is a higher spatial resolution data record than the SITy and SIC CDRs (12 km grid resolution as opposed to 25 km). To investigate the effect of spatial resolution on sea-ice extent estimates, the SIE_L4 is compared against the SITy_L4 CDR. As the two records use the same data processing chains and retrieval methods, the inconsistencies arising in the sea-ice extent calculations must originate in the different resolutions to which the data is gridded.

Pan-Arctic scale

The difference in the grid resolution between the SITy_L4 CDR and the SIE_L4 CDR has a significant impact on estimates of sea-ice extent (Figure 19). While the records show similar long-term trends and regular seasonal and interannual variability, the coarser resolution of the SITy_L4 consistently yields significantly lower extent values than the SIE_L4. This indicates two significant inconsistencies between the records: firstly, that that total surface area classified as open water differs; and secondly, that the position of the ice-edge at the 30% sea-ice concentration threshold varies. These inter-record differences are evident in both seasons but are more significant during the winter (Figure 19b).

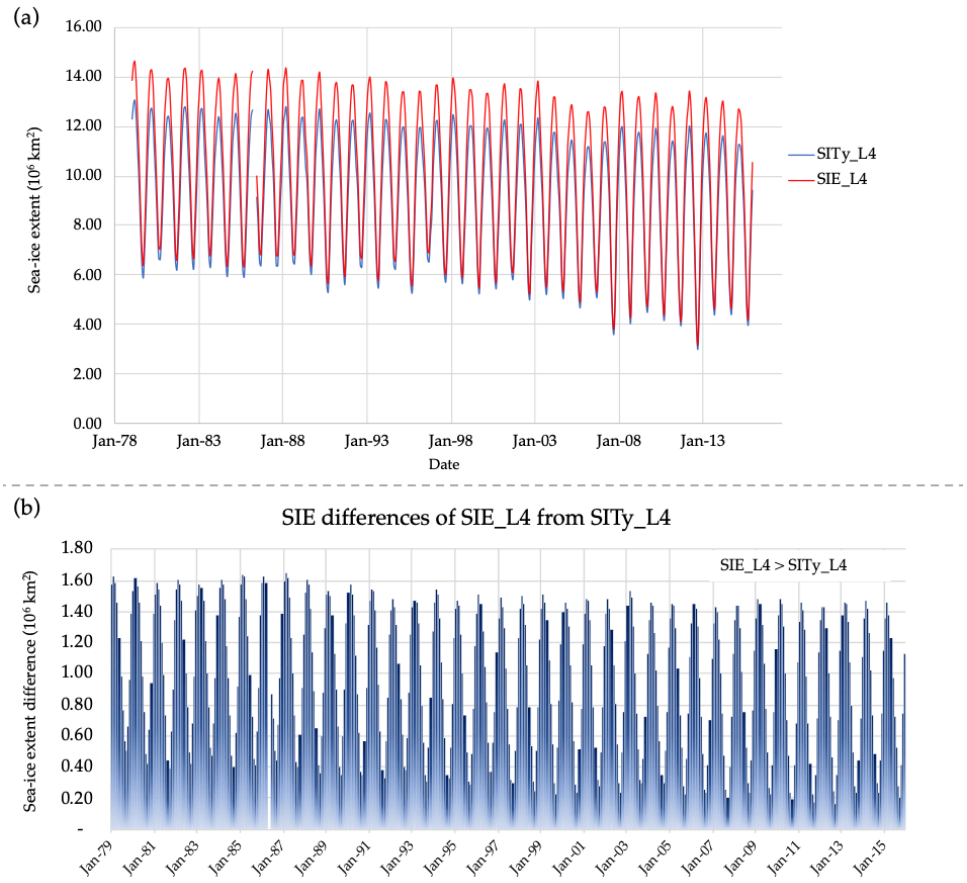


Figure 19: (a) Monthly-averaged sea-ice extent time series from the SITy_L4 and SIE_L4 CDRs, 1979-2015; (b) sea-ice extent difference (SITy_L4 – SIE_L4).

The seasonal variability in the differences is more apparent upon viewing the monthly time series for September and March (Figure 20). Time series for all months are provided in Appendix E, for further reference.

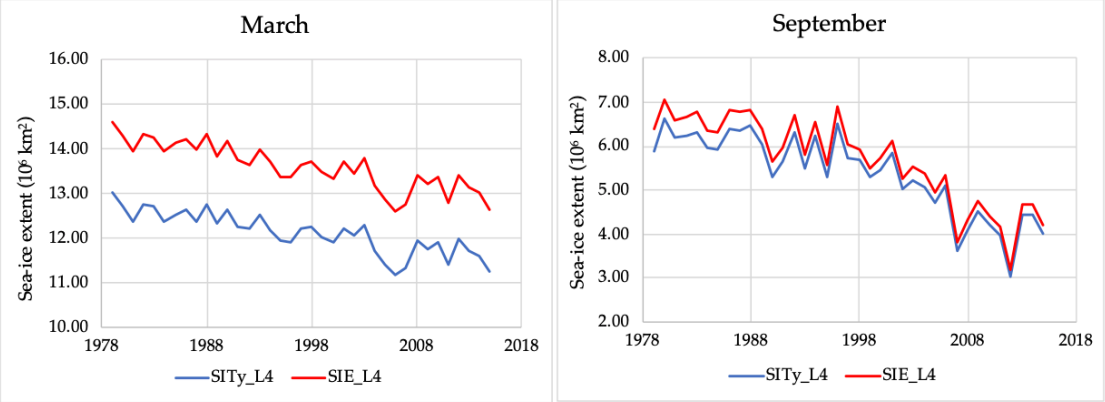


Figure 20: SITy_L4 and SIE_L4 monthly-averaged sea-ice extent time series for March and September, 1979-2015.

As Figures 19 and 20 illustrate, the inter-record differences in sea-ice extent show a relatively consistent seasonal expression throughout the time series. In each year, the differences between the datasets are least significant during the late summer, when the sea-ice retreats to its minimum extent (typically in September). During this time, the SIE_L4 extents are, on average ~0.3 x 10^6 km^2 (~5.5%) larger than the SITy_L4. The inter-record differences gradually increase throughout the autumn and winter, before reaching their peak in March when the SIE_L4 extents are, on average, ~1.5 x 10^6 km^2 (~12%) larger than the SITy_L4.

The pronounced winter differences indicate that the CDRs are least compatible when the sea-ice cover is more extensive. These differences may be attributable to relative amount of detail that can be captured by the two data records, particularly in areas around the coastline and along the ice-margin. The higher resolution of the SIE_L4 dataset is more effective at resolving the surface conditions in narrower regions and small-scale openings than the SITy_L4. Consequently, the SITy_L4 is more likely to misrepresent areas of "true" ice as open water or coastline. This effect is less apparent during the summertime, as less ice is present around the coastal regions.

Spatial distribution of sea-ice extent

Across all regions, the temporal evolution of the SITy_L4 and SIE_L4 sea-ice extent trends are comparable (Figure 21). However, the SIE_L4 consistently yields higher sea-ice extent estimates, particularly in the North American and Atlantic divisions.

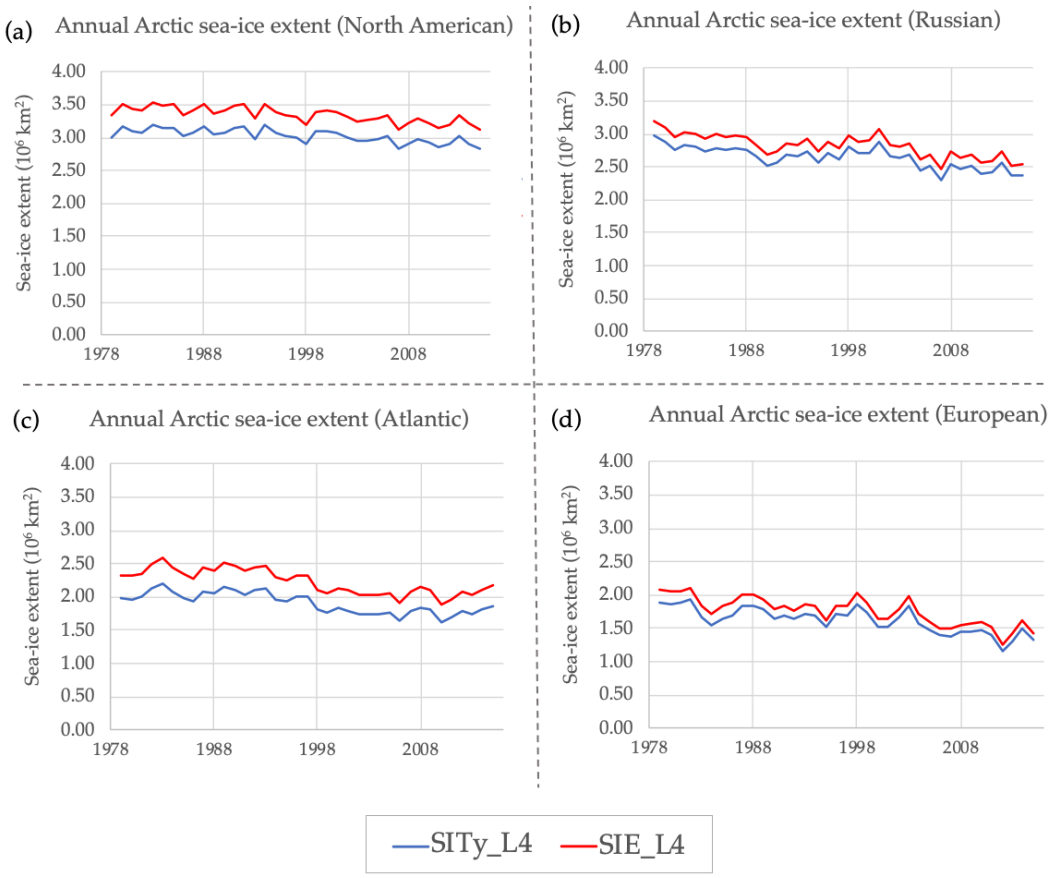


Figure 21: Regional average annual SITy_L4 and SIE_L4 sea-ice extent time series for: (a) North American, (b) Russian, (c) Atlantic, (d) European divisions, 1979-2015.

The time series for March and September confirm that the seasonal variability in the sea-ice extent differences is evident in all four divisions; however, its severity varies spatially (Figure 22 and Table 4). It is most apparent in the Russian and European divisions whereby the records differ significantly during the winter but become strongly aligned into the spring and summer months. Although present, the seasonal pattern is less evident in the Atlantic and North American divisions. Here, the CDRs show considerable incompatibility throughout the year, with average differences consistently greater than 7%.

Table 4: Average differences between the SITy_L4 and SIE_L4 sea-ice extents for September and March.

Division	Average September sea-ice extent differences (abs.)	Average September sea-ice extent differences (%)	Average March sea-ice extent differences (abs.)	Average March sea-ice extent differences (%)
North American	0.15 x 10^6 km^2	7%	0.43 x 10^6 km^2	12%
Russian	0.04 x 10^6 km^2	2.5%	0.3 x 10^6 km^2	9%
Atlantic	0.1 x 10^6 km^2	14%	0.5 x 10^6 km^2	17%
European	0.02 x 10^6 km^2	2.5%	0.25 x 10^6 km^2	12%

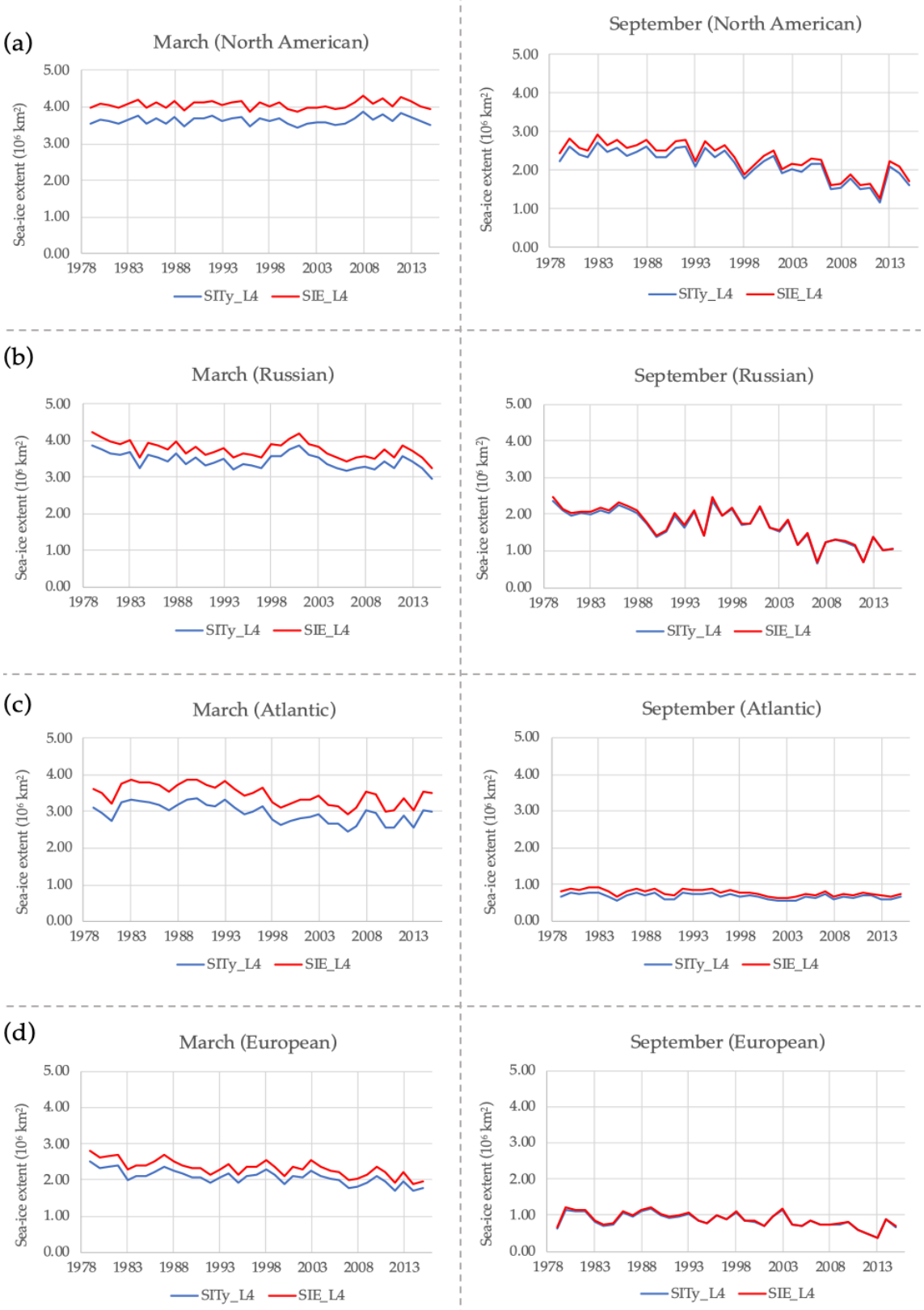


Figure 22: March and September SITy_L4 and SIE_L4 sea-ice extent time series for: (a) North American, (b) Russian, (c) Atlantic, and (d) European divisions, 1979-2015.

The changing position of the ice-margin throughout the year could explain the spatial differences in the severity of the inter-record seasonal expression. Figure 23 presents selected maps of SITy_L4 and SIE_L4 data files which illustrate how the position of the ice-margin

varies spatially between different seasonal regimes. During the winter, the four divisions are characterised by pervasive sea ice which extends along the majority of the Arctic Ocean coastlines (Figure 23a and b). The resolution differences between the CDRs means that the sea-ice conditions in small-scale features and narrow coastal areas are less likely to be captured by the SITy_L4, and more likely to be misrepresented as coastline. Therefore, the high prevalence of coastal ice is likely to be a primary cause of the inconsistencies in winter sea-ice concentration retrieval. This effect would be more pronounced in island groups such the Canadian Archipelago, offering some explanation as to why the CDRs differ more significantly in the Atlantic and North American divisions.

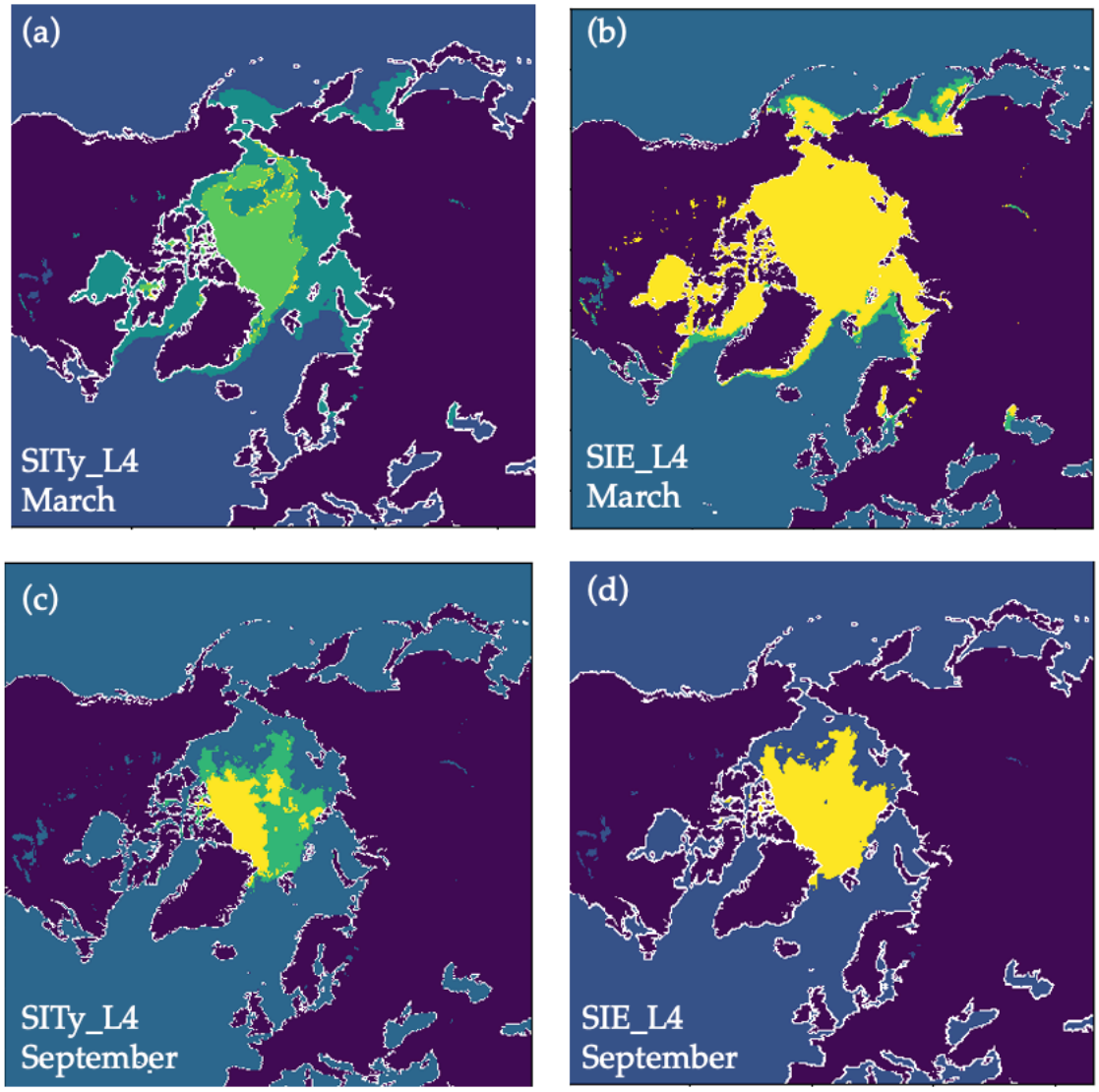


Figure 23: Representative maps of the total daily sea-ice type and sea-ice edge distributions showing the different seasonal regimes for the 1st March and 1st September 2010.

During the summer, the ice-margin retreats away from the coastline and into open water areas (Figure 23c and d). In the Russian and European divisions, where the CDRs differ more severely between March and September, the seasonal retreat of the ice-margin away from the coastline is more widespread than in the North American and Atlantic divisions. In the

latter two divisions, where the seasonal expression is least apparent, a greater amount of coastal ice persists throughout the year.

The spatial and seasonal observations indicate that the differences in the grid resolution of the SITy_L4 and SIE_L4 have a more pronounced effect on the relative accuracy of sea-ice concentration retrieval in coastal areas, as opposed to along the ice-margin. It appears as though the SIT_L4 is significantly underestimating or misrepresenting sea-ice conditions in coastal regions, which in turn, is impacting the relative estimates of sea-ice concentration and extent. However, given that the CDRs continue to differ in areas with a dominant ice-margin during the summer, it necessary to explore the differences in resolution further.

3.3.2. Comparison of SITy_L4 sea-ice extent and SIE_L4, upscaled to 25 km

The significance of the coastal discrepancies between the two CDRs undermines the ability to directly compare sea-ice concentration retrieval. Therefore, to reduce the coastal effect and allow for a more direct comparison of sea-ice concentration estimates, the SIE_L4 data set was upscaled from a 12.5 km to a 25 km grid resolution. This was achieved by duplicating each element of the SIE_L4 data files along both axes, prior to calculating daily sea-ice extent values. Once upscaled, average-monthly sea-ice extent estimates were re-calculated for the SIE_L4 CDR.

Pan-Arctic scale

The upscaled SIE_L4 sea-ice extents correlate strongly with those calculated from the SITy_L4 (Figure 24). The overall time series are very similar with consistent long-term trends, and synchronous seasonal and interannual variability. The SIE_L4 now yields lower sea-ice extent values than the SITy_L4; however, the differences between the datasets are consistently below ~0.07 x 10^6 km^2 (<1%) throughout the time series. Similarly, to the previous comparisons, the severity of the inter-record disagreement varies over the time series, corresponding with the timing of changes in the satellite input data. The most visible change occurs after 1991, following the transition to the SSM/I-F10 satellite (Figure 24b). This is likely to be a reflection of the variability in the spatial resolution of the different frequency channels associated with each satellite sensor (higher frequencies are associated with higher spatial resolution).

Furthermore, albeit very minimal, there is some seasonal variability in the differences, with the most significant disparities occurring during the winter and spring months. This marginal seasonality in the differences is also apparent when comparing the time series for March and September sea-ice extents (Figure 25).

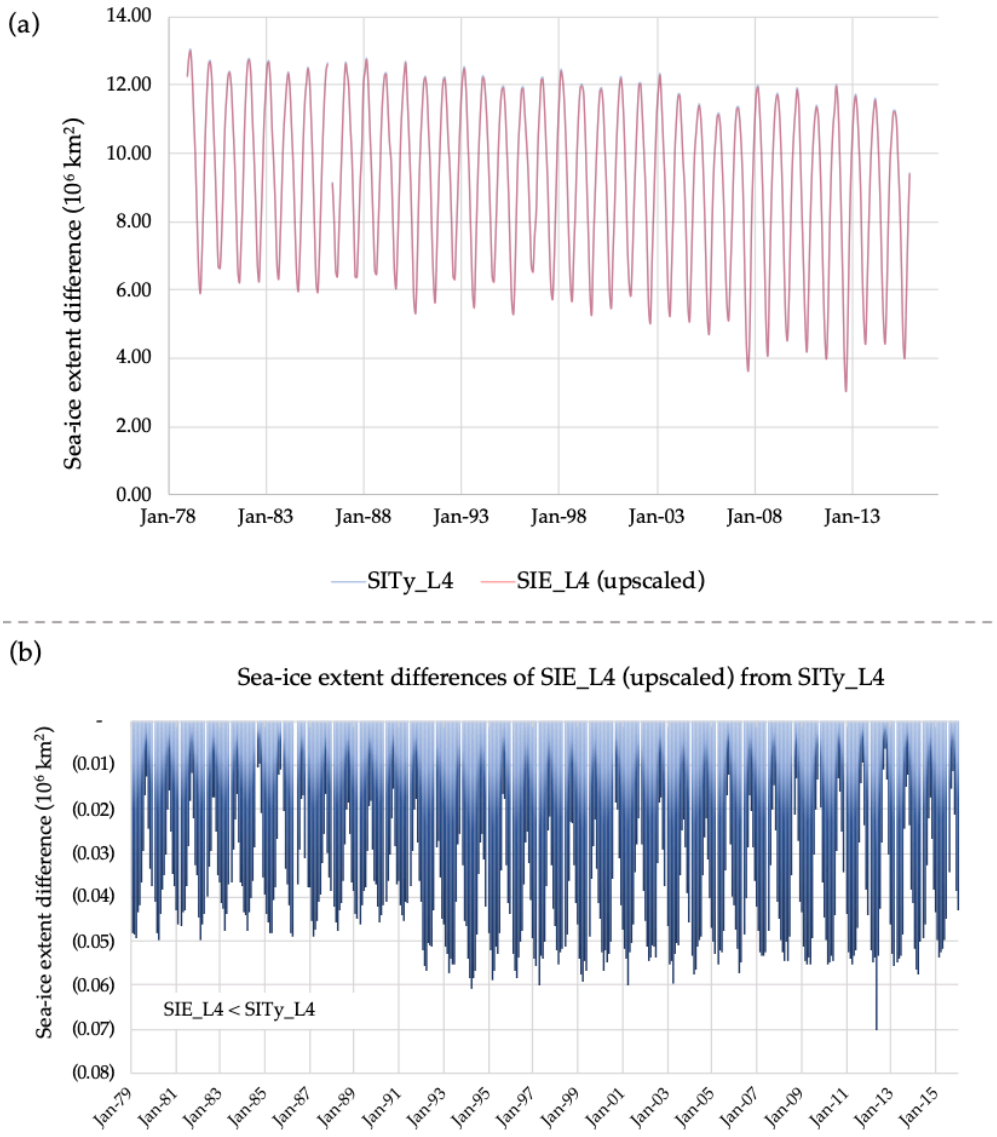


Figure 24: (a) Monthly-averaged sea-ice extent time series from the SITy_L4 and SIE_L4 (upscaled) CDRs, 1979-2015; (b) sea-ice extent difference (SITy_L4 – SIE_L4).

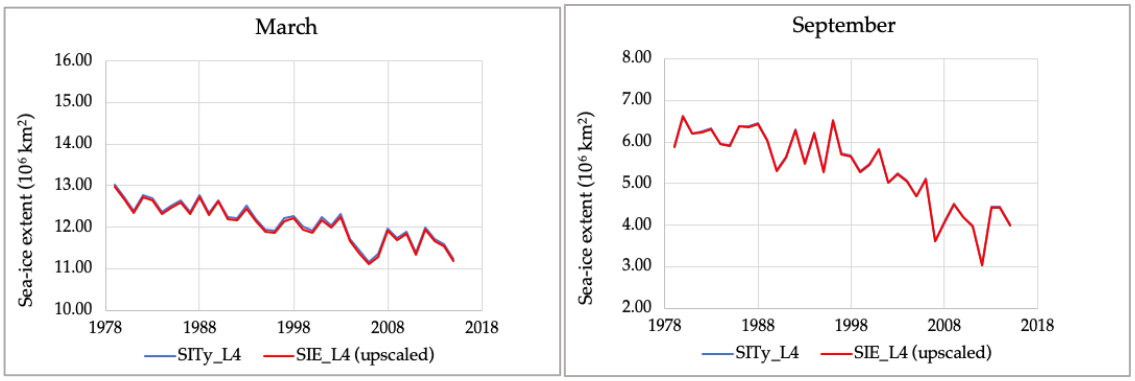


Figure 25: SITy_L4 and SIE_L4 (upscaled) monthly-averaged sea-ice extent time series for March and September, 1979-2015. Time series for all other months are provided in Appendix F, for reference.

Spatial distribution of sea-ice extent

The strong agreement between the SITy_L4 and upscaled SIE_L4 datasets is experienced across the four spatial divisions (Figure 26). As with the pan-Arctic comparison, the SIE_L4 extents are consistently lower than the SITy_L4 in all regions, and differences remain within ~0.03 x 10^6 km^2. The severity of the inter-record agreement differs spatially. The North American division exhibits the greatest consistency in sea-ice extents, with differences consistently ≤ 0.01 x 10^6 km^2 (<0.2%). The CDRs differ most substantially in the Atlantic division, where the SITy_L4 extents exceed the SIE_L4 by as much as ~0.02 x 10^6 km^2 (~0.9%).

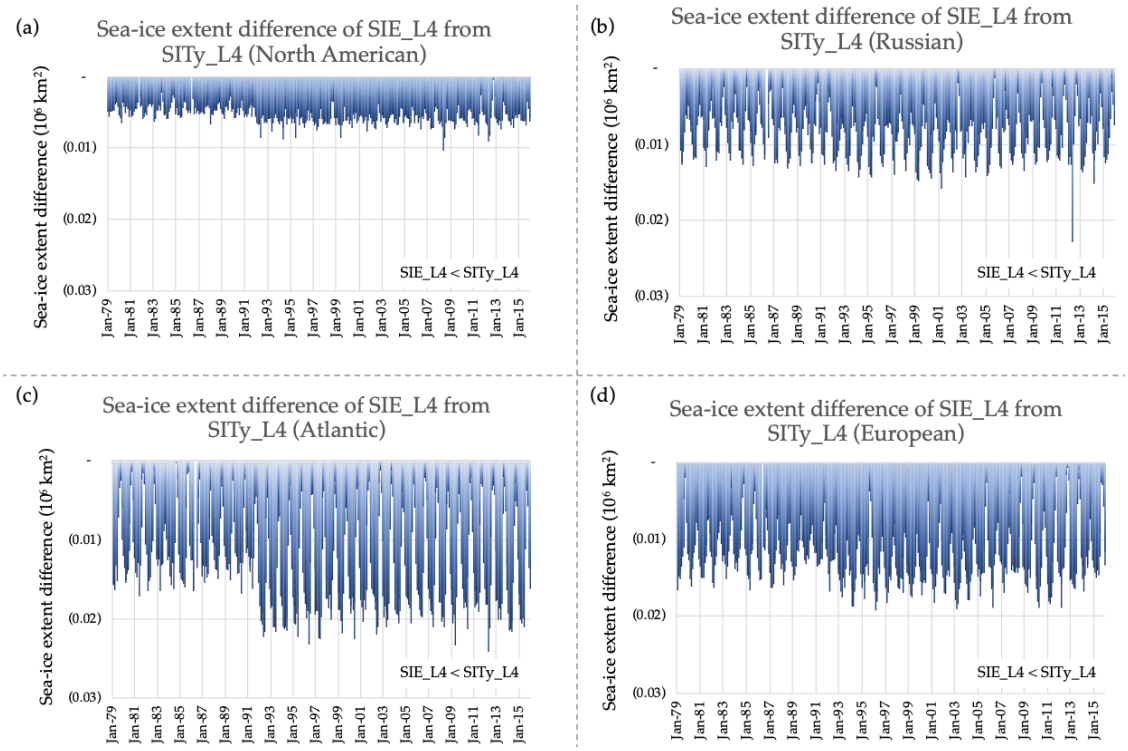


Figure 26: Sea-ice extent differences between the SITy_L4 and the SIE_L4 (upscaled) CDRs, 1979-2015, for: (a) North American, (b) Russian, (c) Atlantic, and (d) European divisions. The baseline is the SITy_L4 extent values.

The significant improvement in the extent agreement between the SITy_L4 and the upscaled SIE_L4 CDRs supports the notion that the inconsistencies in spatial resolution have a greater impact in the coastal regions, as opposed to areas where the ice-margin is situated in open water.

4. Discussion and Conclusions

This work examined how differences in the retrieval methods and processing chains affect the spatial and temporal characteristics of Arctic sea-ice extent. This was achieved through a comparison of various C3S CDRs of essential sea-ice parameters. The results presented throughout Section 3 show variable agreement in sea-ice extents between the CDRs for SIC, SITy, and SIE.

The direct comparisons of the SIC and SITy_L3 CDRs give rise to significant differences in monthly-averaged sea-ice extent estimates. Throughout the time series, the SITy_L3 yields extents that are, on average, ~2.7 x 10^6 km^2 (~23%) lower than those of the SIC. The primary cause of the inter-record differences originates from the inconsistencies in the total area of masked or missing data. This effect is more pronounced in the winter months and throughout the SMMR operating period.

The application of consistent masks significantly improves the agreement in sea-ice extent estimates between the SITy_L3 and the SIC CDRs. While some differences prevail, most of these occur between 1979 and 1991, after which, the datasets align very strongly (the differences are within 1%). This is an important finding as it confirms that the two records are consistently retrieving sea-ice concentrations at the 30% threshold, despite using different retrieval methods and processing techniques. Before 1991, however, there is notable variability between the CDRs, and the total area of masked and unclassified data in the SITy_L3 record is substantially higher. This indicates that differences in the retrieval methods during the SMMR and SSM/I F8 operating periods, have a marked impact on the detection of surface conditions in the SITy_L3 data record, and consequently, reduce its reliability as a long-term CDR. The use of higher frequency channels in the development of the SITy data record following the transition to the SSM/I F10, is a main cause of the reduction in the inter-record variability after 1991.

The revisions to the SITy and SIE CDRs following the L4 update have improved the consistency of the long-term records and reduced the variability in sea-ice concentration retrievals associated with changes to the passive microwave sensors. The comparisons between the SITy_L4 and the SIC CDRs show strong agreement throughout the time series and across the four spatial divisions, with overall differences averaging less than ~0.04 x 10^6 km^2 (<0.5%). The minor variability exhibited on seasonal and decadal scales, and the pronounced differences in the Atlantic, suggest that the SITy and SIC data records vary in their sensitivity to changing surface characteristics. While this variability is likely to be related to the different frequency channels and polarisations used in the retrieval of Tb measurements, the direct cause of this has not been established here and warrants further investigation.

Although the update to the SIT_L4 CDR significantly improves the long-term consistency of the record, it is important to note that the total area of missing or unclassified data remains significantly higher in the SITy_L4, when compared with the SIC CDR. Based on the example provided in Figure 6, the differences are in the order of ~6 x 10^6 km^2. This is a significant limitation of using the SITy CDR in comparisons of sea-ice extent, as large areas of the ocean surface are not included in the calculations.

The results of the SIE_L4 and SITy_L4 comparisons show that differences in grid resolution disproportionately impact sea-ice concentration retrieval in coastal locations. Across the Arctic, the coarser resolution of the SITy_L4 yields lower sea-ice extents than the SIE_L4, however, the differences are more pronounced during the winter months and in regions

where coastal ice is more prevalent throughout the year. Therefore, it is likely that the reduced ability of the coarser resolution SITy_L4 data record to resolve small-scale features and sea-surface conditions in narrow coastal areas is a primary cause of the differences. This is further supported by the reduction in the spatial variability following the upscaling of the SIE_L4 dataset.

In summary, this study provides an indication of how the different retrieval methods and processing chains of the OSI SAF C3S CDRs for sea-ice concentration, type, and edge affect Arctic sea-ice extent trends between 1979 and 2015. The observations show that the CDRs behave similarly across different seasonal, interannual, and decadal timescales, when consistent data masks are applied and the differences in grid resolution are accounted for. This confirms that the three records are consistently retrieving sea-ice concentrations at 30%, with some minor variability present. Further investigations are required to ascertain the causes of this variability.

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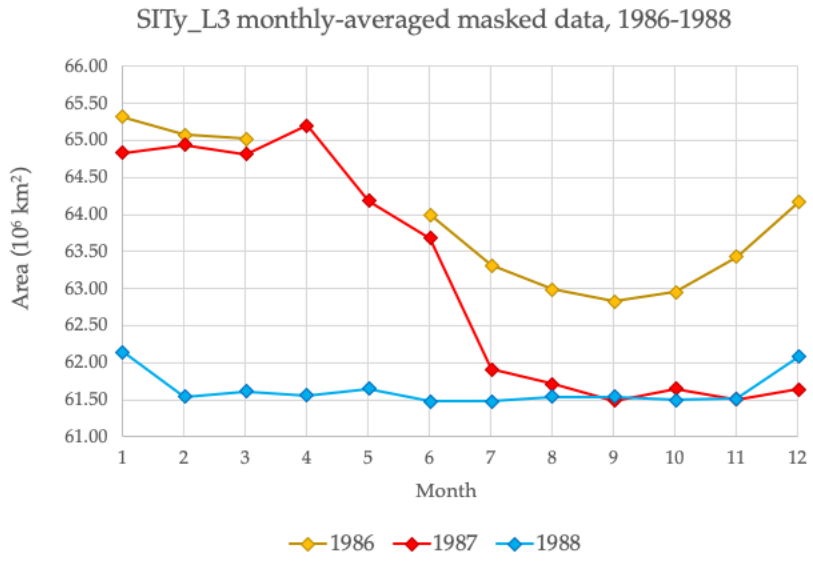
Intercomparison Report Appendices

Intercomparison Report Appendix A

Significant reduction in the average total masked area of the SITy_L3 CDR between 1986 and 1988.

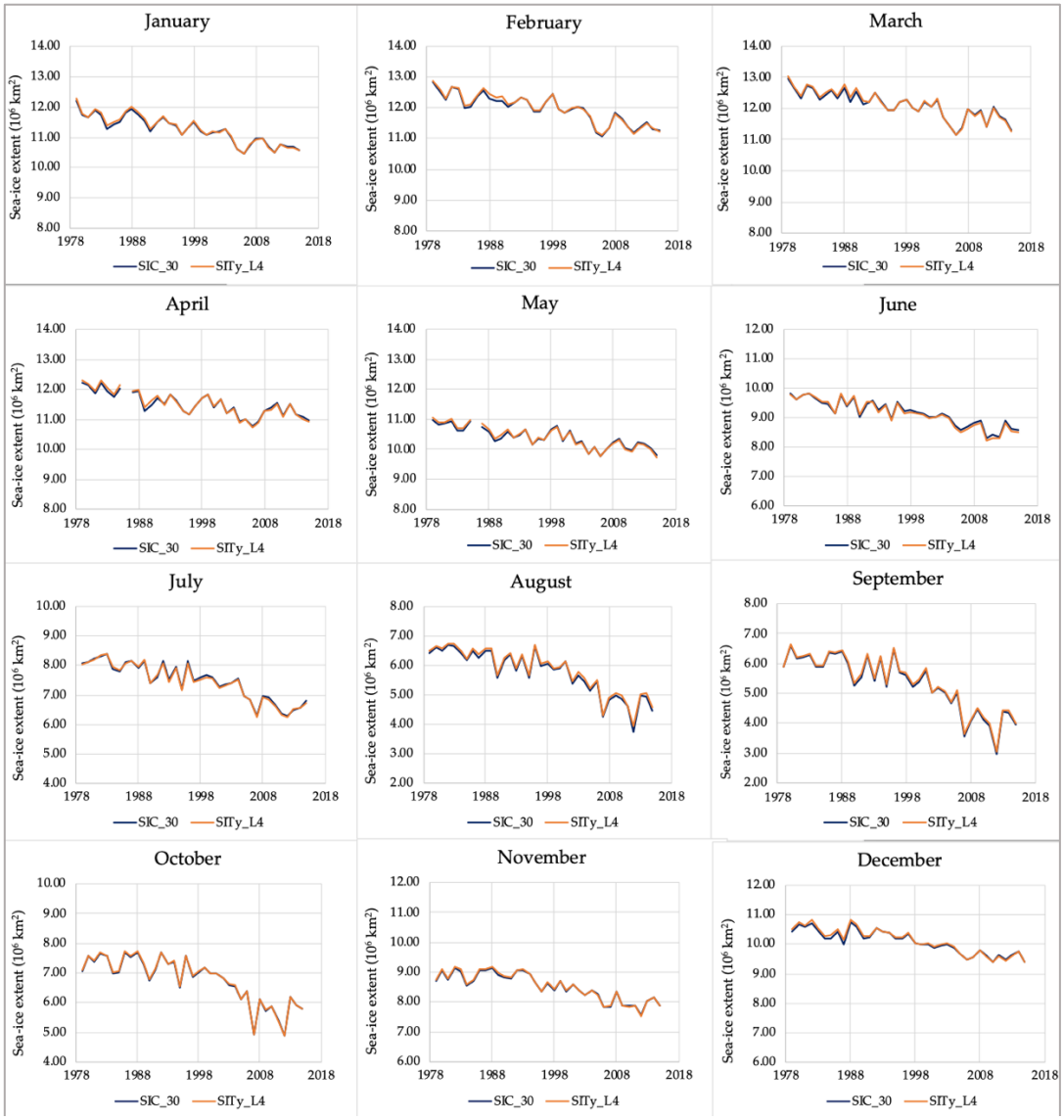


Intercomparison Report Appendix B

SITy_L3 and SIC (masked) monthly-averaged sea-ice extent time series for all months, 1979-2015.

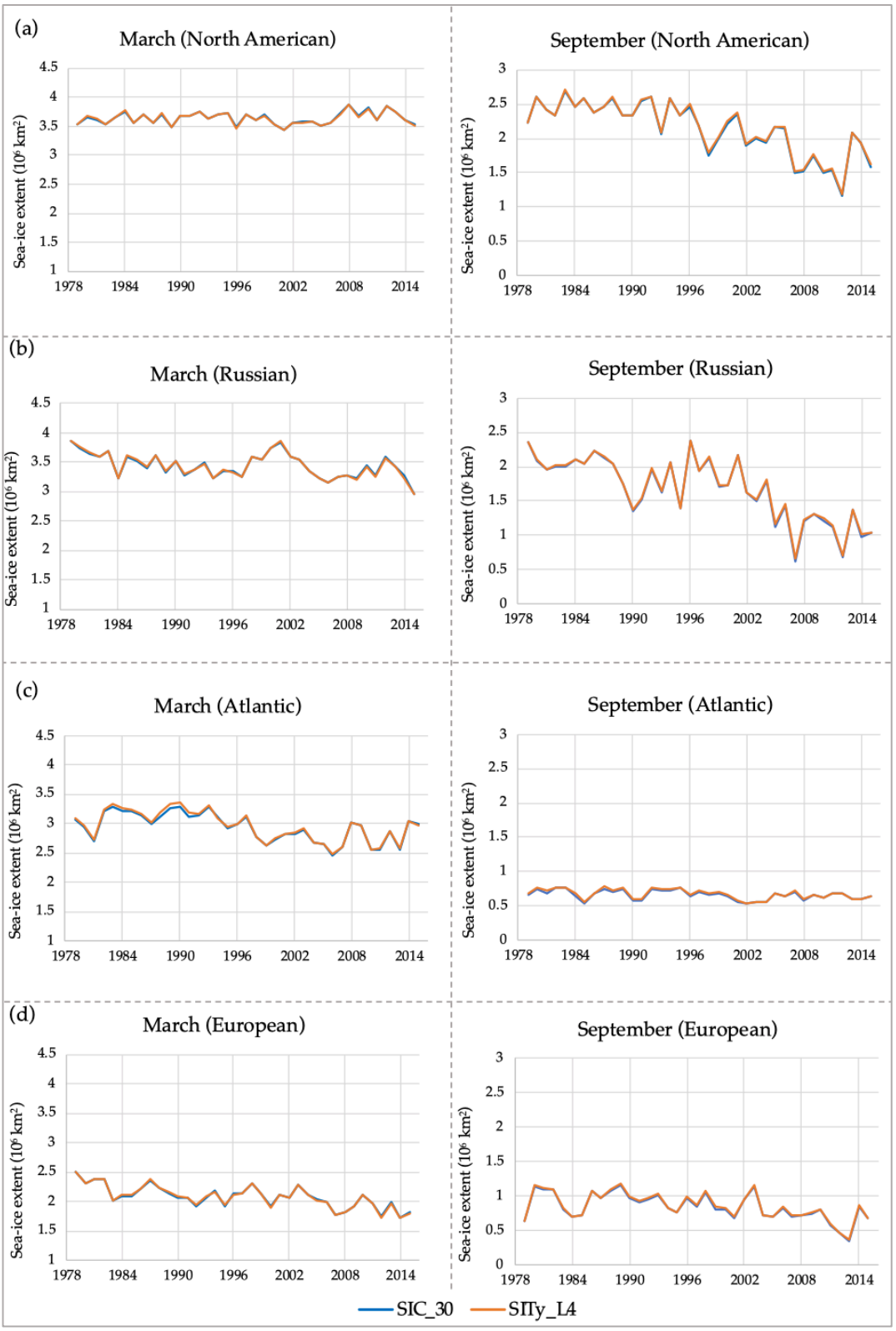
Intercomparison Report Appendix C

SITy_L4 and SIC (masked) monthly-averaged sea-ice extent time series for all months, 1979-2015.



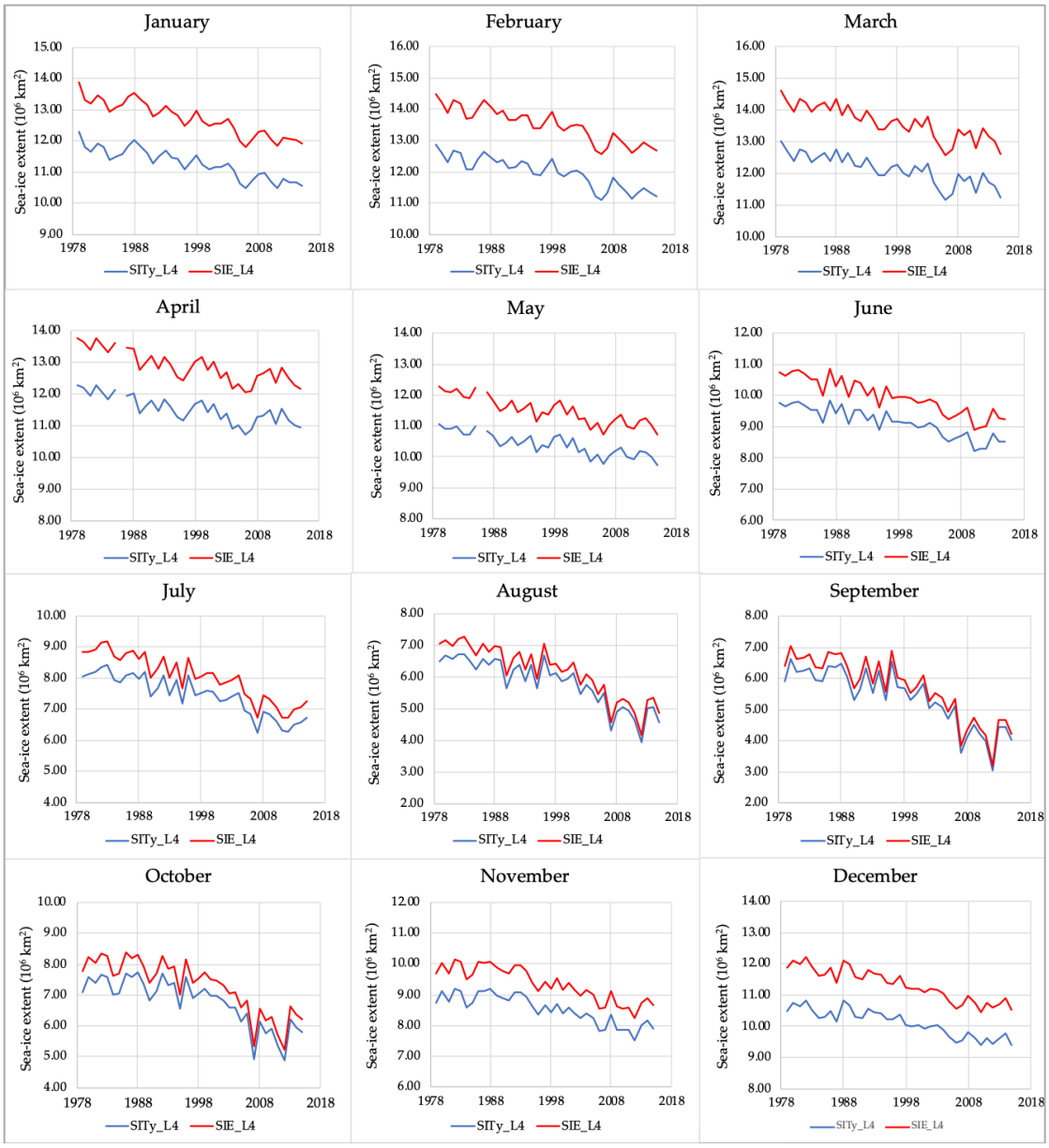
Intercomparison Report Appendix D

SITy_L4 and SIC (masked) monthly-averaged sea-ice extent time series for March and September, 1979-2015.



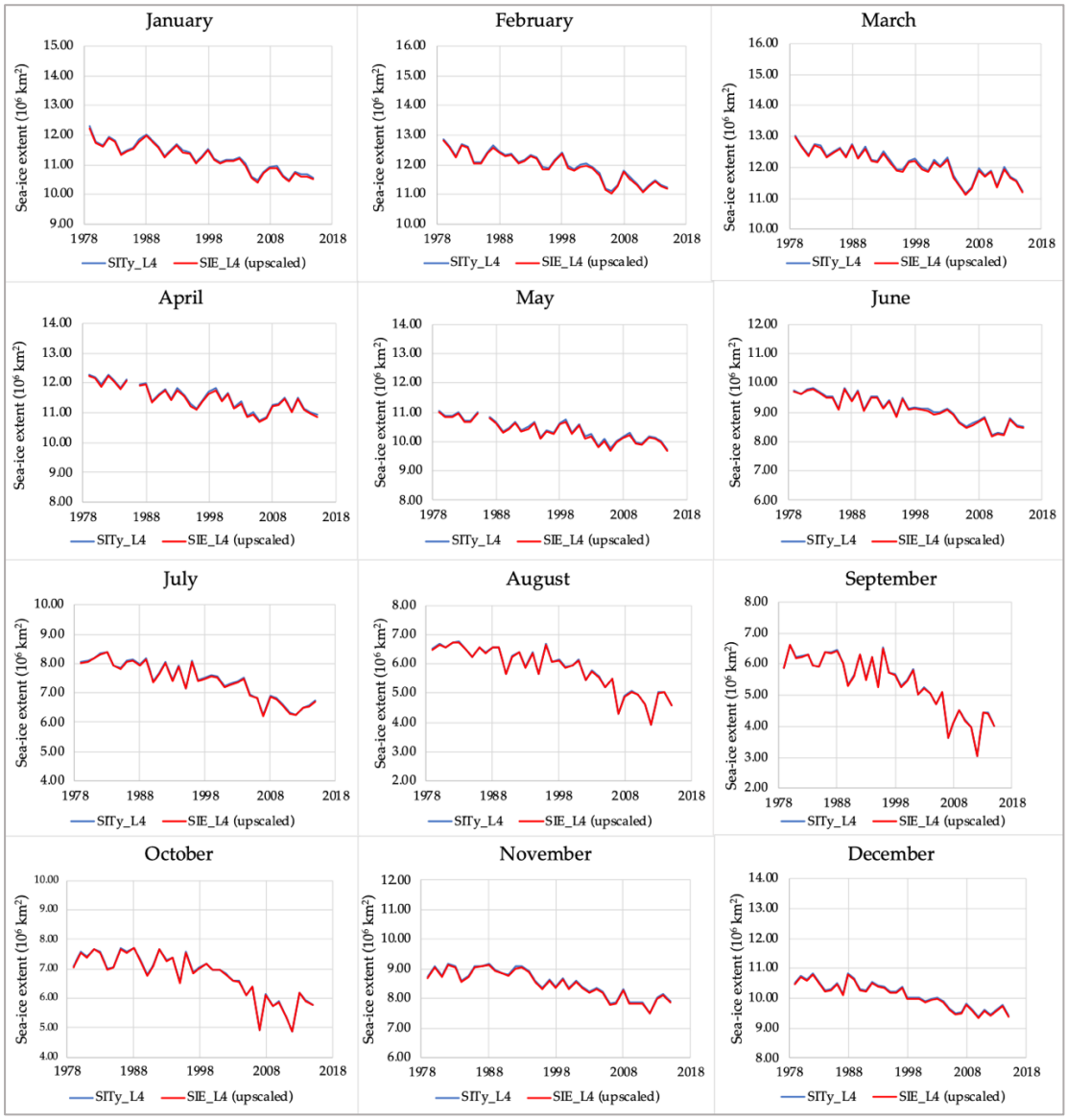
Intercomparison Report Appendix E

SITy_L4 and SIE_L4 monthly-averaged sea-ice extent time series for all months, 1979-2015.



Intercomparison Report Appendix F

SITy_L4 and SIE_L4 (upscaled) monthly-averaged sea-ice extent time series for all months, 1979-2015.



Appendix 9: Observational Questions

Data	*Documentation Method*	*Focus of Observation*
Physical setting	Observation notes, field journal	What is the physical environment of the research setting like? How is the space allocated? What resources, technologies, and objects are in the setting?
Actors	Observation notes, field journal	Who participates in sea-ice research (directly and indirectly)? What are the different roles and responsibilities, and how are they allocated? What are the required skillsets to contribute within this research setting? What is the conversational content between scientists working within the institutional settings? What is the internal organisation of this institution? How does the institute interact and collaborate with external actors and institutions? Who are they? How do scientists talk about uncertainty within the data?
Processes and interactions	Observation notes, field journal, document analysis	How do the scientists interact with each other? What are the institutional rules and ideologies that govern the scientific practice, and who enforces them? What is the institutional approach to managing and representing uncertainty? What are the relationships between the scientists and technologies? How do scientists interact with technologies, and to what degree have technological changes it changed scientific practice? To what degree are the scientific processes automated? What are the social networks between the scientists (formal and informal) and how does this influence factors such as trust, authority, and consensus building? What risks and opportunities of sea-ice decline do the scientists identify? What are the validation procedures used in data processing and reporting?
Documents	Reports, user guidelines, published papers	What is the dominant terminology and nomenclature? What recording/textual processes are involved in sea-ice reporting? Where are the documents are archived? To whom do the institutes report?

Appendix 10: Interview Questions

Some key themes that have informed the questions:

- Technical aspects of the sea-ice products
- Scientific optimisation and productivity
- Research agendas and networks
- Epistemic values: accuracy, uncertainty, and objectivity
- Communication, reporting, and accountability
- Looking to the future: technological developments and challenges

1. What is the purpose of the sea-ice data products?
- *Are they a response to a knowledge gap? Pro-active decision based on ideas about what sea-ice parameters are important? National interests? User requests?*

2. Generally, what steps are involved in the initial development of a sea-ice data product?
- *What are the underlying objectives and purposes?*
- *When were they first developed, and were you involved in the initial development of the products?*
- *What factors inform the development of the processing chains and features that are implemented in the products?*
- *How is it decided which algorithm is most suitable for a particular product?*

3. Why do the products I worked with differ in their data input and processing chains?
- *Who makes these decisions and how are they justified?*
- *To what extent are these decisions made by the individual scientist/research group?*
- *Are they influenced by the established practices of the wider sea-ice community?*

4. Who are the primary user groups of your products?
- *How do you gain an understanding of what they need from the products and ensure that their interests are being addressed?*
- *What about conflicting needs of users? How do you deal with a scenario whereby user interests may not be consistent, or perhaps conflict?*

5. What do you value the most in sea-ice monitoring/reporting: **truthfulness**, or **usefulness**?
- *Is it context dependent?*

6. What informs the design of the products?
- What about choice of projection that the data is mapped to?
- What about the focal point and orientation of landmasses?
    - *Is this the default of the processing/tools used?*
- Is the choice of colours a conscious decision? What about the omission of national borders and place names?

7. How do you validate the sea-ice data products?

8. To what extent is the processing and reporting of the products automated? If so, what steps are in place to check that the output is correct?

9. What are the main steps involved in the reporting of the data?
- *To whom do you report?*
- *What features do you report? E.g. final numerical output, details of methods…*

10. Once reported, do you have any involvement in the data applications? E.g. how it communicated to/used to inform policies; are you asked to advise once it has been disseminated?

11. What proportion of your working time is spent working on the sea-ice products, and how would you characterise that time?
- *For example, is it mostly R+D and refining of the methods?*

12. How much autonomy do you have in relation to ongoing product development?

13. Is there much collaboration with external actors and institutes (national and international)? For example, do you (actively) share data or methods?
- *If not, then why?*
- *If yes, then are there specific institutes that you collaborate with more than others?*
- *Sharing of data impacted by data protection? Ownership? Competition? Funding?*

14. There are an increasing number of studies that suggest the 15% SIC threshold is not necessarily the most representative of threshold of ice-margin conditions… How do you think this will affect MET Norway's reporting of sea-ice extent?
- What about the sea-ice community more generally?

15. Relating to that last point, when changing a method has a measurable impact on the outputs of the product, how do you go about reporting this? (e.g. the recent and ongoing update of the SIC sea-ice climatology)

16. More generally, interest in sea ice has increased significantly over the last decade or so. How has this influenced your work?
- *Have you noticed a change in research objectives?*
- *Has there been an increase in research projects pertaining to sea ice within a climate change context?*
- *Has it affected how you report on your findings e.g. caution required; outreach opportunities; modes of communication (Twitter etc)?*

17. How do you expect the launch of the CMIR satellite to affect the sea-ice community?

18. During your time as a sea-ice scientist, what are the biggest developments that have happened in relation to how sea ice is measured, processed, and reported?

19. What would you like to see become a major focus of sea-ice research?

Appendix 11: Interview Consent Form

Consent form for participation in the research project titled, "Measurement, Knowledge, and Representation of Arctic Sea Ice"

This is a PhD research project developed by Laura Seddon, a postgraduate student in the Department of Geography at Durham University, UK. For more information on the aims and purpose of the research, please refer to the information sheet provided.

The purpose of this interview is to gain a more in-depth and comprehensive understanding of the scientific practices used to acquire, process, and report sea-ice conditions in the Arctic.

This consent form is to ensure that you are aware of the purpose of your involvement in the research project and agree to the conditions of your participation. Please read through the below statements and tick the boxes to confirm your agreement.

If you have any questions, please do not hesitate to ask.

☐ I confirm that I have read through the information sheet provided and have been given the opportunity to ask questions.

☐ I understand that my participation in this project is voluntary and that I can choose to withdraw at any time I choose to do so, without reason. In such a case, the decision to withdraw will remain confidential.

☐ The questions asked are designed to invite an interesting and thought-provoking discussion. However, if at any stage I feel uncomfortable during the interview, I am free to decline a question or terminate the session without reason.

☐ The interview is to take place via video conferencing software. I agree to the use of video-/audio-recording during this interview. I understand that the recordings will be exclusively heard/seen by the researcher, and on transcription, all responses will be anonymised. Following the completion of the project, the recordings will be destroyed. I am aware that the same conditions apply to any written notes taken during the session.

☐ I am aware that the information discussed during this interview may be used to inform the researcher's PhD thesis and associated means of research dissemination, including presentations and posters at conferences, and publication of research findings in academic journals and online resources.

☐ I understand that my responses will be treated in the strictest of confidence and will be subject to standard data protection policies. All personal information collected will be treated as confidential information and remain anonymous

unless disclosure is specifically requested by the researcher, and permission is granted by the participant.

☐ I am aware that absolute anonymity may not be achievable at all times due to, for example, the nature of my involvement with a particular scientific activity or organisation. If this situation should arise, the researcher will provide details on how the information will be used to inform the research, and I will be offered the opportunity to withdraw or decline its use.

☐ I agree to take part in this interview.

Participant name	Date	Signature
Researcher name	Date	Signature

Thank you for agreeing to participate in this study. If you have any further questions relating to this research, please contact the researcher at the following email address: laura.seddon@durham.ac.uk.

Appendix 12: Sea-Ice Extent Differences

Percentage differences between the 15%, and the 30%, 50%, and 60% threshold sea-ice extents.

Difference between 15% and 30% SIC

	J	F	M	A	M	J	J	A	S	O	N	D
1979	-4%	-4%	-4%	-5%	-6%	-5%	-9%	-10%	-8%	-10%	-6%	-5%
1980	-5%	-4%	-5%	-4%	-6%	-6%	-8%	-10%	-8%	-5%	-7%	-5%
1981	-5%	-4%	-4%	-5%	-4%	-6%	-11%	-10%	-8%	-5%	-6%	-7%
1982	-5%	-5%	-5%	-5%	-5%	-6%	-10%	-10%	-8%	-7%	-6%	-5%
1983	-5%	-4%	-5%	-6%	-5%	-5%	-9%	-11%	-9%	-6%	-6%	-5%
1984	-5%	-5%	-4%	-5%	-5%	-5%	-10%	-11%	-12%	-7%	-6%	-5%
1985	-5%	-5%	-5%	-4%	-5%	-7%	-11%	-10%	-9%	-6%	-6%	-6%
1986	-5%	-5%	-5%	-5%	-5%	-5%	-9%	-10%	-8%	-7%	-4%	-5%
1987	-5%	-4%	-4%	-5%	-4%	-5%	-11%	-12%	-8%	-5%	-6%	-5%
1988		-5%	-5%	-5%	-6%	-6%	-10%	-10%	-8%	-5%	-6%	-5%
1989	-5%	-5%	-6%	-7%	-4%	-5%	-11%	-10%	-8%	-8%	-9%	-6%
1990	-6%	-5%	-5%	-6%	-6%	-8%	-13%	-10%	-9%	-10%	-6%	-6%
1991	-6%	-5%	-5%	-6%	-5%	-6%	-11%	-8%	-9%	-6%	-6%	-6%
1992	-6%	-5%	-5%	-6%	-5%	-5%	-10%	-10%	-7%	-5%	-7%	-5%
1993	-6%	-5%	-5%	-5%	-6%	-6%	-11%	-13%	-9%	-6%	-7%	-5%
1994	-5%	-4%	-5%	-6%	-6%	-5%	-10%	-11%	-8%	-8%	-6%	-6%
1995	-5%	-5%	-5%	-7%	-6%	-7%	-10%	-9%	-8%	-13%	-8%	-5%
1996	-6%	-5%	-4%	-6%	-5%	-5%	-10%	-10%	-9%	-5%	-7%	-6%
1997	-6%	-5%	-5%	-6%	-6%	-6%	-10%	-9%	-6%	-8%	-5%	-5%
1998	-5%	-4%	-5%	-5%	-5%	-7%	-8%	-11%	-9%	-6%	-5%	-7%
1999	-5%	-4%	-5%	-5%	-5%	-8%	-6%	-14%	-13%	-6%	-5%	-6%
2000	-6%	-4%	-4%	-5%	-5%	-6%	-9%	-11%	-8%	-5%	-5%	-5%
2001	-5%	-5%	-4%	-5%	-6%	-7%	-9%	-10%	-8%	-6%	-5%	-7%
2002	-6%	-4%	-5%	-5%	-5%	-6%	-12%	-10%	-10%	-7%	-8%	-6%
2003	-5%	-4%	-4%	-6%	-5%	-7%	-12%	-10%	-8%	-9%	-5%	-6%
2004	-5%	-5%	-5%	-6%	-5%	-5%	-9%	-11%	-7%	-7%	-5%	-5%
2005	-5%	-5%	-5%	-5%	-5%	-7%	-11%	-10%	-8%	-16%	-6%	-5%
2006	-6%	-5%	-5%	-5%	-6%	-7%	-11%	-10%	-10%	-7%	-6%	-6%
2007	-5%	-5%	-5%	-5%	-6%	-8%	-12%	-14%	-12%	-19%	-7%	-6%
2008	-6%	-4%	-5%	-5%	-6%	-7%	-11%	-16%	-10%	-11%	-6%	-5%
2009	-6%	-5%	-5%	-5%	-5%	-6%	-12%	-13%	-10%	-11%	-8%	-5%
2010	-5%	-5%	-4%	-5%	-7%	-7%	-10%	-13%	-12%	-11%	-5%	-6%
2011	-6%	-5%	-5%	-4%	-6%	-9%	-12%	-15%	-11%	-16%	-6%	-6%
2012	-5%	-5%	-5%	-5%	-5%	-10%	-12%	-18%	-12%	-20%	-8%	-7%
2013	-5%	-4%	-4%	-5%	-5%	-6%	-12%	-10%	-9%	-8%	-7%	-5%
2014	-6%	-5%	-4%	-6%	-5%	-8%	-11%	-12%	-10%	-16%	-6%	-5%
2015	-5%	-5%	-5%	-4%	-5%	-7%	-13%	-16%	-11%	-11%	-6%	-7%
2016	-5%	-5%	-5%	-5%	-6%	-8%	-11%	-17%	-15%	-14%	-7%	-8%
2017	-6%	-5%	-5%	-5%	-5%	-9%	-12%	-11%	-9%	-10%	-7%	-6%
2018	-6%	-5%	-5%	-5%	-5%	-6%	-13%	-11%	-11%	-16%	-7%	-5%
2019	-5%	-5%	-5%	-6%	-5%	-7%	-15%	-12%	-11%	-16%	-8%	-6%

Difference between 15% and 50% SIC

	J	F	M	A	M	J	J	A	S	O	N	D
1979	-9%	-9%	-9%	-10%	-11%	-11%	-18%	-21%	-16%	-19%	-11%	-10%
1980	-10%	-9%	-10%	-9%	-12%	-12%	-19%	-20%	-17%	-11%	-12%	-9%
1981	-10%	-10%	-8%	-10%	-9%	-13%	-23%	-23%	-17%	-14%	-12%	-13%
1982	-10%	-10%	-10%	-9%	-11%	-13%	-21%	-21%	-17%	-14%	-12%	-10%
1983	-11%	-9%	-9%	-11%	-9%	-10%	-20%	-24%	-18%	-14%	-11%	-9%
1984	-10%	-9%	-9%	-10%	-9%	-11%	-19%	-23%	-21%	-13%	-14%	-11%
1985	-11%	-11%	-11%	-8%	-10%	-14%	-24%	-19%	-18%	-13%	-13%	-11%
1986	-11%	-10%	-10%	-10%	-9%	-11%	-20%	-20%	-16%	-14%	-11%	-10%
1987	-11%	-9%	-9%	-10%	-9%	-12%	-22%	-25%	-17%	-12%	-12%	-9%
1988		-9%	-11%	-10%	-11%	-14%	-20%	-21%	-17%	-12%	-13%	-9%
1989	-11%	-11%	-12%	-12%	-8%	-11%	-22%	-22%	-17%	-18%	-14%	-10%
1990	-11%	-10%	-10%	-11%	-12%	-15%	-26%	-19%	-17%	-24%	-11%	-11%
1991	-11%	-9%	-10%	-11%	-10%	-14%	-22%	-17%	-17%	-17%	-11%	-10%
1992	-12%	-9%	-10%	-10%	-10%	-11%	-22%	-19%	-15%	-10%	-15%	-9%
1993	-11%	-10%	-9%	-12%	-11%	-14%	-24%	-26%	-18%	-13%	-13%	-11%
1994	-10%	-10%	-10%	-11%	-11%	-11%	-22%	-21%	-16%	-18%	-10%	-12%
1995	-9%	-9%	-10%	-12%	-12%	-16%	-23%	-20%	-18%	-31%	-13%	-9%
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1998	-10%	-9%	-9%	-9%	-12%	-14%	-20%	-25%	-19%	-15%	-11%	-14%
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2003	-10%	-9%	-9%	-11%	-9%	-15%	-23%	-24%	-21%	-24%	-10%	-12%
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2005	-11%	-10%	-10%	-9%	-10%	-15%	-25%	-23%	-19%	-30%	-11%	-11%
2006	-11%	-11%	-10%	-11%	-12%	-15%	-22%	-23%	-22%	-25%	-11%	-12%
2007	-10%	-9%	-11%	-10%	-11%	-20%	-27%	-32%	-25%	-33%	-13%	-12%
2008	-12%	-9%	-9%	-10%	-12%	-15%	-23%	-33%	-23%	-30%	-11%	-9%
2009	-12%	-9%	-11%	-9%	-11%	-14%	-24%	-29%	-22%	-27%	-15%	-12%
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2014	-12%	-11%	-10%	-11%	-10%	-19%	-21%	-25%	-23%	-29%	-11%	-10%
2015	-10%	-9%	-10%	-9%	-12%	-14%	-29%	-32%	-21%	-26%	-13%	-12%
2016	-11%	-10%	-10%	-10%	-12%	-16%	-25%	-38%	-31%	-24%	-14%	-18%
2017	-12%	-11%	-11%	-9%	-10%	-18%	-25%	-26%	-20%	-24%	-14%	-12%
2018	-11%	-10%	-10%	-10%	-10%	-13%	-28%	-25%	-24%	-30%	-14%	-11%
2019	-11%	-11%	-11%	-11%	-10%	-17%	-31%	-26%	-22%	-25%	-15%	-12%

Difference between 15% and 60% SIC

	J	F	M	A	M	J	J	A	S	O	N	D
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1980	-13%	-12%	-12%	-12%	-15%	-15%	-26%	-25%	-23%	-15%	-15%	-12%
1981	-13%	-13%	-10%	-12%	-11%	-18%	-30%	-30%	-21%	-19%	-15%	-16%
1982	-13%	-12%	-12%	-11%	-14%	-17%	-27%	-27%	-22%	-20%	-15%	-13%
1983	-13%	-11%	-12%	-14%	-10%	-13%	-25%	-30%	-23%	-17%	-13%	-11%
1984	-12%	-12%	-12%	-13%	-13%	-15%	-25%	-28%	-25%	-17%	-18%	-13%
1985	-14%	-14%	-14%	-10%	-13%	-18%	-31%	-24%	-22%	-18%	-18%	-13%
1986	-14%	-13%	-13%	-13%	-12%	-15%	-27%	-25%	-21%	-19%	-15%	-12%
1987	-14%	-11%	-12%	-12%	-12%	-15%	-30%	-31%	-22%	-15%	-14%	-11%
1988		-12%	-14%	-13%	-15%	-18%	-27%	-30%	-23%	-17%	-16%	-11%
1989	-14%	-15%	-15%	-15%	-10%	-16%	-28%	-28%	-23%	-23%	-16%	-12%
1990	-15%	-12%	-13%	-15%	-16%	-19%	-32%	-25%	-22%	-30%	-14%	-13%
1991	-14%	-12%	-13%	-13%	-12%	-18%	-27%	-23%	-23%	-26%	-13%	-13%
1992	-15%	-11%	-13%	-13%	-12%	-14%	-29%	-26%	-20%	-14%	-18%	-11%
1993	-14%	-13%	-12%	-14%	-14%	-19%	-33%	-35%	-24%	-19%	-16%	-13%
1994	-13%	-13%	-13%	-14%	-14%	-15%	-28%	-27%	-22%	-22%	-12%	-16%
1995	-12%	-12%	-13%	-15%	-15%	-20%	-31%	-27%	-23%	-34%	-15%	-12%
1996	-14%	-14%	-14%	-13%	-10%	-14%	-25%	-27%	-23%	-15%	-14%	-15%
1997	-15%	-13%	-15%	-12%	-15%	-19%	-28%	-24%	-19%	-22%	-12%	-13%
1998	-13%	-12%	-12%	-11%	-15%	-18%	-28%	-34%	-28%	-19%	-14%	-17%
1999	-12%	-12%	-12%	-12%	-15%	-21%	-24%	-39%	-29%	-22%	-13%	-14%
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2003	-13%	-12%	-12%	-15%	-12%	-20%	-32%	-32%	-29%	-29%	-13%	-15%
2004	-11%	-12%	-13%	-13%	-11%	-15%	-29%	-27%	-20%	-20%	-14%	-13%
2005	-13%	-13%	-14%	-11%	-13%	-20%	-32%	-33%	-24%	-35%	-14%	-14%
2006	-14%	-14%	-12%	-14%	-16%	-20%	-29%	-32%	-28%	-31%	-13%	-16%
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2010	-13%	-12%	-10%	-12%	-18%	-22%	-30%	-38%	-36%	-33%	-14%	-15%
2011	-14%	-12%	-13%	-12%	-16%	-22%	-30%	-45%	-32%	-35%	-15%	-17%
2012	-13%	-14%	-12%	-14%	-15%	-24%	-42%	-48%	-38%	-44%	-19%	-16%
2013	-15%	-12%	-12%	-12%	-14%	-21%	-29%	-33%	-28%	-29%	-16%	-13%
2014	-15%	-15%	-14%	-14%	-13%	-25%	-27%	-33%	-30%	-34%	-15%	-13%
2015	-12%	-12%	-12%	-12%	-15%	-18%	-42%	-40%	-27%	-33%	-16%	-15%
2016	-14%	-14%	-14%	-14%	-15%	-20%	-34%	-51%	-46%	-29%	-19%	-22%
2017	-15%	-15%	-14%	-11%	-13%	-23%	-32%	-38%	-28%	-32%	-18%	-16%
2018	-13%	-13%	-13%	-12%	-13%	-18%	-37%	-33%	-32%	-35%	-17%	-14%
2019	-14%	-15%	-14%	-13%	-14%	-23%	-40%	-39%	-29%	-30%	-19%	-15%

Appendix 13: Institutional Networks

A list of affiliated institutions for authors references in the OSI-450 SIC documentation (Lavergne *et al.*, 2019a, 2019b; Sørensen *et al.*, 2021):

Australia (5):
- Antarctic Climate and Ecosystems Cooperative Research Centre, University of Tasmania
- ARC Centre of Excellence for Climate System Science, University of Tasmania
- Australian Antarctic Division
- Australian Bureau of Meteorology, Centre for Australian Weather and Climate Research
- Institute for Marine and Antarctic Studies, University of Tasmania

Austria (2):
- Department of Meteorology and Geophysics, University of Vienna
- Department of Geodesy and Geoinformation, Vienna University of Technology

Belgium (1):
- Earth and Life Institute

Canada (3):
- Canadian Center for Climate Modelling and Analysis
- Department of Geography, Simon Fraser University
- Environment Canada

China (3):
- Center for Earth System Science
- Joints Center for Global Change Studies
- Key Laboratory of Research on Marine Hazards Forecasting, National Marine Environment Forecasting Center (NMEFC)

Denmark (2):
- Danish Meteorological Institute (DMI)
- Ørsted-DTU, Technical University of Denmark

Finland (1):
- Finnish Meteorological Institute

France (2):
- Collecte Localisation Satellites
- University of Brest

Germany (11):
- Alfred Wegner Institute
- Center for Climate System Analysis and Prediction
- Center for Marine and Atmospheric Research, University of Hamburg
- European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT)
- German Aerospace Centre
- German Meteorological Service
- Institute for Environmental Physics, University of Bremen
- Institute of Oceanography, Centre for Marine and Atmospheric Sciences (ZMAW), University of Hamburg
- Integrated Climate Data Centre (ICDC), University of Hamburg
- Karlsruhe Institute for Technology
- Max-Planck-Institut für Meteorologie (MPI-M), University of Hamburg

Japan (2):
- Japan Meteorological Agency
- Tokai University

Norway (3):

- MET Norway
- Nansen Environmental and Remote Sensing Center (NERSC)
- Norsk Polar Institute

Philippines (1):
- Institute of Environmental Science and Meteorology, University of Philippines

Russia (1):
- St. Petersberg Department of P. P. Shirshov Institute of Oceanology

South Korea (1):
- Korea Meteorological Administration

Spain (1):
- Barcelona Expert Center

Sweden (2):
- Department of Space Earth and Environment, Chalmers University of Technology
- Swedish Meteorological and Hydrological Institute (SMHI)

Switzerland (2):
- Department of Geography, University of Zurich
- Institute for Atmospheric and Climate Science

UK (15):
- British Antarctic Survey
- Department of Mathematics, University of Exeter
- Department of Meteorology, Reading University
- European Centre for Medium-Range Weather Forecasts (ECMWF)
- Hadley Centre, MET Office
- National Centre for Earth Observation
- National Oceanography Centre
- National Physical Laboratory
- Plymouth Marine Laboratory
- Remote Sensing Unit, University of Bristol
- Royal Meteorological Society
- School of Earth and Environment, University of Leeds
- Science and Technology Facility Council
- Department of Earth Sciences, University College London
- University of Edinburgh

USA (20):
- Aerospace Corporation
- Brigham Young University
- California Institute of Technology
- Chemical Sciences Division, NOAA Earth System Research Laboratory
- Cooperative Institute for Climate and Satellites, Earth System Science Interdisciplinary Center
- Cooperative Institute for Research in Environmental Sciences (CIRES)
- Department of Atmospheric Sciences, University of Utah
- Department of Atmospheric Sciences, University of Washington
- Department of Mathematics, University of Utah
- GSFC, NASA
- Institute of Arctic and Alpine Research, University of Colorado
- Interferometrics, Inc.
- Marine Meteorology Division, Naval Research Laboratory
- National Center for Environmental Information
- National Snow and Ice Data Center (NSIDC)
- NOAA
- Remote Sensing Systems
- Stinger Ghaffarian Technologies

- U.S. Air Force
- Wyle Science Technology and Engineering

A list of affiliated institutions for authors references in the C3S SIE and SITy documentation (Aaboe *et al.*, 2018b, 2019):

Austria (1):
- Department of Meteorology and Geophysics, University of Vienna - Austria

Canada (1):
- Environment Canada

China (1):
- Sun Yat-Sen University

Denmark (2):
- Danish Meteorological Institute (DMI)
- Ørsted-DTU, Technical University of Denmark

Germany (3):
- Institute of Oceanography, University of Hamburg
- German Meteorological Service
- University of Bremen

Japan (1):
- Japan Meteorological Agency

Norway (2):
- MET Norway
- Nansen Environmental and Remote Sensing Center (NERSC)

South Korea (1):
- Korea Meteorological Administration

Sweden (1):
- Swedish Meteorological and Hydrological Institute (SMHI)

UK (2):
- European Centre for Medium-Range Weather Forecasts (ECMWF)
- School of Earth and Environment, University of Leeds

USA (10):
- Jet Propulsion Laboratory
- Colorado Centre for Astrodynamics Research
- Naval Oceanographic and Atmospheric Research Laboratory
- Cooperative Institute for Research in Environmental Sciences (CIRES)
- Goddard Space Flight Center, NASA
- National Snow and Ice Data Center (NSIDC)
- Remote Sensing Systems
- Universities Space Research Association
- Department of Electrical and Computational Engineering
- Environmental Research Institute of Michigan

Appendix 14: Online Responses to NSIDC Error

The following links and quotes indicate the breadth of responses from members of the public to the erroneous reporting of the NSIDC SII data in February 2021.

Watts Up With That? – The world's most viewed site on global warming and climate change included a blogpost written by Anthony Watts on 4th March 2021. The blogpost addressed the erroneous reporting of the NSIDC's SII: https://wattsupwiththat.com/2021/03/04/hey-nsidc-looks-like-we-have-a-sea-ice-sensor-failure-again/

- Responses in the comments section to the blogpost:
    - "… they are lying about it being broken… they are [sic] no monitoring the data as they should be…". – 4th March 2021.
    - "Doubtful they have a 'processing error' with a dropout that steep. That was the claim years ago too." – 4th March 2021.
    - "The burden of proof [has been shifted] to the data fiddlers: it is now THEY who must prove their actions are legitimate" – 4th March 2021.
    - "Beyond the data glitch, I have from time to time compared NSIDC to DMI. They purport to measure the same things (Arctic sea ice extent defined as >15% ice coverage), but don't get the same results. Scientific measurements should be independently repeatable. So this is more 'climate science' in the same category as sea level rise in acceleration". - 4th March 2021.
    - "Alert, alert!! All Arctic climate scare programs are suspended for 24 hours."- 4th March 2021.
    - "The question arises whether that sensor has been slowly degrading for some time and painting a false image of Arctic sea ice loss." - 4th March 2021.
    - "While catastrophic failures (suddenly stop working) of sensors can occur, in many cases you are looking at a period of time where erratic performance occurs. To me, this brings into question whether recent readings are accurate at all for quite some time". – 6th March 2021.

Similar responses to the error were circulating on Twitter:

- Replies to an NSIDC tweet (https://twitter.com/NSIDC/status/1365358720591405060) included:
    - "And you guys want to sell us your hypothesis of <<global warming>> ?? You're not even able to [sic] mesure existing data correctly, but you have the arrogance to base your hypothesis on flawed models, not even on (your flawed) data." – 26th Feb 2021
    - "Time to time they tell the truth so I thought maybe this time they are right… But this seems like an organised attempt to cover up things, tell lies.. Not the first time these 'scientists' did this…"– 27th Feb 2021
- Other Tweets with images such as Figure 7.5 (Section 7.3.2):

- "The decrease in ice coverage can indeed be caused by bad data. However, it is a massive coincidence that this ~3 week long NSIDC data glitch occurred during the same period where completely different instruments measured very high air and water temperature anomalies..." – 27th Feb 2021 (https://twitter.com/artus_ac/status/1365824405201432580)
- "I have *never* seen anything like this in the NSIDC data, and I've been following it for nearly 20 years. 'Unprecedented' doesn't even come close." – 27th Feb 2021 (https://twitter.com/bibbleco/status/1365791854105608199)

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