

THE METACOUPLED ARCTIC AND NORTH PACIFIC:
ANALYZING THE SPATIOTEMPORAL PATTERNS AND IMPACTS OF MARINE
VESSEL TRAFFIC IN COUPLED HUMAN AND NATURAL SYSTEMS

By

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A DISSERTATION

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

Fisheries and Wildlife – Doctor of Philosophy

2022

ABSTRACT

THE METACOUPLED ARCTIC AND NORTH PACIFIC: ANALYZING THE SPATIOTEMPORAL PATTERNS AND IMPACTS OF MARINE VESSEL TRAFFIC IN COUPLED HUMAN AND NATURAL SYSTEMS

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Climate change is causing Arctic and sub-Arctic systems to warm at twice the global average rate. Warming temperatures are leading to unprecedented rates of sea ice decline, which is shifting the migratory patterns of animals, increasing accessibility to natural resources, and spurring tourists to travel to the Arctic. Many of these changes have the potential to increase marine vessel traffic in the Arctic. Ships are a primary mode of transportation in the Arctic, which has many remote communities and a fragmented road network. Ships take resources, such as fish, ores, and oil and gas, from the Arctic to global markets, and also serve as lifelines, bringing essential supplies to isolated communities. While these vessels serve to connect distant social-ecological systems and support human wellbeing, they can also have detrimental effects on the ecosystems through which they travel. Noise pollution, habitat degradation, ship strikes, invasive species introduction, and oil spills are all potential consequences of vessel traffic.

Knowledge of the movements of vessels in space and time is necessary to determine the role that vessels are playing within Arctic systems and quantify their impacts. This information is also needed to predict the consequences of different vessel traffic policies for Arctic communities, ecosystems, and the interactions between them. The purpose of this dissertation is to quantify the spatiotemporal patterns of vessel traffic in Arctic social-ecological systems and to relate these patterns to other system components, including sea ice and wildlife movements. In chapter 2, we review the existing Arctic coupled human and natural systems literature and apply the newly

introduced framework of metacoupling to explore the connections among the coupled human and natural systems of the Arctic and between Arctic systems and distant systems. We suggest that applying the metacoupling framework would improve future studies of Arctic coupled human and natural systems by distinguishing between different external connections and their unique impacts on sustainability. In chapter 3, we create a new, six-year data set of vessel activities in the North Pacific and Pacific Arctic Oceans. We then use these data in a case study examining the spatiotemporal patterns of vessel movements in the Bering Strait Region. As the only route connecting the Pacific and Arctic Oceans, the Bering Strait is a critical corridor for marine vessel traffic and migratory animals. While most vessel traffic in the region is local, we find that transient vessel traffic, particularly fishing activities and transport along the Northern Sea Route, increased between 2015 and 2020. In chapter 4, we focus on the movements of marine vessels in the ice-covered waters of the Pacific Arctic. We find that movements in ice differ by vessel type, and that while vessel traffic declines with increasing sea ice concentration, the overall amount of vessel traffic in sea ice increased between 2015 and 2020. In chapter 5, we evaluate the resource selection decisions of an endangered marine predator, the Steller sea lion (*Eumetopias jubatus*), in relation to fishing and non-fishing vessel movements in a sub-Arctic system, the Gulf of Alaska. Our results illustrate that adult female Steller sea lions select areas away from fishing vessel activities at a weekly timescale. This finding supports the hypothesis that large fishing vessels may disturb Steller sea lions, with potential consequences for their fitness. This dissertation expands upon the metacoupling framework by building a foundational understanding of the transportation of metacoupled flows. This work also contributes to the growing body of knowledge of vessel movements and their impacts on marine systems, which can be applied to design policies that promote the sustainable use of marine systems in a changing world.

This dissertation is dedicated to my parents, Steve and Sandy Kapsar.
Unconditional love is a rare gift for which I will be forever grateful.

ACKNOWLEDGEMENTS

This dissertation would have never come together without the encouragement and guidance of many people. First and foremost, I want to thank my parents who have always loved and believed in me. They led by example in showing me the power of perseverance in the face of adversity. Travelling the world together spurred my passion for exploration and wildlife, without which I would have never pursued this degree in the first place.

Thank you also to my advisor, Dr. Jack Liu, for supporting me in pursuit of the research that I found most interesting and guiding me when I strayed away from the realm of significance and feasibility. I also owe a debt of gratitude to my dissertation committee: Dr. Lawson Brigham, Dr. Ashton Shortridge, Dr. Grant Gunn, and Dr. Robert Montgomery, for guiding me throughout the research process, being patient and understanding when it was interrupted, and giving their time and expertise to ensure that I did the best possible job I could.

Thank you also to Dr. Adrián Cerezo and Lisa Lidgus, who trusted me enough to send me to a remote island in the Bering Strait as the lone representative of the Saint Louis Zoo. And thank you to Jack Omelak and Elizabeth Shea for trusting their judgement. Without their trust this dissertation would have never come to be.

I also owe a huge thank you to the many people in Alaska who agreed to work with a strange girl from Michigan wanting to study boats and wildlife. This dissertation could not have happened without the collaboration of Aaron Poe and Ben Sullender. It has been a genuine pleasure to work together to create this giant ship tracking data set. Thank you also to Mike Rehberg for teaching me about Steller sea lions and guiding me through the process of designing a way to analyze their interactions with fishing vessels.

Back in Michigan, Jill Cruth has been a godsend since the start of this program. Transitioning from a 2,000-student college to a 50,000-student university was more than a little jarring, but Jill helped me guide me to and through all the correct hoops and forms to get started and keep going in the program. She also is one of the most kind and easy to talk to people that I've ever met. Additionally, I would have never survived graduate school without the friends and lab mates that I met along the way. Breakfast Club, the Women in Nature Network, Wildside Rehabilitation Center, and the Friday Afternoon Refreshment Team brought a sense of camaraderie and joy to an what can, at times, be a very lonely pursuit.

Before MSU, I went to a nerdy college in the middle of farmland in Minnesota. At Carleton, I met some of my very best friends and was taught by some of the most passionate and intelligent professors that I've ever had. Without their infectious enthusiasm and love of learning, I would have never even considered graduate school.

Finally, I would like to thank my partner, Nic. At the time of writing, he is the only other person who has read the entirety of this dissertation. He has been the most steady and comforting source of support in my life and has brought joy into the extremely extended periods of time we've spent alone together during the past two years of this awful pandemic. Thank you also to the other members of our little family, Natty and Brutus, who have been a constant source of snuggles, entertainment, distraction, and laughter.

PREFACE

The chapters in this dissertation were conceptualized as separate papers and written collaboratively with co-authors. While this research principally represents my own work, I use the pronoun we throughout the dissertation as an acknowledgement of the contributions of my collaborators, without whose contributions and guidance this dissertation would not be possible.

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CHAPTER 1: INTRODUCTION

1.1 Background

Marine vessel traffic is integral to northern latitudes in our globalized society. Ships are integral to the commercial harvest of fish from Arctic and sub-Arctic waters; transport oil, gas, and rare earth minerals to distant markets; and bring essential supplies to remote communities. As the global population grows in both numbers and affluence, demand for the Arctic's abundant natural resources, and the vessel traffic needed to carry them to global markets, are expected to increase (Azzara et al. 2015, Larsen and Huskey 2015, Eguíluz et al. 2016). Receding sea ice further enables access to natural resources that were previously cost-prohibitive to extract from or transport through areas covered by ice for the majority of the year (Gautier et al. 2009, Cao et al. 2022). However, changing climates also place stress on Arctic and sub-Arctic social-ecological systems by thawing permafrost (Streletskiy et al. 2012), increasing disease risk (Dudley et al. 2015), altering wildlife migration patterns and species ranges (van Weelden et al. 2021), and threatening food security in subsistence-based communities (Ford 2009). Together, these changes create a complex system in which the sustainability of Arctic and non-Arctic systems is interconnected.

While marine vessel traffic can improve human wellbeing by transporting in-demand goods around the world, it also can pose threats to sensitive ecosystems and human-nature interactions in marine and coastal environments. As vessels move through the ocean, they produce noise which can cause disturbances, mask communication, or impair the hearing of marine animals (Putland et al. 2018, Halliday 2021). Many vessels also carry ballast water, which can facilitate the transportation of invasive species (Sardain et al. 2019), and fuel oil, which can injure or kill marine animals and threaten the food security of the subsistence-based Indigenous communities

with which they are interdependent (Kawerak Inc. Marine Program 2016, Raymond-Yakoubian 2018). Vessels moving at high speeds also have the potential to injure or kill cetaceans, which are also at risk of entanglement in commercial fishing gear (Conn and Silber 2013, George et al. 2017).

Many of these threats are tied to the position of vessels in space and time. Once a vessel is gone from a region, the risk of oil spill or ship strike, and the noise that a vessel makes are also eliminated from the region. Therefore, mitigating the negative impacts of vessel traffic requires precise knowledge of the movements of marine vessels in both space and time. This knowledge is particularly salient in highly dynamic areas, such as Arctic and sub-Arctic waters, which experience dramatic seasonal transitions in the coverage of sea ice, as well as the distribution of long-range migrants, such as gray (*Eschrichtius robustus*) and bowhead whales (*Balaena mysticetus*). Taken together, the interconnected movements of vessels, sea ice, and marine wildlife form a complex social-ecological system in which the risks and benefits of marine vessel traffic are dynamic in both space and time.

Recent studies of vessel traffic in northern waters have examined traffic patterns across space (Silber and Adams 2019) and over decades-long time periods (Pizzolato et al. 2014). However, few studies have analyzed the spatial patterns of vessel traffic on a sub-annual timescale or in relation to other social-ecological system components, such as the distribution of sea ice or the movements of marine animals. This dissertation seeks to fill this gap in knowledge by studying the seasonal and sub-seasonal patterns of vessel traffic distribution in the northern Pacific and Arctic Oceans. It advances both the operationalization of metacoupled systems theory and the empirical understanding of vessel traffic patterns in a geographically and socio-ecologically important region.

1.2 Theoretical Framework

This dissertation builds upon the theoretical framework of coupled human and natural systems research and, more specifically, the metacoupling framework. Over the past two decades, the field of coupled human and natural systems research (CHANS; e.g., social-ecological systems or human-environment systems) has applied interdisciplinary methodologies to understand the interrelationships (or couplings) between humans and the natural environment (Liu et al. 2007). The integrative nature of CHANS research makes it particularly relevant to policy makers who must consider entire systems rather than individual components. Furthermore, new approaches to CHANS research integrate not just single systems, but also connections between multiple adjacent or distant systems.

Human-nature interactions in a particular CHANS often impact or are impacted by adjacent and distant systems (Liu 2017). For instance, international shipping through areas of subsistence harvest poses a threat to both humans and marine wildlife (Huntington et al. 2015, Hauser et al. 2018). To account for these distant interactions, the umbrella concept of metacoupling has been introduced (Figure 1.1). The metacoupled framework provides a way to characterize and evaluate the relationships within coupled human and natural systems (intracoupling) as well as between two or more adjacent systems (pericoupling) or distantly connected systems (telecoupling) (Liu 2017). Below, I briefly discuss this dissertation's contribution to metacoupling research. Further details on the metacoupling framework and its application to Arctic systems can be found in Chapter 2.

This dissertation advances metacoupling research by laying the foundation for quantifying the transportation of flows in metacoupled systems. With over 80% of the world's trade transported over the ocean (UNCTAD 2017), marine vessel traffic is essential to the transportation of

metacoupled trade from sending to receiving systems around the world. Classifying vessel movements according to the metacoupling framework reveals the spatiotemporal patterns of diverse vessel functions with a system (see chapter 3). Additionally, this research contributes to a growing body of literature on the spillover effects of metacoupled international trade by quantifying the spillover effects of transient vessel activity in an important and ecologically sensitive marine system.

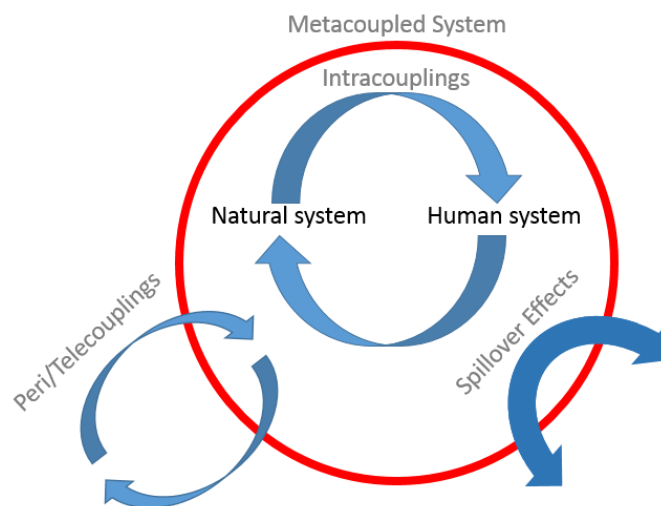


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1.3 Study System

This dissertation takes place at multiple scales throughout the Arctic (Figure 1.2). This region is ecologically, geographically, economically, and culturally important. Nutrient-rich waters of the Pacific upwell onto the shallow Bering Sea, supporting a wide diversity of marine life (Grebmeier et al. 2006). In turn, this biodiversity supports Indigenous subsistence communities that have inhabited the region for thousands of years as well as a globalized commercial fishing industry (Bering Sea Elders Advisory Group 2011, Chen et al. 2020).

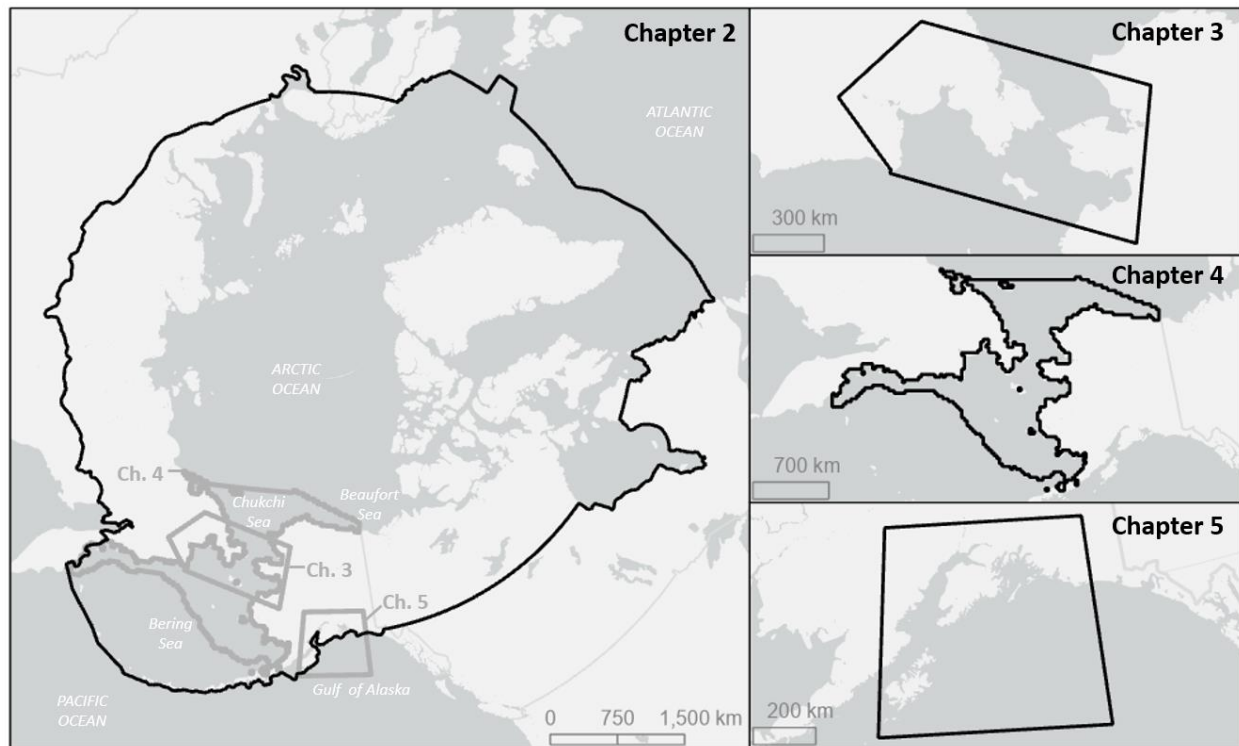


Figure 1.2 Map overview of study areas for each chapter of this dissertation. Chapter 2 is focused on the circumpolar Arctic as defined by the Arctic Council’s Arctic Monitoring and Assessment program (AMAP 1998). Chapter 3 analyzes vessel traffic patterns in the Bering Strait region. Chapter 4 is focused on the ice-covered portions of the Bering, Chukchi, and Beaufort Seas (within the bounds of vessel traffic data collection). Chapter 5 covers the movements of Steller sea lions (*Eumetopias jubatus*) and vessels in the western and central Gulf of Alaska.

In the northern portion of the Bering Sea, the Bering Strait is the only maritime connection between the Pacific and Arctic Oceans. Unlike the Atlantic, which has many access points connecting to the Arctic Ocean, all vessel traffic traveling to and from the Arctic via the Pacific must pass through the Bering Strait. Recent declines in seasonal sea ice extent, concentration, and thickness throughout the Arctic have enabled increases in the number of vessel transits of the Bering Strait (Azzara et al. 2015, U.S. Coast Guard 2016). While the development of Arctic natural resources is the primary driver of marine vessel traffic in the Bering Strait region (Arctic Council 2009), the Northern Sea Route does cut up to 30% off the distance between European and Northeast Asian markets, and projected increases in the length of the ice-free season in the region could mean shipping cost reductions and increased transits (Arctic Council 2009, Khon et al. 2010,

Smith and Stephenson 2013). Recent completion of the Yamal Liquefied Natural Gas (LNG) plant in Russia is likewise expected to increase seasonal vessel traffic via the shipment of LNG to Asian markets through the Bering Strait while also pushing shipping into the marginal ice season with the creation of LNG-carrying icebreakers (Beveridge et al. 2016, U.S. Coast Guard 2016).

1.4 Research Objectives

The overall objective of this dissertation is to quantify the spatiotemporal patterns of vessel traffic in northern social-ecological systems and to relate these patterns to other system components, including sea ice phenology and wildlife movements. This dissertation treats each study area as one or more metacoupled human and natural systems. For example, marine vessel traffic is considered to be part of the human subsystem. Natural subsystem components include sea ice dynamics and Steller sea lion (*Eumetopias jubatus*) movements. The objectives of each dissertation chapter are summarized and reviewed below.

In chapter 2, we present a detailed discussion of the application of the metacoupling framework to Arctic coupled human and natural systems. In chapter 3, we focus on applying the metacoupling framework to classify voyages into functional groups based on their movement patterns in the system: local (intracoupled), regional (pericoupled), transient (telecoupled), and inbound/outbound (peri- and/or telecoupled). chapter 4 examines the effects of natural system components (sea ice phenology) on vessel traffic, and in chapter 5 we apply a resource selection function to analyze the relationship between Steller sea lion and vessel movements. The specific objectives for each chapter are as follows:

- Chapter 2:
 - Review the degree of incorporation of non-local and/or international factors in Arctic coupled human and natural systems research.

- Evaluate the utility of the metacoupling framework for Arctic CHANS research.
- Chapter 3:
 - Apply the metacoupling framework to develop a new typology of shipping traffic based on the function a ship serves within a system.
 - Characterize the spatial and temporal distribution of marine vessel traffic in the Bering Strait Region
 - Identify spatial patterns of trends in marine vessel traffic types.
- Chapter 4:
 - Assess the relationship between shipping traffic and sea ice concentration using ship tracking data and a combination of passive and active microwave remote sensing of Arctic sea ice.
- Chapter 5:
 - Quantify the relationship between vessel traffic and Steller sea lion resource selection in the Gulf of Alaska.
 - Compare the relative effects of fishing and non-fishing vessels on Steller sea lion resource selection.

CHAPTER 2: THE METACOUPLED ARCTIC: HUMAN-NATURE INTERACTIONS ACROSS LOCAL TO GLOBAL SCALES AS DRIVERS OF SUSTAINABILITY

Kapsar, K., Frans, V., Brigham, L., Liu, J. 2022. The Metacoupled Arctic: Human-nature interactions across local to global scales as drivers of sustainability. *Ambio*: 1-18.

2.1 Abstract

The Arctic is an epicenter of complex environmental and socioeconomic change. Strengthened connections between Arctic and non-Arctic systems could threaten or enhance Arctic sustainability, but studies of external influences on the Arctic are scattered and fragmented in academic literature. Here, we review and synthesize how external influences have been analyzed in Arctic coupled human and natural systems (CHANS) literature. Results show that the Arctic is affected by numerous external influences nearby and faraway, including global markets, climate change, governance, military security, and tourism. However, apart from climate change, these connections are infrequently the focus of Arctic CHANS analyses. We demonstrate how Arctic CHANS research could be enhanced and research gaps could be filled using the holistic framework of metacoupling (human-nature interactions within as well as between adjacent and distant systems). Our perspectives provide new approaches to enhance the sustainability of Arctic systems in an interconnected world.

2.2 Introduction

The Arctic is a diverse region with many complex environmental and socioeconomic systems. Researchers attempting to understand these systems have frequently applied a coupled human and natural systems (CHANS) framework (Liu et al. 2007, Alberti et al. 2011). Also known as social-ecological or human-environment systems research, CHANS approaches examine not

only environmental (e.g., ecosystems, hydrological systems) or human systems (e.g., governments, social networks), but also the human-nature interactions that bind them together.

Arctic CHANS research has been at the forefront of several advances in CHANS approaches, including increased integration of human and natural systems as well as the incorporation of traditional and local knowledge (Petrov et al. 2016). Examples of Arctic CHANS studies include resilience assessments of the impacts of natural resource development on reindeer herding practices in Russia (Forbes et al. 2009), participatory mapping of environmental change by Indigenous communities in northern Canada (Gill et al. 2014), and an analysis of the impacts of fisheries privatization in Iceland (Kokorsch and Benediktsson 2018), among others.

However, Arctic CHANS do not operate in isolation. They are frequently impacted by actions occurring in adjacent and/or distant systems. For example, one of the main linkages between the Arctic and the rest of the world is through the influence of greenhouse gas emissions on the Arctic's climate. Climate change, a phenomenon primarily fueled by greenhouse gas emissions from lower latitudes, is causing the Arctic to warm at more than twice the global average rate (Overland et al. 2019). These rising temperatures have cascading effects on Arctic ecosystems and their human residents through mechanisms such as thawing permafrost (Shi et al. 2019), reducing sea ice extent (Parkinson 2014a), and altering the migration timing and patterns of wildlife, which subsequently changes the seasonality and location of subsistence harvests (Kovacs et al. 2011).

Aside from climate change, numerous other external influences, such as natural resource development and global markets, have complex effects on the sustainability of Arctic CHANS. For example, the development of oil and natural gas extraction can have positive impacts on the job opportunities and economic well-being of isolated communities, as was the case in

Hammerfest, Norway after offshore oil development began (Loe and Kelman 2016). However, oil exploration can also negatively impact flora and fauna, such as those in Alaska, where regions proposed for offshore drilling substantially overlapped with cetacean habitats (Reeves et al. 2014).

While connections between the Arctic and lower latitudes are not new, their strength and frequency have dramatically increased in recent decades. These growing connections indicate that the sustainability of Arctic regions could be increasingly influenced by distant actors, foreign policies, and global markets (National Research Council 2015, Callaghan and Johansson 2021). This pattern has sparked concern among Arctic residents and policymakers alike and has resulted in calls for an increased understanding of the complex, interactive effects of multiple external influences operating within or affecting Arctic systems (Members of the World Economic Forum Global Agenda Council on the Arctic 2014, Larsen and Fondahl 2015). To better understand the complex nature of these external connections there is a need for comprehensive conceptual frameworks that incorporate the interactions between multiple CHANS.

In recent years, the conceptual framework of metacoupling has emerged as one such tool. The framework of metacoupling organizes CHANS into five component parts (systems, agents, flows, causes, and effects) for the purpose of categorizing and better understanding system sustainability (Table 2.1; Liu 2017; Liu et al. 2021). Metacoupled CHANS include three types of couplings based on the number of systems and their relationships to each other: intracouplings, pericouplings, and telecouplings. Intracouplings are socioeconomic and environmental interactions within a single system; pericouplings occur when socioeconomic and environmental interactions occur between adjacent systems; and telecouplings occur when these interactions form between distant systems. The term metacoupling is an umbrella concept that encompasses all three types of couplings (intra-, peri-, and telecoupling).

This framework builds upon existing conceptual frameworks, such as Ostrom’s approach to sustainable social-ecological systems (which are examples of CHANS; Liu et al. 2007), by explicitly incorporating the reciprocal influences of external connections to focal system(s) (Ostrom 2007). These external connections to Arctic CHANS are a critical element of CHANS analyses, as they pose a potential challenge for the sustainable governance of common pool resources by violating the first design principle of defining a clear and closed set of resource users (Ostrom 1990). Additionally, when resources are primarily extracted for use in systems that are considered “exogenous” to a focal system (e.g., oil and gas exports from the Arctic), it is unreasonable to assume that the sustainability of a focal system can be achieved in isolation from those to which it is tightly linked through socioeconomic and environmental flows.

To understand the complex interactions between Arctic CHANS and other regions and their impacts on Arctic sustainability, it is necessary to first take stock of studies that have incorporated external influences in existing analyses. To this end, we conducted a literature review of studies analyzing Arctic systems as CHANS. After identifying the state of Arctic CHANS analyses from our literature review, we highlight the potential for using the framework of metacoupling as a method for integrating, advancing, and communicating CHANS research in the Arctic (Liu 2017, Liu et al. 2021). To demonstrate its application to Arctic systems, we provide examples of metacouplings in the Arctic CHANS analyses from our literature review and from other Arctic research. We purposefully chose to illustrate numerous examples from many areas of the Arctic CHANS literature to demonstrate the broad applicability of the metacoupling framework and to lay the groundwork for future analyses. We then discuss ways in which the metacoupling framework can be used to identify the cumulative and interactive effects of multiple

external influences, as well as to identify gaps in the literature and new potential areas of knowledge synthesis.

2.3 Literature review of Arctic CHANS research

2.3.1 Methods of literature review

To conduct a systematic review of the Arctic CHANS literature regarding external influences, we ran a Web of Science topic search using the following sets of terms: (1) “social-ecological” AND “Arctic”; (2) “socioecological” AND “Arctic”; (3) “coupled human and natural” AND “Arctic”; (4) “human-rangifer” AND “Arctic”; and (5) “human-environment” AND “Arctic”. Topic searches identified all articles containing the search terms in the title, keywords, or abstract. We chose these search terms to represent the varied terms used to refer to the study of coupled human and natural systems.

We screened the abstracts and methods sections of articles identified in the Web of Science search and selected relevant articles based on four criteria. First, we excluded papers conducting studies outside the boundaries of the Arctic as defined by the Arctic Monitoring and Assessment Program (Arctic Monitoring and Assessment Programme (AMAP) 1998). Second, we excluded papers that did not conduct qualitative or quantitative analyses (e.g., conceptual papers, reviews, or papers without explicitly described methodologies), as we were primarily interested in the degree to which external influences were incorporated in the data collection process. We identified analytical papers as those that specifically described the methods used to develop or aggregate the information presented. We included papers presenting a case study based on a conceptual framework or meta-analysis if data collection methods were present. We also excluded book chapters and gray literature. Third, we excluded papers that did not use CHANS language (see above search terms) in the context of discussing the study system. This approach alleviated the

need to make arbitrary decisions about the study's qualification as CHANS research by using the study authors' self-designated definition of the system as a CHANS. Lastly, we excluded papers that did not use a CHANS approach (e.g., ecological analyses that acknowledge the system is a CHANS). To ensure that all relevant articles were identified, even if they were not in the search results, we conducted forward and backward reference checks using a snowballing method for all studies retained after initial screening (Wohlin 2014). All papers published through June of 2020 that fit the screening criteria were included in the analysis.

From each paper, we collected the number of countries studied, the name(s) of the Arctic country or countries studied, the type of research, the geographic scale(s) of the research, and the degree of community involvement in the research (Table S1.0.1). We also used the research questions, study area description, methods, and abstract to determine whether an analysis of external influences was a primary focus of the paper, and used inductive coding to categorize these external influences into groups (Thomas 2006).

2.3.2 External influences identified in the analyses of Arctic CHANS

We identified a total of 103 studies conducting an analysis of the Arctic as a CHANS. External influences were a focus of analysis in 61% of these Arctic CHANS studies. Climate change was the most commonly studied external influence (Figure 2.1). Other common external influences included policy (11% of studies) and natural resource development (8%). Eight percent of studies focused on “change” in a broadly defined way that included external influences (e.g., broadly speaking about globalization). Global markets, invasive species, trade, technology transfer, and tourism were each the focus of research in less than 3% of studies. While a few studies examined Arctic CHANS as one of multiple case studies, no study explicitly examined the connection between an Arctic CHANS and one or more non-Arctic CHANS.

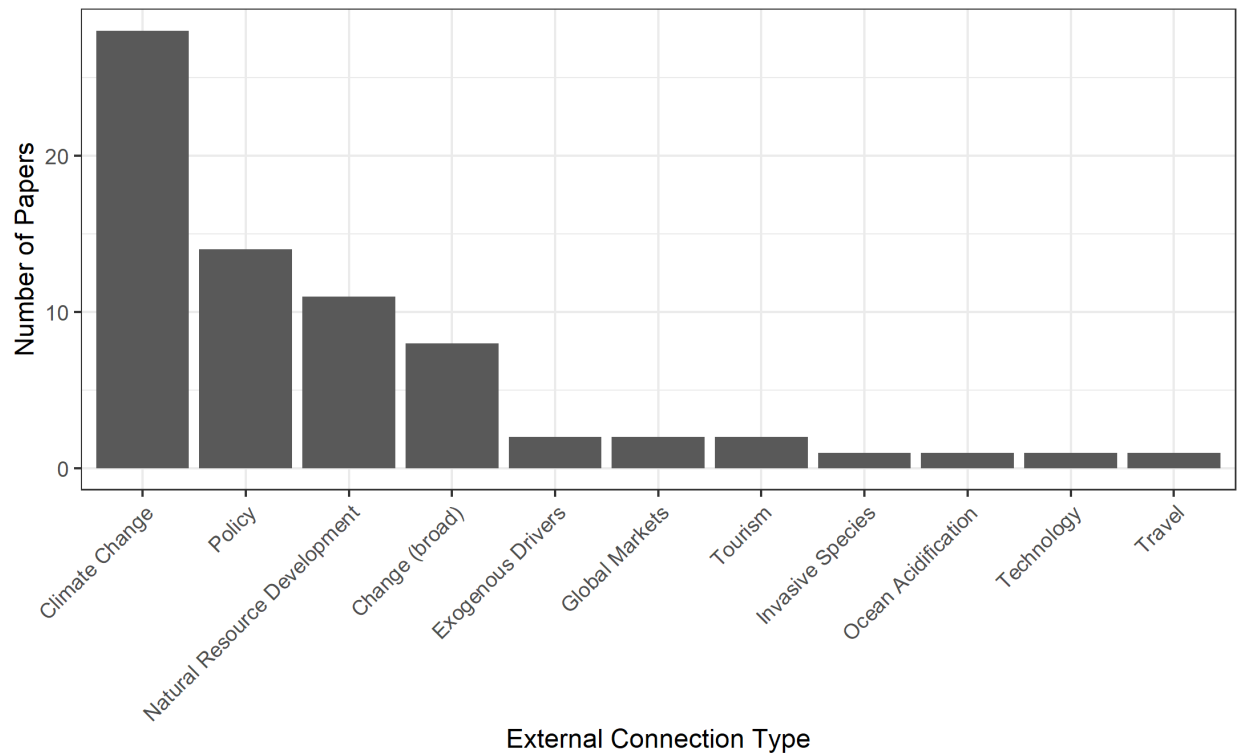


Figure 2.1 Most common external influences in Arctic CHANS analyses. Note that papers can have more than one external influence.

In our study sample, academic research on external influences appeared to be heavily focused on climate change. Climate change was the sole external influence studied in 22 of the 64 studies that analyzed at least one external influence. While not the primary focus of analysis, other types of external influences, such as international trade, natural resource development, governance, and tourism, were often discussed by Arctic residents in interviews (Moerlein and Carothers 2012, Ford et al. 2013). For example, when Moerlein and Carothers (2012) asked Inupiaq elders in northwestern Alaska about the environmental impacts of climate change, they found that residents holistically incorporated both social and environmental change into their responses. This observation contrasts with traditional academic approaches that treat social and environmental problems as separate. In their conclusion, Moerlein and Carothers state that “these communities face a total environment of change, whereby environmental changes and broader socioeconomic

challenges are jointly shifting and remaking human-environment relationships” (Moerlein and Carothers 2012). Results such as these demonstrate the need for more integrative frameworks that can be applied to examine the socio-environmental interactions and feedback effects of multiple external influences on Arctic CHANS.

Similar to the types of external influences, the scales of analysis and geographic distribution of Arctic CHANS research in our sample were also skewed. Most Arctic CHANS analyses took place at the regional (within-country) extent (54%). These studies typically presented the aggregated results and/or a comparison of results of data collected from several focal communities. Single community studies were the second most frequent scale of analysis (22%), followed by studies with multiple scales of analysis (14%), international studies (9%), and national scale studies (1%). The United States was the most common study location for Arctic CHANS analyses (50 studies), followed by Canada (25), Norway (22), and Russia (17). Finland, Sweden, Iceland, and Greenland (Denmark) collectively had fewer than 7 studies.

Qualitative methods were the most common form of analysis, comprising 45% of studies, followed by mixed qualitative and quantitative (35%), and quantitative (20%) studies. Over 75% of studies involved local communities in some manner. The most common form of involvement for local communities was as participants in data collection, with co-design and/or co-production of knowledge described in only 23% of studies.

External influences on the Arctic have been analyzed in numerous disciplinary and even multidisciplinary combinations (e.g., climatology (Overland and Wang 2018); climatology and economics (Petrick et al. 2017); climatology, economics, and fisheries science (Eide 2008)). However, despite increasing calls from researchers and policymakers for more interdisciplinary research on Arctic systems (Arctic Council 2016, Petrov et al. 2016, Anderson et al. 2018), our

review demonstrates that external influences, particularly those other than climate change, are infrequently the focus of analysis in the Arctic CHANS literature. Less than half of the papers in our review analyzed an external influence that was not climate change.

This finding indicates a need for more analyses of the interconnections between Arctic and non-Arctic systems and their implications for the sustainability of Arctic CHANS. To this end, we present the conceptual framework of metacoupling and describe how it can be used to synthesize knowledge on connections between multiple CHANS and their effects on sustainability in the Arctic.

2.4 Application of the metacoupling framework

To promote more studies on the interactions between Arctic and non-Arctic systems and to address the lack of integration of external influences in the Arctic CHANS literature, we suggest the application of the metacoupling framework. This framework builds upon CHANS research, as well as scholarship related to the distant connections between CHANS, known as telecouplings (Liu 2017, Kapsar et al. 2019). Stemming from the field of geography and other fields such as ecology and socioeconomics, the metacoupling framework allows researchers to integrate disciplinary research into interdisciplinary understandings of complex systems. The framework is general and can be applied to any CHANS although the specifics (e.g., agents, flows, effects) may differ. For example, the framework has been applied to global marine fishing (Carlson et al. 2020), freshwater ecosystem services to global cities (Chung et al. 2021), and impacts of international trade on global sustainable development (Xu et al. 2020b). In different systems, we would expect that the unique socio-economic and environmental contexts would lead to different system structures and sustainability outcomes under the metacoupling framework. However, comparative

studies between metacoupled systems could help to identify similarities and differences as well as important structures that facilitate or hinder sustainability objectives.

As a conceptual construct, the metacoupling framework serves to guide researchers in situating their research within a broader context by taking into account transboundary socioeconomic and environmental interactions in a systematic manner. (Figure 2.2). Similar to the way the umbrella concept of “ecosystem services” has integrated disciplinary knowledge of the benefits of the natural environment for humanity, the metacoupling framework can be applied to synthesize knowledge of diverse connections between CHANS and their impacts on social-ecological sustainability.

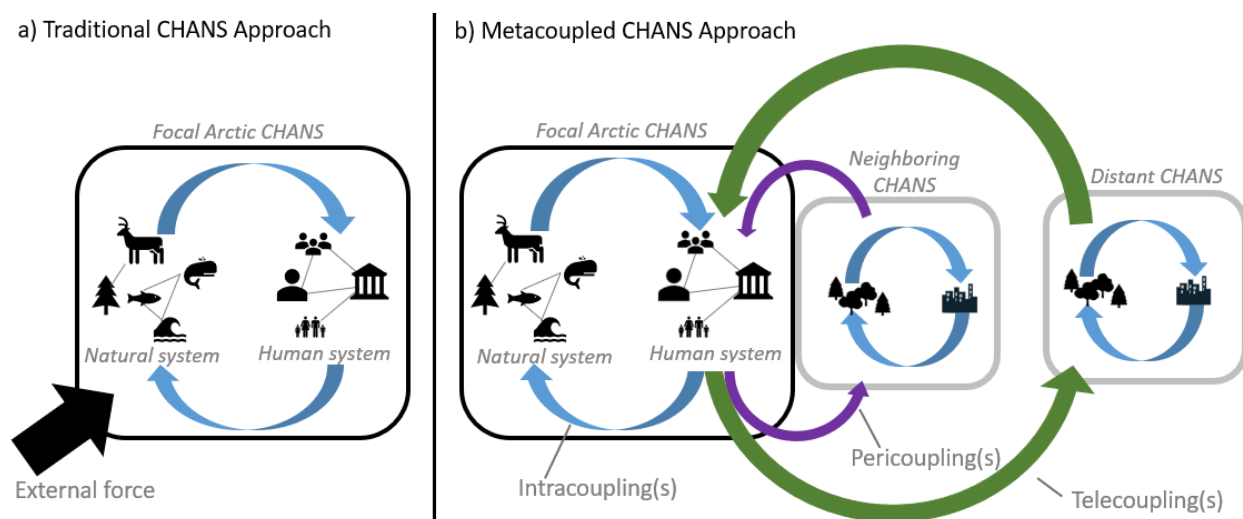


Figure 2.2 Conceptual diagram demonstrating the differences between a traditional CHANS and a metacoupled CHANS approach to analyzing the effects of external forces on Arctic systems. Focal systems are outlined in black while non-focal systems are outlined in grey. Blue arrows represent intracoupled flows of materials, information, people, and/or energy. Purple arrows represent pericoupled flows (between neighboring CHANS). Green arrows represent telecoupled flows between distant CHANS. In addition to external influences on Arctic systems, the metacoupled approach also considers the impacts of the Arctic on other systems (e.g., feedback, provision of Arctic resources to lower latitudes, cold spells, and heavy precipitation to lower latitudes).

The metacoupling framework provides several conceptual advances that can build upon previous Arctic CHANS scholarship, such as the explicit incorporation of feedback effects.

Previous research on the role of external influences on CHANS has examined their role in shaping system sustainability in a unidirectional way. For example, when analyzing the influence of exogenous drivers on Indigenous subsistence communities in the western Arctic, Fauchald et al. (2017) distinguish between exogenous drivers that act directly on a natural resource (e.g., commercial fishing) and those that act on resource users (e.g., technology access). The metacoupling framework builds upon this foundational knowledge of exogenous drivers through the incorporation of feedback effects, whereby actors influence the driver itself or the system from which the driver originates. Feedback effects are commonly studied in complex adaptive systems like CHANS (Levin et al. 2012), and are a key aspect of metacoupled systems (Hull et al. 2015, Yang et al. 2018).

Another conceptual advancement of the metacoupling framework is the explicit incorporation of external systems and cross-scale interactions. In our review of Arctic CHANS studies, many analyses acknowledged the role of external forces (Figure 2.2a). For example, ten studies had analytical approaches focused on broadly defined “change” or “exogenous drivers”. These studies often fail to account for the scale of operation of that driver (e.g., global, regional, local), the distance between exogenous drivers and the focal system, and/or the relative orientation between the interconnected systems (e.g., neighboring, distant). Furthermore, the metacoupling framework facilitates studies regarding not only impacts of adjacent and distant systems (e.g., lower-latitude regions) on the focal system (e.g., Arctic), but also impacts of the focal system on other systems nearby and far away.

Scale and geographic proximity of systems may play a more significant role in certain metacoupling types than others. For example, information and governance decisions can be transmitted across long distances in very short time spans over the internet. Thus, the distance

between the sending and receiving systems (and thus the definition of peri- vs. telecoupling) may not be as critical under some circumstances. However, in the context of the marine transportation of oil and gas from northern Russia to Asian ports, the voyage distances between sending and receiving systems is a very relevant factor that influences the rate of transportation of the flow as well as the spillover environmental effects of marine shipping.

Timescale is also an important part of metacoupling processes. Metacoupling processes are dynamic over time, such as with anthropogenic climate change, and different metacoupling processes take place across dramatically different timescales. For example, crop domestication takes place over years to centuries, while financial transfers can complete over seconds. Additionally, metacoupling processes may exhibit common trajectories of formation, growth, and dissolution over time (Liu 2017), however this is an emerging area of metacoupling research that is in need of further study.

The metacoupling framework explicitly identifies five components of CHANS: *flows*, *systems*, *agents*, *causes* and *effects* (Figure 2.2b; Table 2.1). *Flows* are defined as the movement of materials, information, or energy within or between metacoupled system(s). Flows can be both material (e.g., copper, nickel, oil) or immaterial (e.g., information). For instance, in the case of commercial fishing, the flow would be the movement of fish; in the case of pollution, the flow would be the movement of the pollutant; and in the case of policy implementation, the flow would be the movement of information. Flows are frequently associated with feedback effects that work to strengthen (positive) or weaken (negative) the original flow (e.g., Yang et al. 2018). *Systems* are the coupled human and natural systems in which the metacoupling processes take place. They can be sending systems if the metacoupled flow originates from them, receiving systems if the metacoupled flow is sent to them, or spillover systems if they are impacted by the metacoupling

processes, such as interactions between sending and receiving systems. *Agents* are the entities involved in the transfer of those flows. Agents could be the regulating authorities controlling the flow or the flows themselves (e.g., migratory wildlife). *Causes* are the human and/or natural factor(s) that initiate a metacoupling process, and *effects* are the outcomes of a metacoupling process within all involved systems.

Table 2.1 Description of the five components of the metacoupling framework with common examples and relevant literature focusing on each component.

Components of the metacoupling framework	Definition of metacoupling component	Examples	Relevant literature
Sending systems	Systems in which a given flow originates	• Community/Village • Region • Biodiversity hotspot • Country	• Friis and Nielsen 2017 • Liu et al. 2015 • Andriamihaja et al. 2019 • Herzberger et al. 2019
Telecoupled Receiving Systems	Distant systems in which a given flow terminates	• Importing countries • Tourist destinations	• Sun et al. 2018 • Yao et al. 2020
Pericoupled Receiving systems	Adjacent systems in which a given flow terminates	• Seasonal migration destinations • Intermediate processors	• Hulina et al. 2017 • Herzberger et al. 2019
Spillover systems	Systems that affect or are affected by the flow or its transportation from sending to receiving systems	• Coastal areas • Downstream or neighboring ecosystems/communities	• Liu et al. 2018 • Zhao et al. 2020
Flows	Movement of materials, energy, or information	• Animal migration • Tourism • Trade • Technology transfer • Investment • Human migration • Knowledge transfer • Species dispersal • Water transfer • Waste transfer	• López-Hoffman et al. 2017 • Chung et al. 2020a • Xiong et al. 2018 • Tonini and Liu 2017 • Yang et al. 2016 • Zimmerer et al. 2018 • Carlson et al. 2017 • LaRue et al. 2021 • Deines et al. 2016 • Liu et al. 2014

Table 2.1 [cont'd]

Agents	Individual actors or institutions involved in the development, maintenance, or termination of a metacoupled flow	• Community members • Policy makers • Regulators • NGO representatives • Industry representatives	• Liu and Agusdinata 2021 • Yang et al. 2018 • Kalt et al. 2021 • Andriamihaja et al. 2019 • Marola et al. 2020
Causes	Environmental, socioeconomic, political, or technological drivers that work to initiate a flow within or between systems. Can occur in sending, receiving, or spillover systems.	• Demand for resources • Natural disaster • Policy implementation	• Carlson et al. 2017 • Zhang et al. 2018 • Herzberger et al. 2019
Effects	Environmental, socioeconomic, political, or technological impacts of a metacoupling process. Can occur in sending, receiving, or spillover systems.	• Land use/Land cover change • Improved/diminished wellbeing • Biodiversity change	• da Silva et al. 2021 • Llopis et al. 2020 • Kuemmerle et al. 2019

Comparative analyses can help identify knowledge gaps and generate hypotheses about the relevant links. While there is no single prescribed methodology for identifying metacoupled system components, commonly applied methods from previous studies include literature review, field work, and qualitative research. For example, Friis and Nielsen (2016) used ethnographic field research to examine local communities' perceptions of telecoupled foreign investments in banana plantations in Laos. In addition, a wide variety of methods have been used to analyze telecoupled flows, causes, and effects, including network modeling and cluster analysis (Chung et al. 2020b), agent-based modeling (Dou et al. 2019), time series analysis (Carlson et al. 2020), life-cycle analysis (Xu et al. 2020a), and remote sensing of land use and land cover change (Leisz et al. 2016).

Not all components of a given metacoupling process may be relevant in all studies. Intracoupling processes may exist in isolation from telecouplings and vice versa. Or, there may not be significant spillover effects related to a given pericoupling process. In this way, the metacoupling framework is not a panacea, but rather a tool that can be applied to unearth potential new aspects of a given system or to examine the effects that changes in one system could have upon other systems.

Below, we describe each metacoupling type in turn, discuss how they relate to existing Arctic CHANS analyses or studies, and provide further examples of existing research reframed under the conceptual framework of metacoupling. In addition, we discuss challenges for Arctic metacoupling research and the value of the metacoupling framework to Arctic sustainability research and policy.

2.4.1 Arctic intracouplings

Intracouplings are human-nature interactions that occur within a system, such as the subsistence harvest of plants and wildlife inside Arctic CHANS. In our literature review, community and regional-scale studies comprised over three-quarters of the studies we analyzed. Moreover, over three-quarters of analyzed studies involved the input of local communities in some manner, indicating that intracouplings are a key topic of academic research interest in the Arctic. These findings are expected given the prevalence of pastoralist and subsistence livelihoods in the circumpolar Arctic. In many parts of Alaska, for example, Indigenous communities maintain the traditional subsistence harvest of well over 50% of the foods that they consume (Fall 2016). The subsistence way of life, practiced by Indigenous communities for thousands of years, is interdependent with a healthy ecosystem that can support the large mammals harvested by many communities as key elements of their diet and cultural wellbeing. Additionally, the concept of food

security in Arctic Indigenous communities is inextricable from the practice of subsistence (ICC Alaska 2015). When viewed through the metacoupling framework, subsistence can be considered an intracoupled process or intracoupled human-environment interaction. While subsistence is one of the most straightforward intracouplings in the Arctic, other examples include farming, forestry, and environmental restoration, among others.

2.4.2 *Arctic pericouplings*

Pericouplings are human-nature interactions between adjacent coupled systems. The interconnected nature of the Arctic has resulted in the development of many pericoupled processes, which can occur at multiple scales. While not explicitly identified as pericouplings in the literature, we found multiple examples of pericoupled systems in our literature review. For example, Risvoll et al. (2016) use interviews and participant observation to examine human-wildlife conflict between wild carnivores and pastoralists in the Nordland, Norway and identify challenges for cross-boundary management of wildlife between Sweden and Norway. This represents a pericoupling whereby wildlife (the flow) move between Norway and Sweden (receiving and sending systems).

The pericoupled movement of wildlife populations across geopolitical boundaries also occurs in marine systems, and may be increasing in frequency as climate change alters the distributions of commercially important species (Pinsky et al. 2018). For instance, Pacific cod (*Gadus microcephalus*), an important United States export, are harvested from neighboring regions of Alaska and Russia and are likely genetically similar (Spies et al. 2020). However, they are currently managed independently by each national government. The mismatch between a pericoupled flow of fish between two systems, and independent governance of those two systems poses a threat to the sustainability of the fish populations in the long term.

In several instances of pericoupled animal migration, there have been bilateral or multilateral policies put in place to coordinate management, promote collaborative research, and ensure sustainable harvest of shared fisheries and wildlife populations. For example, the Chukchi Sea polar bear (*Ursus maritimus*) sub-population is co-managed by Indigenous communities and federal government representatives from both the United States and Russia who meet regularly to share knowledge and update policies to ensure the sustainability of this polar bear sub-population (U.S. Fish & Wildlife Service 2017). This sharing of information in and of itself represents a pericoupled information-sharing flow that is used to manage the pericoupled polar bear sub-population. Pericoupled (and telecoupled) information flows between the Arctic Range States are extremely common. Arctic countries have historically maintained a record of peaceful collaboration through intergovernmental forums and other organizations, such as the Arctic Council, the regional Barents Council, the Inuit Circumpolar Council, and others (Young 2016).

Pericoupled flows of humans and resources throughout the Arctic also allow for access to resources in isolated communities. At a sub-national scale, rural-urban transportation networks allow remote communities access to health care and other resources that are not available at home. Permanent or semi-permanent migration from rural to more urban or hub communities has also arisen as a concern in the Arctic and may exacerbate capacity-building challenges in remote communities (Larsen and Fondahl 2015). Problems such as rising fuel costs and a lack of job opportunities have been cited as reasons for this phenomenon (Berman 2017). In particular, the loss of adult women and children from remote communities can result in the loss of key community assets, such as school buildings and the jobs and community gathering spaces they provide (Martin 2009).

2.4.3 Arctic telecouplings

Telecoupling processes occur when human-nature interactions are separated across large distances (i.e., distant coupled systems). While the Arctic is often thought of as a region isolated from the rest of the world, climatological, ecological, and social processes have long connected this region to lower latitudes. Multiple studies in our literature review examined “exogenous drivers” that would be classified as telecouplings when analyzed under the metacoupling framework (e.g., Meek 2011; Fauchald et al. 2017).

One prominent example of an Arctic telecoupling process occurring at an international scale is the concept of climatological teleconnections. In recent years, the Polar Vortex phenomenon, whereby Arctic air is transported south, has brought extreme cold spells and heavy precipitation to lower latitudes (Overland et al. 2016), and has gained much attention among both academic and non-academic audiences. While academics have primarily focused on the Polar Vortex phenomenon as a climatological event, it also has economic and social consequences in both the Arctic and lower latitudes. Examples of its socioeconomic effects in the northeastern United States include infrastructure damage, lengthy travel and transportation delays, and the loss of human life. When both the environmental phenomenon and its socioeconomic consequences are considered, the Polar Vortex can be viewed as a telecoupling process.

Beyond climate-related telecouplings, other telecoupling processes also connect the Arctic to lower latitudes. Long-distance species migrations, such as that of the Arctic tern (*Sterna paradisaea*), which can migrate up to 80,000 kilometers between the Northern and Southern Hemispheres over the course of a year (Egevang et al. 2010), also connect Arctic and non-Arctic systems, with conservation and management implications throughout their migratory range.

Many telecoupling processes in the Arctic are ultimately connected to global markets. Global commodity prices are key drivers of natural resource development, including mining and oil and gas industries in Arctic countries (Arbo et al. 2013). This is particularly true for natural resource development projects in the Russian Arctic. Such processes include oil and gas drilling, commercial fishing, and mining. Gautier et al. (2009) estimate that up to 13% of the world's undiscovered oil and 30% of its undiscovered gas may be located on or above the Arctic Circle. Additionally, walleye pollock (*Theragra chalcogramma*) harvested in the North Pacific make up 5% of total global fisheries and approximately 40% of United States fisheries (Bailey et al. 1999). Despite the apparent outsized influence of global markets on Arctic natural resource development and their subsequent impacts on local communities, these connections appear to be relatively understudied in the Arctic CHANS literature. A notable exception, however, is Forbes (2013) who used intensive participant observation with nomadic Nenets reindeer herders in the Russian Arctic to examine the factors that influenced their resilience to climate change as well as land encroachment by large-scale oil and gas development. Forbes found that herder's agency over their relatively small, privately held herds as well as flexible institutional oversight allowed for increased and rapid adaptability to the changing conditions and migration routes.

Tourism is another prominent telecoupling process occurring in many Arctic regions. In general, the phenomenon of "last chance tourism" has inspired many people to visit sites affected by climate change to see them "before they're gone for good" (Lemelin et al. 2010). Visitors often travel to the Arctic to view iconic sights, such as glaciers, polar bears (*Ursus maritimus*), and the lights of the Aurora Borealis. While their travel brings money to Arctic nations, those funds often remain in the hands of large companies and infrequently benefit members of the communities that host the tourists (Maher et al. 2014), similar to the uneven distribution of

benefits from tourism in remote nature reserves of lower latitudes (He et al. 2008). In addition to the carbon emissions associated with Arctic tourism (Dawson et al. 2010), there are also challenges associated with maintaining local biodiversity in heavily trafficked regions, as well as conflicts between land use for natural resource development and land use for tourism, such as the conflict between hydropower and tourism in Iceland (Saebórsdóttir and Saarinen 2016).

2.4.4 Interactions between metacouplings

Perhaps more important than any individual metacoupling process is the interaction between multiple, co-occurring metacoupling processes. The metacouplings discussed above (intracouplings, pericouplings, and telecouplings) rarely exist in isolation and are often interconnected with each other. These interconnections must be understood in order to accurately predict the cascading effects of any policy decision on Arctic sustainability. For example, the Covid-19 pandemic has spread throughout the world via telecoupled and pericoupled flows of travelers. However, in addition to the spread of the virus itself, the pandemic has had cascading consequences for telecoupled global supply chains (March et al. 2021), metacoupled economies (Pak et al. 2020), and intracoupled human-wildlife interactions (Shilling et al. 2021).

In many Arctic regions, a legacy effect of the extensive harmful impacts of previous pandemics led communities to take rapid actions that resulted in a delayed onset of the Covid-19 pandemic in many Arctic regions (Petrov et al. 2021). In this instance, historical experience with telecoupled transmission of diseases via flows of travelers was preserved through generations via intracoupled knowledge transfer and helped to mitigate some of the most devastating impacts of the current pandemic. In spite of these efforts, the Covid-19 pandemic has still had substantial cascading economic and social impacts on Arctic communities. Furthermore, scientific data collection in the Arctic, which is often conducted by scientists travelling from distant locations,

has been hampered by the pandemic, resulting in a loss of critical observations and disruptions to data time series. However, this gap in research has also opened up opportunities and space for reflection on the benefits and importance of co-production of knowledge and long-standing, equitable partnerships between researchers and Arctic communities (Petrov et al. 2020).

While many studies in our review described different types of metacouplings, the lack of a consistent framework for examining these processes made it difficult to make generalizations or find patterns, leading to many broad-sweeping analyses of a diverse array of processes being non-differentially classified as “exogenous”. These different connections can result in various unintended consequences or emergent properties in CHANS. Thus, it is important to differentiate and interrelate them in future Arctic investigations.

For example, the economy of the Arctic is predominantly based on intracoupled natural resource extraction processes driven by telecoupled demand. Commercial fisheries, rare earth minerals (e.g., palladium), and hydrocarbons are all present in the Arctic, and increasing global demand has, in some cases, made them economically favorable for extraction (Glomsrød and Aslaksen 2006). These extractive industries, if unregulated, can pose a threat to the sustainability of Arctic ecosystems and the human communities with which they are interdependent.

In addition to incentivizing the flow of natural resources from the Arctic, telecoupling processes also play a role in local economies and local human-environment intracouplings by creating jobs that facilitate participation in the cash economy. For example, many rural communities rely on a mixed cash and subsistence economy (Kruse et al. 2008). A cash-based income allows for the purchase of materials and equipment needed for harvesting animals and plants. In Alaska, harvests are primarily used for household and community-level subsistence and traditional cultural practices of Indigenous communities. However, in other countries, such as

Greenland (Denmark), wildlife harvest is primarily conducted by commercial hunters for distribution in local markets (Kruse et al. 2008). While it was originally hypothesized that Arctic residents would transition to an entirely cash economy with the introduction of market-driven jobs, the mixed economy has shown to be persistent and is predicted to remain in place (Burnsilver et al. 2016).

While previous research supports the idea that mixed economies are relatively stable (as opposed to a transitional state), the sustainability of rural communities has been drawn into question with regard to the phenomenon of rural-urban migration. This movement of individuals from rural to neighboring urban areas has been attributed to both the ability to participate in local, intracoupled subsistence activities (Berman 2009) and the presence of job opportunities in urban areas (Huskey et al. 2004). For example, using data from the survey of living conditions in the Arctic, Berman (2009) found that a decrease of 1% in harvest was significantly associated with a 1.25% increase in the probability of respondents considering moving away from a community. This finding is particularly relevant in the context of recent declines in Chinook salmon (*Oncorhynchus tshawytscha*) migrations along the Yukon River and subsequent impacts on community food security and wellbeing reported by media outlets (Hughes 2021). In addition to the lack of subsistence opportunities, in a review of rural-urban migration in Alaska Native communities, Huskey et al. (2004) found that economic opportunity was a key driver of migration. Understanding the relative influence of the intracoupled *push* of the lack of subsistence opportunities on the pericoupled migration process (i.e., sending system drives the pericoupled migration) versus the *pull* of job opportunities (i.e., receiving system drives the pericoupling) would provide critical knowledge needed to promote human well-being and sustainable livelihoods in the Arctic.

In the case of certain natural resources, such as fisheries, there is also the potential for conflict between intracoupling and telecoupling processes. Such is the case with commercial and subsistence fisheries in many parts of the Arctic. While subsistence fisheries make up a very small proportion of total harvest compared to commercial harvests (ca. 1% in Alaska), their cultural and economic importance has supported the creation of policies to ensure the ongoing ability of Indigenous communities to practice subsistence (Fall 2016). Subsistence-harvested species, although frequently shared among households or communities in a region, rarely leave the region in which they were harvested (Burnsilver et al. 2016). In the case of commercial fishing, the extraction of fish is driven by telecoupled demand and the fish, once captured, are transported to distant, telecoupled markets. These distant connections lead to a complex web of interconnected costs and benefits that must be negotiated if sustainable and equitable solutions are to be found. Furthermore, while resource harvest for local use and consumption remains relatively small, the magnitude of processes linked to global trade, such as the walleye pollock fishery, is substantially larger.

Security and militarization in the Arctic provide another example of the interaction of multiple metacoupling processes. Relative to other global regions, the Arctic states have prided themselves on maintaining relatively peaceful relations and developing and promoting shared policy agendas through international forums such as the Arctic Council (Kankaanpää and Young 2012). This combination of pericoupled and telecoupled information sharing and policy development has led to important joint analyses and policies, such as the development of the Arctic Marine Shipping Assessment, which in turn influenced the development of the International Maritime Organization's Polar Code and Arctic state treaties on search and research, and oil spill preparedness and response (Arctic Council 2009, International Maritime Organization 2014).

Alongside these successes, however, have come increasing security challenges, particularly in light of increased economic development in the Russian maritime Arctic and the influence of declining sea ice extent on the opportunity for increased telecoupled marine transportation of Russian oil and gas to Asian and European markets (Brigham 2021). As has been the case in other regions, international trade can present challenges to the sustainability of CHANS in sending, receiving, and spillover systems (da Silva et al. 2017, Liu et al. 2018, Sun et al. 2018).

Telecoupled animal migration patterns can also have an influence on other metacouplings. For example, the short-tailed albatross (*Phoebastria albatrus*) only breeds on two islands in Japan but feeds in the North Pacific. Incidental catch of short-tailed albatrosses by commercial longline fisheries, such as the Pacific cod (*Gadus macrocephalus*) fishery in the Bering Sea, is the main source of human-caused mortalities in these birds. At a population size of ~1700 (BirdLife International 2018), human-caused mortalities have significant effects on its persistence. These incidental catches also have significant policy-driven implications for commercial fisheries. In the United States' North Pacific fisheries management system, an incidental catch of just 3 short-tailed albatrosses within a given year has the potential to shut down the entire longline fleet for the rest of that year (U.S. Fish & Wildlife Service 2008, 2015). This is a case where a telecoupling process exists between the albatross' breeding grounds (Japan) and feeding grounds (Bering Sea) through migration and international management, and the intracoupled action of exceeding permissible incidental catch (within the Bering Sea longline fleet) can have cascading consequences across other telecoupled systems (fisheries and the global market).

2.4.5 Transportation of metacoupled flows

Previous research on telecoupling and metacoupling processes has often overlooked the social-ecological impacts of the transportation of metacoupled flows (Kapsar et al. 2019).

Internationally traded commodities, natural resources, and other such physical flows are most commonly transported on large cargo or tanker ships. In fact, more than 80% of the world's trade is transported in ships (UNCTAD 2017). In the Arctic, the majority of shipping is destination (as opposed to trans-Arctic) and driven by global commodities prices (Arctic Council 2009). Ships carry resources from remote mining or oil and gas developments in the Arctic to distant refineries and processing facilities. Small and large cargo vessels are also used to transport supplies to remote coastal communities during summer sealift operations throughout all regions of the coastal Arctic Ocean.

In a metacoupling context, Arctic marine operations and shipping represent the primary ways in which the telecoupled flows of resources are transported into and out of the Arctic. When transiting between sending and receiving systems, these ships can have spillover effects on other systems through which they travel. These effects include noise pollution, the introduction of invasive species through ballast water contamination, the death of large-bodied cetaceans through ship strikes, and the interruption of subsistence practices (Robards et al. 2016).

The environmental, economic, and social impacts caused by the transportation of metacoupled flows contribute to the total impacts of metacoupled processes, such as international trade. Recent advances in ship tracking technology through the International Maritime Organization's mandate of Automatic Identification System tracking technology on large vessels (>300 gross tons), has facilitated an increased understanding of the spatial and temporal distribution of ships over the course of the last two decades (International Maritime Organization 2000). Researchers are increasingly applying Automatic Identification System data to map the distribution of the effects of shipping (Eguíluz et al. 2016, Meyers et al. 2021).

Metacoupled shipping processes in the Arctic have also precipitated the development of international policy frameworks for mitigating potential negative impacts. Entering into full force in 2018, the International Maritime Organization's International Code for Ships Operating in Polar Waters was designed to provide a framework for enhancing marine safety and environmental protection. Also known as the Polar Code, these rules take a risk-based approach to enhance the safety of ship operations and prevent damage to both humans and the sensitive natural environment in polar waters (Deggim 2018). In a metacoupling context, the Polar Code seeks to minimize the spillover effects caused by the transportation of telecoupled flows of natural resources out of the Arctic.

2.4.6 Climate change and the metacoupled Arctic

Climate change is arguably the single most pervasive force affecting metacoupling processes in the Arctic. This importance is reflected in the high prevalence of climate change studies in our literature review. With the Arctic warming at more than twice the global average rate (Overland et al. 2019), there are virtually no human or natural systems left unaffected. A changing Arctic climate not only alters local food webs and human-nature interactions (i.e., intracouplings; Moerlein and Carothers 2012; Cochran et al. 2013), but also has cascading impacts on global geopolitics. In particular, melting sea ice has increased marine access and created conditions whereby previously inaccessible natural resources are now economically favored for extraction. With the retreat of sea ice, shipping routes that could be used to transfer these resources to global markets are now opening (Smith and Stephenson 2013, Stephenson et al. 2013). These changes could result in the development of new telecoupling processes or the strengthening of existing ones.

In a more ecological context, research and concerns for the Arctic fox (*Vulpes lagopus*) provide a robust example of the effects of climate change on multiple metacoupling processes in the Arctic. As climate changes, boreal forests are expanding and the Arctic fox's preferred habitat, tundra, is contracting (Selås et al. 2010). Climate change has also allowed for the northward expansion of the Arctic fox's competitor, the red fox (*Vulpes vulpes*), causing a reduction in the Arctic fox's range. As competitors, one would assume that these are part of normal ecological processes (e.g., competitive exclusion, predator-prey dynamics) affected by climate change. However, a study in Norway revealed that the red fox's expansion is not only due to climate change, but also due to facilitation from an increase of human infrastructure (e.g., roads, cabins) for Arctic tourism, which increased food availability (e.g., human garbage; Selås et al. 2010). The Arctic fox now avoids human-occupied areas, not because of humans, but because of the red fox being present in those areas. Because of such patterns and effects, the Biodiversity Working Group of the Arctic Council has prioritized monitoring and the collection of information on this species (Berteaux et al. 2017). As a result, a total of 34 monitoring projects in Iceland, Greenland, Canada, the United States, Russia, Norway, Finland, and Sweden comprise a circumpolar monitoring system for this species. In sum, the effect of climate change in the Arctic has allowed for the expansion of red fox habitat (boreal forest) to an adjacent system (pericoupling), which aided the red fox's expansion into this expanded habitat and was facilitated with the increase of tourism in the Arctic (telecouplings), causing competition within the system (intracoupling), and concerns for management of the Arctic fox in light of its range contraction has caused flows of information to be shared between and among adjacent and distant Arctic countries for international conservation efforts (peri- and telecouplings). Altogether, these form a complex web of metacoupling processes.

2.4.7 *Challenges for Arctic metacoupling research*

When analyzing metacoupling processes, it is critical to define relevant boundaries and scale(s) of analysis. While defining scale is a fundamental challenge in both social and ecological systems research, it is generally recommended that in order to avoid scale mismatches, the scale of analysis should be proportional to the scale of the phenomena being studied (Cash et al. 2006, Cumming et al. 2012).

Defining boundaries can also be a challenge in metacoupled systems analysis. Boundaries can be defined based on ecological (e.g., permafrost, tree line, currents, species' range), cultural or historical criteria (e.g., geographies of Indigenous lands or during a particular time period), or based on current political jurisdictions (e.g., among the eight Arctic states). The discussion of boundary definition is ongoing in the CHANS literature (Friis and Nielsen 2017, Liu et al. 2019). It is important to recognize that the choice of boundary can have substantial impacts upon the results of the analysis and that the decision of “membership” within a particular system may not be geographical (Friis and Nielsen 2017). For example, qualitative methods such as participant observation and interviews can be used to define membership within a given system from a network perspective. It is therefore critical to be clear as to the criteria used to define boundaries as well as the rationale behind the boundary definition.

Operationalizing the metacoupling framework for a particular system or flow involves the investment of resources to identify relevant components and metrics by which to define and measure them. As with all models, trade-offs exist between the level of effort or detail that is put into understanding a system and the degree of generalization of the model output. One can imagine that following every single flow of resources, material, or energy into, out of, or through a system would eventually result in a global-scale model so detailed that it would be rendered useless for

any other purpose. In the case of metacoupled system models, we suggest that model elements are not useful if they do not impact the output of interest in a meaningful way. Techniques such as fuzzy cognitive mapping or system dynamics modeling can be used to determine relevant system components (Hobbs et al. 2002). It would be difficult to ensure that every relevant metacoupling component is identified in a given analysis. However quantitative techniques (e.g., assessing model fit) or qualitative techniques (e.g., evaluating data saturation; Guest et al. 2020) may be used to ensure that a given model is comprehensive for its purpose. We point readers to recent overviews of modeling techniques and approaches in complex social-ecological systems for further discussion on this subject (Schlüter et al. 2019).

2.4.8 Value of the metacoupling framework to Arctic sustainability research and policy

The metacoupling framework is an integrative tool that can be applied to better understand interactions within and among adjacent and distant CHANS. The qualitative skew in our review of Arctic CHANS literature reveals an opportunity for greater knowledge integration with quantitative, disciplinary evaluations of, for example, Arctic climate and ecology. Findings from specialized analyses or specific local knowledge can be better applied to decision-making when they are integrated and contextualized as part of a metacoupled system (Fidel et al. 2014). This integrated understanding can then be applied to better predict the ways in which a perturbation in one part of a system could have cascading effects on human-environment relationships in local, adjacent, and distant locations.

In individual studies, the application of the metacoupling framework can seem like a needless application of jargon. However, defining and labeling the different components of a metacoupled system fosters comparisons between different circumstances and disciplinary lenses. For example, in a comparative analysis of oil drilling impacts on Indigenous communities in

Ecuador and Alaska, Haley (2004) demonstrated that the tight-knit and cohesive community of agents in Arctic Alaska was a critical element that allowed for Alaska Native communities on the North Slope to advocate for the consideration of subsistence practices in planning for natural resource development for global trade (Haley 2004). However, the lack of cohesion among Indigenous agents in Ecuador led to less successful negotiation practices. In this case, the social cohesion among the agents in Arctic Alaska was a cause that resulted in a modification of the flow of natural resources from the North Slope during subsistence seasons, thus modifying a telecoupling process (natural resource extraction for global trade) in order to maintain an existing intracoupling process (subsistence). When placed in the framework of metacoupling, these findings present a generalizable hypothesis that the facilitation of social cohesion and capacity building among local actors navigating telecoupling processes is a critical element to ensure that local concerns are addressed, and mutually beneficial solutions are developed. This hypothesis could then be tested in other settings or expanded to determine whether the same principles hold true, for example, to ask whether social cohesion among actors is critical for the sustainable maintenance of intracoupling processes in general.

The metacoupling framework also allows for more systematic analyses of CHANS through the identification of knowledge gaps with regard to their constituent components and the relationships between them. Table 2.2 gives an example of an application of the metacoupling framework to Parlee et al.'s analysis of the threats of mining to the Bathurst barren ground caribou herd (*Rangifer tarandus groenlandicus*; Parlee et al. 2018). This application shows that while there is a body of traditional and scientific knowledge demonstrating the impacts of mining activities on caribou herds and subsistence practices, there has been less CHANS research examining the drivers of mining or the motivations and decision-making structures of certain actors, such as

mining corporations. Further research is needed to determine whether these gaps are covered in other studies (and thus a source for future knowledge syntheses) or are areas for future research.

Table 2.2 Application of the metacoupling framework to identify future research directions on the effects of mining on Bathurst barren ground caribou (*Rangifer tarandus groenlandicus*) herd, based on a reading of Parlee et al. 2018 as an example. Underlined items indicate metacoupling components not analyzed within the scope of the study.

Components of the metacoupling framework	Specific metacoupling component analyzed or <u>not analyzed</u> (Parlee et al. 2018 - Bathurst Caribou Herd)
Sending systems	Range of the Bathurst caribou herd (including Ekati and Diavik Mines and the “Jay Project”)
Telecoupled receiving systems	<u>Systems where minerals are utilized</u>
Pericoupled receiving systems	<u>Systems through which minerals are transported and/or processed</u>
Spillover systems	<u>Systems involved in mineral refinement; Systems of origin for non-Indigenous hunters using mining roads to harvest caribou</u>
Flows	Migration of caribou from calving grounds in Bathurst Inlet to central Northwest Territories; Policies banning hunting for Indigenous hunters; <u>Movement of minerals</u>
Agents	Dene First Nation communities; <u>Mining corporations; Governments (e.g., Northwest Territories Environment and Resources)</u>
Causes	Government approval of extraction; Land ownership practices; Lack of communication, trust, and power-sharing between governments and Indigenous communities; <u>demand for mineral resources</u>
Effects	Loss of caribou habitat; Decline of caribou population; Inability to practice subsistence; Increased use of alternative food sources; Altered caribou migration patterns

Additionally, while this paper focuses on environmental and economic aspects of Arctic CHANS, the metacoupling framework could be used to examine other areas of research, such as education. For example, the metacoupling framework could be used to evaluate the relative influence of culturally sensitive approaches and education in traditional knowledge in contrast with western education, and their increasing mix in local communities on the wellbeing of Arctic residents and ecological systems.

The application of the metacoupling framework to Arctic CHANS can not only improve research, but also assist with the development of more effective Arctic sustainability policies. Identifying the various systems, agents, flows, causes, and effects that situate Arctic CHANS within complex metacoupled systems increases transparency, which is a first step toward effective policymaking (Munroe et al. 2019). Additionally, understanding the Arctic as a metacoupled system can also help in the development of polycentric governance processes that coordinate governance in the Arctic with adjacent and distant systems (Oberlack et al. 2018). For example, identifying the ecosystem services provided by migratory species, such as the pest control services provided by Mexican free-tailed bats (*T. brasiliensis*) in the United States (López-hoffman et al. 2017), could assist with ensuring equity in the transboundary management of migratory wildlife. Transboundary management is particularly important for the Arctic where many species of subsistence importance migrate from distant locales where they face substantial anthropogenic threats that in turn affect population dynamics in their Arctic summering grounds.

2.5 Conclusion

Much interdisciplinary CHANS research has been conducted to better understand human-nature interactions in the Arctic. Similarly, many disciplinary studies have analyzed the relationship between the Arctic and lower latitudes. However, these studies are often conducted in isolation and at relatively small scales. Holistic approaches to understanding complex systems could assist with knowledge integration to better place Arctic sustainability in a global context. This review highlights the utility of the metacoupling framework for integrating knowledge across scales and from multiple areas of study into a more complete understanding of Arctic CHANS in a globalized world. The metacoupling framework could be used to guide researchers in identifying knowledge gaps in their study system or areas for knowledge synthesis by answering questions

such as: what socioeconomic or environmental flows connect a focal system to distant systems? Who are the actors involved in perpetuating or weakening these flows? How might actions in distant systems affect the sustainability of a certain aspect of the focal system? How do actors or flows in the focal study system impact other systems that are nearby or far away. Answers to these questions can be used to facilitate knowledge integration and to create comprehensive and effective policies for promoting sustainability objectives while minimizing negative unintended consequences.

CHAPTER 3: QUANTIFYING THE SPATIOTEMPORAL DYNAMICS OF VESSEL TRAFFIC IN A RAPIDLY CHANGING MARITIME BOTTLENECK

Kapsar, K. Shortridge, A., Brigham, L., Liu, J. In Prep. Quantifying the spatiotemporal dynamics of marine vessel traffic in a rapidly changing maritime bottleneck. *To be submitted.*

3.1 Abstract

With a large majority of globally traded goods transported on ships, marine vessel traffic is an essential component of our globalized economy. Arctic systems, with their limited road networks and isolated locations, are particularly dependent on vessel traffic for the transportation of materials. From the Pacific, the narrow waters of the Bering Strait serve as the only entry and exit to the Arctic. While recent reports indicate that vessel traffic in this region is increasing, there has been little examination of the spatial distribution of these trends or the differences between local vessel traffic, which is essential for resupplying remote communities, and transient vessels that just pass through the Bering Strait in route to distant destinations. Here, we use high resolution ship tracking data to examine the spatial distribution in vessel traffic trends across a six-year time series from 2015 through 2020. We find that two-thirds of all voyages occurred in Russian waters. Additionally, while both the United States and Russia had similar numbers of voyages in 2015, growth in vessel traffic activity was concentrated on the Russian side of the Bering Strait, which experienced a 269% increase in the total Fishing activity over the 6-year study period. These increases are of particular concern for the wellbeing of local communities and the sustainability of the populations of marine mammals which they rely on for subsistence. However, spatial management measures, which were put in place in late 2018, appear to be effective in altering the distribution of Transient, Cargo, and Tanker vessels in both Russian and US waters, pulling them further away from the coast. Our findings demonstrate the importance of distant policy and

development decisions on Arctic vessel traffic patterns and highlight the potential for spatial management measures to alter the distribution of vessel traffic in marine landscapes.

3.2 Introduction

Marine vessels transport over 80% of the world's traded goods (UNCTAD 2017), making them an essential component of our globalized society. Arctic systems, which possess a wealth of natural resources (Gautier et al. 2009), declining ice cover (Parkinson 2014b), and isolated communities, are particularly dependent on vessel traffic for transporting essential supplies to remote communities and natural resources to global markets. While historically constrained during the majority of the year by heavy ice cover, the length of the navigable season in critical shipping routes has increased at twice the rate predicted by estimates made a decade ago (Stephenson et al. 2011, Smith and Stephenson 2013). For example, such as the Northern Sea Route, increased by approximately 13 weeks between the 1980s and the 2010s (Cao et al. 2022).

Unlike the Atlantic Ocean, which has numerous points of entry to arctic waters, accessing the Arctic Ocean from the Pacific Ocean requires travelling through the narrow corridor of the Bering Strait. Only 55 miles wide and with shallow waters (~50 m), the Bering Strait serves as bottleneck for marine vessel traffic. Furthermore, as a narrow international strait, vessels have a right to “transit passage” under the United Nations Convention on the Law of the Sea, which limits the ability of the United States and Russia to restrict passages through the Bering Strait (UN General Assembly 1982, Hartsig et al. 2012).

In addition to its geographic importance for vessel traffic in the Arctic, the Bering Strait is also an oceanographically, ecologically, and culturally important region. Nutrient transport northward through the Bering Strait fosters productive ecosystems that attract congregations of marine animals who seasonally feed in the waters within the Bering Strait and up into the Arctic

Ocean (Citta et al. 2012, 2018, Feng et al. 2021). Furthermore, Indigenous communities in the Bering Strait have served as stewards of this region for thousands of years and depend on the harvest of marine mammals for a large portion of their diets (Fall 2014, Oceana and Kawerak 2014). These long-enduring human-nature interactions form a complex coupled human and natural system (e.g., social-ecological system) that is increasingly affected by telecoupled external forces, such as climate change and increases in marine vessel traffic (Liu et al. 2007, 2013).

Marine vessel traffic is an important socioeconomic activity but also poses multiple threats to human and natural systems in the Bering Strait Region. Oil spills, ship strikes, and noise pollution all pose threats to marine wildlife (Huntington et al. 2015). Additionally, overfishing can result in the degradation of key prey species and species of subsistence value in addition to the risk of bycatch of sensitive species. Finally, vessel traffic can pose a direct threat to the health, safety, and culturally-significant subsistence practices of Indigenous communities (Oceana and Kawerak 2014, Kawerak Inc. Marine Program 2016).

Several measures are already in place to mitigate the potential threats posed by marine vessel traffic in the Arctic and, more specifically, in the Bering Strait Region. At the pan-Arctic scale, the International Maritime Organization's International Code for Ships Operating in Polar Waters (i.e., the Polar Code) was signed in 2013 and went into full effect in 2018 (International Maritime Organization 2014). This policy applies to all ships over 500 gross tons operating above 60 degrees North and seeks to ensure that ships have capacity to operate safely in extreme low temperature or ice-covered waters. Additionally, the Polar Code includes provisions to limit the discharge of oil, noxious liquids, sewage, and garbage in polar waters.

In addition to the Polar Code, a set of voluntary ship routing measures approved by the International Maritime Organization went into effect for the Bering Strait Region in December of

2018. These routing measures include two-way routes in both Russian and United States waters, precautionary areas, and areas to be avoided around St. Lawrence Island, King Island, and Nunivak Island (Figure 3.1). The purpose of these routing measures is to streamline vessel movements in the region, to improve safety of navigation, and to move vessels further away from coastlines and areas of fishing and subsistence activities (U.S. Coast Guard 2016). Preliminary research from 2019 indicates that tankers, cargo vessels, bulk carriers, and other vessels transiting through the study area generally adhered to these voluntary regulations (Fletcher et al. 2020).

One way the efficacy of such measures has been tracked is via Automatic Identification System (AIS) data. Over the past decade, the implementation of AIS ship tracking by the International Maritime Organization has led to an abundance of vessel tracking information that can be applied to better understand vessel movements and their subsequent impacts on the social-ecological systems in which they operate (Wright et al. 2019, Svanberg et al. 2019). As AIS data have become more widespread, several reports from governmental and non-governmental organizations (NGOs) have used AIS to examine patterns of vessel traffic in the Bering Strait Region (Fletcher et al. 2016, 2020, CMTS 2019). However, these reports have relied on three or fewer years of data to examine vessel traffic, thus limiting their ability to draw conclusions regarding trends. While it is widely anticipated that vessel traffic in the region will trend upward, understanding the spatial distribution of trends in vessel traffic would help policymakers to identify localized areas of increasing or decreasing vessel activities, which could then be targeted in future impact mitigation efforts. Beyond the examination of trends, there is also a need to compare the differences in space use between vessels operating within the Bering Strait Region (transporting resources to, from, or between communities) with those transiting through the Bering Strait. When combined with our understanding of the distribution of different vessel types (e.g., cargo, tanker),

uncovering the diverse functions that vessels serve in the region would help to create a more complete picture of vessel traffic.

To this end, we use high-resolution ship tracking data to quantify the spatiotemporal distribution and trends in marine vessel traffic in the Bering Strait Region across a six-year period from 2015 through 2020. Our objectives are (1) to characterize the spatial and temporal distribution of marine vessel traffic in the Bering Strait Region, and (2) to identify spatial patterns of trends in marine vessel traffic types. By comparing the distribution of voyages between Russian and United States waters, we are able to generate a clearer picture of vessel traffic than has been previously achieved. Further, we introduce a system of classification for vessel traffic based on the newly developed framework of metacoupling (human-nature interactions within as well as between adjacent and distant systems) (Liu 2017), which we call functional groups. The purpose of this classification system is to use information on vessel movements to infer the role that vessels play within the study system. In combination with information on vessel type and spatial distribution, functional groups contribute to developing a clearer picture of the marine vessel traffic in the Bering Strait Region.

3.3 Methods

3.3.1 Study Area

We based our study area boundaries on previously established definitions of the Bering Strait Region (Figure 3.1) (Berkman et al. 2016, Afflerbach et al. 2017). On the southern edge, the study area begins at approximately 62°N, parallel with the Russian village of Mys Navarin. The northern edge of the study area is parallel with Point Hope at 68°N. To accommodate vessel traffic in the Anadyr River, we extended the western boundary of the study area to approximately 172°W. By intersecting with land on both the eastern and western borders, this study area boundary

captures all vessel traffic entering, leaving, operating within, and passing through the Bering Strait Region.

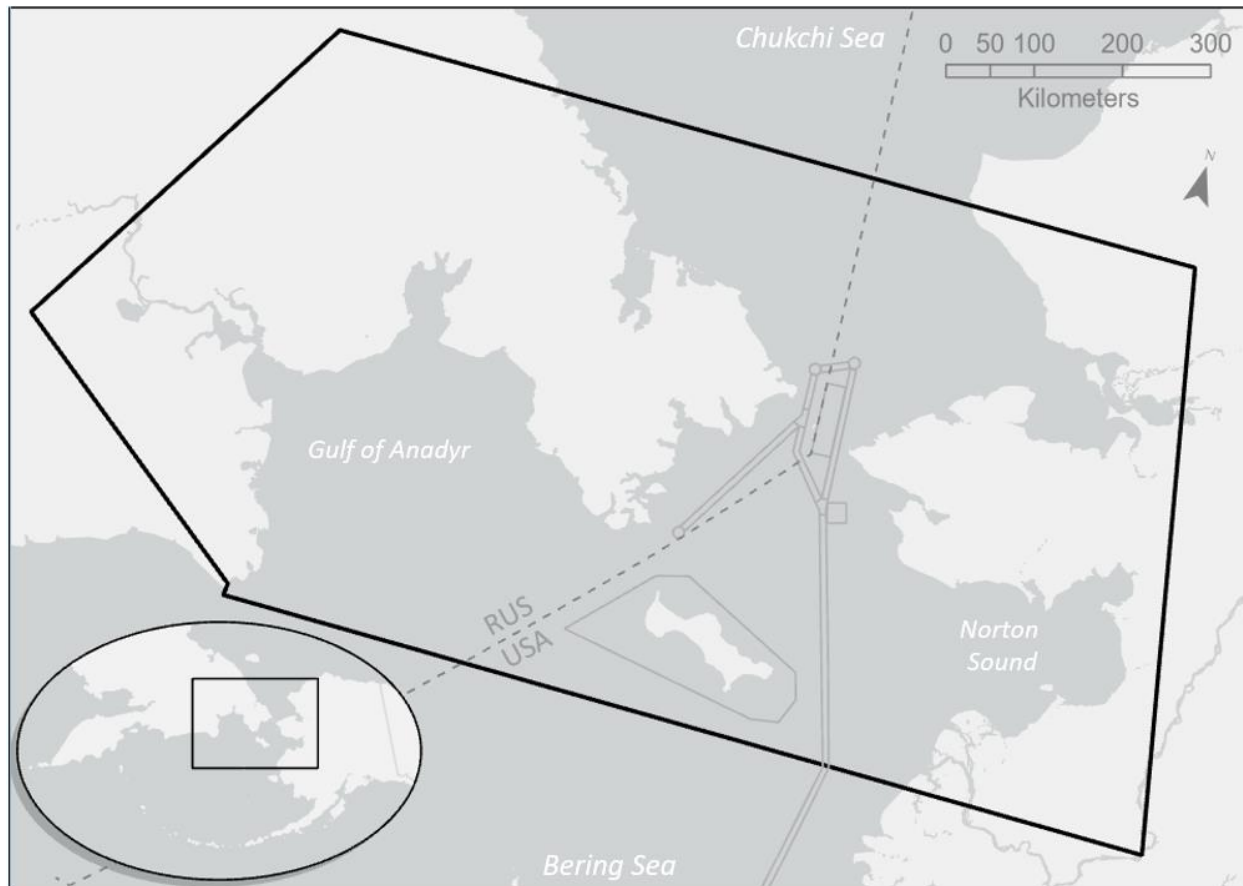


Figure 3.1 Map of the Bering Strait Region with study area outlined in black. Dashed grey line indicates maritime border between United States and Russia. Solid gray lines depict Areas to be Avoided and recommended routes that were implemented by the International Maritime Organization in December of 2018.

3.3.2 Automatic Identification Systems ship tracking data

In this study, we defined marine vessel traffic to be all ships carrying an active AIS transponder. Marine vessel location data, collected via AIS receivers, have recently gained attention as a promising, yet thus far underutilized, new tool for marine spatial planning (Shelmerdine 2015, Robards et al. 2016). By mandate of the International Maritime Organization, AIS transponders are required on all ships with a volume greater than 300 gross tons transiting internationally, all cargo vessels greater than 500 gross tons, as well as all passenger ships (IMO

2002, Robards et al. 2016). Additionally, AIS is required on all commercial vessels greater than 65 feet in the US (Taconet et al. 2019). While some vessels do not carry AIS transponders, such as small boats used by subsistence hunters, AIS transponders are mandatory for most large vessels, which are the focus of this study.

We collected satellite AIS data from January of 2015 through December of 2020 from exactEarth, a private company that maintains a constellation of satellite AIS receivers. We cleaned data by first identifying and extracting position messages from static messages. Position messages transmit information on the location and movements of vessels at a given time point (e.g., speed over ground, heading) while static messages are transmitted less frequently and give further information about ship identifies and attributes (e.g., draft, IMO Number, ship type, destination). Position signals are transmitted approximately every two minutes and include information on vessel longitude, latitude, origin, destination, type, speed, and heading in each transmission (Shelmerdine 2015).

After isolating position signals, we removed transmissions with invalid ship identifiers (i.e., Maritime Mobile Service Identity). We also imposed a speed filter of 100 km/hr between successive points to minimize GPS error in transmissions. Once position signals were cleaned, we joined them with static attribute information and linearly interpolated between successive signals to create daily movement segments (For more information on data cleaning, see Appendix: Chapter 2).

After joining AIS signals into daily segments, we connected successive daily segments into unique voyages for each vessel. We defined unique voyages as sets of consecutive daily segments within or intersecting with the study area in which a vessel was in motion (Table 3.1). We created a new voyage for each vessel if any of the following criteria were met: (1) a gap of 24 hours or

greater in AIS transmissions, (2) the vessel was outside the study area for one day or more, (3) the vessel did not transit more than 10 km in one day (e.g., if it was at anchor or at port but still transmitting AIS signals), or (4) the vessel did not move outside of a 2 km x 2 km bounding box within the span of a day. This bounding box approach accounted for small, yet frequent GPS error in AIS signals, which could artificially inflate the total distance travelled within a day, as well as for vessels loitering near ports without dropping anchor (Figure S3.0.1).

Table 3.1 Definitions of terminology used in this study.

Term	Definition
Voyage	A set of consecutive daily movement segments from the same ship located within the study area that meet the following criteria: (1) no gaps larger than 24 hours between consecutive transmissions; (2) no movement segments entirely outside the study area; (3) no movement segments less than 10 km in length; (4) no movement segments that can be contained within a 2km x 2km bounding box.
Functional Group	A classification method used to aggregate similar voyages into four categories based on their origins and destinations. Local voyages occurred entirely within the study area. Regional voyages started and ended within the study area, but travelled outside for less than one day. Inbound voyages started outside the study area and ended inside, while Outbound voyages started inside the study area but ended outside. Transient voyages started and ended outside the study area.
Vessel Type	A classification method based on AIS signal information input by ship operators. Voyages were grouped into one of four ship types: Cargo, Tanker, Fishing, Other.
Transit	A voyage that crosses the northern and southern boundary of the study area one time each.

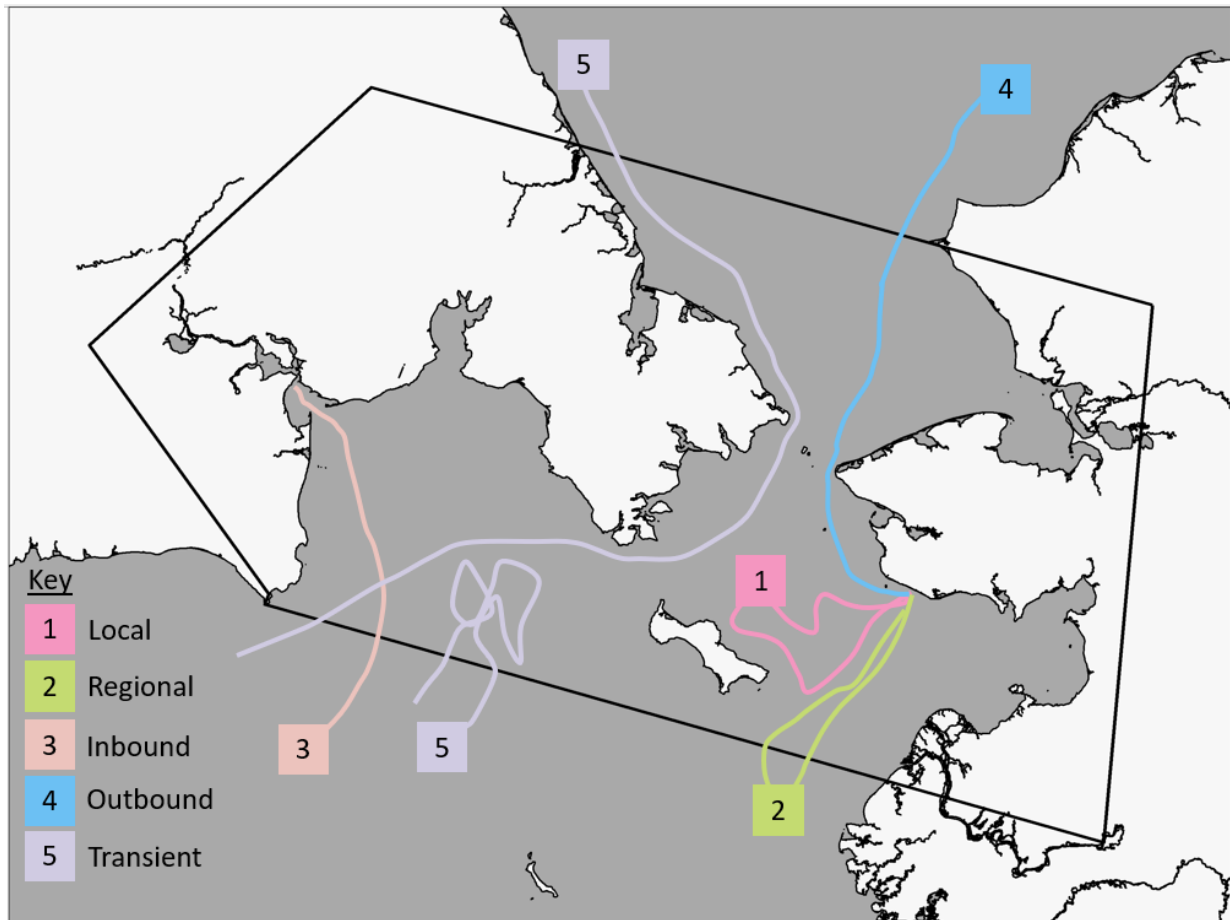


Figure 3.2 Map of the Bering Strait with study area outlined in black and example voyages for each functional group. We classified voyages that started and ended in the study area without travelling outside its boundaries as local (#1, pink) and voyages that started and ended in the study area, but passed outside its boundaries as regional (#2, green). We classified voyages that started outside the study area and ended inside as Inbound (#3, peach) and voyages that started inside and ended outside the study area as outbound (#4, blue). Finally, we classified voyages that started and ended outside the study area, but passed within its boundaries as Transient (#5, purple).

3.3.3 AIS Subsets

To identify spatial patterns and trends in different ship types, we separated vessels into four different categories: Cargo, Tanker, Fishing, and Other. When capitalized throughout this paper, such terms (Cargo, Tanker, Fishing, and Other) refer to the following definitions. We used the 2-digit code transmitted in static AIS messages to define ship type. The first digit of the ship type code identified a broad category (e.g., 7 = Cargo) while the second digit specifies the sub-type of vessel within that category (e.g., 71 = Cargo, Hazardous category A). The ship codes we used to

identify ship types were Cargo (AIS Type = 7X), Tanker (AIS Type = 8X), Fishing (AIS Type = 30), Other (all other ship types). Examples of ships designated as Other vessel types include tug and barge traffic, passenger vessels, icebreakers, and research vessels.

To accurately capture the role that marine vessels are playing in the Bering Strait Region, we also developed a new typology of marine vessels. This new typology is known as a functional group because it helps distinguish the different roles of vessels as they relate to human communities which, in turn, is useful for determining the costs and benefits of different vessel types (e.g., Transient traffic is not likely to bring benefits while Inbound/Outbound traffic transports resources into or out of the study system).

We determined functional groups based on patterns of intersection with the study area boundaries after assigning each daily movement segment to a voyage (Figure 3.2). If a voyage was contained entirely within the study area, we considered it a Local voyage. If a voyage started and ended within the study area but passed outside of its boundaries one or more times, we classified it as Regional. We labeled voyages that both started inside the study area and ended outside the study area as Outbound. Inbound voyages were those that started outside the study area and ended within it. Finally, Transient voyages both started and ended outside the study area, but passed inside one or more times. When capitalized throughout this paper, such terms (Local, Regional, Inbound, Outbound, and Transient) refer to these definitions.

In addition to vessel type and functional group, we also determined whether each voyage took place entirely within US waters, Russian waters, or both. We also considered the voyage to be a complete transit of the Bering Strait if it passed through the northern and southern boundaries of the study area one time each. After characterizing each voyage, we rasterized voyages on a 25 km² grid and quantified vessel traffic intensity for voyages from each functional group and vessel

type. We calculated vessel intensity in each grid cell as the number of kilometers travelled per month (Eguíluz et al. 2016, Pizzolato et al. 2016, Adams and Silber 2017).

3.3.4 Evaluating patterns and trends in the spatiotemporal distribution of marine vessel traffic

To address our first objective of evaluating the spatial and temporal distributions of marine vessel traffic, we created monthly maps of vessel traffic density for each vessel type and functional group. We also plotted the total number of voyages by vessels of each ship type and functional group over the study period. We made both qualitative and quantitative comparisons between the spatial and temporal distribution of voyages.

To meet our second objective of quantifying trends in the distribution of marine vessel traffic, we conducted a non-parametric linear temporal trend analysis. Prior to modeling, we removed pixels with no vessel traffic during the study period from the analysis. To account for the apparent seasonality in marine vessel traffic in the Bering Strait Region, we conducted a Kendall Seasonal Trend test on each pixel using the EnvStats package in R Version 4.1.1 (Millard 2013). This non-parametric method evaluates the median slope value and is recommended for identifying statistically significant trends in temporally autocorrelated data (de Beurs et al. 2015). Following previous research, we isolated vessel traffic only during the shipping season (June through October) for this analysis so as to remove the influence of winter months with little to no vessel traffic on the overall trends (Pizzolato et al. 2014). After modeling, we mapped trends onto the study area to examine areas of growth or decline in vessel traffic.

3.4 Results

We identified a total of 1,259 unique vessels on 12,519 unique voyages covering 831,639 km in the Bering Strait Region from January 1, 2015 through December 31, 2020. Of these voyages, 65.6% occurred solely within Russian waters, 30.18% occurred in US waters, and 3.22%

crossed through both US and Russian waters (Figure 3.3). We identified a total of 1002 voyages that transited through the Bering Strait Region, crossing each boundary only once.

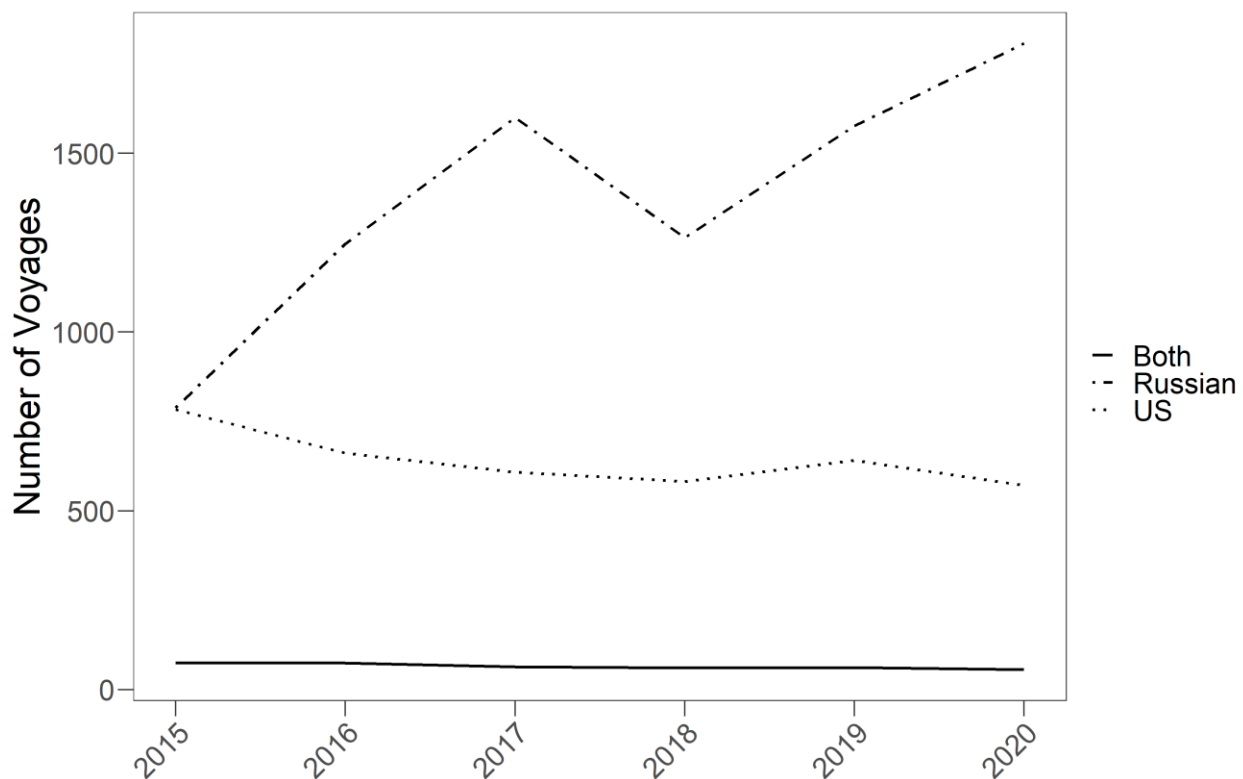


Figure 3.3 Yearly voyage totals for voyages taking place in US waters (dotted line), Russian waters (dash-dot line), and voyages that crossed the international border (solid line).

3.4.1 Comparison of functional group and ship type

Between 2015 and 2020, all four vessel types (Cargo, Tanker, Fishing, Other) had voyages belonging to all five functional groups (Local, Regional, Inbound, Outbound, and Transient; Figure 3.4). Transient voyages made up the largest proportion of all voyages in the functional group (32.28%), followed by Local voyages (30.23%), Inbound voyages (17.92%), Outbound voyages (17.78%), and Regional voyages (0.79%). Fishing vessels were the most common vessel type in the study area (32.77% of all voyages), followed by Other (32.29%), Cargo (25.46%), and Tanker (8.49%).

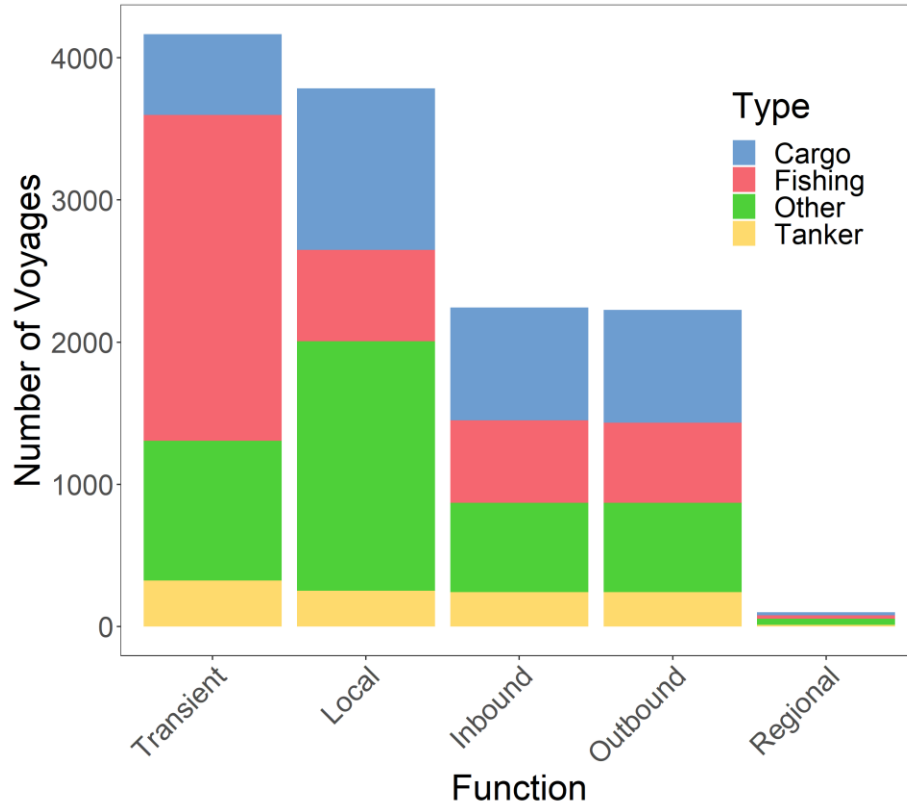


Figure 3.4 Bar plot demonstrating the number of voyages belonging to each vessel type and functional group.

3.4.2 Vessel traffic patterns through time

Over the six-year study period, the total number of voyages in the Bering Strait Region increased by 47.96%. However, increases were not uniform across vessel types and functional groups. The number of voyages by Fishing vessels increased three-fold (269.29%) during the study period while the number of voyages made by Other vessels decreased by 22.60% (Figure 3.5). Cargo and Tanker voyages increased by 46.17% and 84.96%, respectively.

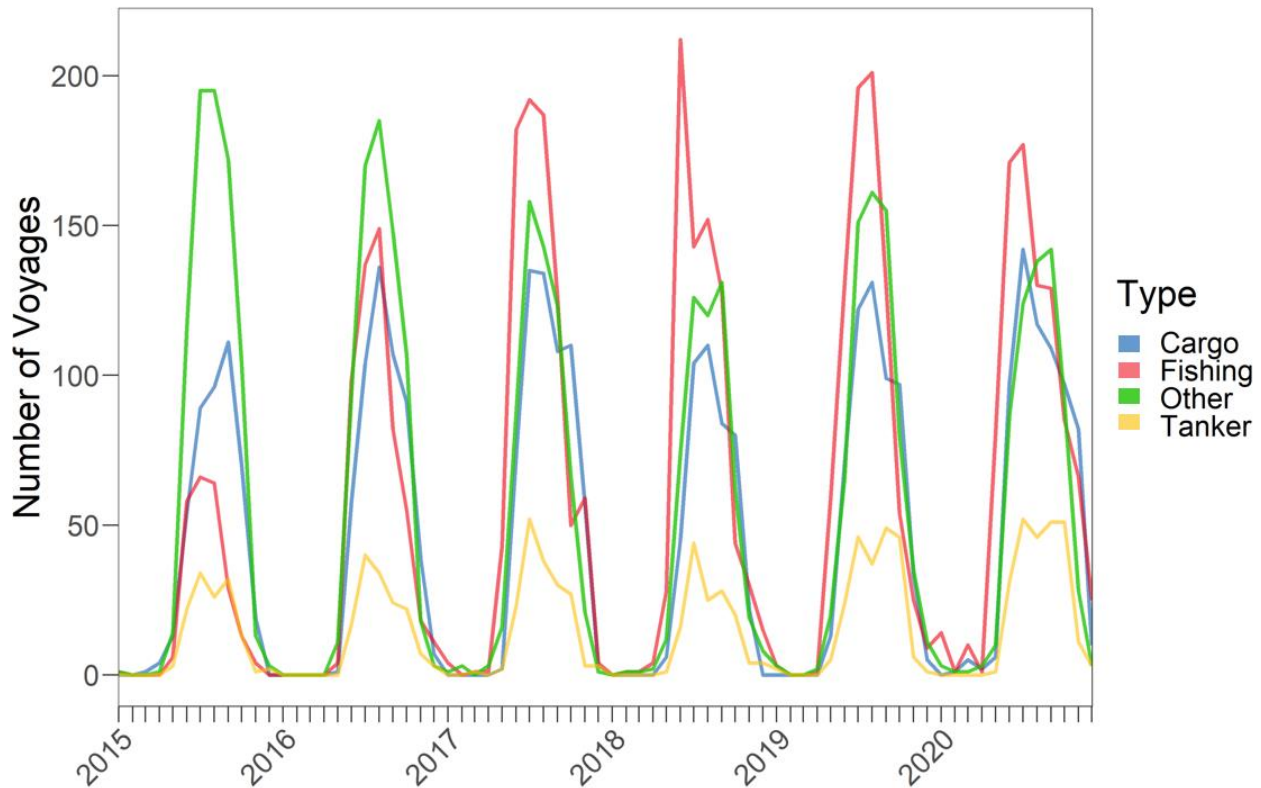


Figure 3.5 Line plot demonstrating the number of voyages through time for each vessel type.

Changes in the total number of voyages over time were similarly variable when examined by functional group (Figure 3.6). Transient voyages increased the most of all functional groups, growing by 149.18% from 2015-2020. Regional voyages also increased by 114.29%, although the total number of voyages for this group was small relative to other functional groups (n=99 voyages). Inbound, Outbound, and Local vessels experienced more modest increases in the total number of voyages (27.07%, 24.84%, and 11.61% respectively).

Voyages for all functional groups and vessel types were highly seasonal with traffic peaks in July or August and few to no voyages in January through April. Notably, 2020 was the first year with at least one voyage in the study area during all 12 months. Additionally, the number of voyages in December increased from 5 in 2015 to 41 in 2020.

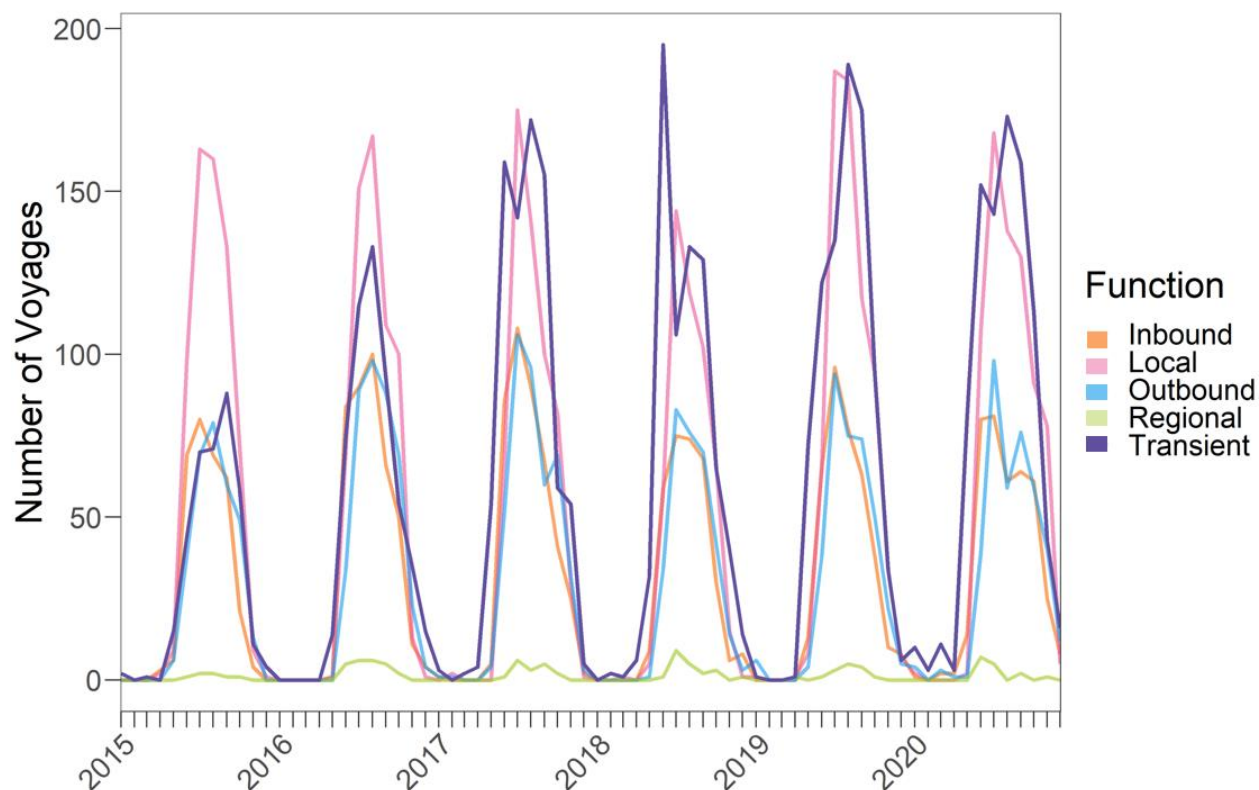


Figure 3.6 Line plot demonstrating the number of voyages through time for each functional group.

3.4.3 Spatial trends in vessel traffic

The spatial distribution of vessel traffic in the Bering Strait Region is highly variable, with clear differences on the Russian and American sides of the Bering Strait (Figure 3.7). Vessel traffic on the Russian side of the Bering Strait is dominated by Fishing vessels in the Gulf of Anadyr and Tankers transiting along the North Pacific Great Circle Route, while United States waters experience more variable traffic patterns.

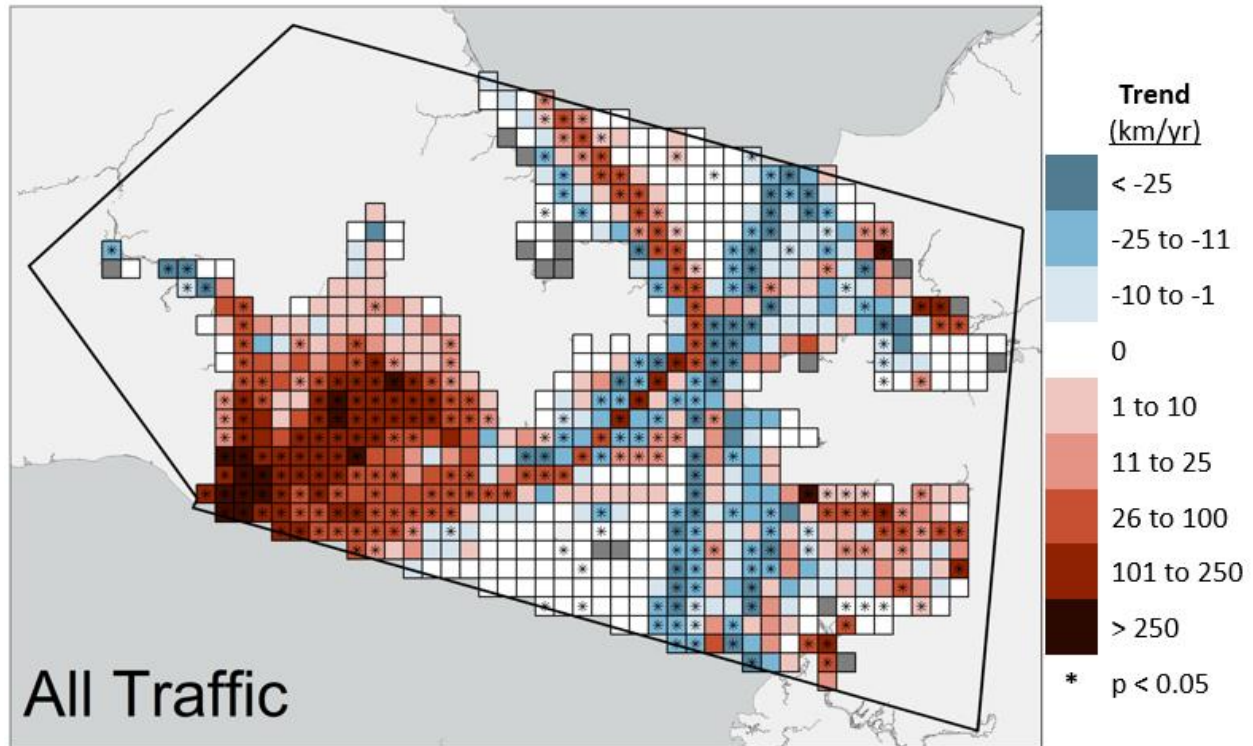


Figure 3.7 Map of trends in voyages from 2015-2020. Red pixels indicate increases in the number of voyages while blue indicates decreases. Pixels with statistically significant trends are marked with a star. Dark gray pixels had no vessel traffic during the study period.

While there is some overlap in the spatial distribution of trends between vessel type and functional group, each category reveals unique information on the distribution of changes in vessel traffic in the study area. Fishing activity in the study area is concentrated in the Gulf of Anadyr and experienced significant increases over the study period. Cargo and Tanker traffic are both concentrated in the central portion of the Bering Strait Region. While Cargo traffic experienced a mix of positive and negative trends across the study area, Tanker traffic primarily increased on the Russian side of the Bering Strait (Figure 3.8). Other vessel traffic also experienced variable trends with declines along the United States' side of the Bering Strait and localized increases along the coast.

Trends in Transient vessel traffic reflect a combination of the significant increases in Fishing vessel and Tanker traffic in Russian waters and the significant decreases in Other vessel

traffic in American waters (Figure 3.8; Figure 3.9). Local vessel traffic experienced spatially variable trends with noticeable increases in Norton Sound. Inbound and Outbound traffic experienced significant increases in the Gulf of Anadyr.

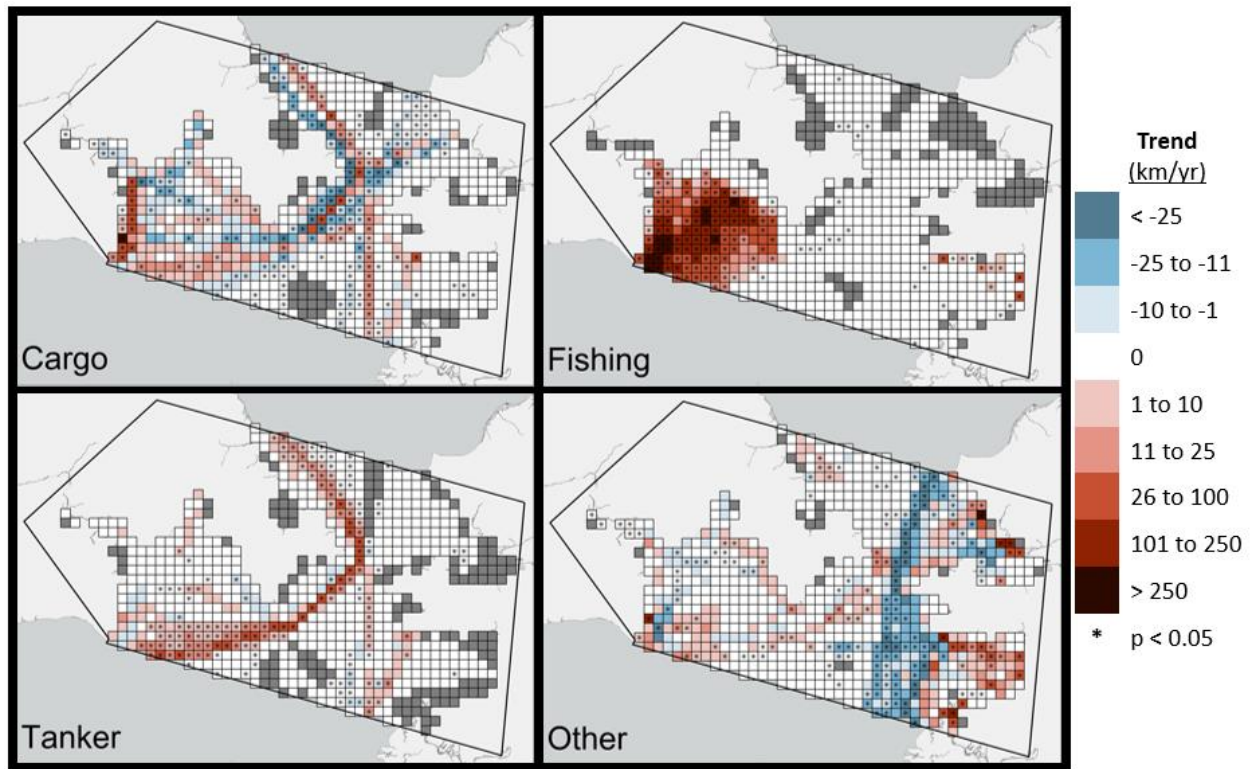


Figure 3.8 Map of trends in voyages from 2015-2020 for each vessel type. Red pixels indicate increases in the number of voyages while blue indicates decreases. Pixels with statistically significant trends are marked with a star. Dark gray pixels had no vessel traffic in the specified category during the study period.

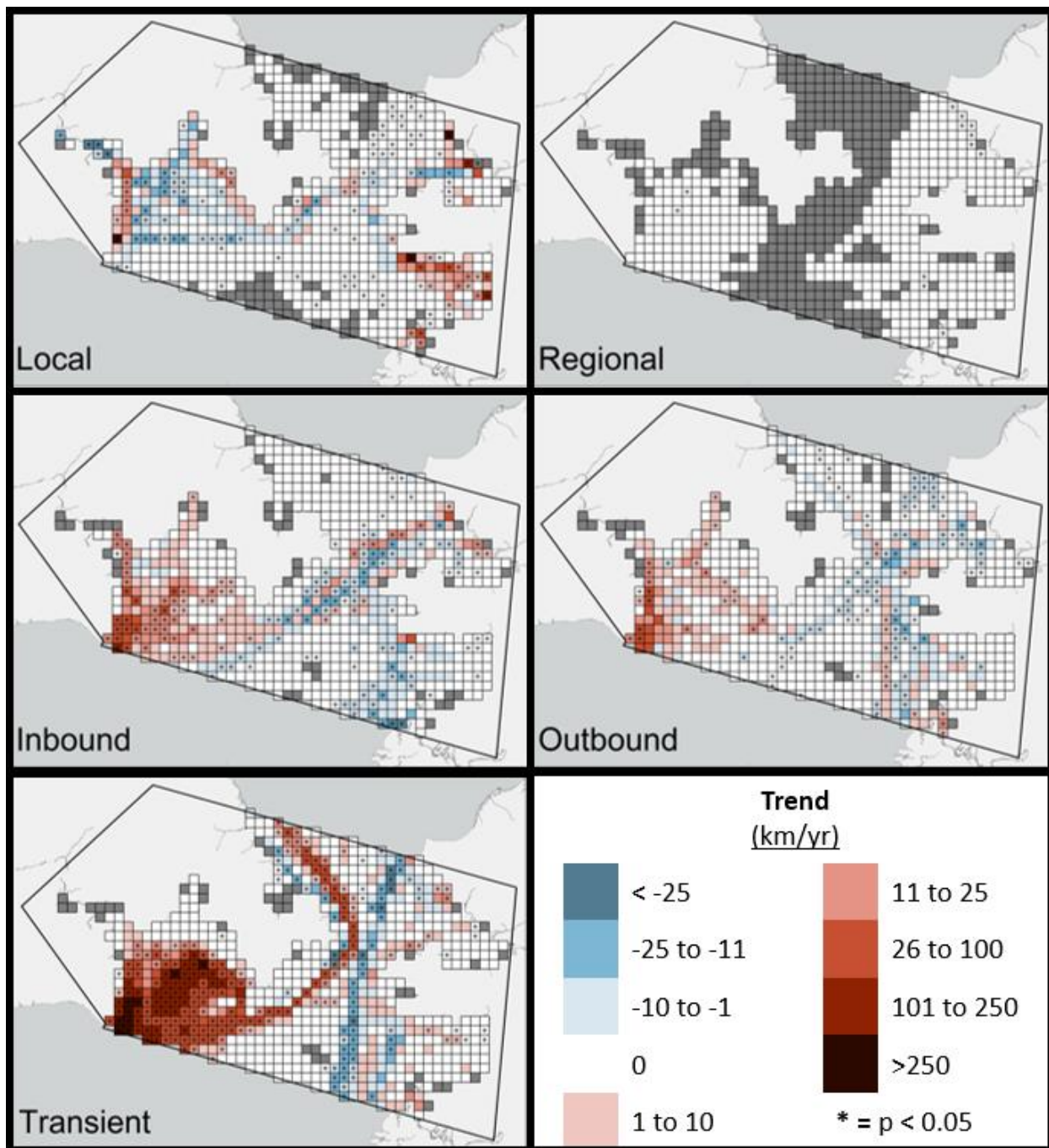


Figure 3.9 Map of trends in voyages from 2015-2020 for each functional group. Red pixels indicate increases in the number of voyages while blue indicates decreases. Pixels with statistically significant trends are marked with a star. Dark gray pixels had no vessel traffic in the specified category during the study period.

3.5 Discussion

Although vessel traffic in the Bering Strait Region is modest compared to other shipping corridors, such as the English Channel or Strait of Malacca, it is an area of relatively substantial

vessel traffic in the Pacific Arctic. On the other hand, the 831,635 km travelled by ships in the Bering Strait Region in 2015 is comparable to the total reported vessel traffic in the entire Canadian Arctic (a larger area with more vessel traffic research) for that same year (Dawson et al. 2018). Furthermore, the 1,259 unique ships that we identified in the Bering Strait Region during this six-year time span represents 22% more vessels than were reported for the Canadian Arctic over the 23 years from 1990 to 2012 (Pizzolato et al. 2014), according to the Canadian NORDREG reporting system, which has similar reporting requirements as AIS data (mandatory on all vessels > 300 GT) (Dawson et al. 2018).

While overall vessel traffic in the Bering Strait Region increased between 2015 and 2020, these trends were highly variable across vessel types and functional groups within the study area. Growth has been concentrated in Russian waters, with the total number of voyages in US waters staying relatively stable over time (Figure 3.3). An examination of trends in vessel type reveals that the largest increases in vessel traffic were associated with Fishing vessels and Tankers in Russian waters. Trends in vessel type on the US side of the Bering Strait were more variable, with localized small increases in Fishing and Other vessels in Norton sound and an eastward shift in Cargo vessels in the central Bering Strait (Figure 3.8).

The analysis of trends in functional groups in addition to vessel type uncovered novel, yet complimentary information about vessel movements. The presence of all vessel types within each functional group indicates that the functional groups capture unique information about vessel movement patterns that are not conveyed by vessel type alone (Figure 3.4). For example, if all Transient voyages were made by Fishing vessels or all Inbound and Outbound voyages were made by Cargo ships, such functional groups would not convey any information beyond what is conveyed by vessel type alone. As this is not the case (i.e., we see each vessel type in each vessel

group), we can conclude that the functional groups are not redundant and convey new information on vessel movements in the Bering Strait Region.

An examination of functional groups reveals increasing Transient traffic on the Russian side of the Bering Strait and decreasing Transient vessel traffic on the US side (Figure 3.9). These changes are most likely the result of policy decisions made by actors in distant locations. For example, some of the largest increases in vessel traffic across our study period were seen in Transient vessels along the Northern Sea Route (Figure 3.9). This trend is attributable to vessels associated with liquified natural gas extraction and export from the Yamal Peninsula of Russia, which are increasingly transported to East Asian markets through the Bering Strait (Li et al. 2021). While historically seasonal, these transits are increasingly occurring in the marginal ice season, including the first ever mid-winter transits without icebreaker escorts in January of 2021 (Staalesen 2021). On the US side of the Bering Strait, declines in Transient vessels are likely attributable to the discontinuation of offshore oil exploration in the Burger Prospect by Royal Dutch Shell PLC and subsequent demobilization in 2015 and 2016 (CMTS 2019). These changes in vessel traffic patterns illustrate the highly telecoupled nature of the Bering Strait Region (see Chapter 1), whereby distant policy decisions cause changes in the telecoupled flow of vessel traffic through the Bering Strait, thereby increasing (in the case of Russian waters) or decreasing (in US waters) the potential spillover effects associated with vessel transits through the region.

In addition to the total magnitude of traffic, the spatial distribution of risk posed by marine vessel traffic is also altered by telecoupled causes, such as the IMO's implementation of vessel routing measures for the Bering Strait Region in December of 2018. Our findings provide some evidence that, on the whole, vessel movement patterns did adjust to comply with these routing measures. This is particularly true for Tanker and Cargo vessels on Transient voyages through the

study area. On the Russian side of the Bering Strait, Transient vessel traffic shifted east and northward in the latter part of the study period (Figure 3.9). Likewise, Cargo traffic on the United States side of the Bering Strait shifted eastward away from the coast of St. Lawrence Island (Figure 3.8). By pulling vessel traffic away from the coastlines, thereby increasing the amount of time before vessels run aground in the case of disablement, these shifts improve vessel safety. These findings are well aligned with previous research, which found a high degree of compliance with recommended routing measures among Cargo and Tanker vessels (Fletcher et al. 2020).

These findings also compliment and expand upon those of previous studies of vessel traffic in the Bering Strait Region. Despite temporal and spatial overlap in the study areas, our analysis identified an average of 37% more vessels in the Bering Strait Region between 2015 and 2017 than were reported in a recently released analysis by the U.S. Committee on the Marine Transportation System (CMTS)(CMTS 2019). While the study area in this analysis is completely encapsulated by the study area outlined in the CMTS report, the most likely cause of this discrepancy is the apparent exclusion of vessel traffic in the western portion of the Gulf of Anadyr from the CMTS data set. This hypothesis is supported by the large discrepancy in the number of fishing vessels reported in the CMTS study compared with this analysis (average of 27.67 per year in CMTS vs. 101.67 in this study). While the CMTS report was focused on the US side of the Bering Strait rather than the Russian side, this vessel traffic could have impacts on social-ecological systems on both sides of the Bering Strait given the shared stocks of many fish and marine mammals that move freely between both sides.

The increase in vessel traffic during the marginal ice season that we observed is of particular concern for many ice-dependent marine mammals who migrate along the ice edge. Between 1990 and 2012, approximately 12% of bowhead whales (*Balaena mysticetus*) harvested

by Alaska Native subsistence hunters showed signs of entanglement with fishing gear and a further 2% had scars associated with vessel strikes (George et al. 2017). In our study, we observed a 269% increase in Fishing traffic that was primarily concentrated in bowhead winter habitat in the Gulf of Anadyr and west of St. Lawrence Island (Citta et al. 2012). While Fishing activities are concentrated in the summer months when bowheads are outside of the study area, increases in late fall and winter Fishing activity are of particular concern for this species.

In addition to impacts on individual animals, increases in vessel traffic can have impacts on ecosystems, communities, and the interactions between them. In the Bering Strait Region, Indigenous communities along the coast harvest more than 100 kg per capita of subsistence foods from the ocean (Fall, 2016). Community members have voiced concerns about the impacts of vessel traffic in the region, including lack of clean-up for accidents/oil spills, unmonitored activities, lack of oil spill response capacity, altered migration patterns of subsistence species, and lack of situational knowledge of vessel operators (Kawerak Inc. Marine Program 2016). Given that local communities are the most likely to directly experience the effects of vessel traffic and to be first responders in the case of any incidents in this remote area, extensive consultation with local communities regarding both vessel traffic impacts, as well as potential solutions, would be necessary to achieve sustainable and effective policy solutions. Furthermore, vessel traffic is just one of many stressors facing the social-ecological systems of the Bering Strait Region. These stressors are often studied in isolation, and more research on the interactive effects of multiple stressors is needed, especially approaches that incorporating seasonality as a factor in this highly dynamic region. Research approaches that work in long-term collaboration with local communities are particularly essential for identifying strategies to improve resilience that are both feasible and effective (Dawson et al. 2020).

While this research contributes to a growing understanding of the numerous stressors facing Arctic social-ecological systems, there are still several limitations and knowledge gaps that should be addressed moving forward. First, not all vessels are required to carry AIS transponders. Thus, the number of vessels reported in this study is likely an undercount of the true amount of vessel traffic in the region. In particular, many fishing vessels do not meet size requirements for AIS and may therefore be undercounted in this analysis. Furthermore, there is limited available information on the rates of adoption for AIS. It may be the case that some portion of the trends uncovered in this study are the result of AIS adoption rather than increases in actual vessel activity.

Second, several vessel attributes, including size, speed, draught, and cargo type affect the magnitude and type of risk posed by vessels in the region, but were not considered in this study. For example, vessel size and speed are two key factors that impact the lethality of ship strikes to cetaceans (van der Hoop et al. 2015). While outside the scope of this study, future analyses could examine the spatiotemporal distributions of long ships (> 65 feet) travelling at over 10 knots to identify areas and times of greatest risk of ship strike.

Third, while the development of functional groups improves our understanding of different vessel traffic patterns in the Bering Strait Region, it is impossible to know the exact purpose that vessels are serving in the region without supplementary information on vessel characteristics or voyage details from vessel operators. Furthermore, while the functional groups are useful for grouping voyages with similar movement patterns, the categorization of functional groups is dependent upon the boundary of the study area. For instance, expanded study area boundaries would likely result in an increase in Local voyages while a contraction of the study area would add to the number of Inbound and Outbound voyages. Therefore, care must be taken to interpret the trends in the vessel traffic patterns for functional groups within the context of the study area and

its boundaries. While functional groups do provide additional complementary information on the distribution of vessels, interpreting the purpose and motivations behind voyages remains a challenge that requires additional contextual information.

3.6 Conclusion

The findings of this study compliment, build upon, and expand those of other analyses seeking to quantify vessel traffic in the region by expanding the study area to include Russian waters in the Gulf of Anadyr, analyzing functional groups of voyages, and examining the spatial distribution of trends in vessel traffic. We find that vessel traffic is heavily concentrated on the Russian side of the Bering Strait and that increases in Fishing vessels and Transient voyages are greatest in the Gulf of Anadyr and along the Northern Sea Route. However, spatial management measures appear to be effective in shifting vessel traffic away from the coasts of Russia and St. Lawrence Island, possibly reducing the risk of vessel groundings. In general, the total magnitude of vessel traffic in the Bering Strait Region is highly dependent on telecoupled policy and economic decisions, and measures to predict the future of vessel traffic in the region must take into account these distant connections. This research provides a foundation for the analysis of vessel traffic in other critical shipping corridors, such as the English Channel, Strait of Gibraltar, and the Strait of Magellan.

CHAPTER 4: AN EMPIRICAL ANALYSIS OF VESSEL TRAFFIC IN THE ICE-COVERED WATERS OF THE PACIFIC ARCTIC

Kapsar, K. Gunn, G., Brigham, L., Liu, J. In Prep. An empirical analysis of vessel traffic in the ice-covered waters of the Pacific Arctic. *To be submitted.*

4.1 Abstract

Sea ice has long been a barrier to natural resource development in the Arctic. Recent declines in sea ice coverage have drawn the attention of industry, governments, and academia by enabling access to previously inaccessible natural resources. In turn, natural resource development has the potential to increase marine vessel traffic activities in seasonally ice-covered regions. However, it is unclear whether patterns of recent growth in vessel traffic in the ice-free season are also occurring in the marginal ice zone or in pack ice. Understanding vessel traffic in these areas is crucial given the importance of sea ice to many ice-associated marine animals. Here, we used high resolution Automatic Identification System (AIS) ship tracking data alongside satellite-derived sea ice thickness and concentration data to determine the degree to which vessels are present in areas of ice coverage. We found that while overall vessel traffic increased by 58% from 2015 to 2020, vessel traffic in the marginal ice zone (ice concentration between 15% and 80%) also increased by 46%, and vessel traffic in pack ice (>80% concentration) increased by 30%. Using the AIS ship type classification system, we determined that Fishing vessels dominated vessel traffic at low ice concentrations, but vessels categorized as Other, likely icebreakers, were the predominant vessel type in pack ice. These findings indicate that vessel traffic growth is occurring in both ice-free and ice-covered waters, which could increase potential effects of vessel traffic on ice-associated marine wildlife.

4.2 Introduction

As the Arctic climate warms at twice the global average rate (IPCC 2014), Arctic sea ice is thinning, melting earlier, and freezing up later (Markus et al. 2009). Across the Arctic, the average length of the sea ice season shortened at a rate of almost 12 days per decade from 1997 to 2017 (Peng et al. 2018). As sea ice patterns shift, so too do the migratory patterns of ice-associated marine wildlife (Tsujii et al. 2021), altering the traditional subsistence patterns of Indigenous communities in the Arctic whose food security can be threatened by changes in the timing, location, and abundance of traditional foods (ICC Alaska 2015).

In addition to its impacts on the social-ecological systems of the Arctic, declines in sea ice are lengthening the ice-free season along important shipping routes into, out of, and through the Arctic (Smith and Stephenson 2013). Though the length of the ice-free season is increasing, sea ice coverage is still a rate-limiting step for Arctic vessel traffic. Even climate models operating under the most extreme emissions scenarios (RCP 8.5) project that the Northern Sea Route and Northwest Passage will still be inaccessible to non-ice strengthened vessels for the majority of the year through 2050 (Stephenson et al. 2013).

In addition to the seasonal limitations posed by sea ice, many other factors influence the overall amount of vessel traffic in the Arctic. The majority of vessel traffic in the Arctic is destinational, meaning that vessels transit to and from destinations in the Arctic rather than passing through the Arctic in route to sub-Arctic destinations (Arctic Council 2009). Destinational shipping between Arctic and non-Arctic systems creates a telecoupling whereby flows of resources into and out of the Arctic are impacted by distant decision-making and global economic factors (Liu 2017, Gunnarsson 2021). Thus, national and international policies (e.g., bans on fishing activities), or investments in natural resource development (e.g., mines, oil and gas), or

infrastructure (e.g., ports, pipelines) can have substantial impacts on the overall amount of vessel traffic in a region. Such was the case in the United States (US) Arctic, where decreased growth in the total number of vessels from 2015-2017 was attributed to Royal Dutch Shell PLC's cessation of oil and gas exploration activities. While Arctic shipping routes between Europe and Asia are approximately 30% shorter than the Suez or Panama Canal routes (Khon et al. 2010), the extreme weather, unpredictability of navigability, and lack of search and rescue capacity have all been cited as concerns by operators considering these routes (Lee and Kim 2015). Additionally, interest in natural resource developments in the Arctic is tied to global market prices. When prices are depressed, the increased cost of operating within the seasonally ice-covered waters of the Arctic makes extraction within this region relatively less competitive than other options (Larsen and Huskey 2015).

Despite these complexities, vessel traffic in the Arctic is increasing. Between 2013 and 2019, the overall number of ships in waters subject to the International Maritime Organization's Arctic Polar Code increased by 25% and the total distance travelled by such vessels increased by 75% (PAME 2020). The main driver of these increases was fishing activity. At a regional scale, similar patterns have been identified around Svalbard (Stocker et al. 2020), throughout the Canadian Arctic (Dawson et al. 2018), and along the Northern Sea Route (Gunnarsson 2021).

While vessel traffic has been growing, it is unclear whether this growth has been constrained to the ice-free season or if vessel traffic has also pushed into the marginal ice season. Previous approaches to estimating the "navigable season" in Arctic waters have used ice thickness and concentration information to project season length for theoretical vessels of particular ice classes (Stephenson et al. 2011, Smith and Stephenson 2013, Melia et al. 2016, Aksenov et al. 2017, Mudryk et al. 2021). However, these studies do not indicate whether or to what degree

vessels are actually traveling along these theoretically accessible routes. In two studies of vessel activities in sea ice in the Canadian Arctic, researchers used least cost path interpretation of once-daily positions to track a vessel's movement in combination with Canadian Ice Charts, and determined that sea ice coverage is negatively associated with vessel traffic in the Canadian Arctic at both an annual scale and during the shipping season (Pizzolato et al. 2014, 2016). It is unknown whether these associations hold true for other regions or during the marginal ice season. Understanding vessel use of marginal ice seasons is critical given potentially increased overlap with sensitive ice-dependent marine mammals as well as subsistence harvesters who use ice as a platform for hunting. This knowledge is particularly salient for regions inhabited by marine mammals that are vulnerable to vessel traffic, such as the Pacific Arctic and Bering Strait region (Hauser et al. 2018).

The Pacific Arctic region is a geographically important area for studying vessel activity. Within the Pacific Arctic, the Bering Strait serves as an important migratory corridor for marine wildlife. The Bering Strait also represents the endpoint of both the Northwest Passage and the Northern Sea Routes, concentrating all vessel activities into a corridor only 55 miles wide. Indigenous residents of the Bering Strait region, many of whom depend on the subsistence harvest of marine wildlife, have voiced concerns regarding increasing vessel activities in the area (Kawerak Inc. Marine Program 2016). In addition to its geostrategic importance, the Bering Sea in the southern portion of the Pacific Arctic has nutrient rich waters which support a large commercial fishing industry (Kroodsma et al. 2018).

In recent years, news agencies have reported anecdotal observations of increased winter traffic in the Pacific Arctic, including the first ever winter transit of the Northern Sea Route in 2021 (Staalesen 2021). Transits like this are expected to be repeated multiple times in future years.

Given expected further increases, there is a need for a more systematic quantification of vessel activities and sea ice in the Bering and Chukchi Seas to determine whether the anecdotal reports are representative of a broader pattern. To this end, we use high-resolution automatic identification system (AIS) ship tracking data and microwave remote sensing data products to evaluate vessel activities and sea ice in the fall and winter in the Pacific Arctic region. AIS data are increasingly being applied to answer questions in the fields of conservation, maritime safety and navigation, marine spatial planning, and international trade (Shelmerdine 2015, Robards et al. 2016, Yan et al. 2020, Sullender et al. 2021). The objective of this work is to quantitatively evaluate the relationship between vessel traffic and sea ice in the Pacific Arctic. We predict that, in the aggregate, the amount of vessel activity will be inversely proportional to sea ice coverage. Furthermore, we predict that vessel traffic in sea ice will increase over time, particularly along the Northern Sea Route, and that different vessel types will exhibit distinct relationships to sea ice coverage. Overall, this study provides one of the first assessments of vessel activities in ice-covered waters and serves as a foundation for future analysis of vessel traffic impacts on ice-associated wildlife and the feasibility of different policies to mitigate these impacts.

4.2.1 Study area

The region of interest for this study is the Pacific Arctic, which includes the northern Bering Sea, Chukchi Sea, and Beaufort Sea (Figure 4.1). We defined the boundaries of our study area based on both climatological and logistical constraints. In the northern portion of our study area, our boundary was delimited by the availability of vessel traffic data. For regions not constrained by vessel data availability, we defined the study area by identifying sea ice pixels (See 4.3.1 below) with greater than 15% sea ice concentration in at least one month during our study period (2015-2020). We chose this definition to include all areas covered by sea ice in the study area.

This study area encompasses 1,650,458 km² and is seasonally ice-covered (Figure 4.1). As sea ice coverage extends southward in the fall and winter months, the leading edge is known as the marginal ice zone (MIZ). The MIZ is a liminal region with ice concentration between 15% and 80%. In winter, when sea ice extent is at its greatest and covers the majority of the study area, the MIZ averages 71 km wide (Strong and Rigor 2013). The MIZ is a key area for biological productivity, as the spring retreat of the sea ice is associated with seasonal algal blooms that feed phytoplankton, a key source of food for marine wildlife (Barber et al. 2015). Additionally, many species closely track the ice edge during their winter migrations south into the Bering Sea (Quakenbush et al. 2010, Citta et al. 2012, von Duyke et al. 2020). Beyond the MIZ is pack ice, defined by areas with greater than 80% sea ice coverage (Strong and Rigor 2013). While pack ice may contain leads (areas of open water), in practice it is treated as an area of near-continuous ice coverage (Strong and Rigor 2013).

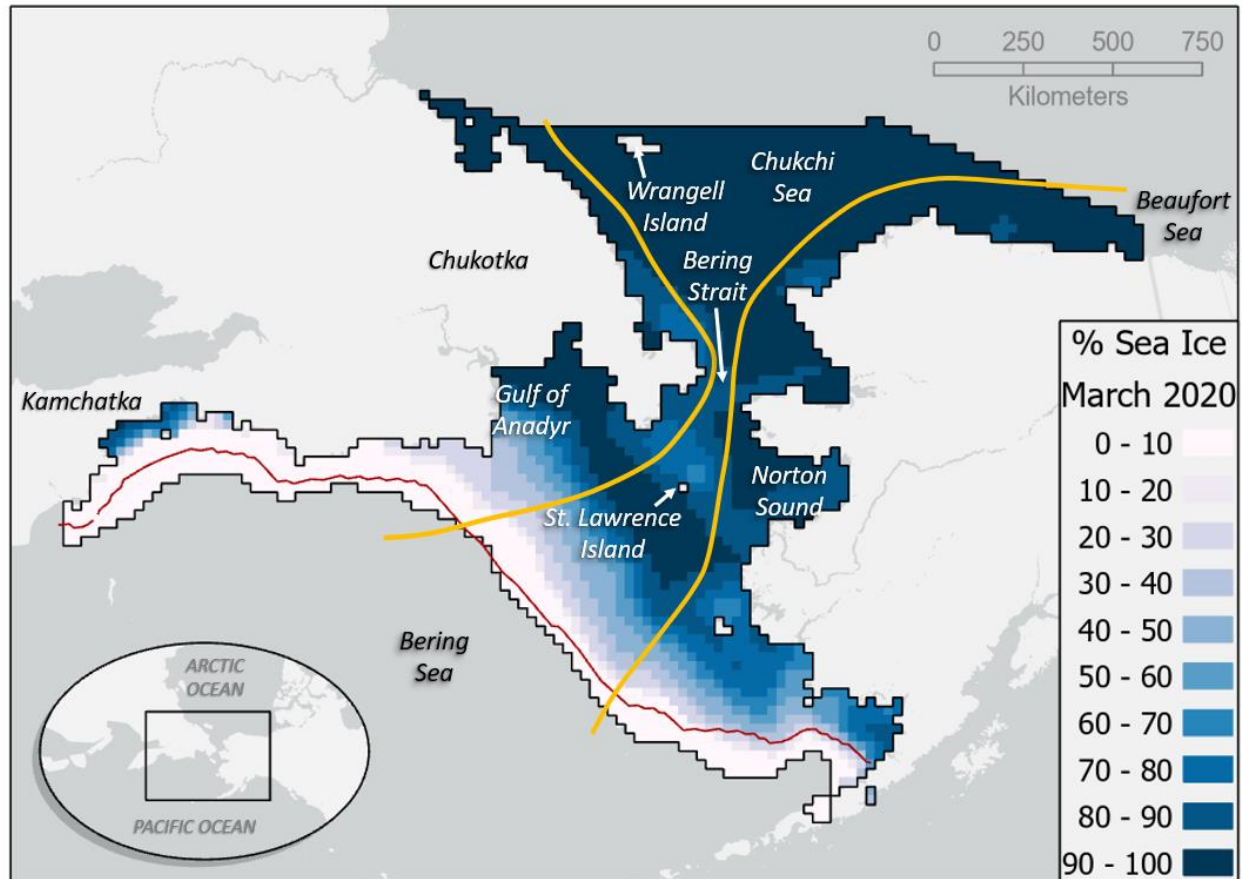


Figure 4.1 Map of Pacific Arctic with percent sea ice concentration in March of 2020. Red line indicates the median March sea ice extent for 1980-2010. Ice extent data were acquired from the National Snow and Ice Data Center (Fetterer et al. 2017). Orange lines represent approximate routes for shipping entering and exiting the Northern Sea Route (west) and Northwest Passage (east), although path through the Bering Sea varies by destination. Pixels are each approximately 625 km² in area.

4.3 Data and Methods

To analyze the relationship between vessel traffic and sea ice, we first collected independent data sets and then merged them to a common spatial and temporal scale. Steps in the analytical process are outlined in Figure 4.2 and detailed below.

4.3.1 Evaluating sea ice concentration and thickness

We evaluated vessel traffic in relation to both sea ice thickness and concentration, which have been explored in the context of vessel traffic in sea ice and theoretical assessments of navigability (Stephenson et al. 2013, Melia et al. 2016, Stocker et al. 2020). We used the CryoSat-

2/SMOS Merged Product from the European Space Agency to calculate sea ice thickness and concentration in our region of interest (Ricker et al. 2017). This data set is a value-added product made from combining observations from the CryoSat-2 and the Soil Moisture and Ocean Salinity (SMOS) satellites (Ricker et al. 2017). This product reduces the root mean squared deviation from aerial ice thickness observations by approximately 0.7 m compared to CryoSat-2 data alone, meaning that it achieves improved accuracy (particularly over thin ice) when compared with single satellite products.

The combined CryoSat-2/SMOS Merged Product contains daily sea ice concentration and thickness estimates for October through April of each year based on a 5-day rolling average at a 25 km x 25 km spatial resolution. After acquiring these data, we aggregated them to monthly average values and cropped them to the extent of available vessel tracking data. To account for inaccuracies in sea ice concentration estimates at very low concentrations, we used a cut-off whereby all pixels with sea ice concentration values less than 15% were considered to be ice-free (Strong and Rigor 2013, Stocker et al. 2020). To align with previous studies of sea ice seasonality, we further differentiated sea ice concentration data into two categories: MIZ and pack ice. Each pixel was designated as being in the MIZ if the sea ice concentration value was greater than 15% and less than 80%. Pixels with a sea ice concentration value of greater than 80% in a given month were designated as pack ice (Strong and Rigor 2013). We quantified the total amount of traffic in the MIZ and pack ice and mapped the spatial distribution of vessel activities in these ice types. We calculated ice extent in a given month by summing the area of all pixels with at least 15% sea ice concentration.

4.3.2 *Evaluating vessel activity*

AIS transponders are required on all passenger vessels, all cargo vessels over 500 gross tons, and all vessels over 300 gross tons on an international voyage (IMO 2002). When operational, AIS transponders project signals at a maximum interval of every two minutes (and more frequently when the vessel is under way) that are received by other vessels, terrestrial receivers, or satellite-based receivers. The higher resolution of this data represents an improvement upon other studies that have analyzed ship locations within sea ice which used imputed track lines between once-daily locations (Pizzolato et al. 2016).

To evaluate the association between vessel traffic and sea ice, we acquired all AIS data for the study area from 2015 through 2020 from exactEarth, a private company that maintains a constellation of satellite-based AIS receivers. We cleaned these data to remove inaccurate positions and/or vessel attributes and joined successive locations into daily segments for each vessel (see Appendix: Chapter 2 for data cleaning details). After cleaning the AIS data, we rasterized daily segments by calculating the number of unique vessels and the total distance travelled (in km) by vessels within each pixel in each month of the study period for which sea ice data were available (i.e., October through April). To ensure the data were completely overlapping with sea ice concentration and thickness values, we used the re-projected CryoSat-2/SMOS grid as the template for rasterization of AIS data. To mitigate potential edge effects associated with partial overlap of pixels with the AIS collection boundaries, we included only pixels that fell entirely within the AIS data collection bounding box. To remove the frequently erroneous AIS signals (and subsequent errors in traffic values) from ships loitering near ports, we removed pixels containing or adjacent to known ports from the analysis. For each pixel in each month of the study, we calculated the number of unique ships and total distance travelled by all AIS-transmitting

vessels. Additionally, we also calculated these metrics for four unique vessel types: cargo, tanker, fishing, and other vessels. (See Chapter 3 for details on AIS type differentiation.)

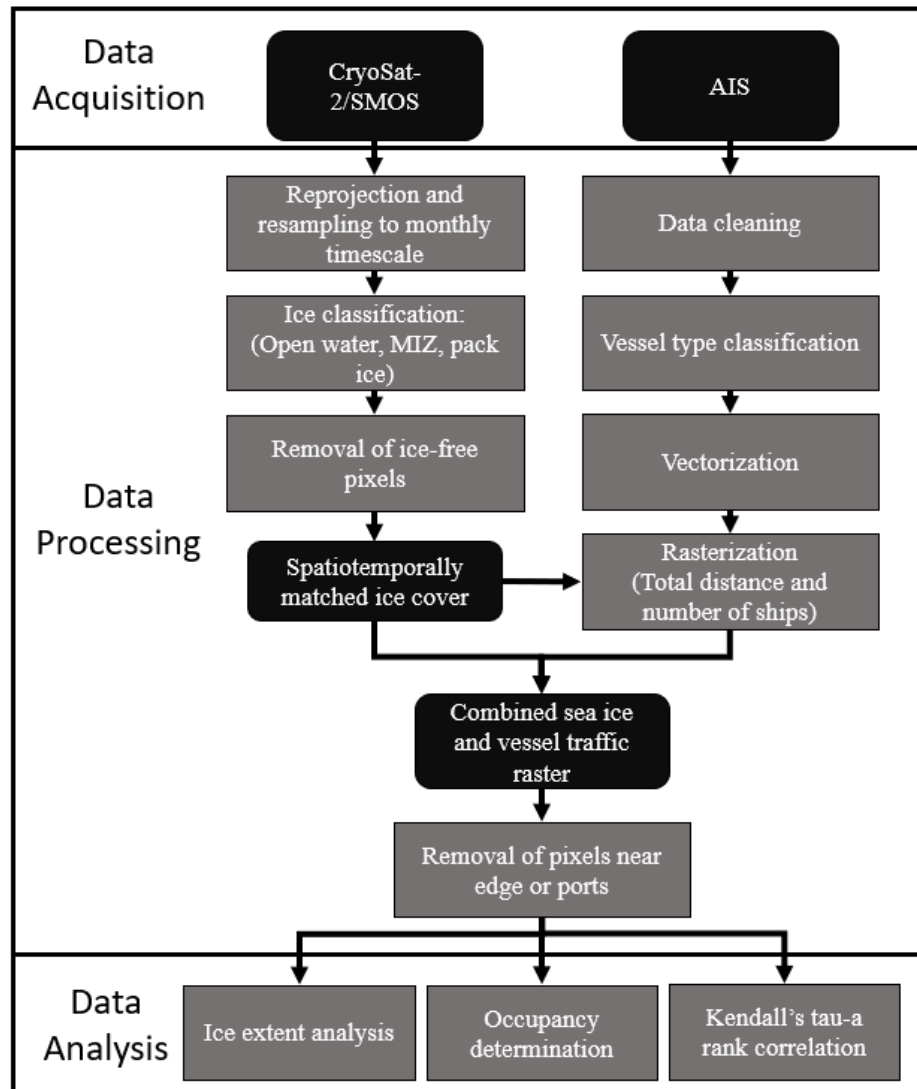


Figure 4.2 Flow chart for automatic identification system (AIS) and CryoSAT-2/SMOS data acquisition, processing, and analysis. Black boxes represent data sets while gray boxes represent steps in the analysis.

4.3.3 Vessel traffic and sea ice analysis

To determine the relationship between vessel traffic and sea ice in the Pacific Arctic, we first mapped and aggregated the changes in vessel traffic and sea ice across space and through time. For each time period, we defined occupied pixels as those that had at least one vessel pass through them. We then examined the relationship between sea ice concentration and the proportion

of occupied pixels for the entire study period as well as the average amount of vessel traffic per occupied pixel across all values of sea ice concentration. To determine whether this relationship differed by vessel type, we also examined the total distance travelled by vessels compared to sea ice concentration.

To assess the significance and direction of the relationship between sea ice and vessel traffic in the study area, we applied a non-parametric correlation analysis, following Pizzolato et al. (2016). On a per-pixel basis, we identified the maximum ice concentration value in months for which the total vessel traffic was greater than zero. We then identified all months with no vessel traffic and sea ice concentration greater than the aforementioned maximum. Of these months, we kept the month with the lowest sea ice concentration value and removed the rest of the months from further analysis. The purpose of this method is to remove ties from the data set, which are not accounted for by the Kendall's tau-a rank correlation. Unlike Pizzolato et al. (2016), we did not de-trend the data prior to correlation analysis because our time series was short enough in duration (six years) that we would not expect to see long-term climate-related trends in sea ice concentration. To remove ties, we also removed all months with no vessel traffic and no sea ice. After this procedure, we calculated the Kendall's tau-a rank correlation to determine the relationship between vessel traffic and sea ice at a pixel scale. We calculated the correlation for both measures of sea ice (thickness and concentration) and vessel traffic (number of ships and total km travelled).

4.4 Results

4.4.1 Spatiotemporal patterns of sea ice in the Pacific Arctic

Fall and winter vessel traffic in the northern Bering Sea increased from 2015 through 2020. This increase was consistent across vessel metrics (number of vessels and total distance travelled)

and across all months of the study period (October through April; Figure 4.3). Patterns of vessel traffic were highly variable across months, but relatively consistent between years, with maximums in October for all years and traffic minimums in January or February, depending on the year.

Patterns of sea ice and vessel traffic were inversely related, with sea ice extent reaching its maximum in December (2018), February (2020), or March (2015, 2016, 2017, and 2019). The maximum annual sea ice extent was lowest in 2018, covering 63% of the study area. This represents a reduction of 13-27% over other years in the study period. In all years, sea ice extent was relatively consistent during the freeze-up period from October through December, but was more variable in the winter months. Sea ice extent was particularly low in February through April of 2018 and 2019.

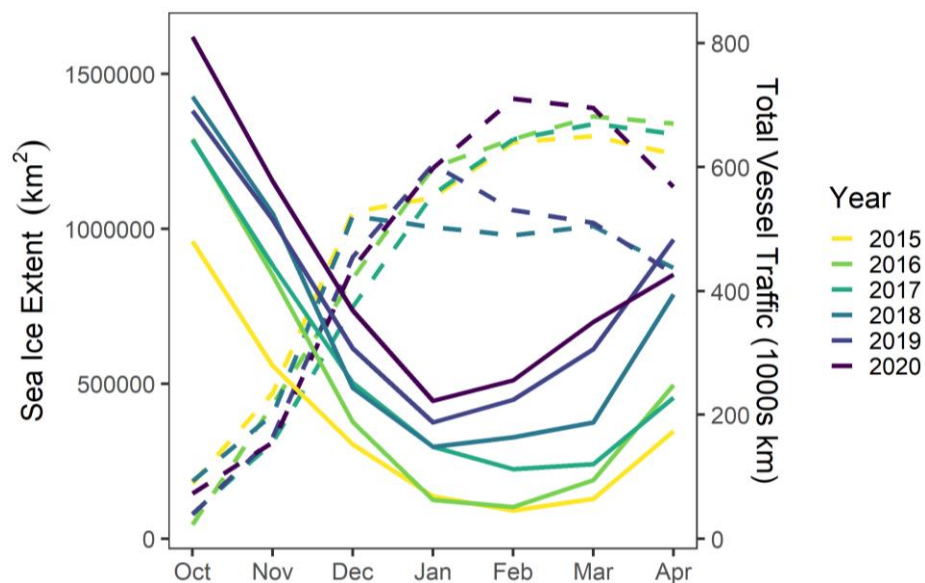


Figure 4.3 Monthly total vessel traffic (solid lines) and sea ice extent (dashed lines) for the study period.

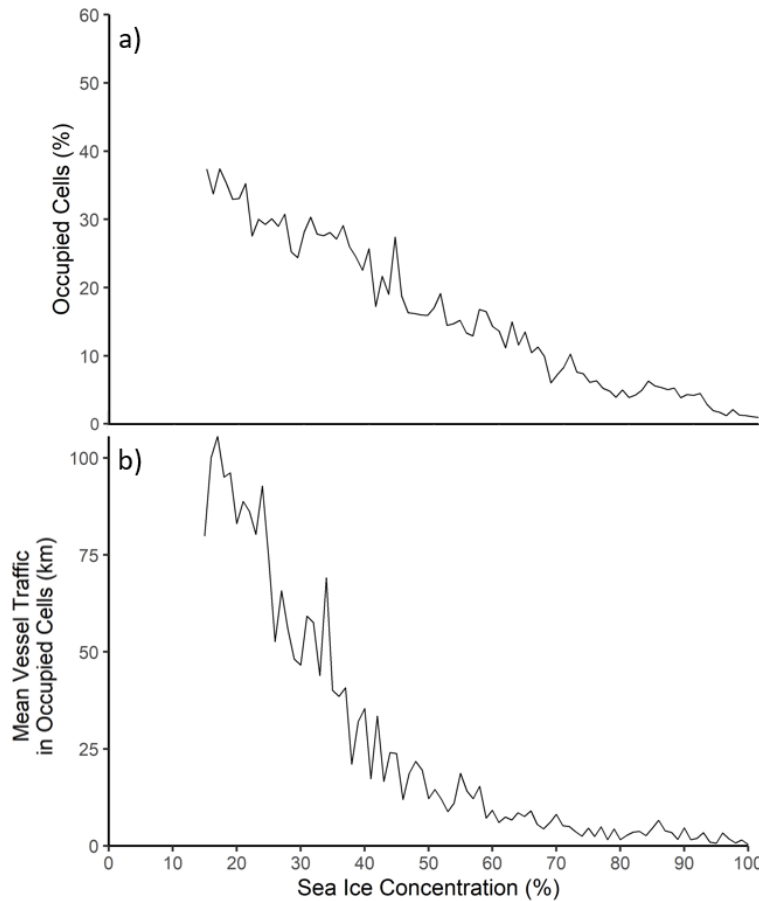


Figure 4.4 Changes in vessel traffic by sea ice concentration for the entire study period. (a) Occupied pixels are defined as those with at least 15% sea ice concentration and total distance travelled by vessels greater than zero for a given month; (b) Mean vessel traffic (km travelled) in pixels with at least 15% monthly average sea ice coverage. Values were combined across all months of the study period.

Between 2015 and 2020, the total amount of vessel traffic occurring in the MIZ increased by 46%, while overall vessel traffic increased by 58%. Growth of vessel traffic in pack ice was 30%. In general, vessel traffic decreased with increasing sea ice concentration (Figure 4.4). In pixels with no sea ice in a given month, 57% contained at least some vessel traffic. At 15% ice concentration, the proportion of pixels with vessel traffic decreased to 37%, and at 80% ice concentration, this proportion decreased to 4% (Figure 4.4a). In addition to a higher proportion of pixels with vessel traffic at lower ice concentrations, there was also more traffic overall in each pixel at lower ice concentrations (Figure 4.4b).

In both the MIZ and pack ice, the total amount of vessel traffic was higher in 2020 than in 2015 (Figure 4.5 a and b), albeit with substantial variability among years. There was a greater inter-annual variability in vessel traffic in pack ice than in the MIZ, with peaks in 2018 and 2020 and very little traffic in pack ice in 2016. The amount of vessel traffic per pixel in the MIZ and pack ice were both heavily skewed with a few pixels containing significant traffic and many pixels with very little traffic.

Spatial patterns of the distribution of vessel traffic were distinct between the MIZ and pack ice (Figure 4.5c and d). Vessel traffic in the MIZ was widespread throughout the study area, with the exception of the central Bering and Chukchi Seas and Norton Sound (Figure 4.5c). Vessel traffic in pack ice appears to be a subset of vessel traffic in the MIZ and was concentrated in the western Beaufort Sea and the western Chukchi sea, along the Northern Sea Route and up to Wrangell Island.

The relationship between vessel traffic and sea ice concentration varied among vessel types (Figure 4.6). Fishing vessels travelled extensively along the ice edge ($< 30\%$ concentration), but were rarely found in areas with more than 50% concentration of sea ice. Other vessel traffic was the dominant vessel type in pack ice, likely indicating icebreaker activity. (Icebreakers fall under the Other vessel type in this typology.) Cargo and tanker traffic both decreased consistently with increasing ice concentrations.

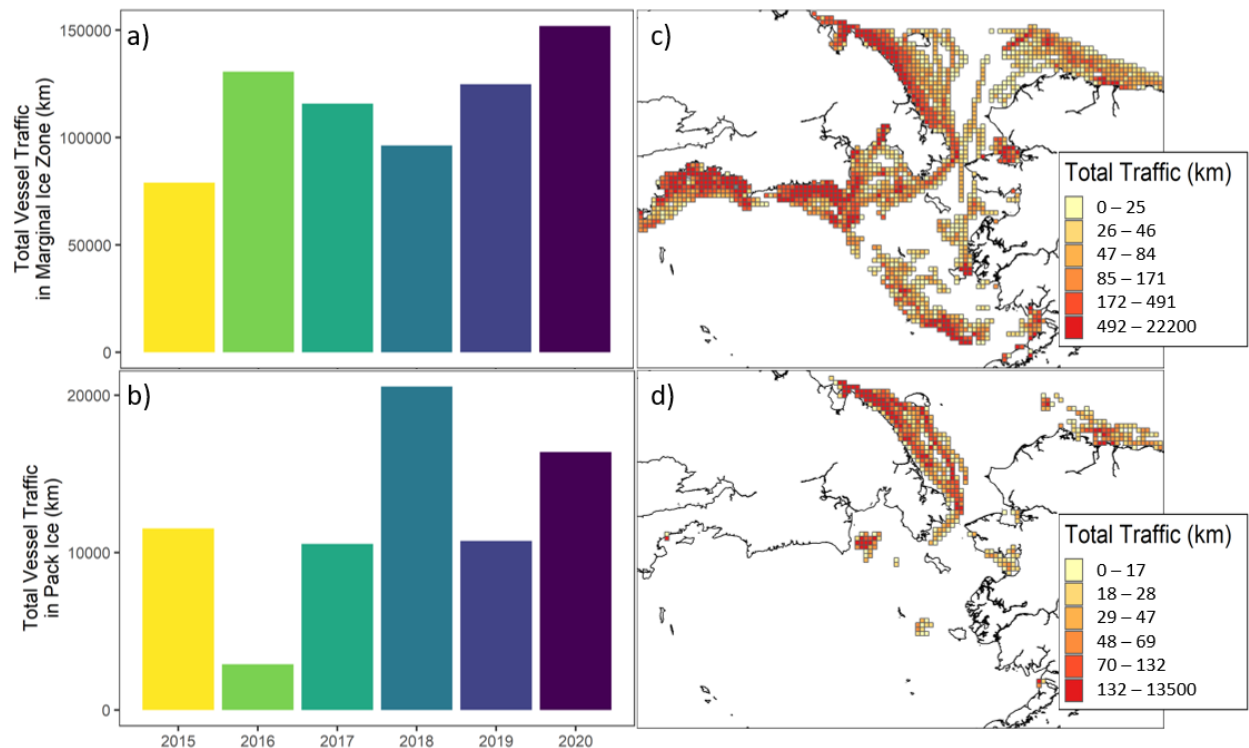


Figure 4.5 Vessel traffic (total km travelled) from 2015 to 2020 in (a) marginal ice zone (MIZ; i.e., sea ice concentration between 15% and 80%), (b) pack ice (i.e., sea ice concentration > 80%). Maps of the study area with total amount of traffic occurring in (c) MIZ and (d) pack ice. Scales are unique to each sub-figure. Map data are presented on a quantile scale.

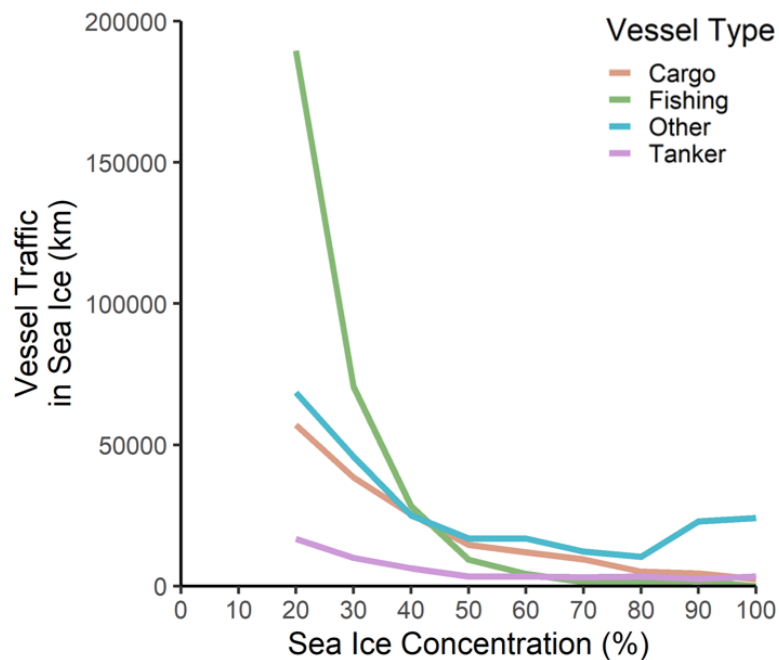


Figure 4.6 Changes in total vessel traffic (km) by sea ice concentration and vessel type. Green lines represent Fishing vessels, blue lines represent Other vessels, orange lines represent Cargo vessels, and purple lines represent Tankers.

4.4.2 *Correlation between vessel traffic and sea ice*

Vessel traffic and sea ice were inversely correlated in coastal portions of the study area (Figure 4.7). The direction of correlation and patterns of significance were roughly consistent across all four combinations of metrics (ice concentration and traffic (km), ice concentration and number of ships, ice thickness and traffic (km), and ice thickness and number of ships). For the sake of clarity, we focus on the results of sea ice concentration and vessel traffic.

Of the pixels with significant correlations between vessel traffic and sea ice, the vast majority (99.8%) were negative, indicating that as sea ice concentration increased, total vessel traffic declined. Significant negative correlations were concentrated along the coast lines with the strongest relationships along the Northern Sea Route. There was little to no association between vessel traffic and sea ice in the central Chukchi and Bering Seas, likely due to the minimal amounts of vessel traffic in those areas.

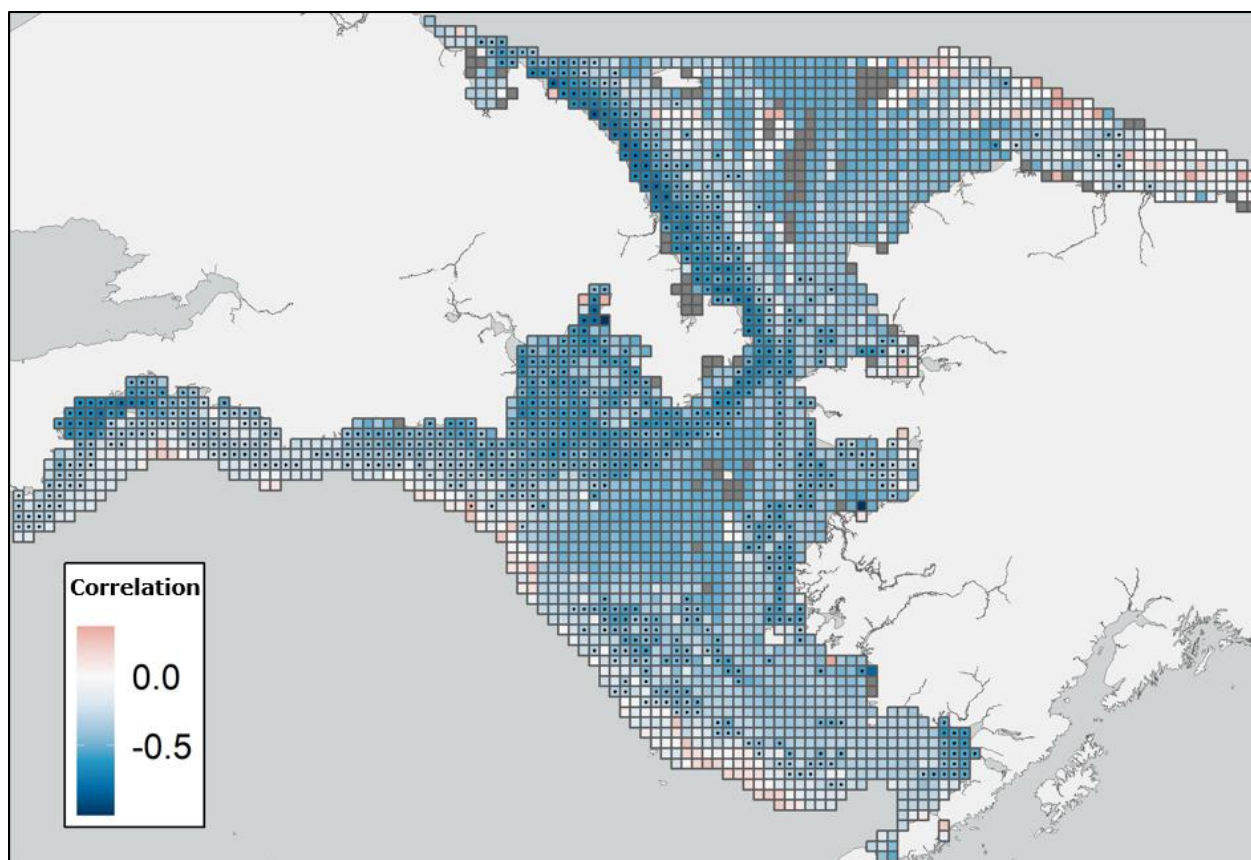


Figure 4.7 Kendall's tau-a correlation values for monthly average sea ice concentration and total vessel traffic (km) from October to April in 2015 through 2020. Significant correlations ($p < 0.05$) are marked with a *. Grey pixels had insufficient sample sizes to conduct correlation analysis.

4.5 Discussion

Vessel traffic across the Pacific Arctic is increasing in both the ice-free and the marginal ice seasons. However, sea ice is still a significant limiting factor that constricts the majority of vessel traffic to the ice-free season. By examining vessel traffic in the fall and winter, this analysis contributes new insights into the spatiotemporal relationships between vessel traffic and sea ice that can be used to better predict the impacts of policy decisions as well as climate-induced sea ice reductions on vessel traffic in the future.

The overall amount of vessel traffic in the study region does not appear to respond to sub-annual changes in sea ice extent (Figure 4.3). During the winters of 2018 and 2019 when ice extent

was substantially lower than previous years, the overall amount of vessel traffic did not increase proportionately. This result supports previous findings that decision-making by maritime industry stakeholders with regard to vessel operations in the Pacific Arctic occurs not in response to current conditions, but rather based on historical knowledge of navigation season length (Wagner et al. 2020). Furthermore, at the scale of vessel operators seeking navigational information about, for example, the location of the ice edge, operators frequently face bandwidth restrictions that limit access to high-resolution, near real time products (Wagner et al. 2020).

The majority of traffic in the MIZ was associated with fishing vessel activity. While commercial fishing is limited to non-trawling activities above approximately 60° North on the US side (North Pacific Fishery Management Council 2020), fishing activities on the Russian side extend northward into the Gulf of Anadyr. Fishing vessels appear to approach the edge of ice-covered areas without entering into areas of >50% sea ice cover, which could pose a safety hazard given that these vessels are not typically ice-strengthened.

Vessel traffic in pack ice was dominated by Other vessels. The Other vessel traffic category covers a broad range of vessel types, including passenger vessels and icebreakers. Icebreakers are the most likely contributor to vessel activity in pack ice, however due to limitations in the AIS data set, we were unable to distinguish icebreakers from other vessel types. Future research integrating auxiliary data sets of vessel information could be used in a more detailed analysis of the relationship between different vessel types and sea ice.

4.5.1 Social-ecological consequences of increasing vessel activity

Increasing vessel traffic in the marginal ice season could have negative consequences for the social-ecological systems of the Pacific Arctic. The western Bering Strait and northern coast of Chukotka is an area of heightened vulnerability for marine mammals exposed to vessel traffic

in the fall (Hauser et al. 2018). While ship strikes are less probable in the MIZ and pack ice, given that vessels travel more slowly in these regions and vessel speed is a key determinant of ship strike risk (Kite-Powell et al. 2007), the presence of vessel traffic in sea ice has the potential to amplify some threats and also brings new concerns. For example, vessel noise is a concern for Arctic marine mammals in both open water and sea ice as it can mask communication or, in extreme cases, cause hearing damage (Erbe et al. 2019). However, vessel noise is amplified in moderate to heavy ice coverage, thus elevating potential risk of negative consequences (Roth et al. 2013). Other potential impacts of vessels, such as oil spills, are also exacerbated by the presence of sea ice, which complicates both access to spill sites and traditional containment techniques. Finally, the presence of vessels in pack ice has the potential to disrupt habitat of ice-dependent species, particularly during the spring months when, for example, ice seals use this habitat for denning (Lindsay et al. 2021).

Indigenous communities in the Pacific Arctic frequently use sea ice as a platform for subsistence hunting. Vessel traffic in pack ice in the western portion of the Bering Strait and northern coast of Chukotka could impact subsistence activities in this area. However, recent routing measures for the Bering Strait region have moved vessel traffic away from the coast beginning in December of 2018, which could provide a buffer against these impacts (U.S. Coast Guard 2016). Further consultation with Indigenous communities in the region is needed to better understand the potential consequences of increased vessel traffic in pack ice on subsistence livelihoods and wellbeing.

4.5.2 Evidence of policy and resource development impacts on vessel traffic in ice

Vessel traffic in pack ice reflects the policy decisions and investment in infrastructure of the United States and Russia. On the North Slope of Alaska in the Bering Sea, vessel traffic in

pack ice is most likely associated with oil and gas activity. For example, after an exploratory well drilled in the Nikaitchuq lease area in late 2017 (State of Alaska 2018), vessel traffic activities in the pixel containing the drilling area increased from 130 km and 1,743 km in 2015 and 2016, respectively to 5,208 km and 5,734 km in 2017 and 2018, respectively. On the Russian side of the Bering Strait, vessel activities in sea ice were far more expansive. Russia has an extensive ice-breaking fleet, including several nuclear-powered ice breakers, that it uses to clear ice along the Northern Sea Route. This enhanced capacity can be seen in concentration of vessel traffic in pack ice along the northern coast of Chukotka (Figure 4.5d).

4.5.3 Limitations and future directions

While this analysis assumes that ice coverage within a pixel is homogenous, this is likely not the case. In many instances of low ice concentration, ice coverage is most likely clustered in one portion of a pixel. This means that, in some cases, vessel traffic that has been categorized as “in ice” is not in actuality transiting through ice directly, but rather is moving close to the ice edge. Despite this assumption, the increases in total vessel traffic in both the MIZ and pack ice indicate that this change is not the result of increased vessel traffic along the ice edge given that cells with a high concentration of sea ice (i.e., pack ice) are not likely to exhibit the same edge effects. Future analyses at finer spatiotemporal scales with higher resolution data on sea ice concentration could help to tease out the ice conditions encountered by individual vessels.

Future research would also benefit from an enhanced understanding of the decision-making of vessel operators moving through or near sea ice. While economic and policy barriers for shipping companies have been identified (Lee and Kim 2015), it remains unclear which sources of information about sea ice coverage vessel owners and operators are using to make decisions about whether to travel into Arctic waters and how to navigate potentially ice-covered areas,

respectively. Variability among different sources of information on ice conditions may affect the decisions, and thus the movements of vessels.

4.6 Conclusion

While this analysis demonstrates that sea ice remains a limiting factor for Arctic vessel traffic, the absence of sea ice does not in and of itself create more traffic. The increases in vessel traffic in the MIZ and pack ice that we observed in this study were most likely driven by policy decisions. Given that policy approaches have a substantial impact on vessel traffic patterns, any extrapolations of trends from this analysis should be made with caution. Future analyses and projections of vessel traffic in the Arctic should take into consideration not just the degree of accessibility by hypothetical vessels, but also other factors, including political regimes, investment in infrastructure (e.g., ports), routing guidelines, and the decision-making processes of vessel operators.

CHAPTER 5: AVOIDANCE OF NEARBY ANTHROPOGENIC ACTIVITIES IDENTIFIED IN RESOURCE SELECTION BY A MARINE PREDATOR

Kapsar, K. Montgomery, R., Rehberg, M., Liu, J. In Prep. Avoidance of nearby anthropogenic activities identified in resource selection by a marine predator. *To be submitted.*

5.1 Abstract

Quantification of the threats to animal population persistence is essential to effective conservation practice. In marine environments, for instance, vessel traffic can be a source of disturbance via noise and chemical pollution which can threaten marine species. Importantly, these threats are dynamic; in other words, the spatiotemporal configuration of these threats changes as ships move throughout the ocean. Quantifying the nature and strength of these effects has historically been challenging given irresolute data on vessel traffic. Recent advancements in ship tracking technology now enable concurrent mapping of vessel traffic and movement of telemetry-tagged marine animals. Here, we quantified the spatiotemporal relationships of endangered Steller sea lions (*Eumetopias jubatus*) and marine vessel traffic (divided among fishing and non-fishing vessels) in the Gulf of Alaska. We constructed Bayesian discrete choice resource selection function models fit to the movement of individual Steller sea lions across weekly timescales. We found that distance to fishing vessels significantly affected the resource selection of a majority ($n = 7$ of 11) of Steller sea lions. Notably, Steller sea lions tended to select areas away from fishing vessels. Five of eleven Steller sea lions exhibited similar avoidance behavior toward non-fishing vessels. While previous work has not demonstrated fishery effects on Steller sea lions at seasonal scales, our methodology highlights that adverse associations between fishing vessels and Steller sea lions may occur at finer spatiotemporal scales.

5.2 Introduction

Human activities are a dominant and growing force in the world's oceans (O'Hara et al. 2021). As the influence of humans in marine systems increases, so too does the potential for conflict between humans and marine animals. Competition for shared resources, mortality due to bycatch, or depredation of commercially harvested species by marine animals are common examples of human-wildlife conflict in marine systems (Guerra 2019). Fisheries, in particular, are a common source of human-wildlife conflict in marine systems (Jog et al. 2022).

While fishing and other vessel activities are a source of human-wildlife conflict, they also play a key role in a globalized economy. For instance, ships carry over 80% of all globally traded goods (UNCTAD 2017) and fish consumption is growing faster than that of any other protein source, except poultry (FAO 2020). These activities are often driven by distant demand for goods that are either harvested from the ocean (e.g., fish) or transported through the ocean (e.g., on cargo ships) before they reach their final destinations. Together, these activities create a complex, metacoupled system where local human-wildlife conflict is ultimately driven by distant demand for resources (Liu 2017, Carlson et al. 2020).

While marine vessel traffic facilitates the transfer of various goods and services between metacoupled human and natural systems around the world (Liu 2017), it poses a number of serious threats to biodiversity. Marine vessel traffic is an important source of disturbance and mortality via vessel strikes, bycatch, as well as chemical, vibration, and noise pollution, by-catch potential, and oil spills that contribute to the cumulative impacts on marine environments (Halpern et al. 2015, Afflerbach et al. 2017). These effects can contribute to other stressors extant within the system which can negatively impact the persistence of already-stressed species and habitats (Crain et al. 2008, Halpern et al. 2015).

Many of the threats to marine species posed by fishing and vessel traffic are dynamic in nature, changing across space and through time with the movement of vessels (Chen et al. 2017, Stocker et al. 2020). Traditional approaches to understanding species' response to such dynamic human activities tend to rely on static measures, such as distance to the nearest town or, in the case of fisheries, the spatial distribution of seasonal catch per unit effort data (Harju et al. 2011, Hui et al. 2015). However, new insight into marine vessel activities across space and through time enables direct comparison of human activity at the same spatial and temporal scale as that of marine mammal behavior (McKenna et al. 2015, Kroodsmma et al. 2018, Stocker et al. 2020) .

To better understand how marine species may respond to vessel traffic, we examined the resource selection of an endangered marine predator, the Steller sea lion (*Eumetopias jubatus*). Across their range and over last quarter of the 20th century, Steller sea lions experienced dramatic declines in population size. These declines led to the listing of Steller sea lions as endangered under the United States Endangered Species Act in 1990 (55 FR 49204). The Steller sea lion population was subsequently separated into two Distinct Population Segments (DPS): a threatened eastern DPS (eDPS) east of Cape Suckling, Alaska, and an endangered western DPS (wDPS) divided at the boundary of Cape Suckling. Across the 1990s and 2000s, the eDPS recovered and was subsequently delisted in 2013 (78 FR 66140). However, the wDPS has remained well below historic levels. While the decline has stabilized somewhat since 2002, the recovery of the wDPS has been spatially variable (Muto et al. 2020) and thus has yet to achieve the recovery criteria required for down-listing (e.g., from endangered to threatened). In recent years, Steller sea lions in the eastern and central Gulf of Alaska have experienced some of the highest rates of growth in both pups and non-pups of all survey regions for the endangered wDPS (Muto et al. 2020). However, between 2015 and 2017, pup counts dropped by approximately 33% and 18% in the

eastern and central Gulf of Alaska regions, respectively (Muto et al. 2020). To date, no clear consensus has emerged to explain the causes of both historical and current declines in the wDPS (Lander et al. 2020).

One leading hypothesis for these declines is competition with fishing vessels (National Marine Fisheries Service 2008). Steller sea lion diets overlap with several commercial fisheries in Alaska, including walleye pollock (*Gadus chalcogrammus*), Atka mackerel (*Pleurogrammus monopterygius*), and Pacific cod (*Gadus macrocephalus*). Competition with the commercial fishing industry could cause nutritional stress in Steller sea lions through a reduction in the nutritional quality, a change in the distribution, or a reduction in the overall abundance of available fish (Hui et al. 2015). Nevertheless, previous research has not found evidence that declines in prey biomass associated with summertime commercial fish harvest were associated with changes in Steller sea lion population size at the rookery scale (Hui et al. 2015). Thus, the availability of pollock, cod, and mackerel may not be the factor limiting Steller sea lion population growth in the wDPS in the early 2000s.

Another possible mechanism of commercial fisheries impacts on Steller sea lion movement and habitat use is through behaviorally-mediated responses to vessels. Attraction and avoidance are both examples of behaviorally-mediated responses, which occur when the presence of an entity (e.g., predator, competitor) elicits a sub-lethal behavioral response in an individual or population (Schmitz et al. 1997). While behaviorally-mediated responses have been identified in juvenile Steller sea lions, which alter their foraging patterns based on predation risk (Frid et al. 2009), there is little understanding of how Steller sea lions alter their movement based on marine vessel traffic.

Although they have yet to be demonstrated in Steller sea lions, avoidance of and attraction to dynamic anthropogenic activities have been demonstrated for other predators in both terrestrial

and marine environments. For instance, terrestrial carnivores avoid periods of heavy road traffic (Kautz et al. 2021). Conversely, large albatrosses (*Diomedea spp.*) have been shown to follow fishing vessels, likely attracted by the aggregation of prey (Corbeau et al. 2021). Similar to the albatross, anecdotal reports also indicate that Steller sea lions may be attracted to fishing vessels (NOAA 2019).

We hypothesize that Steller sea lions will accommodate the potential risk of proximity to heavy fishing vessel traffic in order to benefit from concentrated foraging opportunities they find in a prey patch. Because other vessel types pose risks without the benefits of concentrated prey, we hypothesize that Steller sea lions will instead avoid areas of heavy non-fishing vessel activity.

In this study, we evaluate Steller sea lion resource selection via concurrent tracking of Steller sea lions and marine vessel traffic. Our objective is to determine whether Steller sea lion movements are associated with fishing and/or non-fishing vessel activities. To achieve this objective, we fit a Bayesian discrete choice resource selection function (RSF) relating individual Steller sea lion movement data to a number of environmental characteristics. We constructed the model at the 3rd order of selection to capture variability in selection within individuals' home ranges (Johnson 1980), and measured both distance to and intensity of fishing and non-fishing vessel activities at all used and available locations on a weekly timescale. By incorporating weekly changes in environmental parameters, Steller sea lion movement, and vessel movements, we gain new insight into individual Steller sea lion responses to vessel traffic.

5.3 Methods

5.3.1 Study area

We established a study area of approximately 459,000 km² in Prince William Sound and the Gulf of Alaska within which we telemetry-tracked 11 Steller sea lion (hereafter referred to as

sea lions) between 2018 and 2019 (Figure 5.1). This region is located along the south coast of mainland Alaska in the northern Pacific Ocean, and is characterized by a sub-arctic climate with currents moving predominately from northeast to southwest along the coast (Stabeno et al., 2016). Nutrients transported from coastal freshwater inflows as well as localized eddies and upwellings over the continental shelf support a rich ecosystem with productive commercial fisheries, including Pacific cod and walleye pollock (Gaichas et al., 2015; Stabeno et al., 2004). During our study period, in the summer of 2019, the region experienced an extreme warming event during which sea surface temperature exceeded historical records (Litzow et al. 2020). Ecosystem-wide effects of this warming period remain uncertain (Litzow et al. 2020). However, some evidence of increased metabolic demand and poor body condition in Pacific cod during this heatwave have been documented (Barbeaux et al., 2020). Notably, the Pacific cod fishery was closed for the 2020 season (84 FR 70438), an unprecedented move forced by the 20% decline of spawning biomass against 2019 estimates.

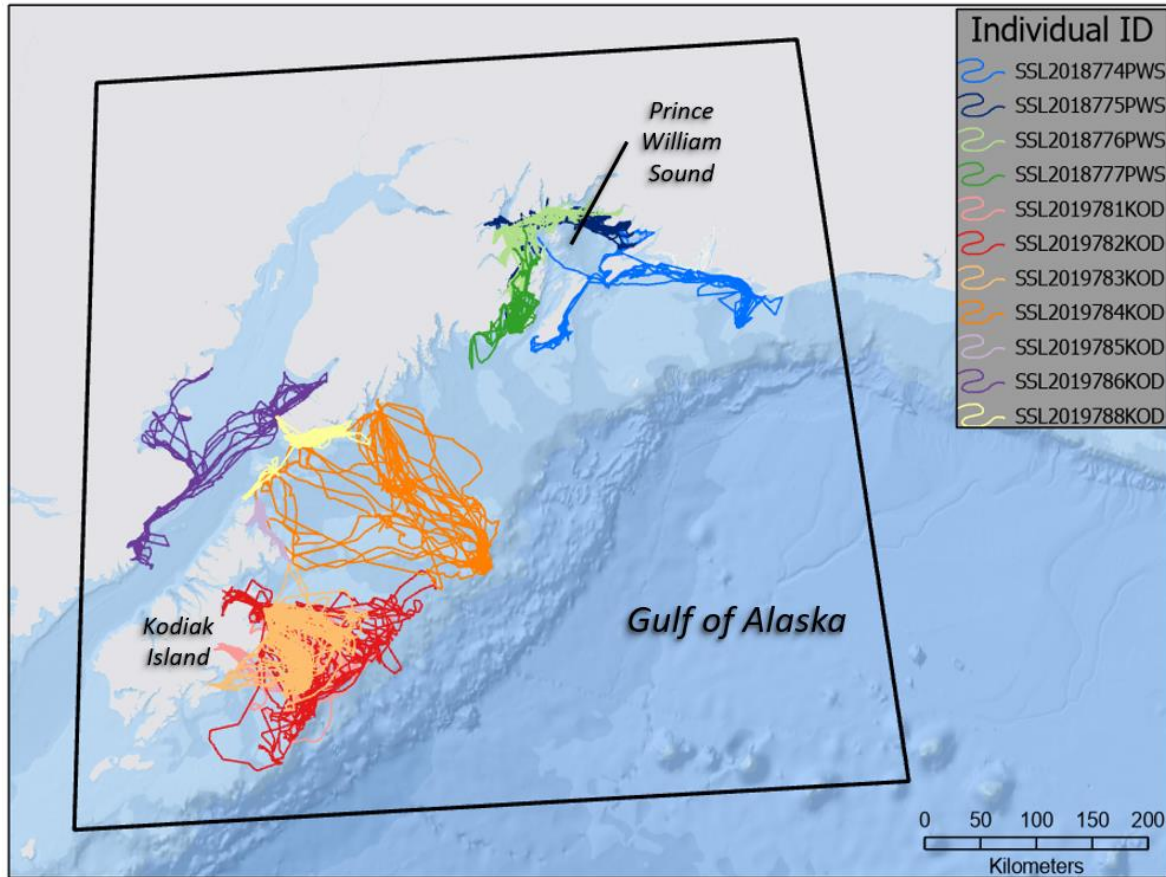


Figure 5.1 Map of locations of 11 telemetry-tagged adult female Steller sea lions in the Kodiak Island and Prince William Sound areas of the Gulf of Alaska. Data were collected between November 7, 2018 and July 1, 2020. Our study area, which bounded the analyses we conducted, is marked in black.

5.3.2 Telemetry data collection

Between November of 2018 and October of 2019, we captured and fitted 11 adult female sea lions with GPS telemetry tags (SPLASH 10, Wildlife Computers, Inc., Redmond, Washington USA). The first capture occurred in November of 2018, where we tagged four adult female sea lions in Prince William Sound and the second occurred in October of 2019, when we tagged seven additional sea lion females near Kodiak Island. All capture and handling protocols were approved by the Alaska Department of Fish & Game Animal Care and Use Committee (Protocol 0048-2019-64). Following chemical immobilization, we attached a satellite-linked GPS location and dive recording (SPLASH 10) tags (hereafter referred to as tags). We programmed tags to acquire GPS

positions every 15 minutes. A set of lower-accuracy, non-GPS locations acquired at variable intervals were also computed by the Argos/CLS satellite system. These data were transmitted via satellite (Argos/CLS) using a lossy transmission method, and while each unit of data was transmitted multiple times to improve odds of reception, most data streams include gaps of minutes to hours.

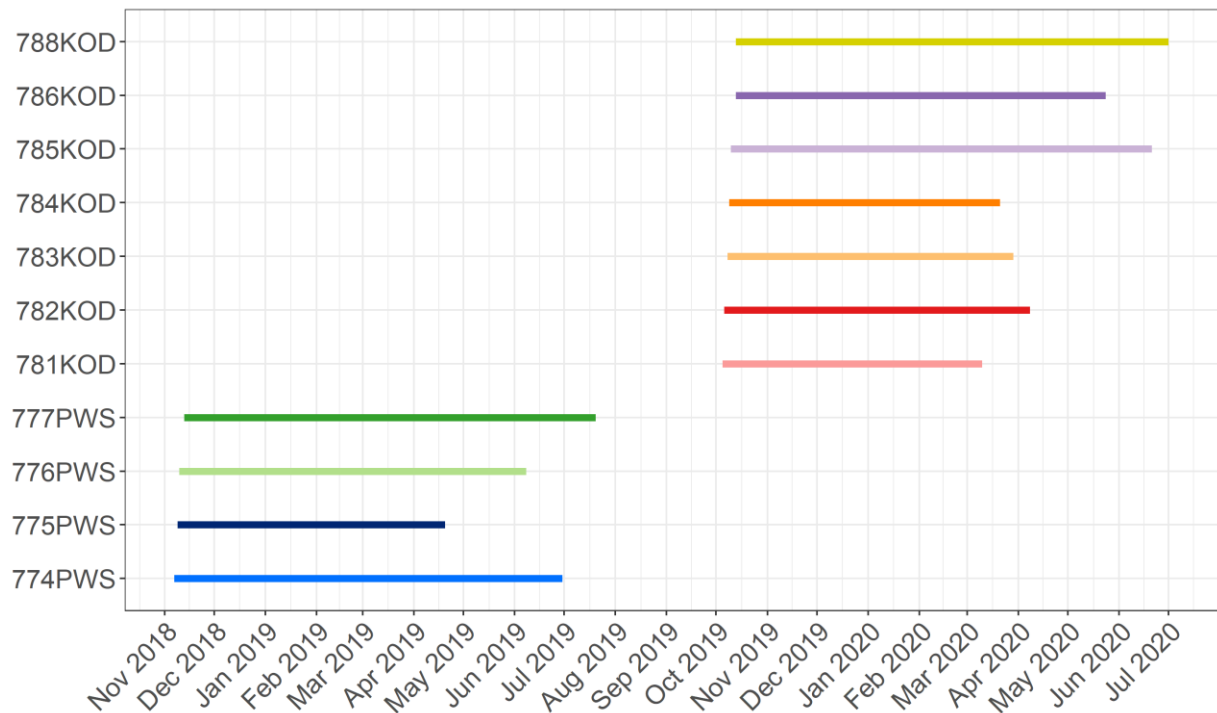


Figure 5.2 Duration of data collection from each sea lion GPS tag. These tags, glued to sea lion fur, have lifetimes limited by the annual fur molt (August-October), premature battery exhaustion, or mechanical damage.

We collected location data from sea lions between November 7, 2018 and July 1, 2020 (Figure 5.2). To evaluate the accuracy of locations returned from our telemetry system we used a Kalman filter (Lowther et al. 2015). After filtering, we initially retained Argos location classes 3, 2, and 1, which have been shown to be accurate to within 1.2 km among pinnipeds at sea (Costa et al., 2010). Next, we applied a speed filter of three meters per second to all locations using the McConnell (1992) algorithm from the argosfilter R package version 0.63 (Witt et al. 2010, Freitas

2015). We selected this speed limit to represent an intermediate value between previous studies which have used speed filters ranging from two to eight meters per second for sea lions (Rehberg et al. 2009, Bishop et al. 2018, Lander et al. 2020). Finally, we removed locations at haul-out sites using a land mask derived from NOAA's Generic Bathymetric Chart of the Oceans (GEBCO Compilation Group 2021). After accounting for data cleaning, GPS tags transmitted an average of 116.15 (SD = 31.9) sea lion locations per week across an average of 31 weeks each (SD = 5.48; Figure 5.2).

5.3.3 *Environmental and Anthropogenic variables*

We developed a geographic information database comprised of *a priori* environmental and anthropogenic variables that could explain sea lion resource selection (see Table 1). We developed each of these variables as rasters at a weekly temporal resolution and used cost surfaces to ensure that the layers calculated around land features (e.g., bays, inlets, islands, and peninsulas) that present obstacles to sea lion swimming, and masked to remove cells on land prior to analysis (see further details provided in Appendix S1). As central place foragers who have been shown to take foraging trips to areas on the continental shelf break, we predicted that increasing depth, distance to land, and distance to shelf break would be negatively associated with probability of selection by sea lions (Lander et al. 2020). Sea lions have also been shown to travel along canyons in shallow waters, which may serve as local areas of prey concentration through upwelling events (Rehberg et al. 2018), leading us to predict that increased bathymetric slope would be associated with increased probability of selection. While wind speed may not affect sea lions at a seasonal scale (Lander et al. 2020), we predicted that increased wind speed at a weekly resolution could be associated with decreased probability of selection. We also considered sea surface temperature (SST) as a variable in the model given that previous studies have suggested that it may influence

sea lion selection at fine spatial scales (Lander et al. 2011). However, given unclear findings of previous research and lack of a causal mechanism, we did not make an *a priori* assumption regarding the anticipated direction of the relationship.

To develop vessel traffic variables, we used ship location information returned from Automatic Identification System (AIS) data. The use of AIS transmitters is mandated by the International Maritime Organization on all vessels over 300 gross tons on an international voyage, all cargo vessels over 500 gross tons, and all passenger vessels regardless of size (IMO 2002). Further, in US waters, AIS is mandatory on all commercial vessels > 65 feet (Taconet et al. 2019). While smaller fishing vessels may not be covered, AIS data can provide reliable estimates of large vessel activities.

Based on anecdotal evidence of sea lion habituation to and pursuit of fishing vessels in search of prey (NOAA 2019), we predicted that sea lions would be attracted to fishing vessels. In contrast, other vessel types (e.g., cargo, tanker, passenger) present threats to sea lions in the form of noise, pollution, and risk of collision without the potential benefit of nearby food acquisition (Huntington et al. 2015). We therefore predicted that sea lions would avoid non-fishing vessel traffic. Given these differing hypotheses, we measured activity for fishing vessels and non-fishing vessel traffic separately (Table 1). To test these hypotheses, we developed two measures of vessel activity to differentiate between intensity and distance. Intensity values captured the total distance travelled by vessels in a given week in a raster cell while distance values measured the distance to the nearest vessel track line from each used and available point.).

Table 5.1 Environmental ($n=6$) and anthropogenic ($n=4$) variables used to parameterize sea lion resource selection function.

Variable	Data Type	Unit of measurement	Hypothesized relationship to probability of selection
Distance to land [†]	Static	Meters	-
Distance to shelf break [†]	Static	Meters	-
Bathymetric depth ^{†*}	Static	Meters	-
Bathymetric slope [†]	Static	Degrees	+
Wind speed	Dynamic	Meters/second	-
Sea surface temperature (SST)	Dynamic	Degrees Celsius	unk
Fishing vessel intensity	Dynamic	Kilometers	+
Non-fishing vessel traffic intensity	Dynamic	Kilometers	-
Distance to fishing vessel	Dynamic	Kilometers	+
Distance to non-fishing vessel traffic	Dynamic	Kilometers	-

[†] Indicates significant predictors of sea lion utilization distribution from Lander et al. (2020).
Depth was measured using a negative scale (i.e., increasing values indicate shallower water).

5.3.4 Discrete-Choice RSF modeling

Next, we fit a discrete-choice RSF model relating the sea lion movement data to our geographic information database of environmental and anthropogenic variables. Discrete choice approaches to RSFs are particularly well-suited for our research question because they allow for the selection of available habitats to be paired with a used location in both space and time. They do so by assuming that individuals will select a habitat unit from a set of available habitat units and that this selection indicates a preference of the characteristics of used units over the other available units in the choice set (Cooper and Millsaugh 1999).

In use-availability models, such as RSFs, the definition of availability must be appropriately matched to the level of selection to obtain accurate coefficient estimates (Montgomery et al. 2010; Northrup et al. 2013). The habitat patches used by sea lions, known as used habitat, can be known with relative certainty from our temporally and spatially accurate telemetry data (Montgomery et al. 2011). However, the set of available habitat units may contain

used habitat that was unmeasured by the observer (i.e., via telemetry error or un-tagged animals). This phenomenon is known as contamination. Johnson et al. (2006) use artificially contaminated examples from collared elk (*Cervus elaphus*) data to demonstrate that contamination levels under 20% are unlikely to significantly affect the coefficient estimates. In samples with a high degree of contamination (i.e., a large proportion of used locations in the available location set), the coefficient estimates for the parameters would approach zero, thus underestimating the true impact of the parameters on resource selection. In other words, the presence of contamination in the data set would lead the use and availability samples to appear similar and thus lead the researcher to conclude that the parameters had no impact on resource selection.

Previous discrete choice RSF studies have commonly calculated available habitat based on random locations collected within a radius of a used location, the width of which is proportional to the average movement rate of an individual (Durner et al. 2009, Montgomery et al. 2018). However, the movements of a central place forager, such as the sea lion, include substantial time spent in area-restricted searches, which could result in many overlapping availability circles, and subsequently a high degree of contamination in the data set. After identifying this high degree of contamination in our sea lion availability data using radius-based methods, we decided to draw available locations randomly from within each individual sea lion's weekly 95% kernel density estimate home range. We calculated home range using the `hr_kde` function from the `amt` package in R (R Core Team 2021; Signer et al. 2019). This method avoids contamination while obtaining spatially and temporally explicit availability samples.

Within each weekly home range for each sea lion, we randomly sampled five habitat units per used habitat to be designated as the available habitat, following Montgomery et al. (2018).

Together, six locations (one used and five available), were counted as a single choice set. Individual sea lion models consisted of an average of 3544.36 choice sets (SD = 1163.01).

Prior to model building, we tested all pairwise correlations between variables for each individual sea lion to check for evidence of collinearity ($R^2 > 0.6$). We identified a high degree of collinearity among at least two variables for ten of the eleven sea lions. After removing models with collinear parameters for each individual sea lion, the number of total models run for each sea lion ranged from 287 to 1023.

Following the methods of Montgomery et al. (2018), we applied a Bayesian discrete choice resource selection function model to individual sea lion locations. The probability that a sea lion chose a particular location (P_{il}) over a set of available alternatives (c) was the response variable in the model. Thus, the model was defined as:

$$P_{il} = \frac{\exp(\beta x_{il})}{\sum_{c=1}^C \exp(\beta x_{il})}, \quad \text{Equation 1}$$

where

$$\beta x_{il} = \beta_1 x_{il1} + \beta_2 x_{il2} + \dots + \beta_k x_{ilk}, \quad \text{Equation 2}$$

represents the suitability of habitat unit l to individual i and is calculated as the sum of the suitability values of k variables within that habitat unit. We standardized all parameters to a mean of zero and standard deviation of one to facilitate interpretation and comparison. We fit these models for each individual sea lion ($n = 11$). We ran all possible combinations of models for each individual in parallel on a high-performance computing system to enable efficient processing of the large number of model combinations.

We implemented the model in a Bayesian framework using the Stan package in R with weakly informative priors. We used four chains of 1000 iterations for each model, burning the first

200 to remove initial variability in the posterior estimates. We checked for model convergence by ensuring that all models had R-hat values less than 1.10 and effective sample sizes greater than 100 for each parameter. To assess goodness of fit for each RSF model, we calculated the posterior predictive, or Bayesian, p -values, comparing the proportion of iterations in the chain in which the simulated likelihood was more extreme than the actual likelihood (Carter et al. 2010, Montgomery et al. 2018). We evaluated the significance of variables using 95% Bayesian credibility intervals. We considered the 95% Bayesian credible interval ($\alpha \leq 0.05$) to signify a significant effect of a given parameter on sea lion resource selection when the interval did not overlap zero.

We then implemented a leave-one-out cross validation (LOO-CV) method as our model selection tool (Vehtari et al. 2017). We first fit all possible combinations of variables (excluding models featuring previously identified collinear variables) and evaluated the expected log pointwise predictive density values for all models. After model processing, we selected the top 5% of the ranked models for each individual. We examined the rate of inclusion of the marine vessel traffic variables in the top 5% of ranked models for each individual sea lion. Additionally, we evaluated the relative strength and direction of the variables' influence on resource selection by examining the 95% credible intervals in the single best fitting model for each individual sea lion.

5.4 Results

5.4.1 Rates of parameter inclusion in top 5% of models

The rate of inclusion of model parameters in the top 5% of all possible combinations of models (hereafter referred to as the top model set) differed substantially among the individual sea lions (Figure 5.3). Bathymetry was the most commonly included parameter, present in the complete top model set for ten of eleven sea lions. Slope and wind speed were all present in at least 45% of models in the top model set for all individuals. Distance to land, distance to the shelf

break, and sea surface temperature had a high degree of variability and were present in the entire top model set for some individuals and absent for others.

With regard to marine vessel traffic, parameter frequency in the top model sets were similarly variable. All individuals' top model sets included at least some models with fishing vessel intensity, non-fishing vessel intensity, and distance to fishing vessels. In general, fishing vessel metrics (distance and intensity) were more common in the top model sets than non-fishing vessel metrics. Of the vessel metrics, distance to fishing vessels was the most frequently included parameter in top model sets, ranging from one individual with distance to fishing included in 100% of their top model set, to one individual with distance to fishing in 45% of their top model set.

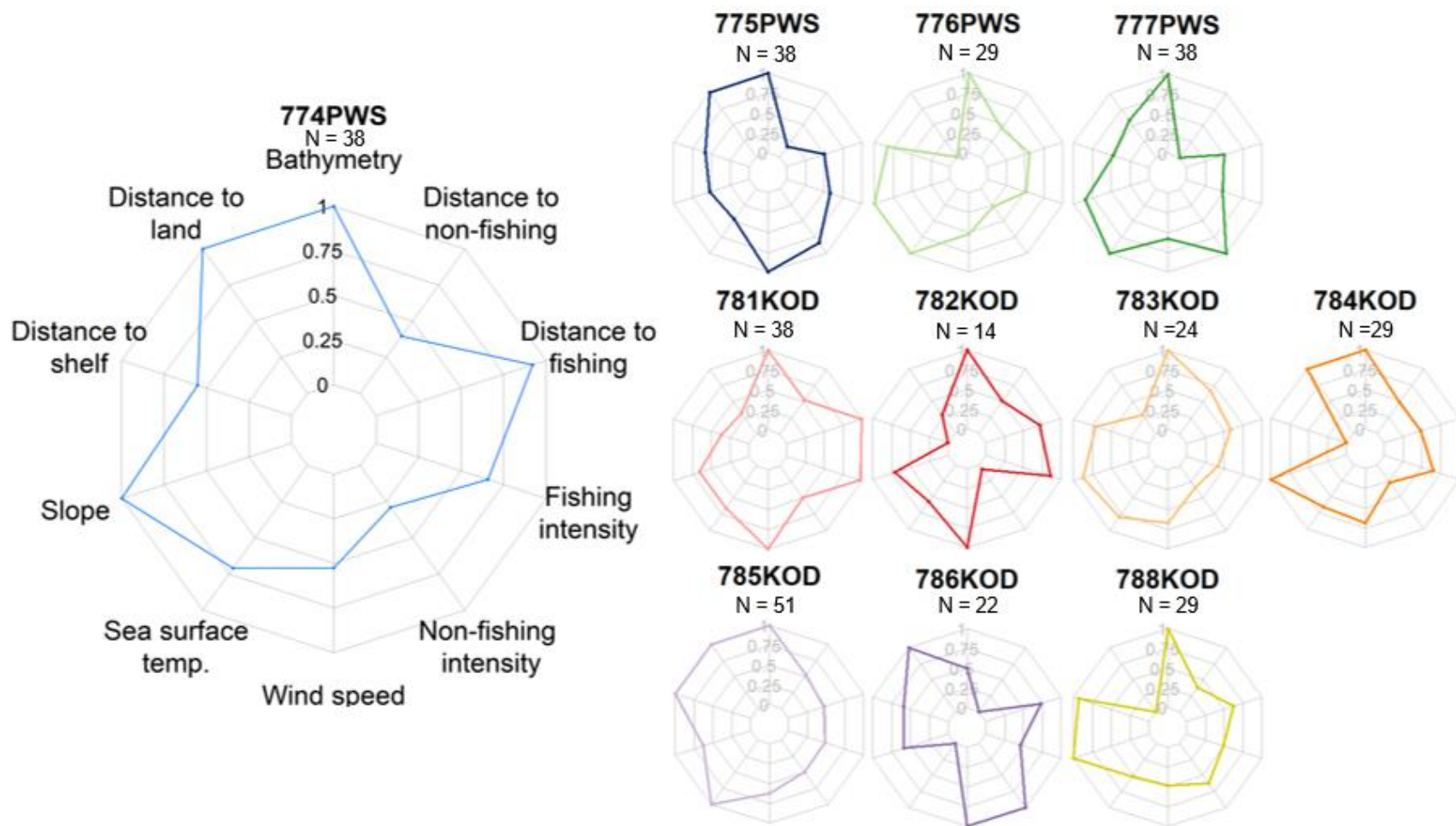


Figure 5.3 Radar plots demonstrating the frequency of inclusion of each parameter in the top 5% of models for each individual sea lion, as identified by leave-one-out cross validation. Sample size varied among individuals due to collinearity among parameters limiting the total number of models available in all possible combinations.

5.4.2 *Composition of parameters in best fitting model for each individual*

The number of parameters included in the best fitting model (identified from LOO-CV) for each individual ranged from a minimum of five ($n = 2$) to a maximum of eight ($n = 5$). Chi-square discrepancy tests for all individuals resulted in p-values less than 0.01, indicating that data simulated from models were significantly different from the data used to parameterize them.

Bathymetric slope was included in the best fitting models for all 11 sea lions (Figure 5.4). Wind speed and bathymetry were both included in 10 of the 11 best fitting models. Sea surface temperature and distance to fishing vessels were included in 8 of the best fitting models, while distance to land and fishing intensity were present in 7 individuals' best fitting models, followed by distance to shelf break ($n = 6$), distance to non-fishing vessels ($n = 5$), and non-fishing intensity ($n = 5$).

Slope, wind speed, bathymetry, and distance to non-fishing vessels were significantly positively associated with probability of use in all models in which they were included (Figure 5.4). Distance to land was significantly negatively associated with probability of use. Sea surface temperature, distance to shelf break, distance to fishing, fishing traffic intensity, and non-fishing vessel intensity each had multiple effect types across the best fitting models.

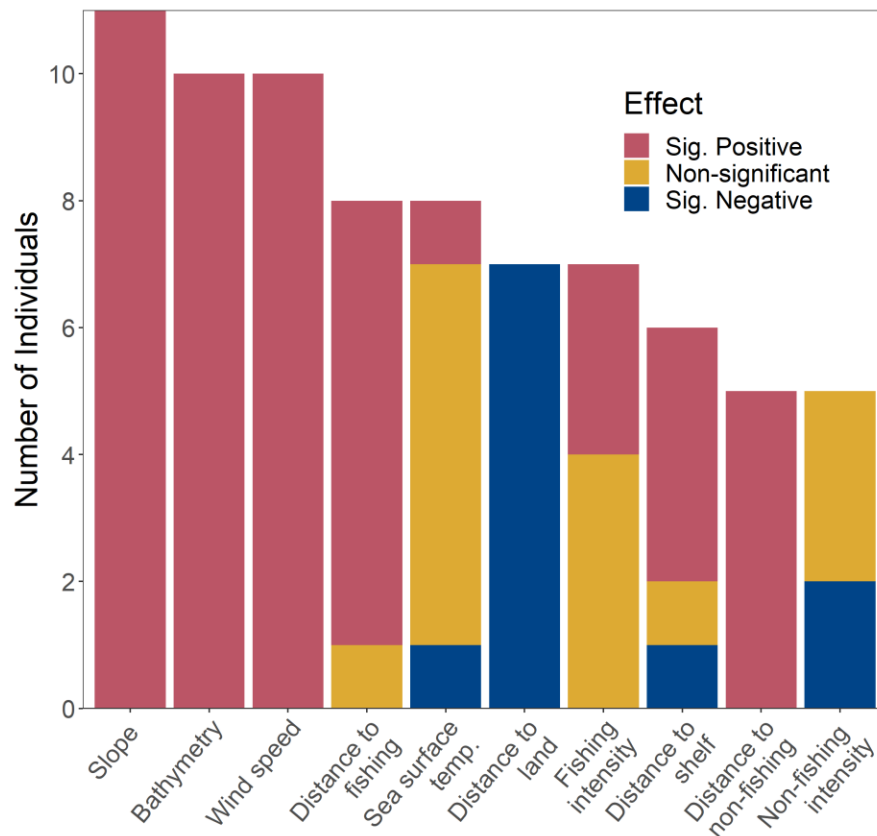


Figure 5.4 Bar plot demonstrating the number of best fitting models (out of 11) that included each parameter. Pink bars indicate significant positive effects (i.e., 95% credible interval does not include 0). Yellow bars indicate non-significant effects, and blue bars indicate significant negative effects.

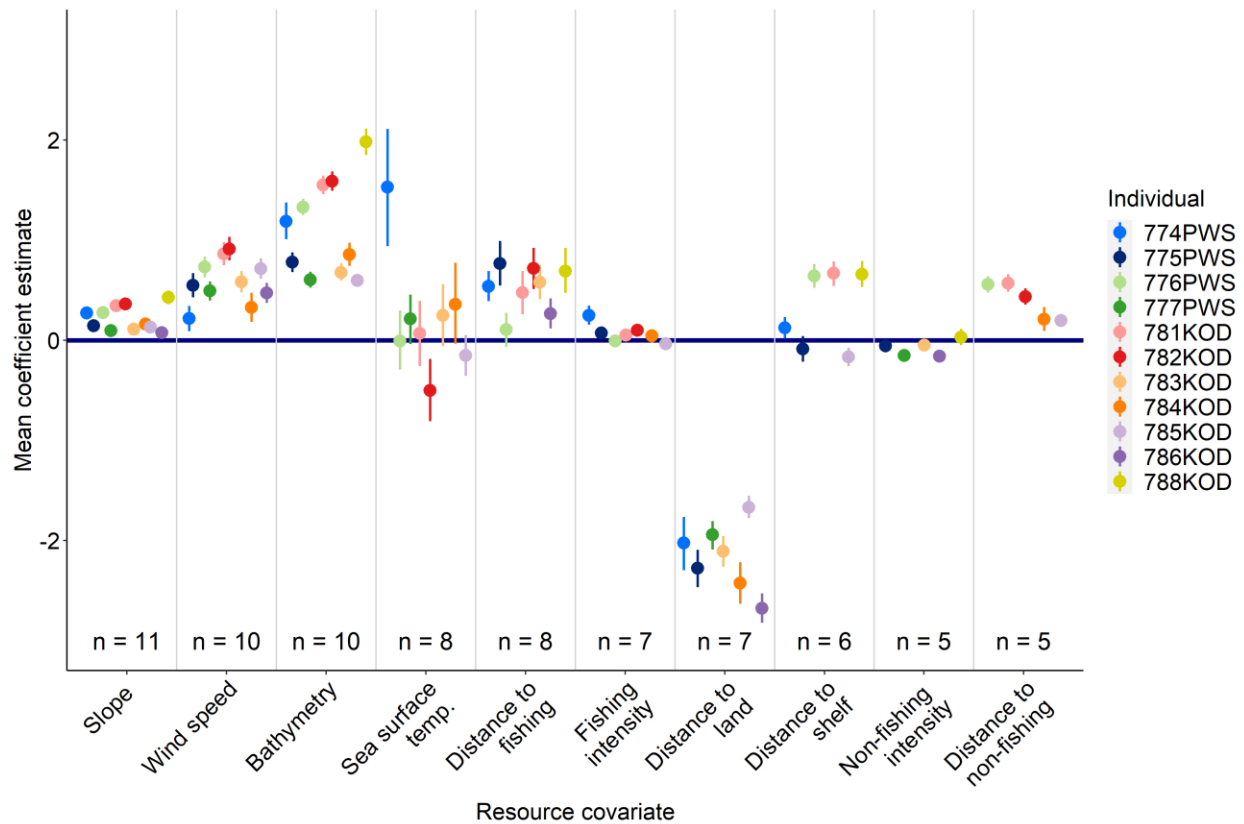


Figure 5.5 Individual RSF variable estimates with 95% Bayesian credible intervals for the best fitting model for each sea lion. Sample sizes above each variable indicate the number of best fitting models (out of 11) in which the variable was included.

5.5 Discussion

Steller sea lion populations in the wDPS have yet to fully recover from the substantial declines seen in the latter portion of the 20th century. The causes of this decline and absence of recovery remain largely unknown. Therefore, identifying potential threats to sea lions in the wDPS is a critical first step to effective conservation and population management. While commercial fishing activity has long been seen as a potential threat to Steller sea lions, little research has examined the relationship between fishing vessel (as well as non-fishing vessel) and Steller sea lion movements. In this study, we measured the resource selection of individual Steller sea lions within their home range in relation to vessel traffic and environmental covariates at a weekly timescale.

5.5.1 *Steller sea lion resource selection in relation to fishing and non-fishing vessel traffic*

We found that marine vessel traffic is significantly associated with sea lion habitat selection. At least one of the four measures of marine vessel activity was present in over half of the top model set for each individual sea lion in the study (Figure 5.3). While the positive association between distance to non-fishing vessel traffic in the best fitting models among five individual sea lions is aligned with our hypothesis of avoidance, we also found a similar trend of increasing distance to fishing vessels associated with increased probability of selection in seven of the 11 sea lions in our study (Figure 5.5). Positive coefficient estimates for distance to fishing and/or non-fishing vessel traffic indicate that individual sea lions were more likely to select areas farther away from vessels (i.e., larger distances values) than would be expected if they were choosing randomly. Overall, sea lions appear to respond more strongly to distance to vessels rather than the total amount of vessel activity occurring at a given used location (Figure 5.5).

Taken together, these results suggest sea lions avoid all types of vessel traffic. While previous research at a coarser scale found no evidence of a relationship between sea lion population change and summertime fisheries catch per unit effort data (Hui et al. 2015), our findings suggest a possible mechanism in that individual sea lions may avoid travelling near fishing vessels and/or non-fishing vessels. This finding does not support our original hypothesis that sea lions may be attracted to areas of fishing activity. One explanation for this observation could be related to the Gulf of Alaska cod fishery closure in 2020. During the 2019 cod fishing season (January to approximately August), the four sea lions carrying tags were located in the Prince William Sound, which is more than 150 km to the northeast of the areas of highest catch per unit effort (CPUE; Barbeaux et al. 2021). Thus, we would not expect to see a high degree of overlap between the PWS sea lions and cod fishing vessels. On the other hand, seven adult females were tagged in 2020 in

the Kodiak region where cod CPUE is typically higher, but the cod fishery was closed. While other fisheries remained open in 2020, there may have been little spatiotemporal overlap between the distribution of these fishing vessel activities and sea lion foraging given that cod represent one of the key species overlapping both commercial fisheries and sea lion diets.

Another potential reason for the lack of overlap between fishing intensity and sea lion movements could be sex-or age-dependent differences in resource selection among sea lions. Male sea lions have been shown to travel longer distances and maintain larger home ranges than females (Bishop et al. 2018, Rehberg et al. 2018), and may tend to be more gregarious and aggressive towards humans. However, to the best of our knowledge, no study has examined male sea lion resource selection or movement with relation to vessel activity. Future research on sex-specific resources selection could help to elucidate the underlying patterns behind anecdotal reports of sea lions following fishing vessels.

5.5.2 Steller sea lion resource selection in relation to environmental covariates

Effect sizes of parameters were highly consistent among individuals' best fitting models. The majority of individuals (10 of 11) showed strong selection for shallower areas closer to land (Figure 5.5). Similarly, all individuals showed a slight preference for areas with higher slope values. These findings are well-aligned with those of previous research from the western Aleutian Islands which found that adult female Steller sea lions dive more frequently in shallower areas closer to shore (Lander et al. 2020).

The incorporation of distance to land and distance to shelf break in individual sea lion best fitting models was highly variable. This finding could be the result of diverse foraging strategies. Notably, we observed four individuals making long-distance, multi-day foraging trips to the continental shelf break (Figure 5.1). While adult females from the wDPS have previously been

shown to make broad ranging explorations in search of diverse prey, this directed movement of the four females who made repeated trips from haul-outs to particular areas on the continental shelf break may be more indicative of targeted foraging behavior in locations of known prey abundance (Rehberg et al. 2009). The duration of these multi-day foraging trips in lactating females is of concern as it could have negative consequences for pup survival, as has been the case with northern fur seals (*Callorhinus ursinus*) in the study area (Merrill et al. 2021).

5.5.3 *Resource tracking in regions of dynamic anthropogenic activities*

Our study shows that animal movements can overlap with regions of highly dynamic anthropogenic activities (e.g., roads and shipping lanes) at coarse spatiotemporal scales (e.g., seasonal overlap), yet exhibit fine-scale avoidance when viewed at a higher resolution (e.g., weekly vessel and animal activity with high location accuracy). Furthermore, these avoidant behaviors appear similar to those of sympatric marine predators, who exhibit spatial and/or temporal niche partitioning behaviors, presumably to minimize the probability of antagonistic interaction (Lear et al. 2021). While the findings of this study are limited to adult female sea lions in the Gulf of Alaska, this research contributes to a growing body of literature in the field of resource tracking by examining the resource selection of individuals in a spatially and temporally dynamic environment (Abrahms et al. 2021). In addition to traditional approaches to resource tracking studies, which have typically focused spatiotemporal variability in resources, we examined the response of sea lions to dynamic anthropogenic activities by including marine vessel traffic as a factor in this study. For this reason, we believe that our approach would be highly relevant to a wide variety of terrestrial and marine animals who interact with dynamic anthropogenic threats.

5.5.4 *Limitations*

Our conclusions are limited by the representativeness of sea lion data we used to the sea lion population, and the representativeness of the vessel traffic data we used to the fishing fleet as a whole. Further analyses incorporating movement data from more Steller sea lions in general, and individuals from different demographic groups, such as males and juveniles, would strengthen the conclusions of this study. That being said, the cohesiveness of results between individuals in the study as well as the compatibility of results with previous research provide support that the findings of this study are representative of broader patterns in Steller sea lion resource selection, despite a relatively small sample size.

The representativeness of AIS data is another limitation of this study. Small fishing and non-fishing vessels may be excluded from this data set given that AIS is required on US commercial vessels > 65 feet in length (Taconet et al. 2019). However, while data on the characteristics of the trawler fleet from 2019 and 2020 are not available, the AIS requirement would cover approximately 88% of the active trawlers operating in the region in 2010 (NPFMC 2012).

Despite these limitations, managers are charged by the Endangered Species Act to use the “best scientific and commercial data available” (16 USC Ch 35) to make decisions regarding conservation practices such as habitat protection, conserving food supply and other actions.

5.6 Conclusion

As data on the movements of both humans and animal become increasingly widespread, researchers will have more opportunities to evaluate human-animal interactions across spatiotemporal scales. These analyses should reveal scales of selection that are relevant for particular behaviors, such as spatial or temporal partitioning behaviors to avoid fine scale

interactions in carnivores living sympatrically alongside humans. In a world increasingly dominated by human activities, developing a better understanding of these behaviors could be used to promote human-animal coexistence and support sustainable the populations of species of conservation concern into the future.

CHAPTER 6: SYNTHESIS

Marine vessel traffic is essential for the transportation of resources in a metacoupled world. Nowhere is this more true than the Arctic, where the road network is fragmented and vessels provide essential supplies to remote communities and connect Arctic resources to global markets. By analyzing the spatiotemporal patterns of marine vessel traffic and its relationship to sea ice and marine animals, this dissertation advances both the operationalization of metacoupled systems theory and our empirical understanding of the dynamics and ecological impacts of vessel traffic in the North Pacific and Arctic Oceans. Below, we first discuss some of the major findings of each chapter. We then identify overarching themes and contributions of this dissertation and postulate potential policy implications.

6.1 Main findings of research chapters

In chapter 2 we used a systematic literature review to evaluate the “state of the field” for Arctic CHANS research. We found that while external influences are common to Arctic CHANS, with the exception of climate change, they are rarely the focus of Arctic CHANS analyses. We further demonstrated ways in which the metacoupling framework could be applied to fill research gaps in the Arctic CHANS literature by classifying different types of external influences and differentiating between external influences among adjacent and distant CHANS. The application of the metacoupling framework to Arctic CHANS research has the potential to improve Arctic sustainability analyses by explicitly incorporating external systems, identifying knowledge gaps, highlighting the interactive effects of multiple metacouplings, and uncovering feedback effects.

In chapter 3 we developed a six-year automatic identification system (AIS) ship tracking data set and applied it to quantify the spatiotemporal patterns of marine vessel traffic in the Bering Strait region. We found that from 2015 through 2020, the majority of vessel traffic occurred in

Russian waters. By applying the metacoupling framework to classify voyages based on their movement patterns, we also found that Transient voyages (which started and ended outside the study area) increased the most out of all functional groups (i.e., Local, Regional, Inbound, Outbound). Spatial management measures, such as the implementation of voluntary routing recommendations for the Bering Strait region, appear to be effective at moving vessel traffic further away from coastlines, thereby decreasing risk of disabled vessels running aground. Given the highly interconnected ecosystems on the US and Russian sides of the Bering Strait region, these results also demonstrate the importance of bilateral policy measures.

In chapter 4 we combined remotely sensed sea ice data with AIS to better understand the use of sea ice by vessels. We found that vessel traffic and sea ice are inversely correlated at monthly timescales, but that vessel traffic did not necessarily increase during years of decreased ice extent. These results highlight the influence of non-climatic factors (e.g., national-scale policies, infrastructure investment, and global commodities prices) on vessel traffic in the Pacific Arctic. These results are further strengthened by evidence that the spatial distribution of vessel traffic occurring in sea ice is concentrated in areas of known oil development on the North Slope of Alaska and also along the Northern Sea Route, which has been heavily promoted by Russia in recent years. Overall, this analysis improves upon previous research estimating the accessibility of ice-covered areas to hypothetical vessels by quantifying the use of ice by actual vessels.

In chapter 5, we analyzed the resource selection decisions of an endangered population of Steller sea lions (*Eumetopias jubatus*) in the presence of fishing and non-fishing vessels. This analysis represents one of the first studies to examine Steller sea lion resource selection in relation to fishing vessel activity at a sub-seasonal timescale. While previous studies have found no relationship between the spatial distribution of vessel catch per unit effort and Steller sea lion

population dynamics at a seasonal scale, we found that the majority of Steller sea lions in our sample chose locations away from nearby fishing vessel traffic. This research contributes to the ongoing dialogue surrounding the causes of Steller sea lion population declines by highlighting the potential sub-lethal impacts of vessel activities on Steller sea lion movements.

6.2 Advances in the field of metacoupling research

This dissertation advances the field of metacoupling research by focusing on two understudied areas: the analysis of spillover systems and the transportation of metacoupled flows (Kapsar et al. 2019). By focusing on the Bering Strait region, a chokepoint for the spillover effects of marine vessel traffic, this dissertation contributes new knowledge to both of these areas. Specifically, in chapter 2 we pioneered methods for joining AIS signals into independent voyages and used these voyages to quantify the increases in transient vessel traffic traveling through the Bering Strait region without stopping inside. This represents the first attempt to systematically quantify the spillover effects of vessel traffic in a metacoupled system.

The advances in quantifying the metacoupling framework made by this dissertation have broader applicability to marine CHANS around the world. Worldwide, there are many narrow shipping corridors similar to the Bering Strait, such as the English Channel and the Strait of Malacca, that connect global trade routes. Our approach to the analysis of vessel traffic in the Bering Strait could be applied to systematically compare and contrast vessel traffic in these regions. This knowledge could then be applied to identify policies that effectively minimize detrimental impacts of vessel traffic and promote the sustainability of these coupled human and natural systems.

6.3 Better understanding drivers of vessel traffic in Arctic systems

As sea ice recedes, academic researchers have frequently focused on quantifying changes in the accessibility of different regions to vessels with varying degrees of ice strengthening. These analyses produce products that estimate the theoretical shipping season length under different climate scenarios (Stephenson et al. 2011, Smith and Stephenson 2013, Melia et al. 2016, Aksenov et al. 2017, Mudryk et al. 2021). However, just because ships could navigate through an area does not mean that they will.

In this dissertation, we found that while sea ice does limit vessel traffic, the absence of sea ice does not, in and of itself, facilitate vessel traffic. In other words, ships aren't traveling into, out of, or through the Arctic just because the ice is melting. Our findings highlight that marine vessel traffic in the Pacific Arctic can often be attributed to specific decisions made by corporations and/or governments. Even in the absence of sea ice, the remoteness and extreme weather of the Arctic still present substantial challenges to vessels operating in the region. The benefits of transiting through this area must therefore outweigh the added risks for vessels to venture there. A changing climate does mitigate some of these risks by increasing the length of the open water season and minimizing potential challenges associated with navigating through sea ice. However, even the most extreme climate projections still predict seasonal ice coverage throughout the Arctic.

While climate change and receding sea ice do not result in increased vessel traffic on their own, they can have cascading consequences for Arctic CHANS that could result in increased vessel traffic. In chapters 2 and 3 of this dissertation, we identified substantial increases in fishing vessel activity in the Gulf of Anadyr from 2015 through 2020. While there are multiple explanations for why these increases may have occurred, one of the most likely reasons is changes in the distribution of commercially harvested fish species. Such northward shifts have been

demonstrated in the eastern Bering Sea (Spies et al. 2020), and are likely also occurring in the western side of the north Pacific as well. As the fish move northward into the Gulf of Anadyr, the fishing vessels follow them.

Another possible cascading effect of climate change is on the cost of accessing and transporting resources out of the Arctic. While thawing permafrost threatens transportation of oil and gas via pipelines, melting sea ice and longer open water seasons could decrease the cost of transporting oil and gas via ships (Stephenson et al. 2011). The relative costs of land-based and vessel-based transportation of natural resources may play a substantial role in determining the future of destination shipping in the Arctic.

6.4 Impacts of dynamic anthropogenic activities on wildlife

The final chapter of this dissertation serves to advance the literature on wildlife resource selection in areas of dynamic human activities. In the past, approaches to resource selection studies have frequently examined wildlife movements in relation to a static environment. For example, the field of road ecology has been developed around the concept of assessing the impacts of roads on wildlife (Coffin 2007), but has largely overlooked the role of the number and spatiotemporal distribution of vehicles on those roads as a factor in determining the intensity of their impacts on wildlife. In marine systems, vehicles (i.e., ships) are not limited in their choice of routes by the presence of road infrastructure. In other words, the threats posed by vessel activities change along with the movements of the vessels themselves. Our finding that Steller sea lions select areas away from fishing vessels provides evidence that the dynamic movements of vessels in marine environments impact wildlife resource selection. If fishing vessels are occupying areas of prey concentration for sea lions, this could have cascading consequences for access to key prey species, and subsequently, individual fitness.

This finding highlights the need for further research into the impacts of dynamic anthropogenic activities on wildlife in both terrestrial and marine habitats. In marine systems, examining the response of marine wildlife to changes in the distribution of anthropogenic activities (i.e., fine scale changes in fishing vessel movements), could help to uncover further behaviorally mediated impacts of humans on wildlife. In terrestrial systems, teasing apart the impacts of roads from the impacts of the vehicles that travel on them could help to better inform predictions of the impacts of further development or changes in traffic patterns on wildlife.

This research also opens the door for further investigations of the impacts of scale or ecological niche on the nature of human-wildlife interactions in a dynamic environment. Future studies could examine resource selection at multiple spatiotemporal scales to identify the appropriate scale(s) of selection or also compare resource selection among different life history traits (e.g., sex, age) or regions. Additionally, comparisons among multiple species could help to determine whether these impacts are widespread throughout the ecosystem or limited to particular species. This research is also relevant to other dynamic anthropogenic activities, such as airplanes and drones, which can disturb wildlife and alter their behavior. Taken together, developing a better understanding of the impacts of dynamic human activities on wildlife movements and behaviors can be used to promote sustainable human-wildlife coexistence in an increasingly interconnected world.

APPENDICES

APPENDIX A:

CHAPTER 2

Table S1.0.1 Variable names and definitions used in the literature review of Arctic CHANS analyses.

Paper Data Category	Description
Number of Countries Studied	Indicate whether one or more countries were studied. Also includes specifications for entirely high seas or marine analyses that do not consider country boundaries.
Country/Countries Studied	Countries from which data or other information were collected for the purposes of the analysis conducted in the article.
Type of Research	Indicate whether the data or other information that was collected for the purposes of the analysis conducted in the article were qualitative, quantitative, or a combination of the two.
Single scale or multi-scale research	Determine whether the collected data were analyzed at multiple geographic scales (e.g., at community and regional scales) or aggregated into a single scale of analysis.
Geographic extent of research	The largest scale that encompasses the geographic range at which data were collected. For example, a study involving a survey of three communities within a country would be considered regional, while an analysis of three communities in two different countries would be considered international.
Community involvement	Indicate whether local communities were involved in the research process. We distinguished between involvement as participants (e.g., in a survey/focus group) and involvement in the design and/or approach of the research (e.g., participatory methods).
External influences	Indicate whether an external or exogenous influence was a primary focus of the analysis of the study system. The definition of “external” was relative to the description and boundaries of the study area as described in the paper.

APPENDIX B:

CHAPTER 3

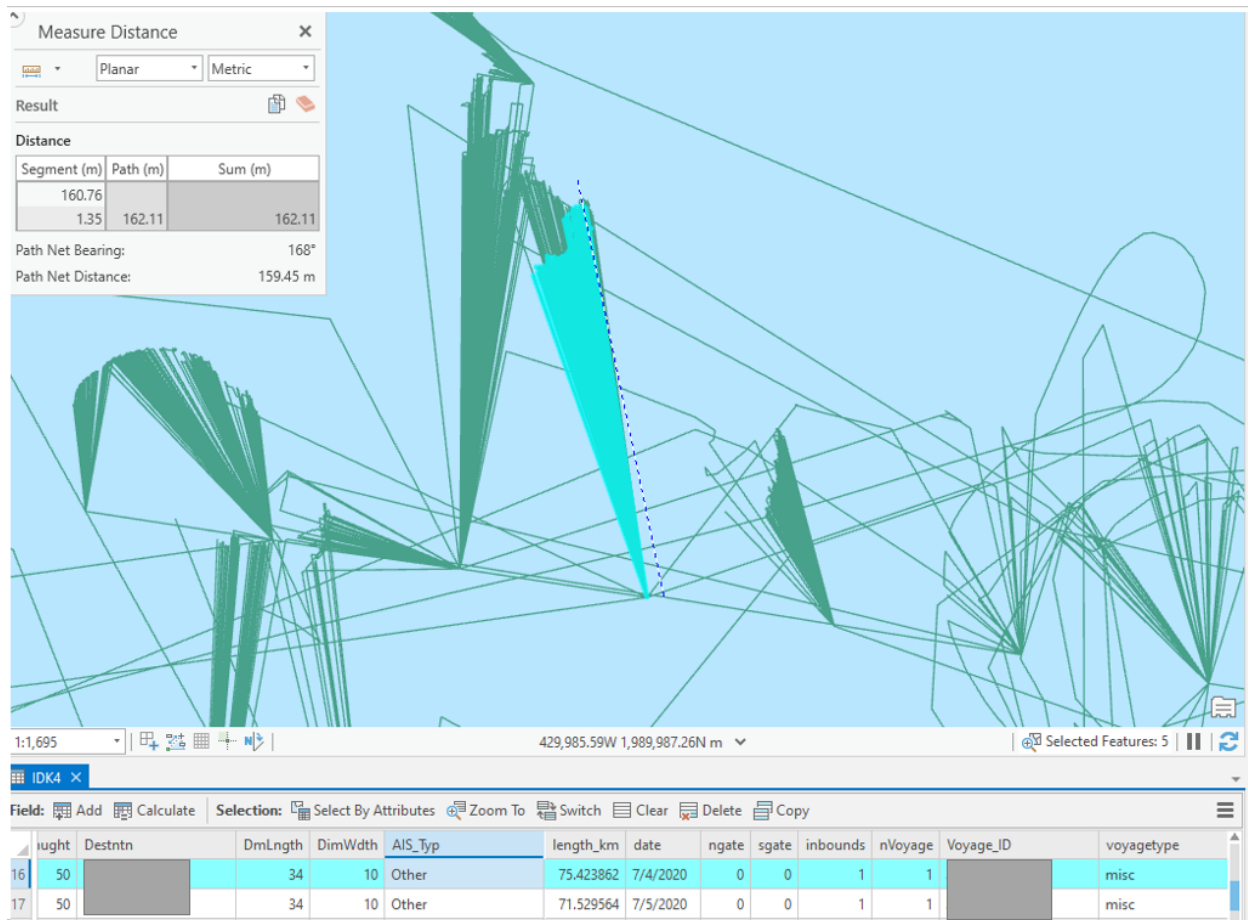


Figure S3.0.1 Screenshot demonstrating effect of erroneous AIS signals on total distance travelled by vessels. When vessels stay in the same location (e.g., at port), small, repeated errors in GPS positions can result in artificially elongated daily segments when successive points are joined. In this example, the daily segment highlighted in light blue is approximately 75 km long, but occurs within an area of less than 170 m. Including these segments within the final voyages would artificially inflate total distance travelled. Identifying information has been removed to preserve anonymity per contract with the data providers.

NORTH PACIFIC AND ARCTIC MARINE TRAFFIC DATA SET (2015-2020)

Kapsar, K., Sullender, B., Liu, Ji., Poe, A. North Pacific and Arctic marine traffic data set (2015-2020). *To be submitted.*

Abstract

In this paper, we present a spatially explicit dataset of monthly shipping intensity in the Pacific Arctic region from January 1, 2015 to December 31, 2020. We calculated shipping intensity based on Automatic Identification System (AIS) data, a type of GPS transmitter required by the International Maritime Organization on all ships over 400 gross tonnes, all ships over 300 gross tonnes on an international voyage, and all passenger ships. We used AIS data received by the exactEarth satellite constellation (64 satellites as of 2020), ensuring spatial coverage regardless of national jurisdiction or remoteness. Our analytical approach converted raw AIS input into monthly raster and vector datasets, separated by vessel type. We first filtered raw AIS messages to remove spurious records and GPS errors, then joined remaining vessel positional records with static messages including descriptive attributes. We further categorized these messages into one of four general ship types (cargo; tanker; fishing; and other). For the vector dataset, we spatially intersected AIS messages with a hexagon (hex) grid and calculated the number of unique ships, the number of unique ships per day (summed over each month), and the average and standard deviation of the speed over ground. We calculated these values for each month for all vessels as well as vessels subdivided by ship type and for messages from vessels >65 feet long and traveling >10 knots. For the raster dataset, we created a series of spatially explicit daily vessel tracks according to unique voyages and aggregated tracks by ship type and month. We then created a raster grid and calculated the total length, in meters, of all vessel tracks within each raster cell. These monthly datasets provide a critical snapshot of dynamic commercial and natural systems in

the Pacific Arctic region. Recent declines in sea ice have lengthened the duration of the shipping season and have expanded the spatial coverage of large vessel routes, from the Aleutian Islands through the Bering Strait and into the southern Chukchi Sea. As vessel traffic has increased, so has exposure to the myriad environmental risks posed by large ships, including oil spills, underwater noise pollution, large cetacean ship-strikes, and discharges of pollutants. This dataset provides scientific researchers, regulatory managers, and other decision makers as well as local community members and the maritime industry with a quantitative means to evaluate the distribution and intensity of shipping across space and through time.

Value of the data

- **Unique and comprehensive source of data for maritime shipping in the north Pacific and southern Arctic oceans:** These data present the most comprehensive information available on the spatial and temporal patterns of shipping in an expansive study area (~8,000,000 km²) across a broad time horizon (six full years). Because this data type is not yet publicly available on a wide scale, there are very few comparable data sources available. These data enable critical and timely analyses of previously unknown issues surrounding the expansion of vessel traffic into novel portions of the Arctic marine ecosystem. Recent declines in sea ice have allowed unprecedented commercial accessibility, but until now, little was known about where, when, what types, and how many vessels are traveling the Pacific Arctic.
- **Broad utility:** These data can be immediately added to maps, statistical models, or other spatial representations of marine plans, including ongoing Arctic vessel routing discussions at local, national, and international levels.

- **Applicable to a diverse audience:** Our data benefits marine biologists, Arctic ecologists, transport and commerce analysts, resource managers, regulatory agencies, policymakers, Arctic diplomats, the maritime industry, marine-focused advocacy and non-profit organizations, and, most importantly, local stakeholders particularly Indigenous communities.
- **Foundation for environmental analyses, human health impact assessments, and enhancing safety of life at sea:** The datasets presented in this paper can be expanded upon through incorporation in a wide variety of applications, including those related to marine spatial planning, anthropogenic impact assessments (e.g., underwater noise propagation, vessel debris and pollution), oil spill risk assessments, marine search and rescue asset allocation, and projections of future shipping under climate change.

Data description

The datasets presented in this manuscript represent six years of vessel traffic in the north Pacific and southern Arctic Oceans collected through satellite-based Automatic Identification System (AIS) ship tracking technology. AIS transponders are required by the International Maritime Organization on all cargo ships greater than 500 gross tonnes, all ships greater than 300 gross tonnes on an international voyage, and all passenger vessels (IMO 2002). AIS data are not publicly available and were acquired from exactEarth (<https://www.exactearth.com/>). Although atmospheric conditions, deliberate anthropogenic interference, or technological issues may limit occasional AIS signals, AIS data are increasingly recognized as one of the best sources of information on the spatial and temporal distribution of maritime traffic worldwide (Wright et al. 2019).

The study area extends from Prince William Sound, through Cook Inlet and the Kodiak Island archipelago up through the Aleutian Islands north through the Bering and Chukchi Seas, past the northern edge of Wrangell Island and the western Beaufort Sea (approximately 51°-72° N). The study area spans the international dateline and includes both Russian and US exclusive economic zones (approximately 162°E to 145°W). Figure S3.0.2 depicts the region across which AIS data were collected. The data begin in January of 2015, extend through December of 2020, and are temporally aggregated to a monthly scale.

We derived two independent data products from the AIS signals: hexagon (hex) cells and raster grids (Table S3.0.1). Both data formats are projected from the original WGS 84 (EPSG 4326) to the Alaska Albers projection (EPSG 3338). To preserve anonymity and comply with AIS data licensing agreements, identifying attributes for all vessels have been removed and data have been aggregated from points into hex and raster cell values.

Hex data are saved as 72 individual monthly shapefiles. Each hex has an area of 625 km², resulting in an apothem of 13,432m, or about 27 km from northern to southern edge. Individual hex cells contain five attributes: (1) a hexID that uniquely identifies each hex cell and is preserved across all hex files; (2) number of unique ships (as calculated by the total number of unique maritime mobile service identity (MMSI) numbers; (3) number of operating days (measures as the number of unique MMSI/date combinations); (4) average speed over ground (SOG) of all points within the hex; (5) standard deviation of the SOG. These five attributes are calculated for six subsets of data (cargo, tanker, fishing, other, all vessels, and long-fast vessels). See Hex Data Processing section below for a description of how these subsets and attributes were developed.

We developed raster datasets at three spatial resolutions, with varying subsets of data at each resolution (Table S3.0.1). A 1-km resolution coastal raster contains shipping traffic within

10km of the coastlines of the study area. There are six total yearly files (all months combined), 12 total monthly files (all years combined), and 72 files of traffic in each month of the study period (Table S3.0.1). The 10-km resolution dataset consists of 288 rasters containing values of total traffic subdivided into unique ship type, month, and year combinations (12 months x 6 years x 4 ship types = 288 files). Finally, the 25-km resolution raster dataset also contains the 288 rasters subdivided by ship type, month, and year, as well as aggregated into six yearly files (all months combined), 12 total monthly files (all years combined), and four ship type files (all months and years combined). Unlike the hex data, the raster cells contain only one attribute, the total shipping traffic, measured as the total meters travelled for that given time step.

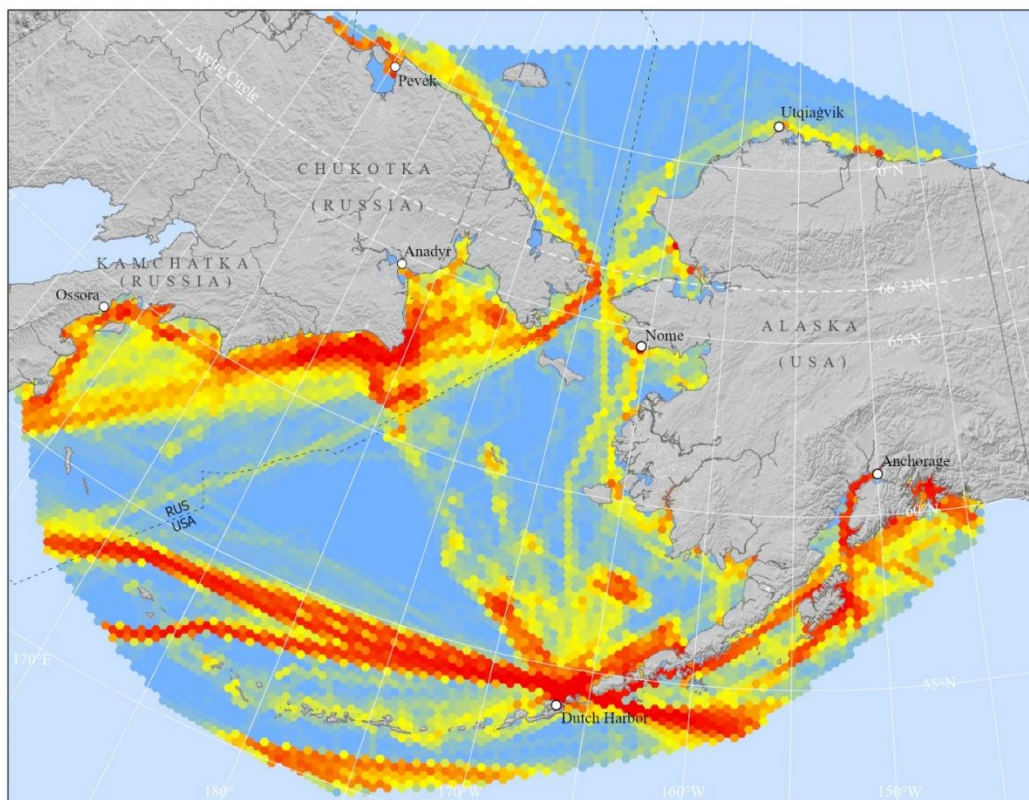


Figure S3.0.2 Map of study area boundaries with hex data depicting the relative number of unique maritime mobile service identities (MMSIs) identified within each hex in September of 2020. Cooler colors indicate fewer unique vessels while warmer colors indicate more vessels.

Table S3.0.1 Summary of marine vessel traffic data products.

Format	Resolution		Attributes	Subsets					File Type
	Pixel/Hex Size (km)	Spatial Extent		Type (by month and year)	By month and year	Yearly (all months)	Monthly (all years)	Type (all years and months)	
Raster	1	Coastal (10km buffer)	Distance traveled (m)		✓	✓	✓		.tif
Raster	10	Entire study area	Distance traveled (m)	✓					.tif
Raster	25	Entire study area	Distance traveled (m)	✓		✓	✓	✓	.tif
Hex	26.9*	Entire study area	Average Speed (km/hr)	✓					.shp
			SD of Speed (km/hr)	✓					
			Number of ships	✓					
			Number of operating days	✓					

**This is an approximate calculation of the distance between the northern and southern edges of each hex.*

Experimental design, materials, and methods

General data processing

We received the data in tabular format after initial pre-processing from the original binary messages was completed by exactEarth. The tabular data were organized into daily comma separated value (csv) files with each row containing a single AIS message. In total, this amounted

to 1,462 individual csv files containing 1,169,510,073 AIS messages. To minimize memory usage and increase efficiency, we processed each month separately. All data were processed using R version 4.0.3 (R Core Team 2020).

To clean the data, we first isolated position messages from static message types. While AIS signals come in one of 27 distinct message types (United States Coast Guard Navigation Center 2019), they fall into two primary groups. Position messages relay dynamic information from the vessel (e.g., navigational status, speed over ground, heading), while static messages convey information related to ship attributes (e.g., ship name, IMO number, draught, destination). Position messages are typically automatically derived by the AIS transponder and thus are not prone to human input error whereas static messages are manually input by shipboard AIS operators.

To process the data, we followed the steps laid out in Figure S3.0.3. After isolating the position signals, we cleaned the data by removing messages with missing latitude or longitude values or messages with MMSI values less than eight digits. Large magnitude GPS errors are a relatively common occurrence in tracking datasets, but can be removed using a speed filter. We implemented a speed filter of 100 km/h using the Euclidean speed calculated between successive points. We assumed that points which would require vessels to travel faster than this speed are the result of GPS error and removed these points from the dataset.

Due to inconsistencies in data entry, we removed many of the static data attributes. We retained ship type, distance to bow, and distance to stern. Distance to bow and distance to stern can be used to derive ship length, which has been used as a proxy for ship size, a key correlate of lethal ship strikes to cetaceans (van der Hoop et al. 2015). We therefore retained this attribute to enable future calculations of ship strike risk. To calculate ship dimensions, we first removed all zero value entries from the distance to bow and distance to stern categories. We did this under the

assumption that AIS transponders are typically placed on the bridge of a vessel and would thus have a non-zero distance to one of the vessels' edges. Furthermore, these distance values are entered by operators and thus prone to manual entry errors. From the remaining values, we calculated the length of a vessel as the sum of the distance to bow and distance to stern.

Ship types are designated according to a 2-digit code transmitted in static messages. The first digit corresponds to a broad vessel category (e.g., 8 = Tanker), and the second digit corresponds to a specific vessel sub-category (e.g., 81 = Tanker, Hazardous category A). To minimize human error in ship type designation, we aggregated vessels into four broad categories: Cargo (AIS Type = 7X), Tanker (AIS Type = 8X), Fishing (AIS Type = 30), Other (all other ship types). After cleaning the data, we joined static messages to position messages using shared MMSI values.

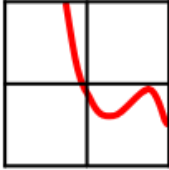
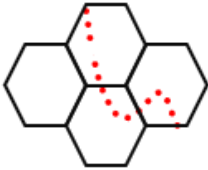
	Raster	Hex
Isolate positional messages	✓	✓
Remove invalid/incomplete data	✓	✓
Speed filter	✓	✓
Remove "spoofed" data	✓	
Vectorize	✓	
Calculate metrics	✓	✓
		

Figure S3.0.3 Data processing schematic for raster and hex grid datasets.

Hex data processing

Hex grids are an increasingly prevalent geospatial data format. Hexagons have several advantages over traditional raster representations, including regularly and evenly distributed neighbors, the ability to store multiple attributes within a single geometry, and reduced distortions when projected at large scales (Sahr 2011). We created a hex grid across our study area using the `sf` package version 0.9-8 in R version 4.0.3 (Pebesma 2018, R Core Team 2020). We chose a hex cell size of 625 km² (13,432m apothem; approximately 27 km north to south) to align with our 25km raster scale.

Another advantage of hex grids is the ability to store multiple attributed values within the same spatial unit. In our case, we calculated hex unique identifier and four metrics of shipping activity on six unique subsets of data (Table S3.0.2). We calculated hex cell values by spatially intersecting AIS messages with the hex grid. We then calculated all metrics by aggregating the values from all AIS messages within each hex.

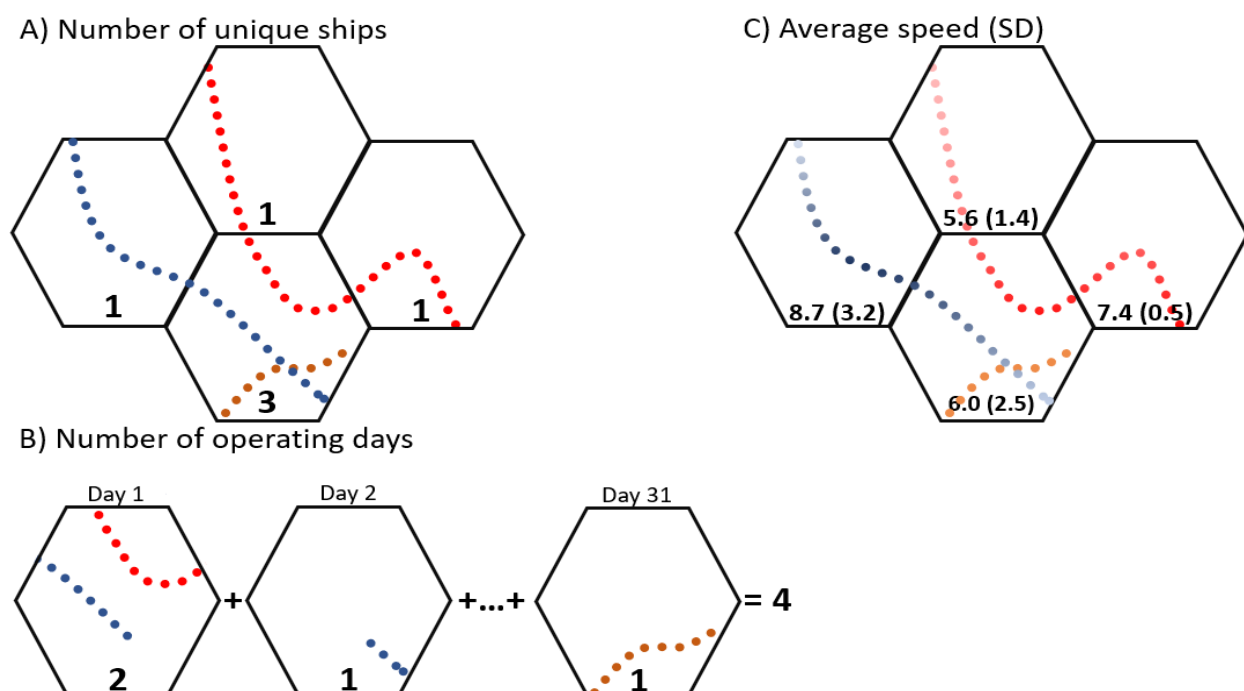


Figure S3.0.4 Schematic diagram explaining monthly hex data metrics. Dots represent individual automatic identification system (AIS) messages. Unique colors represent individual vessels. Subsets are (A) Number of unique vessel occurring within each hex in a given month; (B) Number of operating days (i.e., sum of the number of ships per day across a given month); (C) Average vessel speed in kilometers per hour, and standard deviation of this speed value in parentheses. Darker colors represent higher average speeds.

We quantified the number of ships by calculating the total number of unique MMSIs present within the dataset in each month (Figure S3.0.4A). MMSIs are permanent identifiers associated with unique vessels and are managed by the International Telecommunication Union (International Telecommunication Union 2019).

While the number of unique ships per month gives a broad idea of the amount of traffic in a given area, it does not convey any information about residency time within a given region. For example, a single fishing vessel may occupy a given area for a week and that cell would only have a value of one unique ship. In order to capture a measure of vessel intensity within each cell, we developed a measure of operating days. We defined an operating day as the number of unique days one unique vessel occupied a given hex (Figure S3.0.4). In the above example, a fishing vessel

working within one cell for the span of a week would have a value of seven operating days. If two vessels share the same cell for seven days, the number of unique ships would be two, but the number of operating days would be 14.

Depending on the purpose of the study, vessel speed can also be an important metric of the intensity of vessel traffic within a region. Faster vessel traffic is associated with increased underwater noise, elevated risk of ship strike to large cetaceans, and increased risk of collision with navigational hazards (van der Hoop et al. 2015). We calculated the average speed over ground (SOG) and the standard deviation of the SOG across AIS messages received within each hex within each month (Figure S3.0.4C). While this metric does not present information about specific ships travelling at high speeds, it can be used to distinguish areas of transit (i.e., higher average speed) from ports and other areas of lingering vessel activity (i.e., lower average speed).

Table S3.0.2 Description of hex data metrics.

Attribute	Units	Name in Shapefile	Description
Hex ID	NA	hexID	Unique ID number of each hex in the dataset. Hex IDs are preserved across all shapefiles.
Number of ships	vessels	nMMSI	Number of unique ship ID numbers (MMSIs) within each hex cell.
Number of operating days	operating days	nOper	Number of unique operating days (MMSI/date combinations) within each hex cell.
Speed	knots	SOG	Average speed over ground (knots) within each hex cell.
Speed (Standard Deviation)	knots	SOG_SD	Standard deviation of the speed over ground (knots) within each hex cell.

We designed these four metrics of vessel activity to be used either independently or in combination. For example, a hex with a small number of unique ships and a large number of

operating days would indicate potential lingering activity, such as fishing. Furthermore, hexes with many vessels travelling at higher average speeds could be used to identify shipping routes.

To further parse out different spatial and temporal patterns of vessel activity, we calculated these metrics for six different subsets of data: all vessels (denoted with suffix “_A”), vessels categorized by ship type (cargo [_C], tanker [_T], fishing [_F], other [_O]), and long-fast ships (_LF). For a description of how ship types were identified, see the section “General data processing” above. In the hex dataset, vessels with “NA” for ship type were predominately associated with non-ship entities (e.g., aids to navigation, terrestrial AIS receivers, floating platforms) and were removed from the dataset. Long-fast ships were defined as any ship over 65 feet in length with one or more AIS signal(s) with a SOG value greater than 10 knots in a given hex during a given month. Robust ecological models indicate that this class of vessel (>65 feet and traveling >10 knots) poses a significant risk of lethal injury to large cetaceans (Vanderlaan and Taggart 2007, Conn and Silber 2013).

Raster data processing

To capture the intensity of traffic within a pixel, we evaluated the total distance travelled by vessels within each cell in each month. This calculation required the addition of two extra processing steps not included in the hex data processing (Figure S3.0.3). First, to calculate the distance travelled, we generated vessel tracks from the AIS point data. We did so by linearly interpolating between successive points at a daily timescale. This process resulted in daily segments that we then spatially intersected with raster grids of varying resolutions. Once intersected, we were able to calculate the total distance travelled by vessels within each pixel.

One challenge that we encountered after the data vectorization was the presence of vessel “spoofing”. AIS spoofing occurs when the position of a vessel is falsified or a vessel’s identity is

faked, either intentionally or by accident (Balduzzi et al. 2014, Cutlip 2016). We identified several instances of spoofing in which two vessels were simultaneously transmitting AIS signals using the same MMSI number. When these signals were vectorized into daily track lines, this spoofing resulted in a zig-zag pattern as the AIS signals bounced back and forth between two indistinguishable ships. When vectorized, these spoofed track lines erroneously inflated the total distanced travelled within each pixel. To remove these spoofed lines from the dataset, we implemented a total daily distance travelled limit of 10,000 km. This 10,000-km value was chosen to be large enough that no ship could reasonably travel this distance within a 24-hour period, and yet small enough that spoofed vessel track lines would result in daily segments longer than this distance threshold.

Once AIS data were vectorized and spoofed lines were removed, we rasterized the data at three different spatial scales (1km, 10km, and 25km). The 10- and 25-km resolution raster datasets were chosen to represent the approximate spatial resolution of ecological data within the region. The 1-km resolution raster was calculated only for the coastal region surrounding the study area (identified by a 10-km buffer around all land area). The purpose of this coastal subset was to provide a high-resolution view of vessel traffic at a finer scale to evaluate potential interactions with both marine wildlife and human communities along the coast.

Similar to the hex dataset, we subset the raster data by month, year, and vessel type. However, to enable a broader view of trends in the data, we also created annual total vessel traffic rasters for each year of the study period. We also created vessel traffic maps for the entire study period for each vessel type (cargo, tanker, fishing, other) as well as monthly total vessel traffic (i.e., total vessel traffic in January across all six years). These aggregations enable more detailed

analysis of seasonal vessel traffic patterns, trends over time, as well as comparisons between different types of vessel traffic.

Data omission

We used the number of unique ships (i.e., unique MMSIs) in the dataset to quantify rates of data removal during the data cleaning process for each month. Only a small percentage ($0.29 \pm 0.25\%$) of ships were removed for a lack of position information (i.e., static messages only). However, the largest number of vessels were removed due to invalid and/or incomplete MMSI numbers or latitude and longitude values ($13.91 \pm 8.12\%$). No unique ships were removed from the final data during the speed filtering step. Beyond this point in the data cleaning process, percentages of data removed differed slightly between the hex and raster data products due to differences in the data processing pipeline (Figure S3.0.3). They are each discussed separately below.

For the speed hex data, another 13.81% of unique vessels were removed because they came from non-ship entities with an NA value for ship type (e.g., stationary platforms). Finally, $1.99 \pm 1.05\%$ of unique ships were removed because they were outside of the boundaries of the hex data (e.g., inland vessels). In total, this comes to a monthly average total of $30 \pm 8.13\%$ of unique MMSIs removed during the data cleaning process. While 30% of all unique ships may appear large, this only represents the removal of an average of $14.13 \pm 2.53\%$ of all AIS signals. This discrepancy between the larger percentage of unique ships removed and the smaller number of points removed is most likely due to data loss during the transmission to AIS satellite receivers resulting in a large number of unique vessels with very few, incomplete signals or from numerous non-ship entities infrequently transmitting AIS messages. In addition to these removals, during the

data cleaning process $11.57 \pm 3.24\%$ of vessel width values, $10.98 \pm 2.43\%$ of vessel length values, and $0.28 \pm 0.25\%$ of speed over ground values were marked as NA.

For the raster datasets, an additional $11.99 \pm 4.13\%$ were removed for having less than three points or for failure to convert to a vector format. This error frequently occurred when ships transmitted AIS signals while in port. During this time, vessels were moving distances so small that they were beyond the granularity limits of the software, which resulted in a failure to interpolate between successive points. All combined, there was an average monthly removal of $26.19 \pm 8.05\%$ for raster data. However, given the large size of the study area, the six-year timeframe of the study, and the high transmission frequency of AIS (circa two minutes at maximum), these exclusions do not likely include a large number of unique vessels that were omitted from the analysis, but rather particular points within ship transits, data from non-ship platforms, or invalid signals (e.g., invalid MMSI).

Limitations and considerations for data usage

While AIS data provide an unprecedented level of detailed information on vessel activities, several considerations must be taken into account when applying these data to an analysis.

First, AIS data do not present a complete picture of all marine vessel traffic. Specifically, AIS transponders are not required on small vessels (<300 gross tons) and thus many small vessels are excluded from this analysis. This gap in coverage may be particularly important in coastal areas and inland waterways and lakes around the world, where smaller craft are more likely to be located.

Second, vessel type and vessel dimensions are subject to human error in the data entry process. Unlike positional messages which contain information derived directly from the vessel, static ship information is manually entered by AIS operators. In our dataset, this error can be seen

in the large number of “other” ship types. It is thus important to note that when interpreting vessel activity, the total number of ships of a given type within a given area is likely a conservative estimate. Ships with AIS transponders disabled, small craft, and ships mislabeled as “other” all contribute to an undercount of the total number of vessels in an area.

Third, any increases in vessel activity should be interpreted with a degree of caution as two confounding factors could influence the interpretation of the number of ships within our study area: (1) increasing satellite coverage and (2) increasing adoption of AIS transponders. We discuss each of these factors and their potential influence on vessel activity metrics below.

As interest in AIS has grown over the past two decades, so too has the number of satellites with operational AIS receivers. During the study period, the number of satellites in the exactEarth constellation increased dramatically such that the number of satellite passes over our study area increased from approximately 70 per day in 2015 to over 700 per day in 2020 (with minor deviations in these numbers associated with maintenance and other activities). Concurrent with this increase in satellites, we see an increase in the total number of AIS signals received. However, an examination of the number of ships detected during this same period does not reveal a similar increase (Figure S3.0.5). This discrepancy is most likely due to the fact that while the number of satellites did increase dramatically in 2018, the percent coverage (i.e., percentage of the day during which there was a satellite over the study area) only increased by approximately ~10% (exactEarth, personal communication, 21 August 2021). Therefore, it is likely the case that entire ships did not go undetected early in the study period, however some AIS signals from those ships were lost due to limited satellite capacity to process all AIS signals. As the number of satellites increased, this rate of signal loss decreased leading to an increased number of AIS data points, but a relatively stable number of ships. While it is unlikely that a substantial number of vessels went undetected

during the early portion of the study period that were later detected with the augmented satellite constellation, we advise caution when interpreting increases in the number of vessels across the entire study period.

Another factor to consider when interpreting increases in vessel activity over time is the increasing adoption of AIS transponders, particularly among smaller vessels. While large vessels (>300 gross tons) on international voyages and passenger vessels were mandated to transmit AIS since approximately 2004 (depending on construction date), smaller vessels are not required to maintain operational AIS transponders. However, the advantages of AIS for safety of navigation are gaining recognition and more mariners are choosing to use AIS transponders. Without the incorporation of external information on the number of vessels using AIS transponders, it is difficult to distinguish between an increase in the number of vessels and an increase in AIS adoption rates within a given region. Examining shorter time periods (e.g., months) is one possible way to minimize the influence of AIS adoption rates on the total amounts of vessel traffic.

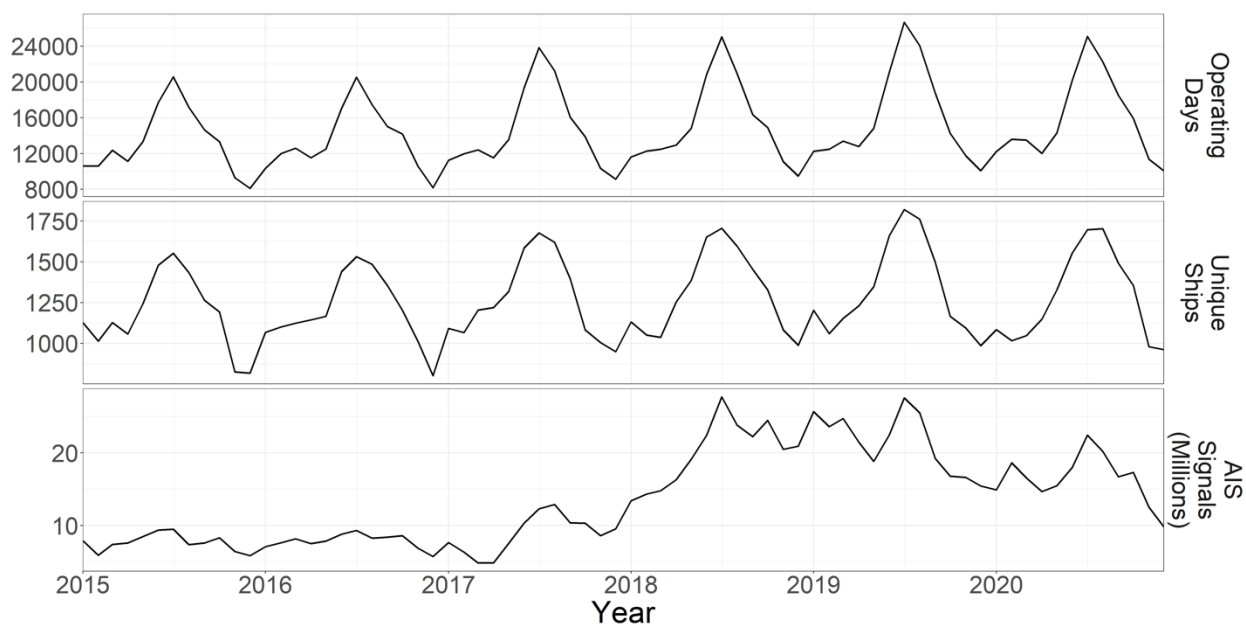


Figure S3.0.5 Comparison of the number of AIS signals, unique ships (i.e., MMSIs), and operating days (i.e., unique MMSI/date combinations) over the course of the study period.

APPENDIX C:

CHAPTER 5

Calculation of environmental and anthropogenic parameters

Distance to land & shelf break

In a previous study, Lander et al. (2020) identified a negative relationship between sea lion utilization distributions and both distance to continental shelf and distance to shore, indicating that individuals are attracted to both nearshore and near-shelf environments. As central place foragers that typically return to land to haul out after foraging excursions, we would expect to see a negative relationship between distance to land and location. With regard to the continental shelf, we would expect sea lions to be attracted to areas of upwelling along the shelf that could concentrate important prey species, such as Pacific Cod (*Gadus macrocephalus*; (Yang et al. 2019b)). This attraction would also result in a negative relationship between location and distance to the shelf break.

Similar to previous studies (Schuyler et al. 2016, Lidgard et al. 2020), we used data from the National Oceanographic and Atmospheric Administration's General Bathymetric Chart of the Oceans to calculate bathymetry, distance to land, distance to shelf break, and slope. We calculated distance to land and distance to shelf break at the centroid of each raster cell using the raster package in R version 4.0.3 (R Core Team 2020). This package calculates the great circle distance between a set of points (in this case, the raster centroids) and a given isobath. While a depth of 200m is typically used to delineate the continental shelf break, for our study area, we followed Swartz et al. (2015) who used high-resolution multibeam sonar data from the eastern portion of the Gulf of Alaska and estimated a shelf break depth of between 300 and 500 meters. Because some portions of our study area that were inside the continental shelf exceeded 300 meters depth,

we chose the distance to any point between 500 and 510 meters of depth, excluding locations in Prince William Sound, as our measure of the distance to the shelf break.

Bathymetry & slope

Bathymetric depth and slope are hypothesized to influence the amount of foraging habitat accessible to sea lions. With regard to sea lion utilization distributions, Lander et al. (2020) found that bathymetric depth was negatively related to sea lion density at the population level, but produced mixed results at an individual level. The authors speculate that this inconsistency may be due to correlations with other explanatory variables as previous research demonstrated a stronger relationship between depth and sea lion distributions (Lander et al. 2011). Given that depth has been shown to be a dominant predictor of habitat selection in two primary prey species for sea lions, Pacific cod and pollock, we expect depth to be a significant predictor of sea lion habitat selection as well (Pirtle et al. 2019). We calculated depth and slope values using National Oceanographic and Atmospheric Administration's General Bathymetric Chart of the Oceans as detailed above.

Wind speed

Oceanic wind speed is indicative of weather patterns in the Gulf of Alaska and has been shown to influence the haul-out behavior of other pinniped species in the region (Boveng et al. 2003). While wind speed may not affect sea lion at a seasonal scale (Lander et al. 2020), we predict that weekly wind speed may be influence habitat selection by sea lions by capturing variability in weather patterns that could influence haul-out and/or foraging patterns.

To evaluate wind speed, we gathered data from the Copernicus Programme's Global Ocean Wind Near Real Time observations (Abderrahim Bentamy 2019). We calculated the average weekly wind speed by taking the mean value across all observations within a given week.

Sea surface temperature

In recent years, dramatic increases in sea surface temperature in the Gulf of Alaska (including the four hottest years on record) have spurred intense interest in the potential relationship between sea surface temperature and ecosystem function (Litzow et al. 2020). Shifting temperatures could influence the distribution of sea lion prey at both fine (i.e., weeks) and coarse (i.e., decades) scale temporal resolutions (Yang et al. 2019b).

We used the Operational Sea Surface Temperature and Sea Ice Analysis from the Copernicus Marine Environment Monitoring Service as our source of sea surface temperature data (Good et al. 2020). This multi-sensor data set integrates information from multiple satellites with in situ buoy data to produce a daily 0.054° resolution data set, which we then aggregated to a weekly average value.

Fishing and non-fishing vessel activity

To model the activity of vessels in the study area, we used satellite-derived Automatic Identification System (AIS) ship tracking data. The use of AIS transmitters is mandated by the International Maritime Organization on all vessels over 300 gross tons on an international voyage, all vessels over 400 gross tons, and all passenger vessels regardless of size (International Maritime Organization 2002). Over the past two decades, the use of AIS data in research has increased exponentially (Svanberg et al. 2019, Meyers et al. 2021). In particular, AIS data are being applied to evaluate impacts of vessels on marine ecosystems (Reeves et al. 2014, Halpern et al. 2015, Robards et al. 2016, Rockwood et al. 2020).

Because different types of vessel traffic are hypothesized to differentially affect sea lion behaviors differently, we evaluated fishing vessel activity and non-fishing vessel activity (e.g., cargo, tanker, passenger) as two separate variables in our resource selection function. We also

created two different measurements of vessel activity that sea lions may respond to: distance and intensity. We calculated vessel distance as the distance to the nearest vessel track from each sea lion location, and we measured intensity as the total amount of vessel traffic (in km) within each occupied cell.

To create these measures of vessel activity within the study area, we first acquired satellite-derived AIS data for the study area during the entire of the study period (2018-2020). We removed points with invalid latitude, longitude, or maritime mobile service identity (MMSI) numbers. To remove erroneous points resulting from errors in the global positioning system (GPS) signal, we calculated the Euclidean speed between consecutive points and removed those at which vessels were estimated to be travelling at greater than 100 km/hr. We then aggregated sequential records from each vessel into daily segments. We used these vector lines to calculate distance from each used and available location to the nearest vessel at a weekly timescale. To calculate vessel intensity, we rasterized daily segments into a measure of the total weekly distance travelled by ships within each cell at a five-kilometer resolution. We completed this process for fishing vessels and all non-fishing vessels to obtain four separate measures of vessel activity within the study area (Table S3.0.1).

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