Cryomobilities: Vessel mobilities amidst the ice-prone waters of the Bering Strait

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Cryomobilities

Vessel mobilities amidst the ice-prone waters of the Bering Strait

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Abstract

In recent years, the overall decrease in sea ice and the increase in vessel traffic in the Arctic has raised questions over how to conceptualise vessel mobilities in icy ocean spaces. Drawing on the mobilities literature, this research turns to oceans and seas that sustain annual cycles of sea ice as an arena for exploring interactions between vessel mobilities and the mobilities of the (partially) frozen ocean amidst which they move. This thesis engages with the cryomobilities of the Bering Strait region through an interdisciplinary approach across human and physical geography, whereby "cryomobilities" refers not just to the mobile interactions between vessels and sea ice, but also points to the ways in which the vibrant and distinct materialities of our planet's frozen oceans (as well as other cryoscapes) warrant dedicated and specific conceptualisations. Specifically, turning to icy ocean spaces raises questions for conceptualising entities in motion within an environmental that is itself also in motion. The Bering Strait region, located between Alaska and Siberia, comprises the ice-prone waters of the Bering and Chukchi Seas. By analysing interactions between vessels and sea ice in the Bering Strait region, this thesis explores how vessel mobilities are entangled with sea ice mobilities, and how these are experienced by people who engage with these mobilities in various ways.

In order to analyse these multiple aspects of cryomobilities in the Bering Strait region, this thesis employs a mixed methods approach, combining spatial data analysis and interviews. Spatial data analysis uses sea-ice concentration and vessel traffic data from remote sensing to map and compare the interactions between the mobilities of sea ice and the mobilities of vessels between 2013 and 2022. Interviews with sea-ice scientists, sea-ice forecasters and people with on-ice and sailing experience explore the knowledge-making practices surrounding cryomobilities through embodied experience.

The findings reveal how cryomobilities in the Bering Strait region are characterised by an avoidance of sea ice, with 95% of vessel traffic operating in open water. However, not all ships and not all sea-ice conditions are the same, as there are many diverse users of these varied and ever mobile icy-watery spaces, who all relate to sea-ice conditions in different ways. For example, tourist cruise ships, fishing vessels, drifting scientific stations and icebreaker vessel mobilities all rely in various ways on the presence – rather than the absence – of sea ice and its mobilities. Technological advances in shipbuilding are also enhancing the ice capabilities of ships and icebreakers such that, over the past decade (2013-2022), vessel traffic in ice-covered areas has been increasing at a faster rate than vessel traffic in open water. Cryomobilities are also influenced by the ways in which knowledge emerges through a combination of highly specific personal expertise, embodied experiences, and rigorous collection and analysis of scientific data about sea ice and vessel activities. By presenting a multifaceted and interdisciplinary perspective on cryomobilities in the Bering Strait region, this research pushes the boundaries of the existing mobilities literature, often dominated by terracentric and liquid-ocean accounts of mobilities. It also contributes to understanding vessel behaviour in ice-prone waters for informing present and future management of icy ocean spaces, especially in view of a warming climate.

Table of Contents

List of Figures

List of Tables

List of Abbreviations

AAOKH	Alaska Arctic Observatory and Knowledge Hub
AIS	Automatic Identification System
AMSR2	Advanced Microwave Scanning Radiometer 2
AMSR-E	Advanced Microwave Scanning Radiometer for Earth Observing System
ANCSA	Alaska Native Claims Settlement Act
ASI	ARTIST (Arctic Radiation and Turbulence Interaction STudy) Sea Ice
ASTD	Arctic Ship Traffic Data
DurhamARCTIC	Durham Arctic Research Centre for Training and Interdisciplinary Collaboration
GIS	Geographic Information System
GSFC	Goddard Space Flight Center
IACS	International Association of Classification Societies
IMO	International Maritime Organisation
JAXA	Japan Aerospace Exploration Agency
MMSI	Maritime Mobile Service Identity
MOSAiC	Multidisciplinary Drifting Observatory for the Study of Arctic Climate
NASA	National Aeronautics and Space Administration
NOAA	National Oceanographic and Atmospheric Administration
NSIDC	National Snow and Ice Data Center
NWS	National Weather Service
PAME	Protection of the Arctic Marine Environment
SAT	Surface Air Temperature
SST	Sea Surface Temperature
SHEBA	Surface Heat Budget of the Arctic Ocean
SIPN	Sea-Ice Prediction Network
UNCLOS	United Nations Convention on the Law of the Sea

Statement of Copyright

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Dedication

To Andrew Sutton and Richard Cosgrove.

1

Introduction

1.1. Introduction

In August 2017, the Russian-owned tanker *Christophe de Margerie* completed the first transit of the Northern Sea Route without the need for icebreaker assistance (Barkham, 2017). The portion of the journey that used the Northern Sea Route (between Novaya Zemlya and the Bering Strait) took merely 6.5 days, setting a new record; the entire voyage spanned 19 days, shaving a third off the Suez Canal route that is conventionally used by commercial vessels to transit between Asia and Europe (Staalesen, 2017). Four years later, in January 2021, three commercial tankers transited the Northern Sea Route in winter, for the first time without icebreaker escort (Chen et al., 2022). As Arctic sea ice has been declining over the past several decades, this has changed the ways in which people are able to use and be mobile within these icy ocean spaces. Combined with technological advancements giving ships more powerful icebreaking capacity, new records such as the *Christophe de Margerie*'s crossing of the Northern Sea Route have become possible in recent years. These changes in icy oceans, and how people make use of them, have the potential to shape and create new global geographies of mobilities and connections across the globe.

Over the past several decades, the Arctic has warmed up two to four times faster than the rest of the planet, and sea ice has declined at an unprecedented rate (Kinnard et al., 2011; IPCC, 2019; Meredith et al., 2019; Rantanen et al., 2022). The Arctic is losing its reserves of older sea ice, as warmer temperatures make it increasingly difficult for sea ice to survive multiple summer melt seasons and continue circulating in the Arctic as multiyear ice (Comiso, 2012). Sea ice is also becoming thinner, as increasing air and ocean temperatures fail to provide consistently cold enough conditions for the formation of thick ice (Maslanik et al., 2007; Stroeve et al., 2012). As a result, sea ice is forming later and melting sooner each year (Frey et al., 2015; Peng and Meier, 2018; Wang et al., 2018), altering the timings of countless other processes that rely on its seasonal cycles, from algal blooms and marine mammal migrations to subsistence hunting for Indigenous coastal communities (ICC Alaska, 2020; Hauser et al., 2021; Tsujii et al., 2021). In addition, atmospheric instability and increasing extreme weather events such as winter storms are breaking up the ice pack more frequently, and overall weakening sea ice's ability to remain frozen for longer, exposing the coastline to rapid erosion (Fang et al., 2018).

In parallel to a decrease in sea ice, shipping in the Arctic has been increasing. Between 2013 and 2019, the number of ships entering the Arctic[1] grew by 25%, from 1,298 ships to 1,628 ships (PAME, 2020b). Similar trends were observed in the Bering Strait region[2], where total vessel traffic increased by 50% between 2015 and 2020 (Kapsar et al., 2023). This increase has raised a flurry of excitement over the potential navigability of previously ice-bound routes that might become ice-free in the near future (e.g., Lasserre, 2014, 2015; Melia et al., 2016; Matthews et al., 2020; Sui et al., 2021; Min et al., 2023). However, protecting this area's fragile ecosystem and biodiversity is a key concern for policymakers in this region. The recent increase in shipping traffic through the Bering Strait (Kapsar et al., 2023), for example, has led the International Maritime Organisation (IMO) to define new shipping routes in 2018 to guide vessels through the Bering Strait and the Bering Sea to reduce the risks of incidents, protect the marine environment and safeguard local fishing activities (IMO, 2018).

Mobility studies, interested in the mobile networks that shape and uphold global flows of people, goods and ideas, have recently taken an interest in analysing the mobilities that take place within watery spaces (e.g., Lambert et al., 2006; DeLoughrey, 2007; Anderson, 2014; Vannini and Taggart, 2014; Anderson and Peters, 2016; Peters and Squire, 2019; Peters, 2020a). Since the early 2000s, this has inspired a steady stream of scholarly work concerned with the ways in which mobilities unfold in watery spaces, including surfing (Anderson, 2014), containerisation and global shipping (Parker, 2013; Anim-Addo et al., 2014; Birtchnell et al., 2015; Steinberg, 2015; Peters, 2020a), passenger experiences on board vessels (Ewertowski, 2023), yachting culture (Spence, 2014), workers at sea (Turgo, 2023), radio piracy (Peters, 2014, 2020b) and ice roads (Vannini and Taggart, 2014), to name a few. This focus within mobility studies also follows a broader 'blue turn' within the humanities that looks to the seas and the ocean to take seriously the place of the ocean in early modern history and culture, and explore the cultural significance of the maritime world (Mentz, 2009, 2023).

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[1] The 'Arctic' is here delimited by the Polar Code Area, as defined in the IMO Polar Code. Roughly, this area includes all waters north of the 60°N parallel, except around Greenland, Iceland and north of Norway to Cape Kanin Nos in Russia, where the delimitation follows a different boundary.

[2] The 'Bering Strait region' is comprised of the Bering Sea and the Chukchi Sea, that respectively connect the Pacific Ocean and the Arctic Ocean through the Bering Strait.

Despite these interventions, Peters and Squire (2019) point out that mobility studies have yet to fully engage with several aspects of oceanic and watery mobilities, including how vessel mobilities play out amidst sea ice. As such, through this thesis, I contribute to "deepening and widening" (Peters and Squire, 2019: 107) the scope of mobility studies by analysing the mobile interactions between sea ice and vessels, as they unfold and are experienced amidst the icy waters of the Bering Strait region. As I contend in this thesis, analysing vessel mobilities amidst (frozen) watery spaces requires an attentiveness towards the mobile backgrounds against and alongside which these mobilities occur. As such, I introduce 'cryomobilities' as this thesis' key theoretical foundation (Chapter 2). Cryomobilities focuses on analysing mobile interactions between sea ice and vessels, conceptualising the ocean as multidimensional, mobile and with agency, characterised by the capacity to shape new geographies of mobile encounters with other mobile entities.

Borrowed from the Greek word *κρύος* (krýos), 'cryo' is used as a prefix to denote a presence of or relatedness to ice, frost, or extreme cold (Oxford English Dictionary, 2023). As such, I employ this term within the context of 'cryomobilities' to bring attention to the specificities of mobile encounters that unfold amidst or are in various ways connected to cold, icy, frosty or frozen conditions. Whilst this term can be employed broadly to address the cold and frozen components of a plethora of mobile networks (see Chapter 8), in this thesis I begin the endeavour of bringing attention to the specificities of cryoscapes by addressing the unique mobilities that emerge from the 'cryo' relating to the frozenness and coldness of sea ice and its interaction with vessels. Through a focus on sea ice, this thesis reveals the connectedness of the 'cryo' not just to its frozen elements but also to broader networks of oceanic spaces, whose influences also spill over onto land. As such, the 'cryo' becomes an epistemological starting point for exploring ontologies whose consequences extend beyond the 'cryo' itself.

The Bering Strait region, specifically, features as this research's main area of study for various reasons. The Bering Strait region is implicated within various mobile networks on a planetary scale, making it a key area for understanding broader patterns of change and movement in global environmental and sociopolitical systems. Located between the Arctic Ocean and the Pacific Ocean, the Bering Strait is a global gateway that facilitates human and non-human interactions across distant regions (Waloven et al., 2023). The Bering Sea is one of the world's ocean's most biologically productive regions (Springer et al., 1996; Macdonald et al., 2004), sustaining local livelihoods of fishermen and Indigenous communities, as well as global trade. The annual migrations of several marine animals also intersect in the Bering Strait, including those of as polar bears, whales and various species of ice-dependent seals (Hauser et al., 2021; Mahoney et al., 2021). From a shipping perspective, vessel traffic in the Bering Strait region has been increasing since at least 2015 (Kapsar et al., 2023) and, combined with its fragile ecosystem (IPCC, 2021), makes the Bering Strait region a priority area to study for better understanding the future trajectories of these changes. Both the Northern Sea Route and the Northwest Passage start (or end) at the Bering Strait, raising challenges for the sustainable management of shipping activities in this region, especially in light of recent developments to the Northern Sea Route for commercial shipping (e.g., Vanhatalo et al., 2021). As the Bering Strait creates a bottleneck passageway, it concentrates the sea ice, vessels, marine mammals and fish that must all make their way through it. As such, the Bering Strait region provides an exciting arena for further developing understandings of the mobile interactions between vessel traffic and sea ice unfolding in this region, and contributing to the informed management of the intense relations between all the human and non-human inhabitants of this region.

Arising from these points of departure within existing research and the present-day contexts of the intensification of sea ice and vessel mobilities, this research sets out to address the following main research question, that is further partitioned into three sub questions:

> ***In the Bering Strait region, how are vessel mobilities entangled with sea ice mobilities, and how are these perceived?***

> a. *What patterns of sea ice and vessel mobilities are present in the Bering Strait region?*
> b. *How have mobile interactions between sea ice and vessels changed over time (in particular, during 2013-2022)?*
> c. *How do people who engage with sea-ice and vessel mobilities in various ways perceive and understand the mobile interactions between sea ice and vessels?*

The next sections in this chapter further situate this research in light of the oceanic mobilities unfolding in the modern day (Section 1.2) and provide an outline of each of the chapters that constitutes the rest of the thesis (Section 1.3).

1.2. Ocean Mobilities in the Modern Age

Today's world is characterised by a multitude of interconnected and co-dependent mobile networks. There are huge amounts of materials in constant circulation around the globe, as well as more people moving more, and consuming more animals and plants than ever before (Nail, 2019; Jensen et al., 2020). The SARS-CoV-2 coronavirus pandemic that started in 2019 revealed the power held in the mobilities of a virus, able to cross the globe via its hosts in a few hours, and infect entire nations in a matter of weeks by moving through the air (Adey et al., 2021). The mobility restrictions that ensued as countries locked down revealed how financially and personally reliant we are on mobility, as businesses closed, markets crashed and mental health problems spiked (Mazur et al., 2021; Zuev and Hannam, 2021). These more-than-human mobility entanglements remind us of the interconnectedness of modern society; we cannot wall ourselves off (Adey et al., 2021). As such, mobility is at the heart of better understanding the complex configurations of modern society, revealing both its opportunities and vulnerabilities.

The intensification of mobility in the modern age is not limited to that of human beings. Despite humans being the core drivers of modern society's intensification of mobilities, some mechanisms are speeding up beyond human control. Anthropogenic climate change is triggering a variety of planetary mobilities with positive feedback cycles that have a life of their own and whose mobilities need acknowledging (Nail, 2019). Steffen et al.'s (2015) 24 graphs of human and environmental indicators show that society's 'great acceleration' over the past century involves exponentially growing volumes of material resources set in motion as they are extracted, processed and distributed globally. The widespread use of fossil fuels reveals mobilities down to the molecular level, as increased fuel combustion sets greater quantities of carbon dioxide in motion throughout the atmosphere. Environmental equilibria are being disrupted, causing increasingly erratic, unpredictable and extreme weather patterns.

Among these planetary intensifications is the ocean, whose shifting patterns of mobilities alert us to the changes that our planet is undergoing. Humanity's existence is intrinsically bound to the ocean and, in particular, by the mobilities that the ocean permits (Steinberg, 2001; Vannini and Taggart, 2014; Anderson and Peters, 2016; Peters and Squire, 2019; Peters, 2020a). The ocean nurtures life on our planet, as it provides a habitat for phytoplankton production, the building block that sustains animals throughout the food chain, all the way to humans (Hill et al., 2013; Demuth, 2019). The ocean regulates animal habitats and global climate through a complex system of currents, winds, tides, and water column mixing and stratification through temperature and salinity (Timmermans and Marshall, 2020). The ocean stores potent greenhouse gases, such as methane, locked away in crystal structures – clathrates – kept intact by a delicate balance of temperature and pressure at the bottom of the ocean; when set in motion under warming conditions and released into the atmosphere, they have the potential for disastrous consequences on the planet's climatological balance (Archer and Buffett, 2005). Past and present mobilities through and over the ocean are intrinsic to cultural identities throughout the world (Mentz, 2009, 2023; Eicken, 2010; Helmreich, 2011; McCannon, 2018; Beveridge, 2020). Beyond the internal mobilities of the ocean are broader atmospheric and global climate mobilities that the ocean supports, including teleconnections that influence weather patterns across the globe. Oceans and seas are intertwined with our everyday lives and the globalised 21st Century is highly dependent on water worlds for transportation, food and creative inspiration (Anderson and Peters, 2014).

Whilst the ocean exists for the most part in its liquid form, the ocean also freezes into sea ice, given the right conditions. Primarily, sea ice is found at the poles, in the Arctic and the Antarctic waters of the global ocean. Much like the liquid ocean, Arctic sea ice regulates and is implicated within broader interconnected mobilities of atmospheric circulation, such as the polar vortex that is occasionally disrupted and brings unexpectedly frigid winter storms to more southerly latitudes (e.g., National Weather Service, 2022). Sea ice also contributes to ocean-atmosphere moisture exchange, leading to less inland precipitation during months of more extensive sea-ice cover in surrounding waters (Higgins and Cassano, 2009; Kopec et al., 2016). Sea ice itself is constantly undergoing physical and material alterations through processes of snow accumulation, lead formation, wind advection, brine rejection, and numerous others (Steinberg et al., 2023). Sea ice also sustains plentiful animal mobilities, including the annual migrations of marine mammals such as polar bears, whales, walrus, and several species of ice-dependent seals (Hauser et al., 2021; Mahoney et al., 2021). Additionally, Indigenous peoples of the Arctic have been harnessing the mobilities of sea ice for millennia for subsistence hunting of marine mammals, as well as fish, crabs and birds (Jolles, 2006; Aporta, 2010; Kapsch et al., 2010; Demuth, 2019). Therefore, exploring human encounters with the ocean in all its forms is a fundamental aspect of understanding present and future challenges for humanity.

Whilst an icy ocean is in many ways similar to a liquid one through similar mobilities of the ocean itself, as well as its implication within broader networks of mobilities, a frozen (or partially frozen) ocean does not share *all* the same qualities of a liquid ocean. Therefore, it cannot be understood and approached in the same way as a liquid ocean. In a physical sense, sea ice is a complete transformation from saltwater in its liquid state, giving it a unique set of properties. Indigenous hunters harness the solidity of sea ice (specifically, of shorefast sea ice[3]) for accessing areas in the ocean that would otherwise be open water in the summertime, providing access to marine mammal habitats for subsistence hunting (George et al., 2004). Likewise, vessels must be specially designed and winterised in order to handle navigational challenges posed by the material specificities of icy waters (IACS, 2023).

As such, I turn to the icy waters of the Bering Strait region to explore the ways in which a frozen ocean's specific materiality and structural presence has shaped the cryomobilities unfolding in this region over past millennia and centuries, how changing sea ice in a warming climate creates a constantly evolving relationship between vessels transiting those icy watery spaces, and how a better understanding of these interactions can shape cryomobilities in the future.

1.3. Thesis Outline

In this introductory chapter, I have situated this research within broader contexts of oceanic geographies, mobility studies and contemporary issues of Arctic shipping and climate change. In **Chapter 2**, I draw on existing mobilities literature to situate this research's novel interventions within current research efforts. I discuss the ways in which watery spaces and, in particular, frozen oceanic spaces, challenge existing ontologies that view human mobilities as occurring over a frictionless, inert, and often immobile background. As I contend in this thesis, analysing vessel mobilities amidst (frozen) watery spaces requires an attentiveness towards the mobile backgrounds against and alongside which

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[3] Shorefast sea ice is stationary ice extending from shore, usually fixed by sections of thicker ice that are grounded on the seabed.

these mobilities occur. As such, in this chapter, I introduce 'cryomobilities' as the key theoretical foundation of this thesis. Cryomobilities focuses on analysing mobile interactions between sea ice and vessels, conceptualising the ocean as multidimensional, mobile and with agency, characterised by the capacity to shape new geographies of mobile encounters with other mobile entities.

In **Chapter 3**, I present an overview of the Bering Strait region as the study area. In particular, I highlight the ways in which the Bering Strait region has always been implicated within mobile processes of the ocean, atmosphere, ice, people, plants and animals, and that these processes have shaped the Bering Strait region throughout its history. As part of this discussion, I also present current understandings within physical geography of existing ocean-atmospheric mechanisms and forcings that impact spatiotemporal patterns of sea ice. These form the basis of an interdisciplinary understanding of sea-ice mobilities, which in turn informs the analysis of cryomobilities presented in this thesis.

In **Chapter 4**, I lay out the methodology employed in this thesis, contextualising it within the theoretical framework of cryomobilities, and elucidating how it addresses the research questions. A mixed methods approach informs the findings presented in this thesis and operationalises the analysis of the mobilities of vessels and sea ice in an interdisciplinary medley across human and physical geography. First, I employed spatial analysis to analyse the spatial and temporal trends of sea-ice and vessel traffic. The spatial data analysis uses i) sea-ice concentration satellite data from the Advanced Microwave Scanning Radiometer 2 (AMSR2) spanning 2013–2022, ii) sea-ice concentration satellite data from National Snow and Ice Data Center (NSIDC) spanning 1979–2022, and iii) vessel traffic data from the Arctic Council's ASTD (Arctic Ship Traffic Data) spanning 2013–2022. In addition, as the ASTD ship traffic data required considerably more processing before it was useable compared to the other data products, creating a Python script for automated processing of the vessel data became a large undertaking and a core contribution of this research. Second, I conducted interviews to elaborate on and further illustrate the findings arising from the spatial data analysis. Fieldwork took place during 2022 in collaboration with the International Arctic Research Centre (IARC) located in Fairbanks, Alaska. During this time, I carried out the interviews and began processing the ship traffic data. In this chapter, I also address some of the research challenges and limitations, reflecting on matters of ethics, positionality and Indigenous involvement.

In Chapters 5-7, I present the empirical findings of this Ph.D. In **Chapter 5**, I discuss the cryomobilities of the Bering Strait region in light of the various ways in which sea ice poses an obstacle to navigation. In this chapter, I also trace some of the histories and developments in overcoming sea ice in the context of navigation. Since the early European voyages to the Arctic in the 18th and 19th Centuries, the distinct materiality of sea ice disrupts the ways in which vessels designed for moving through oceans in their liquid form are able to handle an ocean that turns (to varying degrees) solid. This realisation led to a variety of technological advances, particularly in the 20th Century, aimed at overcoming the challenging ocean conditions posed by sea ice and improving the ice capability of ships. In order to better understand the cryomobilities associated with changing dynamics of sea ice and vessel traffic in the Bering Strait region in the 21st Century, this chapter also presents the results of spatial analysis of sea-ice concentration and vessel traffic datasets to reveal the ice-avoidant cryomobilities that take place in the Bering Strait region.

Complementing the antagonistic relationship between sea ice and vessels presented in Chapter 5, in **Chapter 6**, I consider those cryomobilities in the Bering Strait that are instead characterised by an affinity towards sea ice, drawing on vessels whose activities emerge from and co-exist alongside sea ice, rather than in opposition to it. In this chapter, I highlight the heterogenous cryomobilities that unfold in the icy waters of the Bering Sea region. Four examples drive and illustrate the findings presented in this chapter. First, the 1893–96 expedition of Arctic voyager Fridtjof Nansen, for whom sea ice was an ally, allowing him to drift with the ice pack and set the record, at the time, for getting closest to the North Pole. Second, fishing and crabbing vessels in the Bering Sea, whose relationship to sea ice is two-fold, as sea ice is a serious inconvenience and danger to their fishing activities, but a necessary – and extremely profitable – one. Third, tourist cruise ships, as an example of a unique industry that is interested in the active pursuit of sea ice, as sea ice itself has become a tourist attraction, as well as for the rare opportunity of spotting ice-dependant Arctic wildlife, such as whales and polar bears, in their iconic Arctic habitat. Finally, icebreakers, whose increasing presence in areas of dense pack ice demonstrates that Arctic ship traffic is not just increasing *in areas of open water*, but that it is increasing *everywhere*.

In **Chapter 7**, I elaborate on the ways in which various groups of people who interact with sea ice and vessel mobilities across a range of disciplines and lifeways come to perceive, mediate and make sense of the mobile interactions between sea ice and vessels. In this chapter, I reflect on the various ways in which knowledge about sea ice and its mobilities is produced, looking at forms of knowledge production that aim for objectivity and reliability (such as scientific sea-ice products and operational sea-ice forecast charts), as well as other knowledge approaches that rely on direct encounters with sea ice and the expert subjective and embodied synthesis of information gained through such experiences (such as the intimate knowledge of sea-ice behaviour held by skilled boat captains, or Indigenous hunters). As this chapter reveals, sea-ice knowledge emerges through a combination of highly specific personal expertise and rigorous collection and analysis of scientific data about sea ice. Likewise, practical navigational endeavours, that often involve subjective knowledge gained through personal encounters with sea ice, are also heavily informed by scientific understandings of sea-ice dynamics. In turn, this melange of understandings and knowledges about sea ice shapes attitudes towards navigation and, subsequently, cryomobilities in the Bering Strait region

This thesis concludes with **Chapter 8**, where I present a discussion that draws on the findings in the three empirical chapters (Chapters 5–7). In this chapter, I elaborate on the ways in which the insights gained from the empirical findings contribute to advancing existing understandings of vessel mobilities in icy waters, and geographical thinking more broadly. Fundamentally, this research contributes to existing bodies of literature that turn to the ocean to gain insight into the sociopolitical orderings that shape the world. In this research, I draw on sea ice not only to disrupt Western dominant narratives of the ocean (as liquid and outside of land-based modernity), but also to disrupt narratives of mobilities as occurring over static and meaningless backgrounds. In doing so, in this thesis I shed light not only on the empirical realities of cryomobilities – a topic which has itself eluded much analysis – but also on other marginalised discourses within mobility studies and, more broadly, the discipline of geography. These understandings can also contribute to informing the spatial management of ocean and frozen spaces in a world that is increasingly on the move through globalisation and climate change. In light of the ongoing and intensifying changes that Arctic sea ice is undergoing, this thesis makes a timely contribution to understanding our planet during a time of transformation under climate change.

2

Cryomobilities: A Theoretical Framework

2.1. Introduction

In order to analyse mobile interactions between vessels and sea ice in the Bering Strait region, and how these are perceived, in this chapter I draw on existing mobilities literature to situate this thesis' novel interventions within current research efforts. In this chapter, I elaborate on the ways in which watery spaces and, in particular, frozen oceanic spaces challenge existing ontologies of human mobilities as occurring over a frictionless, inert, and usually immobile background. On a conceptual level, I contend that analysing vessel mobilities amidst (frozen) watery spaces requires an attentiveness towards the mobile backgrounds against and alongside which these mobilities occur. As such, within the context of this thesis, I conceptualise the ocean in all its forms – including frozen – as being multidimensional, mobile and with agency, characterised by the capacity to shape new geographies of mobile encounters with other mobile entities. Turning to icy ocean spaces – an arena largely left behind within mobility studies (Peters and Squire, 2019) – presents a novel way of conceptualising not only mobilities occurring in watery spaces, but also rethinking mobile encounters beyond the ocean, including on land.

In this chapter, I present an analytical review of existing literature within broader mobilities approaches and, more specifically, watery, oceanic and frozen mobilities. Within this discussion, I establish the theoretical framework of 'cryomobilities', a neologism that guides and underpins the empirical and theoretical work carried out for this research and presented in the rest of the thesis. This chapter is structured in three main sections. In Section 2.2, I discuss the various ways in which classical mobility studies have been predominantly underpinned by ontologies that have resulted in the omission of mobile backgrounds from analytical scrutiny. In particular, this has been through an anthropocentric focus of mobilities as experienced, sensed and perceived by humans and the human body, which has sidelined the mobilities of backgrounds that – as sensed by the human body – appear to be still. As such, I argue that the existing mobilities literature lacks a framework for adequately and holistically analysing the ways in which entities are in motion within an environment that is itself also in motion, and that the background's mobilities matter for how other mobile encounters play out. Then, in Section 2.3, I review mobilities work that has turned to the sea. Accounts of watery mobilities have in various ways had to engage with the materialities and the mobilities of the oceanic background against which these mobilities unfold. Finally, in Section 2.4, I present the notion of cryomobilities, as a specific intervention within the oceanic literature that expands the efforts of watery mobility scholars to focus specifically on the ways in which vessel mobilities unfold amidst watery spaces in their (partially) frozen states. Arctic waters, in particular, are constantly shifting between solid and liquid states of frozen or unfrozen, fresh or brackish, as well as multiple transitional phases in between (Steinberg and Peters, 2015; Steinberg et al., 2023). In conceptualising the icy ocean as constantly in motion, multidimensional and with agency, cryomobilities moves away from understanding ocean-ship mobile interactions as surficial and frictionless routes *over* the ocean. Instead, cryomobilities focuses on the mobilities that emerge from the ocean's mobile, voluminous and material agency in shaping new geographies as it interacts with other mobile entities that move through, over, in and amidst its icy presence.

2.2. Immobile Backgrounds in Mobility Studies

Movement of people, objects and ideas has been an interest of scientific inquiry for a long time; however, the way mobility is characterised and understood has shifted over the centuries. As I review some of the prominent theoretical approaches employed within mobility studies, I elaborate on how these ontological orientations have largely resulted in the omission of mobile backgrounds from analytical scrutiny within mobility studies. Whilst I broadly trace these in chronological succession, it is the conceptual content that drives the discussion, in order to tease out the ontologies underpinning various approaches within mobility studies[4].

Mobility studies emerging in the late 20th Century were born out of the desire to monitor and manage movements of people, resulting in an anthropocentric orientation within the discipline. Mobility studies in the 1980s and 1990s were interested in the movement of humans across the globe and sought to quantify, manage and predict patterns of movement (Kelly, 1983; Sicherman and Galor, 1990; Epple and Romer, 1991). The fact that people moved was taken as a given (Cresswell, 2010),

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[4] For a chronological account of the development of ontological orientations within the mobilities literature, see Cresswell (2006).

creating a body of literature that understood movement as an abstracted and homogenous form of motion, detached from social implications and political meaning (Cresswell, 2006). In turn, people's movements also became detached from the material and embodied realities of the backgrounds and environments within, across, over, through and with which they took place. As work on tourism, globalisation and commuting (among others) increased, scholars began to question the homogeneity of mobilities, and began to bring attention to the divisions between different categories of mobile people. This brought the realisation that movement never occurred on its own but was always embedded within a socio-political context that acted and manifested itself in heterogenous mobile flows (Schiller and Salazar, 2013). This expanded the realm of mobility studies from the mere quantification and management of a homogenous mass of people moving from A to B, to include more politically and geographically contingent ways of understanding how mobilities unfold. Yet, even as mobility studies became more sensitive to the nuances of various forms of human movement, it continued to pursue an anthropocentric orientation that side-lined the non-human backgrounds against which these human mobilities take place.

In following the movements of people, mobility studies have been so focused on that which is mobile on the human scale that entities that are not immediately perceivable as being in motion (as perceived by the human body) have eluded scrutiny. Deleuze and Guattari contend that the immobile backgrounds against which human mobilities take place are sidelined from studies of mobilities because this understanding of motion is based on how motion is perceived by the human body:

> Movement has an essential relation to the imperceptible; it is by nature imperceptible. Perception can grasp movement only as the displacement of a moving body or the development of a form. Movements, becomings, in other words, pure relations of speed and slowness, pure affects, are below and above the threshold of perception (1988: 280–281).

So, as mobility studies are concerned with that which moves, and when the significance of mobilities is analysed relative to the human body, the imperceptible movements become considered immobile and secondary (if not altogether unimportant) to the analysis of entities on the move. Within studies of automobilities, for example, asphalt roads over which cars drive are of no particular importance (for the most part) to the driver, as its material composition feels stable, immobile and unchanging (Vannini and Taggart, 2014). However, in his interventions on *The Ontology of Motion*, Nail (2018) argues that everything is always in motion and, therefore, that mobility studies must move beyond only considering those mobilities which are perceived as being in motion by the human body.

One of the ways in which the material backgrounds against which mobilities unfold began to be incorporated within the mobilities discourse is in the form of seemingly immobile infrastructures that support the flows of mobilities. The 'new mobilities paradigm', emerging in the early 2000s, consolidates an agenda for mobilities research. One of its most notable interventions is the incorporation of immobile entities within discourses of mobility, by bringing attentiveness to the ways in which immobilities contribute to and shape the flows of other people and objects on the move. According to Hannam et al. (2006), who propose the new mobilities paradigm, all mobile systems rely on a series of immobilities, or 'moorings', without which mobile networks would be less mobile or would altogether cease to exist. For example, for goods to move smoothly through the system of global commerce, colossal immobile nodes are needed throughout the network, such as ship and air ports, distribution centres and standardised containers (Cidell, 2015). Likewise, such high volumes of production rely on a cheap and available workforce, often also the product of political or climatic (im)mobility crises (Nail, 2019). The new mobilities paradigm advocates for an appreciation of existing territorially-bound structures in providing the geographically defined and concentrated centres for managing the emerging volume of dissipated mobilities (Sassen, 2002). On the one hand, this provides a useful framework for bringing attentiveness to the distribution of mobile structures as heterogeneously mobile and geographically localised, and the ways in which mobility is not homogenous and equally distributed. On the other hand, it provides a problematic categorisation of mobile and immobile entities because it arbitrarily defines the threshold of what constitutes mobility and immobility, creating an arbitrary relativism of motion. In this sense, the binary distinction between mobility and immobility serves to include (immobile) backgrounds within the mobilities framework as the necessary immobile infrastructures that sustain and make possible other flows of mobilities. However, backgrounds here are still framed as secondary and subservient to the primary focus that is still on the mobile entities that make use of these immobile backgrounds or infrastructures to facilitate their own mobilities. These backgrounds are thus never truly elevated to the same level of importance as the primary mobile processes under scrutiny. And, most importantly, they are denied a mobility of their own, for it is by virtue of being conceptualised as immobile that backgrounds and infrastructure enter the mobilities discourse.

In response to the mobility/immobility dichotomy, Nail (2018) returns to the physics of motion, arguing that because everything is always in motion on an atomic and subatomic level, there is little ontological sense in framing mobility analyses through the lens of an artificial and arbitrary division between mobile and immobile entities. However, too great a focus on the pure physics of motion runs the risk of creating a body of knowledge that is ontologically unable to analyse the meaning embedded within motion, which is a key tenet of mobility studies (Cresswell, 2006, 2014; Hannam et al., 2006). In fact, critics of Nail's work point out that his theories of mobility flatten personal choice and circumstance, creating a narrative of homogenous masses (of things, people, or Mexican migrants, in Nail's specific case; Nail, 2015) all pushed and pulled by equal forces, each individual's experience indistinguishable from the next (Westmoreland et al., 2016; Kolers, 2017; Sager, 2017). Indeed, Cresswell reflects on how theoretical constructs that consider everything to always be in motion restrict the analytical power of immobility discourses:

> While it is the case that the world is always in motion at a molecular level, it still presents plenty of immobilities at both experiential and political levels. Molecular vibrations are not much comfort, I

> expect, to Palestinians who cannot walk through the wall that has been built between their homes and their farmland. Immobilities (and indeed time-spaces) such as these cannot be wished away with a theoretical wand (2014: 719).

As such, mobilities approaches that are attentive even to the molecular vibrations of materialities that otherwise appear to be immobile to the human senses must always return to consider the sociopolitical implications of these molecular, atomic and subatomic movements (Merriman, 2019).

In addition, it is also worth noting those scholars whose work has departed from focusing exclusively on the mobilities of entities on the move, and instead has turned to acknowledge the mobilities of the backgrounds, environments, and contexts that co-constitute the mobilities of other entities. As Massey (2000), Adey (2006) and Merriman (2004) argue, the perception of mobility and immobility is a matter of relative perception of movement. Therefore, when mobility scholars refer to entities as mobile or immobile, it must be acknowledged that this is merely a relational choice, for everything is always in motion, as Adey (2006) argues at length. So, even if the focus of enquiry might be on the commuters rather than on the tarmac road they use to get to work, the immobilities of the background are merely a reflection of the politics of relatedness at play within those relationships of movement. Therefore, this does not in itself imply a lack of recognition of the mobilities of those 'background' entities or infrastructures that appear less mobile, simply the focus is on one rather than on the other. The tarmac feels immobile because, relatively, the car is moving faster (Merriman, 2004). And, likewise, Massey proposes a view of the car's mobility from the opposite direction:

> … remember that this car trundling so mundanely up the M1 … is moving, so minutely it seems once the perspective is changed, on an earth that is itself spinning in a wobbly fashion upon its axis. … All movement, as they say, is relative (2000: 229).

As such, these perspectives open up the realm of mobility studies to infinite possibilities of endlessly nested, co-constituted and chained networks of mobilities. For example, Merriman's extensive work on the M1 motorway in the UK emphasises the ways in which the motorway itself was contingently assembled and ordered through the movements, experiences, work and materials associated with labourers, engineers, architectural commentators, drivers and passengers (2003). Similarly, Massey (2005) reflects on the ways in which mountains, often considered immobile entities *par excellence*, are born out of the immense and extraordinary motion of tectonic plates, glaciers and isostatic rebound[5], and continue to be in motion through smaller-scale processes of weathering and erosion. Despite these contributions, however, mainstream mobility studies continue to demonstrate an ontological preference for the study of entities that are more obviously on the move. If we take seriously that everything is in motion – and therefore subject to inquiry within mobility studies – it

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[5] Isostatic rebound is the process by which continental crust rebounds upwards as a result of reduced mass loading following the melting of ice sheets that previously covered these areas and weighed them down.

would be impossible to study everything in one go, and selections, simplifications and orientations must inevitably be made. However, it is the fundamental appreciation and acknowledgement of the importance of mobile backgrounds that I argue is still lagging behind in mainstream mobility studies.

Overall, despite the notable exceptions discussed above, current ontological orientations in land-based mobility studies still struggle to take seriously the mobilities of the backgrounds against which other – and supposedly more important – mobilities occur. This mobilities literature does not provide a framework for analysing mobilities in a way that takes into account interactions between entities on the move and the background, infrastructure or medium, through, alongside and with which they move. Anthropocentric accounts of mobilities draw the line between what is mobile and what is immobile based on an idea of mobility as perceived by the human body, thus excluding non-perceptible as well as non-human mobilities from the scope of study. Moreover, in a terracentric view, land, roads and soil feel stable, whereas other spaces, such as watery ones, lack similar characteristics of firmness, solidity and stability (Vannini and Taggart, 2014). As such, when turning to study mobilities in ocean spaces, these 'solid' and 'immobile' backgrounds against which mobilities occur require rethinking in order to account for the mobile character of water – in all its forms – and of water's interactions in shaping the mobilities of other mobile entities that move in, through, within, over and amidst these watery spaces.

2.3. Watery Mobilities

In his article on a 'blue cultural studies', Steve Mentz (2009) turns to the seas and the ocean to take seriously the place of the ocean in early modern history and culture, and explore the cultural significance of the maritime world. Mentz (2009: 997) argues that "reconsidering the ocean as ocean", rather than focusing on just the land, challenges established habits of thought and opens up new analytical frames for scholars to revisit existing narratives that structure modern society. Mentz's 'blue humanities' contribute to reviving the ocean as an arena for socio-political action, challenging long-standing conceptualisations of the ocean as beyond the remit of humanity as a prescriptively terrestrial civilisation (see also: Steinberg, 2001; Gillis, 2013; Anderson and Peters, 2016; Mentz, 2023).

In line with this blue turn in the broader humanities, mobility studies have also 'gone to sea', broadening their scope to incorporate watery, oceanic, maritime and marine mobilities (Lambert et al., 2006; Peters, 2012; Anderson and Peters, 2016; Deloughrey, 2017; Peters and Squire, 2019). Watery spaces, including the people who inhabit and engage with them, are no longer positioned on the margins of the discipline of geography; instead, they are valued for the expanding possibilities that they offer in revealing new geographies (Spence, 2014). Beginning in the early 2000s, this has led to the emergence of scholarly work concerned with the ways in which mobilities unfold in watery spaces. These research endeavours have included analyses of watery encounters through surfing (Anderson, 2014), containerisation and global shipping (Parker, 2013; Anim-Addo et al., 2014; Birtchnell et al., 2015; Steinberg, 2015; Peters, 2020a), passenger experiences on board vessels (Ewertowski, 2023), yachting culture (Spence, 2014), workers at sea (Turgo, 2023), radio piracy (Peters, 2014, 2020b) and ice roads (Vannini and Taggart, 2014), to name a few. In this thesis, I align myself with and contribute to mobility studies situated within the blue humanities by proposing an analysis of vessel and sea-ice mobilities that takes the ocean (and its mobilities) seriously, as a fundamental component of how these mobile interactions play out.

On an epistemological level, Bear and Bull (2011) propose two primary organising principles that have guided and continue to guide approaches to studying movements in and of the hydrosphere, broadly conceived. The first approach directs analytical attention to following water. Following water provides the opportunity to move away from anthropocentric accounts of the hydrosphere, including how water is often framed in terms of its management, consumption and distribution (e.g., Waley and Åberg, 2011). The second approach looks at movements in, around and of water. For example, through his work on angling, Bull (2011) highlights the importance of recognising the frictions and tensions of moving through water, and shows the ways in which water's materialities move bodies in specific ways, challenging and moulding those bodies. In this thesis, I align myself with the latter approach, placing the focus of this research not so much on following sea ice itself, or a specific ship on its journey through ice-prone waters (although individual ship voyages do inform various points of discussion throughout the thesis). Rather, the analysis that I present in this thesis is centred around a specific region – the Bering Sea and the Chukchi Sea, connected via the Bering Strait – and I focus on understanding the movements of entities in water, and the movements of water (and sea ice) itself. As such, the following discussion on some of the main ontological orientations underpinning marine and watery mobilities research draws primarily on examples that also employ an approach guided by analysing movements in and around water.

Cross-cutting these wide-ranging interventions are various ontological orientations that guide how watery spaces are conceptualised *vis-à-vis* the ways in which they interact with and co-constitute the mobilities being studied. In the discussion that follows, there is no particular chronological evolution of the ontologies being presented, as many of these evolved in parallel since the early 2000s. As such, whilst different branches of mobilities have developed (interested in different aspects and types of mobilities that unfold in relation to watery spaces) there appears to not be one predominant ontological approach that supersedes all others. As the dates in the cited material suggest, all of the ontological orientations discussed below continue to appear in recently published oceanic and watery mobilities literature.

First, mobility studies have approached watery spaces following a surficial ontology of networks that operate *on* the ocean's surface. Ingold (2008) identifies the analytical obsession to focus on the movement of objects across surfaces instead of the movement of bodies through media. Work on global shipping, for example, has created an ontology of connection and understanding of global trade as driven by surficial networks of routes mapped *onto* rather than *into* the sea (Peters, 2020a). Following this approach, the ocean becomes secondary – if not entirely forgotten – and the focus is placed entirely on the mobilities of goods and people that take place on its surface. Consequently, there is little interest in analysing the ocean's qualities, rendering the ocean a smooth, frictionless and characterless background against which other – more important – mobilities occur. In these surficial ontologies of marine mobilities, the ocean is not defined through its own qualities, but exists predominantly in relation to the land. In the case of containerisation and global shipping, the ocean is important insofar as it supports landed consumer habits. For example, in recent work on the home-making practices of Filipino workers at sea (Turgo, 2023), the focus of analysis is placed entirely on the material objects that workers take with them during their employment at sea to remind them of their home on land. The ocean does not feature as a characterful presence in and of itself (such as in how feelings of homesickness might mirror feelings of seasickness induced by the ocean's own mobilities), and the meaning mobilities of Filipino workers at sea are only made significant through their attachment to the home on land that they are leaving behind, and trying desperately to take with them. As such, conceptualising mobilities *onto* watery surfaces side-lines the processes and interactions arising from the material encounters with the ocean itself, reinforcing Schiller's (2013) critique of mobility studies for often engaging with mobile phenomena in agentless and frictionless ways. Whilst an ontology of surficial networks provides an entry point for engaging with mobile processes beyond the predominantly terracentric focus of mobility studies, it remains only an entry point. The ocean, in its vibrant and motionful materiality, requires a deeper approach to better understand the mobilities that merely appear to be unfolding only on its surface.

Taking a deeper approach to watery mobilities is a second ontological positioning that conceptualises mobile interactions with the ocean in light of its multidimensionality, taking into account the depth and volume of watery spaces. The ocean's distinctive materiality forms the basis of this line of thought. As Sheller (2004) argues, mobility is always located and materialised; it occurs through the rearrangements of the materiality of places. Correspondingly, the ocean is constantly undergoing material reformation, through its currents, waves, tides, spray, saline and thermal stratification, sea ice formation and countless other processes (Peters, 2012; Vannini and Taggart, 2014; Steinberg and Peters, 2015; Deloughrey, 2017; Steinberg et al., 2023). Through a focus on materiality, mobility studies have engaged with the depths and volumes of these watery spaces. On the one hand, several scholars have argued that a true engagement with the ocean as voluminous still lags behind in geographical oceanic thinking and specifically so within the mobilities literature (Steinberg and Peters, 2015; Peters and Squire, 2019). On the other hand, work that has delved *deep* into the ocean's materiality has revealed the ways in which the ocean's voluminous presence is fundamental to understanding mobilities across, over, through, under and within these watery spaces. For example, in Peters' (2014) intervention on the legalities of radio piracy, smaller vessels who were illegally resupplying the anchored radio pirate ship were managing to evade being captured by using shallower routes where the larger surveillance ships would not follow them for fear of grounding. In a related piece of work, Peters (2012) elaborates on the ways in which the motionful nature of the sea has agency, resulting in consequences both for the pirate radio crew aboard the ship (e.g., experiences of seasickness, or needing to stack items carefully in the galley cupboards so they would not fall out when the winds picked up), as well as for their listeners tuning in from land (e.g., when the vinyl records skipped following the rhythm of the sea). Furthermore, as the 2021 grounding of the *Ever Given* in the Suez Canal reminds us, shipping mobilities are inextricable from the voluminous nature of the ocean, which often involves a careful management of its depth (such as in canals, gated straits and shipping lanes at ports; Peters, 2020a) and knowledge of its bathymetry (as in the case of the Arctic, where inaccurate bathymetric charts impede navigation; Section 5.3). When vessels run aground, such as the *Ever Given*'s sister ship, the *Ever Forward* container ship, outside Baltimore in 2022, it is by engaging with the volumetric properties of the sea that these vessels are set free. As 500 containers were removed from the ship (BBC, 2022), this altered the volume of water that was displaced by the ship's hull, re-establishing the ship's buoyancy. In addition, tugboats pulled on the *Ever Forward* during a full moon, a known tactic used to free grounded vessels, as the unusually high tide generated by the moon's gravitational pull temporarily increased the water depth at that location (BBC, 2022; Markkula, 2022). Following this approach, the ocean's agency in shaping the mobilities that occur through it comes to the fore. The ocean is no longer conceptualised as a frictionless background atop which mobilities take place independently of the ocean's mobilities or its voluminousness. Rather, the ocean plays an active role in shaping these mobilities, through the channels, routes, depths and other voluminous qualities that (dis)allow specific types of mobilities to take place in specific ways.

Third, within the watery mobilities literature, some scholars have turned to assemblage theory as a means of bringing together the multiple and overlapping mobilities of human bodies and non-human materialities on the move that characterise watery mobilities. In viewing a phenomenon as assemblage, different (material) parts come together to form a new and unique arrangement which can be durable in time or continuously break apart and come together again (DeLanda, 2006; Robbins and Marks, 2009). Recent work that approaches mobility as assemblages shows how materialities meet to create new material compositions (Anderson, 2014). Anderson looks at the surfed wave as assemblage, where surfers feel they can "*be one with the sea*" (2014: 81 emphasis in original) and the multiple materialities of wind, saltwater, body, wetsuit and surfboard come together in that singular moment that is the surfed wave. Through this approach, non-human entities play a key role in the ways in which mobilities unfold, shifting the focus of mobility studies beyond the anthropocentric focus of other mobilities approaches. In *Floating Coast*, Bathsheba Demuth (2019) paints a historical picture of the assemblages that have repeatedly formed and unformed to shape the Bering Strait region through the past several centuries. In the 1840s, the Bering Sea and other Arctic waters were brimming with whales and seals, attracting ship captains and their crews in search of wealth by hunting and selling whale oil and baleen (Demuth, 2019). The history of the Bering Strait emerges from the assemblages that flow through from plankton in the ocean becoming whale body fat, which is hunted amidst ice and harpoons, refined into whale oil and shipped back to mainland America to light the homes, shops and streets of bourgeoning American citizens (Demuth, 2019). For the Arctic, whaling brought guns, alcohol and metal to a land that had only ever traded in hunted goods and natural fibres. The material attraction of the whale sparked new sociocultural assemblages, where Natives and whites married, or women were left pregnant with children from abusive sailors. In this view, the ocean itself emerges as co-constituted by and connected to broader mobilities of people, objects, currents, winds, waves, marine mammals, aspiring whalers, ocean spray and so on, thereby implicating the ocean within broader mobile assemblages.

Finally, watery mobilities have also engaged an ontology of material dynamism and transformation through water's different physical states. Ocean-focused scholarship has radiated out to include many other forms of water, including in its frozen state (Mentz, 2023). In their work on driving on ice roads (consisting of frozen ocean), Vannini and Taggart (2014) highlight the ways in which the McKenzie River delta and the Beaufort Sea become ice roads during the winter, creating the conditions for a constellation of mobile interactions (between air, water, ice, tyres, driver, passengers and passersby), that are only possible through the transformation of these watery spaces from liquid to frozen solid. Reflecting on watery spaces not just as discretely either frozen or liquid, Vannini and Taggart (2014) also highlight the mobilities that are interrupted during the shoulder seasons of 'break-up' (spring) and 'freeze-up' (autumn). Here, during these periods, the river and sea are not frozen enough to drive on but not liquid enough to sail on, limiting remote communities to access only via air.

Connecting these various ontological orientations to oceanic mobilities is the idea that the ocean has a distinct material, multidimensional and mobile character, and that this character matters in understanding how mobilities unfold in these oceanic spaces. The ocean, long considered an agentless background against which other and more important mobilities occur (c.f. Anderson and Peters, 2014), instead emerges as having agency through the mobilities that it facilitates and those that it impedes. Building on these existing interventions within the literature on marine mobilities, I propose an even more direct appreciation of the ocean as a medium with agency with and alongside which mobilities of other mobile entities intersect and are shaped by the mobilities of the ocean itself, in both its liquid and frozen states. In continuing to push the boundaries of existing marine interventions that also include the frozen aspects of the ocean, I present the idea of 'cryomobilities' to analyse the ways in which mobile encounters between vessels and sea ice play out in the ice-prone waters of the Bering Strait region.

2.4. Cryomobilities

Within the context of this thesis, and building on existing work within mobility studies, I propose ‘cryomobilities’ as a neologism that encapsulates the mobile interactions between vessels and sea ice in icy ocean environments. Like many other neologisms, ‘cryomobilities’ does not reinvent a discipline, nor create a new one altogether; rather, it is the recognition of a specific line of thinking withing existing mobilities literature on oceanic and watery environments, and serves as a consolidating research agenda for bringing together past and future interventions from scholars interested in these research fields.

As the main point of departure that ties together the interventions and elaborations presented in this thesis, the notion of ‘cryo’ makes explicit the ways in which cold or frozen contexts destabilize existing notions and present opportunities for rethinking the geographical relations unfolding in these environments. I draw inspiration from other existing terminology that denotes fields of study that arise out of the recognition that relations (chemical reactions, material properties, geopolitics, and so on) unfold differently in circumstances of extreme cold, including in icy or frozen environments. Some examples of these include the cryosphere (the part of the earth's surface where water exists as ice), cryogenics (the branch of physics interested in the behaviour of materials at very low temperatures), cryobiology (the branch of biology concerned with organisms cooled to temperatures lower than those at which they normally function) and cryopolitics (understanding the importance of ice within geopolitical discourse about changing Arctic security; Bravo and Rees, 2006; https://www.cryopolitics.com/). This specificity and attentiveness to the frozen components of unfolding relations – including geographical ones – must be considered in two ways. On the one hand, whilst ‘cryo’ generalises all frozen and icy aspects, it must not be taken as a generalising term for the insights that emerge out of cryo-specific research. In other words, not all ‘cryo’s are the same, and the unique relations of each circumstance must be accounted for and acknowledged in their own right. In fact, as the empirical chapters of this thesis reveal, not all interactions between vessels and sea ice are the same, despite all being shaped and conditioned by the ‘cryo’ of these encounters in one way or another. On the other hand, the specificities of the insights gained by focusing on cold environments does not necessarily have to be limited to the frozen realm. Thinking with the cryo is envisioned as a starting point, a source of inspiration for imagining and analysing relations through a lens of opportunities that a temperate environment might not offer. As such, I do not advocate for thinking from the cryo as a preferable analytical lens that sits in opposition to temperate thinking and trumps all that came before it; rather, it is a complementary line of inquiry that can shed light not only on processes unfolding in icy environments, but inspire new ways of thinking about processes in temperate environments too.

As a starting point, this thesis responds to the call by Peters and Squire (2019) for mobility studies to more seriously engage with the mobilities taking place amidst frozen ocean environments. Sea ice, and the mobilities that emerge from and in relation to it, are on the one hand connected to the liquid ocean because this is where sea ice forms and becomes tied to broader oceanic processes of bathymetry, water temperature and circulation (among others) that create the conditions for sea ice to exist. On the other hand, sea ice is distinct from the liquid ocean in that its frozen materiality diverges from that of the liquid ocean. As such, the frozen ocean differs from a liquid ocean in both its own mobilities, as well as the mobilities that it facilitates (or impedes) of other mobile entities (e.g., ships, marine mammals and people). Throughout this thesis, I draw on both the connections and distinctions between frozen sea ice and the liquid ocean to analyse the ways in which cryomobilities unfold amidst the ice-prone waters of the Bering Strait region.

In this sense, sea ice offers a productive arena for exploring mobilities through the diverse material manifestations of the ocean. Sea ice itself is born out of specific material encounters of atmospheric and oceanic processes that produce sea ice in different space-time patterns across the Arctic (Onarheim et al., 2018). The Bering Sea, in particular, exhibits its own trends and processes for sea-ice formation and persistence (Danielson et al., 2011; Brown and Arrigo, 2012; Cavalieri and Parkinson, 2012), showing how the material realm is both crucial and specific in allowing particular surfaces, volumes and, subsequently, mobilities to take shape. Sea ice both emerges out of material mobility and is implicated within broader material mobilities. It both inhibits mobility (e.g. shipping vessels struggle to navigate heavily iced waters) and permits it (e.g. Indigenous hunters using it as a platform for fishing and hunting marine mammals, and for transport between communities). Looking at sea ice therefore allows us to step across different networks of mobilities and the ways in which they intersect in the spaces that they share, moving away from traditional mobility studies that tend to focus on a specific 'type' of mobility (e.g. railway transport, or shipping) and analysing the material consequences of these mobilities. Here, the focus stems from specific materialities that are themselves products of mobile environments and encounters, and that, in turn, shape, allow and inhibit various other forms of mobility, including those of vessels.

In analysing how mobile encounters between sea ice and vessels unfold in the Bering Strait region, cryomobilities conceptualises the ocean as an interconnected and multidimensional mobile environment across multiple scales. Sea ice, as a material transformation and extension of the liquid ocean, is always in a process of becoming and dissolution across space and time, undergoing continuous structural alterations through snow accumulation, lead formation, wind advection, brine rejection, and countless other ice-related processes (Steinberg et al., 2023). On a macro scale, sea ice is connected to broader processes that determine its spatiotemporal patterns. Atmospheric circulation, bathymetry, water column stratification, ocean currents, tides and winds all contribute to creating the conditions that determine its formation and dissolution through the annual sea-ice cycle (e.g., Zhang et al., 2010; Sun et al., 2019) (Section 3.4). Through this understanding, the multidimensional and volumetric properties of the icy ocean come to the fore, not just in the volume that sea ice itself occupies, but also in the icy ocean's bathymetric depth and atmospheric height that contribute to determining the properties and timings of sea-ice mobilities.

On a molecular scale, sea ice is also always in motion, to varying extents and in various ways. The decrease in temperature that leads to freezing is in itself a reduction in molecular movement, which eventually (at or below the freezing point) leads to a stable crystal lattice where molecules are locked into position (although continue to vibrate). Yet, as Nail (2018) reminds us, even substances that appear to be solid and stable (with greatly reduced molecular and viscous mobility) are still always moving. Indeed, even after freezing, sea ice continues to expel salt throughout its lifetime. This process speaks not only to the ways in which sea ice is internally mobile through brine expulsion, but also to how the material character driven by the different stages of brine expulsion shapes sea ice's ability to move, float, form and crack, and how people and ships are mobile in relation to sea ice's various states. For example, multiyear ice (sea ice that has survived at least one summer melt season) has had time to expel most, if not all, of its salt, making it a perfect source of drinking water for Indigenous hunters spending long periods of time away from shore (George et al., 2004). Due to its lack of salt, multiyear ice is also very hard and very brittle. For ship captains, this means avoiding patches of multiyear ice, as it can cause significantly more damage to the vessel than other types of younger sea ice (Kubat and Timco, 2003). As some Indigenous hunters have reported, they too have also become wary of large patches of multiyear ice, once considered the safest and strongest type of ice to use as a hunting platform, after an event where pack ice blew into shorefast ice consisting of multiyear ice, and its brittle qualities made it shatter into pieces, instead of flexing and deforming in more elastic ways as younger and more saline ice would (George et al., 2004). Arising from these multiple processes of sea ice formation, Steinberg et al. (2020: 86) point out that "sea ice can never be defined as simply frozen water. Sea ice exists amid processes of freezing, melting, and other vectors of transformation and is thus always in a state of formation and dissolution." As such, in considering the mobilities of sea ice and its broader connections to an icy ocean, cryomobilities also moves beyond a binary understanding of the ocean as either exclusively solid or exclusively liquid, and instead considers the ways in which sea ice exists in heterogenous conformations of different materialities.

Intersecting these understandings of frozen ocean mobilities as I propose through a cryomobilities framework, I further conceptualise the icy ocean as having agency. Bear and Bull (2011: 2262) argue that research concerned with the hydrosphere should be attentive to water's agency through its materiality: "Water is an agent and its materiality matters." Sea ice's materiality, distinct and yet related to that of a liquid ocean, presents new opportunities for analysing mobilities in light of the material specificities of a partially frozen ocean. As such, cryomobilities is concerned with the ways in which "water […] actively shapes new geographies" (Bear and Bull, 2011: 2261). Specifically, I employ cryomobilities in the context of this thesis to better understand the ways in which the materialities of a frozen ocean interact in agentful ways with the materialities and mobilities of vessels moving through these (partially) icy ocean spaces. In response to Schiller's (2013) critique of mobility studies as often engaging with mobile phenomena in agentless and frictionless ways, this thesis' concern with the specific materialities of icy waters contributes to advancing mobility studies as attentive to the frictions and struggles *en route*. Cryomobilities moves away from understanding the ocean and the vessels that move through it as distinct and independent processes that somehow glide past each other without much interaction. In this sense, the icy ocean ceases to be a 'background' altogether, and instead becomes a co-constituting component of the mobile ensemble formed through the mobile interactions between vessels and sea ice.

2.5. Conclusion

In this chapter, I have laid out the various ways in which the existing mobilities literature conceptualises the interactions between mobile entities and the (mobile) backgrounds amidst which these mobilities take place. In analysing the complex interactions between vessels and the multiple states of ice-prone oceans in the Bering Strait region, in this chapter, I have highlighted the limitations of existing ontological orientations within mobility studies in accounting for entities that are mobile within environments that are themselves mobile too. The traditional frameworks, largely centred around human-centric perspectives and assuming a static background, fail to encapsulate the multidimensional and dynamic nature of oceanic spaces, particularly in their frozen states. Through the proposed lens of cryomobilities, this chapter offers a theoretical framework that acknowledges and is attentive to the ocean's agency. The agency of watery spaces as manifested through its mobility and its multidimensionality (of frozen surface, bathymetric depth and atmospheric height) becomes a key co-constituent that influences mobile interactions and shapes new geographies amidst frozen spaces.

Through the concept of cryomobilities employed in this thesis, I begin to address some of the theoretical gaps present in current analyses of mobilities in watery spaces and, specifically, within frozen oceanic spaces. In this chapter, I have argued that analysing marine mobilities in icy ocean spaces requires engaging with the watery spaces in, through, with, across, over and under which they occur, blurring established boundaries between the mobile entities under scrutiny and the backgrounds against which they move. Through the notion of cryomobilities, this research contributes to rethinking existing understandings of vessel mobilities amidst frozen watery spaces, emphasising the need to acknowledge the ever-shifting, multi-state and agential nature of icy waters in the Arctic and beyond. By recognizing the ocean's constant motion, volume and agency, cryomobilities departs from viewing mobile interactions between vessels and the ice-prone ocean as surficial networks flowing frictionlessly over its surface. Instead, cryomobilities engages with the character of the ocean, paving the way for a more nuanced understanding of the multifaceted mobile geographies that emerge out of these encounters.

3

Study Area: The Bering Strait region

3.1. Introduction

The Bering Strait is a global gateway that facilitates human and non-human interactions across distant regions (Waloven et al., 2023). At this point of intersection, the Bering Strait and its surrounding waters, people and land masses have for millennia been implicated within global mobilities and flows of people, animals, water and ice. As the study area of this thesis, in this chapter I provide background context to the Bering Strait region, as a dynamic arena with overlapping mobile systems that offers an exciting setting for analysing mobile interactions between vessels and sea ice.

The rest of the chapter is structured as follows. In Section 3.2, I provide an overview of the physical geography of the Bering Strait region, focusing on the conformation of land masses and the ocean, as well as the bathymetry, mountain ranges, rivers and the annual sea-ice cycle. These aspects of the geography of the Bering Strait region contribute to the processes of sea ice mobilities that are discussed in the subsequent sections. Then, in Section 3.3, I trace some histories of the Bering Strait region. I view this through the lens of how the mobilities of the surrounding ocean spaces, particularly in their frozen form, have shaped the histories of this region. In particular, I highlight that even processes unfolding primarily on land, including the construction of the 800-mile Trans-Alaska Pipeline and the subsequent establishment of the Alaska Native Claims Settlement Act (ANCSA), emerge from the (im)mobilities imposed or made possible by the presence of sea ice in the surrounding ocean. In Section 3.4, I discuss the ways in which sea ice is mobile and constantly changing throughout the annual cycle, by reviewing the existing literature on sea-ice trends and the various forcing mechanisms that drive them. Within this section, I address pan-Arctic sea-ice trends (Section 3.4.1), as well as sea-ice behaviour specific to the Bering Sea (Section 3.4.2), as the two are not always aligned. In looking at sea ice in the Bering Sea, I go into further detail on the atmospheric processes that contribute to localised sea-ice behaviour (Section 3.4.2.1), the strong interannual variability that characterises sea-ice patterns in this area (Section 3.4.2.2), how sea-ice patterns in the Bering Sea might point to a decoupling of sea-ice processes between the north and south of the Bering Strait (i.e., between the Arctic Ocean and the Bering Sea; Section 3.4.2.3), and what current projections of climate change suggest about the future of sea ice in the Bering Strait region (Section 3.4.2.4).

3.2. Geography

The Bering Strait lies between Alaska, United States (to the east), and Siberia, Russia (to the west), as shown in Figure 3.1. It connects the Chukchi Sea in the north with the Bering Sea in the south. On a broader scale, the strait links the Arctic Ocean to the Pacific Ocean. From a navigational perspective, vessels use the Bering Strait to transit between the Chukchi Sea and the Bering Sea, as it is the only passageway in and out of the Arctic Ocean on the Pacific side. It is a relatively narrow strait, spanning a mere 85 km (53 miles) at its narrowest point (between Cape Dezhnev on the Russian Chukchi Peninsula, and Cape Prince of Wales in Alaska on the American side). It is also relatively shallow, at around 30 to 50 m (98 to 164 feet) in depth. The islands of *Imaqłiq* (Big Diomede Island, Russia) and *Iŋalik* (Little Diomede Island, United States) sit in the middle of the strait, effectively dividing it into two narrower navigational corridors on either side. This research is centred around the Bering Strait region and includes the surrounding waters of the Chukchi Sea and the northern parts of the Bering Sea (Section 4.2.1.4). As this research is interested in the encounters between sea ice and vessels, the study area does not explicitly stretch past the coast onto land. Whilst at various points in this thesis I recognise that ocean encounters are connected to processes on land, the overall scope of this thesis and, therefore, the study area, still remains very much marine. This study area, centred around the Bering Strait and extending to the surrounding seas, is henceforth referred to as the ‘Bering Strait region’.

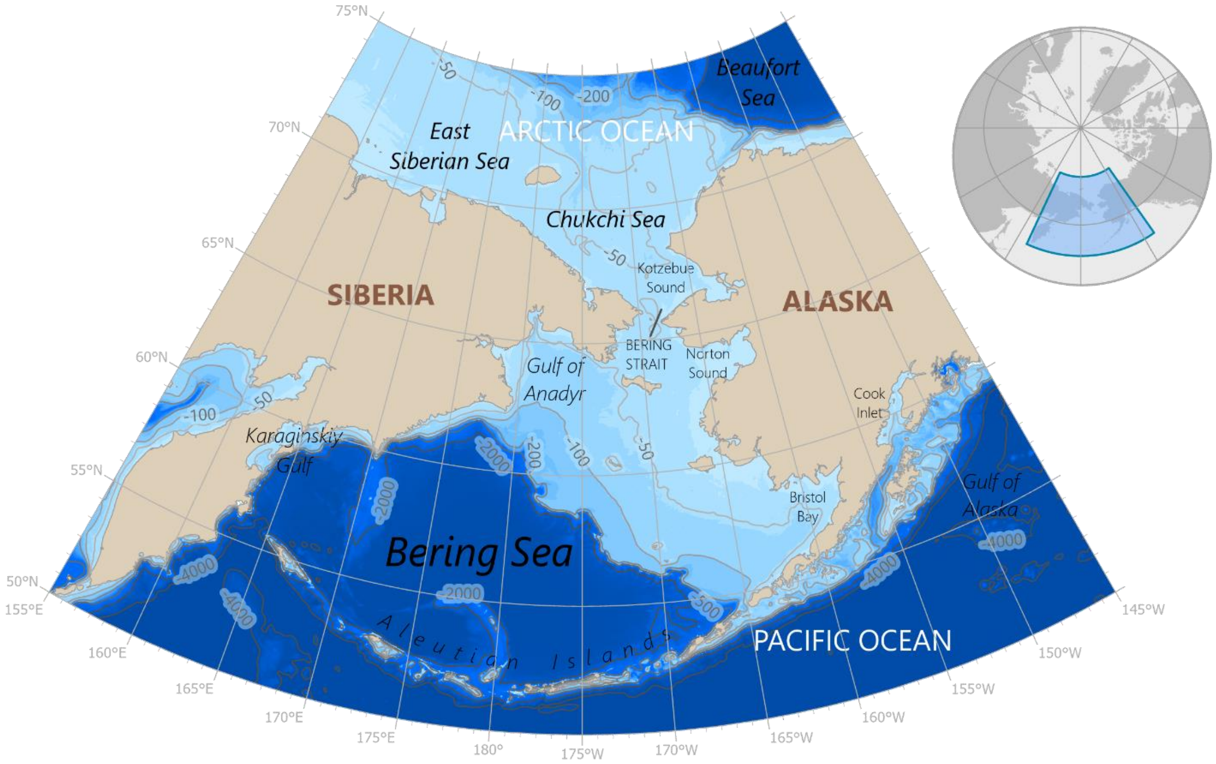

Figure 3.1 – The Bering Strait and surrounding oceans and land masses. Source: coastline and labels from Natural Earth (www.naturalearthdata.com); bathymetry from GEBCO (2022).

The bathymetry in the Bering Strait region is characterised by extensive shallow shelves that drop steeply into deeper waters. The Chukchi Sea is for the most part between 50 and 100 m deep, extending for about 1000 km north of the Bering Strait. It becomes even shallower in the west towards the East Siberian Sea, and deeper in the east until it steeply drops where it becomes the Beaufort Sea. Similarly, the Bering Sea is characterised by a broad and shallow continental shelf on the eastern side of the Bering Sea (up to 200 m deep), spanning some 1000 km north-to-south and around 500 km westward from the Alaskan coast. Where the shelf ends in the central Bering Sea, there is an abrupt drop in the seabed down to 3000 m. The bathymetry in the Bering Strait region is of significance, as a shallower water column cools faster when air temperatures drop, especially during winter months, which aids sea-ice formation (Zhang et al., 2010).

Sea ice in the Bering Strait region follows a relatively consistent annual cycle. In summer (July – September[6]), the Bering Sea is ice free (Figure 3.2) and the water column reaches its maximum heat content in early-mid September (Zhang et al., 2010). In October, sea ice begins to form in shallow coastal regions in the north, and by November has usually advanced well into the Chukchi Sea. Sea ice continues to grow quickly in November, covering most of the shallow northern shelf of the Bering Sea

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[6] When dealing with Arctic sea-ice conditions, seasons are usually defined as follows: winter (Jan – Mar), spring (Apr – Jun), summer (Jul – Sep) and autumn (Oct – Dec), as used in NSIDC's calculations for seasonal sea-ice trends (Parkinson et al., 1999).

by December (Frey et al., 2015; Wendler and Wong, 2019). The Chukchi Sea is usually completely covered between November and December, whereas maximum sea-ice extent in the Bering Sea can be anytime between January and May, although typically between mid-February and early April (Stabeno et al., 2012a). The month of greatest sea-ice melt in the Bering Sea is May, bringing the entire Bering Sea to once again be ice free by late June (Wendler et al., 2014). Throughout the summer, sea ice continues to retreat north through the Bering Strait and into the Chukchi Sea, which becomes ice free typically by August.

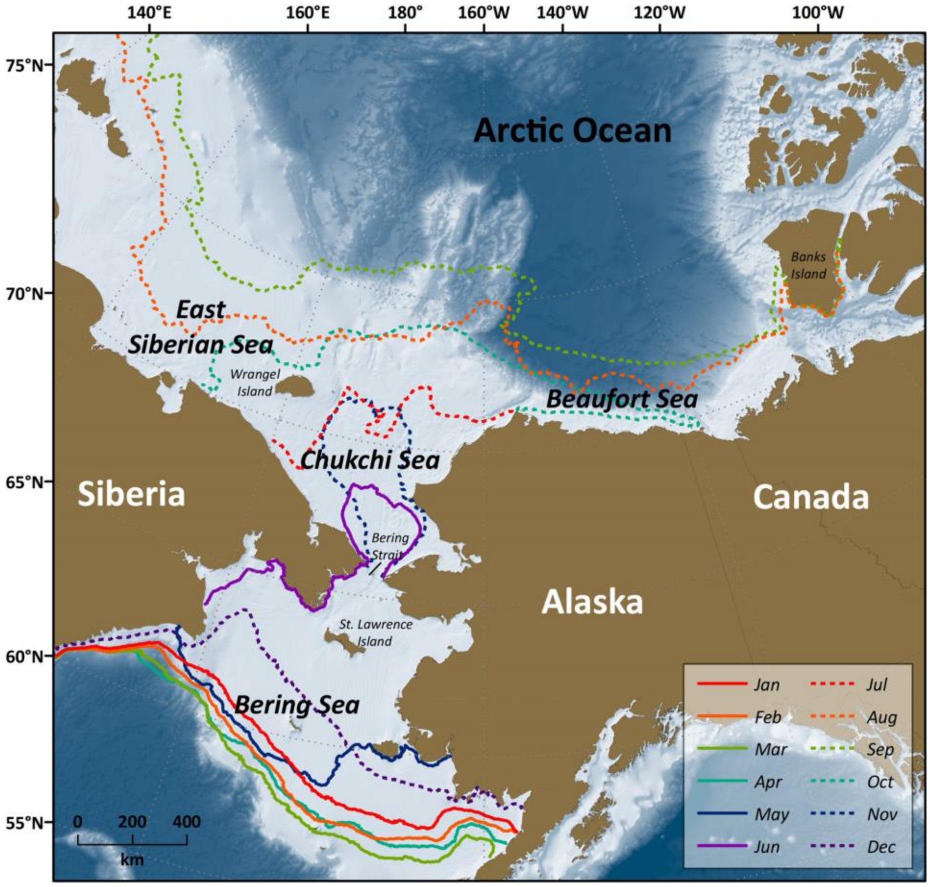

Figure 3.2 – *Mean monthly ice edge position (defined using a 15% sea-ice concentration threshold) in the Bering Strait region, based on AMSR-E satellite data from 2003 to 2011 (January–September) and 2003 to 2010 (October–December). Source: Frey et al. (2015).*

Surrounding these waters, both the Russian and American mainland boast extensive mountain ranges. In Siberia, these include the Koryak Range on the Chukchi Peninsula and the volcanic Sredinny Range on the Kamchatka Peninsula. In Alaska, the Brooks Range and the Alaska Range provide some elevation to an otherwise mostly flat topography of tundra plains, especially in the northern half of the state. This topography feeds large river systems that end up in the surrounding seas. Some of the largest include the Anadyr River feeding into the Chukchi Sea, and the Yukon River feeding into the Bering Sea. The presence of large rivers is fundamental for supporting the region's biodiversity, especially by providing spawning grounds for six of the world's seven species of Pacific salmon. In addition, freshwater influx from these rivers is an important factor that impacts sea-ice formation and breakup in the spring (e.g., Mahoney et al., 2021). Combined, the thriving biodiversity and reliable sea-ice cycle provide ideal conditions for marine mammals. Notable in this region are the migrations of bowhead whales (*Balaena mysticetus*), Pacific walrus (*Odobenus rosmarus divergens*) and ringed seals (*Pusa hispida*) that follow sea ice as it retreats northwards in the summer, and extends southwards in the winter, crossing the Bering Strait twice each year (Audubon Alaska, 2011; Hauser et al., 2018). These mobilities are also important for the Indigenous hunters who rely on these migrations for yearly subsistence practices (Huntington et al., 2016), as well as for avoiding collisions with vessels that seek to traverse the region seasonally (Huntington et al., 2015; Wilson et al., 2017).

Protecting this area's biodiversity is a key concern for policymakers in this region. The recent increase in shipping traffic through the Bering Strait, for example, has led the International Maritime Organisation (IMO) to define new shipping routes in 2018 to guide vessels through the strait as well as in the Bering Sea, aimed at reducing the risks of incidents and protecting the marine environment and local fishing activities (IMO, 2018). Of particular note when it comes to managing the marine environment in this region is that the international border between the United States and Russia, as well as the International Date Line, run north-south through the middle of the Bering Strait, extending into the Chukchi and Bering Seas. Relations between the United States and Russia extend far into the region's history, as I discuss in further detail in the next section.

3.3. An Oceanic History of the Bering Strait

The Bering Strait is a key site featuring in a series of much-debated hypotheses relating to human origins on the North American continent. Western archaeologists still consider the origins and identities of people in America to be largely a mystery (Naske and Slotnick, 2014; Braje et al., 2017). Over the past few decades, the field has become a buzz of competing theories to explain who the 'first Americans' were and where they came from, theories that are debunked or reinforced with every new archaeological discovery (Gannon, 2019). The Clovis-first theory suggests that Siberian populations used a mostly ice-free corridor over the Bering Land Bridge to migrate from the Asian to the American continent during the last ice age around 13,500 years ago (Braje et al., 2017). The Bering Land Bridge, or Beringia, is a portion of seabed between Siberia and Alaska that became exposed during the last ice age as sea levels dropped[7] (Clark and Mix, 2002; Lambeck et al., 2014). After

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[7] During the last ice age, sea levels dropped by up to 135 metres compared to present-day levels due to the vast amount of water that was exchanged from the ocean to ice sheets (Lambeck et al., 2014). However, sea-level change during glacial periods is also impacted by planetary responses to surface (ice and ocean) mass loading, leading to deformation of the Earth's surface and perturbations to both the gravitational field and rotation axis

crossing, they are then believed to have quickly spread over land all the way into South America following an ‘ice-free corridor’ between two ice sheets covering much of present-day Canada and some northern American states (Figure 3.3). Around 10,000 years ago, as the ice melted at the end of the last ice age (which began shortly after 18,000 years ago; Dalton et al., 2020), it caused sea levels to rise, and the Bering land passage became submerged to become the present-day Bering Strait. However, archaeological findings at other sites much farther south, such as Monte Verde at Chile’s southern coast, dating back at least 16,000 years, suggest that humans were on the continent long before the Bering Land Bridge became traversable (Gannon, 2019). This has led archaeologists to the Kelp Highway hypothesis, suggesting that early humans may not have exclusively crossed over on a land bridge, but may have instead taken an earlier seafaring route following the nutrient-rich Pacific shoreline from Beringia southwards (Erlandson et al., 2007). Sea level rise since the last ice age has meant that the prehistoric sites for the coastal route hypothesis are on the seabed, making the Kelp Highway theory a challenging one to prove from archaeological records (Hoffecker and Scott, 2007; Potter et al., 2018). Nonetheless, what does appear to be a common understanding in this field is that no hominids ancestral to the modern humans were present in the Americas, making it a place that was reached from other continents, rather than a site of prehistoric human evolution (Naske and Slotnick, 2014).

(Borreggine et al., 2022). This leads to uneven spatial and temporal patterns of sea-level change, meaning that whilst there may have been a significant drop in global *mean* sea level, some coastlines may have witnessed slower rates of decrease. Unfortunately, archaeological models of paleoenvironments commonly use a “bathtub” model to reconstruct sea level, assuming it rises and falls based on a eustatic (global average) value over time, therefore disregarding the geophysical complexities of how sea level may have behaved differently on smaller scales, which in turn influences the availability and feasibility of migration routes (Borreggine et al., 2022). The fact that Western migration theories propose exact timings and very specific migration corridors, yet these are based on simplified models of past sea-level change, further exposes the fickle foundations of such theories.

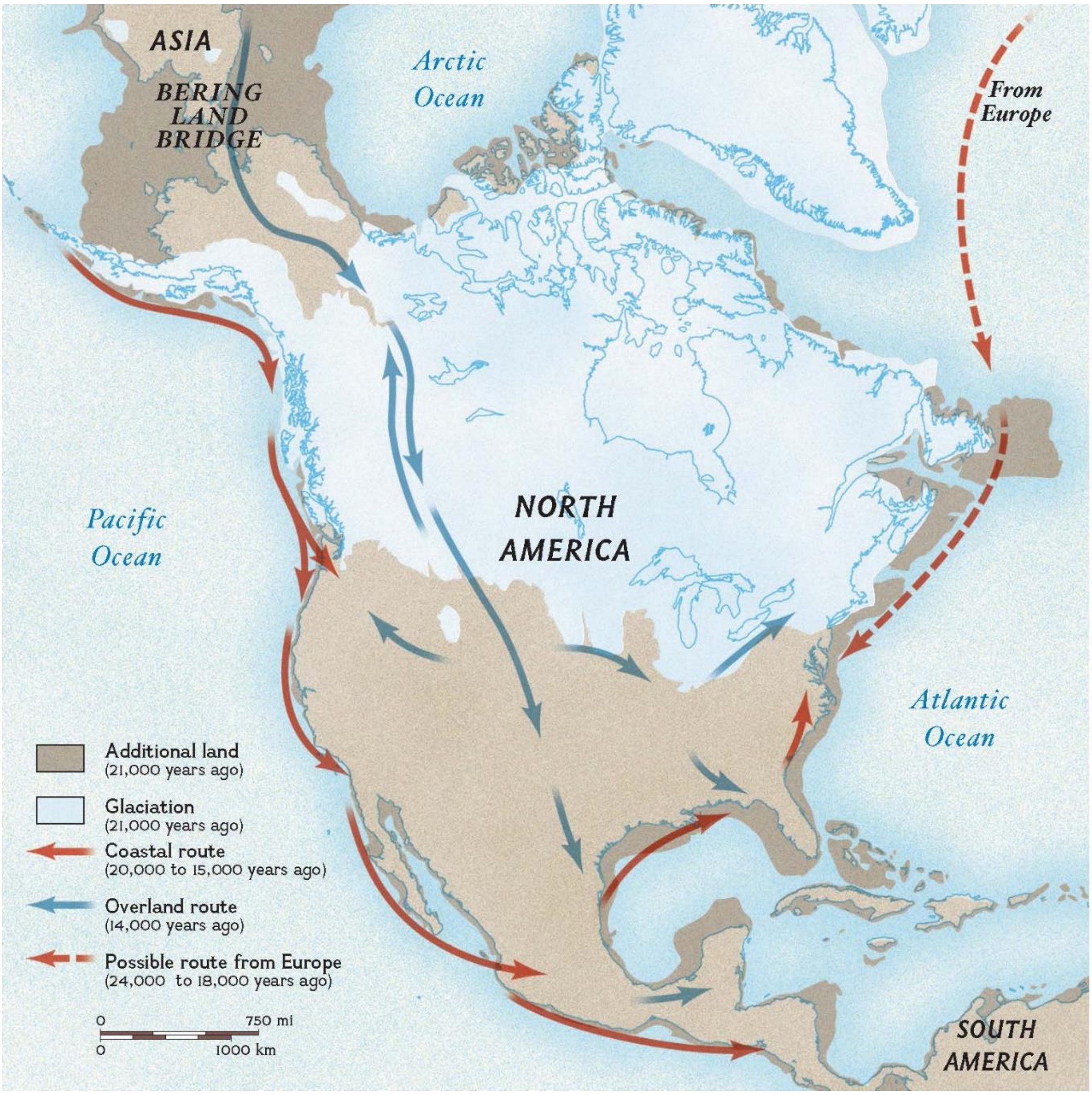

Figure 3.3 – Map of North America and the Bering Land Bridge during the last ice age. The Bering Land Bridge connected the continents of Asia and North America as the last ice age lowered sea levels. The Clovis-firth theory suggests that the ancestors of today's Native Americans reached North America by walking across this land via an overland route, whereas the Kelp Highway theory proposes an earlier migration via a coastal route. Source: National Geographic (2002).

Indigenous accounts of origin stories provide a different historical account. Native American oral histories place a greater emphasis on the back-and-forth exchange across the Bering Land Bridge, rather than a single, unidirectional transit from eastern Asia to the American continent (Smith, 2020). Where oral histories mention a journey, it is usually by boat, rather than by foot, and often consists of several journeys from a variety of different places (such as Polynesia and Greenland), rather than just Asia (Carroll, 2007). Indigenous histories also tell of endless expanses of ice as far as the eye could see, stretching across North America from ocean to ocean (Dewar, 2011), and many oral histories throughout North America recount periods of extensive flooding, as well as widespread volcanic activity (Churchill, 2005). These geophysical events are meticulously recorded both in Western and

Indigenous accounts, and some have argued that these can be cross-referenced to place the timing of human presence on this continent to at least 100,000 years ago, when extensive lava flows are estimated to have ended (Churchill, 2005; Deloria, 2018). As such, what today is the Bering Strait features as a controversial site of colonial narratives, where the multiple and interspersed historical marine mobilities of Indigenous memory contest with a Western narrative that favours a singular and monolithic terrestrial crossing.

Despite the disputed origin stories, what is certain is that people lived in Alaska for thousands of years before the first arrival of outsiders in the 1780s, and the seas surrounding the Bering Strait provided opportunities for travel and trade between communities. People were mobile across the Bering Strait since time immemorial (at least as far back as anyone can meaningfully trace), and families stretched across both shores (Bancroft, 1886; Jolles, 2006). These mobilities also included established trade networks with other Native communities across the Bering Strait, through which residents bartered manufactured goods such as beads, kettles and knives from Asia in exchange for furs from Alaska (Jolles, 2006; Worl, 2016).

Detailed knowledge for navigating the ocean in both its liquid and frozen state (as well as all the mixed stages in between) was a necessity, and the plentifulness of the ocean made survival in the tough Arctic environment possible. Natives in Siberia and Alaska became proficient at living along the coast, becoming skilled at hunting marine mammals from sea ice, or by kayak in the open ocean (Worl, 2016). People also lived on and hunted from many of the islands in the Bering Sea, including *Sivuqaq* (St Lawrence Island), *Iŋalik* (Little Diomede Island) and *Imaqłiq* (Big Diomede Island), making them talented seafarers (George et al., 2004; Jolles, 2006). The seasonal mobilities of marine mammals migrating through the Bering Strait twice each year (Figure 3.4) provided coastal communities with enough calorie-dense whales, walrus and seals to support a settled village (bowhead whales carry more calories by weight than any other Arctic species on land or sea)[8] (Demuth, 2019). As such, mobile competence through the ocean geared at harnessing the ocean's migrating bounty was the source of reliable subsistence livelihoods for Native people in the Bering Strait region. However, the ocean's mobile resources also brought mobilities of outsiders, imposing regime after regime of colonial exploitation and abuse.

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[8] By contrast, communities in the Alaskan interior were nomadic, transiting between semi-permanent settlements aligned to their subsistence practices. These typically consisted of winter camps to hunt migrating caribou, and summer fishing camps at river deltas or further inland to catch salmon heading up the river to spawn in freshwater lakes (van Lanen, 2018).

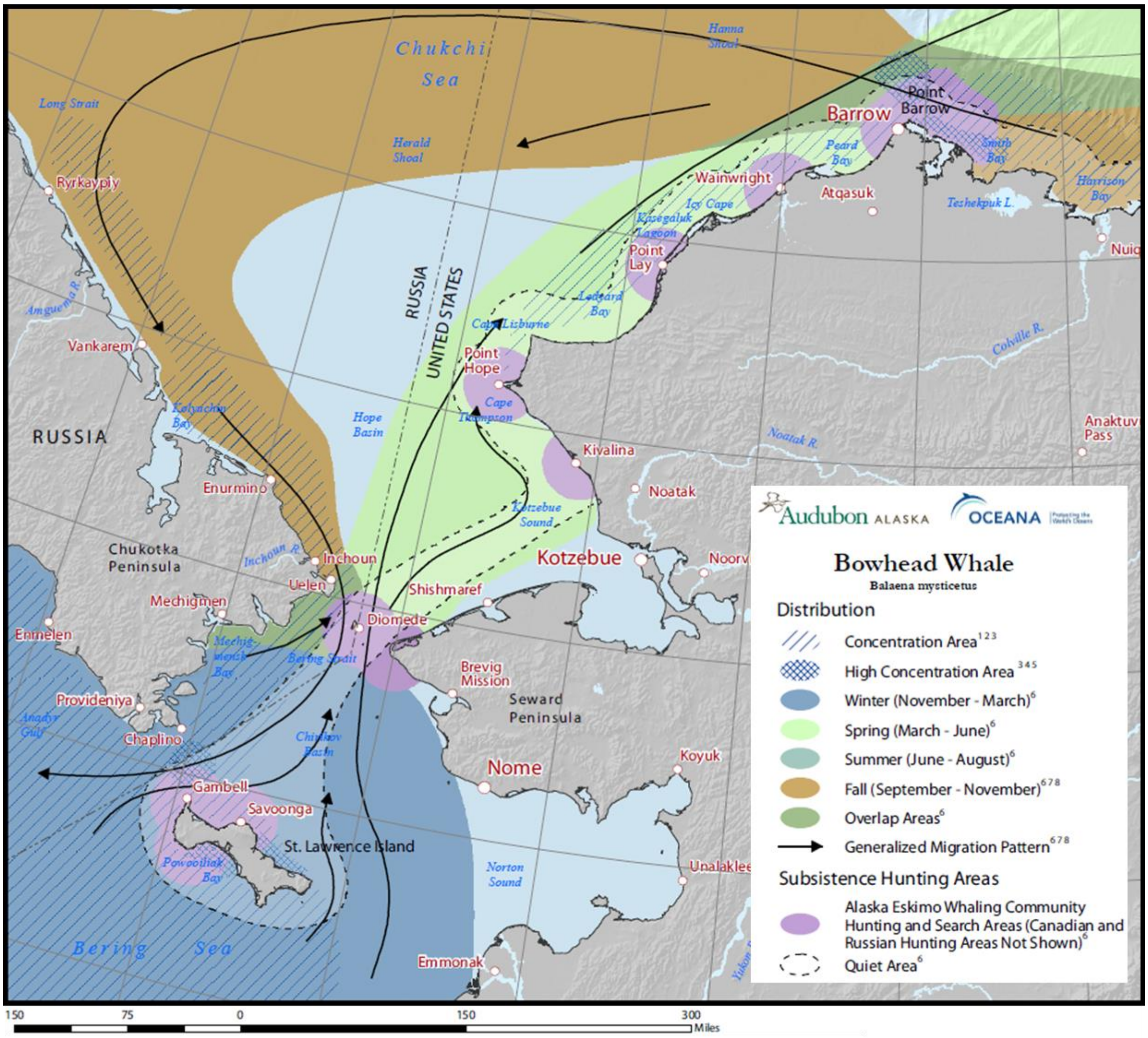

Figure 3.4 – Bowhead whale migration patterns through the Bering Strait. Highlighted in purple are the Native whaling communities along the coast. Source: Audubon Alaska (2011).

First came the Russians (Figure 3.5). Their quest for sea otter fur to be sold at Chinese markets pushed Russian hunters to sail onto the shores of Alaska, marking the first encounter between Alaskan Natives (those inhabiting the Aleutian Islands) and outsiders in the 1780s (Worl, 2016). Following the fur trade, Russia continued east along the Aleutian chain, all the way to Kodiak Island and the Gulf of Alaska. Russian dominance over Alaska was a violent and exploitative affair. Entire villages were forcibly relocated to areas where hunting was better suited to the migratory mobilities of the species that the Russians desired, and Natives were subjected to forced labour to harvest the animals. A notable example is men from the Aleutian Islands being moved to the isolated and until then uninhabited Pribilof Islands for fur seal hunting, whilst the women were held as hostages (Veltre and McCartney, 2002). During the 1800s, the Russians expanded north along the coast as well as inland, in further search of fur-bearing animals.

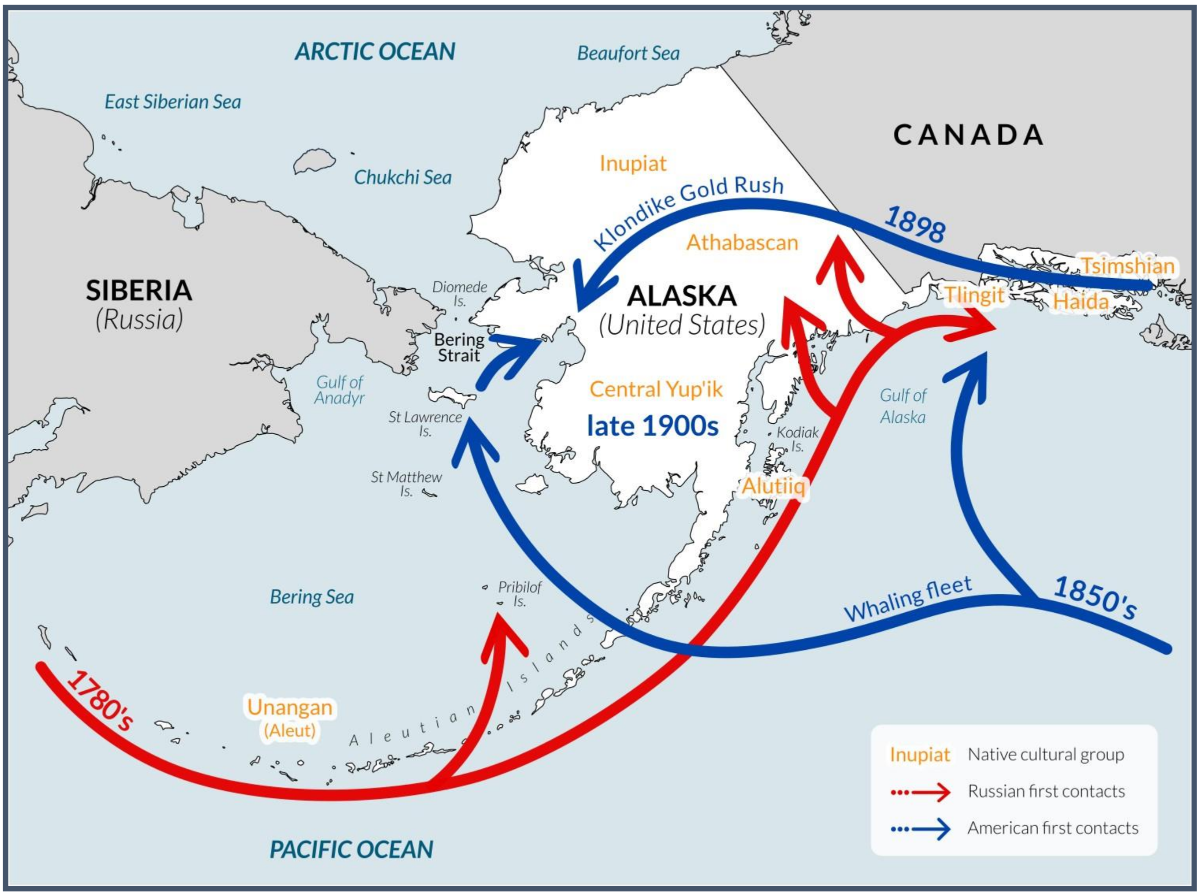

Figure 3.5 – *Map showing the progression of first encounters of Westerners with Native communities in the Bering Strait region (history and timeline from Worl, 2016).*

Then came the Americans. In the 1850s, American whalers arrived in the Bering Sea, in search of valuable whale blubber and baleen from the seemingly boundless ocean (Demuth, 2019). Between 1849 and 1914, the American whaling fleet decimated the bowhead whale population in the Bering Sea from 23,000 to a mere 1,000 (Woodby and Botkin, 1993). The ocean's annual freeze cycle dictated whalers' mobilities, allowing them to sail north during warmer months, and pushing them back south at the end of the short Arctic summer. Those who persevered in the shoulder seasons, intent on maximising their profits, risked finding themselves unprepared for the unpredictable Arctic weather: wooden vessels at the time were not built to withstand a frozen ocean, and risked getting crushed between ice floes. When such misfortunes did occur, it was the Natives who would come to their rescue, and they would feed, clothe and house entire ship crews over winter (Demuth, 2019). The Natives' affinity with the stubborn materialities of the winter ocean made them capable of making their way through an unpredictably mobile environment that the inexperienced whalers hadn't quite become attuned to yet. As such, whilst the ocean lured in whalers who pursued its profitable resources, the economic success that whalers so dearly desired could only be achieved through detailed knowledge and skills in understanding and navigating the ocean's constant material flux.

The mobilities that were made (im)possible due to the ocean's cyclical transformation between its liquid and frozen form also dictated processes on land. During the summer months, the liquid ocean provided easy access to the Alaskan coastline, thus much of Russian and American exploration had come via the sea. As a result of this, many Indigenous communities living in the interior had remained oblivious to Russian rule over their lands, as well as subsequent American rule when Russia sold Alaska to the United States in 1867 for $7.2 million 1987 US Dollars (Figure 3.6) (Hosley, 1981)[9]. With the Klondike Gold Rush of 1898, thousands of hopeful gold seekers arrived in Alaska and moved inland to regions that had largely been spared of contact with Westerners (Worl, 2016). Unfortunately, settler wanderings both along the coast and inland were accompanied by the alcohol they brought with them, a blight that continues in Alaska to the present day.

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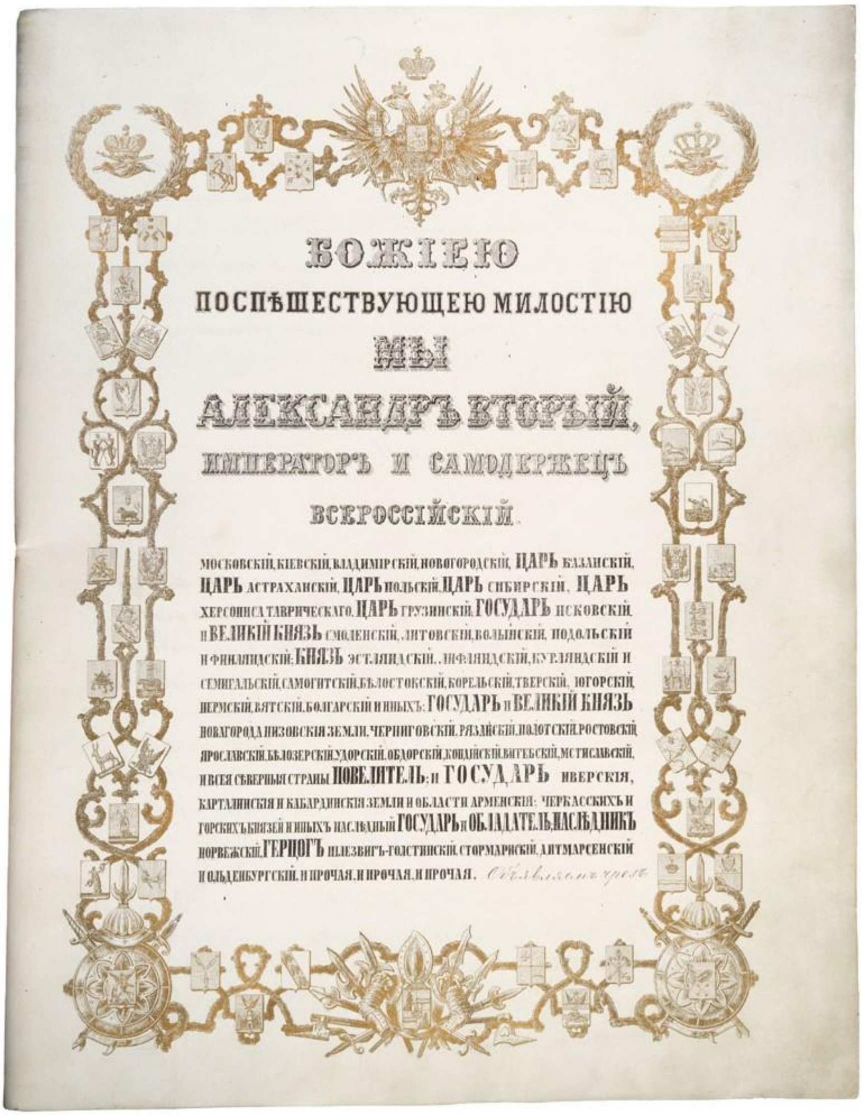
[9] Those who did know about the purchase were angered by it. The Tlingit, for example, who had strenuously defended the ownership of their lands (including their defeat of the Russians in 1802), vividly opposed the Alaska purchase: if the United States wanted their land, they should have paid them, not the Russians (Worl, 2016). Undoubtedly, the exploitative nature of the Alaska Purchase was felt most strongly by Alaskan Natives, and as such their opposition was the strongest. For entirely different reasons, others were also unhappy with the transaction. The Alaska Purchase was driven by Russia's realisation that defending Alaska against American presence in the south and British rule in British Columbia in the east would be unfeasible. Conveniently, the United States took this as an opportunity to expand its own influence while reducing that of Russia. As such, Russians were upset at having ceded land to the United States, and Americans considered it an expensive folly for the acquisition of a frozen wasteland (*Limes*, 2019).



БОЖІЕЮ
ПОСПѢШЕСТВУЮЩЕЮ МИЛОСТІЮ
МЫ
АЛЕКСАНДРЪ ВТОРЫЙ,
ИМПЕРАТОРЪ И САМОДЕРЖЕЦЪ
ВСЕРОССІЙСКІЙ

МОСКОВСКІЙ, КІЕВСКІЙ, ВЛАДИМІРСКІЙ, НОВОГОРОДСКІЙ, ЦАРЬ КАЗАНСКІЙ,
ЦАРЬ АСТРАХАНСКІЙ, ЦАРЬ ПОЛЬСКІЙ, ЦАРЬ СИБИРСКІЙ, ЦАРЬ
ХЕРСОНИСА ТАВРИЧЕСКАГО, ЦАРЬ ГРУЗИНСКІЙ, ГОСУДАРЬ ПСКОВСКІЙ
И ВЕЛИКІЙ КНЯЗЬ СМОЛЕНСКІЙ, ЛИТОВСКІЙ, ВОЛЫНСКІЙ, ПОДОЛЬСКІЙ
И ФИНЛЯНДСКІЙ; КНЯЗЬ ЭСТЛЯНДСКІЙ, ЛИФЛЯНДСКІЙ, КУРЛЯНДСКІЙ И
СЕМИГАЛЬСКІЙ, САМОГИТСКІЙ, БѢЛОСТОКСКІЙ, КОРЕЛЬСКІЙ, ТВЕРСКІЙ, ЮГОРСКІЙ,
ПЕРМСКІЙ, ВЯТСКІЙ, БОЛГАРСКІЙ И ИНЫХЪ; ГОСУДАРЬ И ВЕЛИКІЙ КНЯЗЬ
НОВАГОРОДА НИЗОВСКІЯ ЗЕМЛИ, ЧЕРНИГОВСКІЙ, РЯЗАНСКІЙ, ПОЛОТСКІЙ, РОСТОВСКІЙ,
ЯРОСЛАВСКІЙ, БѢЛОЗЕРСКІЙ, УДОРСКІЙ, ОБДОРСКІЙ, КОНДІЙСКІЙ, ВИТЕБСКІЙ, МСТИСЛАВСКІЙ,
И ВСЕЯ СѢВЕРНЫЯ СТРАНЫ ПОВЕЛИТЕЛЬ; И ГОСУДАРЬ ИВЕРСКІЯ,
КАРТАЛИНСКІЯ И КАБАРДИНСКІЯ ЗЕМЛИ И ОБЛАСТИ АРМЕНСКІЯ: ЧЕРКАССКИХЪ И
ГОРСКИХЪ КНЯЗЕЙ И ИНЫХЪ НАСЛѢДНЫЙ ГОСУДАРЬ И ОБЛАДАТЕЛЬ, НАСЛѢДНИКЪ
НОРВЕЖСКІЙ, ГЕРЦОГЪ ШЛЕЗВИГЪ-ГОЛСТИНСКІЙ, СТОРМАРНСКІЙ, ДИТМАРСЕНСКІЙ
И ОЛЬДЕНБУРГСКІЙ, И ПРОЧАЯ, И ПРОЧАЯ, И ПРОЧАЯ. Объявляемъ чрезъ

Figure 3.6 – Russian exchange copy of the Treaty of Cession of Alaska on March 30, 1867. Source: National Archives (1867).

One particular event – the discovery of crude oil in Prudhoe Bay in 1968 – further connected oceanic mobilities to possibilities on land. To transport the oil, an overland pipeline would be built from Prudhoe Bay to Port Valdez, the northernmost ice-free seaport, as winter sea ice prevents transporting oil year-round using vessels directly from Prudhoe Bay (Alyeska Pipeline Service Company, 2021b, 2022). Wherever possible, vessel tankers are the preferred option for transporting crude oil, as it is overall cheaper and investors are not tied to their large initial investment (Berry, 2021). Additionally, constructing the 800-mile Trans-Alaska pipeline presented several challenges to make it able to withstand specific environmental conditions, including the mobilities of the underlying land. For example, it sits on sliders where it crosses active seismic fault lines to accommodate ground movement underneath (the major ones are at the Denali Fault, McGinnis Glacier Fault and Donnelly Dome Fault), it runs in a zig-zag shape to allow for expansion and contraction in extreme winter and summer temperatures (adding 11 miles of pipeline compared to if it had been built in a straight line), and it is equipped with thermal radiating pipes that remove excess heat from the ground directly beneath the pipeline, to maintain the permafrost underneath frozen (Alyeska Pipeline Service Company, 2021a). As such, the logistical constraints on navigation, driven by the mobilities imposed by sea ice, led to significant megaprojects on land, that in turn are also tied to the mobilities of the crude oil, tectonic plates and thermal expansion.

The decision to construct a pipeline, ultimately driven by the unfeasibility of navigating through sea ice, led to a series of negotiations to settle Native land claims. As part of Alaska achieving statehood in 1958, Congress authorised the State of Alaska to select and obtain land titles up to 103 million acres from "public lands of the United States which were vacant, unappropriated and unreserved", thus excluding any land "the right or title of which may be held by Eskimos, Indians or Aleuts" (U.S. Department of the Interior, 1984: ES-1). By 1968, 40 Native land claims had been filed, claiming 380 million acres as ancestral Indigenous lands (which was slightly over Alaska's total land area at the time, given there were some overlaps between claims), and culminating in the freezing of mineral rights leases until these issues were resolved (U.S. Department of the Interior, 1984). To settle such disputes over whose land it was that the pipeline would cross, and subsequently who would receive payment for the lease of mineral rights, the Alaska Native Claims Settlement Act (ANCSA) was passed in 1971. It established twelve regional corporations and over 200 village corporations, to which land titles amounting to 44 million acres were assigned (ANCSA Regional Association, 2022)[10]. A total of $962.5 million was also distributed among roughly 80,000 Natives who qualified for the settlement benefits if they were at least one quarter Native, in compensation for the extinguishment of all their aboriginal land rights (Administration for Native Americans, 2022). On the one hand, ANCSA was a step forward in the recognition of Indigenous land ownership that had until that point not been attended to. On the other hand, ANCSA indirectly ratified the abuses over Indigenous land rights since Russia's self-proclaimed possession of Alaska and subsequent sale to the United States, by providing a solution that did not reflect Indigenous ancestral uses of land (only 12% of Alaska's land was assigned Indigenous ownership under ANCSA, compared to the 100% that was disputed in previous Native claims that led to ANCSA). Moreover, ANCSA and its structure of land ownership linked to for-profit regional corporations was a legal invention that did not echo Native perspectives that "it is not people who govern land, but rather land and the spiritual beings of the land prescribe relationships among humans as well as human relationships to the land" (Worl, 2016: 311). As such, the knock-on effects of the Trans-Alaska Pipeline that led to changes in Indigenous land ownership exemplifies the far-reaching consequences arising from the mobile navigational (im)possibilities of the frozen ocean that stretch far beyond the ocean itself.

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[10] A thirteenth corporation was later added in 1975 for Alaskan Natives who no longer lived in Alaska. It was involuntarily dissolved by the State of Alaska when their registered agent resigned in 2013 (ANCSA Regional Association, 2022).

Overall, the ocean has always played a key role in the histories of the Bering Strait region. From livelihood sustenance for locals, to economic opportunity for whalers, to revenue through natural resource extraction. Throughout these histories, the ocean's materiality, cycling through liquid and solid phases, both supports and inhibits a variety of mobilities. Whales follow the sea ice edge in their annual migrations, and other marine mammals, such as ringed seals, walrus and polar bears, require sea ice as a platform for making their dens and protecting their pups. Coastal communities use sea ice as a platform for hunting and travel, and yet, for whalers from outside the region, sea ice posed a significant barrier to their activities and a peril for their lives. Today, sea ice continues to be a barrier for navigation in the region, but has also become a point of contention for Indigenous struggles to maintain their traditional lifeways in a warming world (e.g. Watt-Cloutier, 2015). Extraction of natural resources also continues to be a debated issue, as Native communities find themselves at the crossroads between protecting their ancestral lands and cultures, whilst also embracing emerging economic opportunities. This is coupled with the increasing reliance on cash for purchasing goods and food, as climate change, among other things, is impacting the behaviour and reliability of sea ice, making it difficult to maintain traditional lifeways that rely on hunting marine mammals for a reliable source of nutrition. In its entanglement with local livelihoods and global curiosity alike, the next section continues to trace the mobilities of sea ice as a dynamic geophysical environment that shapes processes beyond the ocean itself.

3.4. Sea-Ice Mobilities

As Marchenko (2012: 7) points out, "ice in the Arctic seas is constantly in motion" (Figure 3.7). These mobilities of sea ice are related a host of broader mobile networks connected to broader processes of ocean-atmosphere interactions, as laid out in the sections that follow.

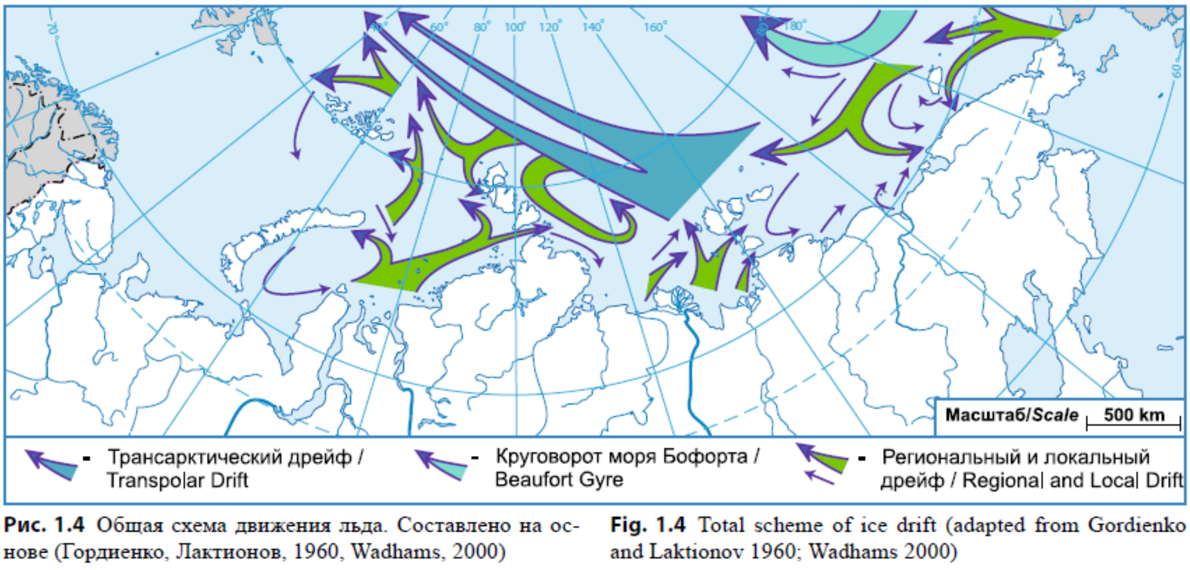


Рис. 1.4 Общая схема движения льда. Составлено на основе (Гордиенко, Лактионов, 1960, Wadhams, 2000)

Fig. 1.4 Total scheme of ice drift (adapted from Gordienko and Laktionov 1960; Wadhams 2000)

Figure 3.7 – General patterns of sea-ice movement in the Russian Arctic seas. Source: Marchenko (2012).

3.4.1. Pan-Arctic Sea-Ice Trends

Sea ice in the Arctic has been decreasing for the past 40 years. This is a result of the combined effects of strong natural variability in the ice-ocean-atmosphere system and increased water and air temperatures associated with rising concentrations of atmospheric greenhouse gases (Serreze et al., 2007; Stroeve et al., 2012; Tschudi et al., 2018; IPCC, 2019). The resulting loss of sea-ice extent, loss of snow cover and increased presence of thin seasonal sea ice further contribute to warming through positive feedback mechanisms. Between 1979 and 2019, average annual sea-ice extent in the Northern Hemisphere decreased by almost a fifth, or 2.14 x 10^6 km^2 (Figure 3.8 and Figure 3.9). This is characterised by loss of multi-year ice (e.g. Comiso, 2012), a longer melt season (e.g. Stroeve et al., 2014) and greater drift speeds and deformation (Rampal et al., 2009).

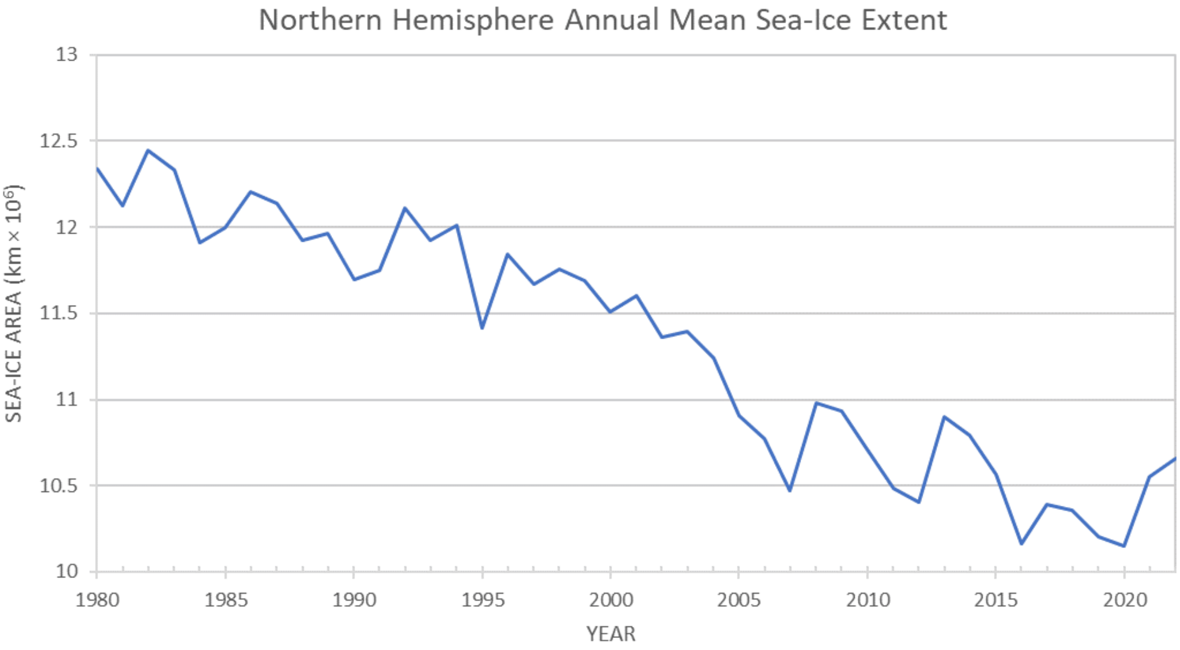
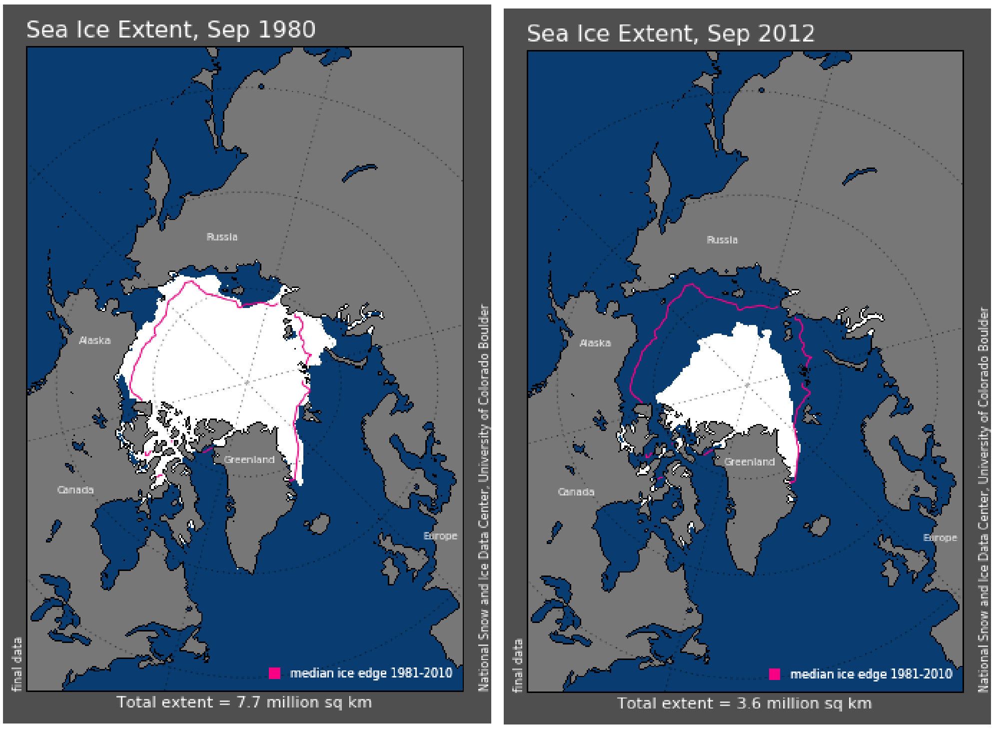


Figure 3.8 – Northern Hemisphere annual mean sea-ice extent 1980–2022. Annual values are calculated by averaging monthly data January - December for each year. 1987 and 1988 are missing monthly data for December and January, respectively. Source: NSIDC Sea Ice Index V3 (Fetterer et al., 2017).


Sea Ice Extent, Sep 1980

Total extent = 7.7 million sq km

Sea Ice Extent, Sep 2012

Total extent = 3.6 million sq km

Figure 3.9 – Northern Hemisphere sea-ice extent for September in 1980 (record high; left) and 2012 (record low; right). Source: NSIDC Sea Ice Index V3 (Fetterer et al., 2017).

Sea ice in the Arctic generally follows an annual cycle of growth from its minimum extent in September to its maximum extent in March (see Figure 3.2). During this cycle, sea ice is subject to thermodynamic and dynamic forcing from atmospheric and oceanic circulation patterns. This results in sea-ice cover that is highly dynamic in both space and time, exhibiting variations in sea ice extent, thickness, areal cover and age.

In the Arctic Ocean, dominant sea-ice motion consists of three well-known primary circulation systems: the Beaufort Gyre, the transpolar drift, and a smaller motion system from the Kara Sea, as shown in Figure 3.10 (Kaur et al., 2018; Timmermans and Marshall, 2020). The Beaufort Gyre is located in the Beaufort Sea, exhibiting a primarily anticyclonic sea-ice drift pattern with brief intermittent periods of direction reversal occurring throughout the annual cycle, especially in late summer (Lukovich and Barber, 2006). The transpolar drift transports sea ice from the Laptev Sea on the Siberian coast, across the North Pole and out of the Arctic Ocean through Fram Strait. In addition to these two dominant sea-ice circulation patterns, there is also a motion system moving sea-ice from the Kara Sea through the passage between Franz Josef Land and Novaya Zemlya. Increases in wind speeds and physical changes in sea-ice cover (e.g. thinner, less compact and less structurally robust sea ice) have led to higher drift speeds, moving more sea-ice out of the Arctic through Fram Strait and creating a feedback loop contributing to the overall decrease in sea-ice cover in the Arctic region (Spreen et al., 2011).

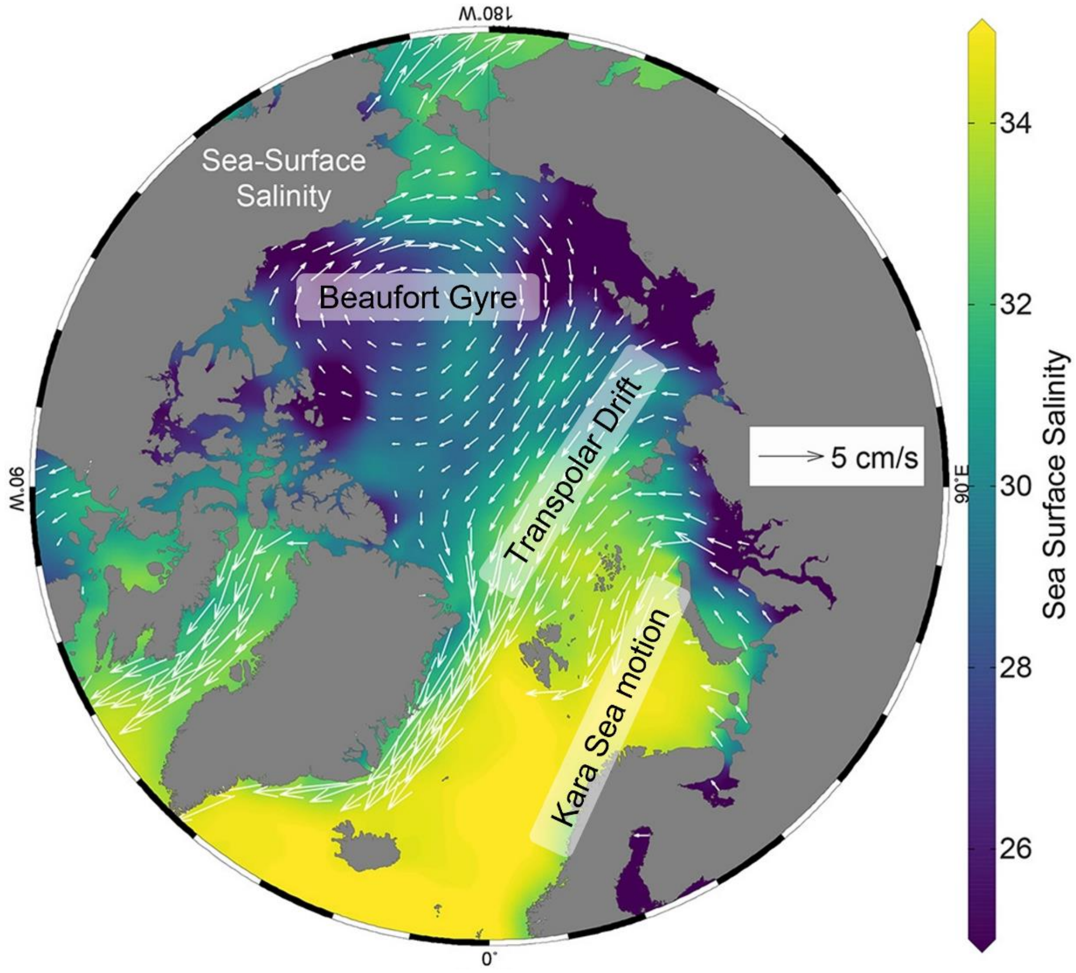


Figure 3.10 – Map of March average sea-ice motion (white vectors) for the period 2005–2017. Colours show sea-surface salinity. Source: Timmermans and Marshall (2020).

The observed sea-ice decline is not homogenous spatially nor temporally across the Arctic. Overall, sea-ice loss is more pronounced in summer than in winter (e.g. Cavalieri and Parkinson, 2012; Close et al., 2015) and is characterised by later freeze-up and earlier breakup dates (Frey et al., 2015), as well as loss of multi-year ice, replaced by thinner seasonal ice (Stroeve et al., 2012). For the period 1979–2016, most summer sea-ice loss occurs in the perennial ice-covered East Siberian Sea, accounting for 22% of total September sea-ice loss; in winter, the largest portion of sea-ice loss takes place in the Barents Sea, responsible for 27% of total March sea-ice loss (Onarheim et al., 2018).

3.4.2. Sea Ice in the Bering Strait Region

Despite pan-Arctic trends of rapid sea-ice decline, the Bering Sea shows different sea-ice trends compared to the Chukchi Sea and the Arctic as a whole. Situated south of the Bering Strait, the Bering Sea is to some extent separated from the ocean-atmospheric processes that drive sea-ice patterns in the Arctic Ocean. Whilst almost every other region in the Arctic contributes to some extent to the loss of sea ice in summer or winter (or both), the Bering Sea makes little or no contribution to sea-ice loss in neither March nor September. It is one of the only two Arctic regions exhibiting this trend (the other region being Hudson Bay; Figure 3.11). In addition, the Bering Sea is the only region showing positive sea-ice trends compared to 1979–2016 mean sea-ice extent for all months January–April (Onarheim et al., 2018) (Figure 3.12), and the only region also showing positive trends in sea-ice maxima for the period 1979–2015 (Peng and Meier, 2018) (Figure 3.13).

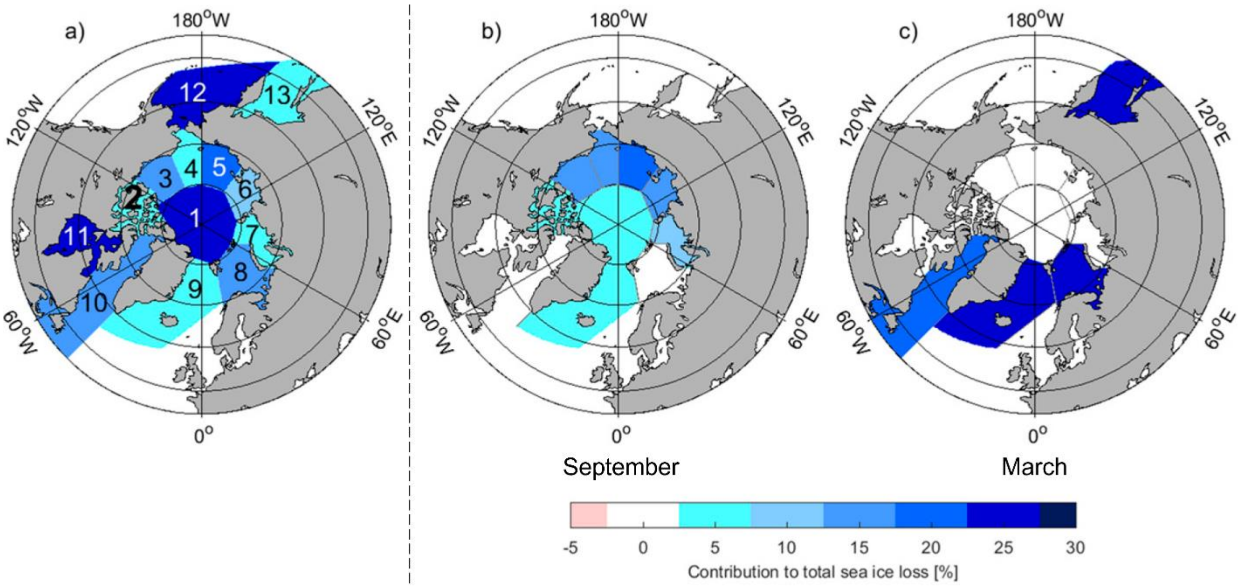


Figure 3.11 – *Contributions of regional seas to overall sea-ice loss in the Northern Hemisphere. (a) The Northern Hemisphere regional seas: 1) central Arctic, 2) Canadian Archipelago, 3) Beaufort Sea, 4) Chukchi Sea, 5) East Siberian Sea, 6) Laptev Sea, 7) Kara Sea, 8) Barents Sea, 9) Greenland Sea, 10) Baffin Bay/Gulf of St. Lawrence, 11) Hudson Bay, 12) Bering Sea, and 13) Sea of Okhotsk. Contribution from each regional sea to the (b) September and (c) March Northern Hemisphere sea-ice extent trends, 1979–2016. Source: Onarheim et al. (2018).*

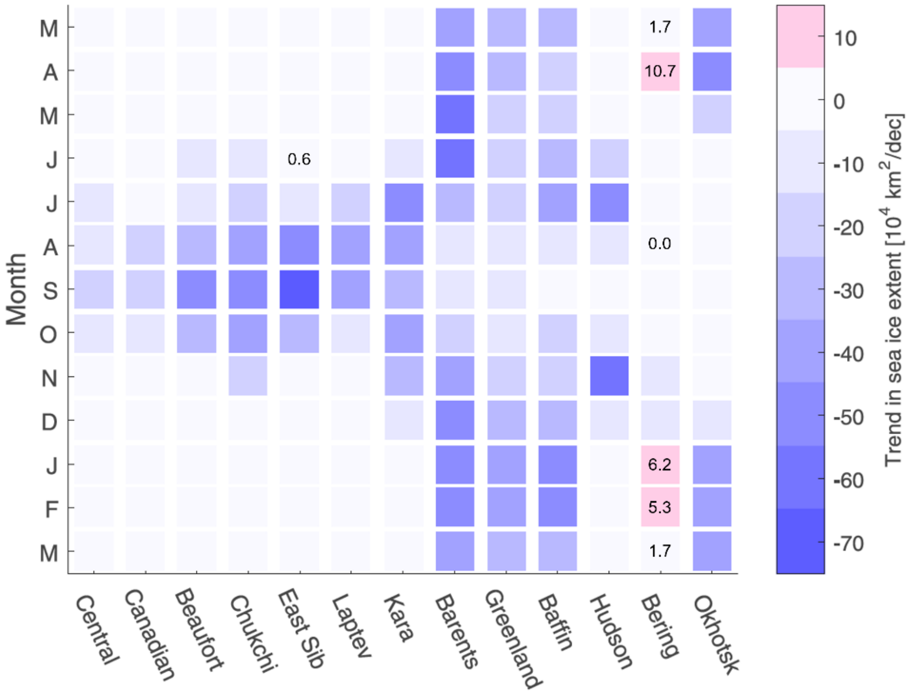


Figure 3.12 – *Monthly trends in sea-ice extent for the Northern Hemisphere regional seas, 1979–2016. Source: Onarheim et al. (2018).*

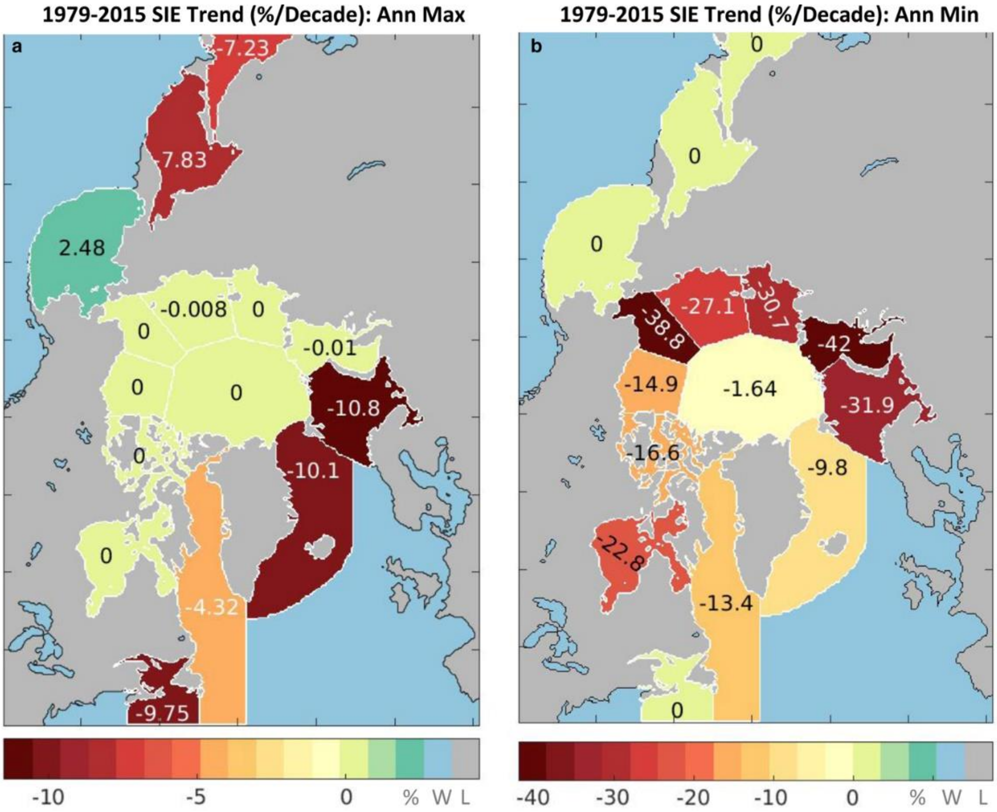


Figure 3.13 – *Regional trends (% decade^{-1}) for (a) annual sea-ice extent maximum and (b) annual sea-ice extent minimum for the period of 1979–2015. Landmasses are shaded in grey; other water masses are shaded in light blue. The Bering Sea is the only region showing positive trends for sea-ice maximum. For names of each region, see Figure 4.2. Source: Peng and Meier (2018).*

3.4.2.1. Atmospheric Forcing

It has long been known that sea-ice growth in the Bering Sea is primarily dependent upon winter atmospheric forcing (wind-driven sea-ice mass advection and wind temperature) and to a smaller degree on ocean temperatures (Pease, 1980; Wyllie-Echeverria and Wooster, 1998; Stabeno et al., 2007; Zhang et al., 2010; Wang et al., 2014; Frey et al., 2015). This is because the sluggish oceanic circulation on the shallow (< 200 m) continental shelf of the eastern Bering Sea is not considered sufficient to drive the observed inter-annual variability of the oceanic environment in the Bering Sea (Niebauer et al., 1999; Stabeno et al., 2001).

Sea ice in the Bering Sea follows a wind-driven 'conveyor belt', moving sea ice from north to south (Pease, 1980), as shown in Figure 3.14. Strong frigid (cooler than -5°C) northerly winds directly cool the water column in the northern Bering Sea, forming ice in association with polynyas along the coast and in the lee of islands (Stabeno and Bell, 2019). Winds continue to drive sea ice southward across the shelf where shallow water temperatures are already low due to the cold winds and are further cooled by the advancing sea ice, creating the necessary conditions for sea ice to persist (Stabeno et al., 2012a). This process is further aided by the opening of leads in the north as the pack ice breaks as it is pulled southwards by wind advection. The exposed water in these leads quickly freezes due to the cold atmospheric conditions, adding to the sea-ice area with thin ice (Zhang et al., 2010). At the leading (usually southernmost) sea-ice edge, warmer waters melt the ice. This occurs especially at the boundary between the shallow continental shelf and the deep Pacific oceanic basin, where the deeper water column is more difficult to cool from melting sea ice, as it stores more heat from warm Pacific waters (Niebauer et al., 1999). Although warm ocean water can delay the advance of sea-ice, persistent cold northerly winds will eventually cool (through radiative heat flux and ice melt) the water column sufficiently to push sea ice southward (Stabeno and Bell, 2019). This process drives sea ice faster than usually observed in the Arctic Ocean, causing sea-ice mass advection comparable in magnitude to sea-ice export through Fram Strait (Zhang et al., 2010).

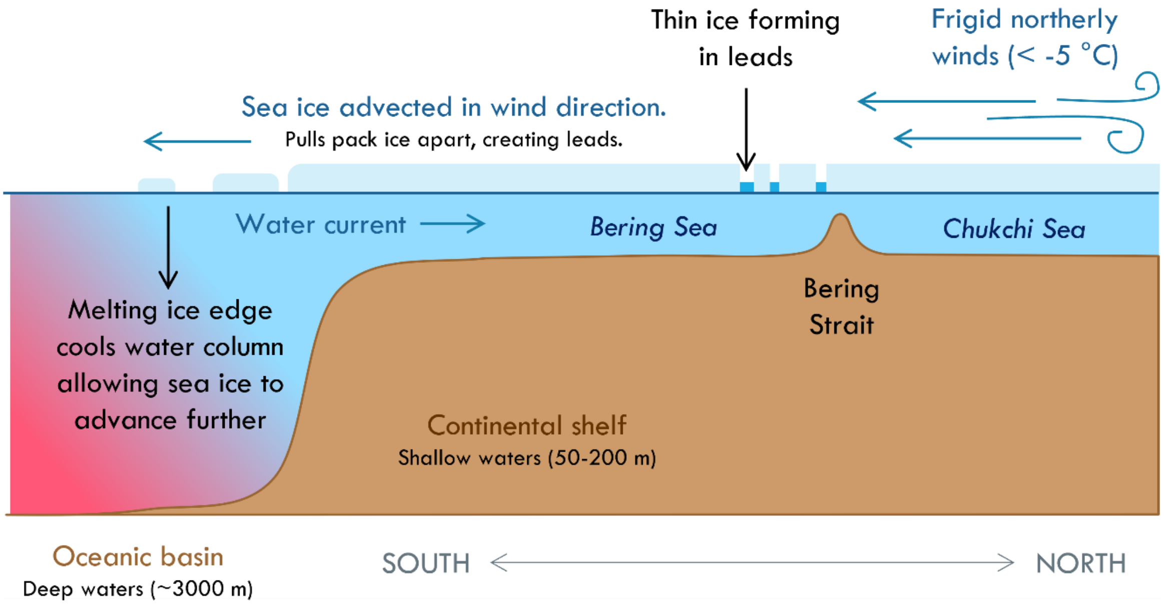


Figure 3.14 – Schematic of the wind-driven 'conveyor belt' system underlying the southwards advance of sea ice in the Bering Sea. Figure created from description of Bering Sea sea-ice dynamics in Pease (1980), supported by Stabeno and Bell (2019), Stabeno et al. (2012a) and Zhang et al. (2010).

The winds that drive sea-ice motion in the Bering Sea are controlled by the position and strength of the Aleutian low. As one of the main centres of action in the atmospheric circulation over the Northern Hemisphere, the Aleutian low is one of two semi-permanent low-pressure systems in the Northern Hemisphere (the other is the Icelandic low), centred over the Aleutian Islands chain (Figure 3.15). It is active during late autumn to late spring and is most pronounced and dominant during the winter. During the summer, the Aleutian low dissipates almost entirely and retreats towards the North Pole as the subtropical high-pressure system dominates over the North Pacific basin. As with all low-pressure systems in the Northern Hemisphere, the Aleutian low causes a cyclonic pattern of winds circulating anti-clockwise about its low-pressure centre. This means that warm air is pumped into the Bering Sea from the Pacific, and cold air is pulled in from the Arctic.

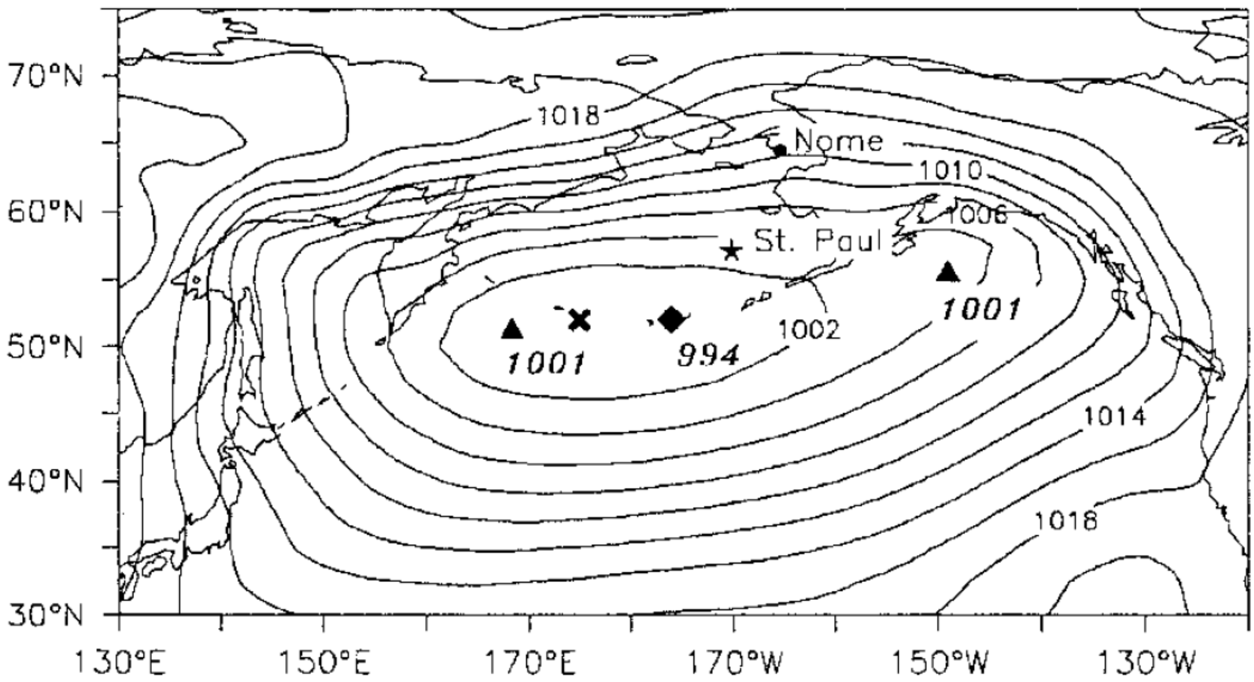


Figure 3.15 – Mean winter (December – March) sea-level pressure (hPa) averaged over 1950–2002. Source: Rodionov et al. (2005).

Overall, the Aleutian low has been weakening over the past several decades (Figure 3.21). This is associated with years of heavy winter sea ice in the Bering Sea, as a weaker Aleutian low results in less warm air being pumped into the Bering Sea and thus favours greater sea-ice cover (Overland et al., 1999; Rodionov et al., 2005; Wendler et al., 2014; Frey et al., 2015). This can also be seen in the weakening of the spring Aleutian low, causing cooling surface air temperature (SAT) trends from reduced warm southerly and westerly winds over Northwest North America, which is the only region in the Northern Hemisphere showing spring cooling trends since 1980 (Sun et al., 2019). The cooler temperatures brought by a weaker Aleutian low have resulted in the lack of systematic sea-ice decline in the Bering Sea, differently to the decline observable in the rest of the Arctic.

The weakening of the Aleutian low is correlated to varying degrees with several other large-scale atmospheric processes and beyond, including sunspot activity (Christoforou and Hameed, 1997). Changes in sea ice, sea surface temperature (SST) and SAT all correlate significantly with the Pacific Decadal Oscillation (PDO; Mantua et al., 1997), but not with the Arctic Oscillation, North Pacific or El Niño Southern Oscillation (ENSO), which are often used as indicators of Bering Sea climate variability (Rodionov et al., 2005; Zhang et al., 2010; Wang et al., 2014; Wendler and Wong, 2019). The PDO is a measure of SST anomalies in the North Pacific (north of 20° N). A positive (negative) PDO value corresponds to above (below) normal temperatures (Wendler and Wong, 2019). As low-pressure systems are caused by hot air rising, and air over Asia and North America is much colder than over the North Pacific, when the PDO is positive (i.e. warmer Pacific waters), the ocean-land temperature difference is greater, creating a deeper Aleutian low. Therefore, a positive (negative) PDO corresponds to a stronger (weaker) Aleutian low which in turn leads to more (less) sea-ice cover (Wendler et al., 2014; Frey et al., 2015).

In addition to the *strength* of the Aleutian low as an important factor for sea-ice conditions, is its *location*. In a warm year scenario, the Aleutian low deepens and shifts west and north of its mean winter position (Figure 3.16). This causes increased cyclonic activity in the Bering Sea which pumps warm air in from the Pacific, especially in the eastern Bering Sea. For example, the winter of 2017/2018 was a record-low sea-ice winter for the Bering Sea, during which sea ice arrived late due to warm southerly winds in November. More typical northerly winds (albeit warm) in December advanced sea ice southward, but warm southerly winds in February and March quickly caused sea-ice retreat again (Stabeno and Bell, 2019).

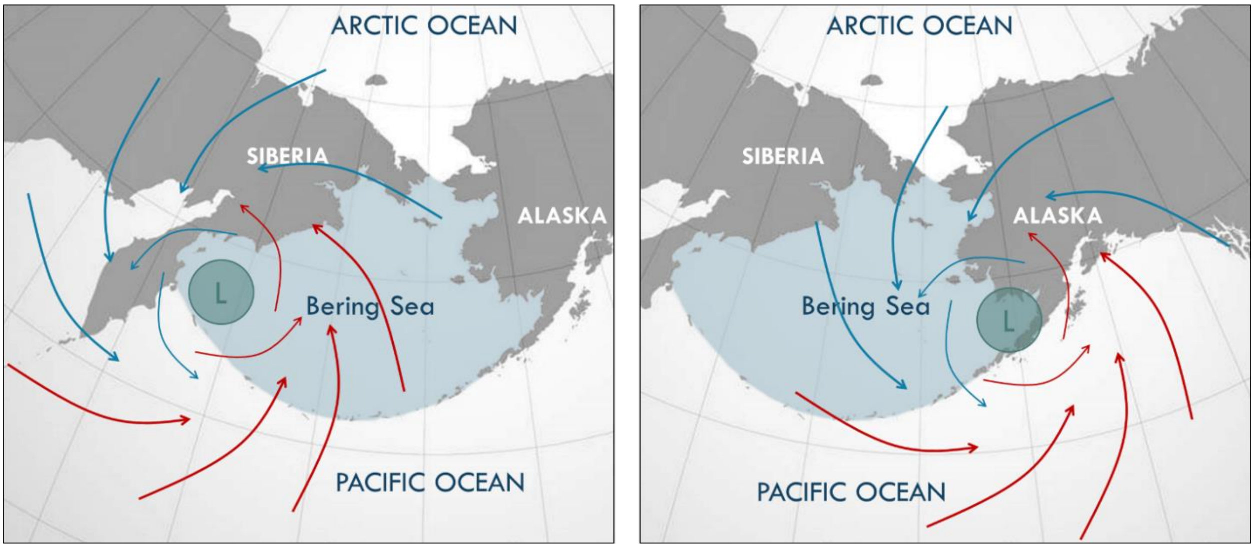


Figure 3.16 *– Common positionings of the Aleutian Low over the Bering Sea. A westerly position of the Aleutian Low pulls in warm air from the Pacific (left), hindering sea ice formation and advance. An easterly position of the Aleutian Low, sometimes split over multiple weaker centres, pulls in frigid air from the Arctic (right), favouring sea-ice formation due to cooler temperatures and allowing southwards sea-ice to advance through wind-driven advection.*

In a cold scenario, the Aleutian low typically splits into having two centres, one in the north-western Pacific and the other in the Gulf of Alaska, and relatively greater sea-level pressure difference between the west (high pressure) and east (low pressure) Bering Sea (Figure 3.17; Zhang et al., 2010; Wendler et al., 2014). This creates the conditions for north-easterly winds that drive more sea ice south and west, cool surface air (2-4 °C below normal; Rodionov et al., 2005), cool the upper ocean, and melt more ice in the southern and western waters (Overland and Pease, 1982; Wyllie-Echeverria and Wooster, 1998). This causes SATs as much as 10 °C lower (Brown and Arrigo, 2012) and increased open water and thin ice creation in leads, which promotes thermodynamic ice growth in the northern sector. Increased sea ice in the west tends to lower SATs and SSTs locally, possibly creating a feedback loop whereby these lower temperatures further strengthen the relatively high sea level pressure in the western sector and on nearby land, likely further strengthening the northerly winds (Zhang et al., 2010). These recurring atmospheric patterns for years of heavy and light sea-ice cover have been observed by several studies over time, as shown in Figure 3.18 – Figure 3.20.

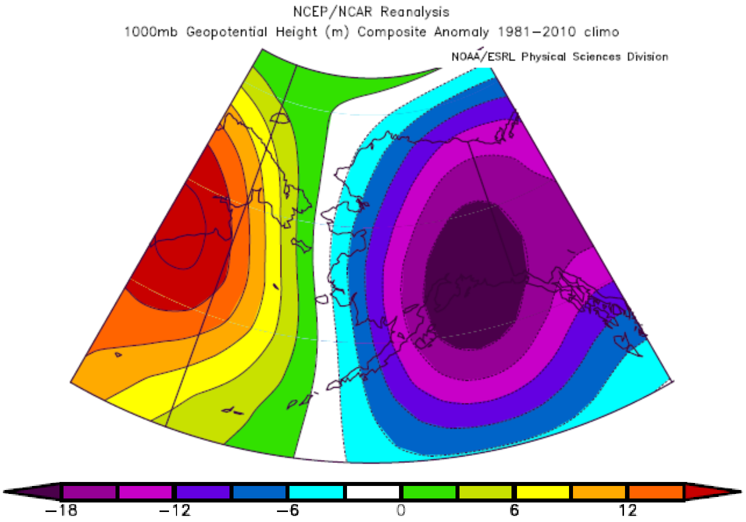


__Figure 3.17__ – Differences in the 1,000 mb geopotential heights between five heavy sea ice years (1992, 1999, 2008, 2009, and 2012) and five light sea ice years (1979, 1989, 1996, 2003, 2004). Source: Wendler et al. (2014).

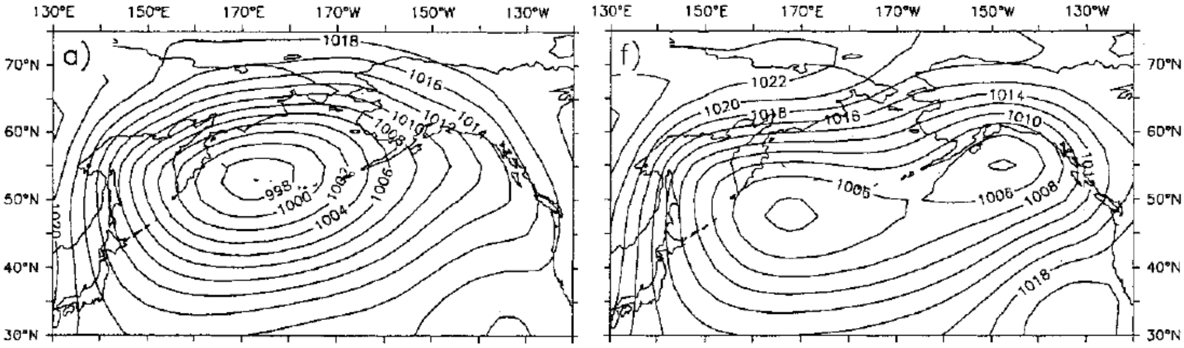


__Figure 3.18__ – Sea-level pressure patterns for warm (left) and cold (right) years. Source: Rodionov et al. (2005).

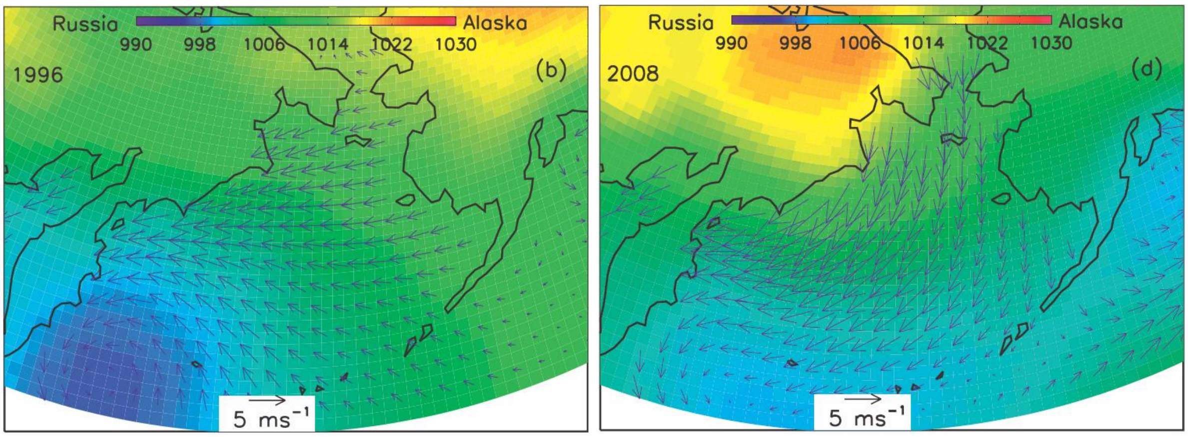


__Figure 3.19__ – January–March mean NCEP–NCAR reanalysis sea level pressure (mbar) and surface wind velocity vectors (m s^{-1}) for a light sea ice year, 1996 (left), and a heavy sea ice year, 2008 (right). Source: Zhang et al. (2010).

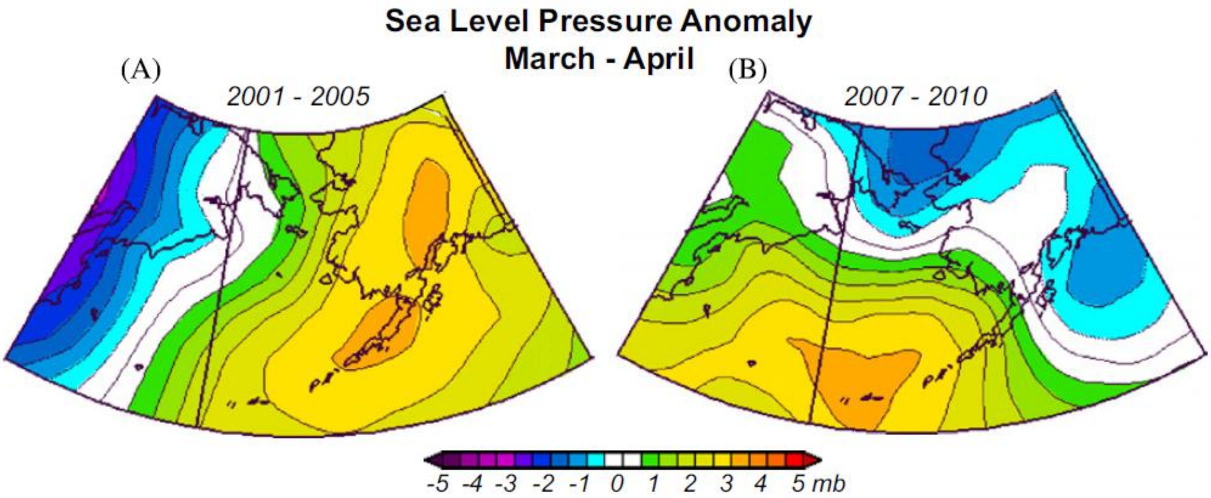


Figure 3.20 *– Sea level atmospheric pressure anomalies. (A) The period of warm years (2001-2005) and (B) the period of cold years (2007-2009). The climatology used to create the anomalies is 1968-1996. Source: Stabeno et al. (2012b).*

Rodionov et al. (2005) show that temperatures in the Bering Sea are more sensitive to the position of the Aleutian low in winter (December – March) than its strength. In fact, Figure 3.21 shows unusually high pressure at Cold Bay in 1989 and 1996, signifying a weaker Aleutian low, which would usually lead to a year of heavy sea ice. However, as both 1989 and 1996 were years of low sea-ice cover, it suggests that the location of the Aleutian low plays a significant role in determining sea-ice cover.

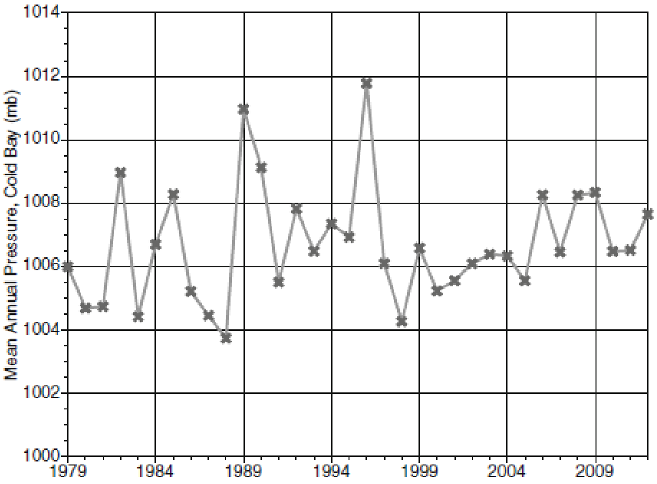


Figure 3.21 *– Time series of the mean annual sea level pressure for Cold Bay, 1979–2012. When the Aleutian low centre is in its easterly position (near Cold Bay; see Figure 3.16), this creates favourable conditions for a high sea ice year. An easterly positioning of the Aleutian low centre will result as low sea level pressure readings at Cold Bay. However, the rising trend in sea level pressure at Cold Bay indicates the weakening or shifting of the Aleutian low. Source: Wendler et al. (2014).*

3.4.2.2. Inter-Annual Variability

Despite a relatively consistent annual cycle, the Bering Sea shows sea-ice patterns characterised by high inter-annual variability, in large part attributable to its latitudinal range and the system's high sensitivity to local atmospheric pressure systems (Figure 3.22; see Figure 3.8 for Northern Hemisphere comparison). The Bering Sea is one of two regions in the Northern Hemisphere (along with the Barents Sea) with the highest inter-annual variability in mean sea-ice area, ranging from <140,000 km^2 to more than double the area at >280,000 km^2 (Francis and Hunter, 2007; Wendler et al., 2014). It is also worth noting that the all-time maximum (2012) and minimum (2018) in sea-ice extent maxima (since records began) in the Bering Sea occurred recently within a relatively short time frame of six years apart (Figure 3.22). In a scenario where sea ice is decreasing more consistently, one would expect the all-time maximum and minimum to occur much further apart.

Until significant sea-ice loss in the recent winters of 2017/2018 and 2018/2019, the Bering Sea was also the only region showing no change or increasing sea-ice trends since 1979 (Wendler and Wong, 2019). The multi-annual variability that occurs in the Bering Sea can be observed in the change in trends over time, with the average during the period 1981–2010 as a baseline: positive during 1979-1996 (+1.0 10^3 km^2 yr^{-1}; Parkinson et al., 1999), negative during 1979-2006 (-0.5 10^3 km^2 yr^{-1}; Parkinson and Cavalieri, 2008), back to positive during 1979-2010 (+0.3 10^3 km^2 yr^{-1}; Cavalieri and Parkinson, 2012) and negative again during 1979-2016 (-0.9 10^3 km^2 yr^{-1}; Onarheim et al., 2018).

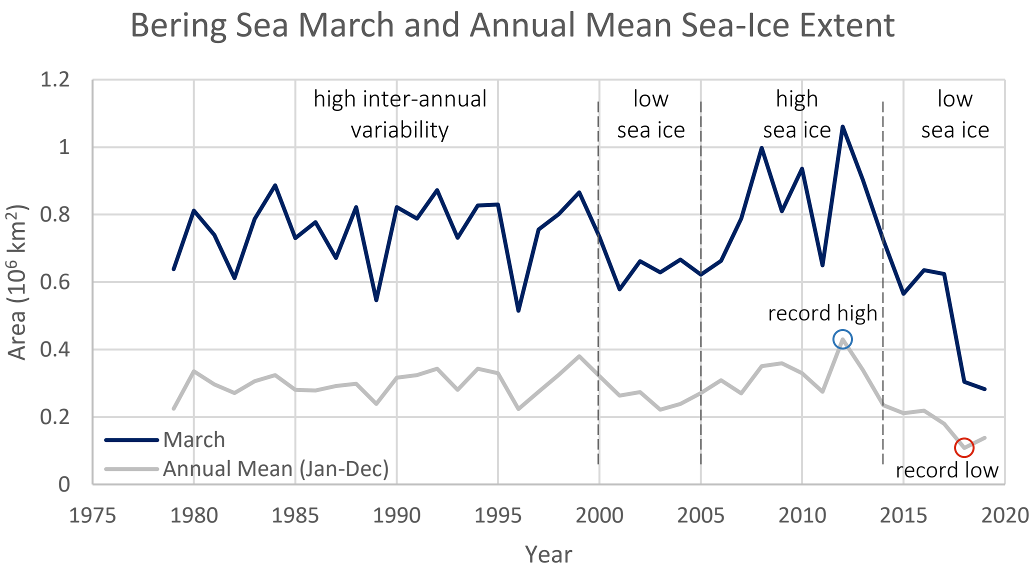


Figure 3.22 *– March and annual mean sea-ice extent in the Bering Sea, 1979–2019. Annual values are calculated by averaging monthly data January–December for each year. 1987 and 1988 are missing monthly data for December and January, respectively. Source: NSIDC Sea Ice Index V3 (Fetterer et al., 2017).*

Since 1979, several periods can be identified characterised by similar patterns of sea-ice cover. Following 1979-2000 as a period of high inter-annual variability, 2001-2005 showed low sea-ice extent, 2006-2012 were heavy-ice years and 2014-2018 were again warm years with low sea-ice cover (Figure 3.22; Frey et al., 2015; Stabeno and Bell, 2019; Stabeno et al., 2019). The lowest winter maximum sea-ice extent on record (1979-2019) in the Bering Sea occurred in winter 2017/2018, and the winters of 2017/2018 and 2018/2019 hold the record low sea-ice extents for all months between

December and June (Stabeno and Bell, 2019). Those years with relatively short sea-ice persistence result from both later freeze-up and earlier breakup of sea-ice, although later freeze-up accounts for more of the sea-ice loss (Frey et al., 2015). This can be seen in 2008 and 2003 as examples of heavy and light sea ice years, respectively. Freeze-up in 2008 was two months earlier compared to 2003 for most of the north-eastern part of the basin, whereas breakup was only a month later in 2008 than in 2003 (Figure 3.23). Despite these differences in timing of sea-ice freeze-up and breakup, sea-ice maxima consistently occurs in March during years of extreme high or extreme low sea-ice extents (Wendler et al., 2014).

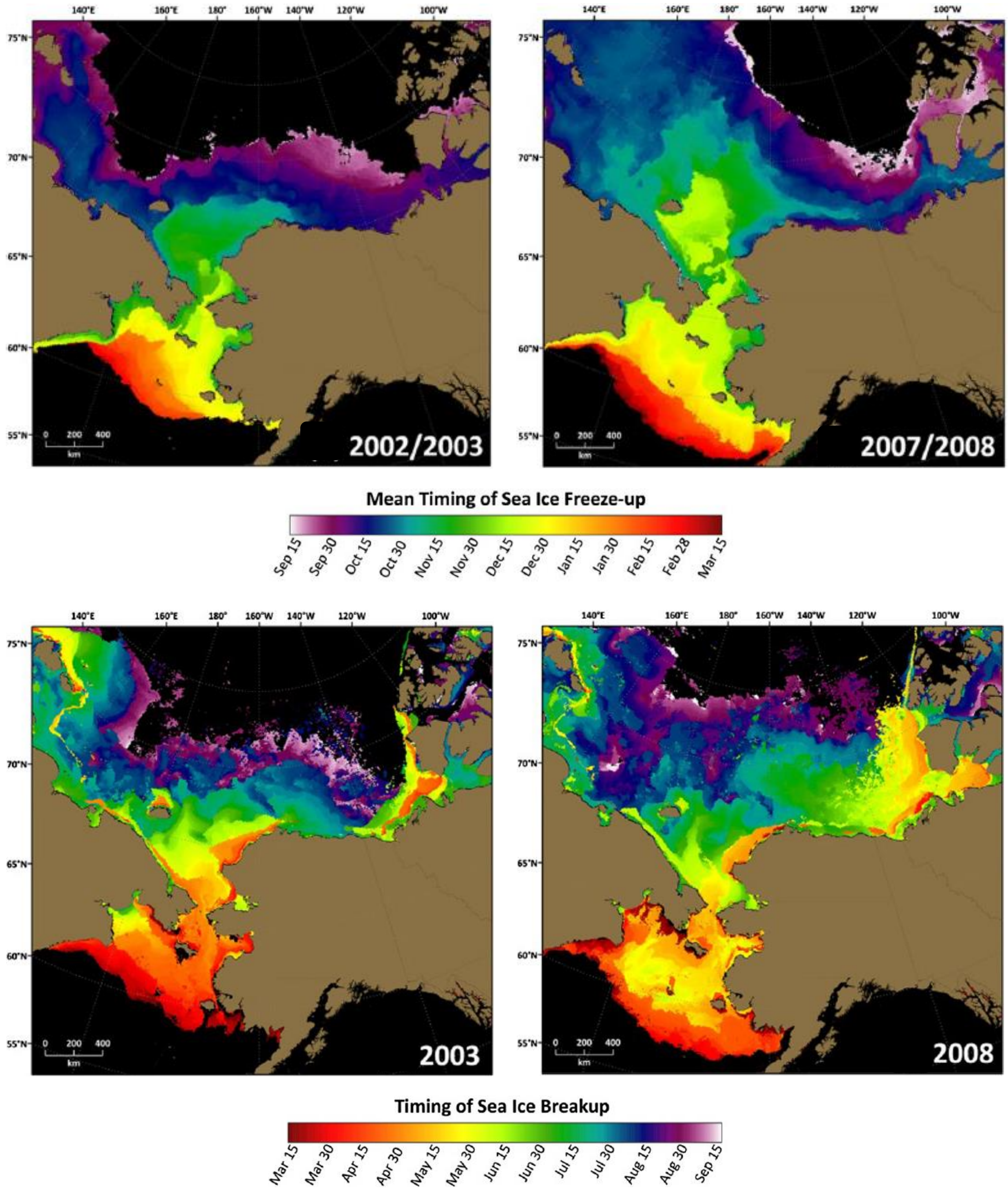


Figure 3.23 *– Timing of sea-ice freeze-up and breakup for a light sea ice year (2003) and a heavy sea ice year (2008). The timing calculated for sea-ice freeze-up (breakup) requires that a pixel register two consecutive days above (below) a 15% sea-ice concentration threshold. Source: Frey et al. (2015).*

In addition to the overall patterns in sea ice as discussed above, there are regional differences within the Bering Sea. Average sea ice varies north to south, with earlier sea-ice arrival, higher concentration and longer persistence in the north than in the south (Figure 3.23; Frey et al., 2015). Year-to-year variability in sea-ice cover increases farther south (Stabeno and Bell, 2019) and, historically, the position of annual southern sea-ice extent has varied by more than 100 km (Stabeno et al., 2012a). While there have not been any significant trends of decreased sea ice in the Bering Sea overall, the Chirikov Basin (between St Lawrence Island and the Bering Strait) has shown significant negative trends in sea ice: since 1979, the average open water area has increased by 1300 km^2 decade^{-1}, the open water season has increased by 8 days decade^{-1} and sea-ice advance has delayed by ~4.6 days decade^{-1} (i.e. a later autumn transition; Brown and Arrigo, 2012).

3.4.2.3. Bering Sea Decoupling from the Arctic Ocean

The lack of systematic decline in sea-ice cover in the Bering Sea suggests a possible decoupling from the rest of the Arctic which is instead undergoing drastic sea-ice decline. For example, 2007, a record-breaking year of low sea ice in the Arctic, was not a year of abnormally low sea-ice conditions in the Bering Sea (Brown and Arrigo, 2012). In fact, overall, in sharp contrast to the Arctic Ocean (Perovich, 2011), during 2007-2010, the Bering Sea was experiencing extensive sea-ice cover (Stabeno et al., 2012b). The co-occurrence of sea-ice minima in the Arctic Ocean and sea-ice maxima in the Bering Sea suggests a 'decoupling' of summer sea-ice maxima in the Arctic Ocean as a necessary condition for heavy sea ice the following winter/spring in the Bering Sea (Stabeno et al., 2012a; Wendler et al., 2014). This overturns a long-standing assumption that the Chukchi Sea must freeze first before the Bering Sea can freeze, because it takes frigid northerly winds to create large amounts of sea ice in the Bering Sea (Stabeno et al., 2012a).

Nonetheless, Stabeno et al. (2019) show that, to some extent, later freezing of the Chukchi Sea also causes later freezing of the Bering Sea (Figure 3.24). This can be observed in the winter of 2007/2008, where the Chukchi Sea did not freeze until early December, and the Bering Sea remained mostly ice-free until mid-December. However, the major sea-ice advance that followed, of 900 km in less than a month (≈30 km day^{-1}), suggests that the driving mechanisms for sea-ice advance in the Bering Sea are not the same as those in the Chukchi Sea and the Arctic Ocean (Figure 3.25). Similar patterns also occurred in 2009 and 2010 (Stabeno et al., 2012a) and, in general, the seasonal advance and retreat of sea ice in the Bering Sea averages about 1700 km, larger than in any of the other sub-Arctic seas (Walsh and Johnson, 1979). Therefore, the Bering Sea appears to be reliant to some extent on the Chukchi Sea freezing in order to 'kickstart' the freezing process in the Bering Sea, although sea-ice extent in the Chukchi Sea remains a poor indicator for sea-ice extent in the Bering Sea the following winter.

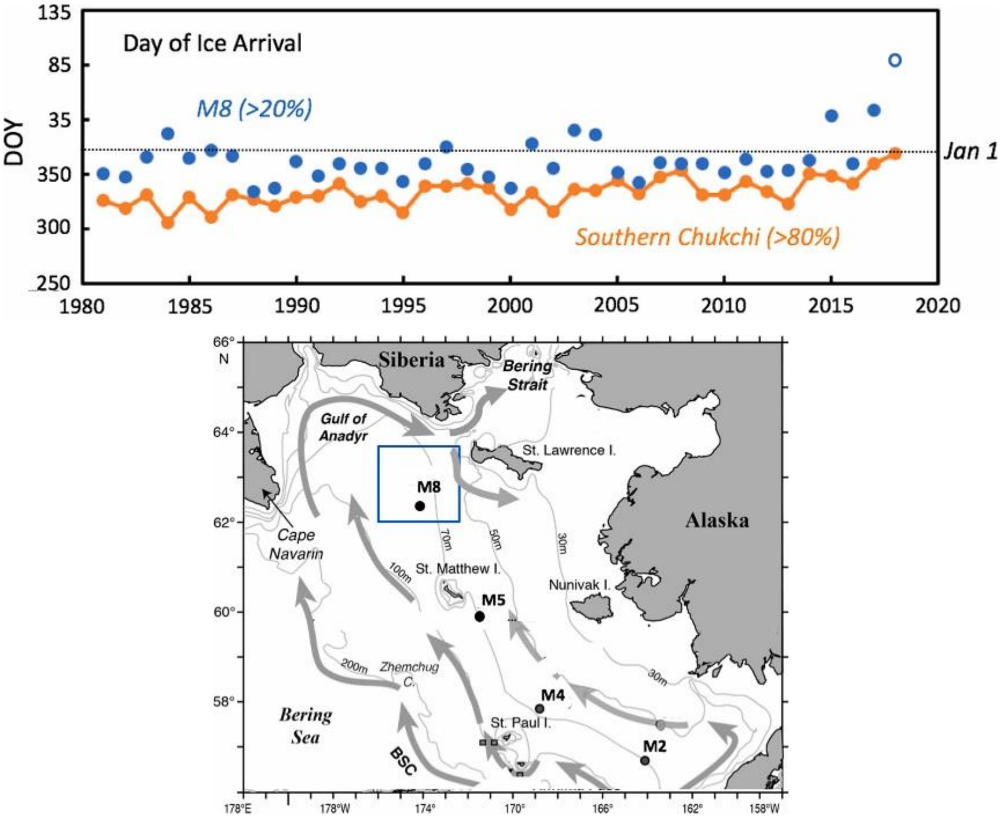


Figure 3.24 – *Timing of sea-ice arrival (i.e., sea-ice concentration >20%) and timing of 80% sea-ice cover in the southern Chukchi Sea, 1981–2018 (top graph). Location of >20% sea-ice arrival in the Bering Sea is at a 50 × 50 km box centred at M8 (blue square in the map below the graph). To some extent, and particularly from 2015 onwards, later freezing of the Southern Chukchi Sea coincides with later freezing of the Bering Sea. In 2018, sea-ice concentration only reached 18% at M8, which is indicated by the open circle. Source: Stabeno et al., (2019).*

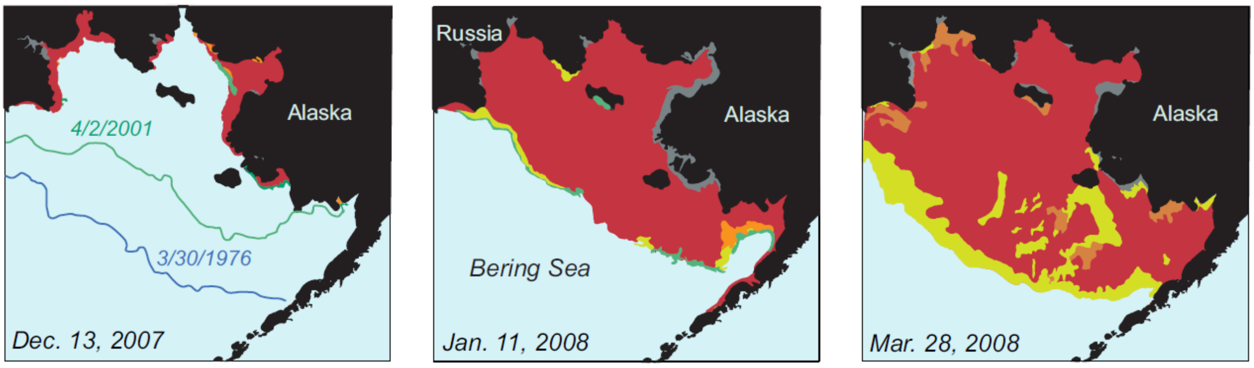


Figure 3.25 – *Exceptionally fast sea-ice advance in the Bering Sea during winter 2007/2008. Each panel shows the sea-ice extent on an identified day during winter 2007/2008. Also shown in the first panel is the maximum sea-ice extent on the eastern Bering Sea shelf during two extreme years of high sea-ice cover (1976, blue line) and low sea-ice cover (2001, green line). Areas shaded green indicate areal ice coverage of less than 40%; yellow 40–60%; orange 70–80%; and red >90%. Source: Stabeno et al., (2012a). The impressive sea-ice growth of 900 km in less than a month (≈30 km day^{-1}) during winter 2007/2008 was a demonstration of how quickly sea ice can advance in the Bering Sea when the shallow water column is cold enough to support rapid sea-ice advance. Additionally, sea-ice advance in the Chukchi Sea is mostly required to 'kickstart' the process of sea-ice advance in the Bering Sea, rather than being an extension of sea-ice growth that continues linearly from the Chukchi Sea into the Bering Sea.*

A further disconnection between sea-ice patterns in the Arctic Ocean and the Bering Sea can be seen in the high inter-annual variability of sea-ice in the Bering Sea in contrast to more consistent trends in the Arctic Ocean. This can be explained by the Bering Sea eastern shelf being very shallow and therefore holding less memory of oceanic heat content that varies year-to-year. In addition, the forcing mechanisms that act in the Arctic Ocean and the Bering Sea are different. Sea ice in the Arctic Ocean is influenced by warm Atlantic inflow, leading to large-scale atmospheric processes (like the Arctic Oscillation and the Dipole Anomaly), ice/ocean albedo feedback, and secular trends related to broad-scale climate warming (Wendler et al., 2014; Frey et al., 2015). Conversely, sea ice in the Bering Sea is controlled by atmospheric forcing through local pressure systems as discussed in the sections below.

While sea ice in the Bering Sea might not entirely rely on Arctic sea-ice conditions, the driving forces behind extensive sea ice in the Bering Sea might lead to better conditions for sea-ice formation in the Arctic. Hu et al. (2017) suggest that when the Aleutian low moves eastward (which corresponds to extensive sea-ice cover in the Bering Sea), it contributes to maintaining a less disturbed and slightly enhanced polar vortex by reducing the meanderings of the Rossby waves at this latitude. This is essential for keeping cold, dense Arctic air locked around the North Pole and separate from the warm mid-latitudes. A disturbed polar vortex is likely to lead to intrusions of warm air in the Arctic and cold air in the mid-latitudes, causing warm temperature anomalies that hinder sea-ice formation (e.g. Tachibana et al., 2019).

3.4.2.4. Future Sea Ice Predictions in the Bering Sea

Wang and Overland (2009) identify the four best models from the IPCC Fourth Assessment Report that most accurately model the seasonal cycle of sea-ice cover in the Arctic over the last 30 years: CCSM3, CGCM3.1-T63, ECHO-G and MIROC-medres. These show that whilst sea ice in the Bering Sea is expected to decrease, extensive sea-ice coverage in May remains a distinct possibility through at least 2050. Therefore, large inter-annual variability will continue to dominate in the southern Bering Sea until at least 2050. Sea-ice may retreat earlier (i.e. less ice in May) but the northern Bering Sea will, for the foreseeable future, continue to be ice-covered in winter and early spring, as shown by model predictions and observations for north of 60° N, including a hypothesised increase of 2 °C in global temperatures by 2050 (Stabeno et al., 2012a).

In the long run, the increased atmospheric CO_2 and rising global temperatures will result in loss of much of the sea-ice in the Bering Sea (Wang and Overland, 2009), leading to a more synchronised loss of sea ice between the Arctic and the Bering Sea (Frey et al., 2015). This will result in local warming in the Bering Sea creating less favourable conditions for sea-ice formation and advance. In addition, as sea-ice formation in the Bering Sea relies on cold northerly winds, a rapidly-warming Arctic (especially in winter) might cause these winds to become warmer and limit sea-ice formation in the Bering Sea

(Brown and Arrigo, 2012; Gan et al., 2017). Not only are northerly winds likely to become warmer, but models show southerly winds increasing in the coming decades (Hermann et al., 2019), and the strong and persistent southerly winds that caused the anomalously low sea-ice extents in winter 2017/2018 might be signalling the start of this transition (Stabeno and Bell, 2019). However, the magnitude of sea-ice loss witnessed in recent years due to late sea-ice freeze-up and early sea-ice breakup was not expected until the 2030s, putting previous predictions of sea-ice loss into question (Wang et al., 2018; Stabeno et al., 2019). Nonetheless, Danielson et al. (2011) argue that there will always be some sea-ice in the Bering Sea due to the ocean-atmospheric heat loss that unavoidably occurs in winter at this latitude.

Overall, sea ice in the Bering Sea is expected to continue to be characterised by high inter-annual variability due to local atmospheric forcing that drives sea-ice formation in this region. Changes in these forcing mechanisms will likely reduce sea ice in the Bering Sea over time (including warmer northerly winds and increased southerly winds), although small amounts of sea ice might continue to persist for much longer due to the generally cold conditions that occur in winter in this region.

3.5. Conclusion

In this chapter, I have provided contextual background to illustrate some of the histories of the Bering Strait region, as they have emerged through their relatedness to the presence of sea ice. In this chapter, I have also reviewed existing understandings of sea-ice dynamics and spatiotemporal patterns taking place in the Bering Strait region. This highlights the ways in which sea-ice patterns are related to broader mobilities of ocean currents and atmospheric conditions. The Bering Sea, whilst subject to sea-ice cover like much of the Arctic Ocean, exhibits slightly different spatiotemporal sea-ice patterns, due to the system’s regional dependency on local atmospheric forcing mechanisms, combined with a specific bathymetric profile that provides a shallow water column that cools easily. Understanding the geophysical processes that underpin sea-ice and oceanic mobilities in the Bering Strait region is fundamental for further developing an understanding of the vessel mobilities that unfold in this region, in relation to sea-ice presence.

4

Methods, Ethics and Positionality

4.1. Introduction

In this chapter, I lay out the methodology employed in this research project. I begin by revisiting the theoretical foundations of this thesis, as laid out in Chapter 2, and elaborating on how these inform the choice of methods employed in this research (Section 4.2). These methods operationalise the analysis of the mobilities of vessels and sea ice in an interdisciplinary medley across human and physical geography. This section also lays out how the use of mixed and interdisciplinary methods that are both quantitative and qualitative have been streamlined into a seamless and complementary methodology that addresses the research questions set out in Chapter 1.

Two methods are used in this research. First, I employed spatial analysis to analyse the spatial and temporal trends of sea-ice and vessel traffic (Section 4.2.1). The spatial data analysis uses i) sea-ice concentration satellite data from the Advanced Microwave Scanning Radiometer 2 (AMSR2) spanning 2013–2022, ii) sea-ice concentration satellite data from the National Snow and Ice Data Center (NSIDC) spanning 1979–2022, and iii) vessel traffic data from the Arctic Council's Arctic Ship Traffic Data (ASTD) spanning 2013–2022. Whilst the sea-ice concentration datasets were ready-to-use products, the ship traffic data required considerably more processing before it was useable. As a result, creating a Python script for the automated processing of the vessel data became a large undertaking and a core contribution that this research makes (Section 4.2.1.3). The combined spatial analysis across datasets of sea-ice concentration and vessel traffic uses a delimited study area (Section 4.2.1.4). Second, I conducted interviews (Section 4.2.2) to elaborate on and further animate the findings arising from the spatial data analysis. Fieldwork for carrying out the interviews took place in Fairbanks, Alaska in 2022.

In the final sections of this chapter, I address some of the research challenges and limitations of this research project. In Section 4.3, I attend to issues of research positionality, ethics and Indigenous involvement that have shaped and guided this Ph.D. research and resulting thesis. Then, in Section 4.4, I elaborate on the methodological implications of the COVID-19 pandemic and how new online means of meeting and communication through Zoom influenced the way that this project unfolded.

This Ph.D. was funded by a Leverhulme Trust grant through the Durham Arctic Research Centre for Training and Interdisciplinary Collaboration (DurhamARCTIC) program. One of the requirements of this program is a placement at a relevant Arctic institution for three months. I carried out my placement at the International Arctic Research Center (IARC) based in Fairbanks, Alaska, where I worked on the Python script to clean up the vessel data as a deliverable to IARC. My placement was joint with three months of fieldwork, for a total of six months between January and July 2022. I then returned to Fairbanks in December 2023 to hold a seminar presentation to share the findings of the research collaboration carried out at IARC, and to continue to build relationships for future joint research projects.

4.2. An Interdisciplinary Methodology for Mobilities

As this research is situated within mobility studies, the methodology employed is designed to capture the mobile aspects of vessels, sea ice and how these are perceived by the subjects who interact with both. Following Nail's (2018) philosophy of motion, this research is driven by the methodological primacy of motion with respect to the domain of study. Mobility studies have recently employed a breadth of 'mobile methods' that seek to 'move with' mobile systems as the object of study (e.g., Büscher et al., 2010). However, Merriman (2014) cautions against an exclusive embracing of mobile methods, as their focus on active and mobile subjects comes at the expense of broader understandings of materialities, practices and events. Indeed, Merriman's critique of mobile methods exclusively centred around mobile subjects sits at the heart of what I seek to address in this thesis: reintroducing a focus not just on the mobile entities on the move, but how these mobilities are entangled with the mobile backgrounds and surroundings alongside which these mobilities take place.

Drawing on the theoretical framework of cryomobilities set out in Chapter 2, the methods employed in this research are aligned to support the analysis of mobile interactions between vessels and sea ice through an interdisciplinary approach between the fields of human and physical geography. As Deleuze and Guattari (1988) point out, the understandings of mobilities (and immobilities) are rooted in the human ability to perceive what is and is not in motion and, as a result, can miss those mobilities that exist both above and below the threshold of human perception. As such, in this research, I employ methods that draw both on human embodied experiences of cryomobilities, but also mobilities as understood from remote sensing of these mobile phenomena. Interviews provide insight into embodied experiences of sea ice and vessel mobilities, whereas satellite imagery of sea ice provides a sense of mobility across larger scales and longer timelines, revealing the ways in which sea ice is mobile beyond the realm of direct human perception. This approach draws on Vannini and Taggart's (2014) argument that the spatialising processes of water worlds need to be analysed in both their precise material and physical details, as well as in their lived experiences and felt practices.

4.2.1. Spatial Analysis of Sea-Ice and Vessel Traffic Data

A key component of this thesis' focus is to gain an understanding of the mobilities of sea ice and vessels through space and time. To this end, I carried out spatial and statistical analysis of two main spatial datasets: the AMSR2 sea-ice concentration data (Spreen et al., 2008) and the ASTD vessel traffic data (PAME, 2022). On occasion, some analyses are further supplemented with sea-ice concentration data from the NSIDC Sea Ice Index V3 (Fetterer et al., 2017).

As the sections below elaborate in more detail, much of the data processing and analysis was automated through Python scripts. As many of the operations had to be repeated for each day or month, and sometimes with multiple variations for each, automated Python scripts significantly sped up the process by only having to launch the task once. In addition, this removed operator errors that might arise from having to manually set up and run the tasks each time.

A combination of proprietary and open-source Python packages were used to carry out the analysis. First, some scripts use the Esri-owned ArcPy package. ArcPy allows users to implement ArcGIS Pro tools in a Python environment, which therefore comes with all the functionalities of automation associated with working in Python. It also allowed me to create custom processes that utilise multiple tools in succession, as well as integrate these with functionalities from Python packages other than ArcPy. ArcPy interfaces directly with the ArcGIS Pro installation and, therefore, using ArcPy requires having an active Esri product licence. Second, other scripts use open-source Python packages including pandas and geopandas. This is primarily the case for the Python script that was created to clean up the ASTD shipping data in order to make it available for use by people who do not have an active Esri licence.

4.2.1.1. AMSR2 Sea-Ice Concentration Data

The AMSR2 dataset is the main daily sea-ice concentration dataset used to run spatial analyses of sea-ice presence relative to vessel traffic. AMSR2 sea-ice concentration data are free to download[11] and is provided by the University of Bremen, Germany (Spreen et al., 2008). Data were obtained using the AMSR2 on board the JAXA (Japan Aerospace Exploration Agency) satellite GCOM-W1, which has been operational since May 2012. The surface brightness measurements obtained from passive microwave sensing are then processed using the ASI (ARTIST Sea Ice) algorithm to obtain daily measures of sea-ice concentration, and this analysis uses dataset version 5.4 (Melsheimer, 2019). The AMSR2 sensor replaces its predecessor, the AMSR-E (Advanced Microwave Scanning Radiometer for EOS) on the NASA satellite Aqua, which was operational from 2002 to 2011. Analyses that span across 2011/2012 therefore use data obtained from both the AMSR-E and AMSR2 sensors and users should be wary of calibration issues between the two sensors, as thorough calibration is still in progress (University of Bremen, 2023). As this analysis only uses data from 2013 onwards, which comes exclusively from the AMSR2 sensor, there are no issues of calibration across sensors.

Daily AMSR2 sea-ice concentration data are available at spatial resolutions of 3.125 km and 6.25 km. These use the same grid alignment as the widely used NSIDC Sea Ice Index (see Section 4.2.1.2), which has a spatial resolution of 25 km, in order to facilitate compatibility across datasets. This analysis uses the 6.25 km resolution data as an appropriate resolution for the overall size of the area under scrutiny comprising the Bering and Chukchi Seas.

AMSR2 data has a daily temporal resolution. Daily sea-ice concentration data were used in this analysis when looking at specific vessel transits that require detailed sea-ice concentration conditions for that day. Daily data are also used for calculating sea-ice concentration values at known vessel point locations by using sea-ice concentration data from the same day as the timestamp on the vessel data points (see Section 4.2.1.3). From these daily data, average monthly sea-ice concentration maps were generated, in order to be able to use monthly sea-ice data alongside the shipping data which is aggregated into monthly datasets. This was done using the “Cell Statistics” tool available through ArcPy, which calculates per-cell statistics from multiple input rasters. In this case, the mean value at each grid cell location was calculated from all the daily raster files for a given month. This generated 120 monthly maps for the entire 10-year sea-ice concentration dataset used for this project (2013–2022), and the process was automated through a Python script. Figure 4.1 shows an example of daily and monthly sea-ice concentration data. The different colour palettes distinguish daily from monthly sea-ice concentration data shown in the figures throughout this thesis.

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[11] AMSR2 sea-ice concentration data can be downloaded for free at https://seaice.uni-bremen.de/data-archive/.

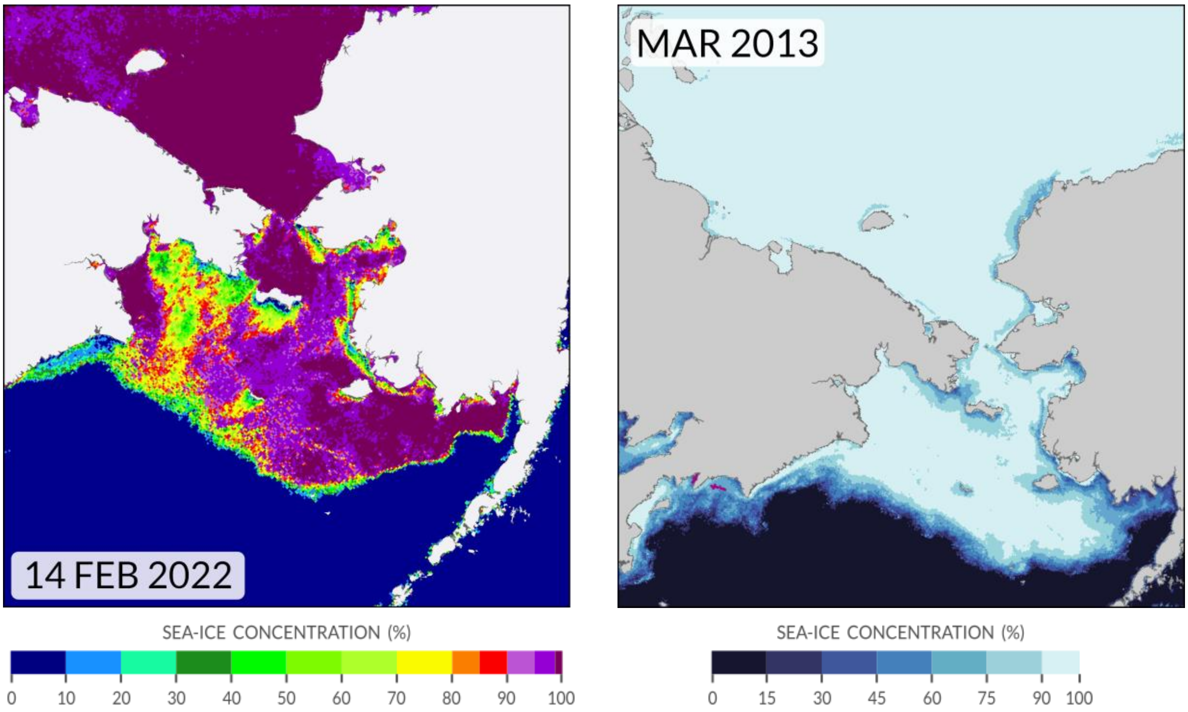

Figure 4.1 – Example of daily AMSR2 sea-ice concentration data and accompanying legend (left). Example of monthly AMSR2 sea-ice concentration data and accompanying legend, calculated by summing all the sea-ice concentration values at each cell location for each calendar month (right).

4.2.1.2. NSIDC Sea-Ice Concentration Data

In addition to the AMSR2 sea-ice concentration data, the freely downloadable NSIDC Sea Ice Index V3 products were also analysed. The Sea Ice Index provides continuous daily and monthly sea ice data since 1979. These consist of daily and monthly datasets for sea ice extent and concentration across the Arctic (and Antarctic). This research focuses on the Arctic monthly sea ice concentration data. Due to its longer time frame, the Sea Ice Index is used to provide longer-term context to the shorter-term trends observable in the AMSR2 dataset (which is only used for the period 2013–2022). The Sea Ice Index resolution of 25 km is also much coarser than the AMSR2 data (where resolution is 6.25 km) and so would not provide the necessary detail for analysing small-scale sea ice and vessel interactions. As such, the Sea Ice Index is only used here to provide broader context for longer time periods not covered by the AMSR2 data.

Accompanying the GeoTIFF files containing the spatial data for the Sea Ice Index variables, the NSIDC also provides tables of summary statistics derived from the spatial datasets. These include calculations of total sea-ice area obtained from sea-ice concentration values across multiple grid cells in a given area. Whilst the Sea Ice Index covers the entire Arctic region, it is also subdivided into regional seas (Figure 4.2). The analysis carried out in this research utilises data pertinent to the Bering Sea and Chukchi Sea regions, as these cover the seas surrounding the Bering Strait.

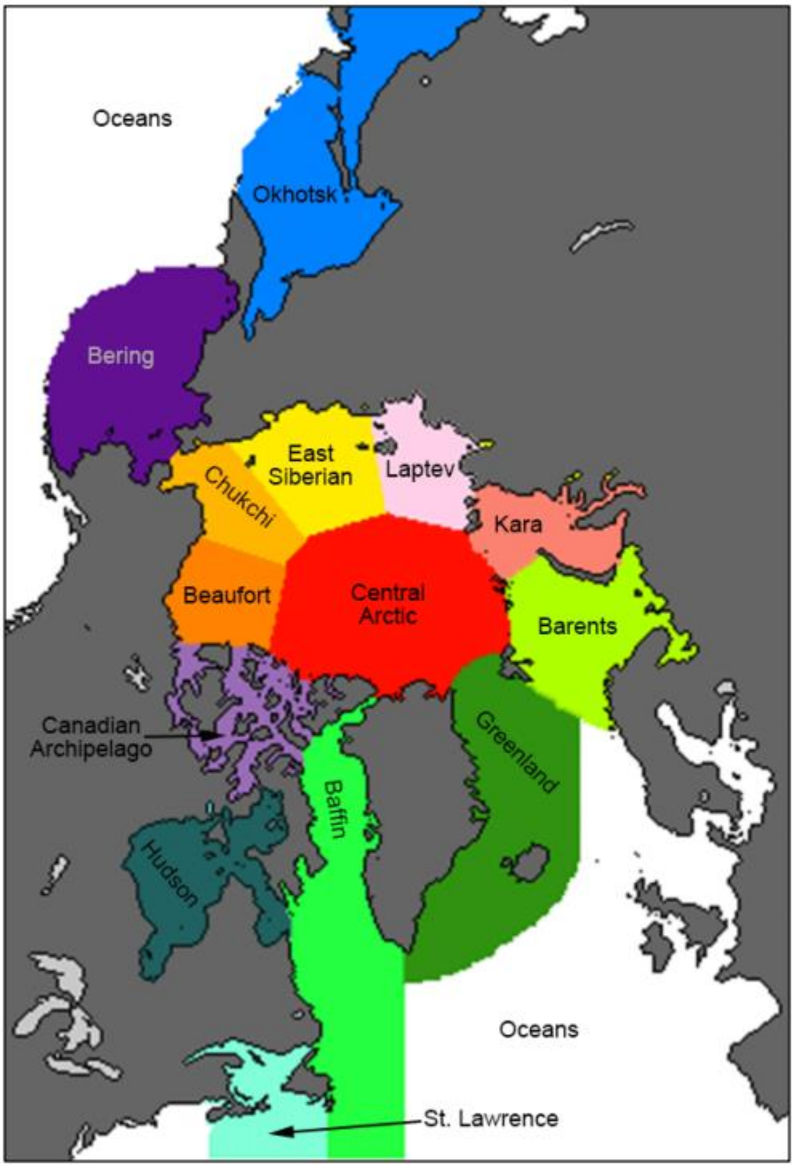

Figure 4.2 – NSIDC Sea Ice Index V3 classification of Arctic regions (Windnagel, 2020).

4.2.1.3. PAME ASTD Vessel Traffic Data

The main focus of my three-month placement at IARC was to analyse the Arctic Council's ASTD database of ship traffic data to which IARC has access. Research faculty at IARC were interested in gaining valuable insights from the ship traffic dataset that would contribute to ongoing research on marine mammals and how their habitats crossed over with vessel activities taking place in the Bering Strait region.

The Arctic Council's PAME (Protection of the Arctic Marine Environment) working group maintains a database of ship traffic data obtained from AIS (Automatic Identification System) ship signals from 2013 to present. AIS is an on-board location transmitting system primarily used for safety at sea, by allowing automatic transmission of ship location (and other information) between ships, and from ships to coastal authorities (NATO, 2021). Using a ground station capable of receiving IAS signals, port authorities and maritime safety agencies can use AIS to monitor and manage live maritime traffic. By collecting these position signals, or pings, emitted by vessels and picked up by satellite and terrestrial stations through time, it is possible to create a log of past ship activities in a given region. The ASTD is one such log of ship traffic activities acquired in this way.

There are two types of AIS transceivers: Class A and Class B. Class A transceivers autonomously relay ship position data every 2-10 seconds (depending on ship speed), have a range of roughly 20 nautical miles (depending on how high the antenna is positioned), and meet the SOLAS Convention (International Convention for the Safety of Life at Sea) regulations for ships that are legally required to carry AIS transceivers[12]. Class B AIS transceivers relay position data less frequently, have a shorter range, and are usually only used by smaller vessels to enhance their safety at sea. The ASTD database only contains signals from Class A transceivers, and these are collected from terrestrial stations as well as Norwegian and U.S. satellites (PAME, 2023). The ASTD has been simplified to contain AIS pings only every 6 minutes, even if Class A transponders emit ship position signals much more frequently than this (PAME, 2023). By default, each AIS ping contains location and timestamp information. In addition, PAME has appended additional vessel information to each AIS ping, such as vessel type, size, flag and gross tonnage. This is done by cross-referencing each AIS ping's MMSI (Maritime Mobile Service Identity) with the Lloyds Register of ships, which holds vessel information for ships registered with an IMO (International Maritime Organization) number since 1790 (PAME, 2023). PAME has also added information on each vessel's ice class using the Finnish-Swedish Ice Class Rules (PAME, 2023; Traficom, 2023). However, the crew can configure their AIS equipment to also send additional voyage-specific information, such as vessel type, destination and estimated time of arrival. As such, via AIS, vessels can transmit some of the same information that is found in the Lloyds Register (e.g., vessel type). There are instances in the ASTD database where the same vessel changes ship type along its journey (e.g., from "refrigerated cargo" to "fishing vessel"). It is unclear from the ASTD metadata how these two sources of information regarding ship attributes have been handled in the ASTD database, and which one has been used to determine the values that are shown in the ASTD.

PAME offers three levels of access to ASTD, ranging in level of aggregation. Level 1 is the most detailed, and Level 3 is the least detailed (Table 4.1). Access to Levels 1 and 2 is free, but only available within the Arctic Council to member states (and their government agencies and ministries), permanent participants, and working groups and task forces (PAME, 2020a). Level 3 subscription-based access to the dataset is available to Arctic Council observer states and organisations, as well as professional institutions meeting a series of criteria laid out by PAME. IARC, as a professional institution, has access

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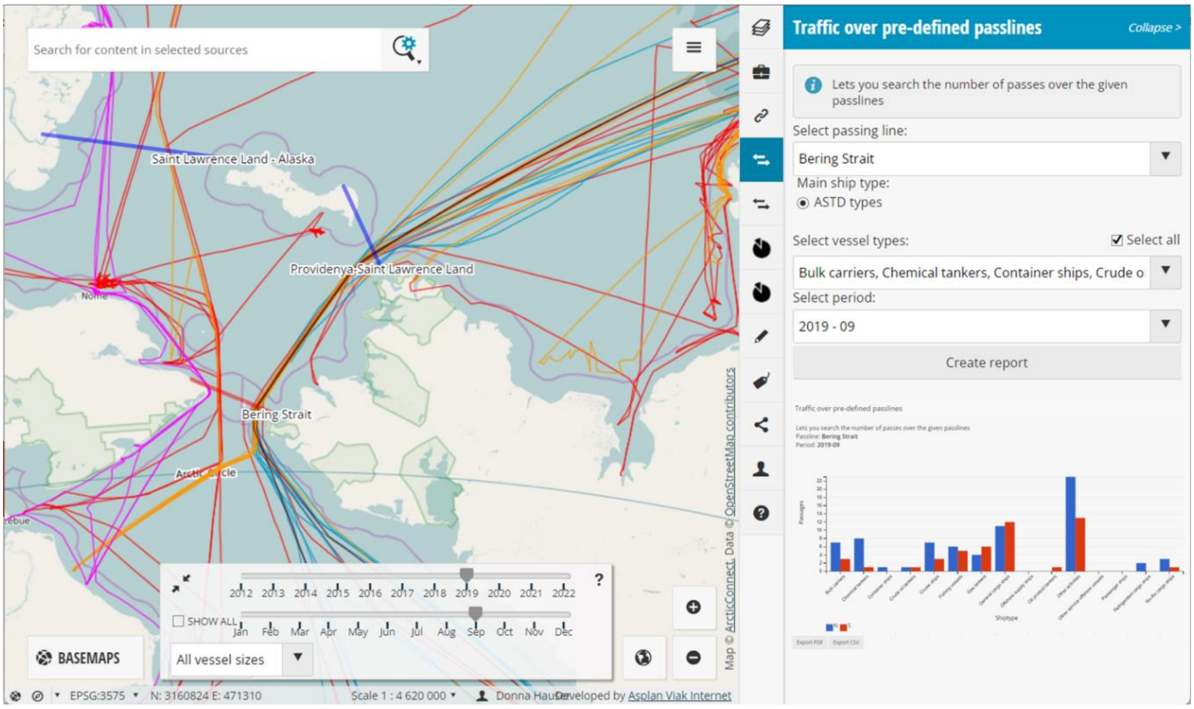
[12] SOLAS regulation V/19 requires the following vessels to carry AIS transceivers: i) all ships of ≥300 gross tonnage engaged on international voyages, ii) cargo ships of ≥500 gross tonnage not engaged on international voyages, and iii) all passenger ships irrespective of size. The requirement became effective for all ships by 31 December 2004 (IMO, 2023).

to Level 3 data. In Level 3, vessel identity data (MMSI, IMO number and ship name) has been reduced to an arbitrary “ship ID” number. A given ship ID refers to the same ship within each monthly dataset but is not consistent across months. In Level 3, Ship type information is also aggregated into only 15 categories (Appendix I).

Table 4.1 – Data fields available from the ASTD database according to the level of subscription, Levels 1-3. Source: PAME (2023).

DATA FIELD	LEVEL 1	LEVEL 2	LEVEL 3	EXPLANATION
mmsi	YES	NO	NO	The identification number of the AIS-equipment on the vessel
imonumber	YES	NO	NO	IMO number of the ship
ship_id	NO	YES	YES	Id of the ship – unique for each month.
date_time_utc	YES	YES	YES	Date/time of the AIS message reported by the vessel
vesselname	YES	NO	NO	Name of the ship
flagname	YES	YES	YES	Name of the ship flag
flagcode	YES	YES	YES	Code for the ship flag
iceclass	YES	YES	YES	Ice class of the ship
astd_cat	YES	YES	YES	Type of ship (ASTD aggregation)
lloyds3_	YES	YES	NO	Type of ship (Lloyds aggregation)
lloyds5_cat	YES	NO	NO	Type of ship (Lloyds aggregation)
sizegroup_gt	YES	YES	YES	Size of ship (ASTD aggregation)
fuelquality	YES	YES	YES	Type of fuel used
fuelcons	YES	YES	YES	Fuel consumption in metric tons from last signal
co	YES	YES	YES	Co emissions in metric tons from last signal
co2	YES	YES	YES	Co emissions in metric tons from last signal
so2	YES	YES	YES	So2 emissions in metric tons from last signal
nox	YES	YES	YES	Nox emissions in metric tons from last signal
dist_nextpoint	YES	YES	YES	Distance sailed since last point in **meters**
sec_nextpoint	YES	YES	YES	Seconds from last point
longitude	YES	YES	YES	Longitude position signal
latitude	YES	YES	YES	Latitude position signal

The primary method of browsing the dataset is through the ASTD online portal (Figure 4.3). The portal also offers interactive functionalities to filter the dataset and generate statistical summaries (as tables and charts) of the entire dataset, as well as just for custom areas. Whilst this is a great tool for obtaining a general overview of the dataset, it cannot be used as input for offline custom spatial data analyses.



Traffic over pre-defined passlines

Lets you search the number of passes over the given passlines

Select passing line: Bering Strait

Main ship type: ● ASTD types

Select vessel types: ☑ Select all

Bulk carriers, Chemical tankers, Container ships, Crude o

Select period: 2019 - 09

Figure 4.3 – Screenshot of ASTD online portal for browsing and accessing ship traffic data. Using the tools on the right, it is possible to obtain customised statistics on the entire dataset or specific user-defined areas.

The online portal includes a tool that allows users to download portions of the dataset in shapefile format and use them for analysis outside of the portal environment. However, at the time of my placement at IARC (January–July 2022), this functionality had known technical issues, so there was no option available to obtain ASTD data from the online portal. At the time of writing (November 2023), the data download function has yet to be reinstated on the online portal. Without the download function, users can submit a request to the technical team of the ASTD dataset and request access to the raw ASTD dataset through their FTP server. Ship data downloaded via FTP is split into monthly datasets. The main issue with the raw data is that it contains a large number of erroneous AIS data points (whereas the data shown in the online portal has already undergone a process of screening and clean-up to remove as many of these erroneous data points as possible). Figure 4.4 shows an example of the raw data downloaded from the FTP server, including the obvious incorrect clustering of points near the North Pole, and how this creates issues when connecting the points to create ship tracks. These incorrect data points interfere with the spatial analysis of the dataset by creating unrealistic tracks of vessels supposedly jumping to the North Pole and back in a few hours. In addition, these points also interfere with the statistical analysis of the dataset because each point also carries information about the next point along the ship's track, such as distance and time between the points. If ship tracks are jumping across the ocean mid-track, the dataset would also carry the time and distance values of these jumps, leading to incorrect estimates for, for example, the total distance sailed by ships in a month.

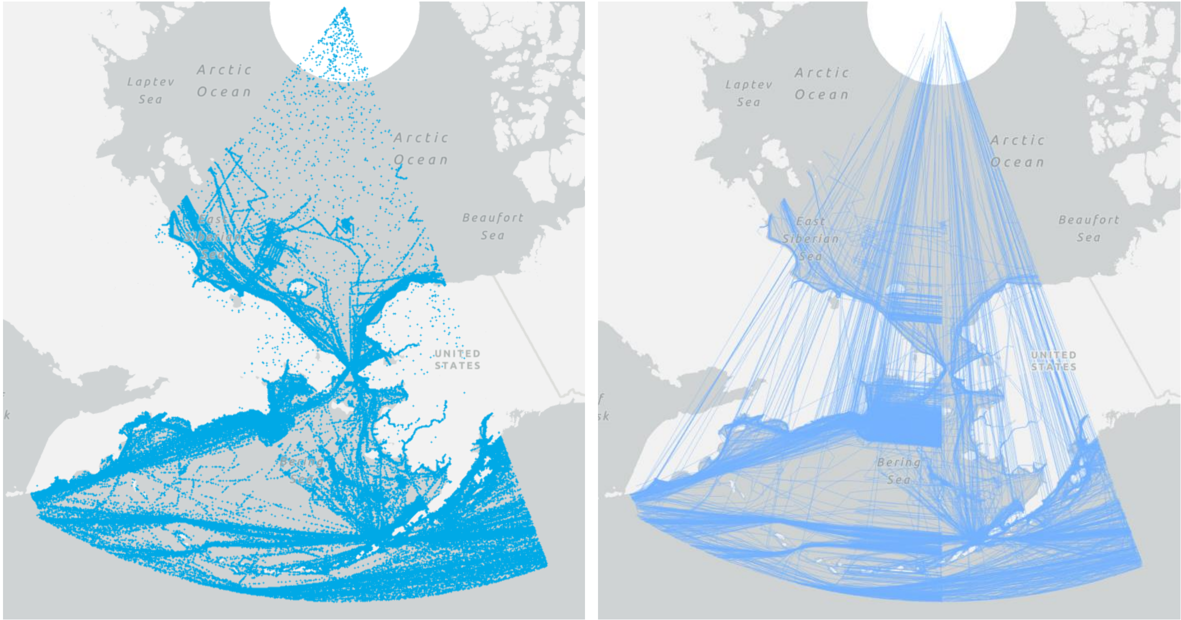


Figure 4.4 *– Example of raw ASTD dataset for September 2019 downloaded from the PAME ASTD FTP server (left). Notice the unrealistic clustering of points near the North Pole, likely an artifact of AIS transponder signals bouncing and being picked up by satellites as originating from incorrect locations. Due to the presence of erroneous AIS signal points throughout the dataset, when these points are connected by ship ID and timestamp to create tracks for each vessel, the tracks appear to jump unrealistically through space and time (right).*

In light of the challenges arising from the raw ASTD data and, in order to be able to use the raw ship data as input in spatial analysis, the focus of my placement at IARC became to develop a Python script that would clean up the raw ASTD data and make it ready to use as input in spatial data analyses. This script (Appendix II) will be made available open source on GitHub, available to be used by anyone with a subscription to the ASTD dataset for cleaning up and processing their own raw ASTD ship traffic data.

The steps that the script takes to clean up the ASTD ship data are illustrated as a flow chart in Figure 4.5. ASTD data were downloaded from the FTP server as monthly datasets for the entire Arctic region in CSV format. These are used directly as input in the clean-up script. First, the script runs a series of setup steps that are only done once at the start of each monthly dataset:

1. Delete any pings from ships for which there are fewer than 10 positions in one month. PAME suggests to do this as part of the data cleaning up process (PAME, 2023).
2. Delete any pings outside a given study extent defined by a set of geographical coordinates. This allows users to only process ship traffic data for their areas of interest.
3. Create geometry attributes for each data point. Latitude and longitude coordinates are stored in the original dataset using the WGS 1984 (EPSG 4326) geographical coordinate system. These are then converted to the North Pole LAEA Europe (EPSG 3575) projected coordinate system, as distances between spatial features can only be calculated using projected coordinate systems. Assigning geometry involves converting the database from a pandas data frame to a geopandas data frame.

4. Calculate the distance from each point to the previous point (in metres). First, points are ordered by ship and timestamp, so that distances are calculated between successive points along a ship’s track. This is added as a new attribute, called “m_from_prev”.
5. Delete any points that are identical in time and space. If the distance calculated in the previous step is zero, these points are deleted, as they are identical consecutive points.
6. Calculate the time (in seconds) and speed (in metres per second) from each point to the previous point. This is done using the timestamp for each data point, and then the distance between points obtained in step 4. These are added as new attributes, “sec_from_prev” and “m/s_from_prev”, respectively.
7. At this stage, the dataset is saved as a CSV file for future reference, and so that users can browse the data in their study area without having to open the entire Arctic dataset.

Following these setup steps, the script begins to iterate through each data point, performing a series of checks (using “IF” statements) in order to determine whether the data point being iterated is to be kept or deleted. Within these series of iterations, rules are set up to identify erroneous data points in a variety of circumstances. Primarily, the script uses the distance and speed attributes calculated in the setup steps to determine which points fall outside reasonable thresholds and should therefore be removed. Finally, when all points have been iterated through, the script saves the cleaned dataset as a new comma-delimited text file.

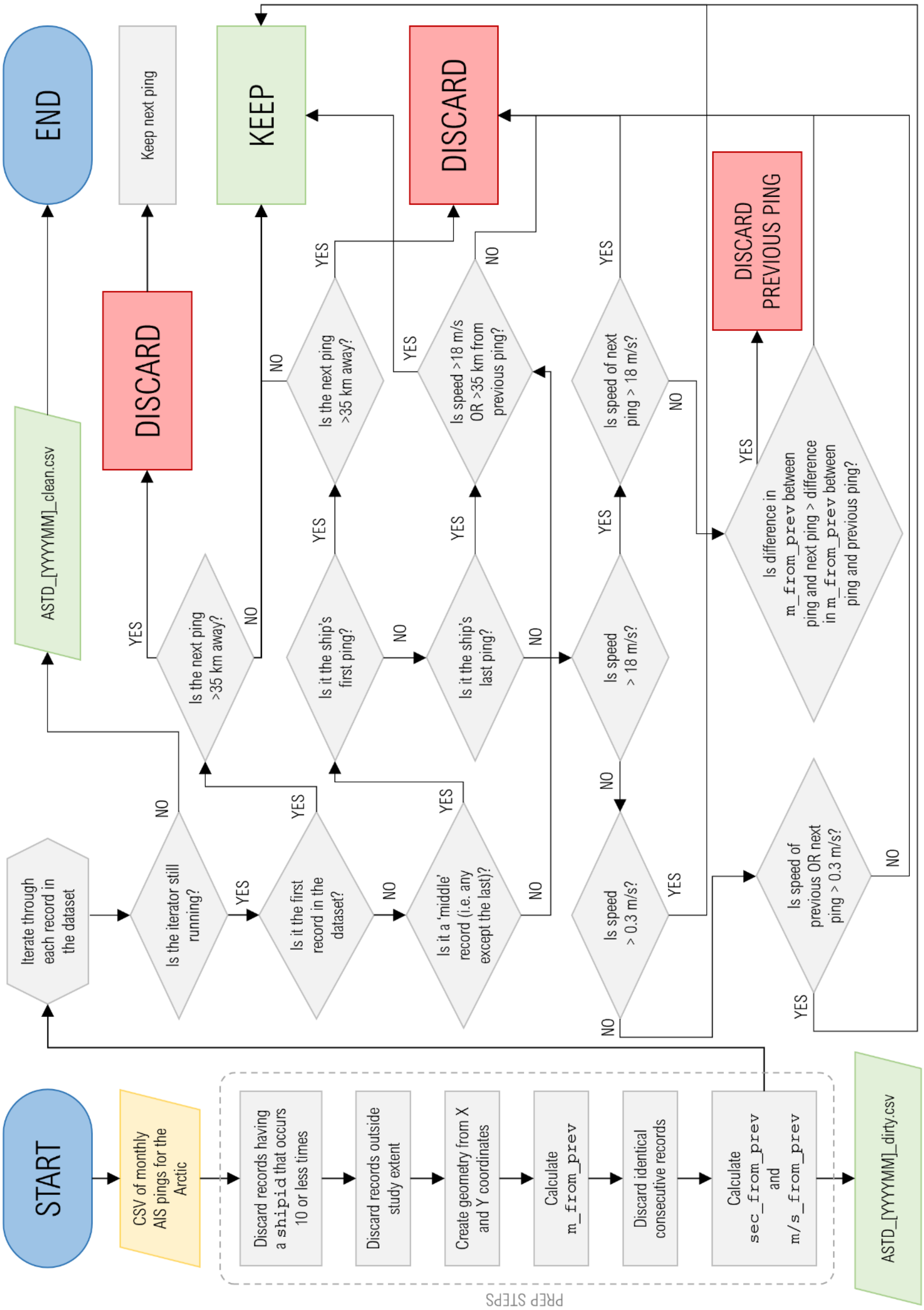
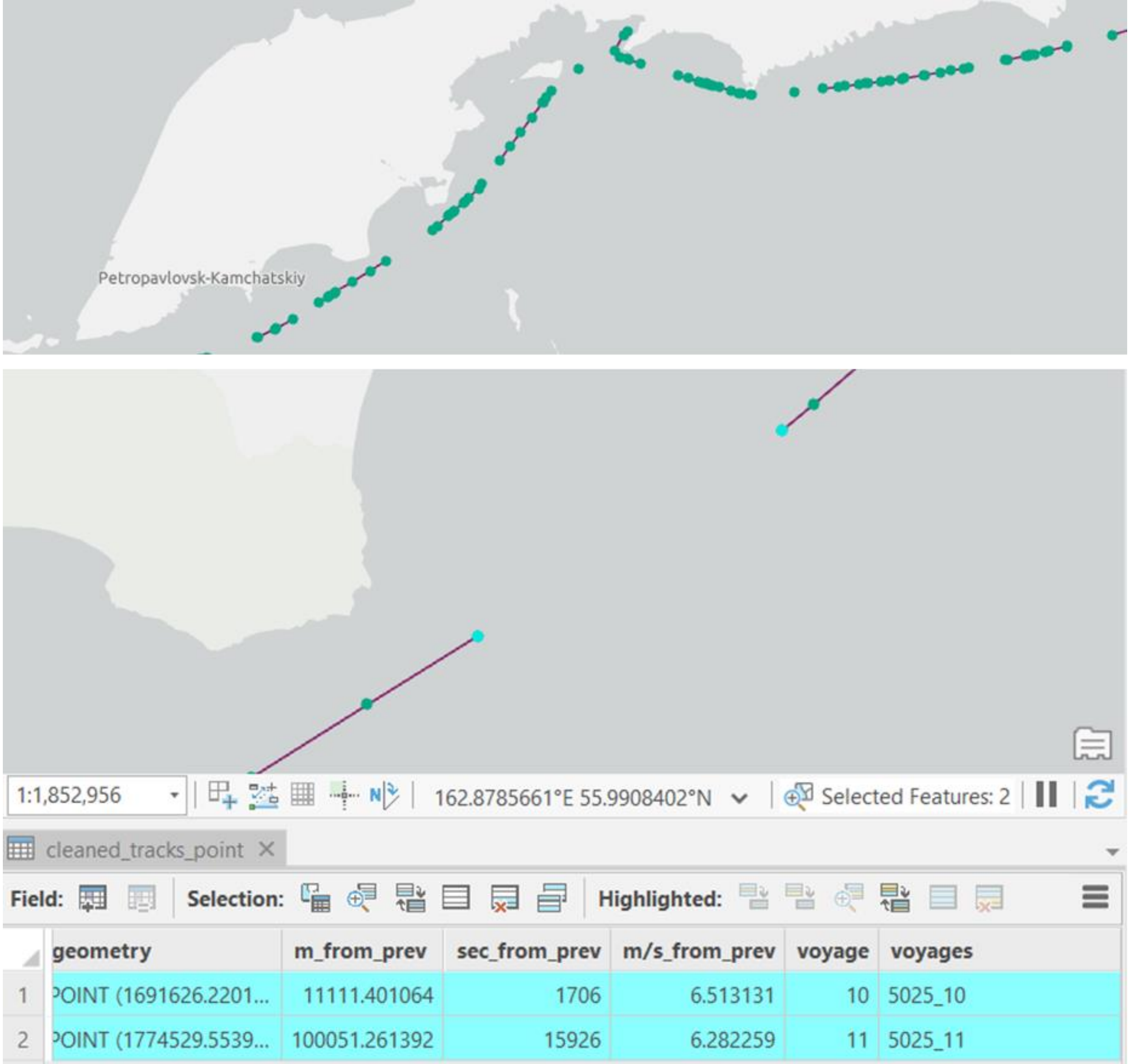


Figure 4.5 – Flow chart showing the process that the Python script goes through to clean up the ASTD AIS ship data.

The clean-up process laid out in Figure 4.5 draws inspiration from the method of processing of AIS data developed by Axiom Data Science (Axiom Data Science, 2019). However, significant alterations have been made to account for the specificities of the ASTD dataset and vessel behaviour in the Bering Strait region. For example, to account for ferry behaviour, Axiom's clean-up process creates separate voyages by the same ship if two ship location points are less than 100 m and 10 minutes apart (i.e., a ferry has stopped at port between voyages). This filtering was removed, as there is no ferry service active within the study area, and those criteria were creating separate voyages for fishing vessels carrying out regular fishing activities that required staying in the same location for more than 10 minutes. Axiom's algorithm also creates a new voyage if two AIS pings are more than 50 km apart. However, the ASTD dataset regularly contains points that are more than 50 km apart and clearly part of the same voyage (e.g., Figure 4.6), so this was also removed to produce more consistent vessel tracks. Therefore, the Python script developed for this research only creates one voyage per ship per monthly dataset, as this is representative of the shipping activities that take place in the Bering Strait region and avoids creating unnecessary separate vessel voyages.



	geometry	m_from_prev	sec_from_prev	m/s_from_prev	voyage	voyages
1	POINT (1691626.2201...	11111.401064	1706	6.513131	10	5025_10
2	POINT (1774529.5539...	100051.261392	15926	6.282259	11	5025_11

Figure 4.6 – Screenshots from ArcGIS Pro showing an example ship track during the development stages of the Python script. The ship track has been erroneously split into over 10 separate voyages that are clearly part of the same ship voyage track (top image). A zoomed-in portion of the ship track showing the attributes of consecutive AIS ping locations (AIS pings are highlighted in light blue, whose attributes are shown in the table) shows that these new voyages were created because consecutive pings were more than 50 km apart (see attribute column "m_from_prev"; bottom image).

Once the ASTD ship-traffic data were cleaned up, several spatial data operations were carried out to both organise and analyse the data. First, the Python script saves the final cleaned up ship points in CSV format. These were i) converted to a point shapefile (using the "XY Table to Point" tool), ii) projected into the North Pole LAEA Europe (EPSG 3575) coordinate system (using the "Project" tool) and iii) connected by ship and timestamp to create ship track lines (using the "Points to Line" tool). This process was saved as a custom tool within ArcGIS Pro in order to be able to easily re-run it, and to be able to share it with colleagues at IARC as a complete workflow for cleaning up the ASTD ship data. Using the "Points to Line" tool only keeps the ship ID as an attribute of the new line features that it creates and loses all the attributes assigned to the points because many point features (that can all have different attributes) are condensed into a single line feature. Some of these attributes, such as ice class, gross tonnage and flag name are single ship-specific attributes that also need to be carried over to the ship tracks, so these were transferred to the ship tracks with the "Join" tool that uses the unique ship ID to match records across the point and line datasets.

In addition, information from the AMSR2 sea-ice concentration data were added to the ship data points based on location. The aim was to assign each known AIS data point the value of the corresponding sea-ice concentration grid cell at that location on that day. This was done using the "Spatial Join" tool available through ArcPy. By using the daily AMSR2 sea-ice concentration data, each point in the ship traffic dataset was matched to the correct daily sea-ice map using its timestamp, and the sea-ice concentration value was extracted and added as an attribute of that point.

4.2.1.4. Delimiting a Study Area for Statistical Analysis

In order to retain consistency throughout the comparisons of statistical trends in sea ice and vessel activities, the analyses carried out in this research refer to a defined study area. The study area (Figure 4.7) is determined using a combination of several area delimitations:

- ***Maximum sea-ice extent*.** This is defined by taking the maximum sea-ice extents from the NSIDC Sea Ice Index V3.0, during the month of greatest sea ice extent in the Bering Sea for each of the 10 years in the period 2013-2022 (these were January 2019; February 2020 and 2022; March 2013-2018 and 2021). These 10 shapefiles were merged to obtain the total maximum sea-ice extent during 2013–2022. A 100 km buffer was added to ensure all sea-ice affected areas would always be included. This boundary based on sea-ice extent (rather than, for example, taking the entire Bering Sea region as defined by NSIDC) allows the study area to exclude much of the Aleutian Islands ship traffic. Vessel activities here are not impacted much by sea ice, and vessel behaviours tend to reflect patterns in other global shipping routes (e.g., the North Pacific Great Circle Route), rather than the Arctic-facing vessel traffic of the Bering and Chukchi Seas. This delimits the southern boundary of the study area, shown by the yellow line in Figure 4.7.

- ***Bering Sea and Chukchi Sea areas.*** This is obtained from the NSIDC Sea Ice Index (Figure 4.2). Given that NSIDC provides statistics for various sea-ice indicators based on these regions, this allows comparability between the shorter-term ASMR2 sea-ice data (2013–2022) and the longer-term NSIDC Sea Ice Index V3 (1979–2022) used in this thesis. A 30 km buffer was added to the NSIDC regions of the Bering and Chukchi Seas to ensure that the study area included small inlets and bays, as the coarse gridded shoreline edge was cutting off some important nearshore ship traffic. This is shown by the purple line in Figure 4.7.

The area where the i) maximum sea-ice extent (with 100 km buffer) and ii) Bering and Chukchi Sea regions (with 30 km buffer) intersect is the study area used in the analyses throughout this project. This is shown by the hashed area in Figure 4.7.

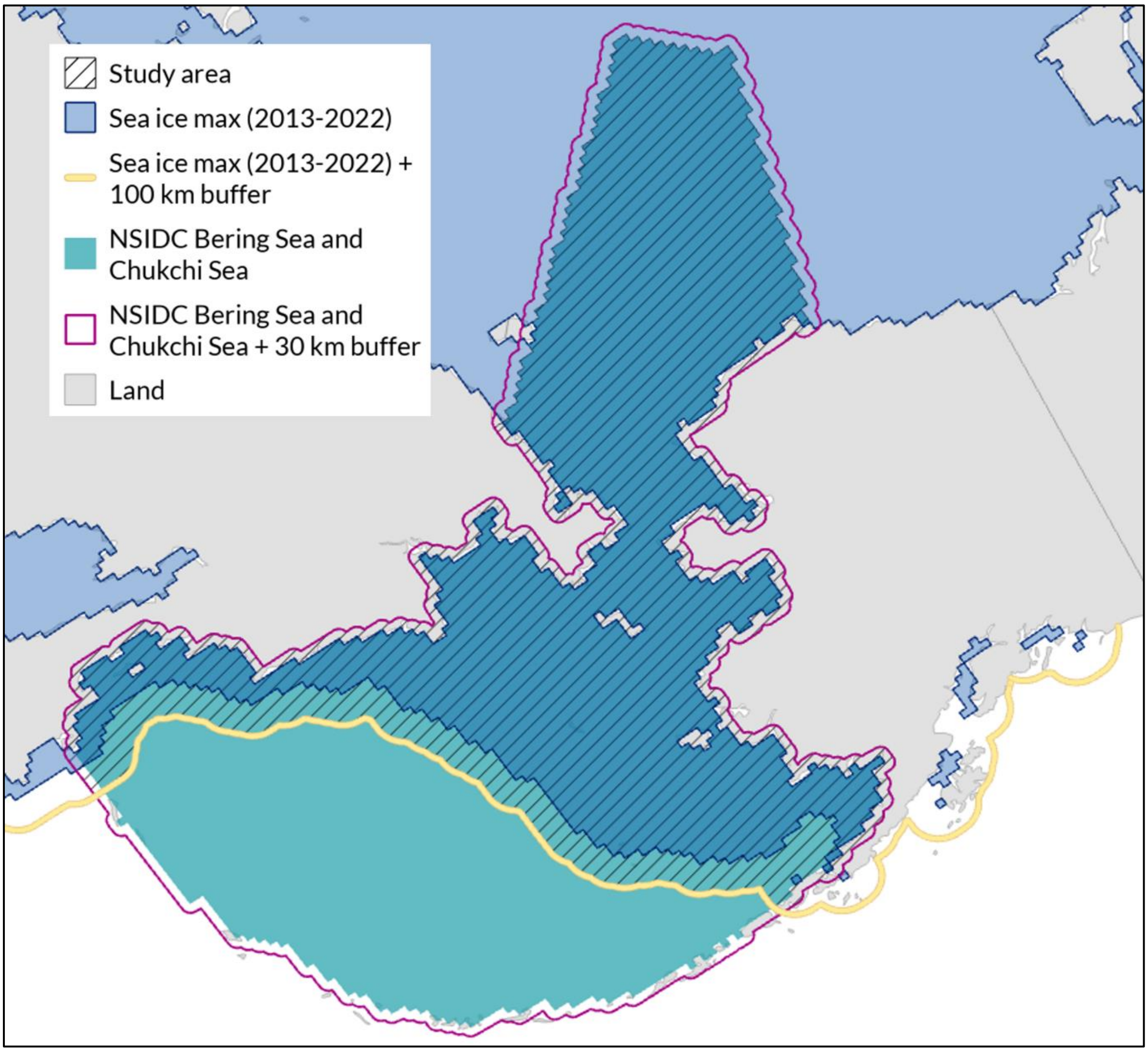


Figure 4.7 – Study area used throughout this thesis for standardising statistical analyses of vessel traffic and sea-ice data.

4.2.2. Interviews

A key component of this project is to gain an understanding of how cryomobilities are perceived by people involved in various ways in the mobilities of sea ice and vessels. As such, the purpose of the interviews was to gain insight into how people created knowledge and made sense of the mobile encounters between vessels and sea ice. In light of this, participants were chosen based on their involvement with sea ice, vessels, or both from a variety of perspectives. Three main types of involvement with sea ice and vessels were used as selection criteria for participants: logisticians and forecasters, academic scientists, and seafarers. This served as a framework for gathering perspectives from people who approached sea ice and vessel interactions from a variety of viewpoints. The logisticians and forecasters are people who are involved with sea-ice behaviour and vessel activities from a very practical point of view; their purpose is to monitor, assess and keep an eye on the status of sea ice or vessels, and provide logistical and forecasting support that contributes to the smooth functioning of vessel operations in ice-prone waters. Academic scientists are those whose work focuses on gaining a deeper understanding of the geophysics of sea ice and vessel activities through it. Their work is often highly specialised in a specific aspect of their field of study, although it usually requires a wider outlook and connection to much broader processes, such as broad-scale atmospheric or oceanographic conditions. Finally, for the purpose of this research, a seafarer is anyone who has had first-hand experience with sea ice or vessel activities in ice-prone waters. This perspective is fundamental in bridging the gap between understandings of cryomobilities gained from more distant or remote forms of data collection and knowledge that is developed through practical and in-person encounters. In many cases, participants' involvement in these areas overlapped, as shown in Figure 4.8. In total, 12 participants were interviewed. Interviews were carried out either in person, over the video-conferencing platform Zoom, or over the phone. Interviews took place between January and July 2022 (Figure 4.8). All participants' involvements with sea ice and vessel activities were based in Alaska and surrounding ice-prone waters. Table 4.2 lays out a short contextual description of each participant, which illustrates their role and their involvement with cryomobilities.

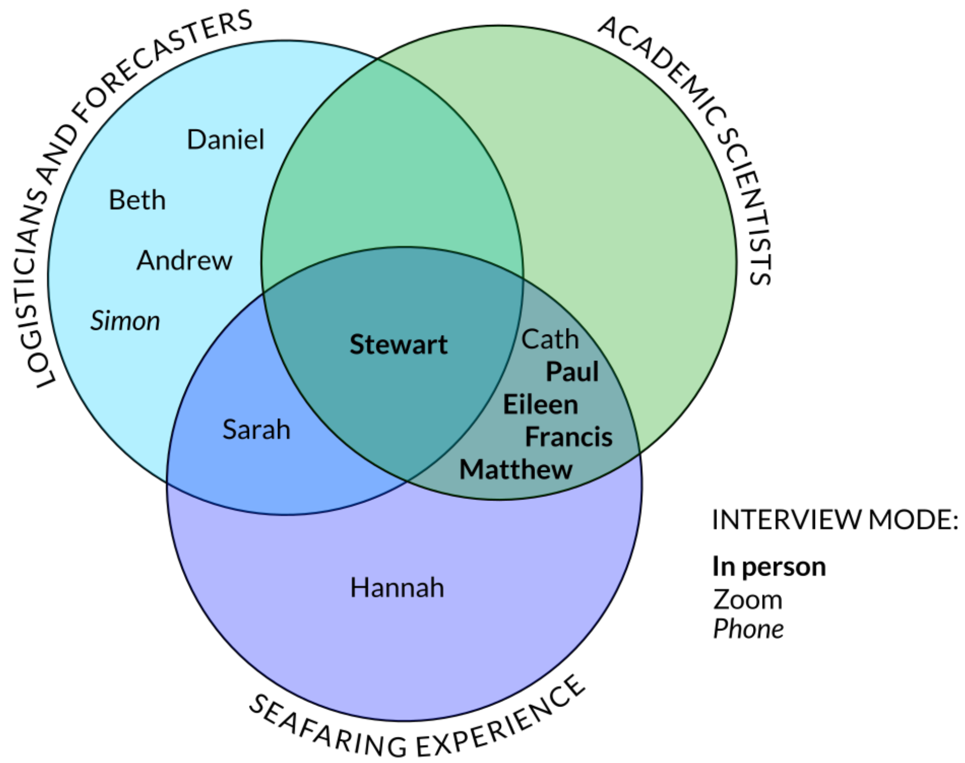


Figure 4.8 – The 12 participants who were interviewed for this research were involved with sea ice and vessel mobilities through i) logistics and forecasting, ii) academic scientific pursuits and iii) seafaring experience. In many cases, these roles overlapped. Interviews took place in person, over the video-conferencing platform Zoom and over the phone.

Table 4.2 – Interview participants and their roles relative to sea-ice and vessel mobilities.

Stewart	*Used to work as a sea-ice forecaster; lived in Nome for several years, where sea ice regularly forms each winter.*	Eileen	*Retired oceanographer; participated in countless research cruises; involved in planning and commissioning an ice capable research vessel.*
Cath	*Researcher interested in mapping interactions between sea ice, vessels, and marine mammals.*	Matthew	*Marine biologist; spent several years living and hunting with the Iñupiat of Ugiuvak (King Island).*
Sarah	*Contributes to operational sea-ice forecasts, has experienced sea ice first-hand on a few occasions.*	Francis	*Sea-ice geophysicist; extensive experience amidst sea ice in northern Alaska.*
Paul	*Sea-ice geophysicist; extensive experience amidst sea ice in northern Alaska.*	Hannah	*Videographer; has documented sea-ice research onboard several research cruises.*
Andrew	*Contributes to operational sea-ice forecasts.*	Beth	*Contributes to operational sea-ice forecasts.*
Daniel	*Contributes to operational sea-ice forecasts.*	Simon	*Involved with live monitoring of vessel traffic in Alaskan waters.*

Interviews were carried out in a semi-structured format. Under this interview style, I followed a general outline of questions as prompts, whilst also leaving space for participants to steer the conversation in directions that I may not have anticipated. This creates a friendly and open structure that feels more like a back-and-forth conversation rather than a one-way interrogation following a strict list of questions (Valentine, 2008; Dunn, 2010). This format puts participants at ease and gives them the opportunity to talk about things that they feel are important, which in itself reveals areas of priorities and concern regarding the topic being studied.

All the interviews were audio recorded, with permission from participants. The audio files were then transcribed, taking care to report as much of the nuances of the interview as possible, such as participants' moments of hesitation, laughter or sarcasm. Some repetition of words that happens colloquially was removed to improve reading of the transcripts (such as "um" and "like, you know…"). However, these colloquial interjections (in particular, "you know") were left in cases where, for example, they indicated hesitation or uncertainty around more sensitive topics. Table 4.3 provides a list of how interview transcripts were formatted to denote such amendments, which also appear in direct quotations of interview excerpts throughout the thesis. This contextual information proved useful during later stages of analysis of the interview data, as they gave a more accurate portrayal of participants' views and provided context for interpreting phrases that could otherwise be misunderstood. The transcripts were coded by themes through the use of the qualitative analysis software NVivo.

Prior to the interview taking place, participants were given a consent form that outlined the purpose of the research, that their involvement as a participant would be voluntary, that they had the right to withdraw without providing a reason, and that they could opt-out from the interview being audio recorded (Appendix I). All original audio recordings were stored in a password-protected folder on my personal password-protected computer. Only anonymised material was moved out of the password-protected folder for ease of access. All participants are anonymised through the use of pseudonyms. Not only does this protect participants from identification and connection to their views expressed during the interview, but it also gives participants the freedom to be more candid and open. This turned out to be especially important in the specific context, as the community involved with sea ice and vessel activities in Alaska is quite small. Everyone knows everyone (if not in person, at least by name), and participants often referenced each other across separate interviews. To this end, the pseudonyms assigned here do not necessarily reflect interviewees' identity attributes such as gender.

Table 4.3 – List of formatting conventions used in the interview excerpts to denote additional information.

Description	*Example*
Words or phrases that were inaudible and therefore not transcribable from the interview recordings	[*unintelligible*]
Words or phrases that were difficult to hear in the interview recordings, so there might be some level of inaccuracy in the transcription	{sea ice}
Words that interviewees did not say, but that were added in the excerpts to improve comprehension or spell out acronyms. The context of the sentence or conversation is always respected, in order to not change the meaning of what was being said.	They [the scientists] went first.
Laughter. This signalled some phrases that might have been sarcastic or be otherwise misinterpreted without a clear sign that they were meant jokingly or accompanied by laughter.	*Haha*
Misspelled or rude words that are included in the transcripts to accurately portray what the interviewee said	I'm gonna [*sic*] go.
Tone of voice	[*whispers*]
Omitted words or phrases from a longer quote	[…] *Not to be confused with "…" (without square brackets) which denotes a pause in speech or when interviewees left a sentence unfinished and moved on to the next, which happens often while speaking.*

4.3. Positionality, Ethics and Indigenous Involvement

One of the key tenets guiding this research is the importance of experience and perception in making sense of the (mobile) world around us. Likewise, in any research project, the individuality of the researcher inevitably influences and guides the design, execution and results of that project. This research has been filtered and shaped by my own experiences, interests, skills, strengths and perspectives as an educated, white, heterosexual female with an academic background in human geography – and all the biases that accompany the intersectionality of these identities. All these factors – and undoubtedly many others – have shaped the research direction of this Ph.D., the interpersonal exchanges in the field, and how the findings have been elaborated and presented in this thesis.

First, whilst I have travelled a lot throughout my life and especially as a child, following my parents' jobs in humanitarian aid NGOs, I had never been to the Arctic or the sub-Arctic. Fairbanks, where I spent six months for my DurhamARCTIC placement and fieldwork, is technically considered "sub-Arctic", although it is often included in reports as part of the Arctic (Arctic Council, 2004; Arctic Monitoring and Assessment Programme, 2023). Regardless of the technical definitions, to me, being in Fairbanks very much felt like I was in the Arctic. The low sun over the horizon, the -30°C (and below) as an expected temperature for months, the frequent encounters with moose, and the uninterrupted blanket of snow, all definitely felt like I was in what I had pictured the Arctic to be. As this research focuses entirely on icy and frozen environments, I had to become aware of how being new to such northern latitudes made me over-sensitive and over-excited about aspects of the "cryo" that were part of everyday life for residents here (and further north). Writing this thesis and its findings required me to approach matters of frozenness with a nuanced maturity that stems from the appreciation of what it means to live in these cold regions for much longer than six months of fieldwork. In particular, interviews with participants put my own views into perspective, and their stories guide as much as possible the findings presented in this thesis.

Second, whilst six months away from my family and partner sometimes felt like an endless amount of time, I also quickly realised how little time this was. As a Ph.D. student in my mid-20s, I lacked the long-term established relationships that can only be built through many years of dedicated efforts towards working together and building trust, especially when it comes to research collaborations with Indigenous communities. As a white foreigner coming to Indigenous lands for the first time, I did my best to include Indigenous perspectives throughout the research journey, as this was an aspect of doing research in the Arctic that mattered to me. I reached out to *Iŋalik* (Little Diomede), an Indigenous community on a small island located in the middle of the Bering Strait, on the United States side. It was clear that they were not in the position to host me or collaborate with me. Through Donna Hauser, my primary collaborator at IARC, I also had a chat with people in *Qikiqtaġruk* (Kotzebue), another Indigenous community on the western coast of Alaska, north of the Bering Strait. They too delivered a clear message: increased shipping was a concern for their community, but they did not see it fit to dedicate the community's resources to a direct collaboration on this topic at this time, so I should go ahead and do the research and share with them any important findings. At the time I felt like I had failed by not presenting a project that Indigenous communities would be interested in; it did not fit the bill for what I had expected "co-production" to look like. Whilst this thesis is by no means co-produced with Indigenous communities, my conversations with people in *Iŋalik* and *Qikiqtaġruk* became a way of sharing with these communities aspects of my research that were contributing to producing knowledge about their peoples, lands and oceans. Throughout this thesis, Indigenous perspectives come through where they are appropriate, and I build on the co-produced efforts of others. I hope that this does justice to the journey that I took to navigate the delicate balances of doing research in, about, and in alignment with Indigenous lands and communities, and the respect that I deeply hold for Indigenous peoples, past present and future.

Finally, this research project was shaped by my specific circumstances around Ph.D. funding. Especially in light of recent debates around the precarity and inadequacy of Ph.D. funding (e.g., Fazackerley, 2023), it is important to recognise the ways in which funding opportunities make certain types of research possible, as not all Ph.D.'s are funded in the same way (if at all). In addition to my stipend, DurhamARCTIC provided £9,000 for covering expenses related to fieldwork, conferences and the three-month placement. The funded placement served as a bargaining chip for approaching potential collaborators – Donna benefitted from my GIS skills for cleaning up the ASTD ship traffic dataset, in exchange for granting me access to use the ship data in my Ph.D. From this placement stemmed my fieldwork, which would have otherwise been challenging to organise in the same way, based in a research centre and with equally rewarding and important research collaborations.

4.4. Methodological Implications of COVID-19

The uncertainties around border closures and travel restrictions associated with the COVID-19 pandemic raised questions as to whether carrying out fieldwork would be at all possible as part of this Ph.D. I considered alternative options and rethought my research project without a fieldwork component. On 8 November 2021, borders to the U.S. reopened and I was able make arrangements for fieldwork in Alaska. However, having been faced with the possibility that fieldwork might not happen made me truly value the importance of fieldwork. At IARC, being around people who had engaged with sea ice and navigation in various ways, and sharing informal moments of everyday life and work with them, gave me insight and guided my research in ways that would have otherwise not been possible. So, one of the methodological implications of the pandemic was the way in which fieldwork, and closeness to people and personal experiences, are valued and taken seriously throughout this project. In light of this, it also became clear that returning after fieldwork to share the findings of my research was a fundamental component of this project. This was also driven by my desire to not reproduce research attitudes whereby scientists go out into the field, extract knowledge – especially in relation to Indigenous knowledge – and never return or share their findings with the people they worked with. During my return trip to Alaska in December 2023, colleagues at IARC repeatedly expressed their appreciation for being able to share the outcomes of our research collaboration and reconnect in person.

The pandemic also provided new means of communication between people. The video-conferencing platform Zoom, in particular, became a common way for people to meet and interact across long distances. Entire conferences and meetings were moved to being completely online. It was suddenly very easy to become part of discussions that would normally have happened only in person, in a conference room somewhere in the world. This made it possible for me to engage with people who would have otherwise been very difficult to reach. It also normalised interactions between people from opposite sides of the world, where having both attended the same Zoom webinar became enough of a common ground to start a conversation. I started one such conversation with Cana Itchuaqiyaq, an Indigenous scholar from *Qikiqtaġruk* (Kotzebue). Cana kindly continued to meet with me several times (again, on Zoom!) over the following months and mentored me, guided me, and answered my many questions around how to approach doing research in and about Indigenous lands. So, whilst the pandemic brought separation through travel restrictions, it also created opportunities for connection. The findings in this thesis – including, but not limited to, engaging with Indigenous knowledge – have been shaped by the countless online encounters and exposure to diverse perspectives that took place as a result of the pandemic.

4.5. Conclusion

In this chapter, I have laid out the methods employed in this Ph.D. research. The mixed methods approach combines insights from i) spatial analysis of sea-ice concentration and vessel traffic data and ii) interviews. It is designed to create a complementary methodology for analysing cryomobilities in the Bering Strait region. A combination of qualitative and quantitative methods also aligns with the interdisciplinary nature of this research across human and physical geography.

5

Cryophobia: Sea Ice as an Obstacle

5.1. Introduction

In recent years, the overall decrease in Arctic sea ice has raised a flurry of excitement over the potential navigability of previously ice-bound routes that might become ice-free in the near future (e.g., Lasserre, 2014, 2015; Melia et al., 2016; Matthews et al., 2020; Sui et al., 2021; Min et al., 2023). This has led to a growing interest in analysing relationships between sea ice and vessels across a multitude of disciplines concerned with issues such as vessel safety (e.g. Dawson et al., 2021; Vanhatalo et al., 2021), the impact of icebreakers on Indigenous subsistence areas (e.g. Carter et al., 2018b; Dawson et al., 2020; van Luijk et al., 2022), and numerical modelling of the physics of hull and sea ice impact dynamics (e.g. Tan et al., 2013; Kim et al., 2019). These avenues of research emerge from the understanding that vessels operating in icy ocean spaces encounter specific challenges that surpass those of vessels operating in open water, and therefore require addressing through dedicated research. As such, this chapter explores the ways in which sea ice is an obstacle to navigation in the ice-prone waters of the Bering Strait region. Within the context of this thesis, this chapter contributes to the understanding that sea ice (and, more broadly, ice-prone ocean spaces), as the 'background' against which vessel mobilities unfold, is in constant motion. This is so on a range of timescales, from recent decades of sea-ice decline, to seasonal variability and hourly movements due to localised weather conditions. In turn, the mobilities of sea ice influence the ways in which vessels respond to these sea-ice conditions and, as I argue in this chapter, lead to a cautious avoidance of sea ice.

To explore the ways in which cryomobilities of sea-ice avoidance take place within the Bering Sea region, I begin with a discussion of the historical context of navigation in icy waters, tracing the ways in which sea ice has been considered an obstacle to navigation during the first European Arctic voyages in the 18th and 19th Centuries (Section 5.2). Building on the historical context of challenging encounters between European vessels and sea-ice, in Section 5.3 I consider the technological advances in shipbuilding technology that have increased the ice capability of ships in order to overcome the navigational obstacles that sea ice poses. Technological advances in shipbuilding and other related fields have shaped the ways in which the challenging conditions of sea ice are attended to through navigation. Finally, in Section 5.4, I analyse sea-ice concentration and vessel traffic trends in recent decades and considers the ways in which navigational challenges shaped by sea-ice mobilities are still present in the 21st Century. Specifically, in Section 5.4.1, I examine changes in sea-ice area in the Bering Strait region for the entire period of the continuous sea-ice data record (1979–2022) and, more specifically, over the last decade (2013–2022). Due to this project's focus on the Bering Strait, which sits between two regions for which sea-ice trends are often analysed separately (the Bering Sea and the Chukchi Sea), I have combined existing data for both these regions to analyse them as a whole (for a map of the NSIDC sea-ice analysis regions, including the delimitations of the Bering Sea and Chukchi Sea, see Figure 4.2). By doing so, this research recognises the interconnectedness of systems across regions, and therefore contributes to existing literature on sea-ice trends by proposing an analysis that begins to go beyond established boundaries. Then, in Section 5.4.2, I present the analysis of vessel traffic trends in the Bering Strait region over the last decade (2013-2022). I conclude with Section 5.4.3, where I compare the trends in sea ice with the spatiotemporal patterns in vessel traffic to reveal the ice-avoidant cryomobilities that take place in the Bering Strait region. I discuss vessel traffic activities relative to sea-ice patterns in a broad sense by looking at the Bering Strait region as a whole, and these broad attitudes of sea-ice avoidance are further illustrated with examples from the voyage of a United States research vessel on its journey through the Bering Strait. The analysis of results of the Automatic Identification System (AIS) vessel tracking data, sea-ice concentration satellite data, and interviews illustrate and guide the discussion. Together, these offer a diverse and complementary set of perspectives that illuminate the factors that shape cryomobilities of sea-ice avoidance in the Bering Strait region today.

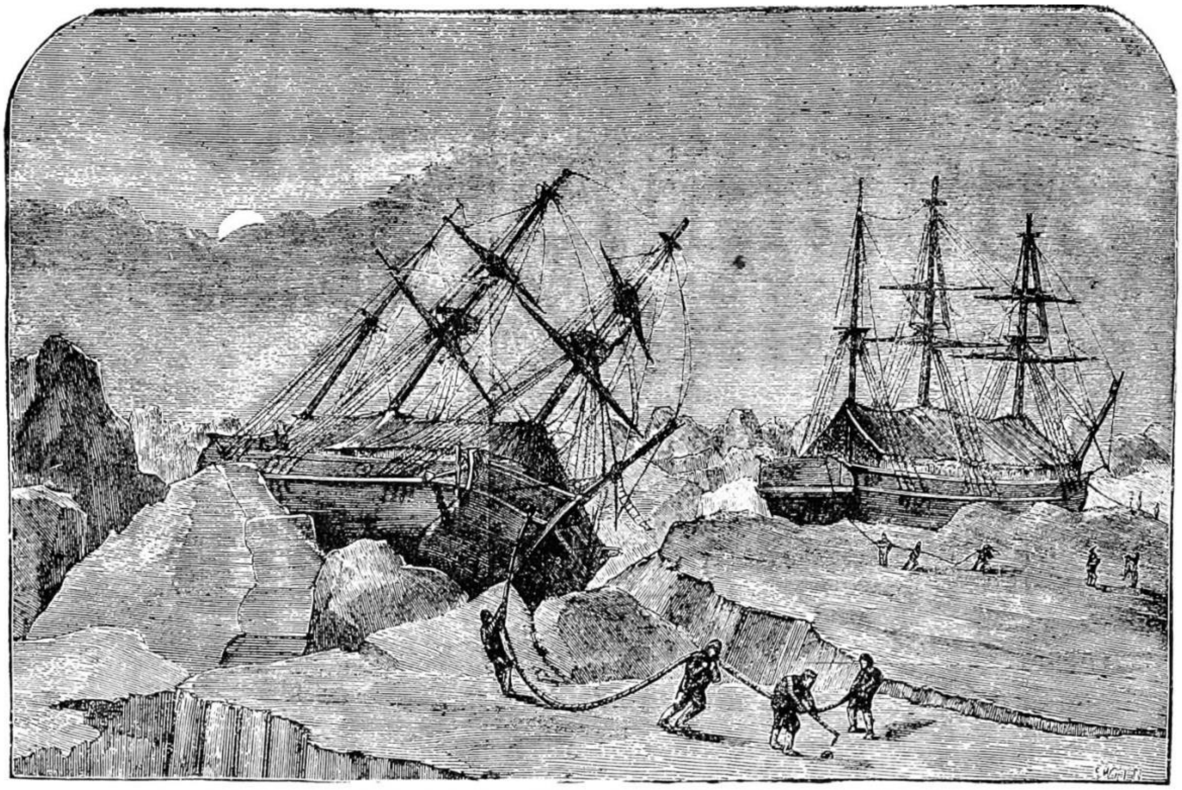
5.2. 18th and 19th Centuries European Arctic Voyages

The 18th and 19th Centuries were the height of European polar exploration. The 19th Century, in particular, saw a flurry of European explorers venture into Arctic waters seeking to chart new routes, such as the Northwest Passage through the Canadian Archipelago. The Arctic as a region was still largely unknown to European civilisations at the time, and what people knew about it came largely from tales, myths and legends that shrouded the Arctic in mystery and fascination. For example, a widespread theory that persisted well into the 1800s and informed navigational decisions in early

European voyages was that beyond an outer and nearly impassable ring of frozen ocean was a warm(er) and mostly ice-free Polar Sea (Wordie and Cyriax, 1945; McCannon, 2018). These were musings developed by Europeans, who could only hypothesise what might exist in the then unknown and poorly understood Arctic. In contrast, for the Arctic peoples who had been living in the Arctic for millennia, these early European voyages were not so much an exploration (for them, these lands were already known) but rather an early signal of coming colonisation.

The presence of sea ice along the routes that the Europeans chose to sail – as well as the extreme cold, wind, remoteness, and lack of a common language with the local people – posed a significant challenge for the captains and crews undertaking these voyages. Captains would often turn their ships around when the route became blocked by sea ice, whereas those that pursued made slow progress using their anchors and windlasses to drag their ships along the ice, or using saws to free their vessels out of the ice (Hutchinson, 2017). It was not unusual for ships to become stuck as sea ice froze all around them, and abandoning ice-bound vessels was common (Marchenko, 2012; Hutchinson, 2017). Another frequent occurrence was for ships to get crushed amidst ice floes that pressed against each other under the driving force of the wind, causing enough damage for vessels to sink, sometimes sinking even those ships that came to the rescue of other distressed expedition vessels (Dodds, 2018). Through these expeditions, the 18th and 19th Centuries solidified the realisation that sea ice posed significant constraints on the possibilities of navigation in Arctic waters.

What became clear from the challenges that sea ice posed during these expeditions was that a partially solid, ice-covered ocean could not be sailed in the same way that a liquid, open-water ocean could. In fact, ships that sailed on Arctic voyages were no ordinary vessels. Their hulls were reinforced to better withstand the crushing materialities of solid sea ice. In 1845, for example, Sir John Franklin and his crew sailed aboard HMS *Terror* and *Erebus*, determined to find a route through the Northwest Passage (Figure 5.1). HMS *Terror* was built as a bomb vessel with a strong hull designed to withstand the impact of explosions, and after being involved in several battles of the War of 1812 against the United States, its career as a ship of war came to an end and HMS *Terror* became a ship of exploration (Hutchinson, 2017). In addition to strengthened hulls, *Erebus* and *Terror* were also abundantly stocked with supplies to feed their crews for up to three years, knowing that sea-ice conditions might lead to slow progress and the impossibility of turning back, thus potentially delaying the expedition by years at a time. Despite these structural and logistical preparations, progress along the Northwest Passage was still dictated by sea ice. Unpassable sea-ice conditions forced the crew to overwinter in ice-covered bays for two winters in a row (1845-46 and 1846-47) until supplies ran out, Sir John Franklin died, a large scurvy outbreak took much of the crew, and the remaining survivors abandoned the ships and attempted to find their way on foot (Wordie and Cyriax, 1945). Whilst some of these exploratory voyages may have not succeeded for reasons other than the hinderances caused by sea ice, its presence undoubtedly presents an additional dimension to the already tricky endeavour of sailing safely across the ocean.



THE EREBUS AND TERROR IN THE ICE-STREAM.

Figure 5.1 – Depiction of the sea-ice conditions during the Franklin 1845 expedition in search of the Northwest Passage. Source: Hyde et al. (1874).

What these early European Arctic voyages reveal is the significance of the mobilities of the icy ocean in shaping vessel mobilities. Incomplete and perhaps somewhat mythical understandings of the location of sea ice and how it moves (e.g., the existence of a mostly ice-free Polar Sea around the North Pole) led captains to make specific navigational decisions, such as heading away from the ice-heavy coast in the belief that there would be a mostly ice-free Polar Sea farther out[13] (Wordie and Cyriax, 1945). From ships making slow progress through the ice, to turning around when routes became too ice-blocked to proceed, the vessel mobilities of these voyages emerged directly from the sea-ice conditions they encountered enroute. When ships overwintered on land due to unnavigable sea-ice conditions and disease broke out, the icy and watery sailing mobilities of ships turned into desperate marches over hard and barren lands. As such, cryomobilities can only be understood through an appreciation not just of the mobilities of the vessels themselves, but also of the mobile character of sea-icescape that they are moving through and the ways in which this is known and understood by captains and crews at the time.

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[13] This is not entirely wrong, as the shallow waters along the coastline can and do freeze up faster than the deeper waters further away from shore; shorefast ice that becomes stable and grounded along the shore would be much more compact to attempt to sail through. However, this is usually only the case during the period of freeze-up, and is based on local weather conditions, rather than it being due to a progressive thinning of sea ice from shore towards a northerly mostly ice-free Polar Sea.

5.3. 20th Century Advances in Sea-Ice Capability

Since the reinforced hulls of the 19th Century European expedition ships, Western shipbuilding technologies and designs that enhance the ice-capability of vessels have come a long way. Specific design requirements on the shapes of hulls (e.g., rounded rather than straight sides, and avoiding bulbous hulls) allow ships to squeeze upwards and out of sea ice instead of getting crushed when subject to ice nipping forces[14] (Marchenko, 2012). Modern icebreakers and ice-capable ships[15] are also fitted with other means of countering sea ice, such as pressurised air bubbling systems on the lower part of the hull that help prevent ice build-up, and additional propellers at the bow of the ship to better channel broken up sea-ice under and away from the vessel (Wärstilä, 2023). In addition, the introduction of nuclear-powered engines gives icebreakers unparalleled power to break through thick sea ice, and massively increases the ship's range between refuelling – which only needs to happen every three to four years (Moe and Brigham, 2017; Nilsen, 2019b). The age of nuclear-powered icebreakers began in 1960 with the launch of the world's first nuclear-powered Russian icebreaker, *Lenin*.

The language surrounding some of the technological advances in shipbuilding clearly conveys how sea-ice presence along routes is constructed as an obstacle. For example, the International Association of Classification Societies (IACS) sets out the rules for Polar Class ratings as recognised by the International Maritime Organisation (IMO). Polar Class designations are used within shipbuilding to classify the ice-going capabilities of ships and include specifications such as hull shape, hull reinforcements, and propellor design. The technical document which sets out the criteria that ships must meet to achieve a Polar Class rating defines Polar Class vessels as "intended for independent navigation in *ice-infested* polar waters", and icebreakers are ships able to "undertake *aggressive* operations in ice-covered waters" (IACS, 2023: I1-1, emphases added). "Ice-infested", in particular, is a term widely used to describe icy waters in relation to various aspects of assessing and aiding navigation (e.g., Brekke and Anfinsen, 2011; Ryan et al., 2021; Vanhatalo et al., 2021), and especially in relation to oil-spill management in ice-covered waters (e.g., Lee et al., 2011; Fingas and Hollebone, 2015; van Gelderen et al., 2017; Kabyl et al., 2022). The stiff language used in shipbuilding relative to

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[14] Ice nipping is the process whereby converging floes press against a ship from opposite sides. This is often under the influence of wind advection and currents that move sea ice around a ship in such a way as to 'nip' or 'pinch' the ship between the ice. Along with hits from ice floes and drifting, ice nipping is one of the major causes of shipwrecks in Arctic waters (Marchenko, 2012).

[15] It is important to note that vessels can have enhanced ice capability without necessarily being classed as 'icebreakers'. Whilst icebreakers can sometimes also have other purposes (such as carrying cargo or be fitted with oceanographic research equipment), their main role remains to carry out heavy-duty ice clearing operations such as escort for other vessels or ice management in general. Vessels intended for other purposes and that do not qualify for icebreaker status but still have enhanced ice capabilities, will usually hold a Polar Class rating (IACS, 2023). Additionally, vessels that do not meet the requirements for Polar Class might also venture into (partially) ice-covered waters, at the discretion of the captain and crew.

the advances in vessels' ice capability also comes through in some of the interviews. Eileen, who was involved in the commissioning of a research vessel, recounts her experience during the process of ensuring that the ship was appropriately built for handling a variety of sea-ice conditions:

> *Eileen:* So, we were looking at different hull shapes, especially those being initiated primarily by the Finns. We looked at different ways of disposing of the ice, as opposed to just… attacking. That was one thing I definitely learnt.
>
> *Interviewer:* And what do you mean by "disposing of the ice"?
>
> *Eileen:* Well, they sort of push it out of the way {and let it sink}, and they [the pieces of sea ice] move with brute force, instead of neatly follow a trajectory away from the ship. (Eileen, lines 21-26).

Eileen's account is peppered with nods to the forcefulness required by vessels operating in icy waters. This ranges from vessel "attacking" the ice in order to get through it, to needing to "dispose of the ice" like it was garbage, and that even the ice itself is described negatively as it moves out of the way of the passing ship "with brute force". As such, these continued advances in "aggressive" icebreaking technologies are a testament to the ongoing challenges that sea-ice poses as an obstacle to navigation and the persistent desire to overcome the undesirable icy "infestation" that the ocean is supposedly experiencing.

Sea ice as an obstacle stretches beyond its material stubbornness to also include the logistical and economic barriers involved with overcoming sea ice for navigation. In fact, it is precisely because of the existence of the successful icebreaking technologies discussed above that Lasserre (2015) argues that the feasibility of Arctic routes is no longer a technical issue, but rather a question of business profitability. Indeed, routes prone to sea-ice cover also pose other difficulties beyond physically getting though sea ice itself. The primary limitations include additional fees (e.g., for compulsory icebreaker escort along the Northern Sea Route), the unpredictability of sea ice leading to delays that disrupt the just-in-time logistics of modern supply chain management, and the higher costs associated with employing more experienced (and, specifically, ice-experienced) captains and crews (Willoch and Ragner, 2000; Ho, 2010; Lasserre and Pelletier, 2011; Humpert and Raspotnik, 2012; Lasserre, 2014; De Silva et al., 2015; Tseng and Cullinane, 2018). Moreover, there are issues related to the overall conditions within which sea ice occurs, which impose additional measures regardless of the immediate presence (or lack thereof) of sea ice. For example, the extreme cold requires using costly freeze-resistant fuel, and the remoteness of Arctic routes often implies limited access to search and rescue services, scarce port facilities, and old or incomplete navigational charts – all of which also result in higher insurance costs (Lasserre, 2015). In this case, whilst sea ice might not be the direct cause of concern, it is nonetheless inseparable from the surrounding conditions within which sea ice occurs. As such, commercial shipping operators remain hesitant to re-route traffic that currently passes through the Suez and Panama Canals through the Arctic, despite the often-advertised 40-60% shorter distance and the abundance of research focussed on predicting when these Arctic routes might become reliably ice-free (e.g., Wang and Overland, 2009; Smith and Stephenson, 2013; De Silva et al., 2015; Melia et al., 2016, 2017; Sui et al., 2021). During her interview, Cath, whose research focuses on Arctic vessel traffic, also points out some of the concerns that inform decision making around the usability of Arctic routes:

> Even if they want to go that way, even if [it's] the fastest route, is there a port for them to refuel or drop their waste or all of these other things that really go into the decision to go there? […] There's a lot of talk also about, you know, Arctic shipping routes along the Northern Sea Route is shorter than the Panama or Suez Canal. But even in ideal scenarios for vessel traffic along this route, it's only open a couple of months of the year, and then you have to pay fees to have escorts from Russian ships with you. And so there's a lot of industry that I've seen in the literature saying, maybe we'd do it in the future, but right now it's too unreliable because we don't know if it's going to be open or not, there's not enough support and it costs a lot with those fees. (Cath, lines 90-97)

Cath's interview reinforces the view that companies interested in Arctic routes are those already operating there (Lasserre and Pelletier, 2011), or those interested in destination – rather than transit – traffic (e.g., to transport raw materials out of mines, or to resupply remote communities[16]) (AMSA, 2009). Therefore, what still stands is that ice-prone Arctic routes remain troublesome for navigation for a variety of compounding logistical and economic reasons, directly and indirectly related to the conditions surrounding the presence of sea ice.

The technological advances surrounding vessel operations in sea-ice ocean environments (such as increasing vessels' ice capability and improving search and rescue services) illustrate the ways in which cryomobilities arise out of the mobilities of the icy ocean environment through which vessels operate. Technological advances in vessels' ice capabilities emerge out of the challenging conditions surrounding sailing through sea ice. In turn, these enhanced ice capabilities shape the mobilities of vessels operating in sea ice, by modulating what certain vessels are and are not able to do in these icy ocean spaces (which changes through time as technologies advance to address specific situations). In addition, recognising the importance of the mobile icescape 'background' in shaping cryomobilities further highlights a network of interconnected mobilities that impact vessel navigation. The same atmospheric mobilities that create the conditions for sea ice also cause extreme weather conditions more broadly in the Arctic. This leads to a cascading slowing down of a variety of mobilities, from poor search and rescue to inadequate bathymetry charts, which in turn makes navigation challenging for vessels in these ice-prone waters. Therefore, cryomobilities emerge out of the multitude of obstacles

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[16] Remote communities are often in favour of resupply via shipping for various reasons: i) shipping is cheaper than flying goods in (the latter is often the primary mode of resupply during winter) which helps lower the already very high costs of living in remote communities and ii) vessels can carry much bulkier and heavier cargo compared to planes, such as machinery and vehicles (AMSA, 2009).

that a mobile sea-ice environment poses to vessels, and how this shapes the effort and dedication required for vessel mobilities to overcome these challenges.

5.4. Avoiding Sea Ice in the 21st Century

Due to recent climate change, Arctic sea ice has been declining, with drastic consequences for the flora, fauna and human livelihoods that rely on this precious and fragile environment (Meredith et al., 2019; Thoman et al., 2020; IPCC, 2021). As such, monitoring the state of sea ice has become a priority within the field of sea-ice science, leading to an abundance of research aimed at analysing the trends and trajectories of sea-ice decline since the late 1970s (e.g., Wyllie-Echeverria and Wooster, 1998; Parkinson et al., 1999; Parkinson and Cavalieri, 2008; Cavalieri and Parkinson, 2012; Frey et al., 2015; Wang et al., 2018). In addition, the global shipping system relies on strict timetabling, and year-on-year route planning takes into account past ocean conditions, where having a predictable ocean is paramount (Palma et al., 2019). In light of the importance of tracking how sea-ice – and, subsequently, sea-ice related activities – are changing through time, this section considers the changes in sea-ice area and vessel activities in the Bering Strait region (comprising the Bering Sea and the Chukchi Sea) for the period 2013–2022. By analysing trends in sea ice and vessel traffic, this section highlights patterns of sea-ice avoidance in the 21st Century.

5.4.1. Changes in Sea-Ice Area

Sea-ice is decreasing throughout the Arctic, yet individual regions contribute to varying degrees to the overall observed Arctic-wide sea-ice decline, as discussed in Section 3.4.2 (see Figure 3.11). Indeed, the Bering Sea and Chukchi Sea regions follow slightly different sea-ice decline patterns. Overall, sea-ice area in the Bering Sea is not declining at the same dramatic rate as in the Chukchi Sea or in the rest of the Arctic as a whole (Figure 5.2), and even shows positive trends across some decadal-scale periods (Parkinson et al., 1999; Cavalieri and Parkinson, 2012; Frey et al., 2015; Onarheim et al., 2018; Peng and Meier, 2018). This chapter combines the regional sea-ice analysis from both the Bering Sea and the Chukchi Sea. By looking at these two interconnected regions in conjunction, this chapter contextualises local sea-ice behaviour within a broader setting.

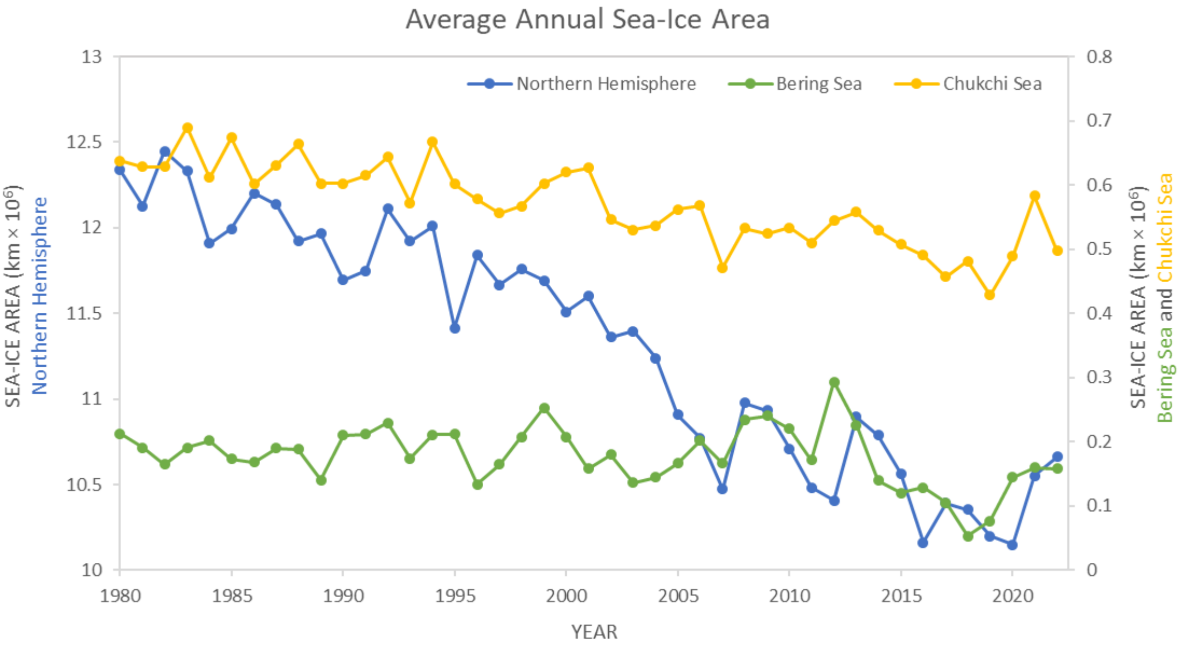

Figure 5.2 – Average annual sea-ice area in the Northern Hemisphere, the Bering Sea, and the Chukchi Sea for the period 1980–2022. Decline in sea-ice area is most pronounced in the Northern Hemisphere, followed by the Chukchi Sea. The Bering Sea is showing the slowest decline in sea-ice area. Source: NSIDC Sea Ice Index Version 3 (Fetterer et al., 2017).

Over the 44-year period of continuous sea-ice data, sea-ice area[17] for the Bering Sea and Chukchi Sea is in decline. Figure 5.3 shows that mean sea-ice area in both the Bering Sea and the Chukchi Sea has declined over the period 1979–2022. The Bering Sea is showing the slowest sea-ice decline, losing 0.51% of its sea-ice area per year, compared to the Chukchi Sea at 0.60% per year. Combined, the Bering and Chukchi Seas are losing sea ice at a rate of 0.58% per year. Despite the comparable declines in regional percentage, absolute sea-ice area decline in the Chukchi Sea is almost four times that in the Bering Sea (3,975 km^2 per year and 1,013 km^2 per year, respectively), for a total of 4,988 km^2 per year in both regions combined (Figure 5.3). In addition, the Bering Sea sustained a relatively constant annual mean sea-ice area until around 2014, after which sea ice started to decrease noticeably. This is in line with several analyses that consistently find the Bering Sea to have near-zero or positive sea-ice trends up to around 2014, in sharp contrast to the Arctic as a whole (e.g., Figure 5.2) as well as all other individual Arctic regions, which show negative trends (e.g., Parkinson et al., 1999; Cavalieri and Parkinson, 2012; Stabeno et al., 2012a; Wendler et al., 2014; Onarheim et al., 2018). In general, the Bering Sea is considered to be responding slower than other Arctic regions to the warming conditions from climate change and, as a result, the Bering Sea contributes only marginally to overall Arctic sea-ice loss (Onarheim et al., 2018). In comparison, the Chukchi Sea shows a steady decline in sea-ice area

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[17] Sea-ice area is calculated by multiplying the sea-ice concentration at each grid cell (obtained from passive microwave surface brightness satellite imagery) by the total area of the grid cell. Sea-ice area values for multiple cells are summed to obtain sea-ice area values for larger geographical regions.

since the 1990s, which is earlier than when sea ice in the Bering Sea starts significantly declining at around 2014, as shown in Figure 5.3 (Stabeno and Bell, 2019; IPCC, 2021). As such, whilst sea ice in both the Bering and Chukchi Seas is declining, sea ice in the Chukchi Sea has been steadily declining for a longer time, and is also now declining more rapidly than in the Bering Sea.

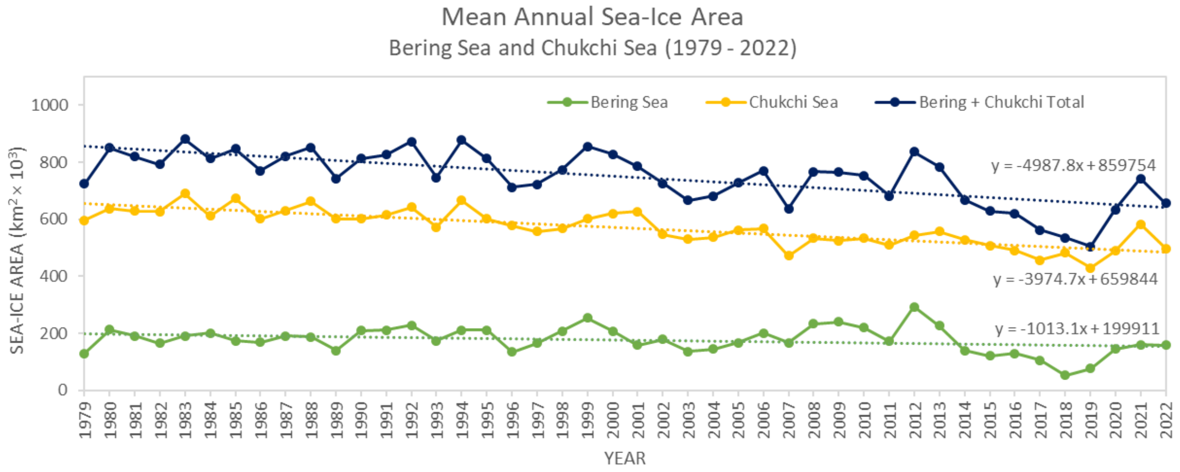

Figure 5.3 *– Mean annual sea-ice area for the Bering Sea, Chukchi Sea, and both combined, for the period 1979–2022. Whilst sea-ice is declining in both seas, the Chukchi Sea is losing four times the sea-ice area compared to the Bering Sea (in absolute terms). Source: NSIDC Sea Ice Index Version 3 (Fetterer et al., 2017).*

The last ten years (2013–2022) of the sea-ice record are of particular interest, as this period overlaps with the availability of AIS data used in this research project. Figure 5.4 shows sea-ice area for the Bering Sea and Chukchi Sea over the last ten years. Sea ice is declining in both seas at a similar rate in absolute terms, with the Chukchi Sea decline still slightly faster than the Bering Sea (Chukchi Sea at -8,959 km^2 per year; Bering Sea at -7,459 km^2 per year). In relative terms, the Bering Sea is losing 4.4% of its sea-ice area per year, whilst the Chukchi Sea is declining at a rate of 1.63% per year (primarily because the Chukchi Sea is a larger region than the Bering Sea; therefore, whilst absolute values are similar in both seas, it is proportionately a smaller percentage of the Chukchi Sea region as a whole). These are much higher rates of sea-ice decline compared to the longer-term trends shown in Figure 5.3 and discussed in the paragraph above, demonstrating that sea-ice area decline is occurring faster in recent years compared to average trends since 1979.

In addition, due to the way that sea ice advances and retreats each year, the maximum and minimum annual sea-ice areas are dictated by the sea-ice contributions of sea-ice area in the Bering Sea and Chukchi Sea, respectively. In other words, for the sea-ice maxima in winter, the Chukchi Sea becomes entirely covered in sea ice (generally following a north-to-south sea-ice growth pattern), and sea ice then continues to extend into the Bering Sea. This is particularly obvious in the 2017/2018 and 2018/2019 winters (Figure 5.4) where Chukchi Sea sea-ice area reaches the same high values as all other years, yet the combined Chukchi and Bering sea-ice maxima is significantly lower than all other years because of the low sea-ice area in the Bering Sea. This means that the maximum sea-ice area for the Bering Strait region, which occurs during the winter months, is dictated by how much sea-ice forms that year in the Bering Sea. Similarly, for the annual sea-ice minima during the summer months, Figure 5.4 shows that the Bering Sea has zero sea ice during the summer months; therefore, the minimum sea-ice area for the Bering Strait region is dictated by the extent of sea-ice cover in the Chukchi Sea. The seasonal contributions of each sea to sea-ice area are important to consider in the context of the Bering Sea region as a whole, and are to be kept in mind when looking at data that combines sea-ice contributions from both the Bering and Chukchi Seas.

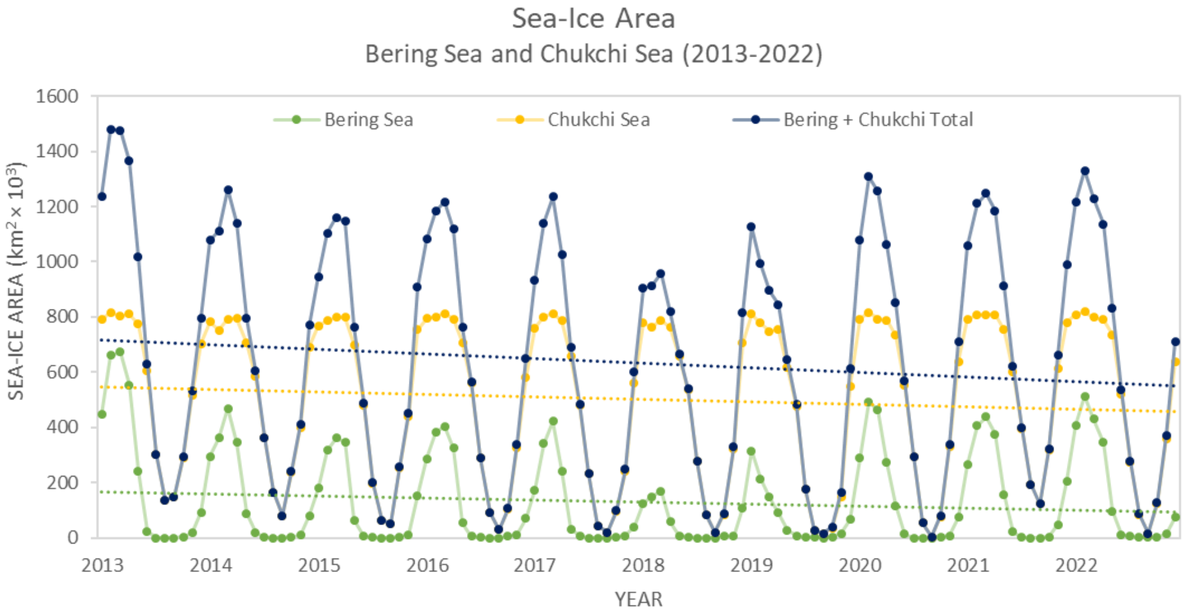

Figure 5.4 – Mean monthly sea-ice area for the Bering Sea, Chukchi Sea, and both seas combined, for the period 2013–2022. Sea ice is declining at a similar rate in both seas over this time period. The winter sea-ice maxima are determined by the sea-ice area contribution from the Bering Sea, given that the Chukchi Sea becomes entirely ice-covered in winter. Vice versa is true for the summer sea-ice minima (i.e., it is determined by sea-ice area contribution from the Chukchi Sea, as the Bering Sea becomes entirely ice-free in summer). Source: NSIDC Sea Ice Index Version 3 (Fetterer et al., 2017).

Whilst the overall annual patterns show a general decrease in sea-ice area, this is not distributed equally across seasons. Over the past ten years (2013–2022), sea-ice is declining in all seasons across the Bering Sea and the Chukchi Sea combined (Figure 5.5). In absolute terms, spring sea-ice area is declining at a faster rate than any other season, at a rate of -27,177 km^2 per year, which is over three times the loss rate during summer (-8,496 km^2 per year). Summer is the season that is losing the least amount of sea-ice in absolute terms. In winter and autumn, sea ice is declining at a similar rate in both seasons (-18,410 km^2 per year and -17,300 km^2 per year, respectively), although still at more than double the rate of summer. Whilst the Bering Sea and Chukchi Sea combined show sea-ice decline, the individual seas show slightly different patterns of sea-ice loss between seasons. In the Chukchi Sea, sea ice is declining in all seasons except for winter, which shows a slight increase in sea-ice area over the period 2013-2022 (+4,272 km^2 per year; Figure 5.6). Likewise, in the Bering Sea, sea ice is declining in all seasons except for autumn, which shows a slight increase in sea-ice area (+3,678 km^2

per year; Figure 5.7). However, these small increases in sea-ice area in individual seas during specific seasons are not sufficient to compensate for the overall decline in sea-ice area in the Bering Strait region.

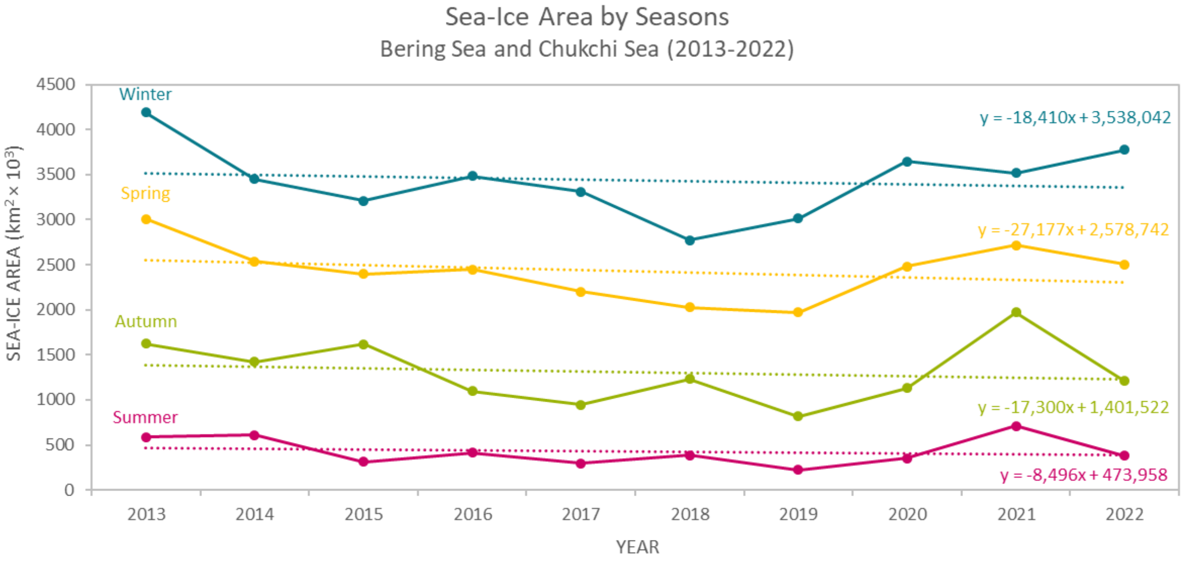

__Figure 5.5__ – Seasonal sea-ice area by year for the Bering and Chukchi Seas combined (2013–2022). Seasonal sea-ice area is calculated as the total sea-ice area for the months in each season: JFM (winter), AMJ (spring), JAS (summer) and OND (autumn) (as used in NSIDC's calculations for sea-ice trends; Parkinson et al., 1999). Source: NSIDC Sea Ice Index Version 3 (Fetterer et al., 2017).

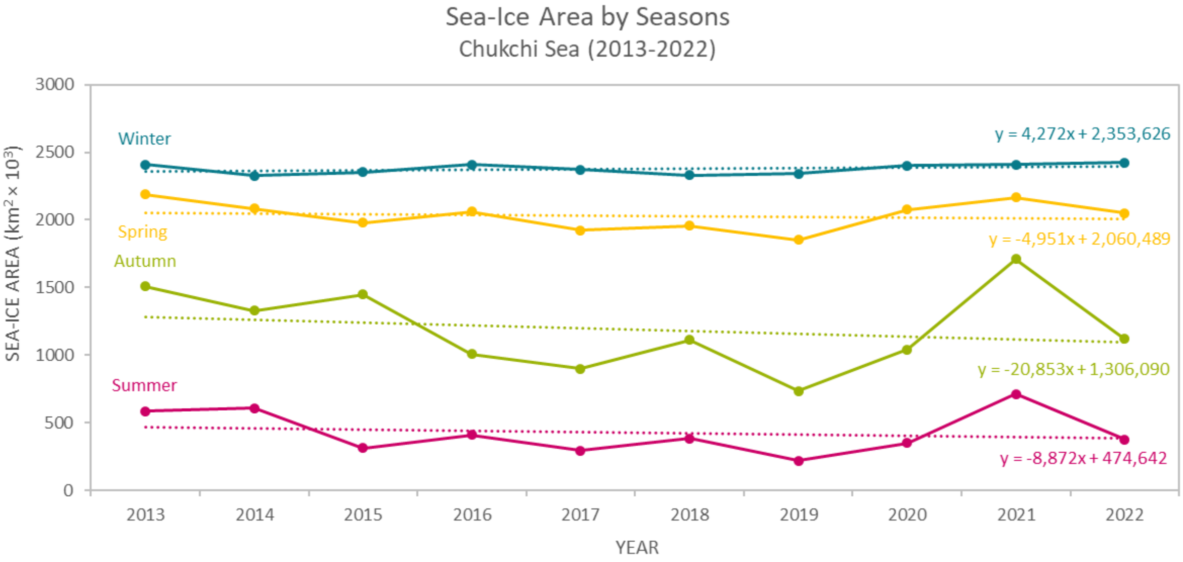

__Figure 5.6__ – Seasonal sea-ice area by year for the Chukchi Sea (2013–2022). Winter is the only season showing a slight increase in sea-ice area. Seasonal sea-ice area is calculated as the total sea-ice area for the months in each season: JFM (winter), AMJ (spring), JAS (summer) and OND (autumn) (as used in NSIDC's calculations for sea-ice trends; Parkinson et al., 1999). Source: NSIDC Sea Ice Index Version 3 (Fetterer et al., 2017).

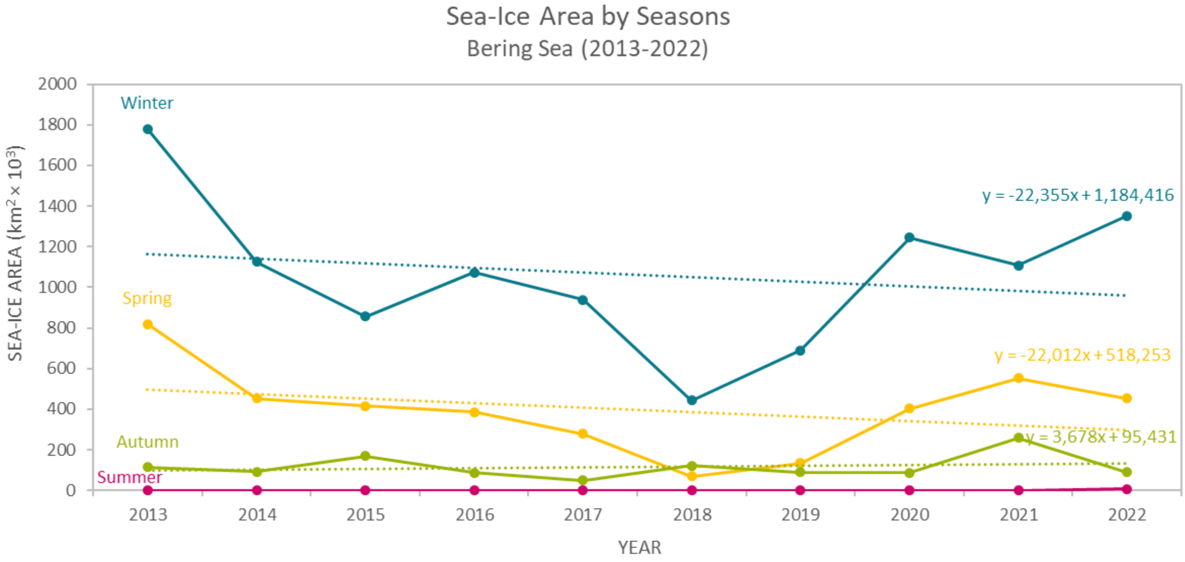

Figure 5.7 – Seasonal sea-ice area by year for the Bering Sea (2013–2022). Autumn is the only season showing a slight increase in sea-ice area. Seasonal sea-ice area is calculated as the total sea-ice area for the months in each season: JFM (winter), AMJ (spring), JAS (summer) and OND (autumn) (as used in NSIDC's calculations for sea-ice trends; Parkinson et al., 1999). Source: NSIDC Sea Ice Index Version 3 (Fetterer et al., 2017).

Whilst sea-ice is declining overall in the Bering Sea and Chukchi Sea, sea-ice patterns in this region are characterised by large interannual variability. Figure 5.8 shows monthly sea-ice area over the past ten years (2013–2022). For example, 2013 was generally a high sea-ice year across all months, and especially during the winter and spring (January–June). Whilst in general there is a decline in sea-ice area, some recent years do sometimes reach record highs that surpass sea-ice levels of a decade prior, attesting to the large interannual variability present in this region. For example, 2022 had the second-highest sea-ice area in January and February (surpassed only by 2013; Pratt, 2022), likely in part due to 2021 having the highest sea-ice area in July–August and October–December that supported high sea-ice formation the following year. Whilst 2022 had comparatively high sea-ice cover in the winter months, several sea-ice analyses have shown that sea ice in 2022 went on a "roller coaster ride" due to the large fluctuations in sea-ice cover in the winter and spring months (Bernton, 2022). In fact, Figure 5.9 shows that the high sea-ice area of January–February in 2022 did not persist for long into the rest of winter, spring and summer, and instead peaked intermittently in mid-February and early April (with heavy sea-ice loss in between) to then melt rapidly again during the summer (i.e., the "roller coaster ride"). The days with the highest and lowest sea-ice area during February–April 2022 are highlighted in Figure 5.9, and the sea-ice concentration maps for these days are shown in Figure 5.10. This is in contrast to high sea ice years such as 2013, where, despite month-to-month variability, sea-ice area remained high throughout the winter and persisted longer into the summer, maintaining a higher sea-ice area in summer than most other years. Therefore, whilst the Bering Strait region has overall experienced steady sea-ice decline since around 2014, there is high sea-ice variability within the same sea-ice cycle as well as between years, which at times lead to unexpectedly high sea-ice presence comparable to that of previous decades.

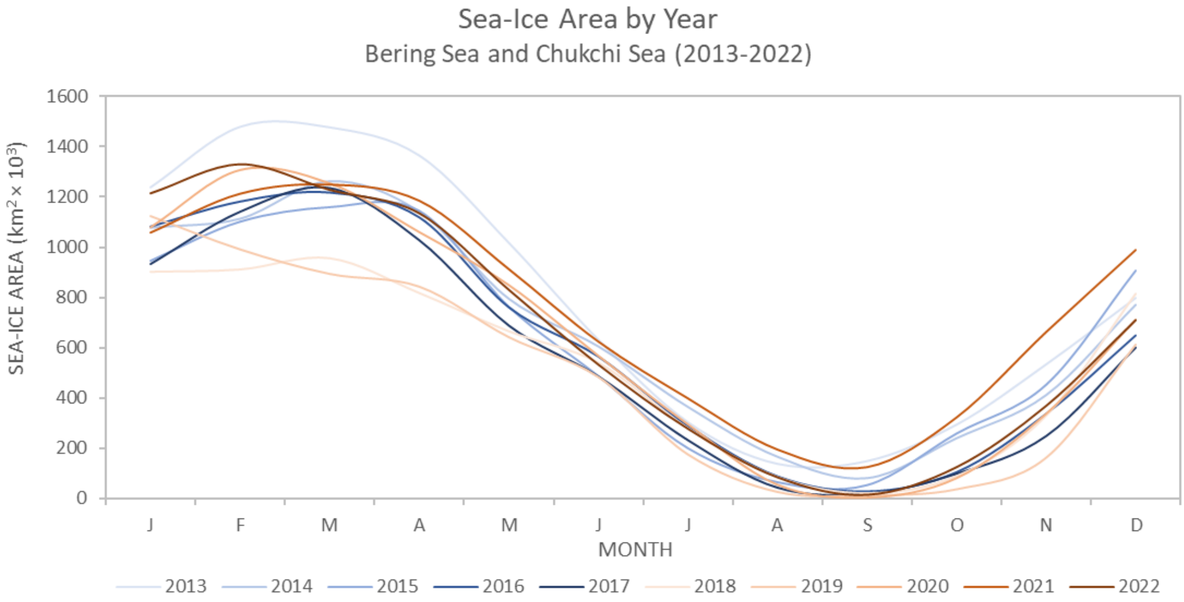

Figure 5.8 – Monthly sea-ice area stacked by year for the Bering and Chukchi Seas combined (2013–2022). Source: NSIDC Sea Ice Index Version 3 (Fetterer et al., 2017).

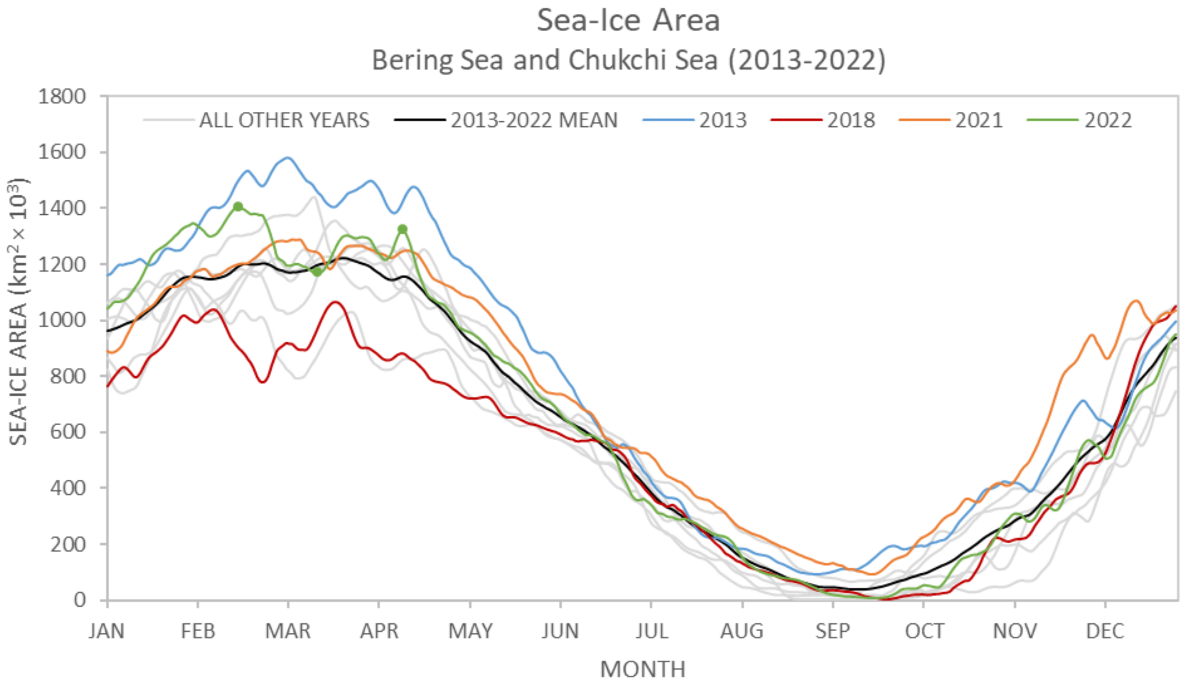

Figure 5.9 – Daily sea-ice area plotted by year for the Bering and Chukchi Seas combined (2013–2022). Black line is the mean daily sea-ice area over this period. Markers along the green line (2022) indicate the extreme days of low and high sea-ice area for which maps are shown in Figure 5.10. Source: NSIDC Sea Ice Index Version 3 (Fetterer et al., 2017).

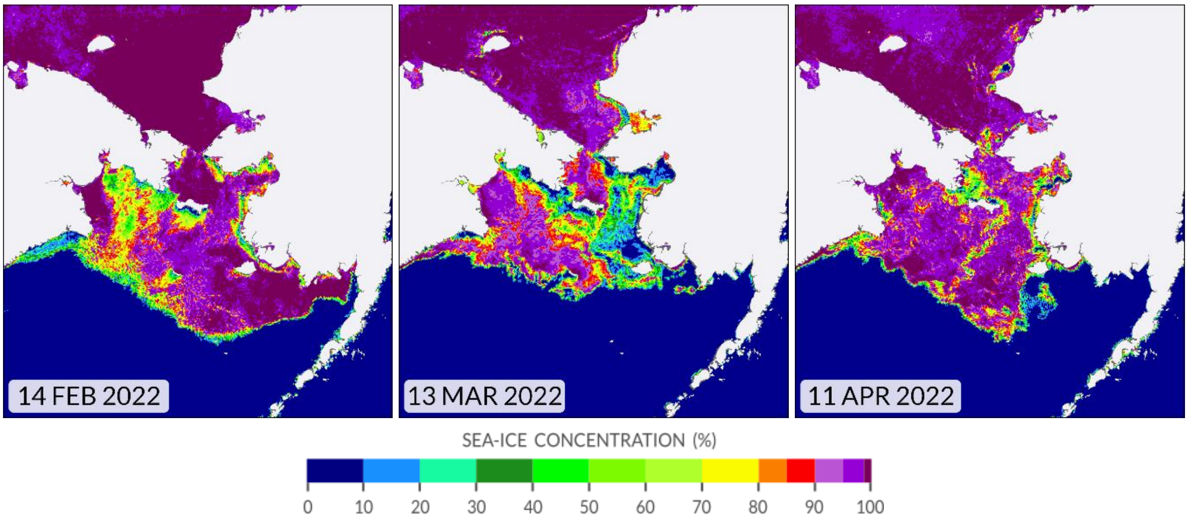

Figure 5.10 *– Days of peak sea-ice area in February and April, and minimum sea-ice area in March. This shows the vast month-to-month variability in sea-ice concentration in the Bering Strait region within a single sea-ice season. To get a sense of the significance of the sea-ice area on these dates relative the 2022 sea-ice cycle, see Figure 5.9, where they are indicated by markers along the green line (2022). Source: Spreen et al. (2008).*

Analysing trends in sea-ice area highlights the ways in which the sea-ice environment is constantly in motion. Throughout its annual cycle, sea ice in the Bering Strait region advances and retreats over hundreds of kilometres, emphasising the mobilities involved in the repeated freeze-melt processes that sustain the annual sea-ice cycle. In addition, these mobile cycles of sea ice are themselves constantly shifting, as seen in the strong annual variability of sea-ice cover, and as climate change alters the conditions that shape the ways in which sea ice grows during freeze up, melts during breakup, and drifts in between. As such, the mobile nature of sea ice underscores the importance of bringing an attentiveness to the mobilities of sea ice, or the 'background' against which vessel mobilities occur, in order to better understand cryomobilities.

5.4.2. Changes in Vessel Traffic

Overall, vessel activity in the Bering Strait region has increased over the period 2013–2022. The number of unique vessels is increasing at an average rate of about 14 ships per year (Figure 5.11). As a consequence of the increase in the number of vessels, the total sailing time in the Bering Strait region is also increasing. This has increased by an additional 6,389 sailing hours per year on average between 2013 and 2022 (Figure 5.12). The average sailing time per vessel is also increasing, as each vessel is spending on average an additional 9.8 hours at sea each year (Figure 5.13). This means that the overall increase in vessel activity in the Bering Strait region is partially due to individual vessels spending more time at sea, rather than just an influx of new vessels. Stocker et al. (2020), who analyse vessel traffic around Svalbard, also find that individual ships are overall spending more time sailing. Therefore, increased vessel traffic in the Bering Strait region is due to the combined effect of more vessels and longer voyages for individual vessels.

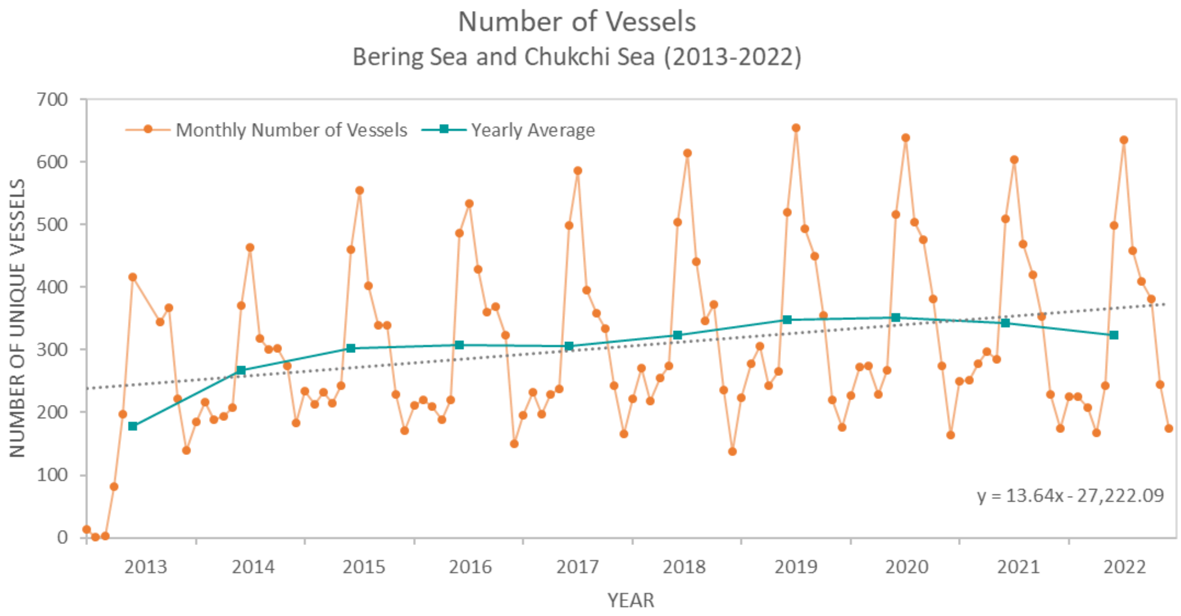

Figure 5.11 – Number of unique vessels sailing each month in the Bering Sea and Chukchi Sea, as well as the annual average, for the period 2013–2022. Source: PAME (2022).

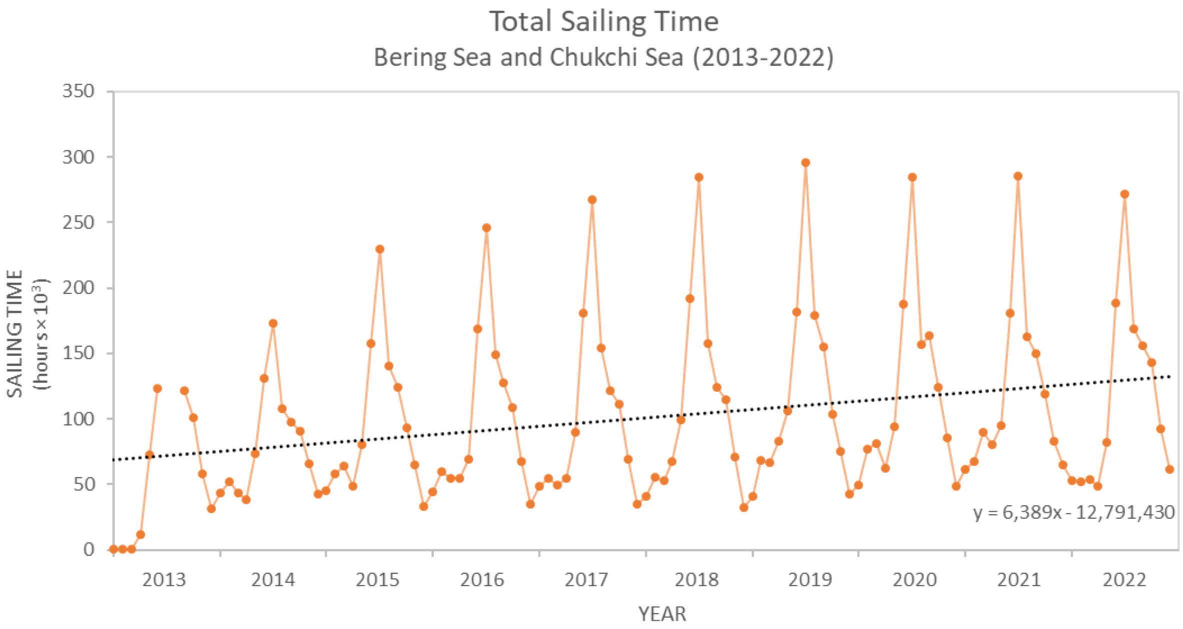

Figure 5.12 – Total sailing time each month in the Bering Sea and Chukchi Sea, for the period 2013–2022. Source: PAME (2022).

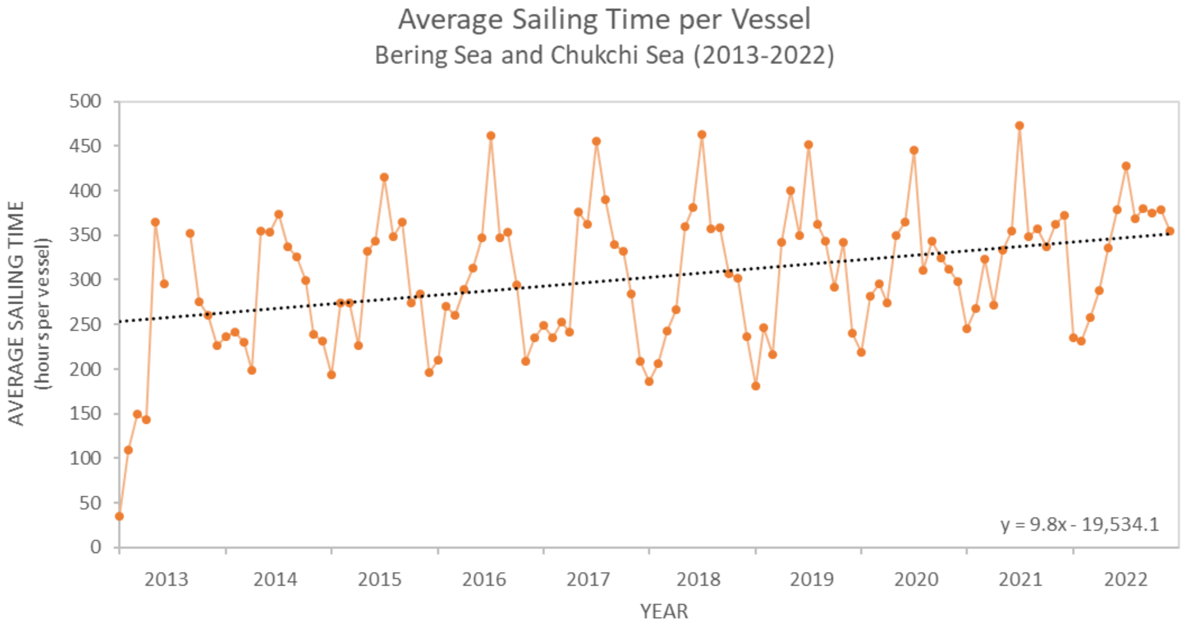

Figure 5.13 – Average sailing time per vessel each month in the Bering Sea and Chukchi Sea, for the period 2013–2022. Source: PAME (2022)

Shipping activity in the Bering Strait region usually follows an annual cycle. The number of unique vessels (Figure 5.14), the total sailing time (Figure 5.15), and the average sailing time per vessel (Figure 5.16) all peak in July, and this has been the case consistently throughout the period 2013–2022. This peak in July within the annual cycle is likely due to ideal weather conditions, less extensive sea-ice cover, longer daylight hours, and several large fisheries being open at this time of year, such as cod (Alaska Department of Fish and Game, 2016). As can be seen in the progression of years in Figure 5.11, Figure 5.12 and Figure 5.13, there is a clear upwards trend of increased vessel activity with time. This can also be seen in the lengthening of the high-traffic season, as the number of vessels is staying higher for longer at the end of the summer season and into autumn (see Figure 5.17 and also note the growing 'bulge' in Figure 5.14 during August, September and into the beginning of October). The high-traffic season does not appear to be lengthening earlier into spring. The only notable exception to the overall increase in vessel presence in the Bering Strait region is the number of vessels sailing in November (Figure 5.14), where numbers have stayed low or are declining. This is likely due to November being a 'shoulder month' between the ice-free and ideal sailing conditions during the summer season, and the profitable crab fisheries that only begin in December and January. The average sailing time per ship (Figure 5.16) shows a less obvious pattern throughout the annual cycle compared to the total sailing time and number of unique vessels. However, the largest peak in average sailing time does reliably occur in July, which is consistent with the other figures. Additionally, there are clear trends in October–December where more recent years show vessels spending up to 175 additional hours at sea compared to earlier years (e.g., comparing 2015 and 2021 for December), and similar trends are also noticeable in March and April.

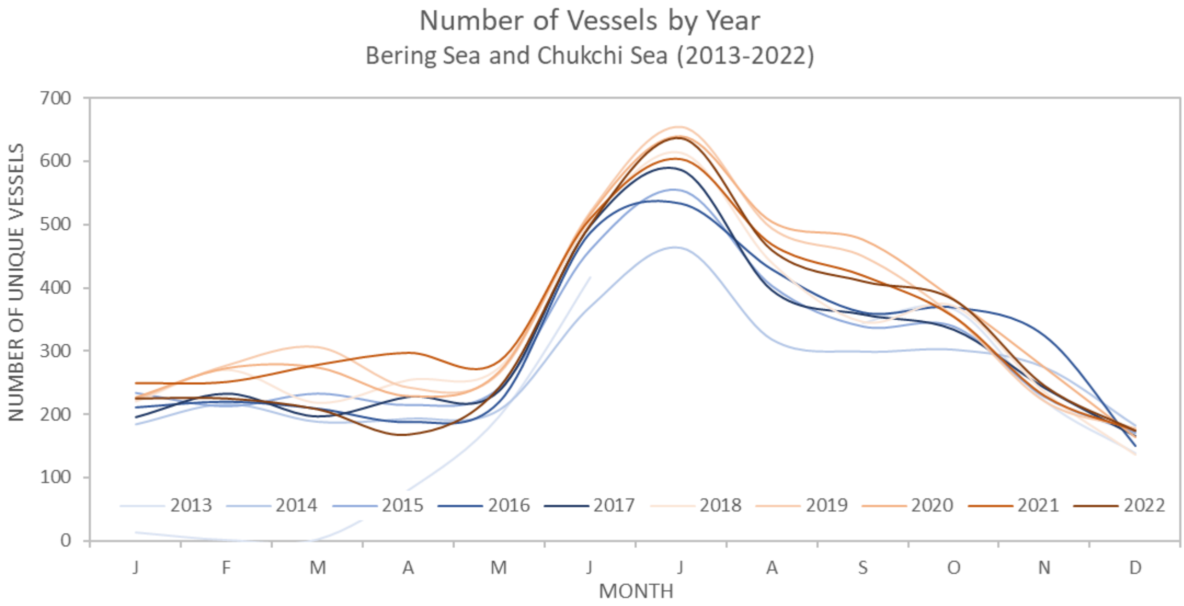

Figure 5.14 – Number of unique vessels each month in the Bering Sea and Chukchi Sea by year, for the period 2013–2022. Source: PAME (2022)

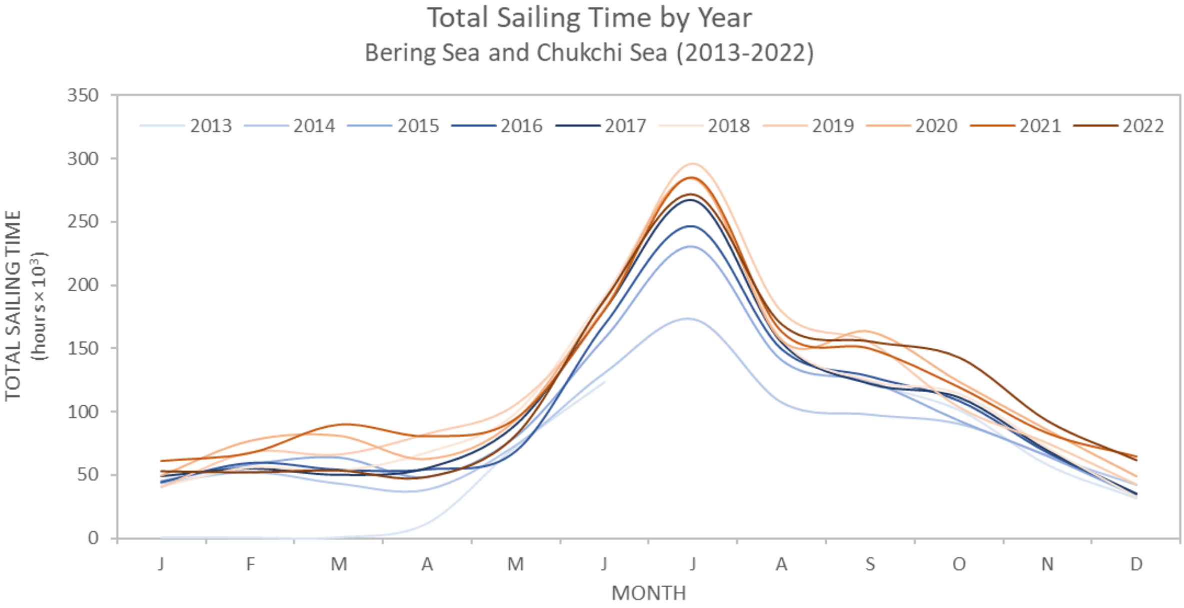

Figure 5.15 – Total sailing time each month in the Bering Sea and Chukchi Sea by year, for the period 2013–2022. Source: PAME (2022)

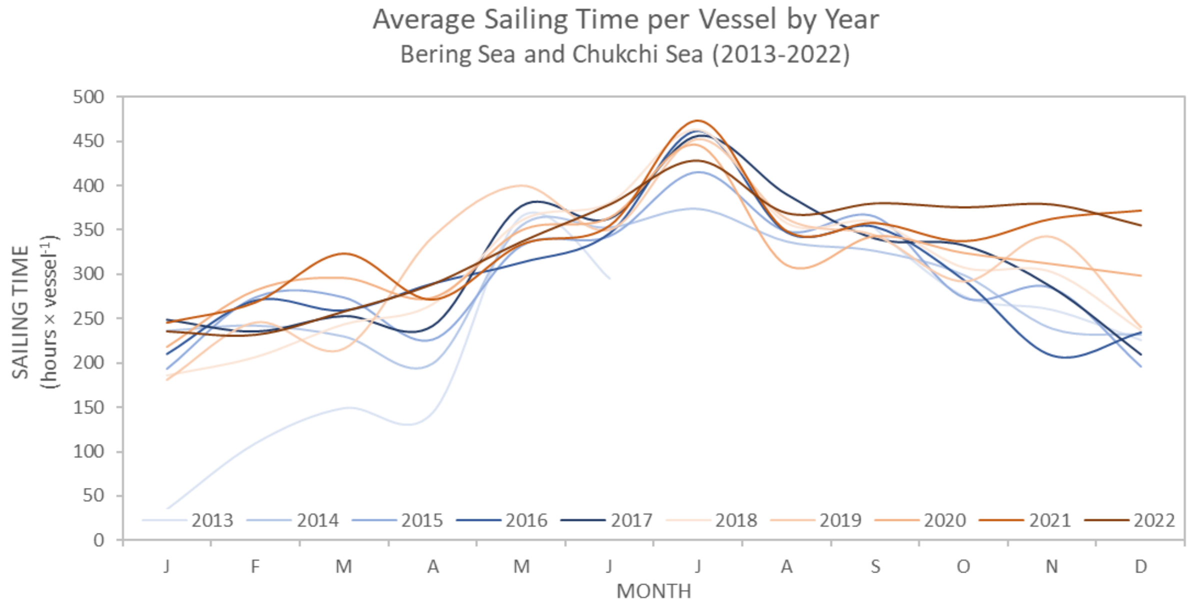

Figure 5.16 – Average sailing time per ship each month in the Bering Sea and Chukchi Sea by year, for the period 2013–2022. Source: PAME (2022)

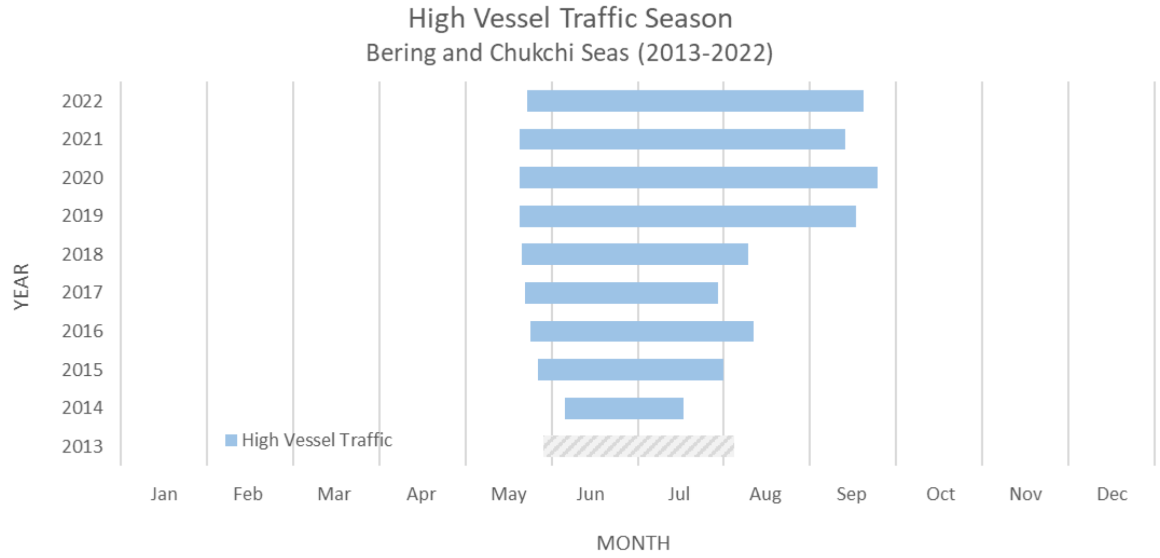

Figure 5.17 – Duration of the high-traffic season for the period 2013–2022. This figure is derived from Figure 5.14 by calculating the number of unique vessels midpoint of the range for the entire dataset (excluding 2013, due to missing data for July and August), and then plotting the period where each line in Figure 5.14 is above that midpoint value. Source: PAME (2022).

Whilst there is an overall increase in vessel activity during all parts of the annual cycle, this is not distributed equally across seasons. The 2015–2021 comparison for December (discussed in the previous paragraph) averages out to an annual average increase of 29 hours per vessel, which is much larger than the annual average increase of 9.8 hours per vessel over all months and all ten years (Figure 5.13). This shows that the increase in vessel traffic is unevenly distributed across years and months. Figure 5.18, Figure 5.19 and Figure 5.20 show seasonal trends in the number of vessels, total sailing time and average sailing time per vessel, respectively. Every season for each of these indicators shows a positive trend, meaning that vessel traffic is increasing across all seasons, albeit at different rates. Firstly, summer is consistently the season with the highest volume of traffic for all three indicators. Summer also has the highest rate of increase for both the number of vessels (52 vessels per year) and total sailing time (23,885 hours per year). This is visible not only in the seasonal data but also from the period of highest traffic, which consistently falls almost entirely within the summer months of July, August and September (Figure 5.17). However, summer has a slower increase rate for average sailing time per vessel than any other season (9.2 hours per vessel per year). This is likely because sailing conditions – in terms of ice-free waters, daylight hours, and weather – have likely always been good in the past. As such, vessels are spending a similar (but already much higher than any other season, and still slightly increasing) amount of time at sea during summer. Secondly, spring is consistently the second highest season in terms of volume of vessel traffic across all indicators. The only exception is in 2021 and 2022, where the average sailing time per vessel in autumn surpassed that of spring (Figure 5.20). Whilst spring shows the second-highest rate of increase in total sailing time (14,238 hours per year), it has the third highest in terms of number of vessels (31 vessels per year) and average sailing time per vessel (18.4 hours per vessel per year), where rates are higher in winter (49 vessels per year and 28.3 hours per vessel per year, respectively). Thirdly, autumn is consistently the season with the second lowest vessel traffic across all indicators. There is one main exception to this, where the total number of vessels was slightly higher during the winters of 2019 and 2021. Autumn has the lowest rate of increase both in terms of number of vessels and total sailing time (5 vessels per year and 10,980 hours per year, respectively). However, somewhat surprisingly, autumn has the highest rate of increase in average sailing time (39.8 hours per vessel per year). A possible explanation for this is that several highly profitable crab industries open in December, and the overall decline in sea ice means that crabbing boats can spend more time out at sea. Finally, winter is consistently the season with the lowest volume of traffic for all three indicators. However, it has the second highest rate of increase for the number of vessels (49 vessels per year) – which is very close to that of summer (52 vessels per year) – and average sailing time per vessel (28.3 hours per vessel per year). An obvious explanation for these patterns is that as the period of sea-ice cover is shortening, with breakup happening earlier and growth starting later (Frey et al., 2015), this provides more opportunity for spending time at sea during the harsher seasons compared to previous years.

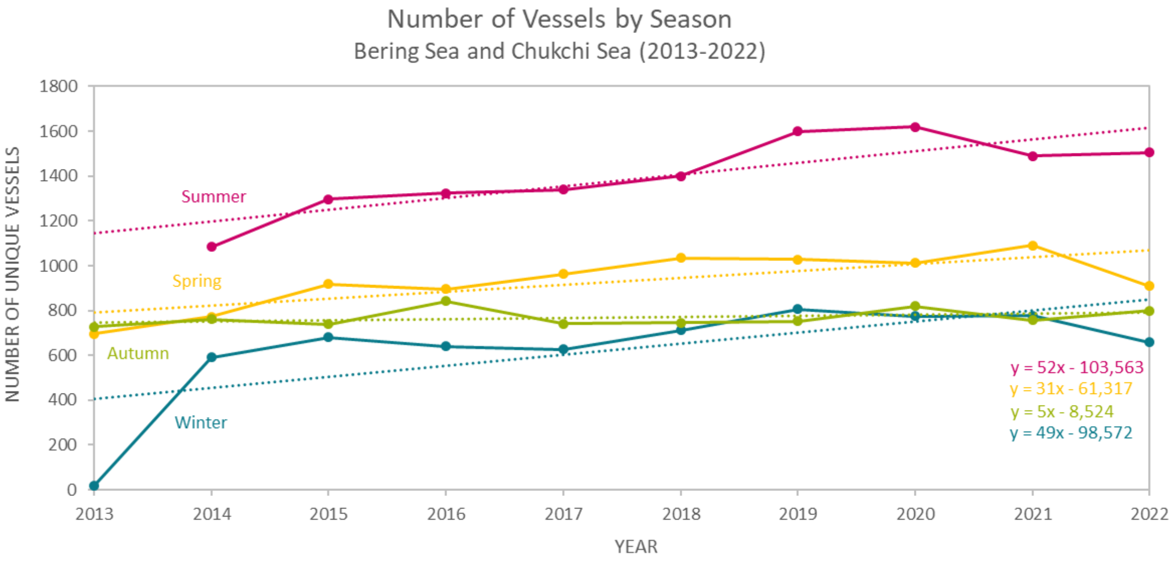

Figure 5.18 – Total number of vessels in the Bering Sea and Chukchi Sea by season, for the period 2013–2022. Seasonal number of vessels is calculated as the total number of unique vessels for the months in each season: JFM (winter), AMJ (spring), JAS (summer) and OND (autumn) (as used in NSIDC's calculations for sea-ice trends; Parkinson et al., 1999). Source: PAME (2022).

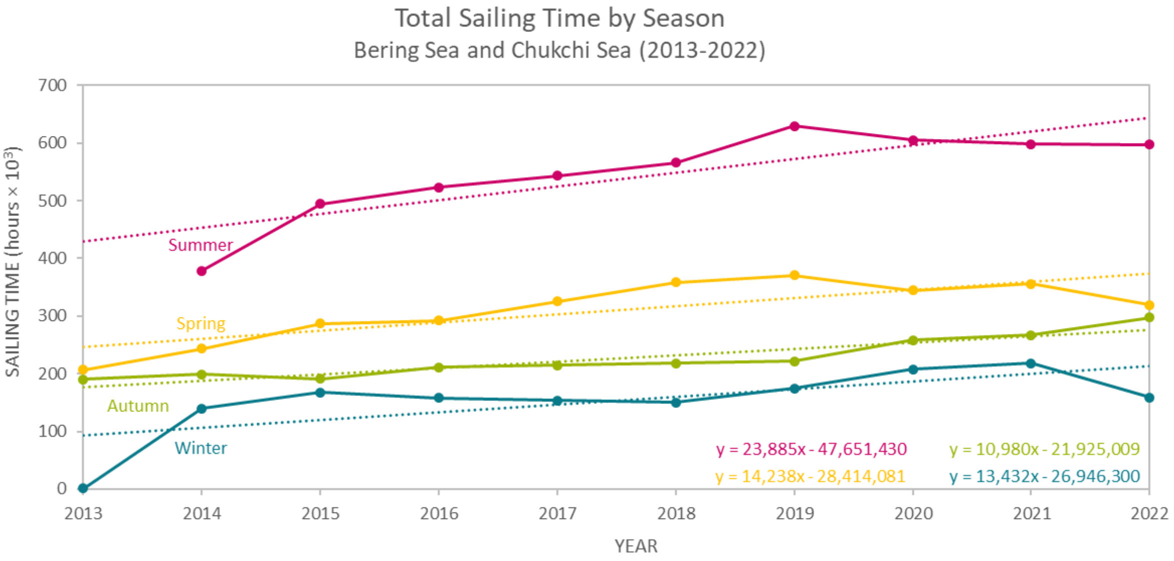

Figure 5.19 – Total sailing time in the Bering Sea and Chukchi Sea by season, for the period 2013–2022. Total seasonal sailing time is calculated as the total sailing time for all vessels for the months in each season: JFM (winter), AMJ (spring), JAS (summer) and OND (autumn) (as used in NSIDC's calculations for sea-ice trends; Parkinson et al., 1999). Source: PAME (2022).

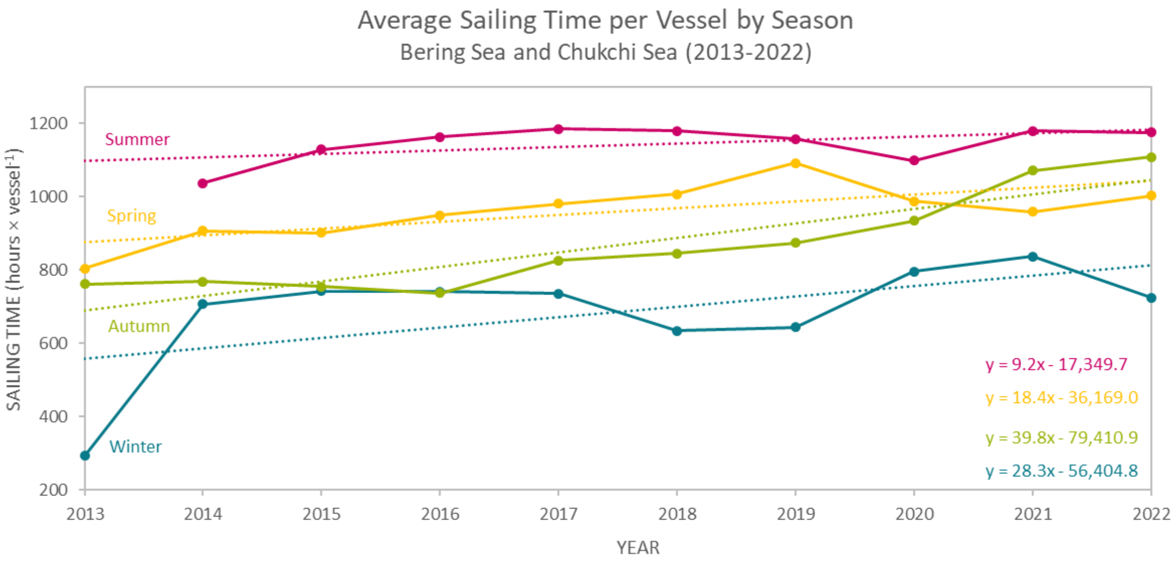

Figure 5.20 *– Average sailing time per vessel in the Bering Sea and Chukchi Sea by season, for the period 2013–2022. Seasons are defined as follows: JFM (winter), AMJ (spring), JAS (summer) and OND (autumn) (as used in NSIDC's calculations for sea-ice trends; Parkinson et al., 1999). Source: PAME (2022).*

5.4.3. Avoiding Sea Ice

In broad terms, the majority of vessel traffic in the Bering Strait region occurs in ice-free waters. The decrease in sea-ice area and increase in vessel traffic discussed in the previous sections (5.4.1 and 5.4.2) suggests that vessel navigation in ice-prone waters is becoming easier due to the greater availability of open water both spatially (expanding to more extensive areas) and temporally (for longer periods of time). This general avoidance of sea ice during navigation is reflected in the sea-ice concentration at each AIS ping location (AIS ping locations are individual known point locations from where a vessel has transmitted using its on-board AIS transceiver). As Figure 5.21. shows, 95% of sailing time is spent in waters where sea-ice concentration is below 15%, compared to other sea-ice concentration bands (16-30%, 31-45%, 46-60%, 61-75% and >76%). As sea-ice concentration increases, the total sailing time spent in those areas decreases, as shown by the progressively decreasing percentages for higher sea-ice concentrations (Figure 5.21). As such, vessels navigating in the Bering and Chukchi Seas, which are waters prone to sea-ice cover, tend to prefer navigating in areas with the least amount of sea-ice cover.

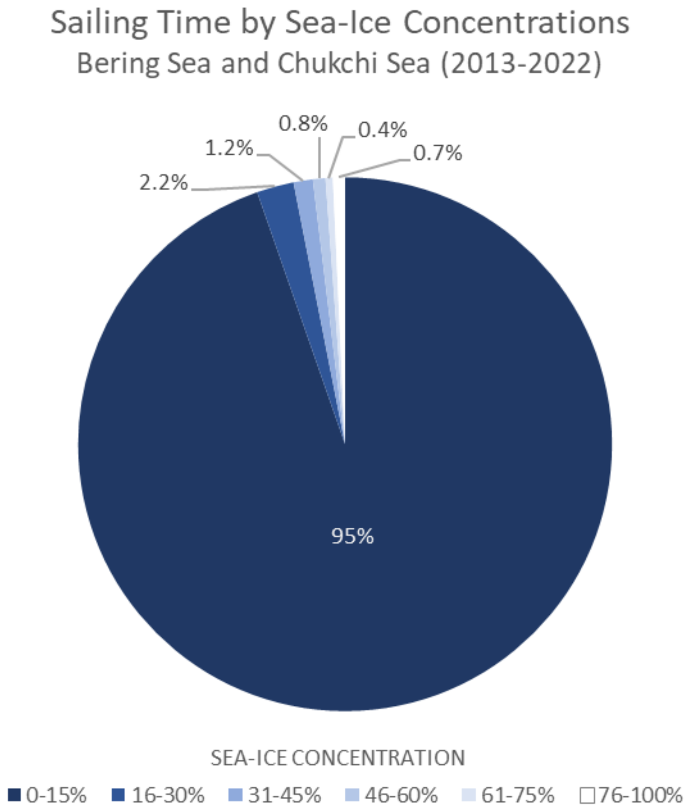

Figure 5.21 – Proportion of sailing time spent in different levels of sea-ice concentrations in the Bering and Chukchi Seas. Obtained from analysis of all AIS pings for the period 2013-2022. Source: AIS data from PAME (2022); sea-ice concentration data from Spreen et al. (2008).

The overall avoidance of vessel encounters with sea ice, combined with the annual cycle of sea-ice formation and sea-ice melt in the Bering Strait region, results in a seasonal 'peak' of sea-ice cover and vessel activities. The volume of vessel traffic in the Bering Strait region generally follows the annual sea-ice cycle (see Chapter 3). The annual 'peak' of sea-ice growth and melt is accompanied by a corresponding 'peak' in vessel activities. Figure 5.22 shows an animated GIF of monthly sea-ice and vessel data for the period 2013–2022, which clearly demonstrates the annual correlation between low sea ice concentrations and high vessel presence[18]. As sea ice retreats in the summer, vessel traffic immediately fills the available mostly ice-free ocean space. Conversely, vessel traffic retreats southwards as sea-ice grows in the autumn and into winter. Each year, the volume of vessel traffic peaks during the summer months (July–August), which generally aligns with the lowest sea-ice area usually occurring around August and September (Figure 5.23). The month with the lowest number of ships navigating in the Bering and Chukchi Seas is December during most years, and sometimes a little earlier in November (there is, however, a small rise in vessel activities around January, which is

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[18] To view the animated GIF online: https://tinyurl.com/bering-seaice-2013-2022. If having trouble accessing the GIF, as an alternative, see Appendix for monthly snapshots of average sea-ice concentration and total vessel traffic for the period 2013–2022.

attributable to the winter activities of the fishing and crabbing fleet and is further discussed in Section 6.3). Whilst this is not the time of year when sea ice is at its absolute maximum (usually around January–March), these months are characterised by a rapid growth in sea ice. The Bering Sea, in particular, is known for its potentially quick sea-ice onset once ocean and surface temperatures drop sufficiently to consistently support sea-ice growth (Stabeno et al., 2012a). This can lead to fast-changing and unpredictable sea-ice conditions that are risky and difficult to account for from a navigational perspective (Marchenko, 2012)[19]. As such, vessel traffic follows quite closely the growth and retreat of sea-ice throughout its annual cycle and responds to the seasonally specific mobile nature of sea-ice conditions.

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[19] The drop in vessel traffic during the winter period can also be accounted for by considering other factors that hinder navigation, such as polar nights and the higher frequency of winter storms (Guy and Lasserre, 2016; Stocker et al., 2020).

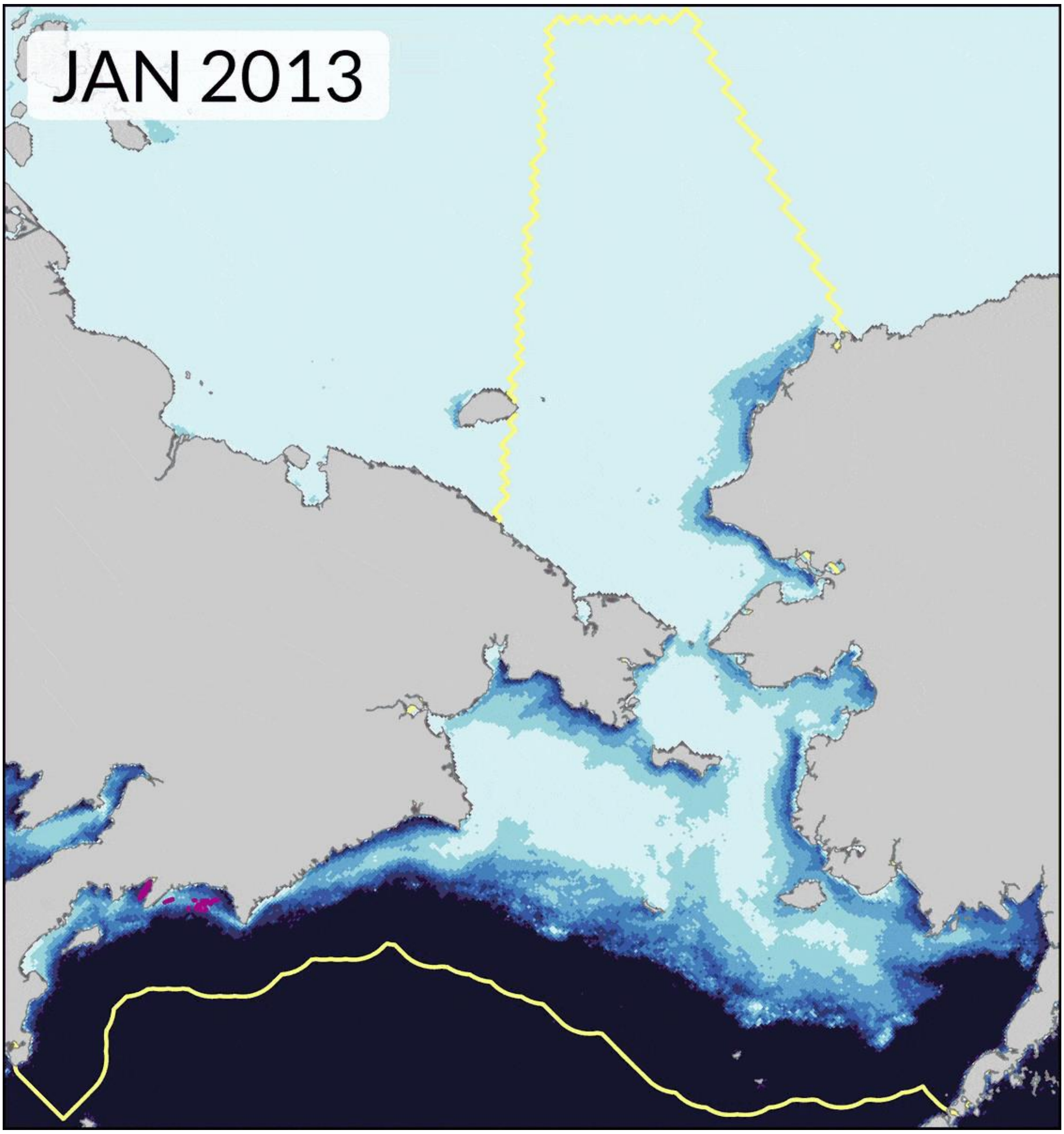

Figure 5.22 – Animation of average monthly sea-ice concentration and monthly vessel traffic for the entire study period 2013-2022. The animation shows the pulsating seasonal rhythm of the annual sea-ice cycle and corresponding vessel activities. Data shown in Figure 5.23 applies to the study area (yellow line in this figure). Source: AIS data from PAME (2022); sea-ice concentration data from Spreen et al. (2008).

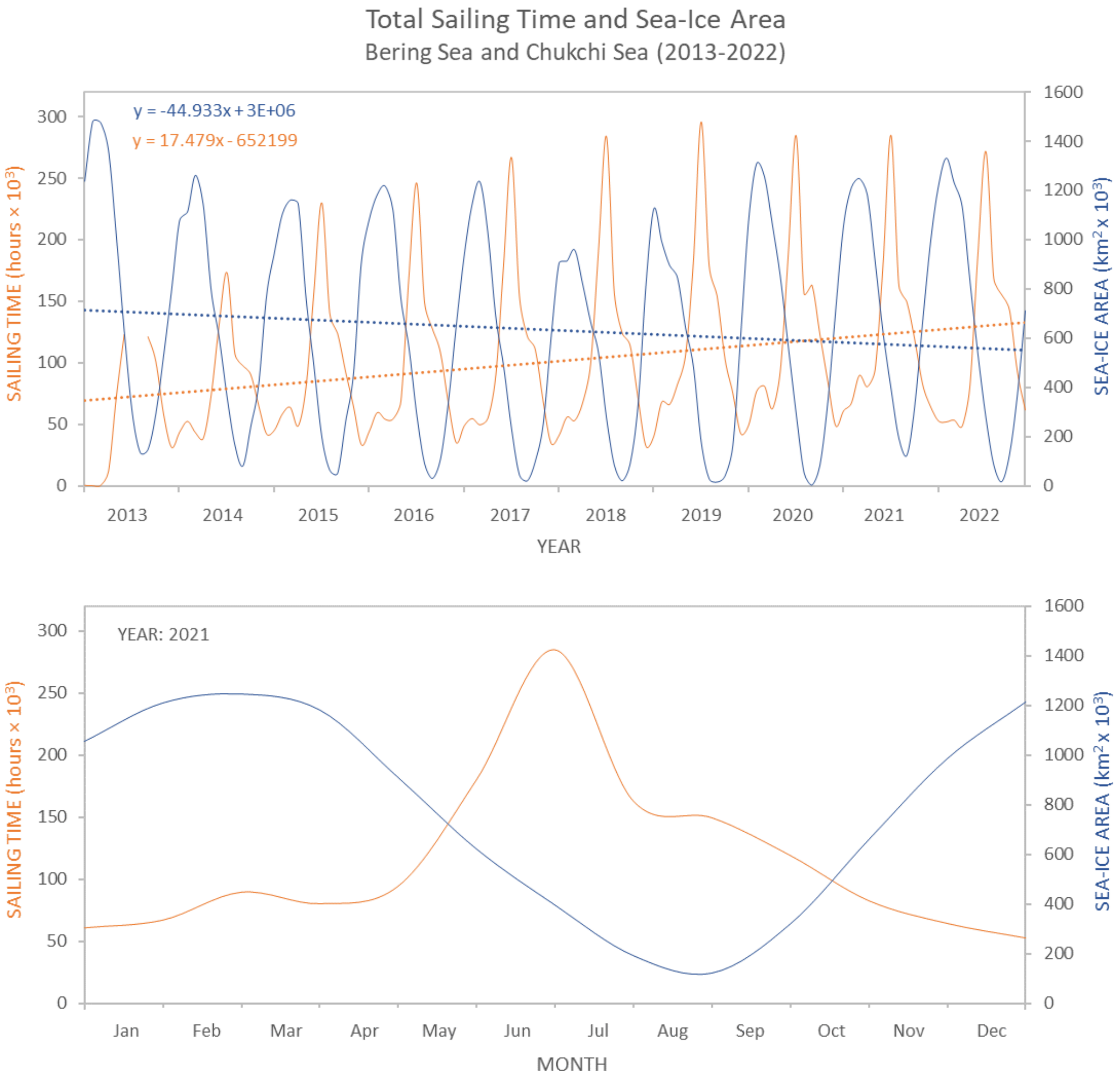

Figure 5.23 – *Sea-ice area and total sailing time in the Bering and Chukchi Seas over the period 2013–2022 (top) and, as an example year, 2021 (bottom). Vessel activities intensify as sea-ice melts in the summer, and conversely decline as sea ice grows in the winter. Source: AIS data from PAME (2022); sea-ice area data from NSIDC Sea Ice Index Version 3 (Fetterer et al., 2017).*

Seasonal vessel traffic patterns in the Bering Strait region are also apparent in the spatial patterns of vessel traffic by latitude. Figure 5.24 shows annual heat maps of total sailing time by latitude in each month for the period 2013–2022. Each year, there is a clear northwards migration of vessel presence during the summer months when sea ice retreats, as shown by the northwards summertime 'wave' visible in each annual heat map. In addition, vessels are spending more time at higher latitudes in winter (January–March; purple box outline in Figure 5.24). In addition, there is greater vessel presence at higher latitudes earlier in the autumn (October–December; green box outline in Figure 5.24). This could be related to the observable decrease in vessel traffic at lower latitudes during those months (yellow box outline in Figure 5.24). There is also an overall intensification of total vessel sailing time during the warmer summer months, with traffic intensifying in the higher latitudes (where vessel traffic already takes place but is less frequent), as well as persisting later into the season (June–August; white box outline in Figure 5.24). Finally, whilst traffic is intensifying at various latitudes and periods of the year, the northern limit of where vessel activities occur is remaining stable at around 72.5°N. This means that the changing cryomobilities in the Bering Strait region are characterised by a redistribution and intensification of vessel activities at latitudes where vessel traffic already takes place (and has been so for at least a decade), rather than an expansion of the overall northerly range of vessel activities. Taken together, these changes in vessel traffic indicate an overall shift towards greater vessel activities in the northerly latitudes, as well as a stretching of the sailing season both earlier in winter and later in summer and autumn.

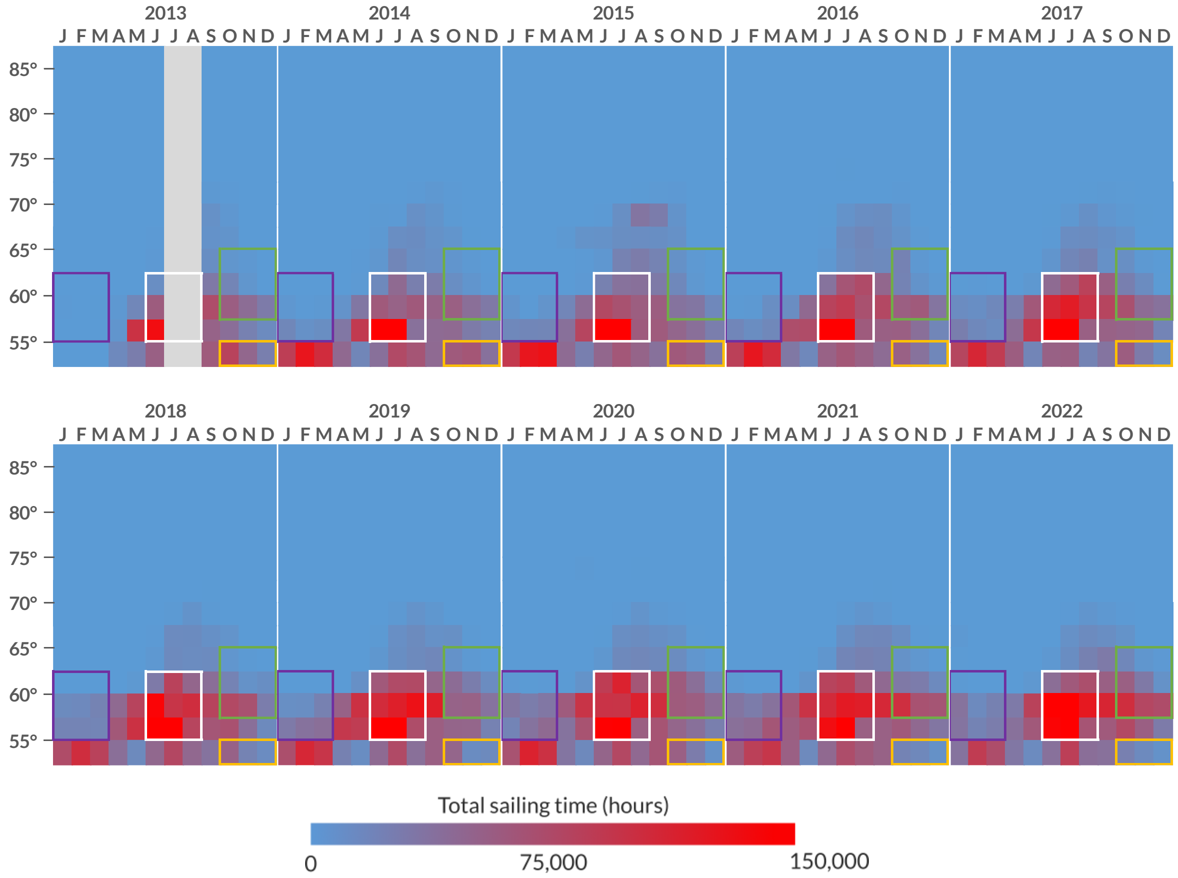

Figure 5.24 – Total sailing time by latitude and by month in the Bering Strait region for the period 2013–2022. Bounding boxes highlight the same months and latitudes for easy comparison across years: winter (purple), summer (white), autumn high latitudes (green) and autumn low latitudes (yellow). Source: PAME (2022).

Looking at specific vessel voyages, these overall patterns of sea-ice avoidance are also observable on smaller spatial and temporal scales. Having reviewed all the ships in the dataset that spend time in higher sea ice concentrations north of the Bering Strait, one United States vessel stood out as a notable example of how vessels might choose to avoid sea ice despite having ice capability. This ship's journey is shown in Figure 5.25, as it travels north through the Bering Strait on 17 May 2014 and returns south on 21 June 2014. On its way north, this Unites States vessel clearly avoids a patch of sea ice near the Bering Strait, as there are more navigable waters around it with much lower sea-ice concentrations. What is of significance here is that after passing through the Bering Strait, it heads directly for pack ice in the Chukchi Sea and spends the rest of its time there before journeying south again. Although not visible in Figure 5.25, the ship's track does not extend much further north than the edge of the map, staying entirely within areas of >90% sea-ice concentration and making no port stops north of the Bering Strait.

This ship is in the medium size category of 10,000–24,999 gross tonnes, the ship type is "Other activities" and the value for its ice class rating is null, so it's difficult to determine for certain what the ship was doing and its level of ice capability. However, some of the ship's behaviour inferred from the ship track indicates that the ship might be carrying out scientific research or oceanographic surveys. This is based on i) the lack of a port destination (typical of most other ship types except for fishing), ii) the long and straight trajectories in all kinds of directions (which could signify established transects that are repeatedly visited for consistent data collection), and iii) the regular grid pattern visible at the top of the June map in Figure 5.25[20]. In terms of the ship's ice capability, the data show that the ship spends 34 continuous days in the pack ice, suggesting that it is capable of successfully handling significant levels of ice cover[21]. Despite this, the ship still circumnavigates sea ice whenever this is an option. During his interview, Simon, whose previous job involved monitoring charts of live ship traffic, points out that efficiency is key when it comes to navigation: "I'm not an expert, […] but time is money. If you can find a shorter way to get somewhere, you're going to do it every time" (lines 140-141). In fact, the ship travels almost twice the distance between 20 and 21 June in open water compared to 16 and 17 May when it passes close to denser sea ice (Figure 5.25). This aligns with the notion that even if sea ice does not pose a life-threatening danger to the ship and its crew, navigating through ice-covered waters still slows down and restricts a ship's full operational capacity. Therefore, on the small scale of individual ship voyages, even when ships do have ice capability, sea ice remains a hinderance to be avoided if possible.

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[20] I showed Figure 5.25 at a presentation at IARC in December 2023. An oceanographer at the University of Alaska Fairbanks, who had attended the presentation, got in touch after the presentation to suggest that the ship track could belong to the icebreaker USCG *Healy*. Indeed, the vessel track from the ASTD matches that of *Healy*'s 2014 research cruise activity log (https://www.rvdata.us/search/cruise/HLY1401).

[21] Whilst sea-ice concentration on its own cannot provide a complete picture of sea-ice conditions and therefore be a proxy for a vessel's ice capability, a ship with no ice capability is unlikely to spend 34 days (which is a relatively long time) in pack ice.

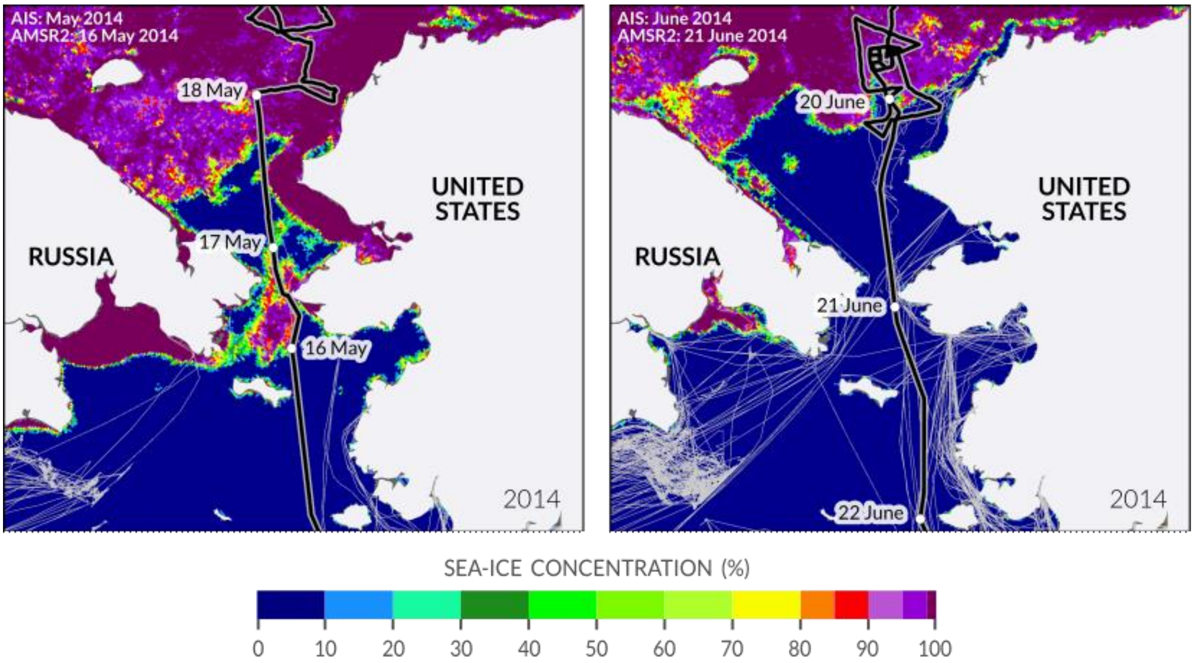

Figure 5.25 – A ship travels north through the Bering Strait in May 2014, clearly avoiding a patch of denser sea ice (left). Five weeks later, the same ship[22] returns south the same way, although the significantly reduced sea ice allows for a more direct route through the Bering Strait (right). Ship tracks for the entire monthly datasets are shown for context as thin grey lines. Source: AIS data from PAME (2022); sea-ice concentration data from Spreen et al. (2008).

This preference for navigation in ice-free waters comes through in several of the interviews. Simon, who has experience monitoring live traffic in Alaskan waters, points out: "None of these vessels [navigating in Alaskan waters] want to go through ice, especially if it's thick ice. They're trying to avoid thick ice at all costs" (lines 123-124)[23]. Sarah, who is involved with providing daily sea ice forecasts, also agrees, adding that "the tugs and barges that are bringing resupply stuff up to the coastal villages [are] really looking at the times when there's no ice" (lines 265-266). In fact, avoiding sea ice is such a primary concern that at times it can trump other navigational constraints that would normally forbid navigation in certain areas. This notion is reflected in the following interview excerpt, in which Simon, through his experience in monitoring live vessel traffic, discusses vessel behaviour along the western and northern coast of Alaska:

> They [Marine Exchange] can pass it on to the Coast Guard, but these vessels can claim force majeure and say that for the safety of vessel and crew they had no other choice but to take the route that they did. […] And you're gonna [*sic*] consistently have more and more conflict with that to sort out what is

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[22] As there is no correspondence between ship IDs across months, joining tracks belonging to the same ship across months must be done on a case-by-case basis. In this instance, a visual inspection determined that the ship tracks split across May and June 2014 belonged to the same ship because i) there were no other ships in the area, ii) the end of the May track was very close to the start of the June track, and iii) the June track provided a sensible continuation (both in terms of bearing and overall navigational pattern) to the May track.

[23] Whilst sea-ice concentration cannot necessarily be used as a proxy for sea-ice thickness, it is reasonable to suggest that vessels trying to avoid thicker sea ice would also want to avoid higher sea-ice concentrations.

> the best way to handle this. I guess every vessel captain seems to have a different idea of the best way to handle each situation their vessel is in. It's kind of their responsibility to do that so I mean… […] The Coast Guard may fine them with a nautical rule on it… realistically… few thousand dollars […] if they found they'd violated one of the routing requirements. (Simon, lines 26-33)

Amongst other things, Marine Exchange also monitors live ship traffic in waters around Alaska, ensuring that vessels are aware of and comply with active navigational rules, and Marine Exchange can also provide information and assistance for ships via radio. What Simon points out here is that in some situations, sea-ice conditions along a ship's route can force the ship to change course on short notice. This can be to an extent that leads the ship to violate other nautical rules, such as approved shipping lanes, which in the absence of sea ice would be respected without issue. As such, there is at times a conflicting intersection between the existing navigational conventions and the unexpected sea-ice conditions, meaning the former are occasionally violated in favour of avoiding the immediate threat of sea-ice.

Overall, the cycles in sea ice and vessel activities shed light on the patterned ways in which vessels avoid sea ice in the cryomobilities of the Bering Strait region. On multiple spatial and temporal scales – from seasonal changes in sea ice to the navigational preferences of individual ships – sea ice represents an obstacle to navigation in ice-prone waters, which results in a strong tendency to avoid, whenever possible, the challenging mobilities involved with moving through sea ice. In addition, this preference for avoiding sea ice intersects with other mobilities in watery ocean spaces more broadly. As Simon's long interview excerpt suggests, responding to sea ice is important to captains and their crews, but is only one among several other intersecting factors that influences captains' decisions regarding where to route their vessels. Recommended shipping corridors, national and international conventions on sailing regulations, and monitoring practices such as Marine Exchange and the Coast Guard, are all examples of the multiple contexts which intersect with the cryomobilities of sea-ice avoidance. These may, in certain cases, push vessels closer to sea ice, contending with the intention to steer clear of sea ice (for example, see Section 6.3 for how the location of good hunting areas for valuable crab species pushes fishing vessels farther into the ice pack). As such, sea ice plays an important role in the ways in which ice-avoidant vessel mobilities develop in the Bering Strait region, whilst recognising that cryomobilities also sit within an extensive web of interactions that shape mobilities in watery ocean spaces more broadly.

5.5. Conclusion

In this chapter, I have considered the various ways in which sea ice poses an obstacle to navigation in the Bering Strait region, as revealed through the analysis of AIS ship data, sea-ice concentration satellite data, interviews, and existing literature. As this discussion has revealed, the presence of sea ice is an important factor that shapes the navigational patterns of cryomobilities in the Bering Strait region.

Since the early European voyages to the Arctic in the 18th and 19th Centuries, the distinct materiality of sea ice disrupts the ways in which vessels designed for moving through oceans in their liquid form are able to handle an ocean that turns (to varying degrees) solid. As such, navigation that is usually designed for a liquid ocean must adapt to be able to navigate in a partially frozen solid ocean. In addition, the difficulties that come with navigation in ice-prone waters exceed the presence of sea ice; the harsh conditions and extreme climate of the Bering Strait region have made it a remote and scarcely populated area, with limited resources for supporting navigation. This realisation led to a variety of technological advances, particularly in the 20th Century, aimed at overcoming the challenging ocean conditions posed by sea ice and improving the ice capability of ships. Even the language surrounding some of the technical documentation that sets out guidelines for shipbuilding requirements describes the ocean as “ice-infested” and requires vessels to be “aggressive” in order to get through it. This demonstrates the extent to which the nautical community conceives of sea ice as an obstacle.

Furthermore, in this chapter I have presented the findings from the analysis of both sea-ice area and vessel activities over the past decade (2013–2022) in order to better understand the cryomobilities associated with changing dynamics of sea ice and vessel traffic in the Bering Strait region in the 21st Century. Firstly, sea-ice in the Bering Strait region has been declining, albeit unevenly both spatially (sea-ice loss is more severe in the Chukchi Sea than in the Bering Sea) as well as temporally (spring in particular shows more pronounced sea-ice decline than other seasons in terms of absolute sea-ice loss). Moreover, the overall sea-ice decline is characterised by large fluctuations in sea-ice area within a single sea-ice season, leading to high seasonal variability characterised by alternating high and low sea-ice cover over just a few months, such as in 2022. Secondly, the analysis of vessel traffic trends reveals a consistent increase in activity over the studied period (2013–2022). Vessel numbers, total sailing time, and average sailing time per vessel have all shown an upward trajectory. The greatest increases in vessel traffic are occurring during the summer (July–September), although autumn (October–December) is showing the largest increase in average sailing time per ship. Notably, the high-traffic summer season is expanding, with more vessels sailing for longer during the end of summer and into autumn. While vessel traffic growth is highest during summer, autumn sees a substantial increase in average sailing time per ship, indicating an extended presence at sea during these months.

By using a complementary mix of datasets, I have demonstrated in this chapter that vessels today still avoid sea ice in a variety of ways: i) the vast majority of vessel traffic occurs in areas of open water, ii) the volume of vessel traffic follows the annual sea-ice cycle, iii) even when vessels have ice capability, they still avoid sea ice whenever possible, and iv) sea ice as an obstacle can trump other legally-defined navigational rules that ships are usually bound to and do follow in ice-free conditions.

6

Cryophilia: An Affinity for Sea Ice

6.1. Introduction

The ocean in its frozen form can be considered in many ways an obstacle to navigation (see Chapter 5). However, this conceptualisation of sea ice primarily relies on a prescriptive understanding of sea ice as a problematic material presence that denies the ocean its liquid form. Following this line of thinking, only in an ice-free ocean can vessel navigation truly thrive. This chapter departs from a conceptualisation of cryomobility rooted in sea-ice avoidance, and instead recognises that not all ships and not all sea-ice conditions are the same – there are many different users of the varied and continuously mobile icy-watery spaces of the Bering Strait region, which all need acknowledging in order to better understand the cryomobilities at play. Whilst this does not detract from the fact that direct encounters with sea ice still pose challenges to vessel activities (even those driven by the opportunities surrounding sea ice, e.g., Stocker et al., 2020), it complements the understanding of sea ice discussed in Chapter 5 as exclusively an obstacle to navigation.

The vessels that navigate in the icy watery spaces of the Bering Strait region consist of different types of ships, each with their own level of ice capability, captain, crew, and purpose to their voyage. As such, this chapter challenges an antagonistic view of sea ice as an obstacle to be overcome, and as an undesirable “infestation” of the ocean in its liquid form (e.g., IACS, 2023). Instead, this chapter considers those cryomobilities in the Bering Strait characterised by an affinity towards sea ice, drawing on vessels whose activities emerge from and co-exist alongside sea ice. The focus, therefore, is on highlighting the heterogenous cryomobilities that unfold in the icy waters of the Bering Sea region. In other words, for these vessels, sea ice does not pose an obstacle towards other goals (as in the narratives in Chapter 5 of Arctic European conquerors, for example), but rather, the very reason for sailing in the first place is – to varying degrees – emergent from sea ice. Within the context of this thesis, this chapter continues to build on understanding the ways in which different types of vessels relate to the icy waters within which they operate. This chapter therefore presents a more intricate understanding of the relationships between vessel activities and sea ice and seeks to uncover the possibilities that sea ice presents to navigation in the Bering Strait region.

In this chapter, I draw on four examples that drive and illustrate the discussion. In Section 6.2, I discuss the 1893–96 expedition of Arctic voyager Fridtjof Nansen, for whom sea ice was an ally, rather than an enemy, as in many of the expeditions that went before his. For Nansen, the drifting mobilities of sea ice became the key to the success of his expedition. In Section 6.3, I look at fishing vessels, highlighting that whilst fishing during months of high sea-ice cover puts the lives of fishermen at risk (crabbers, in particular), the sea ice cycle also generates abundant fish stocks. Whilst sea ice is still a significant hinderance to fishing activities, especially those occurring during fall and winter months, it is the very presence and annual cycle of sea ice that provides the thriving fish and crab stocks that fishermen are willing to put their lives at risk for. So, for fishermen, their relationship to sea ice is somewhat two-fold, where sea ice is a serious inconvenience and danger, but a necessary – and extremely profitable – one. In Section 6.4, I explore tourist cruise ships as an example of a unique industry that is interested in the active pursuit of sea ice, as sea ice itself has become a tourist attraction, as well as for the rare opportunity of spotting ice-dependant Arctic wildlife, such as whales and polar bears, in their iconic Arctic habitat. For cruise ships, sea ice remains a navigational hazard that is best avoided, yet it is juxtaposed with a desire to pursue sea ice as a 'last chance' tourist attraction, along with the marine mammals that thrive at the sea-ice edge. Finally, in Section 6.5, I consider the trends in vessel traffic occurring in higher sea-ice concentrations over the last decade (2013–2022). I presents findings from the AIS vessel tracking and sea-ice concentration datasets, challenging the widespread notion that vessel activity will increase in the Arctic as sea ice decreases in the coming years due to the greater availability of open water. Instead, I demonstrates that vessel activities in the Bering Strait Region – and icebreakers in particular – are increasing not just in areas of open water, but also in areas of dense pack ice. Overall, in this chapter, I bring attention to the ways in which the intersecting vessel and sea-ice characteristics result in a variety of cryomobilities not exclusively aimed at avoiding sea ice (as in Chapter 5), but that arise from an affinity for, or a seeking out of, encounters with sea ice.

6.2. Expeditions: Drifting with Sea Ice

Many of the early European voyages into the Arctic consisted in attempting to break through the ice (see Chapter 5). The challenges encountered during these expeditions revealed that a frozen, partially solid ocean could not be sailed in the same way as a liquid one. However, attempts to overcome the ice, such as reinforced hulls and specific vessel shape designs, still failed to fully embrace (and make the most of) the unique complexities of the materialities and mobilities of sea ice. In other words, the advances in ice capabilities of early European Arctic vessels – efforts which also continue to the present day – are aimed at working *against* the ice, rather than *with* the ice.

One explorer whose expedition departed significantly from this approach, was Fridtjof Nansen. In 1884, during his doctoral studies, Nansen came across the work of Professor Henrik Mohn, a meteorologist who proposed the existence of transpolar drift, a current that carried sea ice across the North Pole following a general direction from the Bering Strait towards Greenland (Figure 6.1, inset). Mohn's theory was based on the findings of the remains of the *Jeannette*, an American vessel that became frozen into the ice pack just north of the Bering Strait during its 1879–81 voyage towards the North Pole. It then drifted with sea ice until it was north of the New Siberian Islands, where she was crushed by the ice and abandoned by her crew (Figure 6.1). Pieces of wreckage that unquestionably belonged to the *Jeannette* (including uniforms bearing crew members' names, and documents signed by the captain) were found three years later along the coast of Greenland (Nansen, 1897a). As such, Mohn hypothesised that these items had remained frozen in the ice since the ship sank near the New Siberian Islands and had drifted across the pole carried by the transpolar drift, to re-emerge in Greenland as the ice melted away.

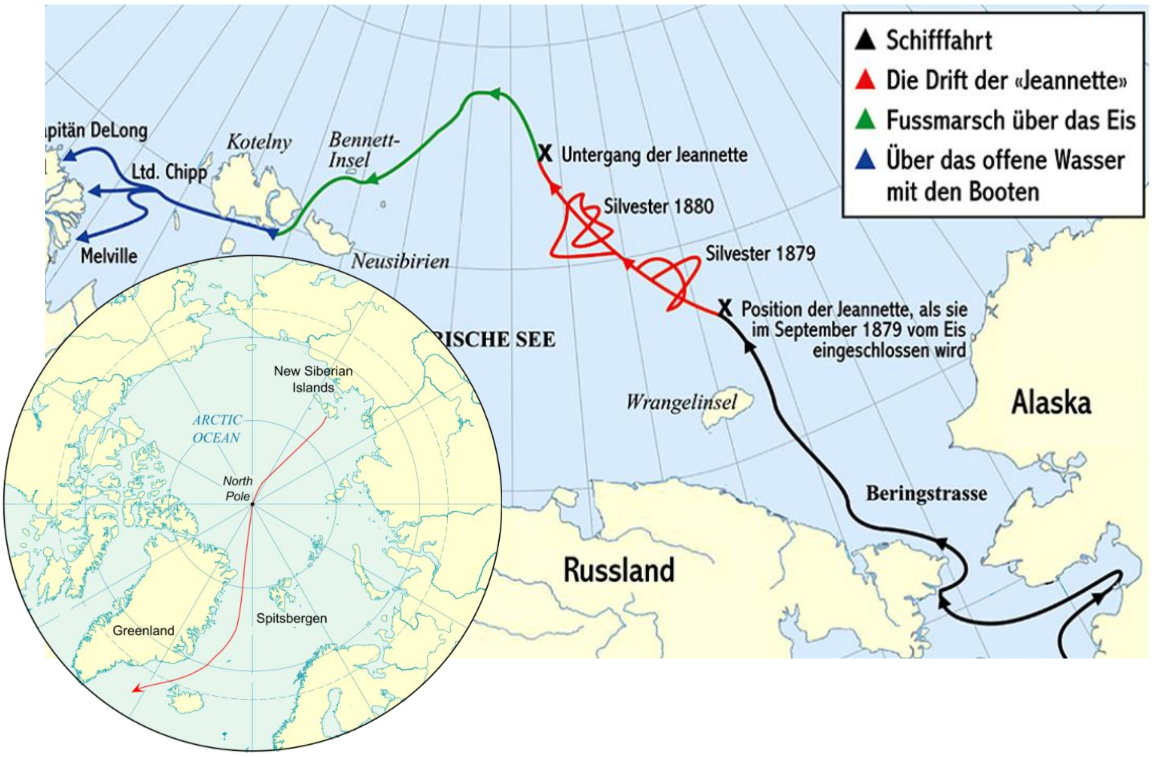

Figure 6.1 – Route taken during the 1879–81 Jeannette expedition (main map). The Jeannette sank near the New Siberian Islands and pieces of its wreckage were found three years later along the eastern coast of Greenland. This led Henrik Mohn to develop a theory of transpolar drift (inset map), which provided the basis for Nansen's Fram expedition. Source: Jeannette route map from Hug (2021), inset transpolar drift map from Wikimedia Commons (2009).

Based on Mohn's idea of transpolar drift, Nansen proposed an expedition to reach the North Pole by deliberately getting a vessel stuck in pack ice and utilising the transpolar sea ice drift to carry the ship to the North Pole. The ice pack would then eventually drift back around to lower latitudes where it would melt, releasing the vessel, and the crew would sail home (much like the wreckage of the *Jeannette*). Not many thought that Nansen's proposal would lead to a successful expedition. Up until that point, getting their vessel stuck in the ice pack was every European Arctic explorer's worst nightmare. Indeed, Nansen's plan received strong critique, especially from other European Arctic explorers who considered it to be, among other condemnations, "sheer madness" (Nansen, 1897a: 41). Despite the doubts that others had in Nansen's proposal, he received funding for his expedition following a passionate speech at the Parliament of Norway. Nansen commissioned the vessel *Fram* – meaning "forward" – to be built especially for this voyage, with a smooth and sturdy hull that would not give the ice anything to grip to; instead, "the whole craft should be able to slip like an eel out of the embraces of the ice" (Nansen, 1897a: 62). In July 1893, the *Fram* and her crew of 12 sailed from Oslo (then called Christiania) northwards along the Norwegian coast and continued into the Barents Sea and then the Kara Sea (Figure 6.2). On 22 September 1893, sea ice surrounded the *Fram*; on 5 October Nansen ordered the rudder to be lifted for the last time and the *Fram* officially began her drift across the Arctic Ocean (Nansen, 1897a). After roughly 18 months of drifting, Nansen's location measurements started to show that the *Fram* was no longer progressing towards the Pole and was instead moving south again – transpolar drift had carried her in the vicinity of, but without quite reaching, the North Pole. Nansen decided to leave the *Fram* under the command of Otto Sverdrup as he set out with Hjalmar Johansen in an attempt to reach the Pole by ski, dog sled and kayak (Figure 6.2). Whilst the *Fram* expedition did not get to the North Pole, Nansen and Johansen reached the then record northern latitude of 86°14′N.

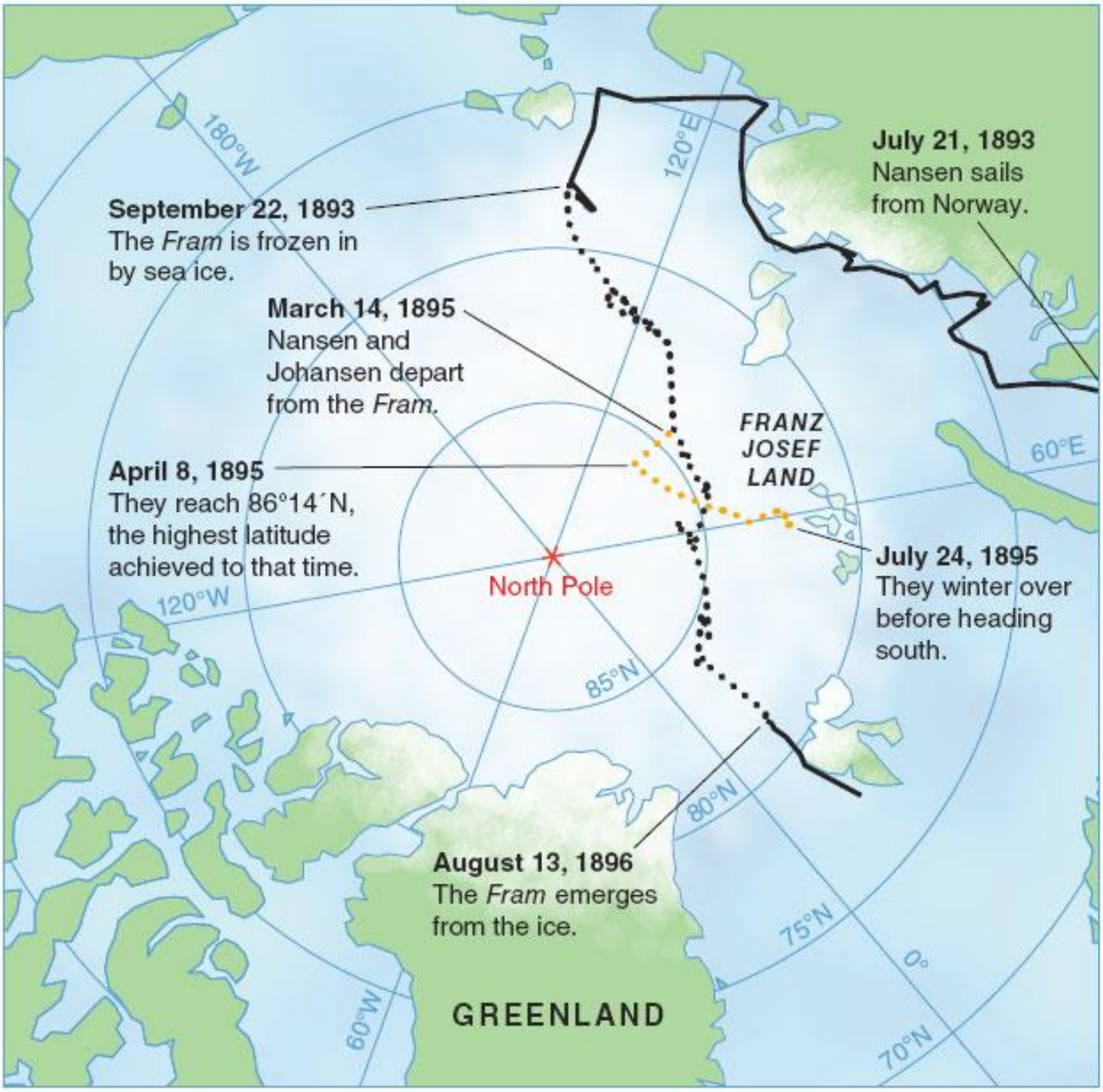

Figure 6.2 – Route taken during Nansen's 1893–96 Fram expedition. A solid black line indicates the Fram sailing; a dotted black line indicates the Fram's drift trajectory in the sea ice; a yellow dotted line indicates the ski, dog sled and kayak route of Nansen and Johansen. Source: Aulicino et al. (2023).

Similarly, several other scientific research endeavours also harnessed the transpolar drift. In 1937, the Soviet Union began deploying manned drifting stations for continuous monitoring of the Arctic. With support from icebreakers and aeroplanes, equipment and a small team of scientists (the first consisted of only four people) would be deposited on a suitably large and stable ice floe, be left to drift with the ice pack and would be picked up by a vessel once the floe began to break and melt away. Between 1937 and 2015, 41 drifting station were deployed by the Soviet Union and Russia, with up to three in operation at the same time (Frolov et al., 2005). Under a different experiment, the NOAA-led Surface Heat Budget of the Arctic Ocean (SHEBA) project set up a drifting station from 1997 through to 1998. Its purpose was to collect data for analysing the "physical processes associated with interactions among the radiation balance, mass changes of the sea ice, storage and retrieval of heat in the mixed layer of the ocean, and the influence of clouds on the surface energy balance" (Uttal et al., 2002: 256). Finally, more than 120 years after Nansen's expedition, an international collaboration of scientists and researchers repeated Nansen's drifting expedition through the Multidisciplinary drifting Observatory for the Study of Arctic Climate (MOSAiC) project. During the 2019-2020 MOSAiC expedition, scientists purposely trapped the German research icebreaker *Polarstern* into Arctic pack ice north of Siberia, drifted with sea ice over the winter, getting within a few degrees of the North Pole (Figure 6.3), and drifted back down into open water northeast of Greenland in the summer thaw of 2020 (MOSAiC, 2020). The aim of the 2019–2020 MOSAiC expedition was to collect year-round observations of the Arctic sea ice and ocean and, in particular, of the seldom observed central Arctic winter (Shupe et al., 2020). These examples of research stations that drift on and with the Arctic sea ice highlight the possible cryomobilities that arise from vessel interactions that move *with* sea ice.

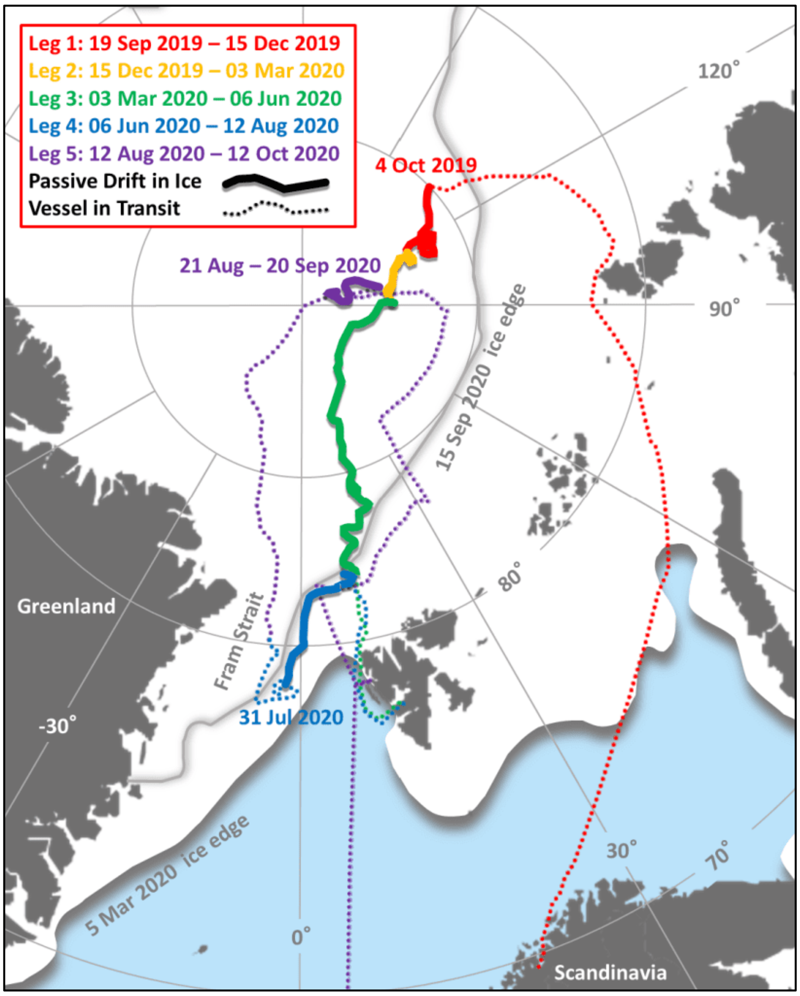

Figure 6.3 – Route taken by the Polarstern during the 2019-2020 MOSAiC expedition. Source: Shupe et al. (2020).

Nansen's voyage, and those modelled after it, highlight the ways in which cryomobilities emerge out of specific interactions between mobile vessels and the mobile background against, and within, which they move. As Peters points out, "the style of drifting at sea [...] alerts us to the ways in which the very character of movement elicits a politics, as such drifts relate to expectations between ships, between ships and crews, and between ships, crews and the shore" (2015: 271). In addition to these, Nansen's voyage also elicited a new politics of relations and expectations *between ships and the ocean*, i.e., between mobile entities and the (mobile) backgrounds against which they move. Prior to Nansen's voyage, sea ice was seen as a challenging background both in its (relative) immobility as well as in its mobility. On the one hand, as a frozen, solid, still wasteland, sea ice did not provide any of the mobile qualities of the liquid ocean that allowed ships to sail. On the other hand, the mobile qualities of sea ice that European sailors did experience, such as ice floes converging and crushing their vessels, were also undesirable. In 1892, one year before the expedition, when Nansen explained his proposal to the Geographical Society in London, Admiral Sir George Nares expressed his concerns:

> […] the ruling principle of [Nansen's proposed] voyage is that the vessel—on which, if the voyage is in any way successful, the sole future hope of the party will depend—is to be pushed deliberately into the pack-ice. Thus, her commander—in lieu of retaining any power over her future movements—will be forced to submit to be drifted helplessly about in agreement with the natural movements of the ice in which he is imprisoned. (Nansen, 1897a: 42)

Nares' critique of Nansen's proposed expedition emphasises the desire to uphold the supremacy of the vessel over the ocean, maintaining control over the vessel's mobility regardless of the ocean's mobilities. Instead, Nansen's voyage made use of the (supposedly) irrelevant background against which (supposedly) more important mobilities were to take place, and instead proposed to harness the mobilities of the mobile icy ocean background to achieve the desired mobilities of the ship. As such, Nansen's expedition highlights that the background against which other mobile entities move are indeed themselves mobile, and these mobilities matter for advancing and, consequently, understanding how cryomobilities emerge out of the effective harnessing, or working *with*, these mobile backgrounds.

For the Western world, Nansen's approach to vessel mobilities relative to sea ice was a revelation, as it challenged the widespread approach among other European Arctic explorers who viewed it as an obstacle. Nansen's harnessing of sea ice's mobilities was a new way of performing cryomobilities for the Western world, and whilst there was strong felt doubt as to whether his expedition would succeed, Nansen and his crew were later hailed as heroes for their endeavours (Nansen, 1897b). However, utilising the mobilities of sea ice was not a new approach for the Indigenous peoples of the Arctic, who had been harnessing the mobilities of sea ice for millennia for subsistence hunting of marine mammals such as seals, walrus, whales and polar bears, as well as fish, crabs and birds (Jolles, 2006; Aporta, 2010; Kapsch et al., 2010; Demuth, 2019). This is not to say that on-ice hunting is risk-free; even for the most experienced Iñupiaq hunters, sea ice is still an extreme and dangerous environment (Laidler et al., 2009; Inuksuk, 2011). However, Indigenous uses of sea ice are underpinned by a deep knowledge of sea ice and all its characteristics, including the way it moves (ICC Alaska, 2020). For example, when movements in sea ice create leads of open water, these provide the ideal habitat conditions for certain marine mammals, such as bearded seals and walrus, and also present Indigenous hunters with boat access for hunting them (Kapsch et al., 2010; Hauser et al., 2021). Moreover, movements of sea ice also create stable shorefast ice, which is used by Indigenous people as a platform for hunting whales and other marine mammals. Given the right atmospheric conditions, thick pack ice is advected by the wind towards the coast, crashing against the coastline. Where the relatively flat sheet of pack ice buckles, it creates deep ridges below the sea ice that anchor the sea ice to the sea floor, creating a stable platform of shorefast ice (Huntington et al., 2016). This is used for accessing areas in the ocean that would be open water in the summertime, allowing subsistence hunting of marine mammals (George et al., 2004). The mobilities of sea ice on a molecular level also mean that through the process of brine expulsion during freezing, and as water from deposited surface snow makes its way down through the sea ice, it loses much of its salt content, which is a source of drinking water when hunting for long periods away from shore (George et al., 2004). These constant mobilities of sea ice on a variety of scales are well understood by Indigenous peoples, as reflected in the countless local names used to describe types of sea ice (Thomas and Dieckmann, 2008; Aporta, 2016). As such, exploratory approaches, such as Nansen's and the MOSAiC, that harness the mobilities of sea ice instead of conceiving of it as an obstacle to navigation, must be considered within the context of the multiple knowledges surrounding sea ice that give its mobilities meaning (as further explored in Chapter 7).

6.3. Fishing Vessels: Abundance from Sea Ice

Sea ice is the driver of multiple interconnected processes that rely on sea-ice presence. At its core, the annual sea-ice cycle regulates and provides the conditions for phytoplankton and zooplankton production, which sustain the entire marine food chain (Brown and Arrigo, 2012). This abundance of primary biomass production makes its way through the food chain, attracting large numbers of fish, marine mammals and birds, and making the Bering Sea one of the most biologically productive regions in the world's ocean (Springer et al., 1996; Macdonald et al., 2004). As a consequence, the Bering Sea also provides unparalleled opportunities for commercial fishing. In particular, the Bering Sea is home to the Walleye pollock (*Gadus chalcogrammus*), the largest commercial fishery in the United States (National Marine Fisheries Service, 2022), as well as Pacific cod (*Gadus macrocephalus*). Another of the United States' largest and most valuable fisheries – crab – is also found in the Bering Sea, consisting of several species of crab: red king (*Paralithodes camtschaticus*), blue king (*Paralithodes platypus*), golden king (*Lithodes aequispinus*) and tanner (*Chionoecetes bairdi* and *C. opilio*, also often marketed as "snow crab") (Alaska Department of Fish and Game, 2022, 2023b).

In order to make the most of the profitable abundance of the Bering Sea's rich ecosystem, fishing vessels must also face the significant dangers associated with fishing in icy waters. The fishing industry is one of the most dangerous occupations in terms of occupational fatalities (Oldenburg et al., 2010;

Rinne et al., 2020) and, in the United States, it is second only to those employed in tree logging (U.S. Bureau of Labour Statistics, 2022). One of the most valuable Bering Sea fisheries is crab; for the most profitable and sought-after species – the red and blue king crabs – the season is only open between October and January, as shown in Figure 6.4 (Alaska Department of Fish and Game, 2016). This means that the crabbing fleet must venture into the waters of the Bering Sea during the coldest, darkest, and stormiest months of the year, circumstances which make for dangerous open water sailing and unpredictable and fast-changing sea-ice conditions (Straka et al., 2015). Due to these operating conditions, as well as the heavy equipment used in crab fishing, requiring the use of massive steel crabbing pots, the shellfish fishery accounted for 46% of all fatalities in Alaska's commercial fishing industry during 1991–1998 (Thomas et al., 2001). Freezing spray, for example, is one of the most dangerous conditions associated with wintertime Bering Sea commercial fishing, as it coats boat decks and superstructures with solid ice, adding uneven weight that, in conjunction with strong winds, can cause the boat to capsize. Captains and crews will often have to stop fishing and take to the deck with hammers, shovels and pneumatic drills to crack away the sometimes feet-thick ice caking the boat (Bernton, 2022). In addition, male red and blue king crabs are found in wintertime on the sea floor at depths of around 80-120 m and 180-250 m, respectively (Pereladov and Miljutin, 2002). This coincides with the depth of the Bering Sea continental shelf, where the shallower water column cools easily and provides the ideal conditions for winter sea-ice formation (as discussed in detail in Sections 3.2 and 3.4.2). As a result, the fishing fleet must contend with ideal crab habitat coinciding with where sea-ice is most likely to form, increasing the dangerous encounters between fishing vessels and sea ice.

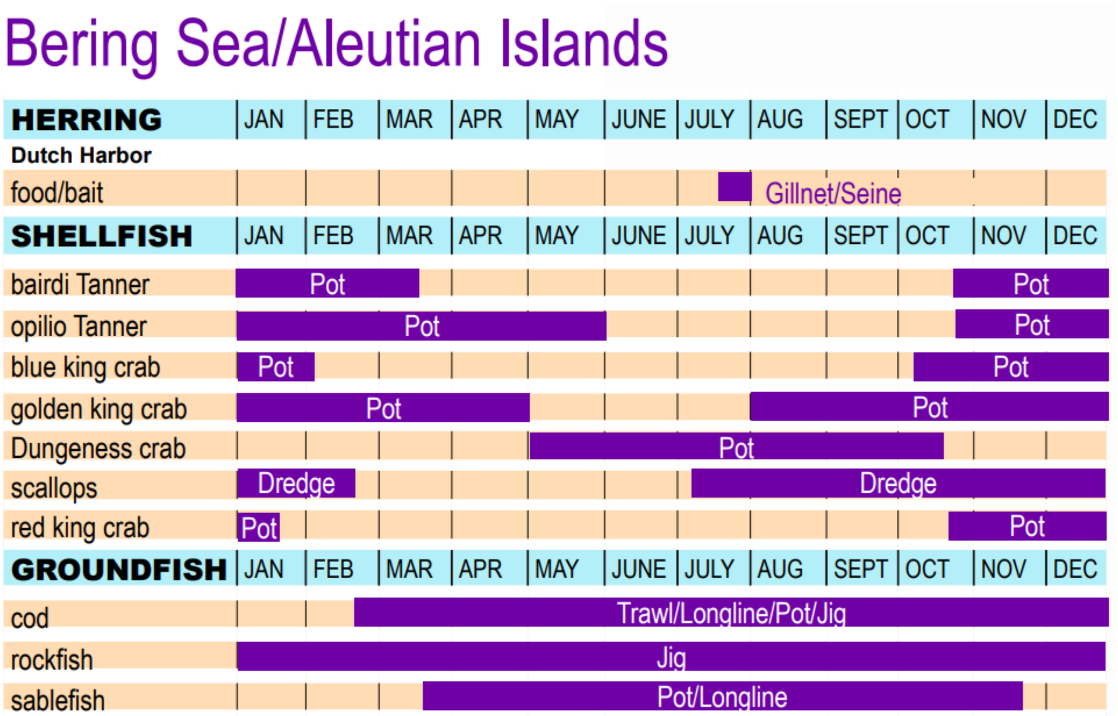

Figure 6.4 – Typical commercial fishing seasons in the Bering Sea and Aleutian Islands region. In general, crab fisheries are only open during the winter months to avoid harvesting during the summer when crab mate and spawn. In particular, the seasons for the most valuable crab (red and blue king crab) are especially short and occur during the coldest and darkest winter months. Source: Alaska Department of Fish and Game (2016).

Despite these dangers, however, the profitability of the Bering Sea fisheries still compels commercial fishing captains and crews to face the dangers of wintertime Bering Sea fishing, whilst doing their best to reduce the risks to their boats, equipment and lives. The location of fishing vessels from AIS data show that fishing vessels stay away from higher concentrations of sea ice. As Figure 6.5 shows, using data from March 2020 as a representative example, there are very few fishing vessels occurring in sea-ice concentrations above 15%. There is one area to the northeast of St Paul Island where fishing vessels are in sea-ice concentrations up to 45%, which is a known area for crab habitat (Alaska Department of Fish and Game, 2023a, 2023b), and the clustering of vessel signals in higher sea-ice concentrations suggests a good fishing spot (Figure 6.5, inset A). Fishing vessels also enter higher sea-ice concentrations at ports, where ships must get through nearshore sea ice to drop off their catch and refuel (Figure 6.5, inset B). Finally, fishing activities in higher concentrations of sea ice tend to be limited to along the Russian coast on the edge of shorefast ice, where there are no ports and it is reasonable to suggest that it would make for good fishing grounds (good habitat for crab due to the shallower waters) and somewhat safer fishing conditions (due to proximity to shore; Figure 6.5, inset C). This is in line with several studies that look at fishing activities in relation to sea ice, which also find that as far as possible, fishing vessels will steer clear of sea ice, even if fishing occurs during the winter months when there is higher sea-ice cover (Pfeiffer and Haynie, 2012; Niiranen et al., 2018). Sarah, who is involved with issuing daily sea-ice forecasts for the Bering Sea region, points out how fishermen stay up to date with sea-ice conditions:

> I'd say mid-January is when they [the crab fishermen] really start fishing the type of crab that are near, closer to the ice edge, *and* when that ice edge is coming down far enough. So […] St Matthew Island is about the point where they start really paying attention to what the ice is doing. […] And so, the more ice that's down there, the more calls we will get regarding the sea ice and asking us, "all right, where is it today? What do you think is going to happen in the next few days? Is it safe to leave my fishing gear here soaking while I go into town to load and come back?" And that kind of thing. (Sarah, lines 238-245)

It is commonplace for crabbing pots to get stuck or dragged away by moving sea ice, as they are often placed close to or just within the marginal ice zone (Citta et al., 2014). Sarah's insight shows that while fishermen keep a close eye on sea-ice conditions and adjust their fishing activities accordingly, the presence of sea ice does not stop them from fishing altogether.

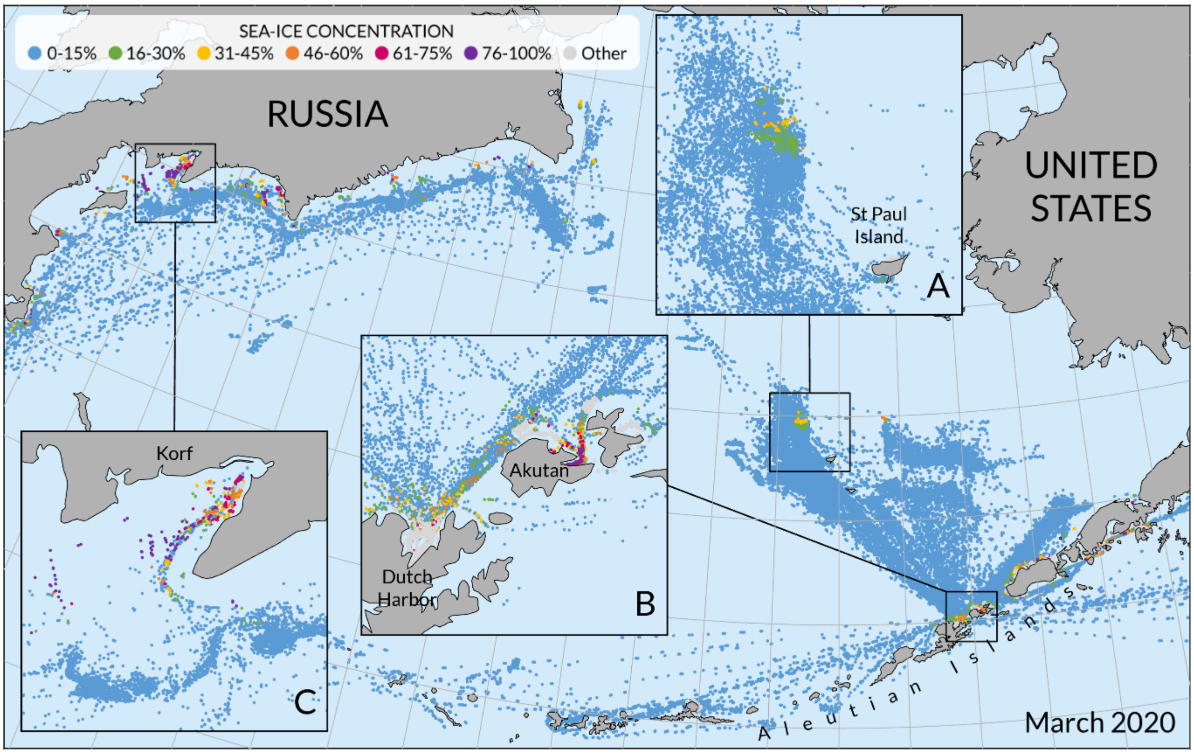

Figure 6.5 *– Map of fishing vessels during March 2020 (used as representative example). Colours indicate sea-ice concentration values at that vessel ping location using AMSR2 sea-ice concentration for the same day as the AIS ping timestamp. Generally, fishing vessels avoid areas of higher sea-ice concentrations, except where there appear to be particularly good crabbing spots (A), where vessels have to get through nearshore ice to get to ports to offload catch and refuel (B), and along the sea-ice edge on the Russian coast where shallower waters make for good crab habitat (C).*

The crabbing fleet's relationship to sea ice is more complicated than merely avoiding it whenever feasible, as there are other ways in which proximity to sea ice is desirable or even helpful. Stewart, who has worked in sea-ice forecasting, points out that "the crab industry […] want to work right at the ice edge because that's where their target species are preferentially found" (lines 51-53), and successful fishing trips can reduce the overall time spent at sea. In addition, Straka et al. (2015) point out that staying close to or amidst sea ice (especially when air temperature is significantly below freezing) reduces freezing spray, as sea-ice cover reduces the wave and wind action that causes ocean spray. In fact, Stewart mentions that sometimes, crabbers do venture into sea ice: "… on occasion, back in the day, you could see fishing boat lights, on fishing boats, just inside [the ice edge], they're really cool looking" (Stewart, lines 104-106; Straka et al., 2015). Despite fishing boats not usually being ice-strengthened, the crabbers are willing to venture into sea ice to some extent.

Despite these challenges and the complex relationship with sea ice, commercial fishing in the Bering Sea continues to be a highly profitable industry. Catch from the Bering Sea and Alaskan waters accounts for 60% of the United States' annual fish landings (National Marine Fisheries Service, 2022). Alaska alone accounts for 31% of the United States' total fisheries value, amounting to $1.48 billion in 2020 and second only to the Atlantic fishing region comprising of all the east coast states (National Marine Fisheries Service, 2022). The seafood industry is also the largest private sector employer in the State of Alaska, employing 47,000 people annually (NOAA Fisheries, 2018). Additionally, as Figure 6.6 shows, the fishing fleet alone accounts for a significant proportion of annual vessel traffic in the Bering Strait region, and much of this traffic occurs during winter months with high sea-ice cover. Figure 6.7 shows the number of fishing vessels plotted against sea-ice area in the Bering and Chukchi Seas. There is a first peak in fishing vessel numbers around January–March, likely driven by the open season during these months of the risky but highly-profitable crab fisheries. Then, there is a second and higher peak during the summer months around July as sailing conditions become more favourable and other significant fisheries, such as cod, are open (Alaska Department of Fish and Game, 2016). Through its role in regulating phytoplankton and zooplankton production, sea ice drives the ecological processes that create this profitable opportunity. In turn, this attracts a high presence of fishing vessels in the Bering Sea region, even during times of high sea-ice cover. Despite the dangerous conditions and risk to life, fishing in the Bering Sea continues to be a massive industry. This demonstrates that the opportunity that the sea-ice cycle offers in sustaining valuable commercial fisheries is so unparalleled, that evidently many fishermen consider it to justify the dangers that the immediate encounters with sea ice pose during fishing activities.

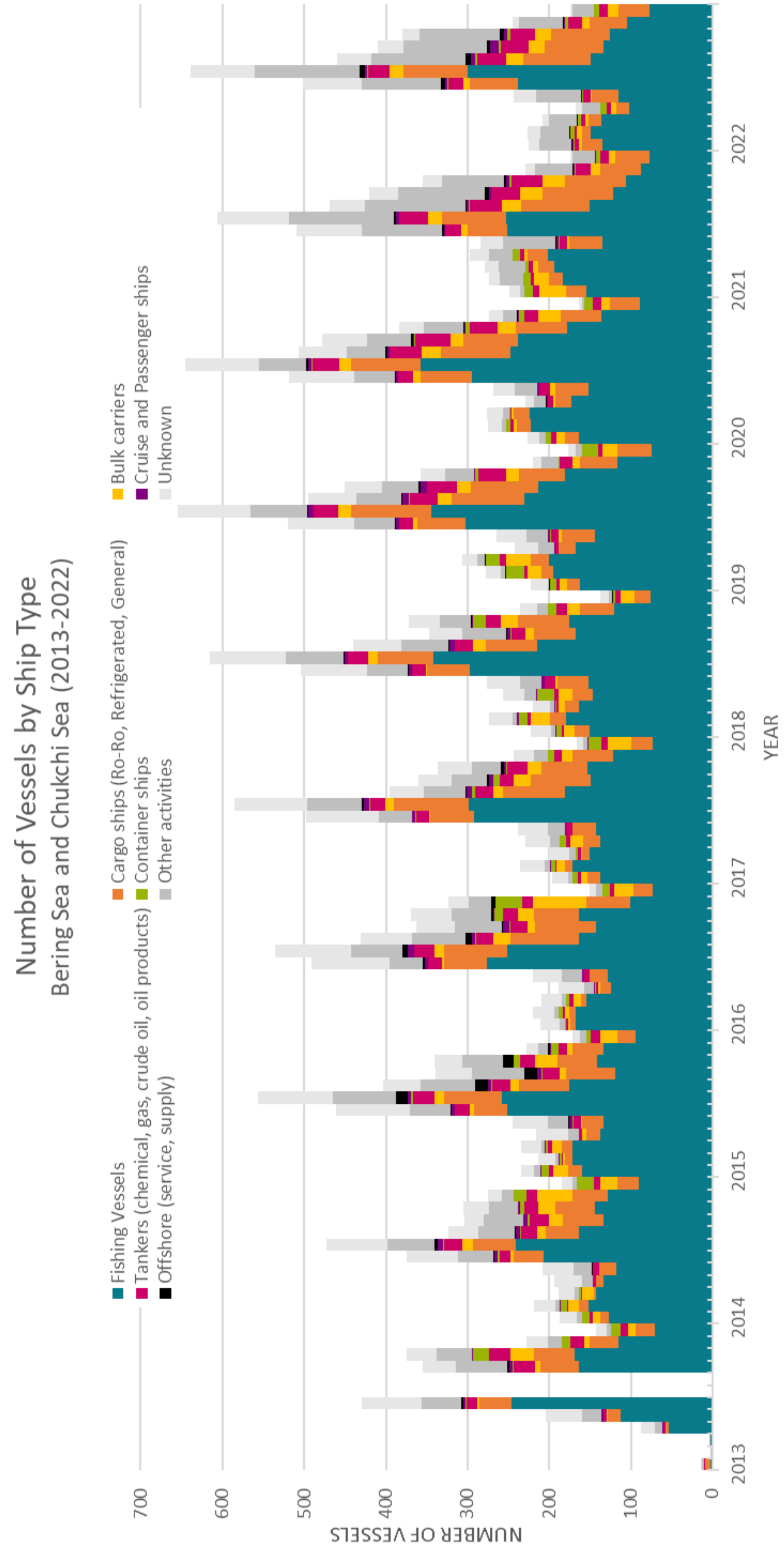

Figure 6.6 – Vessel traffic by ship type in the Bering and Chukchi Seas for the period 2013–2022. Fishing vessels are the single largest category of ships in this region. The dataset was compiled by counting unique vessels by ship type from monthly AIS data. Source: PAME (2022).

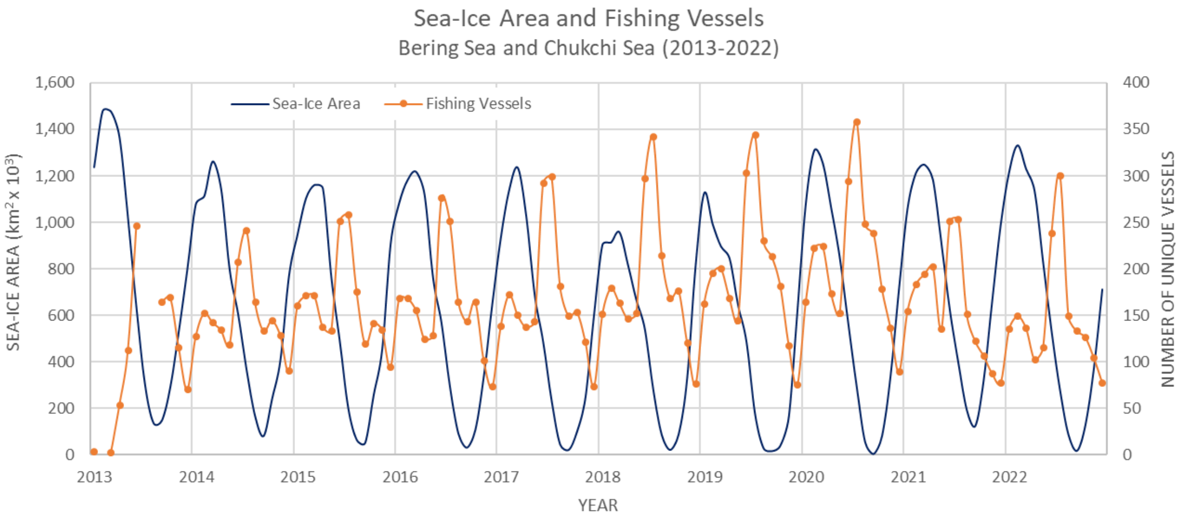

Figure 6.7 – Sea-ice area and number of fishing vessels in the Bering and Chukchi Seas over the period 2013-2022. There is a first peak in fishing vessel numbers around January–March, likely driven by the open season during these months of the risky but highly-profitable crab fisheries. Then, there is a second and higher peak during the summer months around July as sailing conditions become more favourable and other significant fisheries, such as cod, are open. AIS data from PAME (2022); sea-ice area data from NSIDC Sea Ice Index Version 3 (Fetterer et al., 2017)

6.4. Tourist Cruises: Following the Sea Ice Edge

Much like the early explorers and conquerors of the 18th Century, the Arctic continues to fascinate and attract human visitors. Tourism in the Arctic has been growing in recent decades, and a large portion of this is attributable to cruise tourism specifically (Bystrowska and Dawson, 2017). However, whilst early voyagers were drawn to the Arctic by the desire to be the *first* to witness its wonders, much of Arctic tourism today is fuelled by being the *last* to experience endangered landscapes and spot rare wildlife before they disappear or are irrevocably altered (Palma et al., 2019).

Many of these 'last-chance' experiences and sightings cannot be viewed unless one is amidst, or at least in the proximity of, sea ice. This hinges on two main tourist attractions that are endemic to the Arctic. First, there is a tourist interest in seeing sea ice itself. Stewart et al. (2007) argue that the marginal ice zone has become a tourist destination in and of itself. In a fast-changing world characterised by climate change, having the opportunity to experience extreme and endangered land-, sea- and ice-scapes is precisely what fuels the current booming interest in Arctic cruise tourism. Second, as a consequence of rapidly decreasing sea ice, the ice-dependant Arctic mammals and birds have also become a rare wildlife spotting opportunity. The iconic Arctic wildlife, such as polar bears and whales, is most often found in the marginal ice zone (Reeves et al., 2014) and the sight-seeing of endangered marine mammals viewed in their iconic habitat is the very reason some tourists take part in these Arctic cruises (Lück et al., 2010). Cath, a researcher interested in vessel activities related to sea ice, points out some of these aspects during her interview:

> What is the purpose of shipping in the Arctic? […] Tourist vessels are maybe the only ones that are there to see the Arctic. […] With regard to cruise tourism, that is an area that could be challenging to regulate and look at because cruise ships do want to go to the ice edge. They want to see those marine mammals. They want to show their visitors those things. (lines 50-51, 98-100)

This reliance on sea ice by the tourist cruise industry is reflected in the number of tourist cruise ships operating throughout the year and across years. As Figure 6.8 shows, there are two peaks in tourist cruise vessel activities: one around May and another around September. The May peak shows that cruise operators carry out tourist activities when sea ice is not at its lowest (usually around September). In May, there is still a considerable amount of sea ice still present, and within relatively close reach before it retreats farther into the Arctic Ocean later in the summer. Therefore, sea ice, along with its associated Arctic megafauna, have become the trademarks of Arctic tourism and influence cruise ship behaviour in the Arctic (Stocker et al., 2020), similar to the patterns observable in the Bering Strait region.

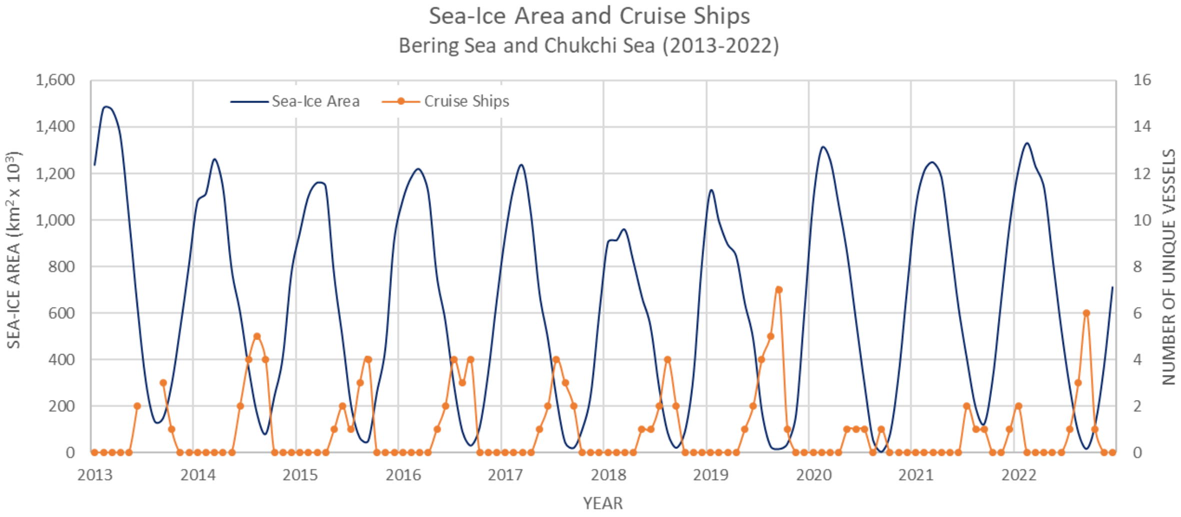

Figure 6.8 – Sea-ice area and number of cruise ships in the Bering and Chukchi Seas for the period 2013-2022. There is a regular peak in tourist cruise ship activities May, showing that cruise operators are interested in operating during periods when sea ice is still present. Summers of 2020–2022 show significantly reduced cruise ship activities as a result of the COVID-19 pandemic. AIS data from PAME (2022); sea-ice area data from NSIDC Sea Ice Index Version 3 (Fetterer et al., 2017).

As a result of these ice-dependant tourism pursuits, ships involved with Arctic cruise tourism have an interest in pursuing sea ice for the various 'last-chance' opportunities that it presents. The tourism industry closely relies on interactions with the marginal ice zone – as far as safety allows – as the further that vessels are able to sail into the ice, the more likely it is that they will spot the sought-after wildlife (Palma et al., 2019). This is clearly visible in the analysis of AIS tracks and sea-ice concentrations. For example, Figure 6.9 shows a Russian cruise ship as it pursues the sea-ice edge in the Chukchi Sea in June 2017. There are two aspects worth highlighting here that illustrate some of the ways in which sea ice shapes cryomobilities. First, the ship spends most of its time along the sea-ice edge. This can be seen in the top map in Figure 6.9, where the cruise ship visits two main sites at the sea-ice edge (one in the western and the other in the north-eastern Chukchi Sea), characterised by a squiggly track that suggests a loitering behaviour of sorts. This contrasts with the direct sailing path taken through open water that connects the two sea-ice-edge sites. Clearly, little time is spent transiting in open water, as there is no sea ice and therefore less chances of spotting wildlife associated with sea ice. This is in line with existing literature that emphasises the cruise industry's dependence on proximity to sea ice for viewing both sea ice and its associated Arctic marine life (e.g., Bystrowska and Dawson, 2017; Palma et al., 2019).

Second, the ship consistently follows the sea-ice edge, responding to its changes through time. This can be seen in the bottom maps in Figure 6.9, where the ship is able to visit areas on June 12 that became available as sea ice moved, and would have been very deep into the ice pack only a few days prior on June 8. This shows that whilst cruise voyages might follow an overall itinerary, the ship is constantly adapting its course on a small scale in response to changes in sea-ice cover. This suggests a desire to consistently be in an optimal setting for the purpose of viewing endangered Arctic icescapes and wildlife, whilst also staying safe. In fact, Stocker et al. (2020) point out that whilst fishermen mostly require sea-ice information about *where* the ice edge is, cruise vessel operators are requesting more detailed information about the *type* of sea ice in the area of their planned itinerary because it provides a sense of how deep into the marginal ice zone they might be able to venture. As such, sea ice offers an opportunity for tourist cruise ships, whose cryomobilities are characterised by the dual need for open water (for safe navigation) as well as the presence of sea ice (to provide experiences and sightings of sea ice, as well as the marine mammals and birds that rely on the sea-ice habitat).

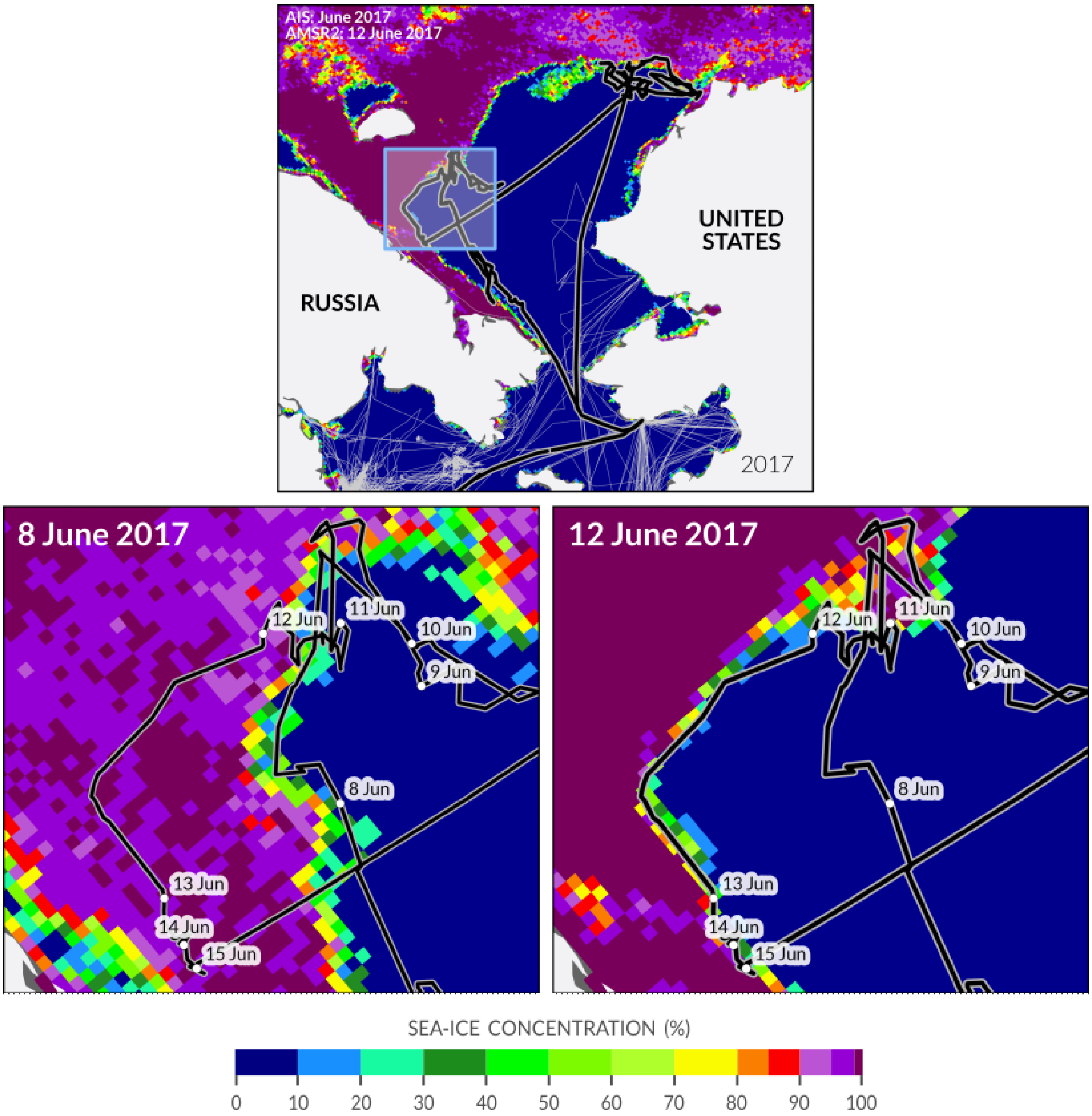

Figure 6.9 – A cruise ship track in the Bering Strait region mapped against sea-ice concentration in June 2017; ship tracks for the entire month of June 2017 are shown for context as thin grey lines (top). Detailed views of a portion of the cruise ship track in the eastern Chukchi Sea with sea-ice concentrations for 8 June 2017 (bottom left) and 12 June 2017 (bottom right). The cruise ship follows the sea-ice edge, as is clearly visible from the ship's tracks relative to sea ice in both bottom maps. Additionally, the ship adapts its course to follow the movement of sea ice, as shown by the differences in locations of the tracks between 8 June and 12 June: where the cruise ship went on 12 June was not accessible on 8 June due to dense sea ice. Source: AIS data from PAME (2022); sea-ice concentration data from Spreen et al. (2008).

6.5. Icebreakers: More Ships in More Sea Ice

The examples described above of drifting expeditions, fishing vessels and tourist cruise ships highlight the ways in which cryomobilities emerge out of a harnessing of the opportunities offered by sea ice and its mobilities. However, as the case studies above exemplify, different vessels harness the opportunities of the mobile sea ice to varying degrees, in a delicate balance between working *with* and *against* sea ice. After all, sea ice still remains an extreme and challenging environment within and in the proximity of which vessels operate. Icebreakers, for example, and their ever-increasing ice capabilities, rely on technological developments and shipbuilding advances to increase their ability to sail amidst increasingly ice-covered Arctic waters. As such, whilst icebreaker cryomobilities emerge less from an approach that seeks to move *with* the mobile qualities of sea ice, icebreakers nonetheless reveal another way in which vessel activities in the Bering Strait region co-exist alongside the presence of sea ice.

The sea-ice cycle and the corresponding annual vessel traffic patterns described in Chapter 5 reinforce the notion that overall, vessels avoid sea ice, and that navigation is preferable in its absence. In a general sense, this is true, as 95% of vessel activities do indeed occur in sea-ice concentrations of 0–15% (see Figure 5.21). However, for the portion of vessel traffic that *does* venture into icy waters, more vessels are spending more time in sea-ice concentrations above 5% or above 15% (Figure 6.10). This is the case when looking at the absolute increase in vessel traffic indicators (such as total sailing time), and part of this is because vessel traffic in the region is increasing overall (as discussed in Section 5.4.2). As such, it is useful to consider vessel traffic in higher sea-ice concentrations as a *proportion* of total vessel traffic each year to cancel out the overall traffic increase in the region. As Figure 6.11 shows, there is a lack of any significant trend in proportional traffic in higher sea-ice concentrations (above 15%), and vessel traffic in pack ice (96–100% sea-ice concentration, red line in Figure 6.11) is consistently higher than in other lower sea-ice concentrations. This means that despite the sea-ice decline in recent years, resulting in the more frequent and more extensive availability of open water, similar proportions of vessels are continuing to operate in all types of sea-ice conditions. In other words, there is not more vessel traffic *just in open water*; there is more vessel traffic *everywhere*. In fact, traffic in sea-ice concentrations of 0–5% (which is the single category that accounts for the largest portion of vessel traffic) is slightly decreasing as a proportion of total traffic (Figure 6.12). This means that vessel traffic is increasing more rapidly in areas of pack ice compared to areas of open water. Kapsar et al. (2023) also present similar findings for traffic trends in the Bering Strait region, showing that between 2015 and 2020, the total distance travelled by vessels in the marginal ice zone (sea-ice concentration 15–80%) increased by 14%, and increased by 17% in pack ice (sea-ice concentration 80–100%). For context and for comparability to research that employs the widely-used 15% sea-ice concentration threshold to distinguish open water from ice-covered water (e.g., NSIDC's sea-ice analyses or other Arctic shipping routeing analyses; Cavalieri and Parkinson, 2012; Sui et al., 2021), Figure 6.12 also shows that vessel traffic is proportionately declining in sea-ice concentrations of 0–15%. As these figures demonstrate, the fact that navigation is proportionately increasing in pack ice and proportionately decreasing in open water challenges the view proposed by the extensive literature on Arctic shipping as well as a multitude of Arctic shipping feasibility studies and models, which suggest that a decline in Arctic sea-ice will attract more vessel activities due to the greater availability of open water (e.g., Willoch and Ragner, 2000; Howell and Yackel, 2004; Wang and

Overland, 2009; Ho, 2010; Smith and Stephenson, 2013; Stephenson et al., 2013; Lasserre, 2015; Melia et al., 2016, 2017; Bennett et al., 2020; Stocker et al., 2020; Sui et al., 2021; Ryan et al., 2021; Cao et al., 2022; Li and Lynch, 2023; Min et al., 2023).

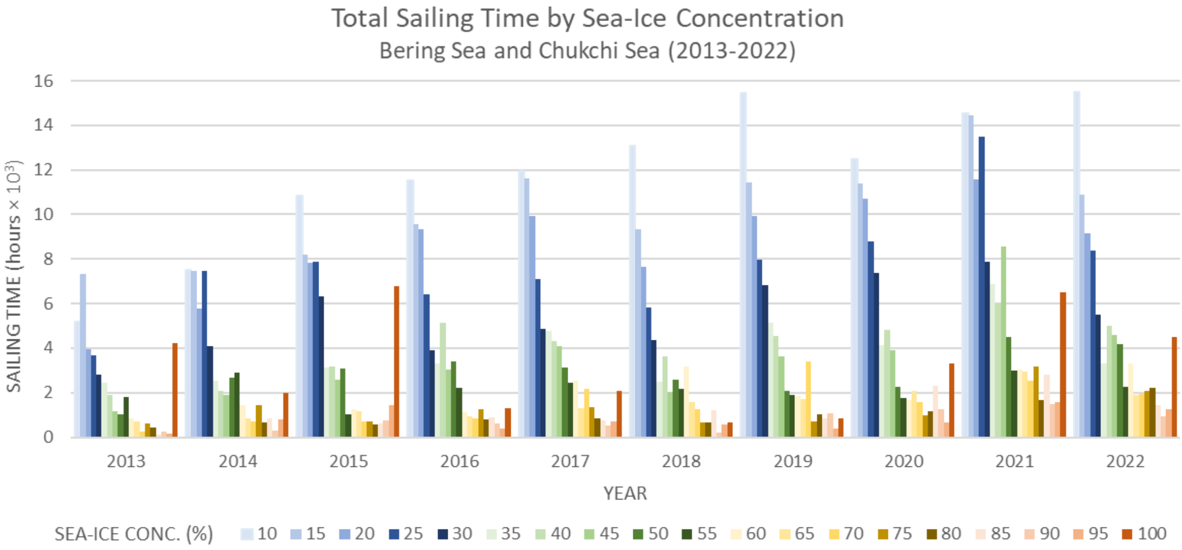

Figure 6.10 – *Total sailing time by sea-ice concentrations above 5% in the Bering and Chukchi Seas for the period 2013–2022. Whilst overall sailing time decreases as sea-ice concentration increases, there are unexpectedly high sailing times where sea-ice concentration at 96–100%. Also, there is a general increase in sailing time in all sea-ice concentrations in later years. Sea-ice concentration bands progress in 5% increments, and the stated sea-ice concentrations indicate the upper limit of each 5% band (for example, "100%" stands for "96–100%"). The lowest sea-ice concentration band (0–5%) is not shown, as its values are so high that it impedes visual clarity of the other sea-ice concentration bands. Source: AIS data from PAME (2022); sea-ice concentration data from Spreen et al. (2008).*

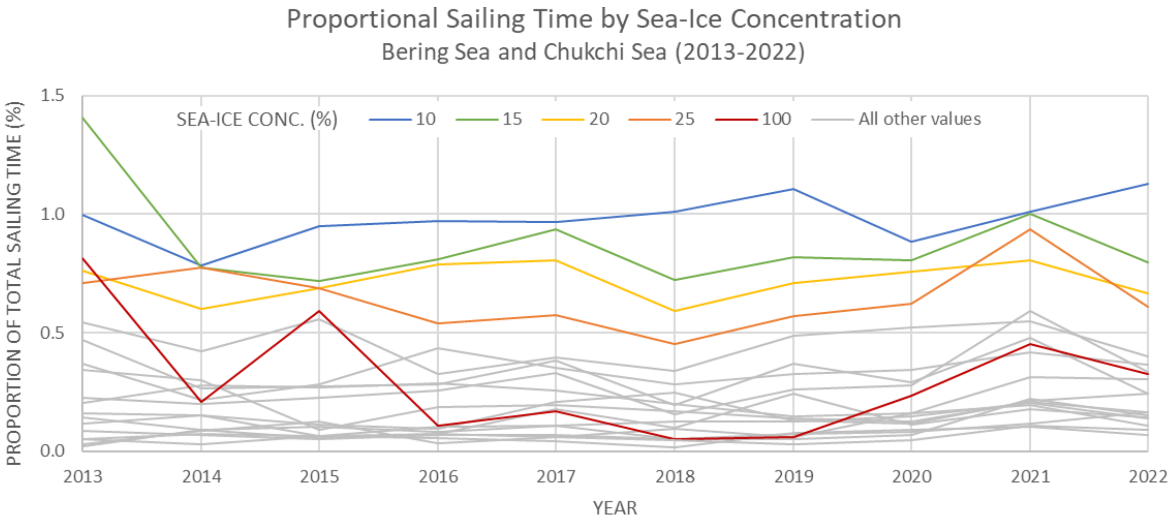

Figure 6.11 – *Proportional sailing time by sea-ice concentration in the Bering and Chukchi Seas for the period 2013–2022. Proportional sailing time in all sea-ice concentrations remains generally the same throughout the years, meaning that the overall increase in vessel traffic in the region is spread out equally across all sea-ice conditions. Traffic in sea-ice concentrations of 96–100% (red line) consistently accounts for a much higher proportion of traffic than several other lower sea-ice concentrations (grey lines). Sea-ice concentration bands progress in 5% increments, and the stated sea-ice concentrations indicate the upper limit of each 5% band (for example, "100%" stands for "96–100%"). The lowest sea-ice concentration band of 0–5%) is not shown (see*

Figure 6.12), as its values are so high that it impedes visual clarity of the other sea-ice concentration bands. Source: AIS data from PAME (2022); sea-ice concentration data from Spreen et al. (2008).

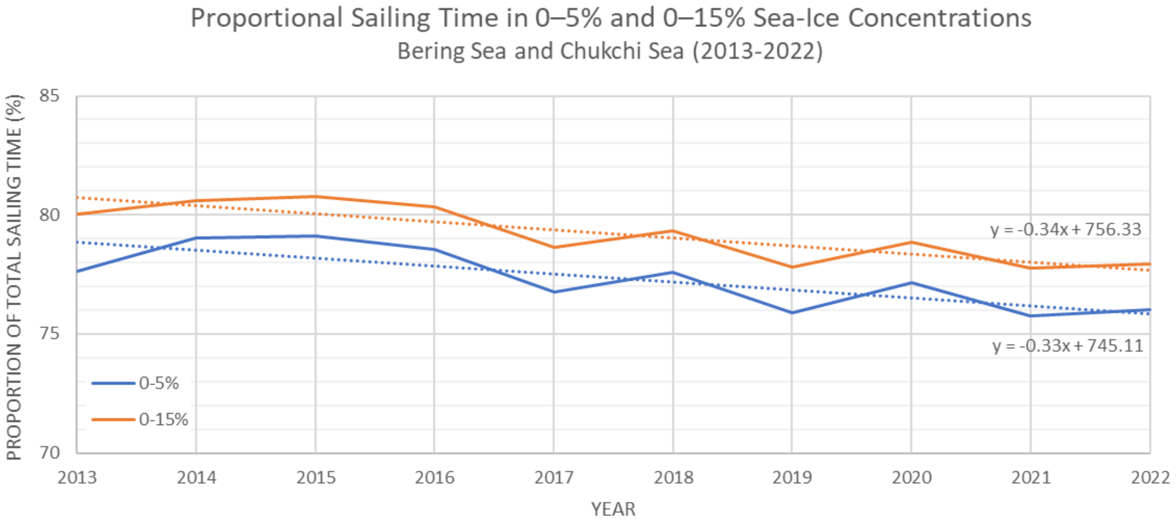

***Figure 6.12** – Proportional sailing time in sea-ice concentrations of 0–5% and 0–15% in the Bering and Chukchi Seas for the period 2013–2022. Sailing time in open water is decreasing as a proportion of overall vessel traffic. This is an extension of Figure 6.11, where the 0–5% sea-ice concentration band is not shown. Source: AIS data from PAME (2022); sea-ice concentration data from Spreen et al. (2008).*

In addition, within the overall trend that more vessels are spending more time in higher sea-ice concentrations, there is a distinctive peak in vessel activities in areas where sea-ice concentration is 96–100%. Figure 6.13 shows that the proportional sailing time spent in various sea-ice concentrations generally decreases as sea-ice concentration increases (this pattern is also clear in Figure 6.10 and Figure 6.11), which is to be expected based on the additional challenges associated with navigating in progressively ice-covered waters (as discussed at length in Chapter 5). However, there is a sharp rise in the amount of time spent in areas where sea-ice concentration is at 96–100%. This is the case across all years, but – with the exception of 2013 and 2015 – the increase is more pronounced in recent years, as highlighted in Figure 6.13. Existing research that looks at vessel behaviour when moving through sea-ice shows that vessels move more slowly through ice-covered waters than through open water (e.g., Tan et al., 2013; Melia et al., 2017). Vessels operating in ice-covered waters are also more likely to become beset in sea-ice, which in terms of AIS data manifests itself in long periods of time spent in these higher sea-ice concentrations (i.e., the total amount of time appears as a larger number, albeit the vessel not being in motion until it is rescued; Vanhatalo et al., 2021). As such, some of the additional time spent in 96–100% sea-ice concentrations could be attributable to these phenomena. However, there is also an increase in the *total number* of vessels sailing in areas where sea-ice concentration is 96–100%, as shown in Figure 6.14. Taken together (sailing time and number of vessels), this suggests that the increased vessel traffic observable in sea-ice concentrations of 96–100% cannot simply be attributed to the same number of ships moving more slowly, or being more often beset in sea-ice, but points to an actual overall increase of vessel presence in ice-covered waters.

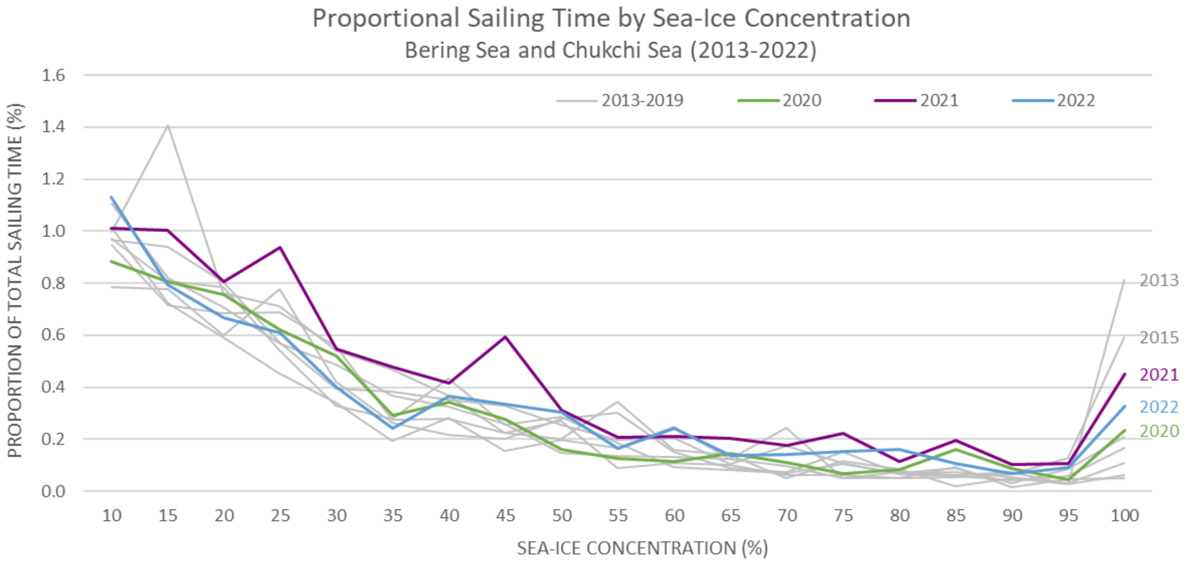

Figure 6.13 – Proportional sailing time by sea-ice concentration in the Bering and Chukchi Seas for the period 2013–2022. Whilst the proportional sailing time generally decreases as sea-ice concentration increases, there is a sharp increase in the highest sea-ice concentration band (96–100%). Sea-ice concentration band 0–5% is not shown for visual clarity. Source: AIS data from PAME (2022); sea-ice concentration data from Spreen et al. (2008).

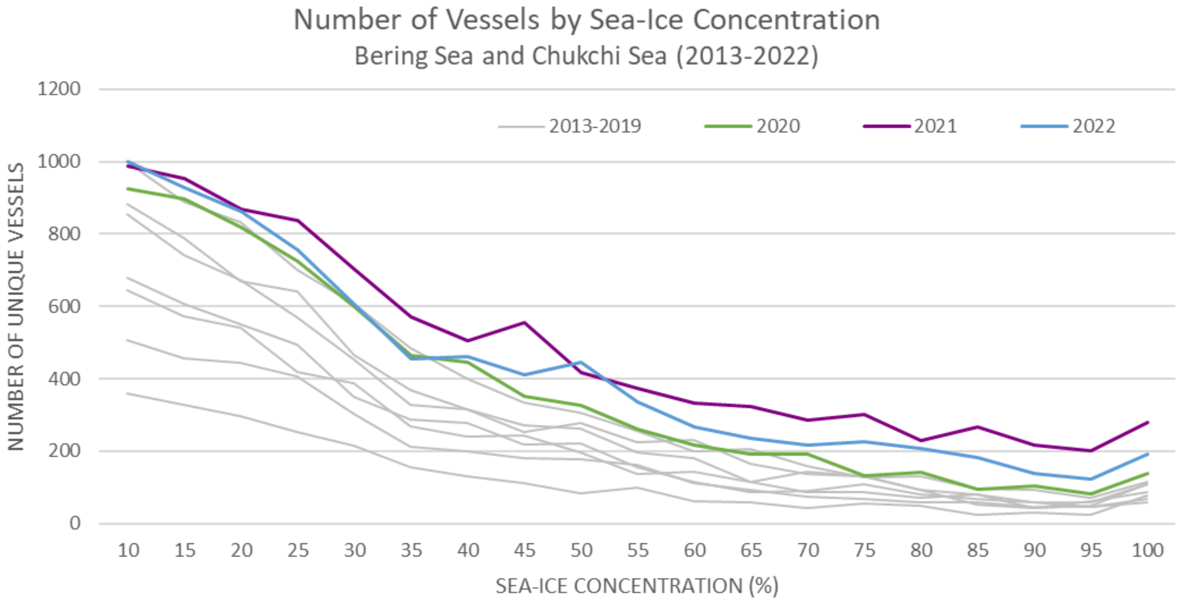

Figure 6.14 – Number of vessels by sea-ice concentration in the Bering and Chukchi Seas for the period 2013–2022. Whilst the number of vessels generally decreases as sea-ice concentration increases, there is an increase in the highest sea-ice concentration band (96–100%). Sea-ice concentration band 0–5% is not shown for visual clarity. Source: AIS data from PAME (2022); sea-ice concentration data from Spreen et al. (2008).

The increased navigation in higher sea-ice concentrations is more prominent in winter months. The biggest increases can be noticed starting in 2019 and peaking in 2021, in particular for the months of November–March (Figure 6.15). The years 2014 and 2021 offer a good comparison of vessel activities (taking 2014 as a year of low traffic, for example) due to the sea-ice conditions in these two comparison years. 2021 has significantly more extensive sea-ice cover than 2014, yet vessel traffic in higher sea-ice concentrations is still much greater in 2021 than in 2014 (see Figure 6.16). Comparing 2014 and 2021 shows that this increase occurs primarily along the Russian coastline in the Bering Sea and along the Northern Sea Route (Figure 6.16). A significant portion of the vessels that operate in these higher sea-ice concentrations have ice capability, demonstrated by their Polar Class status (Figure 6.17). To this day, Russia's fleet has the world's most powerful icebreaking ships, and is the only country in the world that owns and operates nuclear-powered icebreakers (Nilsen, 2019a). As of March 2023, Russia already operates eight nuclear-powered icebreakers and has commissioned an additional five to be built by 2035, whose designs supersede the power, size and ice-breaking capabilities of any of the world's existing icebreakers (Nilsen, 2019a; Staalesen, 2023)[24]. As such, the intensification of cryomobilities in the Bering Strait region is not exclusively centred around increasing operations during the (increasingly longer) summertime open water season, but also includes significant efforts to increase ice capability year-round and in higher sea-ice concentrations.

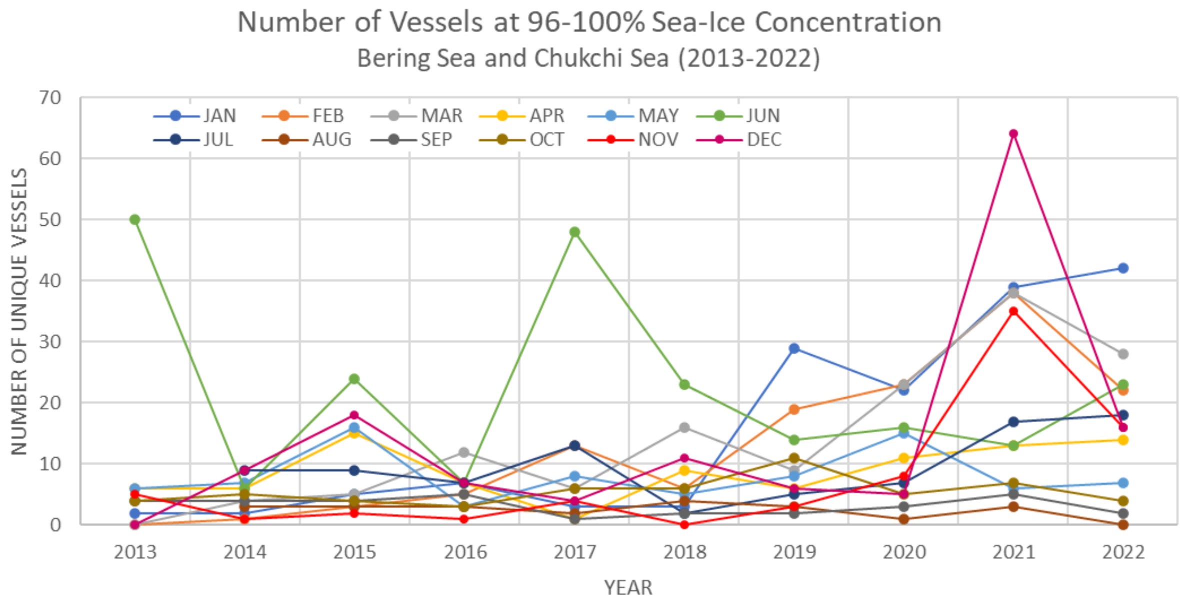

Figure 6.15 – Monthly number of vessels at sea-ice concentrations of 96–100% in the Bering and Chukchi Seas for the period 2013–2022. Source: AIS data from PAME (2022); sea-ice concentration data from Spreen et al. (2008).

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[24] Project 22220 (LK60Ya) operational icebreakers: *Arktika* (2020), *Sibir* (2021) and *Ural* (2022). Planned: *Yakutia* (2024; under construction), *Chukotka* (2026; under construction), *Kamchatka* (2028) and *Primorie* (2030). Project 105010 (LK120Ya) "Lider" planned icebreaker: *Rossiya* (2027; under construction). The "Lider" icebreaker class, twice the size and over 13 m wider than the Project 22220 fleet, can cut through sea ice up to 4.1 m thick, meaning these vessels can sail virtually anywhere in the Arctic at any time of year (Nilsen, 2019a).

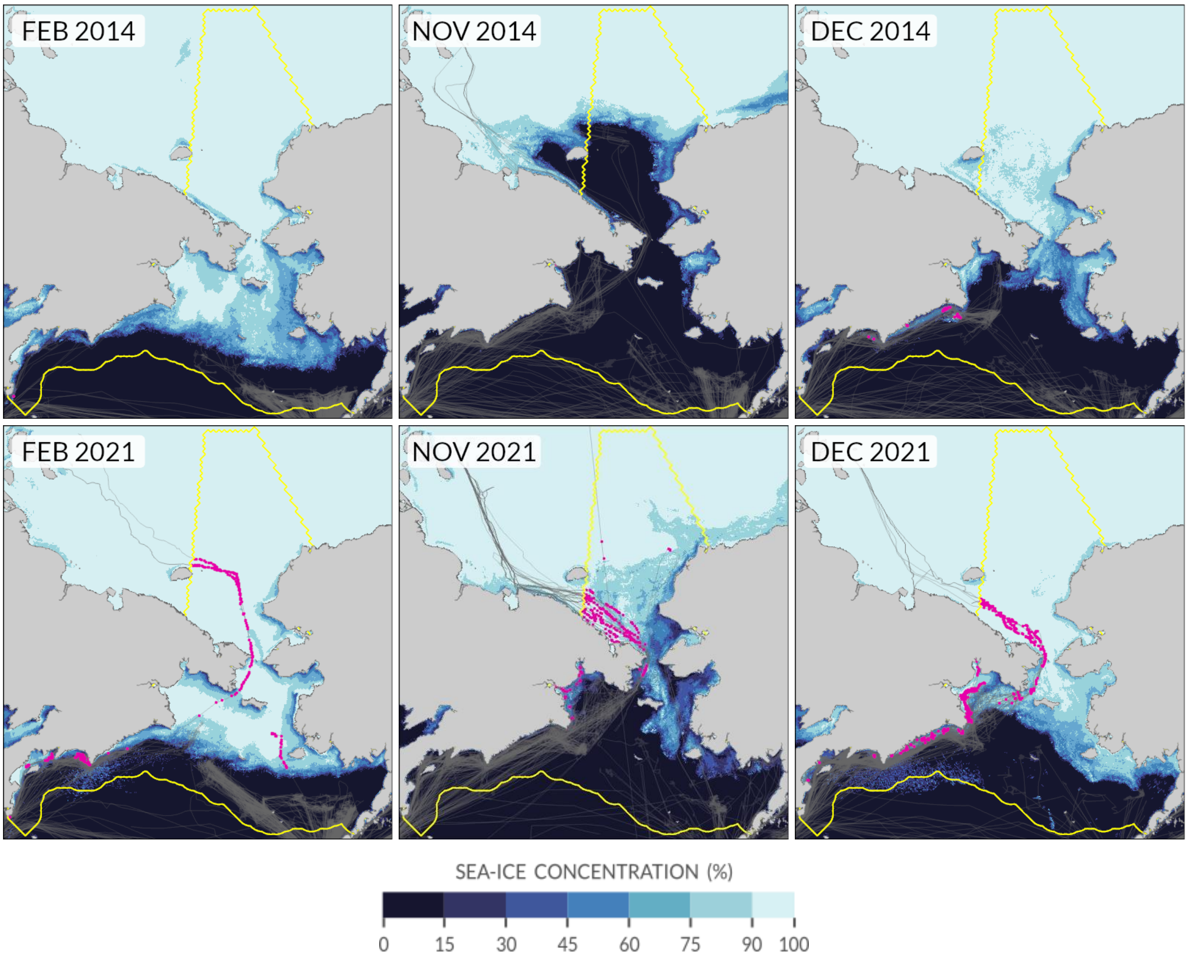

Figure 6.16 – Vessel pings that occur in sea-ice concentrations of 96–100% (pink dots) in the Bering Sea and Chukchi Sea shown for a selection of months and years for indicative comparison. Average monthly sea-ice concentration, total monthly vessel tracks (grey lines) and study area (yellow line) are shown for context. Sea-ice concentration values are calculated at each AIS ping location using AMSR2 sea-ice concentration for the same day as the AIS ping timestamp. Vessel presence in high sea-ice concentrations is increasing in recent years, particularly along the Russian coastline and the Northern Sea Route. Source: AIS data from PAME (2022); sea-ice concentration data from Spreen et al. (2008).

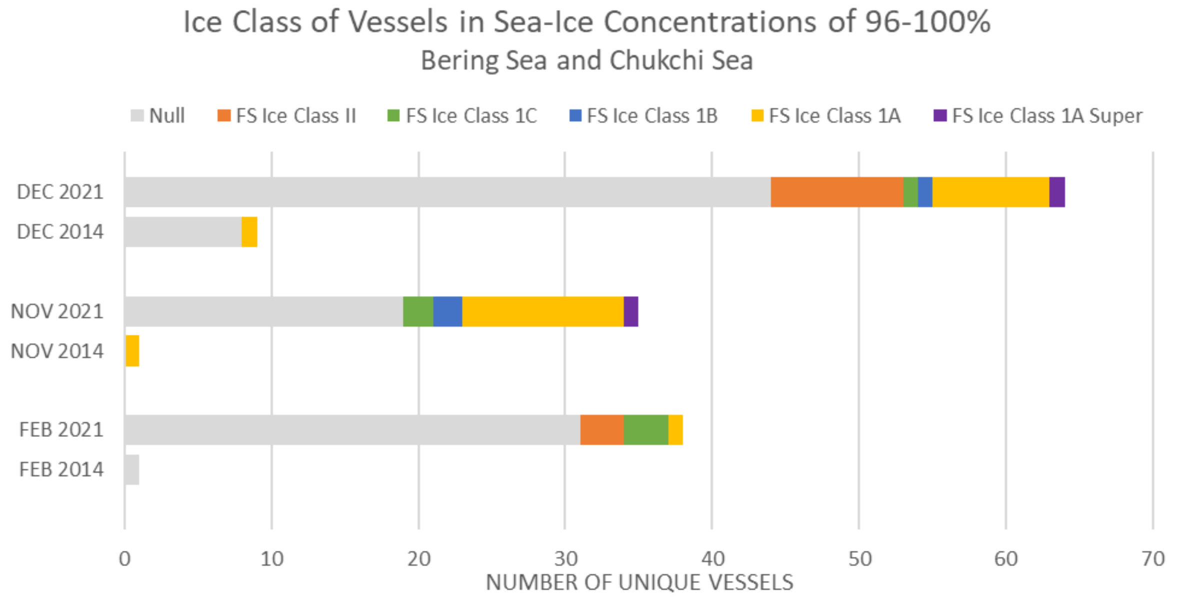

Figure 6.17 – Polar Class rating of vessels operating in sea-ice concentrations of 96–100% in the Bering and Chukchi Seas shown for a selection of months and years comparing 2014 and 2021 (same as Figure 6.16). A significant portion of vessel traffic in high sea-ice concentrations is by vessels with ice capabilities. Source: AIS data from PAME (2022); sea-ice concentration data from Spreen et al. (2008).

Whilst the world's most powerful icebreakers might be facilitating people's mobilities through the thickest sea ice in the depths of winter, these vessel activities also have negative impacts on other mobilities related to sea ice. For instance, Indigenous Arctic communities such as the Inuit and Iñupiat live along the coast and rely on sea ice as a platform for hunting marine mammals and as a 'highway' between communities (in some cases, travel over sea ice is the only route between villages; Inuit Circumpolar Council Canada, 2008). Icebreaker activities impact Indigenous ways of life related to sea ice in several ways. First, icebreaker activity alters the structural and material properties of sea ice. Icebreaker activity may cause sea ice to refreeze in a rubble mess, or not refreeze at all, potentially cutting off hunters' trails on their way home, requiring extra effort to cross the uneven path left by the icebreaker, or even alter caribou migration routes as they circumnavigate the areas of uneven sea ice (Laidler et al., 2009; Stammler-Gossmann, 2010; Inuksuk, 2011; Kelley and Ljubicic, 2012; Inuit Circumpolar Council Canada, 2014; Carter et al., 2018b; Dawson et al., 2020; Steinberg et al., 2023). Second, icebreaker activities impact the mobilities of marine mammals at the core of Indigenous subsistence. Icebreakers are loud (see also Section 7.3). Some have underwater bubbling systems which push away pieces of broken ice and reduce ice accumulation on the hull. Icebreakers also make crashing noises when repeatedly 'charging' the sea ice in an attempt to break through it, and their propellers make sharp, intermittent ramming noises when they get stuck in the ice. These noises mask cetacean communication, wellbeing, and migration (Erbe and Farmer, 2000; Wilson et al., 2017). Third, icebreaker activity can also disrupt seal and polar bear denning habitats, by flooding their dens with the waves from their wake (Carter et al., 2018b). These waves also endanger hunters, whose hunting boats are usually small and risk capsizing (Carter et al., 2018a). Finally, hunters' detailed local knowledge that keeps them safe whilst mobile amidst sea ice relies on learned environmental cues and the ability to read sea ice through its qualities such as colour, roughness, snow cover and so on. Icebreaker activity creates unnaturally deformed and jumbled sea ice making it more difficult for hunters to apply their knowledge to assess sea ice safely (Aporta, 2010; Eicken, 2010). Therefore, whilst the cryomobilities of icebreakers emerge out of the desire to solve issues of mobility amidst sea ice, they also contentiously disrupt other aspects of sea-ice mobilities, such as Indigenous subsistence livelihoods.

6.6. Conclusion

In this chapter, I have considered cryomobilities in the Bering Strait region in light of those vessel activities that are not deterred by sea-ice presence, as well as those where there is an active pursuit, or affinity, towards sea ice. Many cryomobilities in the Bering Strait region have developed alongside, or in co-existence with, sea ice and its mobilities, and in some cases emerge directly from the opportunities that the mobilities of sea ice present. Drawing on the analysis of AIS ship data, sea-ice concentration satellite data, interviews, and existing literature, I show how different users of icy watery spaces interact with sea ice in different ways, each with their own balance of repulsion and attraction towards sea ice. For Nansen, whilst him and his crew had to face extreme conditions on the ice and risk their vessel being crushed, the mobile nature of sea ice provided the answer to issues of navigation towards the North Pole that had halted other Arctic voyagers before him. Fishermen and crabbers face the harsh conditions of fishing during the coldest, iciest and stormiest winter months because they rely on the ecological plentifulness driven by the annual cycles of sea ice freeze and melt. Tourist cruise ships cannot show their tourists marine mammals that thrive in the marginal ice zone without navigating close to or even within sea ice, resulting in the emergence of 'last-chance' tourism dedicated to taking people to see sea ice and the Arctic wildlife that lives in the marginal ice zone. Finally, icebreaker technology and shipbuilding capacities continue to advance, creating icebreaking vessels that could move through any thickness of sea ice at any time of year. Therefore, sea ice shifts from existing exclusively in opposition to vessel activities, and instead becomes a source of co-existence and opportunity for vessel activities. These interactions all highlight that sea ice is constantly mobile in space and time. Sea ice moves, drifts, cracks, expels brine, melts and re-freezes, and the cryomobilities that unfold in these icy seascapes respond to and make use of these changes.

Sea ice is at the heart of the Bering Strait region ecosystem, driving processes that uphold one of the world's most biologically productive areas. The plankton, fish and marine megafauna that converge around this ecological abundance sustain human activities and cultures that rely on the existence of this rich ecosystem. Commercial fishing, Arctic cruise tourism and Iñupiat subsistence practices all rely (albeit in different ways) on the opportunities that sea ice makes possible.

Importantly, in this chapter I present two significant findings regarding the interaction between sea ice and vessel traffic over the past decade (2013–2022), as seen through AIS vessel tracking data and sea-ice concentration satellite data. Firstly, vessel traffic in ice-covered waters is increasing. This is both in absolute terms – as vessel traffic is increasing in the region overall – but also proportionately, as there are higher proportions of vessel activities taking place in areas of sea-ice concentrations above 15%[25]. Consequently, there is proportionately less vessel traffic occurring in areas of open water (where sea-ice concentration is 0–5% or 0–15%). Second, vessel traffic is not just increasing in ice-covered waters generally, but there is a more pronounced increase in vessel presence in pack ice (where sea-ice concentration is 96–100%). This intensification of vessel activities in pack ice is mostly during the winter months when sea-ice concentrations of 96–100% are more common, and this is attributable to ice-strengthened vessels, which are also increasing in number, presence and ice capability in the Arctic. In other words, there is not more vessel traffic *just in open water*; there is more vessel traffic *everywhere*. For example, this is in line with Russia's continued plans to expand their icebreaker fleet and increase wintertime ice capabilities along the Northern Sea Route (Nilsen, 2019a). This also supports Lasserre's (2015) argument that the feasibility of Arctic routes is no longer technical issue, but rather a question of business profitability. In this case, the business profitability manifests itself in Russia's expansion of icebreaking capacity, as this allows other vessels without ice capability to traverse the route while being escorted. These findings challenge a view often proposed in analyses of Arctic shipping feasibility and more broadly in (Western) conceptualisations of navigation in ice-prone waters: that sea-ice is such a hinderance to navigation that it is the increasing availability of open water that will attract additional vessel activities to the Arctic. Rather, this chapter demonstrates that Arctic waters in the Bering Strait region are becoming more accessible in all their forms, whether liquid, solid or anywhere in between.

Overall, the findings presented in this chapter emphasise the complex and evolving relationship between sea-ice dynamics and vessel traffic patterns in the Bering Strait region. The research contributes valuable insights into the interconnectedness of Arctic systems and challenges existing perspectives on navigation in ice-prone waters, where open water usually emerges as the preferred condition for sailing. Instead, this chapter proposes a less antagonistic conceptualisation of sea ice, acknowledging the multiple and diverse ways in which cryomobilities emerge alongside sea ice, and not just in opposition to it. Understanding these changing dynamics is crucial for policymakers, stakeholders, and researchers involved in Arctic marine transportation, resource management, and environmental conservation, in order to implement changes that reflect the current conditions and future trajectories of cryomobilities in the Bering Strait region.

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[25] Whilst 15% is a widely-used threshold for determining areas of ice cover (e.g., Parkinson et al., 1999; Parkinson and Cavalieri, 2008; Cavalieri and Parkinson, 2012), the analysis also considers a stricter threshold of barely 5% sea-ice cover to determine ice-covered water, which shows similar trends to the 15% threshold.

7

Cryology: Knowledges of Sea Ice and Vessel Mobilities

7.1. Introduction

The sea-ice system is complex and, as such, there is significant uncertainty around the precise mechanisms, drivers and feedbacks that impact its behaviour through space and time. Understanding the sea-ice system is fundamental for supporting safe and reliable navigation in ice-prone waters in the Bering Strait region, as well as more broadly throughout the Arctic. This chapter presents some of the ways in which various groups of people who interact with sea ice across a range of disciplines and lifeways come to understand sea ice and its mobilities. Subsequently, these various ways of knowing shape the ways in which cryomobilities unfold in the Bering Strait region.

In a broad sense, in this chapter I reflect on the various ways in which knowledge about sea-ice and its mobilities is produced, looking at forms of knowledge production that aim for objectivity and reliability (such as scientific sea-ice products and operational sea-ice forecast charts), as well as other knowledge approaches that rely on direct encounters with sea ice and the expert subjective and embodied synthesis of information gained through such experiences (such as the intimate knowledge of sea-ice behaviour held by skilled boat captains, or Indigenous hunters). As I emphasise in this chapter, sea-ice knowledge emerges through a combination of highly specific personal expertise, and rigorous collection and analysis of scientific data about sea ice. As a result, sources of information about sea ice that are typically considered to hold a significant level of objectivity and trustworthiness (e.g. sea-ice forecasts), are inextricably tied to the human subjectivities of the people involved in their production (Seddon, 2022). Likewise, practical navigational endeavours that often involve subjective knowledge gained through personal encounters with sea ice, are also heavily informed by scientific understandings of sea-ice dynamics. In turn, this melange of understandings and knowledges about sea ice shapes attitudes towards navigation and, subsequently, cryomobilities in the Bering Strait region.

First, drawing on insights from the interviews, I point to some of the concerns within the scientific sea-ice community regarding better understanding the complexities and uncertainties of sea-ice processes (Section 7.2). The ambiguities and unknowns within sea-ice science pose challenges in other applications, such as providing reliable operational sea-ice forecast charts. In turn, these complexities and uncertainties in understanding the sea-ice system trickle down to the demanding realities of navigating in icy waters. Second, in Section 7.3, to complement scientific understandings of sea-ice dynamics and feedback mechanisms, I look at embodied experiences and encounters with sea ice, which contribute to knowledge production and the process of making sense of the complexities of the sea-ice system. Within this section, I also consider some of the ways in which embodied encounters with sea ice are mediated, for example by experiencing sea-ice mobilities through the ship. Finally, in Section 7.4, I elaborate on subjectivity and the value of ‘the expert’ in bringing together the more objective forms of sea-ice knowledge (such as sea-ice science and operational sea-ice charts described in Section 7.2) with the more subjective ways of knowing the ice (such as through embodied encounters as discussed in Section7.3). At this intersection of knowledge production, sea-ice experts shape sea-ice knowledge and, in turn, the cryomobilities that unfold in the Bering Strait region.

Within the context of this chapter, I situate these diverse ways of knowing within a theoretical understanding of embodied and sensuous experiences of mobilities (e.g., Rodaway, 2002; Cresswell, 2011). The challenge of commensurability between concurrent and competing knowledges is not a metaphysical issue at a high level of theoretical abstraction; rather, it emerges directly from real-life practical clashes with existing knowledge structures and how these knowledges come to co-exist (such as the long-standing issues of knowledge co-production between Western and Indigenous views; e.g., Nadasdy, 1999; Bering Sea Elders Group, 2019; Yua et al., 2022). This contention is active in everyday realities and remains active in how these realities produce understandings of cryomobilities. As such, I consider the body as a site of knowledge production (Rodaway, 2002; Sheller, 2004; Cresswell, 2006, 2011; Sheller and Urry, 2006; Adey et al., 2012; Merriman, 2019). As Doughty and Murray (2016) argue, the materialities of everyday embodied engagements with mobile objects is important for understanding dominant discourses of mobilities. Consequently, in agreement with Doughty and Murray, I maintain that “locating subjectivity in the body is not an essentialist position but an understanding of subjectivity as arising from lived and complex experience within multiple discourses and physical positions” (2016: 305).

In order to better situate the ways in which bodies make sense of the surrounding ocean, it is also fundamental to acknowledge the ways in which these encounters are mediated not just by the body itself, but also by the various technologies that accompany these bodies and make their endeavours of producing knowledge about the ice-prone ocean possible. Drawing on approaches within science and technology studies, this chapter explores some of the ways in which scientific and technological practices of knowledge production are socially situated. Sea-ice forecasters, sea-ice scientists and seafarers all rely on a plethora of tools and technologies to make their work possible, from hats, gloves and thick insulating coats, to satellites, powerful computers and icebreaker vessels. As this chapter demonstrates, these tools and technologies are situated within social practices and historical contexts, resulting in the production of knowledge about sea ice and the ocean as co-constituted by the material presence of these tools and the people who employ and rely on them (Goodwin, 1995; Lehman, 2018; Crockford, 2020). Spaces are iteratively constituted through the actions that both make use of the structures in place (such as the ice-prone ocean), while simultaneously articulating and shaping them into meaningful objects or entities suited to the activity or scientific endeavour in progress; in other words, the concrete places where science is done has consequences for the knowledge that is produced there (Goodwin, 1995). These ways of 'seeing' are situated not just in the material technicalities of the equipment itself (e.g., the warmth of one's gloves allowing one to operate equipment in frigid Arctic conditions), but also in the political histories and theoretical developments of a particular field that have prioritised what is important to 'see', and have subsequently developed the technologies that make these ways of 'seeing' possible (from spaceborne satellites to well-equipped icebreaker research vessels) (Gabrys, 2019; Lambach, 2022; Eiterjord, 2024). Through this lens, this chapter sheds light on the ways in which the diverse perspectives on the mobilities of sea ice, vessels and subjects expressed by the interviewees in this chapter coexist, inform each other, are shaped by the presence and use of technologies and, ultimately, shape cryomobilities in the Bering Strait region.

7.2. Uncertainty and Complexity

The sea-ice system is complex, as it is tied to a wide range of environmental conditions that influence its cycles of formation, movement and melt, which makes understanding its behaviour challenging. As discussed in detail in Section 3.4, sea-ice behaviour in the Bering Strait region is heavily dependent on wind conditions, which can both help advance or break up existing sea-ice cover (Pease, 1980; Stabeno et al., 2012a; Stabeno and Bell, 2019). In addition to wind, a host of other factors also interact with sea ice to determine its spatial and temporal patterns. Due to the vast array of sea-ice drivers, as well as the complicated interactions between them, many uncertainties remain around the precise mechanisms of sea-ice behaviour. As such, sea ice is situated within an extensive and intricate web of mobilities that impact its behaviour across days, seasons, years and decades, and not all of these are fully known.

During the interviews, there was a strong acknowledgement of the complexities of the sea-ice system, as several participants discussed a multitude of factors that influence the observed patterns in sea-ice cover. These included wind speed and direction, ocean currents, salinity, snow cover, water column temperature, air temperature, dark algae cover increasing sea-ice surface melting, bathymetry, the shape of the coastline, and storms (e.g., interviews with Daniel, Eileen, Matthew and Paul). The interactions between these atmospheric, oceanographic and environmental drivers of sea-ice change create feedback loops which are still not fully understood, and which might drastically affect sea-ice change in the future. For example, when asked about the next big steps in sea-ice science, Francis, a sea-ice geophysicist, describes some of the unknowns in sea-ice science:

> I think some of the other big questions are the feedback […] to the climate system. The ice albedo feedback we've known about for a long time, but another question is, […] how is the circulation of sea ice going to change as it gets thinner? In really broad terms, as the ice gets thinner, it's going to move faster with the same wind. And there's already observations to support this – wind hasn't been observed to increase in the Arctic, but ice velocity is. And so that's saying that, well, the same wind is now making the ice move faster than it used to be. […] If the ice is thinner, it's just easier to push around, it’s not as stiff as thick ice would be. And so, if the ice is moving faster, […] I described how sea ice can act like a teaspoon in a teacup, so now you've got more mixing taking place in the ocean. And one of the unique features of the Arctic Ocean […] is it's quite highly stratified at the surface. There’s a cold, fresh layer that sits on top of a warm salty layer. And there's enough heat in that warm, salty layer to melt all of the ice many, many times over. So, […] if you could mix the top vigorously enough to overcome that stratification, then that's something that could be another significant feedback […] that we don't understand. That's one of those things that could become a tipping point that we don't know about. (Francis, lines 273-288)

Here, Francis is pointing to the dynamic interactions between interconnected forcing mechanisms that impact sea-ice behaviour which, taken together, might lead to unexpected tipping points in sea-ice change. Importantly, Francis realises that questions such as these remain unanswered, and that there is not sufficient knowledge to fully grasp all the possible mechanisms that might create positive feedbacks for sea-ice change in the near future. Better understanding these mechanisms and the interactions between them is an imminent priority within the science field of sea-ice modelling (Blockley et al., 2020; Hunke et al., 2020).

An example of efforts to better understand sea-ice dynamics is the Sea Ice Prediction Network (SIPN), a collaborative community of scientists and stakeholders that aims to improve existing methods of sea ice forecasting and prediction (SIPN, 2023). Since 2008, SIPN has been running the Sea Ice Outlook, which compares sea-ice predictions for Arctic September sea-ice minima, in the form of submissions from any sea-ice modeller or institution wishing to take part. The resulting seasonal reports collate and compare the various sea-ice predictions (e.g., Figure 7.1), provide in-depth analyses of factors driving sea ice, and explore the scientific methods for predicting seasonal ice extent. Other recent efforts in sea-ice modelling feature the introduction of machine learning to progressively fine tune interactions between various sea-ice forcing mechanisms and assess performance against observed sea-ice conditions (e.g., Andersson et al., 2021). These efforts are a testament to the complexity of the sea-ice system, and demonstrate that sea-ice modelling continues to be a rapidly evolving field in response to the overall necessity of gaining a better understanding of sea-ice dynamics for more reliable forecasting.

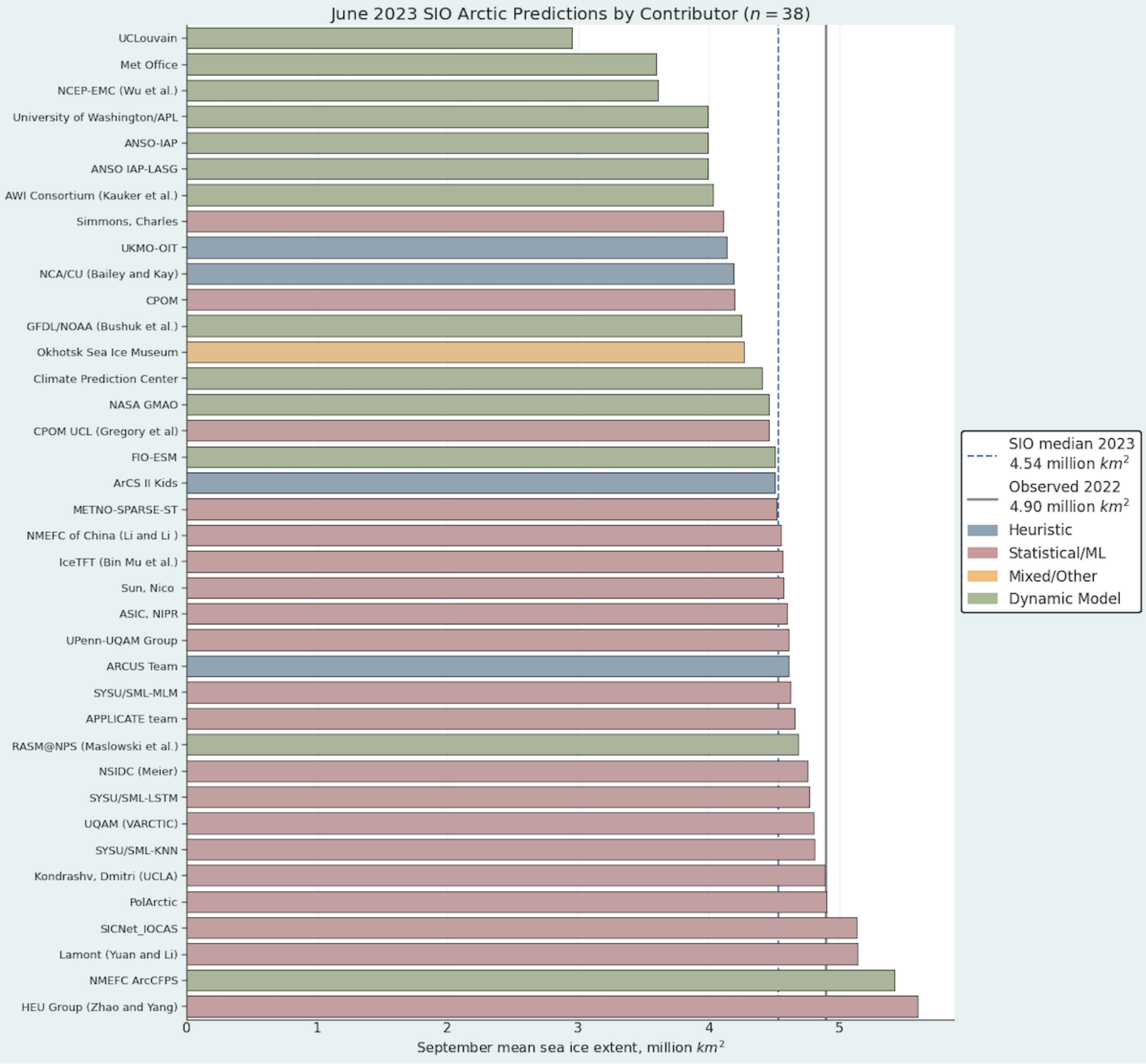

Figure 7.1 – Example from the June 2023 Sea Ice Outlook report by the Sea Ice Prediction Network. Distribution of Sea Ice Outlook contributors for June estimates of September 2023 pan-Arctic sea-ice extent. Solid line indicates observed sea-ice extent to assess models' performance. Source: Meier et al. (2023).

Adding to the complexity of trying to better understand sea-ice behaviour is that the mechanisms driving sea-ice dynamics are also rapidly changing due to climate change. As sea-ice is becoming more variable and mobile (Rampal et al., 2009), forecasting needs to be able to reflect these changes

(Eicken, 2013). As such, current understandings of sea-ice patterns are having to keep up with these changes. Stewart, who used to work as a sea-ice forecaster, as well as Francis, both talk during their interviews about how existing knowledge of sea-ice drivers requires constant revising:

> Back in the day, I don't think it ever occurred to us to [ask]… well, how is the late summer Bering Sea ocean temperatures going to affect sea ice? I don't think anyone ever thought about that because water temperatures were cold enough that the ice conditions will be driven by whatever the winter weather brings. It's clear that's no longer the case, that the heat build-up – the heat that's in the water in the late summer and fall – is now delaying ice development. The same weather patterns that 40 years ago would have produced plenty of ice, now that that cold is going into cooling the water before the ice can form. And I've done some work on that, and there's a reasonable correlation between late summer northern Bering Sea water temperatures and the following season's ice extent. (Stewart, lines 241-248)

> Our knowledge of sea ice at both poles expanded rapidly [in the seventies and eighties]. And now it's becoming increasingly apparent that the lessons learnt during the seventies and eighties just aren't as applicable anymore. The ice pack is different than it was then, and that's largely because it's more composed of annual first year ice than perennial multiyear ice. And so, our computer models aren't tuned the right way. (Francis, lines 161-164)

Both Stewart and Francis identify that sea-ice science needs to be a fast-moving field in order to keep up with the way that sea ice and ocean water temperatures are changing, particularly in response to climate change. As such, the mobile and changing nature of sea ice, not just on short timescales but through decades, means that knowledge about sea ice not only needs to expand to encompass all the interactions between various interconnected sea-ice drivers, but the existing knowledge also needs updating to reflect current sea-ice conditions and dynamics as they continue to be affected by climate change.

Due to the challenges involved in fully understanding not just the driving mechanisms of sea-ice change, but also the interactions between them, sea-ice forecasting is currently not as good as it needs to be in order to sustain safe and reliable navigation in icy waters. During the interviews, several participants brought up the issue of unreliable sea-ice forecasts for navigation as an area that needs advancing. Francis, who worked for many years in weather forecasting, has a deep appreciation for the importance of accurate forecasting especially for Arctic shipping activities, as he describes in the following interview excerpt:

> Better predictions is something that's strongly needed for a wide range of planning [purposes]. […] For example, we can't forecast sea ice with nearly the precision that we can forecast weather these days. […] It would also be helpful to be able to predict how severe an ice season is likely to be. If shipping is really going to take off in the Arctic, then at the least we're going to need six months forecasts, reliable six-month forecasts, of what ice conditions are going to be like. (Francis, lines 267-272)

Here, Francis alludes to the fact that there is sufficient understanding of the mechanisms involved in weather systems to ensure that weather forecasts are reliable. Sea-ice processes, on the other hand, need to be better understood before *reliable* sea-ice forecasts can be made. Similarly, Simon, who used to monitor live traffic in Alaskan waters, presents some insights into the realities of providing logistical support to vessels transiting through ice-prone waters without the availability of suitable sea-ice forecasts:

> It's hard to predict where the ice was going to be, and a week after a vessel's left China or some far distant port, by the time they get up into the Arctic, seven or eight days later, conditions could be completely different. And they have the tank full of fuel, they're going to do everything they possibly can to get through it and deliver it, they don't really have a second option. (Simon, lines 20-23)

Simon's perspective brings attention to the ways in which an overall lack of accurate sea-ice forecasting capacity causes problems for navigation in ice-prone waters. Hannah, a filmmaker interested in sea ice and the Arctic, brings Simon's concerns to life as she shares her experience from being on a research icebreaker off the northern coast of Russia:

> On [that research cruise expedition] there was so much more ice than they thought. I was told I wasn't going to see any ice, that's what the satellites predicted. So, there's so much ice that we had to change directions all the time. […] That's what was so confusing about [it], was that there were all these forecast charts that were forecasting no ice, but there was a shit-ton of ice. So you're like, How did they get that so wrong? […] It was *the* main question unanswered for me, which was like, I don't understand how everyone told me there was going to be no ice, and then all we have encountered is ice. […] I know models are [imperfect], that's why we need the data. But I mean, from no ice to all ice, that is a big swing. (Hannah, lines 260-262, 715-716, 735-737)

As Hannah points out, unreliable sea-ice forecasts result in unexpected sea-ice encounters which interfere with the planned route and requires making changes in order to account for the actual sea-ice conditions. As such, the temperamental nature of dealing with inaccurate sea-ice forecasts leads to finding other means of communication for acquiring sea-ice information for navigation, as Cath shares during her interview:

> When we were coming south, we passed a ship going north and I was on the bridge and the ship called over and was asking about local conditions. What's it like up north? Like, you know, was there any ice, is there any storms? And so, it reinforced to me [that] this area is still very, very remote, there's no Google Maps traffic telling you what like, in 20 miles there's going to be a jam or whatever [*unintelligible*] in the ice. People are still relying on communication between ships that are next to each other or just looking yourself at the area. (Cath, lines 269-274)

Together, these perspectives reveal the complexity of the sea-ice system and the multiple interactions and feedback mechanisms related to other driving factors that make it a challenging system to fully understand. In turn, this impacts forecasters' ability to accurately predict future sea-ice behaviour. This has consequences for shipping operations in the Arctic, as unreliable daily sea-ice forecasts, as well as the lack of longer term (e.g., seasonal) forecasts impedes dependable route planning and ship scheduling. As Funtowicz and Ravetz (2020) point out, the high risks and large potential impacts of global environmental changes confront traditional science with greater and greater uncertainties, which it is unable to neutralise through conventional approaches. As such, knowledge of the sea-ice system for the purpose of navigation can only partially come from scientific and forecasting understandings of sea-ice mechanisms and, therefore, as the next sections discuss, must also come from embodied knowledge and personal judgement gained through encounters with sea ice.

7.3. Embodied Encounters and Mediation

People who interact with sea ice develop knowledge about it through their experiences of embodied sensorial encounters with sea ice. This subjective and qualitative knowledge complements quantitative knowledge of the geophysical complexities of sea ice and the understandings of predicted sea-ice behaviour gained from sea-ice forecasting services. On the one hand, sea ice inspires a sense of the sublime and feelings of awe and fascination towards this epic seascape. Matthew, a marine biologist who spent many years living and hunting with the Iñupiat community on Ugiuvak (King Island), was enthused to be interviewed about sea ice: “You know, it's like the neatest plastic you've ever seen in your life. […] I'm excited about ice, you can tell. […] I mean, I love it” (Matthew, lines 326-333). He went on to describe the spring algal blooms, “And the timing of its {blooming} fshwhuuu [*Matthew makes a sound similar to fireworks flying into the sky*], you know, it's beautiful” (Matthew, lines 401-402). As he recounted this and made the sounds that to him represented the algal blooms, he was allowing himself to be transported to a different place, his gaze off into the distance of his own memories. Similarly, Eileen, a now retired marine scientist who participated in countless research cruises in the Bering Sea to study biological oceanography related to sea ice, also expressed her appreciation for sea ice. When I asked her, “Does sea ice ever get boring? Do you become desensitised to sea ice?”, she replied, “I have not. *Haha* I’m always happy to have anything to do with it” (Eileen, lines 216). Through accounts such as these, participants articulated a sense of appreciation and enjoyment of sea ice as intriguing and beautiful.

On the other hand, encounters with sea ice also prompt feelings of fear and caution. Even participants who overall enjoyed being involved with sea ice expressed mixed feelings about the dangers that sea ice brings. Paul is a sea-ice scientist who has been involved in setting up camps on sea ice 200 miles off the northern coast of Alaska for scientific experiments and military training. When I asked him “How does it feel to be on a camp on sea ice?”, he said, “I enjoy it. I find it relaxing, actually. But some people can't take it. And it does… there are storms which can get scary and it's a lot of work” (Paul, lines 212-213). Similarly, Matthew reminisced about the years he spent alongside the Iñupiat hunters on Ugiuvak (King Island):

> There was a pride in their ability as being the best sea ice hunters there were. [Mainland folks would say,] They know the best. They were respected. And there was high loss rate, very high loss rate. [*unintelligible – his tone implies a snippet of a sad memory*]. (Matthew, lines 595-597)

Here, Matthew points to the difficulties that come with relying on sea ice for subsistence and everyday survival. The fact that the Ugiuvamiut (inhabitants of King Island) felt "pride" and "were respected" in their capacity to successfully hunt on sea ice suggests that this was no easy endeavour, and the associated "high loss rate" compellingly portrays sea ice as an unforgiving force to be reckoned with. Eileen, too, describes navigating in sea ice during a storm as "terrifying" (Eileen, line 133). Matthew and Eileen are not the only ones to have developed a sense of fearfulness for the ice, as Stewart shares a similar feeling in the following excerpt:

> *Interviewer:* You mentioned that your sea-ice [forecasting] career started in Nome where you were able to observe sea ice and experience that. How do you think that impacts your ability to understand sea ice […]?
>
> *Stewart:* Well, there's the obvious things like, I lived it, walked around on the sea ice, saw Iditarod mushers coming in on the sea ice. […] But I think there's another maybe more visceral aspect to it, too, you know. In my mind, I can still hear the grinding of the ice as it was down on the beach in the spring. The ice was starting to break up, but it wasn't broke up yet, but the ice was moving up and down the beach and you could hear that grinding. And that's a very kind of gut level experience, but it's very moving, and it's very… it conveys the power of the ice. (Stewart, lines 186-195)

Stewart's account demonstrates the ways in which he feels and understands sea ice on a deep "visceral" level. Despite his career in providing sea-ice forecasts – a very desk-based and objective job – his close encounters with the movements and sounds of sea ice inform his appreciation for sea ice in a way that goes beyond the mere geophysical qualities of sea-ice dynamics. Similarly, Matthew also mentions his encounter of the dramatic reverberations that sea-ice movement produces, saying that, "I wish you could experience what a really crashing sounds really strong ice movement is. You wouldn't believe it" (Matthew, lines 315-316). These accounts point to the importance of being attentive to the everyday sensorial embodied practices of mobilities; how we experience the world and in return shape it (Cresswell, 2011). As such, sensorial experiences that evoke fear, respect and awe for the ways in which sea ice moves, drifts and breaks up inform understandings of sea ice and its mobilities.

Similar to Stewart's "visceral" knowledge gained through bodily exposure to sea ice and its mobile behaviour, coastal Indigenous Arctic peoples have been developing knowledge about sea ice and its mobilities for millennia. For coastal Iñupiaq communities, sea ice is a site of culture and embodied learning through experience, where knowledge is passed down through generations (Aporta, 2010; Eicken, 2010; Krupnik et al., 2010). As a demanding environment, sea ice teaches important life lessons of patience, hard work, respect, attention to detail and calmness in making decisions (Watt-Cloutier, 2015). Indigenous ways of knowing, and ways of passing on this knowledge, are deeply rooted in practice and experience, making time spent moving over, through and with it – thereby exposing the body to its complex mobile character – an indispensable component of traditional Iñupiat life and its associated cryomobilities (Eicken et al., 2014). This is reflected in the Iñupiat language, which includes extensive terminology to describe sea ice in minute details, including the processes through which it forms, its movements, and its various stages though the annual cycle (Krupnik et al., 2010). Mastering this knowledge and being able to use sea ice to provide for one's family and community contributes to wellbeing as part of what it means to live a fulfilling life as an Indigenous person (Durkalec et al., 2015). These entanglements reveal that sea ice itself matters for the possibilities that it offers materially, culturally and spiritually (Durkalec et al., 2015; Huntington et al., 2017). Therefore, through the lens of Iñupiaq lifeways, sea ice and its mobilities become known through bodily experiences.

In turn, the sensorial connections with sea ice that are forged during these encounters can help to inform navigation in ice-covered waters. During her interview, Eileen recollects that once, on a research cruise, "I made one captain of the NOAA ship *Oceanographer* go 50 miles into the sea ice, solid ice. And we spent the whole night coming out of there, big bangs. And he wouldn't speak to me after that. *Haha*" (Eileen, lines 88-89). Whilst Eileen tells this story somewhat flippantly, it demonstrates the role of personal judgement gained from experience in informing navigational encounters with sea ice. After having successfully manoeuvred the vessel through pack ice, the captain's silent protest against Eileen suggests a personal connection to sea ice, perhaps one of respect and caution, informed by previous experiences of navigating a ship amid sea ice. This is reflected in official documentation which provides guidance to captains operating vessels in sea ice. For example, the Canadian Coast Guard's official manual for ice navigation in Canadian waters states that "Ice is an obstacle to any vessel, even an icebreaker, and the inexperienced navigation officer is advised to develop a healthy respect for the latent power and strength of ice in all its forms" (Canadian Coast Guard, 2022: 88). As such, cryomobilities are shaped by personal perceptions of sea ice, and how knowledge created through embodied experiences of the mobilities of sea ice informs personal judgement, alongside a sense of respect for the might of the ice, and an appreciation for caution during navigation.

Whilst these qualitative judgements based on embodied experience convey a feeling of direct encounter and closeness to sea ice, it remains a challenging and inhospitable environment for people to be in. Encountering it, therefore, is often mediated by the auxiliary amenities and equipment that make survival in its midst possible. As Steinberg (2014) points out, our encounters with the ocean are always mediated, as human survival and one's interpretation of the surroundings rely on outside resources such as scuba equipment, diving masks, boats and so on. Specifically, in the context of cryomobilities, one is separated from the frozen ocean environment through the sensorial mediation of the vessel and other protective personal equipment. Hannah recounts her experience aboard a research icebreaker spending most of its time in the ice pack:

> There was also a lack of direct encounter with it. You're wearing goggles to protect your eyes from the wind, you're wearing hats that cover your ears from the sound, your feet, your mouth is covered with… your hands are covered in gloves. You're not touching, smelling, tasting. One of the big, exciting things is when everybody tastes the ice, you know? And it's like, oh my God, it's salty! Yeah, it's the ocean, duh. But almost everyone's shocked by it because up until then, you're not really directly encountering it. (Hannah, lines 127-132)

In addition to clothing obstructing the senses, the ship plays an important role in mediating encounters with the surrounding sea ice. Hannah continues her account, as she shares how the ship becomes the primary way through which she experiences sea ice:

> It was astounding how quickly it was like nothing else exists except this ship that I'm on, and it becomes your whole world. […] Then I took a helicopter ride, and […] after we get to a certain height, then I can see the full outline [of the ship] and my whole world just shattered because you see this tiny little boat in this just expanse of ocean and ice. And it looks so small and so... Yeah… alone and sad and fragile. (Hannah, lines 65-70)

Despite being on an icebreaker nearly 120 metres long, Hannah still feels tiny, helpless and entirely at the mercy of the surrounding expanse of sea ice, made possible only by the presence of the icebreaker. As Goodwin (1995) points out, the situated nature of the perceptual process is most obviously demonstrated by the very need for specific technologies in order to sense the surrounding ocean. Seeing this difference in scale as viewed from the helicopter makes Hannah aware of the role of the vessel in mediating her encounters with sea ice. Specifically, she realises that experiencing sea ice through an icebreaker and the context of a scientific expedition is not necessarily the only way of encountering sea ice. At another point in the interview, Hannah talks about Bob, a member of the expedition who was likely the only person there who had actually lived (and still did) in the Arctic rather than just experienced it through research cruises like the other scientists on board (Hannah, lines 418-419). As such, Hannah compares her own experience as a newcomer to Arctic environments, to that of Bob's as someone who endured the hostile environment in more protracted ways:

> If you said, You're going to the Arctic and you had to live there, Bob [would say], It's fuckin' hard. […] If people were dropped off in the Arctic without the ship, they would have to focus on surviving. So, you go to one of the most hostile places on the planet for humans to live, and it's the most comfortable that you've ever been. (Hannah, lines 422-423, 455-457).

Whilst not all sailing experiences can be described as "the most comfortable you've ever been" (from the unpleasantness of seasickness to the gruelling and exhausting conditions of fishermen and crabbers at sea, e.g., Bernton, 2022), Hannah's account reveals the ways in which navigating through sea ice aboard a ship *can* mediate the encounter with the surrounding frozen ocean environment, in this case, for the better. As Ewertowski (2023) suggests, the ship provides a safe platform from which mobile subjects can safely engage with their surroundings. As such, the ship's mediation between the sensuous subject and the mobile environment through which they are moving creates a sense of safety and comfort that separates the hostile surroundings from the cosiness of on-board life which, in turn, informs cryomobilities.

In addition to comfort, the ship also mediates perceived motion between the body and sea ice, creating a space of mobility within mobility. On the one hand, the ship exacerbates the perception of the ship's movements through the ice. Several participants highlighted that sailing through sea ice "[is] very different from being in open sea" and that the "ship hitting [the] ice […] can be very noisy" (Eileen, line 32; on the loudness of icebreaking, also Hannah, lines 29-40; Cath, lines 251-252). On the other hand, the ship attenuates the perception of the ice cracking as the icebreaker moves through it. Moving through sea ice is also "much steadier" (Eileen, line 32) and "it was noticeable that once we got into ice, the ship stopped rocking" (Hannah, line 278). Hannah expresses this during her interview:

> When you're on the ship, you feel like you're flying, you're so high up. […] So, I think you don't really feel the ship moving through the ice, you just kind of feel like you're flying through the ice. There's a lot of wind and you're so high up. […] It felt like when you're little and you go on someone who's really tall's shoulders so that you can be up higher. It feels like *that*. […] You could see it, sure, but […] even when it's cracking, you're kind of like flying over it rather than you being the one that's going through it." (Hannah, lines 555-571).

Hannah's account conveys a sense of disconnection between the noisy, harsh and cracking physicality of an icebreaker forcing its way through sea ice. Instead, it feels more like effortlessly "flying" through the ice. To illustrate the ship's sensorial mediation of mobilities, the extensive literature on automobilities reveals how the car becomes the lens through which passengers experience their mobility (Sheller, 2004, 2007; Koslowsky et al., 2013; e.g., Doughty and Murray, 2016; Gregson, 2018). The car (or, in this case, the ship) mediates sensorial encounters of mobility between the body and the car, and the body and the environment through which they are moving, as the car negotiates its (mobile) surroundings, including "bumps or smoothness, straightness and curves, upward and downward gradients, emptiness or crowding" (Sheller, 2007: 179). Similarly, the ship mediates encounters with sea ice and perceptions of movement through the ice, creating an experience of cryomobilities that is inextricably tied to the presence of the ship navigating amid sea ice.

Overall, people who interact with sea ice through navigational experiences also come to know sea ice through embodied encounters. These direct encounters mature a deep personal knowledge and familiarity with sea ice and its properties. As Ewertowski (2023) points out – specifically within the context of ships – sensuous impressions of mobilities are inescapable. In particular, sensorial and embodied encounters with sea ice contribute to the ways in which people who regularly experience sea ice make sense of its complexities and become better attuned to the changes in sea ice patterns. In addition, experiences of sea ice are mediated in various ways, and particularly so by the presence of the ship. By bringing attentiveness to the ways in which bodily experiences of mobilities are mediated in various ways, this chapter recognises the entanglement of mobile entities and subjects through mobile backgrounds, and acknowledges the ways in which mediation contributes to the creation of knowledge about these mobilities (Finbog et al., 2023). As such, it becomes imperative to bring attentiveness to these encounters, the ways in which they are mediated and the knowledges that they produce, in order to develop a more nuanced understanding of cryomobilities.

7.4. The Value of the Expert

Scientific and operational sea-ice data products differ greatly in their scope, purpose and user groups (e.g., see Hunke et al., 2020). The discussion that follows recognises these differences, whilst acknowledging that advances in one field also contribute to advances in other aspects of sea-ice science (e.g., joint workshop between (i) developers of sea ice models, (ii) users of sea ice models in an earth systems models context, and (iii) users of sea ice models for operational forecasting and (re)analyses, as discussed in Blockley et al., 2020). In the context of this discussion, it would be artificially siloing to discuss scientific sea-ice knowledge and operational sea-ice forecast charts separately. As such, this chapter considers both, in order to represent official sources of information about sea ice released by reputable organisations with a strong track record of scientific expertise in sea-ice data dissemination. For the Bering Strait region, sea-ice scientific data products, such as the Sea-Ice Index, are produced and distributed by a collective of highly regarded research centres based in the United States, including the National Snow and Ice Data Center (NSIDC), the Goddard Space Flight Center (GSFC), and the National Aeronautics and Space Administration (NASA). Similarly, sea-ice forecast charts for the Alaska region are produced by the National Weather Service (NWS), a branch of the National Oceanographic and Atmospheric Administration (NOAA), which is the principal agency of the United States federal government responsible for scientific research in these subjects. As such, sources of information about sea ice are accompanied by a sense of trustworthiness regarding the information that they provide as secondary data to the user (Seddon, 2022). The discussion that follows draws on examples from both scientific and operational sea-ice products, as they both carry this implicit sense of objectivity and reliability in producing knowledge about sea ice. This perception of objectivity is important because, as the following discussion shows, it becomes impossible to separate the objective data product (or at least one that aims for a certain level of objectivity) from the aspects of human subjectivity that produce it (Seddon, 2022).

Despite the fact that scientific knowledge production aims for objectivity and reproducibility, it remains inextricably tied to the subjective everyday lives of the scientists who contribute to producing this knowledge. The emotional pressures of being on remote fieldwork for weeks on end (sometimes months), and the unexpected events of everyday life all trickle down in various ways into the process of knowledge production about sea ice (and other phenomena). For example, Hannah, a filmmaker accompanying various Arctic scientific cruises, recalls some of the ways in which emotions and everyday life collided with achieving objectivity during scientific data collection aboard a scientific research vessel:

> I saw the scientists, you know, who were in a fight with their significant other because the WhatsApp message didn't send through and their significant other thought they were ignoring them. So, they didn't want to go out and clean – okay, this was one of the more unhealthy relationships – but they didn't go out and clean the snow off the instrument that day because they were trying to get the message through. It's like, I did not see scientists. I saw very much people, in all the ways that people are people. (Hannah, lines 471-475)

Hannah's account highlights one of the ways in which the emotional stresses of the working conditions of remote and ship-bound Arctic fieldwork influence the extent to which scientists are able to carry out their research duties, potentially resulting in patchy or inconsistent data collection. As Lehman (2018) argues, oceanographic knowledge is always partial and dependent on interactions between nonhuman animals, technologies, and different humans. Sarah, who contributes to operational sea-ice forecasts, shares a similar account of some of the ways in which daily life can interfere with consistently producing high-quality sea-ice forecasts:

> There was one day we had an earthquake, and it was like 8:30 in the morning and it was a 7.1 or .2 that really shook us. And we actually evacuated the building for a time, and then when we were on our way back to the building, I stopped by my house here to just make sure everything's okay and whatever. And I found that my boiler was leaking, like spewing out water. […] And so anyway, by the time I got back to the office to be able to finish things up, you know, we didn't have as much time to be able to do all the details in there [on the sea-ice forecast chart]. And so that was a day when I just kind of went to the highest priority, let's make sure we get what needs to be done, done. And tomorrow I can put in more of the details and that kind of thing. So, you know, there are just days when things happen, that was kind of an extreme example. (Sarah, lines 225-233)

Whilst Sarah is describing a one-off occasion, it shows that, to some extent, the reliability of sea-ice charts and forecasts does not solely rely on an accurate understanding of sea-ice processes (as discussed in Section 7.2) and the practical know-how in mapping these, but is also embedded within the subjective lives of the people who are involved in this system of knowledge production. There are inevitable external factors that can shake (quite literally) the system of knowledge production that aims for objectivity and consistency in producing reliable sea-ice forecasts. As such, the sea-ice forecaster becomes a corporeal site of knowledge production through the ways in which human subjectivities and the objectivities of sea-ice forecasting coalesce to produce knowledge about sea-ice mobilities.

Despite these discrepancies, the scientists and forecasters who are behind sea-ice data products and operational charts also carry an irreplaceable wealth of accumulated knowledge and expertise which allows them to expertly synthesise and skilfully understand sea-ice behaviour. As Hannah so aptly described in her account of WhatsApp interfering with data collection, "all the ways that people are people" (line 475) can be a hinderance as much as it can be a strength, for it also creates a space for applying expert judgement about sea-ice processes and ultimately producing more complete sea-ice data products. In light of this, Sarah illustrates the vital role of experience in identifying different sea-ice types from satellite imagery when making sea-ice charts:

> There's definitely just expertise that's gained over time each season. You're like, Oh, yeah, I remember seeing that this happened similarly last year, or this kind of thing tends to happen. The way that ice melts back in the Chukchi Sea, going around the shoals and then leaving ice over the shoals is really common. And so, it just takes time to gather that experience. […] A lot of it is based on our experience and there are different characteristics that show us the ice is thickening. So, when it's really new, it looks super smooth and it might even look the same colour as the water, just mildly opaque. And then it as it gets into that young category, it tends to be really swirly, maybe. If there's, you know, currents and light winds and the currents are moving it around and things like that that we can pick up on, I think this is getting into that young category. (Sarah, lines 189-192, 318-322)

Additionally, Andrew, who is also involved in producing sea-ice charts, explains that there are different expectations between the fill-in and the full-time sea-ice forecasters, as the fill-ins "don't have the experience base that that we [full-timers] do" (line 197). Andrew goes on to elaborate that "since they don't have that knowledge base" and "they just don't know what's going on in there from an imagery analysis perspective" (lines 199-201), they are expected to focus on simpler tasks such as mapping the ice edge, where the distinction between water and sea ice is more visible, and does not involve the expertise required to classify different types of sea ice within the ice pack. Due to the value of this accumulated expertise, Stewart, who used to work as a sea-ice forecaster, expresses frustration during instances of lacking expert knowledge, as well as the fact that certain situations or policies tend to favour approaches that dismiss expert judgement:

> At least at some point very recently, sea ice analysts [...] had a policy of, if we can't show there's a change, we don't. And that can be a big problem. [If] We've had south winds 40 knots for three days, the ice can't be that far south. [*Playfully starts mimicking the voice of another person, presumably a sea ice forecaster*] Yeah, but I don't have any [satellite] images to show it. [*Back to his own voice*] I don't care. Apply some physics here! *Haha*. (Stewart, lines 212-215)

In a similar way, Matthew, who keeps a close eye on sea-ice data due to his research on bearded seal habitats, talked me through some of the daily sea-ice satellite imagery for the Bering and Chukchi Seas that he had saved on his laptop, and how these can be misguiding for gaining a representative understanding of sea-ice conditions in the Bering Sea and Chukchi Sea:

> The minimum extent usually was ice all across here [*Matthew points to an area on the map that is now ice-free*]. And so, this is very misleading because it shows you coverage, but not condition of the ice. […] There's the data in March and it's near the edge of the continental shelf, as it normally is. But it was trash. I mean, you look at that, you look at ice extent and […] somebody would evaluate it as, oh look, it's just normal. So that's March, right? March 28th. Let's pick April 21st. Look how fast it goes. So, it's

> already starting [summer sea-ice retreat]. And the quality is very, very different. […] You see all the openings in the midst? It's not steady. And if we go, let's say to 10 May here. See how fast it's receding? It's incredible. […] So, this is all 2022. It is misleading in the sense that the ice went very far south. Very poor quality. Very briefly. (lines 19-20, 23-26, 63-66)

In this excerpt, Matthew suggests that whilst remote sensing data often shows Bering Sea sea-ice conditions (especially in terms of sea-ice area and extent) to be comparable to those decades in the past, the quality of the ice has completely deteriorated, as indicated by the reduction in thickness, age, stability and duration (Thoman et al., 2020; IPCC, 2021). The seasonal fluctuations in sea-ice area discussed in Sections 3.4.2.2 and 5.4.1. as well as the fact that recent years (albeit only a few) have reached sea-ice areas similar to or higher than sea-ice cover in the 1980s (Stabeno et al., 2012b), characterise sea-ice behaviour in the Bering and Chukchi Seas. 'Rollercoaster years' such as 2022 are possible because sea-ice onset can be quick, particularly in the Bering Sea (as discussed in Section 3.4.2.3), but the sea-ice that forms is not as thick and stable as it used to be. Hannah, too, expressed this during her interview, when she reminisced about past research expeditions that she assisted as a videographer, where scientists would be "dropped off on ice floes […] drifting with the drifting stations" (line 80). Hannah now wonders "if there's even ice that's available to support that any more" (line 81). In addition to the quality and stability of sea ice, the process by which sea ice forms in the Bering Sea is no longer what it used to be:

> There's no chance that you're going to wake up one morning and oh, I'm stuck now for the winter. That can't happen. [It used to be that] the winds turn north, and the pack ice blew in, and now we're stuck and we're not getting out if the wind direction doesn't change soon. Those days are gone for the Alaskan Arctic. (Stewart, lines 89-94)

Stewart, who used to contribute to the National Weather Service's daily sea-ice forecast maps, points out that there is less sea-ice forming due to advection of pack ice from the central Arctic Ocean, and instead sea-ice formation relies more on in-situ freezing of colder surface water. This takes much longer for sea-ice to form and set in, and because conditions in the lower latitudes are not as cold as in the middle of the Arctic Ocean, for example, the ice hardly becomes as thick or lasts as long. The Indigenous community of *Iŋalik* (Little Diomede), for example, situated in the middle of the Bering Strait, used to plough landing strips onto the ice, making connections with the mainland relatively easy and reliable by bush plane. However, sea ice has not been thick, sturdy and reliable enough to continue landing planes safely on the ice, and according to one *Iŋalik* resident, the last Bering Air flight landed on the ice in May 2013, and there has not been a runway on the sea ice surrounding *Iŋalik* since then (Cornwall, 2019). As such, the changes in sea-ice patterns observed through satellite data, as well as those observed by people who know sea ice from direct personal experience, all indicate the overall decline in extent and deterioration of the quality of sea ice. The synthesised expert knowledge gained through experience and exposure to these phenomena makes each individual more capable of assessing situations and making more confident and informed decisions, which ultimately enhances the depth of the knowledge that is produced. As the interviews with Sarah, Andrew, Stewart, Hannah and Matthew all demonstrate, experience built up through time allows sea-ice experts to identify patterns of sea-ice movement with "way more confidence" (Andrew, line 203), and therefore knowledge production about sea ice hinges on the subjective decision-making processes of experts in this field.

Considering the various ways in which sea-ice knowledge is produced, from more quantitative spatial analyses of sea ice charts to personal judgement and more embodied encounters with sea ice, what emerges is that combining multiple ways of knowing creates a more holistic understanding of a given phenomenon. Sarah expresses this in the following excerpt:

> There's so much traditional knowledge out there […] And so, there's so much that they [people in Indigenous coastal communities] know from a pretty detailed perspective and then I feel like we kind of have maybe more of the big picture perspective from the satellite imagery and everything. And those are really complementary. One is not necessarily better than the other, maybe they can only tell, like I can see that there's open water out there because there's, you know, the bottom of the clouds are grey, but I can't tell you how much is open. Is that just a hole in the ice or is that like there's no ice beyond there? And so, you know, things like that that we can hopefully help each other with to make all the sea ice information more valuable in both directions. (Sarah, lines 574-580)

By comparing Iñupiat traditional knowledge about sea-ice conditions and mapping sea-ice charts using satellite imagery, Sarah highlights the value of combining different ways of knowing towards better understanding sea ice. Several projects have found ways to engage both Indigenous and Western scientific knowledges to develop more nuanced understandings of phenomena such as marine mammals and sea ice conditions, revealing the value of the complementarity of different ways of knowing (Hauser et al., 2021; Mahoney et al., 2021; Farthest North Films, 2022).

This combined knowledge about geophysical sea-ice conditions, operational sea-ice charts, and embodied experiences of sea ice also contributes to the skilful expertise required for safe navigation in icy waters. Indeed, "finding a safe way through the ice in a boat requires much skill and experience, especially during the changing of seasons when the ice can be unpredictable" (see also Marchenko, 2012; Elixhauser, 2019: 104). This view is also shared by Simon and Cath during their interviews:

> Especially for tankers, and then going to Canadian waters, [shipping companies] are just forcing their vessels to have an ice observer on board and their role is basically just to… they specialise in marine ice so they can give an observation, tell the thickness, give an assessment of what type of ice it is and if it's safe to go through based off of your vessel and hull type. (Simon, lines 56-59)

> When you're in the middle of the Bering Sea or the Chukchi Sea or the Arctic Ocean, you don't have access to real time ice information necessarily, still. Because there's not the bandwidth to be able to download SAR imagery. So again, you may know that there's a 25% sea ice concentration in this giant area, but that's not helpful from a navigation standpoint to know that. You need to know, is there a chunk of multiyear ice coming at me from here? So, the thing that people told me was that – or at least

> I inferred from people's stories – is that you start relying a lot more on your own senses and observations. And so, watching out for the ice becomes a lot more important. (Cath, lines 258-264)

Given the complexities of the sea-ice system, with the multitude of atmospheric and oceanographic factors that interact in complex ways to shape sea-ice behaviour, as well as the deep sensorial and embodied encounters with sea ice, the role of the expert emerges as fundamental in bringing together and making sense of these overlapping understandings of sea ice.

These examples illustrate the ways in which people who engage with mobilities (of sea ice, vessels and their own bodies) make sense of these mobile encounters through their embodied experiences. Various ways of sensing mobility – including satellite imagery, scientific equipment onboard a research vessel, visceral sensations of the grinding of sea ice against the beach, and shared intergenerational experiences of hunting on sea ice – all coalesce in the ways in which the body is able to make sense of these sensorial encounters. As Adey et al. (2012) argue, we can start to imagine bodies that develop specific aptitudes for movement (i.e., becoming experts) and, in doing so, the environment through which mobile bodies move ceases to be a spatial architecture or material happening that mobile entities yield to by simply *moving through* it; rather, mobilities become co-constituted by the bodily elaborations of experiences of movement. Therefore, cryomobilities are co-constituted by the mobilities of sea ice, vessels and subjects, how these mobilities are sensed in various bodily experiences, and how knowledges emerge from the bodily synthesis of corporeal encounters produced through the body as a site of knowledge production.

7.5. Conclusion

In this chapter, I have considered various ways in which people who engage with sea ice for the purpose of navigation understand sea ice mobilities and how this influences the ways in which cryomobilities unfold in the Bering Strait region. As I have demonstrated in this chapter, cryomobilities in the Bering Strait region unfold not just in response to sea-ice conditions, but also relative to how these sea-ice conditions are known, understood, experienced and perceived.

The sea-ice system is complex, and during the interviews, participants acknowledged and discussed the vast array of driving forces and feedback mechanisms that can impact sea-ice conditions. In particular, participants pointed to the fact that whilst large research efforts are dedicated to better understanding the sea-ice system, some interactions between various driving forces are yet to be fully understood, such as the effects of positive feedback loops. In addition, climate change is causing rapid changes in global temperatures and weather systems, which have the potential to trigger unknown sea-ice changes and destabilise current regimes. These rapid and unpredictable changes also mean that knowledge about the sea-ice system must keep up, and quickly develop new understandings as the situation evolves.

Due to this incomplete understanding of some aspects of sea-ice dynamics, sea-ice forecasting is not as reliable as it needs to be in order to support predictable and safe navigation in the ice-prone waters of the Bering Strait region. In turn, ships navigating in these areas are likely to encounter sea-ice conditions different to those forecasted, which can place vessels that do not have additional ice capability in danger, worsened by the generally scarce access to search and rescue services in remote Arctic regions. As such, this shapes cryomobilities in the Bering Strait region in the ways in which ships must be ready to respond to changing sea-ice conditions, captains and crews must be experienced in navigating in icy waters and be able to act on the spot.

To complement geophysical understandings of sea ice from both scientific sea-ice studies and sea-ice forecasting services, people with experience in navigating in icy waters also develop knowledge about sea ice through direct embodied encounters. On the one hand, sea ice inspires feelings of awe and excitement that draws people to the impressive sea-ice landscape. On the other hand, the latent power of the ice also fosters a healthy sense of fear, caution and respect for sea ice. These embodied visceral understandings of sea ice inform captains' and crews' navigational choices whilst in icy waters.

In addition, what participants described as direct encounters with sea ice are always to some extent mediated. Embodied encounters with sea ice, and the knowledge that is produced through them, are reliant on the mode through which sea ice is experienced, and the vessel used for moving through sea ice emerged from the interviews as fundamental in this. When moving through ice-prone waters, the ship mediates the perceived motion; on the one hand, it exacerbates the noise and cracking through the ice, as participants often recall how noisy a ship can sound as it breaks its way through ice. On the other hand, the ship also separates the crew from the harshness of breaking sea ice by providing a feeling of flying through the ice, as well as through the comforts and luxuries of life on board. As such, cryomobilities in the Bering Strait region unfold not just due to the geophysical properties and movement of sea ice, but also through the embodied experiences and imagined spatialities of what it means to navigate through icy waters.

Drawing on both scientific understandings of sea ice that aim for objectivity and experiential understandings of sea ice that are to a large extent subjective, this chapter reveals that it becomes impossible to separate the objective data product (or at least one that aims for a certain level of objectivity) from the aspects of human subjectivity that produce it. Whilst aiming for objectivity, even scientific sea-ice knowledge is tied to the subjectivities of the people – and their everyday lives – involved in the various stages of collecting, processing, and disseminating information that contributes to understandings about sea ice. Despite the ways in which human subjectivities might introduce errors into scientific data products, people's subjective judgement can also contribute valuable insight to sea-ice data products, such as the experience required by sea-ice forecasters to distinguish sea-ice types using satellite imagery. Thus, this chapter emphasises the value of expertise gained through people's exposure to sea-ice phenomena over extended periods of time. This expertise, gained largely through personal and subjective exposure to sea-ice phenomena (whether through direct exposure to sea ice or through experience mapping sea ice from satellite imagery), informs even sea-ice understandings that are rooted in objectivity and scientific protocols, such as sea-ice forecasts. This leads to an awareness that combining ways of knowing is fundamental for advancing knowledge about the sea-ice system. As such, cryomobilities in the Bering Strait region are entangled within the web of knowledge, perception, mediation, personal judgement, and accumulated expertise that synthesise and process understandings of sea ice, and in turn shape navigational decisions and patterns of cryomobilities.

8

Of Sea Ice and Vessels: Attuning to Icy Ocean Spaces

8.1. Introduction

Through this research, I set out to analyse the mobile relations between ice-prone ocean spaces and the mobilities of vessels through these spaces, and how people involved in these mobilities perceive, mediate and make sense of them. In doing so, I emphasise the *mobilities within mobilities*, or the mobilities of the backgrounds against (and alongside) which other entities move. This highlights the importance of attuning to the mobilities of sea ice in order to better understand the mobilities of other mobile entities that move through, under, over and amidst it, including vessels, marine mammals, people, fish, other biota, and microplastics. Choosing to situate this analysis in the Bering Strait region (consisting of the Bering Sea and the Chukchi Sea), I set out the following research question and sub-questions:

> ***In the Bering Strait region, how are vessel mobilities entangled with sea ice mobilities, and how are these perceived?***
>
> a. *What patterns of sea ice and vessel mobilities are present in the Bering Strait region?*
> b. *How have mobile interactions between sea ice and vessels changed over time (in particular, during 2013-2022)?*
> c. *How do people who engage with sea-ice and vessel mobilities in various ways perceive and understand the mobile interactions between sea ice and vessels?*

Sea ice is a unique component of the ocean, revealing the complexity of ocean spaces as constantly in motion and with the ability to continuously shift between liquid and solid states (Marchenko, 2012; Steinberg and Peters, 2015). In this thesis, I draw on sea ice not only to reemphasise the endless ways in which the ocean is implicated with social processes and global mobilities (Steinberg, 2001), but also to disrupt narratives of marine mobilities as occurring over static, agentless and homogenous backgrounds (Peters, 2020a). In doing so, I shed light on the empirical realities of cryomobilities – which itself has eluded much analysis – as well as on other marginalised discourses within mobility studies and, more broadly, the discipline of geography.

In this chapter, I draw on the empirical findings presented in Chapters 5, 6 and 7 and I elaborate on their relevance and implications *vis-à-vis* existing theories in mobility studies and geography. First, in analysing the mobilities of the sea ice and ocean background against which other mobilities unfold, the findings in this thesis provide an alternative outlook for transcending the human versus non-human binary and the priority often given within mobility studies to human mobilities (Cresswell, 2006; Merriman, 2019). Second, by looking at mobilities taking place amidst environments that are themselves also mobile, I propose to move beyond the dichotomy of mobility versus immobility, a prevalent lens of analysis within the new mobilities paradigm. This is illustrated through Hannam et al.'s (2006) curious use of "moorings" as a symbol for fixity. Nonetheless, it is also important to recognise that there are differences between modes of mobility and that these do not always play out in the same way. Third, through this research, the ocean emerges as a mobile and productive space which engages with and sustains other mobilities, whilst at the same time being itself mobile. Fourth, and in relation to broader discourses within geography, in reintegrating the ice-prone ocean within traditionally terracentric mobilities accounts, I return to the ocean to destabilise the superiority of the land over the ocean. I draw on Smith's (2020) notion of "temperate-normativity", the idea that 'proper' civilisations thrive best in temperate climates and that, consequently, peoples living in extreme (frigid) environments become considered aberrant and pathological. What is at stake here are the politics behind the marginalisation of ocean spaces and, more specifically, of sea ice and other frozen ocean spaces. Finally, as this research is also concerned with the ways in which knowledge is produced about sea ice and its mobilities, this research makes an important contribution to improving the accessibility of Arctic ship traffic data in order to better study phenomena related to vessel and (icy) ocean mobilities. This has been achieved through the development of a standalone open-source Python script designed to clean and process raw shipping data from the Arctic Council's Protection of the Arctic Marine Environment (PAME) Arctic Ship Traffic Data (ASTD) database into useable point and line features that can be employed in spatial data analyses.

8.2. Mobilities within Mobilities

First, in considering the mobilities of the background against which other mobilities unfold, I argue for moving beyond the human versus non-human binary. Several scholars have recently argued for the inclusion of the non-human and nature in mobility discourses (Swart, 2015; Jensen, 2016; Suliman, 2018; Fishel, 2019). Through this thesis, I show that attending to non-human and more-than-human mobilities is fundamental for gaining a holistic understanding of the mobilities of human bodies, as well as those of non-human entities in their own right. Traditionally, mobility studies have focused on *people* on the move and, due to this anthropocentrism, the mobilities of the backgrounds against which human subjects move have been left behind. As Cresswell reminds us, "Mobility is central to what it is to be human. […] To be human, indeed, to be animal, is to have some kind of capacity for mobility" (2006: 1, 22). Cresswell's focus and research agenda – from which much work on mobilities stems – is on the human, that which is alive, and what eludes analysis are the equally valid and important ways in which other non-living entities are mobile too, and how these matter (also, but not exclusively) in relation to human mobilities. As Fishel points out, "The challenge of […] mobility is even richer and more complex if the planet is no longer a backdrop, and the nonhuman is acknowledged in its nearness to humans and human sites" (2019: 355). Through the arguments presented in this thesis, the planet emerges from being a backdrop to becoming co-constituent of the mobilities that unfold over and through it. For example, the mobilities of sea ice posed challenges to the sailing abilities of captains and crews during 18th and 19th Century European Arctic voyages, which in turn triggered impressive technological advances in shipbuilding to increase ice capability (Chapter 5). Tourist cruise ships, the fishing and crabbing industry, and drifting scientific expeditions intrinsically rely on the mobilities of sea ice for their success in pursuing and achieving their various goals (Chapter 6). In turn, the ways in which people experience and make sense of these mobilities is contingent on the perception of both their own mobilities and the mobilities of the sea ice that surrounds them (Chapter 7). Whilst in this thesis I do place a focus on the human subjects involved in the cryomobilities of the Bering Strait region (e.g., through embodied experiences), their subjectivity and embodiment does not and cannot be conceptualised to exist as separate from the surrounding non-human mobilities. What is clear, then, is that accounting for the mobilities of the non-human surroundings against which mobilities occur is fundamental in gaining a holistic understanding of mobility assemblages in their full interrelatedness. As such, mobility studies must become attuned to including the non-human within its research efforts.

It is also important to note that the dichotomy between the human and the non-human – and the fact that the human gains preference – is fundamentally socio-culturally situated within a Western worldview. In Indigenous traditions, for example, there is not such a dichotomy between human, non-human and more-than-human forms of life. Entities that Western society constructs as part of 'nature' (and, therefore, not 'human') emerge differently in other cosmologies, where entities such as glaciers and plants are attributed sentience and agency, including the ability to move (e.g., Cruikshank, 2012; Kimmerer, 2013). Sea ice, in particular, carries a deep cultural significance for the Indigenous communities who rely on it (and its movements) for their livelihoods, and locals' knowledge of sea-ice behaviour is incredibly detailed and specific (e.g., Krupnik et al., 2010; Watt-Cloutier, 2015; Hauser et al., 2021). Whilst I was unable to work directly with Indigenous communities as part of this research project, I have drawn on the work of others who have, and Indigenous stories and knowledges accompany the work done throughout this research project. Acknowledging the value of alternative worldviews is fundamental for taking seriously Indigenous accounts of the mobile interactions between their people and their lands, in developing a more inclusive research agenda and moving beyond the confines of Western views of the world.

Second, by looking at mobilities within mobilities, this thesis moves beyond the binary of mobility versus immobility. In many mobility studies, immobile entities are considered to be "the very fixities in time and space that enable […] mobilities", as first conceptualised by Urry (2003: 49). This conceptualisation not only renders these supposedly immobile entities *actually* immobile through their escape from analysis, but it also reinforces the notion of entities being mobile over a static and unmovable background. Mobile vessels moving through a mobile ocean (made up of varying configurations of water, sea ice and other mobile components) demonstrate that a 'static background' is a problematic notion. As Deleuze and Guattari suggest, "depending on their degree of speed or the relation of movement and rest into which they enter, [constituent elements] belong to a given Individual, which may itself be part of another Individual governed by another, more complex, relation, and so on to infinity" (Deleuze and Guattari, 1988: 254). By focusing not merely on what is in motion and what is immobile, but rather on the relations between mobile entities in more or less mobile states, the background once again emerges as fundamental to understanding the mobilities at hand. The cryomobilities that I presented in this thesis demonstrate how different mobile entities interact and are mobile in different ways and to varying degrees in relation to each other. Blurring the lines of what is mobile and what is 'immobile', and focusing instead on the relationality of mobilities, shapes the stories that this thesis (and any research aligning itself with this approach) is able to tell. As such, moving beyond the immobility/mobility binary opens up new opportunities for telling stories of kinship and interconnectedness, and generating a politics of inclusivity, where entities that are interconnected and mobile to varying degrees are all recognised as fundamental and co-constituent components of the new geographical constellations that emerge from their relations.

In moving beyond a binary of mobility and immobility, it is still important to recognise that not all mobile relations are the same. Indeed, focusing on the relationality between mobilities highlights the politics and power relations underlying how mobilities are managed and enacted (Cresswell, 2014; Khan, 2016). As such, whilst I propose moving away from entities as being 'immobile', especially those considered as 'background', the different politics unfold around the extent to which the 'background' is considered mobile or immobile. For example, Nansen had always had a unique approach to his scientific endeavours, and was known for being revolutionary and independent-thinking in both his personal and his academic life (Nansen, 1897a). In proposing his expeditions, he was not afraid to come to his own conclusions and depart from the thinking that had come before him, such as with his approach to drift *with* sea ice rather than against it. As such, Nansen transformed what was conceptualised up until that point as a stubborn and immobile background that impeded the mobilities of ships to the useful mobile background that allowed Nansen's *Fram* expedition to get closer to the North Pole than any other European explorer before them, and return home safely. This contrasts with the construction of the Russian "Lider" class *Rossiya* icebreaker (2027; under construction), able to sail through sea ice up to 4.1 metres thick and meaning it "can practically sail everywhere in Arctic waters" (Nilsen, 2019a: 10). The development of icebreakers able to navigate regardless of sea-ice conditions suggests that there is an active desire to turn sea ice into a background whose mobilities or immobilities do not matter. This is demonstrated by the increase in vessel activities in higher sea-ice concentrations, marking a shift towards the ability to sustain marine mobility regardless of the mobile conditions of the ocean, as the background over which other (more important) mobilities occur. Indeed, in the legal framework laid out by UNCLOS (United Nations Convention on the Laws of the Sea), the ocean is ontologically presented as formless, in that there is no significant legal provision that accounts for the structural importance of the distinct materialities of the ocean in its frozen form, and how navigation should respond differently to the ocean in its multiple states (Steinberg et al., 2023). As such, attuning to the extent to which the 'background' is considered 'immobile' sheds light on the politics of mobilities at play and how oceanic places become ontologically defined.

Third, the ocean emerges as a mobile and productive space which engages with and sustains other mobilities, whilst at the same time being mobile in itself. On the one hand, the ocean's mobilities – from waves and currents to sea ice and freezing spray – emerge from other networks of mobilities, such as wind and atmospheric conditions. On the other hand, through its mobilities, the ocean further sustains other networks of mobilities, from marine mammal migrations as they follow the sea-ice edge, to scientific research stations that drift upon sea ice. Despite its clear mobile character, much of mobility studies continue to be interested in land-based mobilities, and it is only recently that mobility studies have "gone to sea" (Peters, 2015; Peters and Squire, 2019). As many scholars engaging in the oceanic turn continue to argue, the role of the ocean is fundamental in sustaining life as we know it, yet the ocean continues to elude geographic imaginaries that consistently demonstrate a preference for land-based processes (Steinberg, 2001; Peters, 2015; McKinley, 2023). In the context of this thesis, I argue that the same has occurred within mobility studies. Much of what mobility studies are interested in, from "flows" and "currents" to "liquid modernity" (e.g., Hannam et al., 2006; Cresswell, 2014; Khan, 2016), emerges from water inspired terminology. Hannam et al. (2006), as one of the first to introduce the importance of immobility and stillness within discourses of mobilities, chose "moorings" as a synonym for fixity and stillness. This is curious not only because moorings are technologies designed for and employed in watery spaces (yet they are employed to conceptualise processes on land), but moorings are not always still. Some moorings are designed to drift with the sea ice, for example, meaning that their purpose is rooted in their mobility, rather than in their stillness. For moorings that do have a more obvious connection to fixity, such as those that are anchored to the sea floor (e.g., for scientific measurements), or are connected to land (e.g., boat moorings at ports), the mooring itself is still always moving. Moorings bob up and down at the surface with action from the waves, they sway with the currents, even the instruments that are tied to a mooring at various depths sometimes rely on motion to drag them sideways to measure speeds of currents. In fact, moorings *must* move, or else they would not be able to adapt to the mobilities of the ocean. As such, when mobility scholars draw on the concept of 'moorings' to analyse the 'fixities' within mobile networks, they are inadvertently and implicitly invoking the mobilities of watery spaces in all their forms. Whilst mobility studies began on land, and maintained for some time a preference for analysing landed processes, the ocean was always there in the background, not least in the language that Hannam et al. chose to operationalise their thinking.

Fourth, and relating to broader discourses within geography, in reintegrating the ice-prone ocean within traditionally terracentric accounts of mobilities, in this thesis I draw on the ocean to destabilise the ontological supremacy of the land over the ocean. On the one hand, the ocean is more like land than geographical imaginaries often portray. For example, sea ice is often described as an extension of the land, as it becomes a connecting "highway" between Indigenous settlements that can be walked and driven on (e.g., Aporta, 2004; Inuit Circumpolar Council Canada, 2008; Vannini and Taggart, 2014; MOSAiC, 2020). On the other hand, and perhaps more powerfully, the land that is referenced in the land-ocean binary against which sea ice is viewed as an outlier is more like the ocean than (Western) geographical imaginaries allow. First, focusing on sea ice shows how even things perceived as solid (e.g., frozen ice) are in fact mobile. The land, in its perceived solid supremacy, is mobile and fluid too, for example, as asphalt roads wear out and develop potholes over time (Vannini and Taggart, 2014), and how the earth's shaking during earthquakes disrupts existing networks of infrastructure that sustain mobilities (Sheller, 2017). To gain a better understanding of mobilities not just in watery spaces but also on land, these planetary mobilities need acknowledging (e.g., Nail, 2019). Secondly, the land and the ocean share a similar story of marginalisation from dominant narratives. In the same way that ocean spaces are marginalised in mobilities accounts that address landed processes, the mobilities of the land are marginalised in mobility studies that focus on the people that move over it (rather than on how the land moves under them). In other words, an epistemology that is informed by the ocean is fundamental in understanding processes on land; likewise, the mobilities of the land (i.e., the background to land based mobilities) are fundamental in understanding people and entities on the move. As such, both the land and the ocean have been marginalised in mobility studies that have largely ignored the mobilities of the backgrounds and surrounding mobilities alongside which other mobilities occur.

What is at stake here are the politics behind the marginalisation of ocean spaces and, more specifically, of sea ice and other frozen ocean spaces. Smith (2020) argues that icy spaces are used to politically exclude and racialize peoples as "aberrant" and "pathological" through their association with frigid climates, and the interconnectedness through their cultures and livelihoods. To explain this way of thinking, Smith proposes the notion of "temperate-normativity":

> "proper" civilizations are said to arise from settlements in temperate locales that depend largely on cultivation via agricultural practices. […] Under this rubric, ice, in its resistance to root and hostility to settlement, is said to not only racialize due to "extreme" climate but the Arctic also becomes a space where pathological migrancy and transit takes place. (2020: 2)

By making sea ice the centre of its focus, this research responds to temperate-normativity thinking and instead normalises the mobilities that take place in and of these icy environments. While Smith is concerned with the precarity of Indigenous political rights through their association with the Arctic's frozen spaces (and how these are conceptualised), through this thesis I demonstrate that rather than constituting an aberrant, pathological and hostile setting, sea ice environments can be generative of unique and precious geographical constellations of mobilities that are not possible in temperate oceans. This includes a wide spectrum of ice-related mobilities, from the abundant marine life sustained by the sea-ice cycle to Indigenous subsistence practices that rely on shorefast ice. Even if not directly addressed by this thesis, culturally-contingent relations with the cold and frozen spaces – and the mobilities made possible by these – still matter in shaping Arctic sociopolitical agendas, for example in Indigenous political movements to assert connectedness to the Arctic in its frozen state as a pressing matter of human rights (Watt-Cloutier, 2015). As such, in this thesis I contribute to shifting perceptions about sea ice and other frozen environments, encouraging a sense of familiarity and approachability, rather than one of distant, inaccessible and deviant geographies. Thus, sea ice emerges not as an aberrant space, but as a fundamental constituent of the lives and livelihoods that Indigenous and Western societies alike rely on.

Finally, in acknowledging the ocean as mobile, the mobile entities moving amidst its icy spaces must also develop an understanding of the ocean's mobilities in order to guide and make decisions about their own mobilities. In addition to the ways in which the ocean is perceived and knowledge is generated through embodied experience, this also requires developing knowledge about how the icy ocean is mobile, and how people and vessels move through it (Peters, 2020b). In terms of applied methods, this requires developing modes of data processing that are able to account for the mobilities taking place within a mobile environment. As such, this thesis makes an important contribution to improving the accessibility of ship traffic data in order to better study phenomena related to vessel and (icy) ocean mobilities, through the development of a Python script. Accessing historical data on ship traffic can be difficult and often very expensive. Whilst the PAME ASTD only covers the Arctic region, it provides an affordable subscription-based service to access data through an online portal, where some statistics and spatial queries can be carried out. For research requiring more in-depth custom analysis, subscribed users can request to download the raw data points through an FTP service. However, the downloadable dataset is raw and, therefore, contains errors that make it unsuitable to use in spatial data analysis. At the time of writing, PAME does not offer a service to download cleaned data, or to clean the data once downloaded. As such, without specialised programming expertise, it is impossible to use the data as is for analysis. The development of a standalone and open-source Python script to automatically clean up and organise the raw ship data opens up avenues for other researchers who obtain a subscription to the ASTD dataset to use this data in further research. As such, the work done as part of this research project provides users who have a subscription to the ASTD database with a user-friendly and ready-to-go solution for independently cleaning up the data and using it for spatial analysis.

8.3. Limitations

This research comes with several limitations regarding the contributions made to understandings of cryomobilities. First, as the focus is on vessels, several other modes of being mobile within icy ocean spaces are excluded. Relying on AIS (Automatic Identification System) data for analysing ship traffic activities means that other smaller vessels which are not legally required to carry AIS transponders – whist they might choose to do so anyway – are likely neither visible nor accounted for. In addition, vessels and shipping are not the only way of being mobile within icy ocean spaces. Indigenous peoples, for example, have intricate and culturally situated mobilities through and over icy ocean spaces, and this thesis has only considered these to a limited extent. Furthermore, this research focuses primarily on cryomobilities *in the middle* of watery spaces. The risk here is creating an account of the mobilities of vessels amidst ice-prone ocean spaces that have few ties to other interconnected networks beyond the confines of the ocean itself. As a consequence, it is important to highlight the importance of the liminal spaces of ports, docks and beaches (to name a few) where entangled mobilities of people, barges, waves, water, sand and land are complicated and shaped by icy conditions.

Second, whilst every care has been taken to make the methods employed as robust as possible, the methodology will never be perfect. In the spatial analysis of sea ice and its interactions with vessels, this research only uses sea-ice concentration to understand the behaviour of sea ice. This excludes other sea-ice indicators, such as sea-ice thickness and velocity vectors which could contribute to a more nuanced and detailed account of sea-ice mobilities relative to vessels. This project's exclusive focus on sea-ice concentration is rooted in a preference for achieving a greater spatial resolution over accounting for more variables. Studies interested in vessel routes in sea ice that employ sea-ice satellite data that accounts for sea-ice thickness (e.g., Kapsar et al., 2023) are limited to a spatial resolution of 25 km, which might obscure some of the vessel-ice interactions occurring on smaller scales (although finer, the 6.25 km spatial resolution used in this thesis will still obscure ice-vessel interdependencies to some extent). In addition, sea-ice thickness is difficult to measure from space, and sea-ice thickness datasets do not cover as wide an area or go anywhere near as far back as sea-ice concentration datasets (Wang et al., 2016). Whilst an important variable, these challenges make it difficult to both find sea-ice thickness data that is available for the same period as the shipping traffic data, as well as situate current trends within longer-term changes in sea-ice properties.

Third, this research would have benefitted from more autoethnographic engagements with both sea ice and vessels. As some of the participants recounted during the interviews, those who had had direct experience with sea ice conveyed a clear sense of how this helped them to better understand sea ice in other contexts too. My participants also taught me a great deal about sea ice, vessels and navigation, which makes me wonder how much more I would have learnt through direct encounters with these icy environments. During my fieldwork, I went on a three-day salmon fishing trip with a colleague and her family in Prince William Sound. Whilst this was in summer and there was no sea ice, being in the ocean provided me with an incredible wealth of context and a more intimate understanding of many of the theories, quantitative analyses and qualitative interviews that I had been working on. The focus of Chapter 7 on embodied experiences also emphasises the importance of having such experiences, even for the researcher themselves. From these experiences and realisations, I believe that a more direct personal encounter with both sea ice and larger vessels than the ones I had the pleasure of being on would have helped me better make sense of the cryomobilities that I set out to uncover.

Finally, whilst I trust that the Python script designed to clean up the ASTD AIS dataset works for its intended purpose, I am also certain that it would benefit from being reviewed and worked on by other, more experienced, Python programmers. Some of the more immediate interventions would be to i) improve its efficiency and reduce running time, and ii) improve the Python grammar and adopt conventional structuring, including a better use of functions and global variables. In order to open the script up for improvement through the collective effort of the open-source community, this script will be published on GitHub and be open for contributions, pending publication of an accompanying methodological paper.

8.4. Conclusion

Overall, as the discussion in this concluding chapter has revealed, focusing on cryomobilities offers an analytical framework for analysing the ways in which particular mobility relations unfold when the focus is placed on the specificities of cold, frozen, frosty, icy and ice-prone environments. In this thesis, I argue for the importance of attuning and attending to the mobile backgrounds against (or alongside) which mobilities occur, or the *mobilities within mobilities*. Through a specific focus on cryomobilities – i.e., the mobile interactions between vessels and icy ocean spaces – I demonstrate the power of this approach in pushing the boundaries of existing theoretical confines within mobility studies and geography more broadly.

In particular, the ocean's vibrant mobilities – including sea ice – offer a productive arena for moving beyond mobility accounts that are primarily interested in human mobilities against a static background that is often conceptualised as carrying little meaning and little agency in shaping the mobilities that occur frictionlessly over it. By analysing cryomobilities, the background emerges not just as mobile, but as fundamental to better understanding interconnected networks of mobilities and how they unfold. This provides a framework for moving beyond certain lenses of analysis that are pervasively employed within mobility studies, such as the mobility/immobility dichotomy and the preference for studying human mobilities rather than attending to those of the non-human realm. More broadly, relating to discourses within geography, cryomobilities turns to the ocean and sea ice, advocating for the return of attention on to the watery ocean spaces of our planet. In many ways, land is characterised by its fixity, and many land-based mobilities *rely* on this fixity to function. Land also moves in much less obvious ways than the ocean, and with mobility studies historically emerging out of the desire to study human mobilities on land, the non-human backdrop to these mobilities has largely eluded analysis. Instead, the ocean's vibrancy reconnects human mobilities to the mobilities of the (frozen) ocean, as well as reconnecting mobilities on and of the land to those in and of the ocean. As such, cryomobilities are attuned to icy ocean spaces, and they contribute to pushing the confines of discourses both within mobility studies as well as more broadly within the field of geography.

While the 'cryo' focus of this thesis has been on sea ice, the notion of cryomobilities offers potential for exploring the processes, phenomena and relations occurring in other 'cryo' realms beyond sea ice. My hope is that this thesis can be a starting point to inspire future research driven by a similar attentiveness towards mobilities unfolding in relation to the cold. How are commuter mobilities shaped by the availability of snow cover, for example using cross-country skiing paths between home and work? How are the mobilities of snow and ice managed when clearing roads in places like Fairbanks, Alaska where any snow or ice removed from the road must be stored and piled until it thaws in the spring? How are the micro material mobilities of surfaces (buildings, cars, roads, skin) impacted by cold environments, for example in speeding up the decay of buildings, removing car paint due to aggressive icing, breaking up road surfaces, and causing frostbite? How do the movements of glaciers impact the mobilities of hikers and outdoor enthusiasts in navigating changing mountain icescapes? How do cold chain mobilities ensure that products (for example, fish) remain perfectly chilled throughout their journey from production to consumer? As the breadth of these potential future research topics demonstrates, the sea ice analysed in this thesis is merely a starting point for cryomobilities, and I am excited at the prospects and possibilities of upcoming research that chooses to employ the notion of cryomobilities to address areas of interest so far left unexplored under this lens.

The findings of this thesis have implications beyond the theoretical elaborations to the study of mobilities and ocean spaces, and offer significant opportunities for informing understandings of ocean spaces within policy. Whilst live monitoring of ship activities is now relatively accessible (e.g., through online portals such as Marine Traffic), historical datasets of ship tracking data are still in their infancy, and difficulties in accessing them are exacerbated by the high cost of obtaining access, and often then requiring highly specialised spatial data management skills to make sense of them. As this thesis makes a contribution in making these more accessible, I would encourage those interested in such fields to make use of this opportunity. Indeed, the processed ship dataset is already being used in an ongoing research collaboration between myself, the International Arctic Research Centre and the University of Washington. The research focuses on bowhead whale habitat and migration areas to identify overlaps with ship traffic areas and inform policies for cetacean protection in the Bering Strait region. Additionally, the wider availability of these data has the potential to empower individuals and communities (including Indigenous communities) who would otherwise struggle to access datasets such as these – and the power that comes with this knowledge. Some of the findings of this thesis have already been disseminated to Alaskan Iñupiat communities through the Winter 2024 issue of the newsletter distributed to communities as part of the Alaska Arctic Observatory and Knowledge Hub (AAOKH) project (AAOKH, 2024). Finally, the findings in this thesis emphasise the heterogeneity of both ice-prone ocean spaces, and those who inhabit and make use of it. As such, taking into account the different ways in which different types of vessels and communities use ice-prone ocean spaces is fundamental for developing ocean management policies that are sustainable, functional and fair in light of real-life conditions.

Moving forward, I hope that this thesis inspires further work on the mobilities taking place amidst icy ocean spaces. Focusing on vessels and sea ice and looking at the relatively limited region of the Bering Strait is only the beginning. Cryomobilities can take similar studies to all four corners of the Arctic circle, and also expand to include icescapes emerging from different types of water other than saltwater, including those on land. As Gillis (2013) points out, “this is the domain of the blue humanities, open, like the sea itself, to further exploration”.

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Appendices

Appendix I

The 15 aggregated ship type categories used by PAME in the Level 3 ASTD dataset.

ASTD Ship Types	*HIS Fairplay – Level 3*	*HIS Fairplay – Level 5*
Chemical tankers	Chemical	Molten Sulphur Tanker
	Other Liquids	Chemical Tanker
	Bulk Dry / Oil	Chemical/Products Tanker
	Tanker	Wine Tanker
		Vegetable Oil Tanker
		Edible Oil Tanker
		Latex Tanker
		Fruit Juice Tanker
		Fruit Juice Carrier, Refrigerated
		Molasses Tanker
		Caprolactam Tanker
		Bulk/Caustic Soda Carrier (CABU)
		Bulk/Sulphuric Acid Carrier
		Chemical Tanker, Inland Waterways
		Chemical/Products Tanker, Inland Waterways
Gas tankers	Liquefied Gas	LNG Tanker
		Combination Gas Tanker (LNG/LPG)
		LPG Tanker
		LPG/Chemical Tanker
		CO2 Tanker
Bulk carriers	Bulk Dry	Bulk Carrier
	Bulk Dry / Oil	Bulk Carrier, Laker Only
	Self Discharging Bulk Dry	Bulk Carrier (with Vehicle Decks)
	Other Bulk Dry	Ore Carrier
	Other activities	Bulk/Oil Carrier (OBO)
		Ore/Oil Carrier
		Bulk Carrier, Self-discharging
		Bulk Carrier, Self-discharging, Laker

		Cement Carrier Wood Chips Carrier Urea Carrier Aggregates Carrier Limestone Carrier Refined Sugar Carrier Powder Carrier Bulk Cement Storage Ship
General cargo ships	General Cargo Other Dry Cargo Dry Cargo/Passenger	General Cargo Ship (with Ro-Ro facility) General Cargo Ship, Self-discharging Open Hatch Cargo Ship General Cargo/Tanker General Cargo Ship Palletised Cargo Ship Deck Cargo Ship Livestock Carrier Barge Carrier Heavy Load Carrier Heavy Load Carrier, semi submersible Yacht Carrier, semi submersible Nuclear Fuel Carrier Nuclear Fuel Carrier (with Ro-Ro facility) General Cargo, Inland Waterways
Container ships	Container Dry Cargo/Passenger	Container Ship (Fully Cellular) Container Ship (Fully Cellular/Ro-Ro Facility) Passenger/Container Ship Container Ship (Fully Cellular), Inland Waterways
Ro-Ro cargo ships	Ro-Ro Cargo Dry Cargo/Passenger	Ro-Ro Cargo Ship Rail Vehicles Carrier Vehicles Carrier Container/Ro-Ro Cargo Ship Landing Craft Ro-Ro Cargo Ship, Inland Waterways
Refrigerated cargo ships	Refrigerated Cargo	Refrigerated Cargo Ship
Offshore supply ships	Offshore Supply	Crew/Supply Vessel Pipe Carrier

		Platform Supply Ship Anchor Handling Tug Supply Offshore Tug/Supply Ship
Other service offshore vessels	Other Offshore Other Activities	Offshore Support Vessel Diving Support Vessel Accommodation Ship Offshore Construction Vessel, jack up Drilling Ship Pipe Layer Crane Vessel Pipe Layer Production Testing Vessel FPSO, Oil Gas Processing Vessel Well Stimulation Vessel Standby Safety Vessel FSO, Oil Trenching Support Vessel Pipe Burying Vessel Anchor Handling Vessel
Fishing vessels	Fish Catching	Factory Stern Trawler Stern Trawler Trawler Fishing Vessel
Crude oil tankers	Oil	Shuttle Tanker Crude Oil Tanker Crude/Oil Products Tanker
Oil product tankers	Oil Other activities Tanker	Products Tanker Tanker (unspecified) Asphalt/Bitumen Tanker Coal/Oil Mixture Tanker Bunkering Tanker Oil Tanker, Inland Waterways
Passenger ships	Passenger / General Cargo Passenger/Ro-Ro Cargo Passenger	General Cargo/Passenger Ship Passenger/Ro-Ro Ship (Vehicles) Passenger/Ro-Ro Ship (Vehicles/Rail) Passenger/Landing Craft

	Dry Cargo/Passenger	Passenger Ship
		Passenger/Ro-Ro Ship (Vehicles), Inland Waterways
		Passenger Ship, Inland Waterways
Cruise ships	Passenger	Passenger/Cruise
	Dry Cargo/Passenger	Cruise Ship, Inland Waterways
Other activities	Other Liquids	Water Tanker
	Other Fishing	Fish Factory Ship
	Research	Fish Carrier
	Towing / Pushing	Live Fish Carrier (Well Boat)
	Dredging	Fish Farm Support Vessel
	Other Activities	Fishery Patrol Vessel
	Other Non-Seagoing	Fishery Research Vessel
	Yacht	Fishery Support Vessel
	Barge	Seal Catcher
	Non-ship structures	Whale Catcher
		Kelp Dredger
		Research Survey Vessel
		Tug
		Articulated Pusher Tug
		Pusher Tug
		Bucket Ladder Dredger
		Cutter Suction Dredger
		Grab Dredger
		Backhoe Dredger
		Bucket Wheel Suction Dredger
		Suction Dredger
		Dredger (unspecified)
		Grab Hopper Dredger
		Suction Hopper Dredger
		Trailing Suction Hopper Dredger
		Hopper/Dredger (unspecified)
		Hopper, Motor
		Stone Carrier
		Crane Vessel
		Pile Driving Vessel
		Icebreaker

Icebreaker/Research

Cable Layer

Waste Disposal Vessel

Effluent carrier

Fire Fighting Vessel

Pollution Control Vessel

Patrol Vessel

Crew Boat

Training Ship

Utility Vessel

Search & Rescue Vessel

Pilot Vessel

Salvage Ship

Buoy Tender

Buoy & Lighthouse Tender

Lighthouse Tender

Supply Tender

Mooring Vessel

Work/Repair Vessel

Hospital Vessel

Tank Cleaning Vessel

Trans Shipment Vessel

Exhibition Vessel

Mission Ship

Mining Vessel

Power Station Vessel

Vessel (function unknown)

Sailing Vessel

Towing/Pushing, Inland Waterways

Other Activities, Inland Waterways

Houseboat

Yacht

Yacht (Sailing)

Sail Training Ship

Replenishment Dry Cargo Vessel

Mooring Vessel, Naval Auxiliary

Research Vessel, Naval Auxiliary
Replenishment Tanker
Unknown Function, Naval/Naval Auxiliary
Diving Vessel, Naval Auxiliary
Minelayer
Submarine Salvage Vessel
Aircraft Carrier
Command Vessel
Destroyer
Frigate
Helicopter Carrier
Patrol Vessel, Naval
Weapons Trials Vessel
Logistics Vessel (Naval Ro-Ro Cargo)
Infantry Landing Craft
Landing Ship (Dock Type)
Tank Landing Craft
Training Ship, Stationary
Accommodation Vessel, Stationary
Lightship
Museum, Stationary
Covered Bulk Cargo Barge, non propelled
Bulk Cement Barge, non propelled
General Cargo Barge, non propelled
Trans Shipment Barge, non propelled
Hopper Barge, non propelled
LPG Tank Barge, non propelled
Products Tank Barge, non propelled
Crude Oil Tank Barge, non propelled
Deck Cargo Pontoon, semi submersible
Bucket Dredger Pontoon
Deck Cargo Pontoon, non propelled
Grab Dredger Pontoon
Suction Dredger Pontoon
Dredging Pontoon, unknown dredging type
Water-injection Dredging Pontoon

Crane Vessel, non propelled

Sheerlegs Pontoon

Work/Maintenance Pontoon, non propelled

Pontoon (Function Unknown)

Air Cushion Vehicle Passenger/Ro-Ro (Vehicles)

Air Cushion Vehicle Passenger

Air Cushion Vehicle Patrol Vessel

Accommodation Platform, semi submersible

Drilling Rig, semi Submersible

Diving Support Platform, semi submersible

Pipe layer Platform, semi submersible

Maintenance Platform, semi Submersible

Accommodation Platform, jack up

Crane Platform, jack up

Drilling Rig, jack up

Support Platform, jack up

Supply Platform, jack up

Mooring Buoy

Wind Turbine Installation Vessel

Appendix II

The Python script created for processing the PAME ASTD AIS vessel traffic dataset.

```
# import required modules
import pandas as pd
pd.options.mode.chained_assignment = None  # default='warn'
import time
import geopandas
import math
from datetime import datetime

# THIS SCRIPT DOES NOT COUNT VOYAGES
# Dates format YYYYMM:
years = ["2013", "2014", "2015", "2016", "2017", "2018", "2019", "2020", "2021", "2022"]
months = ["01", "02", "03", "04", "05", "06", "07", "08", "09", "10", "11", "12"]

print("\nSTART TIME ......................", datetime.now())

for y in years:
    for m in months:

        # record start time to later calculate execution time
        s_time = time.time()

        # automate name substitution in file paths + output .csv per dataset
        dataset = y+m    # iterate through input years and months stated above
        ASTD_rawdata = "C:/Users/Greta/Documents/GIS/ASTD/Raw_data/Dirty/ASTD_" + dataset + "_dirty.csv"
        # OPTIONAL custom shape for clipping dataset
        # studyarea_shp =
"C:/Users/Greta/Documents/GIS/ASTD/ASTD_GIS/Data/ASTD_studyarea_WGS1984.shp"

        # load CSV into dataframe
        # reading dataframe in chunks speeds processing time by only dealing with one
        # chunk at a time in RAM then passing on to next
        print("\nProcessing ASTD dataset " + dataset)
        print("Reading csv...")
        chunks = pd.read_csv(ASTD_rawdata,
                             sep=",",
                             chunksize=10000,
                             dtype={"shipid": int,
                                    "date_time_utc": object,
                                    "flagname": str,
                                    "flagcode": str,
                                    "iceclass": str,
                                    "astd_cat": str,
                                    "sizegroup_gt": object,
                                    "fuelquality": int,
                                    "fuelcons": float,
                                    "co": float,
                                    "co2": float,
                                    "so2": float,
                                    "pm": float,
                                    "nox": float,
                                    "n2o": float,
                                    "nmvoc": float,
                                    "ch4": float,
```

```
                    "blackcarbon": float,
                    "organiccarbon": float,
                    "oilbilgewater": float,
                    "blackwater": float,
                    "greywater": float,
                    "garbage": float,
                    "dist_nextpoint": float,
                    "sec_nextpoint": int,
                    "longitude": float,
                    "latitude": float,
                    })

    df = pd.concat(chunks) # chunks need to be concatenated to 'assemble' entire data frame
    n_raw = df[df.columns[0]].count() # count and print number of records

    print("Raw records:                    ", n_raw)

    # geographical filter on dataframe by coordinate values
    df = df[(((df.latitude >= 50) & (df.latitude < 65)) & ((df.longitude >= 160) | (df.longitude <= -155))) |
((df.latitude >= 65) & ((df.longitude >= 150) | (df.longitude <= -120)))]
    n_clip = df[df.columns[0]].count() # count and print number of records
    print("Clip by coordinates:            ", n_clip)

    # remove all records having a shipid that occurs 10 or less times
    # this runs after geographical clip even if some ship voyages might have
    # <10 occurences as a result of geographical clip (too few points to be of interest)
    v = df.shipid.value_counts() # count how many times each unique shipid occurs
    df = df[df.shipid.isin(v.index[v.gt(10)])] # I've checked this works
    n_10 = df[df.columns[0]].count() # count and print number of records
    print("Remove <= 10 shipid occurrence:  ", n_10)

    #  OPTIONAL - Clip dataset to custom shapefile – very time inefficient!
    ## studyarea = geopandas.read_file(studyarea_shp) # custom shp polygon used for clipping
    ## df = geopandas.GeoDataFrame(df, geometry=geopandas.points_from_xy(
    ##     df.longitude, df.latitude), crs="EPSG:4326") # turning df into geopandas gdf
    ## df = df.clip(studyarea) # clip gdf using custom polygon
    ## n = df[df.columns[0]].count() # count and print number of records
    ## print("Clip to study area:             ", n)

    df = df.sort_values(by = ["shipid", "date_time_utc"], ascending=True) # sort by shipid then timestamp
    df = df.reset_index(drop=True) # reset index to start from 0 after sorting

    # calculate distance from previous point
    df = geopandas.GeoDataFrame(df, geometry=geopandas.points_from_xy(
      df.longitude, df.latitude), crs="EPSG:4326") # turn df into gdf
    df = df.to_crs('EPSG:3575') # change coordinate system to projected for calculating distance
    df_prev = df.shift() # shift the dataframe down by 1 to align each point with the next point
    #df_next = df.shift(-1) # shift the dataframe up by 1 to align each point with the next point
    df["m_from_prev"] = df.distance(df_prev) # calculate distance from previous point and populate df
    #df["m_to_next"] = df.distance(df_next) # calculate distance to next point

    # remove consecutive identical points
    # This is needed even if I activate the filter for duplicates rounded to nearest min
    #   because two consecutive pings might be more than 1min apart, but still be
    #   in the same location.
    df = df[df["m_from_prev"] != 0]
    df = df.reset_index(drop=True) # reset index to start from 0 after removing points
```

```
    n_identical = df[df.columns[0]].count() # count and print number of records
    print("Remove identical consecutives:   ", n_identical)

    # calculate time (sec) from previous point
    df["sec_from_prev"] = pd.to_datetime(
        df.date_time_utc, format='%Y-%m-%d %H:%M:%S').diff(1).dt.total_seconds() # new column and
calculate time from previous point

    # calculate speed from previous point
    df["m/s_from_prev"] = df["m_from_prev"] / df["sec_from_prev"]

    # write df to csv
    df.to_csv("C:/Users/Greta/Documents/GIS/ASTD/Raw_data/Dirty/ASTD_" + dataset +
             "_dirty.csv")

    # add voyage counting column
    ## df["voyage_count"] = 0

    voyage_counter = 0 # uneccesary to have this, unless Axiom's voyage rules are
                       # reactivated by uncommenting sections of the script below.
    prev_row_counter = 1 # counter that keeps track of how many index values the previous row is behind by.
                         # Default value is 1 (i.e. the previous row), but when dropping a ping,
                         # the previous ping is 2 index values behind because one was dropped.
    skip_next = 0 # if 0, next ping is subject to normal if/else parsing (this is the default)
                  # if 1, next ping is kept (e.g. following an operation that requires skipping and keeping next ping)
    drop_next = 0 # if 0, next ping is subject to normal if/else parsing (this is the default)
                  # if 1, next ping is dropped (e.g. following an operation that requires dropping next ping)

    df_len = len(df) - 1 # max index value

    # set progress markers as percentage of total number of rows
    progress_10 = df_len * 0.1
    progress_20 = df_len * 0.2
    progress_30 = df_len * 0.3
    progress_40 = df_len * 0.4
    progress_50 = df_len * 0.5
    progress_60 = df_len * 0.6
    progress_70 = df_len * 0.7
    progress_80 = df_len * 0.8
    progress_90 = df_len * 0.9

    for i in df.index:
        # Percentage messages as code is running to track progress
        if i == math.floor(progress_10):
            e_time = time.time() # calculate and print execution time
            print("PROCESSED 10% ..................." , (e_time-s_time), "sec")
            pass
        if i == math.floor(progress_20):
            e_time = time.time() # calculate and print execution time
            print("PROCESSED 20% ..................." , (e_time-s_time), "sec")
            pass
        if i == math.floor(progress_30):
            e_time = time.time() # calculate and print execution time
            print("PROCESSED 30% ..................." , (e_time-s_time), "sec")
            pass
        if i == math.floor(progress_40):
            e_time = time.time() # calculate and print execution time
```

```
            print("PROCESSED 40% .................." , (e_time-s_time), "sec")
            pass
        if i == math.floor(progress_50):
            e_time = time.time() # calculate and print execution time
            print("PROCESSED 50% .................." , (e_time-s_time), "sec")
            pass
        if i == math.floor(progress_60):
            e_time = time.time() # calculate and print execution time
            print("PROCESSED 60% .................." , (e_time-s_time), "sec")
            pass
        if i == math.floor(progress_70):
            e_time = time.time() # calculate and print execution time
            print("PROCESSED 70% .................." , (e_time-s_time), "sec")
            pass
        if i == math.floor(progress_80):
            e_time = time.time() # calculate and print execution time
            print("PROCESSED 80% .................." , (e_time-s_time), "sec")
            pass
        if i == math.floor(progress_90):
            e_time = time.time() # calculate and print execution time
            print("PROCESSED 90% .................." , (e_time-s_time), "sec")
            pass

        if i == 0: # handle first record differently
            if (df["m_from_prev"][i+1] > 35000 or df["m/s_from_prev"][i+1] > 18): # is next ping more than 35 km away or moving faster than 18 m/s? (rogue)
                df.drop([i], inplace=True)
                df["m/s_from_prev"][i+1] = 0 # reassign m/s_from_prev of next ping as there is no longer a prev
                df["m_from_prev"][i+1] = 0 # reassign m_from_prev of next ping
                df["sec_from_prev"][i+1] = 0 # reassign sec_from_prev of next ping
                skip_next = 1 # skip next ping, assuming there's only 1 rogue point at start of each monthly dataset
                continue # bring control back to start of loop and move on to next row

            else: # first record is not rogue
                df["m/s_from_prev"][i] = 0 # reassign m/s_from_prev as this is first ping
                df["m_from_prev"][i] = 0 # reassign m_from_prev as this is first ping
                df["sec_from_prev"][i] = 0 # reassign sec_from_prev as this is first ping
                continue
        elif (i > 0) & (i < df_len): # for all pings except first and last of each dataset
            if skip_next == 1: # Skip counter is set to 1 at the end of any operation where
                         # following record simply needs keeping and moving on to next.
                # df["voyage_count"][i] = voyage_counter # ensure voyages are maintained even if ping is skipped
                prev_row_counter = 1
                skip_next = 0 # reset skip counter
                continue # bring control back to start of loop and move on to next row, therefore keeping this ping
            elif drop_next == 1: # drop counter is set to 1 at the end of any operation where
                                # following record simply needs dropping and moving on to next.
                                # This avoids deleting i+1 which would return an error
                                # during the following iteration as iterator wouldn't be able to find i.
                df.drop([i], inplace=True)

                drop_next = 0 # reset drop counter

                # recalculate m_from_prev of i+1
                df_next_recalc = df["geometry"][i+1]
                df_prev_recalc = df["geometry"][i-prev_row_counter]
                df["m_from_prev"][i+1] = df_next_recalc.distance(df_prev_recalc)
```

```
          # recalculate sec_from_prev of i+1
          sec_next_recalc = pd.to_datetime(df["date_time_utc"][i+1], format='%Y-%m-%d %H:%M:%S')
          sec_prev_recalc = pd.to_datetime(df["date_time_utc"][i-prev_row_counter], format='%Y-%m-%d
%H:%M:%S')
          df["sec_from_prev"][i+1] = (sec_next_recalc-sec_prev_recalc).total_seconds()

          # recalculate m/s_from_prev of i+1
          df["m/s_from_prev"][i+1] = df["m_from_prev"][i+1] / df["sec_from_prev"][i+1]

          prev_row_counter+=1

          continue # bring control back to start of loop and move on to next row.

        elif df["shipid"][i] != df["shipid"][i - prev_row_counter]: # is this the ship's first ping?
          voyage_counter = 0

          if df_len - i == 1: # this means that i is the ship's first ping, but also is
                    # the second-last point in df, so that ship track would
                    # be made up of only 2 pings.
                    # This is an unlikely scenario, but it did happen in 201908.
                    # So, drop i and i+1 and stop the iterator.
            df.drop([i], inplace=True)
            df.drop([i+1], inplace=True)
            break

          else:
            if (df["m_from_prev"][i+1] > ((df["m_from_prev"][i+2])*2)) or ( # is distance to next ping more
than twice the distance to ping after that? OR
                df["m/s_from_prev"][i+1] > 18) or ( # next ping moving more than 18 m/s OR
                  df["m_from_prev"][i+1] > 60000 and math.isnan(df["dist_nextpoint"][i]) == True): # next
ping is more than 60km away and distance to next point (value from original dataset) is Null
                  # this is the only case where distance between points from the original dataset is used,
                  # because it turns out that often it matches with rogue points that this script would
remove anyway.
            # if (df["m_from_prev"][i+1] > 60000) or ( # is next ping more than 60km away? OR
            #      df["m_from_prev"][i+1] > 35000 and df["m_from_prev"][i+2] < 35000) or ( # is next ping
more than 35 km away AND ping after that less than 35 km away? OR
            #      df["m/s_from_prev"][i+1] > 18): # next ping moving more than 18 m/s

            ## (you can't use speed of first ping because it's sometimes negative
            ## as it's the ship's first ping)
              df.drop([i], inplace=True) # if yes, i is rogue so drop it
              prev_row_counter+=1

              continue # bring control back to start of loop and move on to next row.

            else: # if first ping not rogue, keep ping
              df["m/s_from_prev"][i] = 0 # reassign speed from prev as this is ship's first ping
              df["m_from_prev"][i] = 0 # reassign dist from prev
              df["sec_from_prev"][i] = 0 # reassign sec from prev
              prev_row_counter = 1
              continue # bring control back to start of loop and move on to next row, therefore keeping this
ping

        elif df["shipid"][i] != df["shipid"][i+1]: # is this the ship's last ping?
```

```
                    if df["m/s_from_prev"][i] > 18 or df["m_from_prev"][i] > 35000 or (df["m_from_prev"][i] > 60000
and math.isnan(df["dist_nextpoint"][i]) == True):
                        # is the ping moving unreasonably fast OR is > 35 km away OR (is 60km and distance to next
point is Null)?
                        df.drop([i], inplace=True) # if yes, drop the ping
                        prev_row_counter+=1
                    else: # if ping is NOT moving unreasonably fast nor is > 35 km away, keep ping.
                        prev_row_counter=1
                        continue

                else: # no skipping, no dropping, not ship's first ping, not ship's last ping

                    if df["m/s_from_prev"][i] > 18: # is speed from prev unreasonably fast?
                        if df["m/s_from_prev"][i+1] > 18: # is speed from prev of next ping also unreasonably fast?
                                                          # if yes, it means that i ping is rogue ping.

                            # recalculate m_from_prev of i+1
                            df_next_recalc = df["geometry"][i+1]
                            df_prev_recalc = df["geometry"][i-prev_row_counter]
                            df["m_from_prev"][i+1] = df_next_recalc.distance(df_prev_recalc)

                            # recalculate sec_from_prev of i+1
                            sec_next_recalc = pd.to_datetime(df["date_time_utc"][i+1], format='%Y-%m-%d %H:%M:%S')
                            sec_prev_recalc = pd.to_datetime(df["date_time_utc"][i-prev_row_counter], format='%Y-%m-
%d %H:%M:%S')
                            df["sec_from_prev"][i+1] = (sec_next_recalc-sec_prev_recalc).total_seconds()

                            # recalculate m/s_from_prev of i+1
                            df["m/s_from_prev"][i+1] = df["m_from_prev"][i+1] / df["sec_from_prev"][i+1]

                            df.drop([i], inplace=True) # delete i
                            prev_row_counter+=1

                            continue

                        else: # i.e. speed from prev of next ping is less than 18 m/s
                              # it means that either i is ping AFTER rogue ping (this is the most likely case),
                              # OR that i is rogue ping, but the next segment is < 18 m/s.
                              # Locate the rogue ping by determining which segment it is (before or after i?)
                              # that jumps an unreasonable distance.
                            if (abs(df["m_from_prev"][i] - df["m_from_prev"][i+1])) > (abs(
                                    df["m_from_prev"][i] - df["m_from_prev"][i-prev_row_counter])):
                                # Is difference in m_from_prev between i and i+1 GREATER THAN
                                # difference in m_from_prev between i and i-1?
                                # If so, this means i ping is point AFTER rogue point.
                                # So, drop i-1 and recalculate m, sec and m/s_from_prev for i.

                                df.drop([i - prev_row_counter], inplace=True) # drop previous ping which is rogue point
                                # Because the previous ping had just been dropped, the script needs to find out
                                # what the index number is for the ping before the ping that's just been dropped.
                                # This is needed to recalculate statistics for i.
                                # The below loop iterates backwards through index values in steps of 1
                                # until it finds the index value for the previous ping.

                                # prev_row_counter = 1

                                while True:
```

```
                                     try:
                                         test = df["shipid"][i - prev_row_counter]
                                     except KeyError:
                                         prev_row_counter += 1
                                     else:
                                         break

                                 # print ("i = ", i,)
                                 # print ("prev_row_counter = ", prev_row_counter)
                                 # print ("It worked!")

                                 # recalculate m_from_prev of i
                                 df_next_recalc = df["geometry"][i]
                                 df_prev_recalc = df["geometry"][i - prev_row_counter]
                                 df["m_from_prev"][i] = df_next_recalc.distance(df_prev_recalc)

                                 # recalculate sec_from_prev of i
                                 sec_next_recalc = pd.to_datetime(df["date_time_utc"][i], format='%Y-%m-%d %H:%M:%S')
                                 sec_prev_recalc = pd.to_datetime(df["date_time_utc"][i-prev_row_counter], format='%Y-
%m-%d %H:%M:%S')
                                 df["sec_from_prev"][i] = (sec_next_recalc-sec_prev_recalc).total_seconds()

                                 # recalculate m/s_from_prev of i
                                 df["m/s_from_prev"][i] = df["m_from_prev"][i] / df["sec_from_prev"][i]

                                 # df["voyage_count"][i] = voyage_counter # assign voyage counter to i
                                 prev_row_counter = 1

                                 continue # bring control back to start of loop and move on to next row.

                             else: # i.e. difference in m_from_prev between i and i+1 LESS THAN
                                   # difference in m_from_prev between i and i-1.
                                   # Therefore i is rogue ping.

                                 # recalculate m_from_prev of i+1
                                 df_next_recalc = df["geometry"][i+1]
                                 df_prev_recalc = df["geometry"][i - prev_row_counter]
                                 df["m_from_prev"][i+1] = df_next_recalc.distance(df_prev_recalc)

                                 # recalculate sec_from_prev of i+1
                                 sec_next_recalc = pd.to_datetime(df["date_time_utc"][i+1], format='%Y-%m-%d
%H:%M:%S')
                                 sec_prev_recalc = pd.to_datetime(df["date_time_utc"][i-prev_row_counter], format='%Y-
%m-%d %H:%M:%S')
                                 df["sec_from_prev"][i+1] = (sec_next_recalc-sec_prev_recalc).total_seconds()

                                 # recalculate m/s_from_prev of i+1
                                 df["m/s_from_prev"][i+1] = df["m_from_prev"][i+1] / df["sec_from_prev"][i+1]

                                 df.drop([i], inplace=True) # drop i
                                 prev_row_counter+=1

                                 continue

                     else: # i.e. if m/s_from_prev is NOT > 18
                        # if
                         if df["m/s_from_prev"][i] > 0.3: # is the ship moving?
```

```
                if df["m_from_prev"][i] > 60000 and math.isnan(df["dist_nextpoint"][i]) == True:
                    # i is rogue, so recalculate statistics for i+1 and drop i

                    # recalculate m_from_prev of i+1
                    df_next_recalc = df["geometry"][i+1]
                    df_prev_recalc = df["geometry"][i - prev_row_counter]
                    df["m_from_prev"][i+1] = df_next_recalc.distance(df_prev_recalc)

                    # recalculate sec_from_prev of i+1
                    sec_next_recalc = pd.to_datetime(df["date_time_utc"][i+1], format='%Y-%m-%d
%H:%M:%S')
                    sec_prev_recalc = pd.to_datetime(df["date_time_utc"][i-prev_row_counter], format='%Y-
%m-%d %H:%M:%S')
                    df["sec_from_prev"][i+1] = (sec_next_recalc-sec_prev_recalc).total_seconds()

                    # recalculate m/s_from_prev of i+1
                    df["m/s_from_prev"][i+1] = df["m_from_prev"][i+1] / df["sec_from_prev"][i+1]

                    df.drop([i], inplace=True) # drop i
                    prev_row_counter+=1

                    continue

                else: # ship is moving and not >60km from previous ping AND Null
                    prev_row_counter = 1
                    continue

            else: # m/s from previous is NOT > 0.3? i.e. ship is not (or barely) moving
                if (df["m/s_from_prev"][i - prev_row_counter] > 0.3 or # is either previous ping OR
                    df["m/s_from_prev"][i+1] > 0.3): # next ping moving?

                    # if yes, keep ping and move on to next
                    prev_row_counter=1
                    continue

                else: # i.e. neither previous nor next ping is moving.
                      # so, drop i and recalculate statistics for i+1

                    # recalculate m_from_prev of i+1
                    df_next_recalc = df["geometry"][i+1]
                    df_prev_recalc = df["geometry"][i - prev_row_counter]
                    df["m_from_prev"][i+1] = df_next_recalc.distance(df_prev_recalc)

                    # recalculate sec_from_prev of i+1
                    sec_next_recalc = pd.to_datetime(df["date_time_utc"][i+1], format='%Y-%m-%d
%H:%M:%S')
                    sec_prev_recalc = pd.to_datetime(df["date_time_utc"][i-prev_row_counter], format='%Y-
%m-%d %H:%M:%S')
                    df["sec_from_prev"][i+1] = (sec_next_recalc-sec_prev_recalc).total_seconds()

                    # recalculate m/s_from_prev of i+1
                    df["m/s_from_prev"][i+1] = df["m_from_prev"][i+1] / df["sec_from_prev"][i+1]

                    df.drop([i], inplace=True)
                    prev_row_counter+=1

        elif i == df_len: # handle last row of df differently
```

```
            # df["voyage_count"][i] = voyage_counter # assign voyage count
            if df["m/s_from_prev"][i] > 18 or df["m_from_prev"][i] > 35000: # is the ping moving unreasonably
fast or is > 35 km away?
               df.drop([i], inplace=True) # if yes, drop the ping
            else: # if ping is NOT moving unreasonably fast nor is > 35 km away, keep ping.
               continue

      # merge shipids and voyage numbers in new column
      ## df["voyage"] = df["shipid"].astype(str) + "_" + df["voyage_count"].astype(str)

      # remove all records having a shipid that occurs 10 or less times
      # this runs after geographical clip even if some ship voyages might have
      # <10 occurences as a result of geographical clip (too few points to be of interest)
      v = df.shipid.value_counts() # count how many times each unique shipid occurs
      df = df[df.shipid.isin(v.index[v.gt(10)])] # I've checked it works correctly
      n_10 = df[df.columns[0]].count() # count and print number of records
      print("Remove <= 10 shipid occurrence:  ", n_10)

      n_final = df[df.columns[0]].count() # count and print number of records
      print("Cleaned records:               ", n_final)

      # write output to shapefile
      ## print("Writing output to shapefile...")
      ## df.to_file("C:/Users/Greta/Documents/GIS/ASTD/ASTD_GIS/Data/gdf_clipped.shp")

      # write df to csv
      df.to_csv("C:/Users/Greta/Documents/GIS/ASTD/Raw_data/Cleaned/V2/ASTD_" + dataset +
"_cleanV2.csv")

      # record end time to calculate execution time
      e_time = time.time()
      total_time = e_time-s_time
      # calculate and print execution time
      print("Script executed in .............", (e_time-s_time), "sec")

      # create a log to keep track of how many records deleted etc...
      # Headers: Dataset, Raw records, Records removed by <10 shipid occurrence,
      # Records removed by identical consecutives, Records removed by processing,
      # Final records, Elapsed time (sec)
      log = open("C:/Users/Greta/Documents/GIS/ASTD/Raw_data/Cleaned/V2/log.csv", "a")
      log.write('\n'+
             str(dataset)+','+
             str(n_raw)+','+
             # str(n_clip) + ', ,' +
             # str(n_clip-n_10)+', ,'+
             # str(n_10-n_identical)+','+
             # str(n_identical-n_final)+','+
             str(n_raw-n_10)+','+
             str(n_final)+','+
             str(total_time))
      log.close()

      print("FINISHED")

print("\nEND TIME ......................", datetime.now())
```

Appendix III

Consent form provided to participants prior to starting the interview process.

Participant Consent Form

Project title: Understanding mobilities of sea ice and vessel traffic in the Bering Strait region
Researcher's Institution: Durham University, United Kingdom

Researcher: Greta Ferloni	**Researcher contact details:** greta.ferloni@durham.ac.uk
Supervisor: Prof Phil Steinberg	**Supervisor contact details:** philip.steinberg@durham.ac.uk

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This study has received ethical approval from the ethics committee of the Department of Geography of Durham University, United Kingdom.

This form is to confirm that you understand the purposes of the research project, what your involvement entails, and that you are happy to take part.

1. What is the purpose of the research project?
   - ⇒ This research aims to better understand the connections between sea ice and vessel traffic in the Bering Strait region. The questions that you will be asked are aimed at exploring this theme.
   - ⇒ This project is funded by the Leverhulme Trust through the DurhamARCTIC program at Durham University, whose Director is by Phil Steinberg.
   - ⇒ This research is part of Greta Ferloni's requirements for completing her PhD qualification
2. What does my involvement entail?
   - ⇒ You are invited to take part in an interview. The interview is expected to be about one hour long.
   - ⇒ Your participation is voluntary. You are free to not answer any questions, even without providing a reason.
   - ⇒ You are free to withdraw your consent to participate in this research at any stage. If you wish to do so, no more data will be gathered from you, and you are free to request that any information that you have already provided be deleted.
3. How will my interview data be used?
   - ⇒ The information you provide in your interview is strictly confidential to the researcher, Greta Ferloni.
   - ⇒ No personal data will be shared. Anonymized (i.e. not identifiable) interview data may be used in academic publications and other research outputs. Other generic details, such as your place of work, might be included to provide justification for the relevance of the interview.
   - ⇒ The results of the research project will be written up into Greta Ferloni's PhD thesis. On successful submission of the thesis, the thesis will be published open access.
4. What personal information is being collected, and how will it be protected? (Privacy Notice)
   - ⇒ Personal data is collected for the sole purpose of obtaining consent to participate in the study. This includes your name and signature at the bottom of this form, and an audio recording of the interview if you agree to the interview being recorded. The

sole purpose of the recording is to revisit our conversation. The audio recording itself will not be used in any research outputs.

⇒ Any personal information will be stored securely where only the researcher, Greta Ferloni, has access. Digital data will be stored in a password protected folder on a password protected computer. Hardcopies will be in locked storage.

⇒ All research data and records needed to validate the research findings will be stored for 10 years after the end of the PhD, in line with Durham University's policy.

⇒ Under data protection legislation, you must be informed of the lawful basis being used to process your data. The lawful basis is Public Task: the processing is necessary for an activity being carried out as part of Durham University's public task, which is defined as teaching, learning and research. For further information see https://www.durham.ac.uk/about-us/governance/information-governance/data-protection/privacy-notices/generic-privacy-notice/

Thank you for reading this information and considering taking part in this study.

Consent

Please tick each the items below to confirm your agreement:

☐ I confirm that I have read the information summary and Privacy Notice provided above and I understand the aims of the project.

☐ I have had sufficient time to consider the information and ask any questions I might have, and I am satisfied with the answers I have been given.

☐ I understand who will have access to personal data provided, how the data will be stored and what will happen to the data at the end of the project.

☐ I understand that my participation is voluntary and that I am free to withdraw at any time without giving a reason.

☐ I agree to participate in an interview carried out by Greta Ferloni of Durham University, as part of the research related to her PhD qualification.

– I understand that I may be audio recorded, and I understand how this will be used in research outputs. Please choose one of the following options:

  ☐ I consent to have my interview audio-recorded

  ☐ I **DO NOT** consent to have my interview audio-recorded

Participant's signature: ________________________________

Participant's name: ___________________________________ Date: ___________________

If you have concerns about the research, or would like further information, you can contact the researcher or supervisor using the contact details at the top of this document.
If you remain unhappy or wish to make a formal complaint, please submit a complaint via Durham University's Complaints Process: https://www.dur.ac.uk/ges/3rdpartycomplaints/.

Appendix IV

All traffic 2013–2022 for each month, and average sea-ice concentrations for each month over the 10-year period. The succession of monthly maps shows an annual sea-ice 'pulse', and a corresponding 'pulse' in vessel activities. This figure is provided as an alternative to the animated GIF in **Figure 5.22**. Source: AIS data from PAME (2022); sea-ice concentration data from Spreen et al. (2008).