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Impacts of Climate Change on Human Access
and Resource Development in the Arctic

A dissertation submitted in partial satisfaction of the
requirements for the degree Doctor of Philosophy
in Geography

by

Scott Ryan Stephenson

2014

ABSTRACT OF THE DISSERTATION

Impacts of Climate Change on Human Access and Resource Development in the Arctic

by

Scott Ryan Stephenson

Doctor of Philosophy in Geography

University of California, Los Angeles, 2014

Professor John A. Agnew, Co-chair

Professor Laurence C. Smith, Co-chair

As the Arctic Ocean transitions to a seasonally ice-free state, efforts to strengthen connections between the Arctic and the global economy are underway. After decades of use primarily as local transport arteries servicing settlements and domestic industries, Arctic shipping routes are being recast as international seaways for export of resources to world markets and as potential alternative pathways for global trade. In addition, global demand for oil, gas and minerals has driven expansion of extractive industries into increasingly accessible offshore locations. However, the degree to which reduced sea ice will realistically enable marine access is not well understood, and numerous economic and political uncertainties complicate resource extraction activities. Understanding the interrelationship of the physical environment and the development goals of state- and non-state actors is vital to determining the role of the Arctic in the future global energy mix. This dissertation seeks to articulate a synoptic picture of future human activity in the Arctic by examining a range of plausible scenarios of climate projections,

transport logistics, regional politics, and extractive networks. Future marine access projections were performed by quantitative spatial analysis of climate model output and ocean bathymetry in GIS (Chapters 3 and 4). Analysis of the political and economic context of Arctic resource extraction (Chapters 2 and 5) was based on readings of scholarly literature, government reports, and newspaper articles. Climate scenarios illustrate a future of limited marine access in summer for most vessels throughout the 21st century with significantly higher navigation potential for ice-strengthened vessel types. Environmental conditions, along with national and local political structures, comprise the critical spatial context in which dense networks of state-owned and international oil and gas companies operate. While marine access is projected to increase for all climate scenarios, a wide range of futures is possible, and technology and infrastructure often figure more importantly than climatic forcing scenario alone. Therefore, a central conclusion of this dissertation is that Arctic marine access depends strongly upon capital investment in addition to geophysical considerations of sea ice.

The dissertation of Scott Ryan Stephenson is approved.

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1. Introduction

Global climate warming portends powerful implications for human societies. Across the physical and social sciences, evidence is emerging of numerous interconnected changes to essential systems such as water, agriculture, and transportation (Parry et al., 2007). While the precise impacts of climate change entail considerable spatial and temporal uncertainties, there is broad consensus that warming is likely to be strongly amplified in the Arctic as newly ice-free oceans increasingly absorb solar radiation (Anisimov et al., 2007). As a result, the Arctic is often viewed as a bellwether for global climate change, as thawing permafrost, melting glaciers and ice sheets, and sea ice recession signal the beginning of a warmer climate regime in the northern high latitudes.

The unique geophysical and infrastructural environment of the Arctic engenders heightened climate sensitivity in northern transportation systems. Against a backdrop of remoteness, road and rail scarcity, and frozen seas, climate change has the potential to alter transport accessibility in complex and often competing ways. Whereas sea ice limits navigation at sea to summer months, land access is made possible in winter by frozen roads over lakes and rivers (Stephenson et al., 2011). These transport modes inform essential characterizations of the Arctic as a largely *inaccessible* place, and are thus central to such popular imaginaries of the region as *terra nullius*, nature preserve, and resource frontier (Steinberg et al., 2014). As melting ice enables increased access by sea, the resources in this latter imaginary become likewise accessible, evolving from theoretical national stockpiles to form the basis for greater integration with global markets.

Despite its adverse consequences for the global environment, reduced sea ice is often portrayed as promoting economic opportunity for the region. Projections of a first ice-free Arctic

Ocean in the coming decades have fueled interest in trans-Arctic navigation through the Northern Sea Route (NSR) and Northwest Passage (NWP), with potential distance savings of up to 40% relative to routes through the Suez and Panama Canals. Circumnavigating strategic “choke points” such as the straits of Malacca and Hormuz also offers flexibility in the event of political unrest or pirate activity (EIA, 2011). Most of the vessels currently operating in the Arctic are destinational, driven by resource exploitation, community resupply, and tourism. These drivers are expected to increase considerably over the next decade; by 2020, it is projected that annual demand for resupply operations in Canada alone will exceed the capacity of the current fleet (Arctic Council, 2009). The NSR, in particular, has seen a number of recent milestones. In August 2011, a Panamax-class tanker carrying 61,000 tons of gas condensate sailed the NSR in a record eight days, followed by the first-ever transit by a Suezmax-class supertanker seven days later (Pettersen, 2011a; Pettersen, 2011b). In 2013, 71 ships transited the route carrying 1.35 million tons of cargo, a recent record (NSR Information Office, 2013). Voyages are occurring increasingly later in the navigation season, as demonstrated by the first-ever transit by an LNG carrier in November 2012 (McGrath, 2012).

Resource exploitation, particularly petroleum, will continue to drive shipping activities in the near future. Oil and gas are currently produced in four Arctic states (Canada, Norway, Russia, and the U.S.) which together account for approximately 28% of world oil and 46% of gas output (BP, 2011). Large deposits were discovered at Tazovskoye field in Russia in 1962 and in Prudhoe Bay in Alaska in 1967 (Østreng, 2012). Since then, 61 large oil and gas fields have been discovered in territory north of the Arctic Circle in these four countries. Of these, 42 are located in Russia, 11 in Canada, six in Alaska, and one in Norway (Budzik, 2009). These fields combined with estimated undiscovered deposits represent a significant proportion of world total

potential reserves. A widely-cited USGS study estimates that the Arctic contains 13% of the world's undiscovered oil and 30% of its gas, approximately 84% of which is under exclusive state control less than 200 nautical miles from shore (Bird et al., 2008; Gautier et al., 2009). One-third of the undiscovered oil (30 billion barrels) is in Alaska, while one-third of the undiscovered gas is in Russia's West Siberian Basin. While Greenland is not currently a petroleum exporter, its offshore East and West Basin provinces are estimated to exceed 16 billion barrels of oil. In aggregate, Arctic hydrocarbons represent one of the most significant remaining unexploited sources of nonrenewable energy. Recognizing the lure of such potential, insurance giant Lloyd's of London (2012) declared that "the Arctic is likely to attract substantial investment over the coming decade, potentially reaching \$100 billion or more."

These supplies, however remote and difficult to access, are becoming increasingly attractive prospects in a context of increasing global demand. Shell's willingness to invest \$4.5 billion in offshore Alaskan oil before drilling a single well reflects a belief that world energy demand has undergone a fundamental increase in recent years. In July 2008, the price of oil reached a historic high of \$147.27/barrel, many times higher than the assumed "natural price" of \$22 to \$28 four years earlier (Yergin, 2012). Following a sharp decrease coinciding with the global recession, prices resumed their upward trajectory and averaged approximately \$112 (Brent crude) in 2012 (EIA, 2013b). While some of the pre-recession price increase has been linked to speculation in financial markets in parallel with the real estate "bubble," much was due to fundamental increases in demand from OECD countries and rapidly industrializing economies in China and India in particular. World energy demand is projected to increase 36% from 2008 to 2035, with China alone accounting for 75% of the increase (International Energy Agency, 2010). Owing to their relatively cheap cost of implementation, fossil fuels are expected to cover

approximately 80% of world demand by 2030. These projections suggest that regardless of petroleum commodity financialization, the world oil market has undergone a structural shift toward prices that reflect higher aggregate demand (Yergin, 2012). Likewise, the likelihood that prices will remain close to \$100 for the next few years (EIA, 2013b) suggests that new exploration projects, including those in the remote Arctic, may become increasingly attractive.

Russian political and industry leaders often promote an optimistic view of Arctic development facilitated by the NSR, in which trans-Arctic shipping heralds a new era of direct integration with global logistics industries and resource markets. Putin summarized this viewpoint at the 2011 Arctic Forum: “The shortest route between Europe's largest markets and the Asia-Pacific region lie across the Arctic...I want to stress the importance of the Northern Sea Route as an international transport artery that will rival traditional trade lanes in service fees, security and quality. States and private companies who chose the Arctic trade routes will undoubtedly reap economic advantages” (Bryanski, 2011). Similarly, Russia’s plan to invest heavily in Arctic oil and gas development is underpinned by an assumption that newly accessible offshore supplies will become commercially viable. Russia has a strong incentive to increase oil and gas supplies as heavy reliance on exports has left its economy and government highly vulnerable to price fluctuations. Russia relies on oil and gas for two-thirds of its exports, 20% of its GDP, and 60% of its state budget (Hulbert, 2012). Shale-gas discoveries in North America have driven down gas prices, and oil prices remain ~\$30/barrel below the level required to balance Russia’s federal budget (The Economist, 2012a). Many of Russia’s older and larger fields are in long-term decline, and new production is increasingly coming from smaller and more expensive fields. New Arctic offshore fields represent a means of maintaining output in the

face of such production declines. Russian state officials project up to 40% of oil output coming from new offshore Arctic and Black Sea prospects by 2030 (Westbrook, 2012).

There are reasons to temper such optimism, however. While a seasonally ice-free Arctic appears likely in the coming decades, whether increased access to resources will promote economic development is highly uncertain. Arctic oil and gas plays remain among the most expensive to develop in the world and carry considerable environmental risks, particularly offshore (Mulherin et al., 1996; USARC Permafrost Task Force, 2003; ACIA, 2004b; Verma et al., 2008). Despite projecting substantial future investment in Arctic projects, Lloyd's of London (2012) cautioned that drilling in the Arctic "constitutes a unique and hard-to-manage risk," prompting German bank WestLB to announce that it would not finance offshore projects in the region (Kroh, 2012). Data from Alaska's North Slope indicate that the cost of drilling an onshore well in the Arctic may be as much as 640% higher than the U.S. average (EIA, 2008). Furthermore, costs have risen sharply in the last decade as new exploration has turned toward increasingly remote and marginal fields. From 2000 to 2005, onshore drilling costs in Alaska rose 564%, compared with 165% for the U.S. as a whole (American Petroleum Institute, 2006). Offshore wells are many times more expensive in the Arctic (~\$60 million; Chukchi Sea) than at lower latitudes (~\$7 million; Gulf of Mexico) (Østreng, 2012). Where infrastructure is underlain by permafrost, climate change-induced subsidence and thickening of the seasonal active layer increase construction and maintenance costs further (Cole et al., 1999; Hinzman et al., 2005; Larsen et al., 2008; Streletskiy et al., 2012a; Streletskiy et al., 2012b).

Reduced ice also introduces hazards to navigation even as it enables longer navigation seasons. Elevated temperature over open water promotes fog formation and reduces visibility, especially in late fall when daylight periods are short. Reduced overall ice concentration can

enable thick multi-year ice from the central Arctic Ocean to drift toward coastal shipping lanes, posing significant danger to all but the most ice-strengthened ships (Melling, 2002; Howell and Yackel, 2004). A longer ice-free season also increases wind fetch and heat transfer to the atmosphere, accelerating ice drift and leading to larger and more frequent storm surges (Barber et al., 2010; Vermaire et al., 2013). In this context of enhanced collision risk, the environmental impact of an oil spill would be severe. Oil may remain on or within sea ice after a spill only to be released months later, and cannot be reclaimed using conventional methods (Atlas et al., 1978; Martin, 1979; AMAP, 2007; Pew Environment Group, 2010). In a follow-up report on the 2010 Macondo disaster, the U.S. National Oil Spill Commission (2012) noted that while cleanup methods such as in-situ burning and mechanical recovery of oil have been demonstrated in ice, they have not been successfully tested in the extreme weather conditions likely to be present in the Arctic. The report also cited a lack of preparedness within the Coast Guard to deal with a serious drilling accident. Likewise, a U.S. GAO report (2012) found gaps in Shell's Beaufort Sea spill response plan, noting its failure to account for the unique risks of offshore development in ice. The binding Agreement on Cooperation on Marine Oil Pollution Preparedness and Response signed in May 2013 under the auspices of the Arctic Council is an important step toward multilateral environmental stewardship in the region, but is limited to international coordination of spill response efforts rather than prevention and safety measures. While lack of widespread disaster prevention and response capabilities will not necessarily deter extraction and shipping, it significantly raises the risks and potential consequences of such activities.

The promise and risks of Arctic development clearly entail numerous physical and social uncertainties. Climate systems, trade webs and policymaking are all complex processes that defy deterministic evaluation. Predicting human responses to environmental and economic change is

therefore best served by a scenarios-based approach comprising a number of possible “futures” (Brigham, 2007; Dodds, 2012). This dissertation seeks to articulate a synoptic picture of future human activity in the Arctic by examining a range of plausible scenarios of climate projections, transport logistics, regional politics, and extractive networks. Chapter 2, “**Collaborative Infrastructures: A Roadmap for International Cooperation in the Arctic**,” summarizes the political context shaping current and future economic development, and describes a new paradigm of collaboration among state and private actors founded upon mutual interests. Chapter 3, “**Projected 21st-century Changes to Arctic Marine Access**,” investigates the physical basis for future access to the Arctic through quantitative analysis of climate change scenarios at circumpolar and regional scales. Chapter 4, “**Marine Accessibility Along Russia’s Northern Sea Route**,” examines the accessibility of the eastern Arctic in depth with special attention to the physical and economic challenges of shipping along the NSR. Chapter 5, “**The Network Allure: Spatial Embeddedness in Arctic Extractive Industries**,” presents a first critical analysis of the network concept in the Arctic oil and gas sector, demonstrating the essential role of spatial context in the development of extractive commodity chains. In a brief conclusion, I offer a few remarks on the implications of a new Arctic marine transport regime for northern cities.

2. Collaborative Infrastructures: A Roadmap for International Cooperation in the Arctic

A version of: Stephenson, S.R. (2012). Collaborative infrastructures: a roadmap for international cooperation in the Arctic. Arctic Yearbook 2012, 1: 311-333.

2.1 Abstract

Climate change has spurred global interest in the Arctic as an arena of new potential for petroleum and mineral exploration. The prospect of increased access to resources has informed scenarios depicting the region's future as a theater of geopolitical aggression. Militarization has been increasing in the Arctic despite the existence of multilateral region-building institutions, such as the Arctic Council. However, existing international frameworks for resolving maritime border disputes (UNCLOS) and emerging opportunities for collaborative resource development indicate that cooperation is more likely to occur than conflict among Arctic states in the coming decades.

Contrary to recent media tropes signaling an impending Arctic "Great Game" for resources, many oil and gas deposits are providing the impetus for international cooperation constituted through development and implementation of shared infrastructure. I invoke the term "collaborative infrastructures" to describe a new paradigm of state and private collaboration within which Arctic actors are pursuing mutual economic and environmental interests. These collaborations work to address an imbalance between despotic and infrastructural power in the Arctic, manifest in a rise in post-Cold War militarization and nationalist rhetoric. The benefits to society conferred by infrastructural power are a powerful incentive for long-term cooperation among Arctic states. Even as states unilaterally increase their military presence, they are forging multilateral agreements to promote security and resource development at local and regional scales.

2.2 Introduction

In a world in which relations between states dominate geopolitical discourse, questions of the extent of territorial sovereignty become rather uncomplicated. Sovereignty becomes inextricably linked to territory itself once a doctrine of non-interference has been established among adjacent states. This Westphalian world of neatly-drawn borders leaves “no space between or around the states once the entire world is in sovereignty’s orbit” (Agnew, 2009a). Of course, geopolitical realities rarely afford such simplicities. Lines on a map are a poor indicator of power exerted over bounded space or control of populations within: territorial boundaries fail to represent the power of nonstate actors and misrepresent the power wielded by many nominally sovereign but effectively impotent governments (Agnew, 2009a; Shadian, 2010). Moreover, the fact that oceans cover over 70% of the globe undermines the simple fiction that we live in a completely territorialized world. The provisions of the United Nations Convention on the Law of the Sea (UNCLOS) have led to much of the world’s oceans falling within some sphere of state control, whether by establishing territorial waters (up to 12 nautical miles offshore) or exclusive economic zones (EEZ, up to 200 nautical miles offshore). The latter limits are not immutable: Article 76 allows a state to claim economic exclusivity over sea floor extending beyond the 200 nautical-mile limit if it can scientifically prove that the sea floor is a geological extension of its continental shelf. Nowhere are the implications of this stipulation more salient than in the Arctic.

Far from being a space entirely within “sovereignty’s orbit,” the Arctic is a place that defies the comfortable association of sovereignty with territory. Unlike Antarctica, a continent surrounded by an ocean, the Arctic is an ocean surrounded by continents, to which five countries—Russia, Norway, Greenland (Denmark), Canada, and the United States—have direct access. Because the region is relatively small (approximately 6% of earth’s surface), and because

it has unusually broad continental shelves, a large proportion of the Arctic Ocean is “at risk” of being claimed (Dodds, 2010). Article 76 was not written exclusively in relation to the Arctic—it was intended to settle ocean claims worldwide—and until recently, debates of Arctic seabed sovereignty have been largely confined to the academic realm. However, recent sea ice recession driven by climate change has led to a wave of new maritime sovereignty claims by Arctic littoral states, as well as military activities intended to reinforce sovereignty over existing territory.

There are obvious economic reasons for these claims: receding sea ice means increased access to potentially immense petroleum reserves for those states whose EEZs overlap with oil and natural gas fields. A widely-cited assessment by the U.S. Geological Survey estimated that the Arctic contains approximately 30% of the world’s undiscovered natural gas and 13% of its undiscovered oil, most of which is offshore and in less than 500 meters of water (Bird et al., 2008; Gautier et al., 2009). In the Russian Arctic alone, the total value of proven and potential petroleum reserves is estimated at \$15 trillion (Soloizobov, 2009). Climate models project increased year-round maritime access by midcentury within the EEZs of the five littoral states, particularly in Canada, Greenland, Russia, and the U.S., using ice-strengthened vessels (Stephenson et al., 2011).

The prospect of new access to these vast reserves has sparked a series of sensational media tropes touting such themes as a “great rush for virgin territory,” “race for Arctic riches,” and “fight for the top of the world (Krauss et al., 2005; Graff, 2007; Shalal-Esa, 2011). This surge in geopolitical interest has coincided with a militarization not seen since the Cold War (Huebert, 2009). While violence has yet to erupt, the fact that all Arctic littoral states have exercised demonstrations of military force or made plans to expand their military presence suggests the possibility of armed conflict. Furthermore, anticipation of military engagement

remains prevalent in policy literature (Cohen, 2007; Borgerson, 2008; Borgerson, 2009), fueling anxiety over an emerging northern “Great Game.”

Despite the allure of oil and gas, there is little reason to believe that international “resource wars” are in the Arctic’s future (Brigham, 2010; Smith, 2010). While the UNCLOS framework allows states to pursue national interests by claiming resources beyond their current EEZ, it provides for such activities to be done through peaceful and internationally-recognized means. Furthermore, many petroleum deposits are themselves providing the impetus for international cooperation constituted through the development and implementation of shared infrastructure.

In this paper, I invoke the term “collaborative infrastructures” to describe a new paradigm of state and corporate collaboration within which Arctic actors are pursuing mutual economic and environmental interests. Even as states unilaterally escalate their military capacity in the High North, they are forging multilateral agreements to promote security and resource development at local and regional scales. While provocative displays of titanium flag-planting may grab the headlines, less heralded collaborative efforts are guiding the future of Arctic governance.

2.3 Sovereignty anxiety and limits to shared governance

In his discussion of Alfred Mahan’s (1890) argument for securing state power through sea control, Paul Hirst (Hirst, 2005) points out that “even with modern technology like nuclear submarines, basic facts of geography and the qualitative features of space do matter, and they benefit some powers at the expense of others. The sea is only a great common to some.” Like other oceans, the Arctic Ocean is “a single continuous space across which vessels may move relatively freely” (2005) in comparison to overland travel. Unlike other oceans, however, the

Arctic Ocean imposes unique restrictions on vessel movement. The navigational limits and uncertainties created by temporally and spatially variable sea ice mean that season and regional geography determine the extent to which vessels move freely. Barring the use of ice-strengthened ships, Arctic navigation is currently possible only in ice-free seas, which tend to be located at relatively lower latitudes along coastlines. Thus, territorial coastal waters (such as the straits of the Canadian Archipelago and Russia's Vilkitsky strait) are necessary through-points for shipping along established routes such as the Northwest Passage and Northern Sea Route. Vessels may only avail themselves of these routes under the right of innocent passage, which allows legal transit only in an "expeditious and continuous manner," which is not "prejudicial to the peace, good order or the security" of the coastal state (UNCLOS, 1982a).

This necessity of travel close to (if not directly through) territorial waters increases the likelihood of a foreign vessel entering an area unpatrolled by state authorities (such as the Coast Guard)—a scenario any state government would prefer to avoid. Alexander Sharavin, head of Russia's Institute of Political and Military analysis, justifies the need for special forces in Russia's Arctic "Because we have thousands of kilometers of border [passing] through the Arctic Ocean. This huge space is not generally covered up with anything [or] anybody" (Ishchenko, 2011). Canada's long-standing dispute with the U.S. and EU over whether the Northwest Passage constitutes internal waters or an international strait is in part generated by anxiety over unmonitored foreign vessels entering territorial space. This anxiety was brought into sharp focus in 1999 when the Chinese vessel Xuelong arrived in the Beaufort Sea undetected, raising questions about whether foreign exploitation of Canadian resources could occur without state knowledge (Lasserre, 2010). Recent and projected increases in the volume of Arctic maritime traffic raise the chance of intrusion further: destination transport driven by resource

development, community resupply, and tourism is expected to increase significantly over the next decade. By 2020, it is projected that annual demand for resupply operations in Canada alone will exceed the capacity of the current fleet (Arctic Council, 2009).

That states have begun to increase their Arctic military presence and rhetoric following reports of dramatic sea ice recession is not mere coincidence. Nikolai Patrushev, Secretary of the Russian Security Council, declared in September 2008 that “it cannot be ruled out that the battle for raw materials will be waged with military means” (Schepp and Traufetter, 2009). Others are more blunt: Konstantin Simonov, Director of the National Energy Security Fund in Russia, predicted a military clash between Russia and NATO forces in the next 20 years (Solozobov, 2009). In diplomatic cables leaked by WikiLeaks in May 2011, Russian Ambassador to NATO Dmitriy Rogozin asserted that “the 21st century will see a fight for resources, and Russia should not be defeated in this fight” (Jones and Watts, 2011). States have backed up such rhetoric with military exercises and policy initiatives. Russia’s Arctic Strategy calls for the creation of a polar forces unit fortified by tanks and all-terrain tracked vehicles to be deployed in Pechenga, 100 km from Murmansk near the Norwegian border (Government of Russia, 2008b), and its navy and air force continue to patrol the Arctic Ocean (Barents Observer, 2010). Canada’s plan to establish a military training center in Resolute Bay is one of several implementations of the Harper Government’s “use it or lose it” strategy (Byers, 2009). Despite not having ratified UNCLOS, the U.S. recently conducted submarine exercises north of Prudhoe Bay, meant to “ensure that the United States maintained access to the Arctic” according to U.S. Navy Captain Rhett Jaehn (Shalal-Esa, 2011). Such developments might suggest that states are preparing the Arctic to become a military theater. Are fears of impending conflict legitimate?

A measured approach to the question would begin with acknowledging that northern identity in some countries, particularly Canada and Russia, is intertwined with the recent militarization. Defense of the North through active military and civilian presence has long been a hallmark of Russian policy dating back to Stalinist efforts to assert sovereignty through planned industrialization of the North and Far East (Griffiths, 1991; Hill and Gaddy, 2003). While of no direct political consequence and under no sanction by Moscow, Artur Chilingarov's dramatic flag-planting incident did much to secure post-Cold War Russia's identification with the North, both domestically and internationally. Canada provides one of the clearest examples of northern identity politics through its "Northern Strategy," a Harper Administration-backed federal plan to establish unambiguous sovereignty over Canadian Arctic lands and waters. The Strategy affirms Canada's right to "patrol and protect [its] territory through enhanced presence on the land, in the sea and over the skies of the Arctic" (Government of Canada, 2009) by increasing human presence in the North, including supporting paramilitary Canadian Rangers in communities throughout the region (Lackenbauer and Farish, 2007; Lackenbauer et al., 2008). Outlining the project's goals, Foreign Affairs Minister Lawrence Cannon called the Arctic "an integral part of [Canada's] national identity" and affirmed that heightened military operations would allow the state to "reinforce [its] presence in the region" (CTV, 2009). Such sentiments are reflected by Canadians' strong general support for expanding the Canadian Rangers in the High North (82% northern Canada, 71% southern Canada) (EKOS Research Associates, 2011). A vote by the House of Commons to rename the Northwest Passage the "Canadian Northwest Passage" (Hutter, 2009) would appear to highlight, above all, the symbolic significance that defense of Arctic sovereignty has undertaken.

Such rhetoric may represent little beyond symbolism and political posturing, however. In spite of Harper's repeated public calls for increased militarization, cables released by WikiLeaks reveal his belief that an Arctic military clash is highly unlikely, and that a NATO presence in the region could backfire by exacerbating tensions with Russia (Clark, 2011). Furthermore, military presence as a projection of national identity is not warmongering, as citizens may support their military without supporting militarism. Recent evidence suggests that while nationalist sentiments persist throughout the North, international approaches to governance also enjoy widespread support. A survey of 9000 residents in the eight Arctic states found pluralities of respondents favoring a "firm line in defending its sections of the Arctic" in Canada (42%), Iceland (36%), and Russia (34%), but greater numbers of respondents from these countries favoring either negotiating compromises with other countries, or designating the Arctic as an international territory (Canada, 52%; Iceland, 53%; Russia, 47%) (EKOS Research Associates, 2011). These attitudes comprised strong majorities of the responses from other states (Denmark, 88%; Finland, 87%; Norway, 84%; Sweden, 83%; United States, 55%).

These results appear to vindicate efforts to develop international governance regimes in the Arctic. International governance has had a place in discussions on Arctic politics since the final years of the Cold War, as Mikhail Gorbachev's famous "Murmansk Initiative" speech in 1987 initiated a move toward thinking of the region as a zone of international cooperation rather than a military theater (Osherenko and Young, 1993; Young, 2009). Perhaps the most significant development in this regard was the 1996 inception of the Arctic Council, which established the first circumpolar intergovernmental body intended to promote shared governance among states and indigenous groups. The Arctic Council has succeeded in fostering dialogue among stakeholders concerning sustainable development, environmental protection, and scientific

collaboration, culminating with the release of the Arctic Climate Impact Assessment in 2004. It has raised the geopolitical profile of the Arctic (numerous non-Arctic states have applied for observer status) and is an important forum for the advancement of indigenous interests. Most recently, the landmark May 2011 agreement to coordinate search-and-rescue operations jointly among the eight states marked the first legally binding agreement adopted by the Council.

This recent success notwithstanding, many of the most important issues in the region today remain confined to engagement at the national level. The Arctic Council retains little binding regulatory authority over many sensitive issues of national interest, such as border control, security policy and resource exploration, and remains “essentially an international advisory body providing support to the governments that are seeking consensus-based solutions to common or shared problems” (Heininen, 2004). The 2011 search-and-rescue agreement may pave the way for some binding international regulation of oil and gas development, as Sweden has indicated that it would use its term as Arctic Council chair from 2011-2013 to push for regional coordination on oil spill prevention and response. However, it remains unclear whether the Arctic Council will ever acquire the authority to regulate and/or mediate disputes regarding ownership of oil and gas deposits, given the highly strategic role of these resources in state agendas.

In the near future at least, such a transfer of power appears unlikely. The Ilulissat Declaration issued by Greenland, Canada, Russia and the U.S. in 2008 unequivocally affirmed these states’ commitment to the existing legal framework under UNCLOS. Implying that the terms of Article 76 are sufficient for resolving present and potential future sovereignty disputes, the declaration asserts that there is “no need to develop a new comprehensive international legal regime to govern the Arctic Ocean.” Effectively, this agreement among select governments—

indigenous groups and non-littoral Arctic states Finland, Iceland, and Sweden were excluded from the summit—sent a clear message to the international community that matters of sovereignty and resource development belong foremost on national, rather than international, agendas (Dodds, 2010). In this way, the agreement undermined the spirit of international cooperation the Arctic Council was created to promote, made plain by U.S. Secretary of State Hillary Clinton’s rebuke to Lawrence Cannon at the March 2010 meeting of the “Arctic Five.” Contrary to regimes of “disaggregated” sovereignty coincident with the rise of globalization, the “necessary fiction” that “there is absolute popular sovereignty vested in a national/territorial political community rigidly marked off from all others” (Chandler, 2003; Agnew, 2009a) remains a compelling geopolitical principle in the Arctic.

In spite of this focus on national rather than regional interests, all signs are that the former will be advanced by peaceful means (Young, 2009; Brosnan et al., 2011). UNCLOS offers a peaceful solution to territorial disputes: Arctic oil and gas, like those in any ocean, belong to the state which exercises sovereignty there. Because most known reserves lie within unambiguous state EEZ boundaries, states may pursue development of their own fields within an internationally recognized legal framework. Where boundaries are disputed, Arctic states have shown willingness to find peaceful resolutions: in September 2010, Norway and Russia resolved a four decade-long disagreement on their Barents Sea maritime boundary, and Canada and Russia agreed that the United Nations would be the final arbiter of their overlapping claims in the Arctic Ocean. The line of demarcation in the Beaufort Sea between Canada and the U.S. remains undelineated, but violent conflict between states with such amicable relations and shared interests is practically unimaginable. Unclaimed deposits outside state EEZs may be in play following a successful petition under Article 76, but the recoverability of these deposits is

complicated by greater ocean depth, distance to shorelines, and sheer statistical uncertainty of their presence, making development of near-shore deposits a much more attractive prospect in the near and medium term (AMAP, 2007). For example, nearly all offshore explored gas reserves lie in the Russian Barents Sea, mostly in the Shtokman field 600 km off the coast of the Kola peninsula. It is unlikely that any undiscovered deposits in Russia's pending claim represent a prize of equal or greater value (Gautier et al., 2009).

The commitment to the existing UNCLOS framework (and the preservation of national agendas it affords) may be motivated by a protectionist impulse, but a peaceful one nonetheless. As long as the tenets of UNCLOS remain intact, there is little reason for states to pursue aggressive policies to secure oil and gas, as Norway and Russia recently demonstrated by peacefully resolving a 40-year Barents Sea boundary dispute. The Ilulissat Declaration set a regrettable precedent by excluding indigenous groups and three states from the table. Yet, its unequivocal affirmation of UNCLOS may be the single most significant step toward conflict avoidance in the Arctic.

2.4 Arctic infrastructure: scarcity and investment

While the post-Cold War Arctic has sometimes been perceived as geopolitical backwater, the region's recent militarization reflects an elevated nationalist enterprise at work. This Northern nationalism is linked to an imbalance between despotic and infrastructural power currently unfolding in the Arctic. Michael Mann (1984) distinguishes between despotic power, or power over society by state elites, and infrastructural power, or power to penetrate and coordinate the activities of civil society through implementation of infrastructure. While despotic power works by directly imposing a state's will over its people, infrastructural power works by increasing the amount of contact states have with their citizens and the benefits that result from

this contact. For this reason, infrastructural power may be viewed as a “positive” type of power, as it is effectively a legitimacy to govern ultimately derived from the assent of the people. For example, governments that tax their citizens directly at source without direct consent do so because the authority to tax is given implicitly by the people who receive benefits from government-provided services. Roads, law enforcement, pensions, and medical care are all manifestations of infrastructural power.

Because infrastructural power is often exercised in and around population centers in order to maximize the benefit of services, infrastructural power is highest where territoriality is unambiguous. Borders provide bounded, centrally organized spaces within which taxes may be collected, services rendered, and information gathered. Domestic sovereignty within clearly-defined borders allows states to deliver services to the people who both support and depend on those services, without foreign intrusion (Agnew, 2003). Similarly, social stability flows from a government’s capacity to exercise effective infrastructural power, because a population invested in benefits provided or facilitated by the state is unlikely to overthrow the system providing those benefits. Infrastructural power thus becomes “the quintessential indicator of modern statehood” (Agnew, 2009a).

It is important to note that a state may exercise *infrastructural power* without actually deploying *infrastructure* itself. The Alaskan Native Land Claims Agreement (1971), Canadian Land Claim Agreements (beginning with the James Bay and Northern Quebec Agreement, 1975), and institution of Home Rule in Greenland (1979) were landmark steps toward devolving governance locally and economically empowering communities (Grant, 2010). These agreements bolstered state legitimacy in the North by allowing native populations to become politically and economically invested in a system created and controlled by the state—a clear and tangible

demonstration of sovereignty. Thus, a form of infrastructural power deriving from unique governance systems has been in place in the western Arctic since the 1970s. However, it should be noted that the prospects for similar regimes of native empowerment in Eurasia are dimmer, due to homelands crossing modern political boundaries¹ (Smith, 2011) and extant systems of federal resource control (Stammler and Wilson, 2006; Stammler and Peskov, 2008).

Despite the power afforded by these governance systems, other types of infrastructural power deriving from the presence of physical infrastructure remain lacking in the Arctic relative to southern latitudes. The Arctic has some of the lowest concentrations of built and human infrastructure in the world, due to costs imposed by cold winters and remoteness from large population centers. For example, per-capita transport and communication costs are much higher in the Northwest Territories (+36%) and Nunavut (+160%) compared with Canada as a whole (Statistics Canada, 2009). The penetration of transportation systems in northern countries has often taken the form of vast projects requiring considerable investment by federal governments, such as the Alaska Highway and the Trans-Siberian and BAM railways. Even with government investment, permanent transportation infrastructure remains sparse. Figure 2.1 illustrates the scarcity of permanent roads in the North by depicting total road length and density as a function of latitude. Warmer winters due to future climate change may make some areas more suitable for road construction, but these benefits must be weighed against the additional cost of maintaining existing built infrastructure over thawing permafrost (ACIA, 2004b). Furthermore, elevated temperatures threaten the viability of temporary winter road networks (Hinzman et al., 2005; Hayley and Proskin, 2008) and are projected to reduce winter road potential in all Arctic states by midcentury (Stephenson et al., 2011). Comprehensive surveys have found deficiencies in

¹ The ancestral homeland of the Saami, for example, extends throughout northern Fennoscandia across Norway, Sweden, Finland and Russia.

maritime infrastructure such as timely information needed for safe navigation, availability of search and rescue and pollution response assets, port reception facilities for ship-generated waste, and availability of deepwater ports and salvage resources for vessels in distress (Arctic Council, 2009). Compared to lower latitudes, infrastructure in the Arctic is less developed and more diffuse.

Given this paucity of infrastructure, it follows that the “territorialization of social relations” that results from deployment of infrastructural power (Mann, 1984) would be commensurately lower than at southern latitudes. Infrastructural power has penetrated society less deeply in the Arctic than in other places; here, the state retains full juridical control while lacking in practical control. For example, governments that lack weather stations, coast guard outposts, and trained personnel in their Northern territories may fail to forecast ice conditions, enforce regulations on oil and gas activities, and respond to disasters. Consequently, resident populations may have to cope with the insecurities of uncertain weather, unregulated petroleum extraction, and the specter of an ill-prepared response to oil spills. Policies which address such infrastructural deficits enjoy widespread support among Canadians, particularly those aimed at improving environmental disaster response capacities (92% of Northerners; 90% of Southerners); however, current capacities are rated as “profoundly inadequate” by a majority of Canadians (EKOS Research Associates, 2011).

A relative lack of infrastructural power in the North can impel a state to exercise despotic power in overt ways. Before the North American land claims agreements were settled, policies exerting direct control over indigenous populations—such as Canada’s forced relocation and compulsory boarding schools for Inuit in the 1950s—demonstrated state penetration of daily lives through despotic means. Such policies confer power through coercive control rather than

through a set of freedoms and safeguards afforded by state-sponsored infrastructure and social systems. Militarization and appeals to nationalism are other clear examples of this power imbalance. While built and human infrastructure may take decades to implement in the North, military power and nationalist rhetoric can be deployed relatively quickly and cheaply. Post offices and submarine patrols both affirm state sovereignty, albeit in very different ways.

However, as Arctic states become more attuned to their Northern interests, we are seeing an increase in infrastructural power resulting from government-initiated development programs. States that see their economic future in Northern development such as Russia, Norway, and Canada are investing heavily in transportation, communication, and research infrastructure. Norway, already one of the most infrastructurally developed Arctic states, has long been spearheading scientific research in the Svalbard Archipelago by collaborating with research institutions from numerous countries, including the eight Arctic states. In doing so, Norway is securing its position as a world leader in Arctic research and oil and gas technology. Russia has plans to develop its inland-maritime connectivity by building railways linking ports at Amderma and Indiga with interior settlements Vorkuta and Sosnogorsk, respectively (Pettersen, 2010). These ports are being targeted as potential cargo checkpoints for future shipping along the Northern Sea Route. Together with plans to expand Russia's fleet of nuclear icebreakers, this plan signals Russia's recognition that its 40,000 km-long Arctic coastline, occupying the full extent of the NSR, is one of its most invaluable strategic assets. These investments are effectively transforming what was for centuries a treacherous oceanic frontier into a transcontinental trade corridor. A well-developed northern transit system can only increase the competitiveness of Russia's oil and gas reserves on the global market: larger and more frequent

shipments will lead to greater trade volumes, and insurance costs will fall as icebreaker, disaster response, and ice monitoring services are enhanced.

In the western Arctic, Canada's proposed Arctic Gateway may be one of the most ambitious Northern plans to meet the transportation requirements of a global economy. The Arctic Gateway is the latest in a series of "Gateway" initiatives already guiding development and trade policy in the Atlantic, Asia-Pacific, and central Ontario/Quebec regions (Transport Canada, 2009a; PPM Public Policy Management Ltd., 2010). The National Policy Framework for Strategic Gateways and Trade Corridors aims to promote long-term economic development through direct government investment in physical infrastructure, such as increasing the number and capacity of deepwater ports (such as at Churchill), and by promoting partnerships with the private sector to pursue projects jointly. Among other things, the Framework will direct the spending of a \$33 billion allocation to Building Canada, the federal government's long term plan for infrastructure, committed in the 2006 and 2007 budgets. The Arctic Gateway differs from previous Gateway Frameworks in its effort to fuse state economic development goals with national sovereignty, environmental stewardship, and indigenous empowerment. This is borne out of the recognition that infrastructural investment alone is insufficient to secure livelihoods: economic policies must also recognize the governance needs of local populations in order to promote sustainable development (DiFrancesco, 2000).

The future Arctic infrastructural landscape will look very different from today. The economic potential of the Arctic is being realized on increasingly large scales, necessitating unprecedented imports of equipment and expertise. These infrastructural requirements represent critical opportunities for interstate cooperation, as I argue in the next section.

2.5 Collaborative infrastructures

Many signs indicate that international cooperation is emerging as a dominant *modus operandi* in Arctic geopolitics. The Norway-Russia boundary resolution is the clearest recent example, ending a 40-year period of dispute over a 175,000 square kilometer area of the Barents Sea. Norway's Storting unanimously ratified the treaty in February 2011, with Russia's ratification coming in a landslide vote one month later. The agreement appears all the more remarkable in light of the considerable oil and gas potential of the formerly disputed region. Seeds of the agreement had been sown years earlier as each of the states recognized the strategic benefits of the resolution. In 2008, Jonas Gahr Støre, Norway's Minister of Foreign Affairs, emphasized cooperation with Russia on the prospect of petroleum extraction:

Most of this activity has taken place in the Norwegian Sea, but the major potential is on the Russian side. There are huge opportunities for cooperation...I have raised the issue of infrastructure in my discussions with my Russian colleagues. Is the infrastructure along the coast able to support the extensive offshore activities that are expected to develop in this area? This is a good opportunity for the two coastal states to discuss what will be needed... (Støre, 2008)

While not mentioning Norway specifically, the 2008 Russian Security Policy noted similar opportunities for cooperation:

Russia develops forward practical cooperation with the Nordic countries, including the implementation of a multilateral framework of joint cooperation projects in the Barents Euro-Arctic Region and the Arctic as a whole, taking into account the interests of indigenous peoples. (Government of Russia, 2008a)

Following the historic agreement, the theme of cooperation was again at the forefront of Minister Støre's January 2011 speech at the 5th Arctic Frontiers Conference:

The agreement is a clear reflection of the new dynamic in the Arctic. What was once a frozen region in more than one sense is warming up to the prospects of reaping mutual benefits through cooperation and agreements. (Støre, 2011)

The Barents Sea is believed to contain some 3,700 million tons of oil equivalent (Moe, 2008), equal to 33% of Russia's proved oil reserves (BP, 2011). According to the boundary

resolution treaty, deposits that straddle the boundary line are to be regarded as an indivisible whole, and may only be explored and developed jointly by the two countries (Socor, 2010). With such a substantial prize at stake, it may seem unlikely that the two states would arrive at a resource-sharing agreement so easily. However, Russia's extraction capabilities lag significantly behind its announced offshore platform needs. Plans to develop the Prirazlomnoye field in the Pechora Sea using almost exclusively Russian equipment failed to materialize, and Gazprom's ventures in the Shtokman field stalled due to disagreements on the extent of foreign involvement (Moe and Rowe, 2008). The combination of Russia's offshore ambitions and Norway's relative advantage in equipment and personnel created an attractive partnership opportunity. President Medvedev himself welcomed the collaboration: "We actually want our Norwegian friends to apply all of their best technologies, all of their best designs, to promote the modernization of our oil and gas sector" (Socor, 2010). The Russian Ministry of Natural Resources advocates changing legislation to allow foreign companies to join projects in Russian strategic fields, though it is currently the only Ministry supporting this idea. In the short and medium term at least, an arrangement in which Norway supplies equipment and expertise in exchange for a share of Russia's petroleum profits appears mutually beneficial, as it will take years for Russia to develop its own technical abilities sufficiently to carry out its development plans. Furthermore, that Norway and Russia are both party to the Bologna Accord paves the way for possible longer-term scientific and technological collaborations founded on a common set of educational standards and principles (Bourmistrov and Sørnes, 2007). Upon reflection, it should not come as a surprise that the Barents Sea agreement was reached despite rich resource potential—on the contrary, resource prospects expedited the agreement, rather than impeding it.

Norway and Russia's partnership exemplifies the way in which infrastructural scarcity presents opportunities for cooperative approaches to local and regional problems. These "collaborative infrastructures" stem from mutual interests in expanding the reach and improving the efficacy of Arctic infrastructure. Norway and Russia's collaboration was founded on the sharing of equipment and expertise. While the "on-the-ground" work will be carried out by a number of non-state actors including engineers and corporate executives, the fact that the collaborative framework was conceived and endorsed at the highest levels of state government indicates that states themselves are wholly invested in collaborative infrastructures as a means of advancing their respective agendas. By electing to collaborate rather than pursue development independently, the Russian and Norwegian governments relinquished a measure of autonomy while providing for Barents Sea oil and gas projects to proceed according to mutually agreed-upon standards, setting a powerful precedent for interstate cooperation. In this way, collaborative infrastructures are an example of a "sovereignty bargain" by which states trade autonomy for increased control and legitimacy (Alam et al., 2009). As is often the case in such arrangements, infrastructure forms the foundation of the collaboration, with both physical (facilities, equipment) and human (expertise, legal and business frameworks) infrastructure implemented jointly.

This latter type of infrastructure comprising human practices is central to the collaborative work currently being done in the Arctic. U.S. Interior Secretary Ken Salazar pointed out the need for international oil and gas standards at the May 2011 Arctic Council meeting: "At a minimum what we can probably do is to aim at getting to a set of best practices that can be used in oil and gas exploration and production in the Arctic region" (Quinn, 2011). Other efforts are currently underway. For example, a pan-Arctic team of shipping experts at the

International Maritime Organization (IMO) is working to devise a “Polar Code,” a set of standards intended to harmonize the many national systems of requirements for building polar vessels. The specialized expertise needed to create this regulatory framework represents a type of human infrastructure essential to streamlining and maintaining safety in a rapidly expanding shipping sector. Governments and industry are working together to advance this goal through the Barents 2020 project, which established a dialogue between Russian and Norwegian experts to harmonize industry standards for disaster prevention in the Barents Sea (Det Norske Veritas, 2009). Industry recognizes that cross-border cooperation is an essential element of oil spill prevention and response, particularly in the Arctic where the environmental consequences of an oil spill may be particularly severe (Sæbø, 2011). The success of Barents 2020 led to greater international participation among various companies operating in the Arctic, giving rise to further projects developing new techniques to model, monitor, and respond to oil spills (Mairs, 2011). Thus, collaborative infrastructures may proceed as joint industry projects with potential to respond to regulatory needs faster than government-initiated legislation.

Current infrastructural improvements also hold promise for potential future collaborative infrastructures. Canada recently set aside nearly \$35 million to improve Arctic weather and navigation systems over the next five years (Environment Canada, 2011). The coverage area includes the western coast of Greenland, an area with rich petroleum reserves and considerable hazard potential due to sea ice import from the central Arctic Ocean into Baffin Bay. The key to Greenland’s full independence from Denmark may lie in its oil reserves (Nuttall, 2008), but Greenland’s infrastructure is among the least developed in the region, and has already opened its offshore fields to foreign interests (Izundu, 2010). Safe development of Greenland’s oil fields will require close monitoring of weather and ice conditions, which Canada will be poised to

provide. Though no agreement has taken place as yet, the potential exists for a revenue sharing accord in exchange for high-tech forecasting and navigational assistance.

Collaborative infrastructures have also been built into long-term strategic economic plans to promote the Arctic as a cost-effective alternative to trans-Pacific trade with east Asia. Canada and Russia are working toward a significant expansion of the “Arctic Bridge,” a trans-polar multimodal transportation system connecting North America with China and India by way of Russia. Canada and Russia are already engaging in maritime trade along the Churchill-Murmansk sea route, and both countries have recently made investments in expanding not only trade volume, but also the role and scope of trans-Arctic trade within the global trade network. On the Canadian side, the CentrePort Canada project aims to transform Winnipeg into an “inland port” serving not only as a midpoint for Canadian east-west trade, but also as the west-Arctic termination of the Arctic Bridge air and sea routes (by way of Churchill) (Figure 2.2). By capitalizing on its location in the geographic center of North America, Winnipeg would serve as a distribution center shuttling goods north to Churchill for sea export, as well as a primary hub for air cargo to Russia and China. Russia is investing as much as \$800 million to upgrade airport facilities in Krasnoyarsk as its Arctic Bridge air gateway (Gray, 2010), and will continue to receive and distribute intercontinental cargo through its largest Arctic seaport at Murmansk.

Unlike the previously cited examples, infrastructural development of the Arctic Bridge is coming primarily from within states rather than as international collaborations. However, the economic benefits Canada and Russia stand to gain from independently developing their trade infrastructures are predicated on continued stable diplomatic relations and a mutual desire to promote the Arctic as a fully integrated arena of global trade. Conceiving CentrePort Canada as an international project would have made little sense without commensurate investments in rail

and port upgrades within Russia and between Russia and China, and Russia only stands to gain from the expanded North American market penetration that CentrePort Canada affords. By building their infrastructures toward an intercontinental trade system, Canada and Russia are collaborating on long-term economic strategy, a strong sign of amicable, even harmonious, future Arctic geopolitics.

2.6 Conclusion

The Arctic has always been a part of the geopolitical history of northern states. However, recent years have seen the reemergence of the region as a locus of global economic and political activity. The Arctic is rapidly shedding its post-Cold War status as a geopolitical hinterland to occupy a space near the forefront of state agendas, manifesting in an imbalance between despotic and infrastructural power that has yet to be fully resolved. Likewise, the full potential of collaborative infrastructures in the Arctic has yet to be realized. As states work together to advance northern development, infrastructural power will commensurately rise, building on existing manifestations of infrastructural power such as the North American land claims agreements. These developments will lead to sovereignty being exercised increasingly locally through daily activities rather than as directives from faraway elites. Paradoxically, we may also see a further increase in military presence in absolute terms, as states respond to the defense demands of larger populations, infrastructural investments, and increasingly scarce resources. Regardless, military clashes are not likely to figure in the outcome of a Northern “Great Game,” as the geography of Arctic resources and infrastructure presents critical opportunities for international cooperation. Collaborative infrastructures will lead the way in forging economic and political partnerships between state and private actors. Along with the continued primacy of

the UNCLOS legal framework, these opportunities are a compelling incentive for Arctic states to emphasize mutual interests in the continued transformation of the circumpolar North.

2.7 Figures

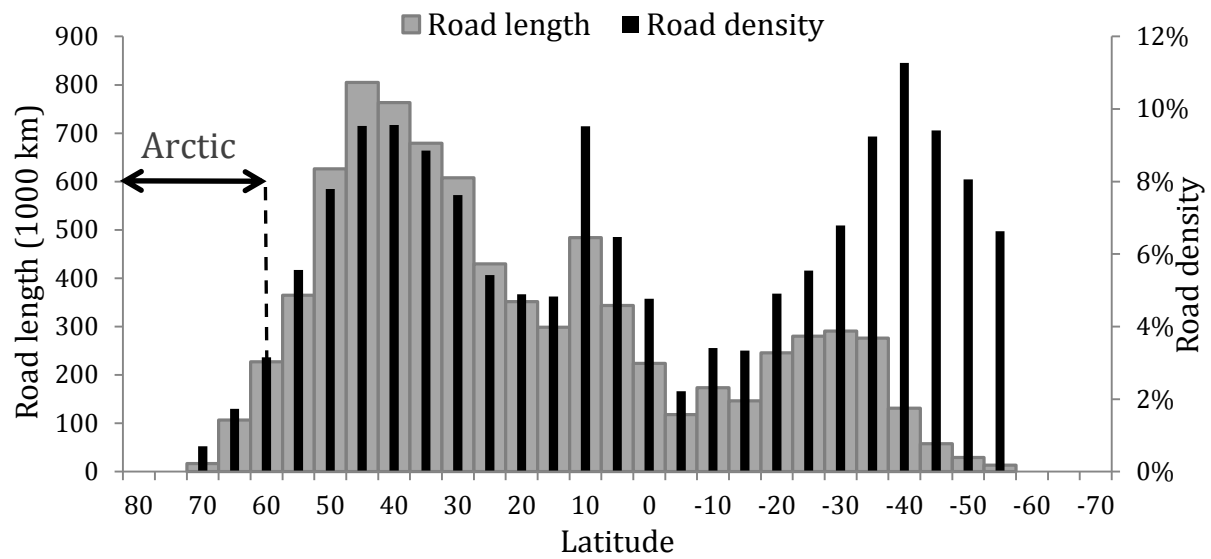


Figure 2.1: Total permanent road length (gray) and road density (ratio of permanent road length to land area; black) (US NIMA, 1997). Arrows show the approximate coverage of the Arctic zone.

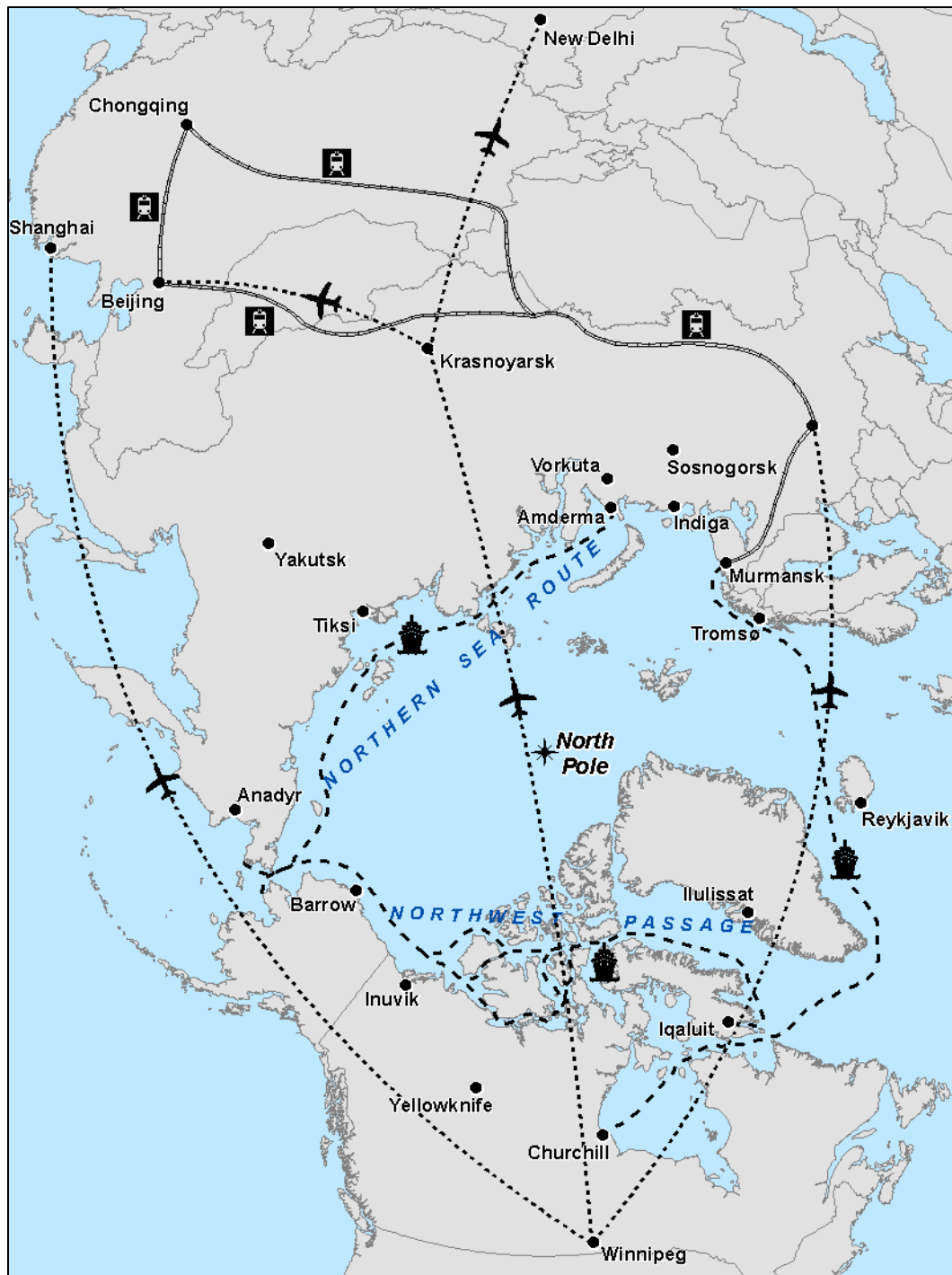


Figure 2.2: Arctic Bridge proposed air and rail routes (adapted from Gray, 2011)

3. Projected 21st-century Changes to Arctic Marine Access

A version of: Stephenson, S.R., Smith, L.C., Brigham, L.W., Agnew, J.A. (2013). Projected 21st-century changes to Arctic marine access. Climatic Change, 118: 885-899.

3.1 Abstract

Climate models project continued Arctic sea ice reductions with nearly ice-free summer conditions by the mid-21st century. However, how such reductions will realistically enable marine access is not well understood, especially considering a range of climatic scenarios and ship types. We present 21st century projections of technical shipping accessibility for circumpolar and national scales, the international high seas, and three potential navigation routes. Projections of marine access are based on monthly and daily CCSM4 sea ice concentration and thickness simulations for 2011-2030, 2046-2065, and 2080-2099 under 4.5, 6.0, and 8.5 W/m² radiative forcing scenarios. Results suggest substantial areas of the Arctic will become newly accessible to Polar Class 3, Polar Class 6, and Open-Water vessels, rising from ~54%, 36%, and 23%, respectively of the circumpolar International Maritime Organization Guidelines Boundary area in the late 20th century to ~95%, 78%, and 49%, respectively by the late 21st century. Of the five Arctic Ocean coastal states, Russia experiences the greatest percentage access increases to its exclusive economic zone, followed by Greenland/Denmark, Norway, Canada and the U.S. Along the Northern Sea Route, July-October navigation season length averages ~120, 113, and 103 days for PC3, PC6, and OW vessels, respectively by late-century, with shorter seasons but substantial increases along the Northwest Passage and Trans-Polar Route. While Arctic navigation depends on other factors besides sea ice including economics, infrastructure, bathymetry, and weather, these projections are useful for strategic planning by governments, regulatory agencies, and the global maritime industry to assess spatial and temporal ranges of potential Arctic marine operations in the coming decades.

3.2 Introduction

Reduced Arctic sea ice continues to be a palpable signal of global change. Record lows in September sea ice extent in 2007 and 2012 underscore robust downward trends in ice extent and thickness observed since 1979 (Maslanik et al., 2007; Serreze et al., 2007; Comiso et al., 2008; Stroeve et al., 2008; Kwok et al., 2009; Stroeve et al., 2012b). Since the 1980s, the extent of older, thicker multiyear ice (MYI) has decreased ~15% per decade, driven especially by reductions in March (declining from ~75% to 45%) and September (~60% to ~15%) (Maslanik et al., 2011; Comiso, 2012; Polyakov et al., 2012). Reductions have also occurred in winter, with circumpolar maximum ice extent falling to ~614,000 km² below the 1979-2000 mean in March 2012 (NSIDC, 2012a). While natural climatic variability has caused interannual fluctuations in sea ice extent throughout human history, the current decline is attributed primarily to anthropogenic greenhouse gas emissions (Kay et al., 2011; Day et al., 2012; Notz and Marotzke, 2012) with a magnitude unprecedented over the past 1,450 years (Kinnard et al., 2011). Climate model simulations share universal agreement on continued ice reductions throughout the 21st century (Zhang and Walsh, 2006; Christensen et al., 2007; Wang and Overland, 2009; Vavrus et al., 2012), though with some significant timing differences. A short period of ice-free conditions in summer has been projected as early as 2030 (Wang and Overland, 2009) and as late as 2100 (Boe et al., 2009). Furthermore, recent satellite observations indicate that many climate model simulations underestimate the true rate of ice loss, perhaps due to observational uncertainties, vigorous climate variability, and gaps in understanding physical processes such as ice drift (Kattsov et al., 2010; Rampal et al., 2011).

Despite model uncertainties these simulations, together with over three decades of satellite observations, have spurred new economic interest in Arctic shipping and offshore

natural resources (Astill, 2012). Reduced ice extent – and lower MYI concentrations, in particular – portend longer, more flexible navigation seasons in the region and increased viability of built structures such as drilling platforms (Arctic Council, 2009). All five Arctic Ocean coastal states (Canada, Greenland/Denmark, Norway, Russia, U.S.) have been conducting mapping projects to extend the limit of their outer continental shelves under Article 76 of UNCLOS, the United Nations Convention on the Law of the Sea (Potts and Schofield, 2008), while offshore oil and gas reserves are stimulating investment in the region (Barents Observer, 2011b). Trans-Arctic routes linking major world oceans are receiving attention as a potential future alternative to the Suez and Panama Canals, encouraged in part by recent shipping milestones in the Northern Sea Route (NSR) (Barents Observer, 2011a; Barents Observer, 2011c).

Maritime activity in the Arctic may be broadly classified into modes, or types of voyages (Arctic Council, 2009). Destinal shipping takes place when a ship sails to the Arctic from a southerly location and returns after performing some activity, such as cruise ship tourism, scientific research, or natural resource extraction. Intra-Arctic transport consists of voyages between Arctic locations, such as the proposed “Arctic Bridge” trade route linking the port of Churchill, Manitoba with Murmansk, Russia (Friesen, 2007). Trans-Arctic shipping refers to links between major world oceans, such as the Northwest Passage (NWP), Northern Sea Route (NSR), and hypothetical Trans-Polar Route (TPR) connecting the North Atlantic to the Bering Strait (Stephenson et al., 2011). While trans-Arctic voyages through the NWP to date have been mainly exploratory (Pharand, 2007), the NSR has seen a number of recent milestones. In August 2011, a Panamax-class tanker carrying 61,000 tons of gas condensate sailed the NSR in a record eight days, followed by the first-ever transit by a Suezmax-class supertanker seven days later (Barents Observer, 2011a; Barents Observer, 2011c). Cargo volumes through the NSR are

expected to reach 1.5 million tons in 2012, twice that of the previous year (Barents Observer, 2012).

Arctic navigation is subject to considerable environmental challenges. Safe passage is contingent on numerous factors including bathymetry, visibility, currents, regional weather conditions, available infrastructure, and economics (Arctic Council, 2009; Brigham, 2010; Brigham, 2011). However, a critical safety issue in the Arctic remains ice avoidance, especially of MYI (Brigham et al., 1999; Mulherin et al., 1999; Timco et al., 2005; Smith, 2011). Ice hazards are especially prevalent among the straits of the Canadian Arctic Archipelago (CAA) and NWP, where MYI concentrations are relatively high. A survey of Canadian ship damage events found ~75% to be associated with MYI collisions (Kubat and Timco, 2003). Ice hazards are expected to persist in the CAA throughout the transition to an ice-free summer due to increased dynamic import of MYI from the Arctic Ocean (Melling, 2002; Howell and Yackel, 2004; Howell et al., 2008; Howell et al., 2009). Furthermore, pressure zones created when sea ice accumulates in high concentrations along coastlines can result in “choke points” restricting passage to only the most powerful icebreakers (Falkingham et al., 2003; Wilson et al., 2004; Stewart et al., 2007). Climate change may also cause coastal waters to remain open longer in winter, increasing ice drift velocity (Barber et al., 2010). For these reasons, navigational safety is also strongly dependent on a ship’s hull strength and power.

Modeling studies of future Arctic maritime activity have typically presented results as a series of scenarios, with shipping potential defined in various ways including technically accessible area (Stephenson et al., 2011), transit time (Liu and Kronbak, 2010; Peters et al., 2011; Stephenson et al., 2011), fuel consumption (Paxian et al., 2010), navigation season length (ACIA, 2004b; Khon et al., 2010), and economic viability (Somanathan et al., 2007; Somanathan

et al., 2009; Liu and Kronbak, 2010). Here, a new approach combines projections of 21st-century Arctic technically accessible area, navigation season length, and temporal variability to simulate marine access as a function of both climatic (ice) conditions and vessel class. Projections are based on sea ice simulations for three climatic forcing scenarios (4.5, 6.0, and 8.5 W/m²) during the early (2011-2030), mid- (2046-2065), and late-21st century (2080-2099); assuming Polar Class 3 (PC3), Polar Class 6 (PC6), and open-water vessels (OW) with high, medium, and no ice-breaking capability, respectively. Unlike previous studies, the prospect that future maritime use of the Arctic will have different modes and purposes is thus recognized with inclusion of OW vessels particularly important because they comprise the vast majority of the world fleet. Results are presented for the entire circumpolar region, the current exclusive economic zones (EEZs) of the five Arctic Ocean coastal states (Canada, Greenland/Denmark, Norway, Russia, U.S.), three potential shipping routes (Northwest Passage, Northern Sea Route, Trans-Polar Route), and the international high seas of the central Arctic Ocean.

3.3 Methods

3.3.1 Study area

The area of analysis covers approximately 14 M km² and consists of the entire Arctic marine environment including the Arctic Ocean and coastal seas of Canada, Greenland, Russia and Alaska within the IMO Guidelines Boundary (IMO, 2002)² (Figure 3.1). The IMO Guidelines Boundary is intended to delineate area with potentially hazardous ice conditions

² IMO Guidelines (2002) define “Arctic ice-covered waters” as marine area containing sea ice concentrations of 1/10 or greater, located “...north of a line from the southern tip of Greenland and thence by the southern shore of Greenland to Kape Hoppe and thence by a rhumb line to latitude 67°03'9 N, longitude 026°33'4 W and thence by a rhumb line to Sørkapp, Jan Mayen and by the southern shore of Jan Mayen to the Island of Bjørnøya, and thence by a great circle line from the Island of Bjørnøya to Cap Kanin Nos and thence by the northern shore of the Asian Continent eastward to the Bering Strait and thence from the Bering Strait westward to latitude 60° North as far as Il'pyskiy and following the 60th North parallel eastward as far as and including Etolin Strait and thence by the northern shore of the North American continent as far south as latitude 60° North and thence eastward to the southern tip of Greenland.”

necessitating ice-strengthened ships. Ice may be present at lower latitudes in winter (e.g., southern Hudson Bay; western Barents Sea) and absent in some areas within the IMO Guidelines Boundary in summer (e.g., Bering Sea; eastern Barents Sea); thus, the IMO Guidelines Boundary represents an approximation of the regulatory scope of ice-strengthened ships at circumpolar scale.

This overall study area is further subdivided into five maritime exclusive economic zones (EEZ) of the Arctic Ocean coastal states (Canada, Greenland/Denmark, Norway, Russia, and the United States), defined as ocean beyond a state's territorial sea extending up to 200 nautical miles from its coast (UNCLOS, 1982b). As the IMO Guidelines Boundary region does not include the Norwegian mainland, the EEZs of the Svalbard archipelago and Jan Mayen falling within the IMO Guidelines Boundary were aggregated as Norway's Arctic EEZ. The central Arctic Ocean beyond EEZ boundaries was defined as "international high seas." The international marine area southwest of Svalbard was omitted from analysis. Unlike Stephenson et al. (2011), the present study considers only current EEZs, omitting potential future EEZ extensions to be potentially granted under Article 76 of the United Nations Convention on the Law of the Sea (UNCLOS).

Three potential trans-Arctic navigation routes were also analyzed, namely the Northwest Passage (NWP), Northern Sea Route (NSR) and Trans-Polar route (TPR) (Figure 3.1). The NWP was defined from the Baffin Bay mouth of Lancaster Sound (74° 9' 53" N, 79° 53' 30" W) westward through the Parry Channel and M'Clure Strait, turning southwest 100 km north of Point Barrow, Alaska, and terminating at the Bering Strait (65° 38' 36" N, 169° 11' 42" W). This particular NWP route was selected because the minimum depths of the Lancaster Sound and M'Clure Strait are sufficient to accommodate larger draft ships (e.g. Panamax). The NSR was

defined in accordance with Russian law as a coastal route running from Kara Gate south of Novaya Zemlya (70° 31' 44" N, 58° 14' 45" E) to the Bering Strait. This route passes north of the New Siberian Islands to avoid the shallow depths of the Sannikov and Dmitry Laptev Straits. The Trans-Polar route (TPR) was defined as a Great Circle route from the Fram Strait (79° 52' 48" N, 2° 25' 48" W) to the North Pole, followed by another Great Circle route to the Bering Strait. While the TPR is the only route crossing the pole, all three routes may be considered “trans-Arctic” as they connect major world oceans. To account for minor navigation deviations, routes were represented as a 25-km buffer around each route centerline (Figure 3.1).

3.3.2 Sea ice data

Future sea-ice characteristics were obtained from ice concentration and thickness simulations from the Los Alamos sea ice model (CICE) component of CCSM4 (NCAR, 2012). CCSM4 is an improved version of its predecessor (CCSM3) with major enhancements in all component models (Gent et al., 2011; Vavrus et al., 2012). CCSM4 was chosen due to its ability to capture well the observed 20th-century and present-day sea ice climatology, with September total ice extent straddling the mean observed extent from 1953-1995 and March extent falling within the maximum and minimum observed values (Stroeve et al., 2007; Jahn et al., 2012; Stroeve et al., 2012a). Under high forcing, CCSM4 projects that a majority of the Arctic will remain ice-covered until approximately 2040 (annual mean), followed by a reduction to 30% coverage by 2100 (Vavrus et al., 2012). Ice extent decline is slow and linear until 2030, holds relatively steady for nearly a decade during the 2040s, and accelerates the rest of the century before slowing down again in the 2090s (Vavrus et al., 2012). Similar to CCSM3, September ice loss is punctuated by periods of rapid retreat lasting from 3-5 years (Holland et al., 2006; Vavrus

et al., 2012). The rate of ice recession in CCSM4 reaches a minimum near 2060, somewhat later than the CMIP5 multi-model mean (CMIP5) (Massonnet et al., 2012). Biases in CCSM4 include a weak Beaufort Gyre leading to unrealistic sea ice motion in all seasons except winter, a high bias in ice concentration in Baffin Bay and a low bias in ice concentration in the coastal Beaufort Sea and central Arctic Ocean, and a too small area of very thick ice north of Greenland and the Canadian Arctic Archipelago (Jahn et al., 2012).

Data were obtained from the Coupled Model Intercomparison Project Phase 5 (CMIP5) archive. Three climate forcing scenarios were used from the forthcoming IPCC Fifth Assessment Report, based on the so-called Representative Concentration Pathways (RCP) by which climate is a function of radiative forcing (W/m^2) rather than GHG emissions directly (van Vuuren et al., 2011), specifically RCP 4.5 (4.5 W/m^2 , medium-low forcing), RCP 6.0 (6.0 W/m^2 , medium forcing), and RCP 8.5 (8.5 W/m^2 , high forcing). These scenarios are roughly correlative to the IPCC AR4 SRES scenarios B1, A1B, and A2, respectively (van Vuuren et al., 2011; Vavrus et al., 2012). Monthly means of sea ice concentration and thickness from one 21st-century CCSM4 simulation (termed simulation #1) were obtained for each RCP scenario, for three 20-year periods representing early-, mid- and late-century conditions (2011-2030, 2046-2065, and 2080-2099), respectively. These 21st-century simulations were initialized from the same historical 20th-century baseline conditions. Data representing a late-20th-century baseline (1980-1999) were also obtained from this historical simulation. Monthly means were averaged over each 20-year sample to obtain a single grid for each month at each time window. In order to calculate navigation season length (Section 2.4), daily means were also acquired for summer (July-October) and winter (December-March) from CCSM4 simulation #6 (simulation #7 replaces #6 for RCP 8.5). Daily simulations for each RCP scenario were initialized from the same 20th-

century conditions as for monthly means. All grids were projected to a Lambert Azimuthal Equal-Area projection at 5-km² resolution using nearest-neighbor interpolation to allow more precise calculation of accessible area within EEZs and navigation routes.

3.3.3 Ship-accessible area

Methods for calculating ship-accessible area at sea are described in detail in Stephenson et al. (2011), and summarized here.

Whether ships may traverse ice-covered waters safely depends on both the structural and engineering capabilities of the ship and the geophysical properties of the surrounding ice regime. The Arctic Ice Regime Shipping System (AIRSS) provides a framework for assessing whether a ship may navigate safely in ice-covered waters based on its design and the ice conditions present (Transport Canada, 1998). Because sea ice type/age is not available in CCSM4, type/age was approximated from ice thickness according to AIRSS guidelines and observational data. Six ice types, plus an “open water” class, were identified in AIRSS with accompanying thickness ranges as follows: “gray” (10-15 cm), “gray-white” (15-30 cm), “thin first-year first stage” (30-50 cm), “thin first-year second stage” (50-70 cm), “medium first-year” (70-120 cm), “thick first-year” (first-year ice over 120 cm). Sea ice with thickness greater than 0 cm and less than 10 cm was aggregated with “gray ice.” Note that this approach does not account for possible thickness variations within age classes, or within ice of uniform age owing to seasonal melt-freeze cycles (Johnston and Timco, 2008). However, it is generally true that age and thickness are well correlated at a given time of year (Fowler et al., 2004; Hunke and Bitz, 2009).

MYI and “second-year” ice that has survived one melt season are also identified in AIRSS, but without associated thickness ranges. For the present study, these ranges were derived from observed age and thickness data. Maslanik et al. (2007) calculated median “proxy” ice

thicknesses for yearly age classes for February-March from 2004-2008 by combining ICESat-derived ice thickness measurements (Kwok et al., 2007) with 12.5-km² ice age grids derived from Lagrangian drift tracking. This methodology was repeated in this study using October-November ICESat data from 2003-2007 to obtain proxy thicknesses for MYI and second-year ice at the beginning of the freeze cycle. Weekly ice age grids were obtained from Maslanik for the period 2003-2007, and mean ice age for October-November of each year was calculated by averaging age grids from weeks 41-48, thus approximately coinciding with October-November ICESat mean thickness grids. Thickness and age grids were spatially overlain in GIS. The median of all thickness values spatially coincident with a given age class was then calculated for each year, and these medians averaged over the 2003-2007 period. The resulting thickness-age classes provide an October-November counterpart to the February-March figures calculated by Maslanik (2007) (Table 3.1). Because ICESat-derived sea ice thickness data were only available for February-March and October-November, age-thickness relationships for other months were inferred using linear interpolation between the February-March and October-November values (aged 1 year: $y = -5.0572x + 173.57$ April-September, $y = 9.6682x + 111.92$ December-January; aged 2 years: $y = -4.3742x + 203.59$ April-September, $y = 8.3624x + 150.26$ December-January; aged 3 or more years: $y = -1.9705x + 225.23$ April-September, $y = 3.7671x + 201.21$ December-January) (Figure 3.2). The minimum thickness of MYI and second-year ice for a given month was defined as the middle value between the mean thickness values of adjacent age classes (Table 3.2).

The ability of a ship to enter a particular ice regime is given by the Ice Numeral:

$$IN = (C_a * IM_a) + (C_b * IM_b) + \dots + (C_n * IM_n)$$

where IN is the Ice Numeral, C_a/C_b is the sea ice concentration in tenths of ice type a/b and IM_a/IM_b is the Ice Multiplier of ice type a/b . The Ice Multiplier is a non-zero integer variable (ranging from -4 to 2) indicating the risk presented by a particular ice type to a given vessel class, with lower Ice Multipliers denoting greater risk. Ice type describes the physical properties of ice and is determined by a variety of qualitative (e.g., topography, ponding) and quantitative (e.g., thickness, compressive strength) factors (Johnston and Timco, 2008). Ice type is closely related to ice age: older ice tends to be thicker and stronger than younger ice due to annual accretion of ice layers and reduced brine inclusions (Bjerkelund et al., 1985; Johnston and Timco, 2008). Ridging and decay also affect the Ice Numeral by reducing or increasing, respectively, the Ice Multiplier by one. However, ridging and decay effects are not considered here as these physical processes are not modeled in CCSM4. A negative Ice Numeral signifies that the ice regime presents a significant hazard to the given vessel. Although passage may be possible in such conditions, the likelihood of accidents has been shown to be considerably higher where the Ice Numeral is negative (Timco et al., 2004).

Three vessel classes were chosen to represent a range of capital investment in ice-strengthened capability:

- Polar Class 3 (PC3), an icebreaker capable of “year-round operation in second-year ice which may include multi-year ice inclusions”;
- Polar Class 6 (PC6), a moderately ice-strengthened ship capable of “summer/autumn operation in medium first-year ice which may include old ice inclusions”;
- Open-water (OW) ships with no ice strengthening.

The Polar Class system was established within the IMO *Guidelines for Ships Operating in Arctic Ice-Covered Waters* (“IMO Guidelines”) as an effort to harmonize construction and operating

standards for Arctic vessels across classification organizations (IMO, 2002). In parallel with the IMO Guidelines, the International Association of Classification Societies (IACS) in 2008 adopted Polar Class nomenclature within its “Unified Requirements for Polar Class Ships” (UR), requiring its member societies to abide by Polar Class standards (International Association of Classification Societies, 2007). AIRSS distinguishes between stronger CAC (Canadian Arctic Category) vessels (classed 1-4) and weaker “Type” vessels (classed A-E) (Transport Canada, 1998). In accordance with international adoption of IMO/IACS Polar Class nomenclature, this study follows the convention that “CAC 3” and “Type A” classes are nominally equivalent to IMO/IACS PC3 and PC6, respectively (IMO, 2002; Transport Canada, 2009b). The “Type E” class includes vessels intended for ice-free operation only and is defined here as “open-water” (OW).

Ice Multipliers for PC3, PC6, and OW ships (Table 3.3) were used to calculate Ice Numeral grids following the AIRSS framework, representing all combinations of the three RCP scenarios, 20-year time windows, and vessel classes. For any given location, ship access for a particular vessel class was deemed feasible if the corresponding Ice Numeral for that class was non-negative. Total accessible area (km^2) was calculated for the five state EEZs, international high seas (central Arctic Ocean), and three navigation routes described in Section 3.3.1.

3.3.4 Navigation season length

Previous studies have defined navigation season as the number of days per year with less than a defined threshold of percent ice cover (ACIA, 2004b), which ignores other navigation-critical properties of sea ice (particularly thickness) and assumes that all vessels have equal ice capability. In order to calculate marine access in terms of navigation season length for multiple vessel classes, the present methodology was repeated using daily CCSM4 data for two seasonal

periods: “summer” (July-October; maximum season length: 123 days) and “winter” (December-March; maximum season length: 121 days). For each forcing scenario and vessel class described above, daily Ice Numeral grids were created for these summer and winter seasons for each year of the 20-year time windows. Yearly “navigation season length” grids for summer and winter were created by computing the number of days during the season that each grid cell was accessible to a given vessel class. These yearly grids were then averaged over each 20-year time window to obtain period-mean navigation season length during a season (Figure 3). Variability in the navigation season was computed by calculating the standard deviation of the navigation season length over each 20-year period.

3.4 Results

21st-century projections of accessible area (hereafter termed “access”; Table 3.4) are presented for the aggregate circumpolar region (Section 3.4.1), disaggregated state EEZs (Canada, Greenland/Denmark, Norway, Russia, U.S.; Sections 3.4.2-3.4.6) and the international high seas (Section 3.4.7). Accessible area is discussed with respect to three vessel classes (PC3, PC6, OW) and three forcing scenarios (RCP 4.5, 6.0, 8.5). In addition, summer navigation season length (i.e. the average number of accessible days between July 1 and October 31, for a maximum season length of 123 days) and variability (i.e. the standard deviation of season length) are also discussed within each regional unit for the early-century time window (2011-2030) under medium forcing (RCP 6.0) only. Finally, projected navigation season lengths and variability along the NWP, NSR, and TPR navigation routes are provided for all forcing scenarios (Table 3.5), and discussed in detail for the early-century RCP 6.0 scenario only (Sections 3.4.8-3.4.10).

3.4.1 Aggregate circumpolar totals for the IMO Guidelines Boundary region

In all time window and forcing scenarios, PC3 vessels have access to a substantial majority of the IMO Guidelines Boundary region year-round (Figure 3.3; Table 3.4). At baseline (1980-1999), 54% of the region is accessible to PC3 vessels on average annually, rising to 75% / 72% / 79% by early-century (for the RCP 4.5 / 6.0 / 8.5 scenarios, respectively) with 84% / 82% / 87% accessible during July-October. By mid-century, average annual access rises further to 89% / 91% / 94%, and by late-century, PC3 vessels gain access to nearly the entire IMO Guidelines Boundary region (93% / 95% / 98%). The rate of this increase is non-linear, with PC3 vessels gaining access more rapidly during the first half of the 21st century than the latter half (Figure 3.4). On average, annual accessible area increases +2.1 M / +2.5 M / +1.9 M km² between early-century and mid-century, and +4.6 K / +5.8 K / +5.7 K km² between mid-century and late-century. The Arctic Ocean is more accessible in summer than in winter today, so these projected gains in summer are minor compared to gains in winter and spring for all forcing scenarios. Seasonal fluctuations are somewhat muted (Figure 3.5A). All mid-century and late-century scenarios suggest access to at least 88% of the IMO Boundary region year-round to PC3 icebreakers, with a maximum of 99% (in summer) by late-century. In general, 21st-century projections for PC3 vessels suggest incremental access gains, especially in the early decades of the century, with a weak seasonal response.

For PC6 vessels, model projections suggest substantial access increases by mid-century (Figure 3.3; Table 3.4). Relative to baseline (36% annual average), access is still limited at early-century (45% / 44% / 48% of IMO Boundary area annual average; 66% / 64% / 71% July-October). By mid-century, however, access is considerably higher in all scenarios (58% / 61% / 69%) with summer levels approaching those of PC3 vessels (82% / 85% / 91% July-October).

By late-century, the region becomes nearly fully accessible to PC6 vessels in summer (90% / 93% / 98% July-October) and, under the highest climate forcing, maintains high access nearly year-round (68% / 73% / 93%). Most of these access gains occur in the first half of the 21st century under RCP 4.5 and RCP 6.0, and in the latter half of the century under RCP 8.5 (+1.8 M / +2.3 M / +2.9 M km² between early-century and mid-century; +1.4 M / +1.8 M / +3.3 M km² between mid-century and late-century; Figure 3.4). In contrast to PC3 vessels, PC6 vessels exhibit a strong seasonal pattern marked by substantially higher access in summer than in winter (Figure 3.5B). Access during July-October is 82% (average of all projections), compared with 56% during December-March. Differences due to forcing and time window are greater in fall and early winter (October-January) than at other times of year. The RCP 8.5/late-century scenario is markedly more accessible in winter and exhibits less seasonal fluctuation than any other scenario.

OW vessel access is limited in all forcing/time window scenarios and is generally restricted to summer months (Figure 3.3; Table 3.4). At baseline, only 23% of the IMO region is accessible to these vessels. Average annual access is low at early-century (29% / 29% / 31%) and remains marginal by late-century regardless of assumed climate forcing scenario (41% / 45% / 62%). By late-century, however, summer access is significantly higher (76% / 81% / 97%) especially under RCP 8.5. Access gains are lower compared to those of PC3 and PC6 vessels and occur mainly in summer (July-October account for 55% / 61% / 58% of the gains between early-century and mid-century) (Figure 3.4). Between mid-century and late-century under the highest forcing (RCP 8.5), access gains are sharply higher in July (+4.6 M km²) and November (+5.3 M km²). OW vessel access fluctuates strongly with season. Winter access is low in every scenario and differences due to forcing and time window are minimal, with the exception of the RCP

8.5/late-century scenario which is substantially more accessible than any other throughout the year (Figure 3.5C). In general, projections for OW vessels suggest incremental access gains in summer throughout the century, with greater gains under higher forcing scenarios, and very low access in winter under all forcing scenarios. This result underscores a future of limited summer operation of OW vessels throughout the Arctic Ocean.

3.4.2 Regional results: Canadian maritime Arctic

While recognizing the limitations of using climate models to study complex, finer scale Arctic sub-regions like the CAA, the CCSM4 simulation results suggest that much of the Canadian maritime Arctic remains inaccessible to PC3 vessels throughout the 21st century. At baseline, year-round access to Canada's EEZ averages 56%, with modest increases by early-century (59% / 57% / 59% annual average; 67% / 65% / 68% July-October) (Figure 3.7). By late-century, however, these figures rise to 78% / 87% / 96% and 86% / 93% / 98%, respectively. Under high climate forcing, the Parry Islands and seas north of the CAA are accessible by late century, even in winter. Navigation season length and variability vary greatly due to the complex geography of the CAA (Figure 3.6). Navigation season at early-century is brief and highly variable in high-latitude regions such as western Parry Channel and the Arctic Ocean north and west of Ellesmere Island (average < 30 days; $\sigma \sim 15-40$), whereas southerly regions such as Hudson Bay and Victoria Strait are nearly fully accessible in summer (average $\sim 110-120$ days). Navigation season variability is higher in some straits than others (e.g. M'Clure Strait with $\sigma > 40$, vs. Hudson Strait with $\sigma \sim 0$). Variability is particularly high along the eastern rim of the Beaufort Sea ($\sigma \sim 25-44$), decreasing westward from the CAA. In general, results suggest that PC3 access in Canada's EEZ will increase but remain highly dependent on local geography, with relatively long navigation seasons at lower latitudes and brief seasons at higher latitudes.

PC6 vessel access to the Canadian EEZ is considerably restricted, even in summer. Baseline access is low year-round on average (38%) and remains marginal by early-century with significantly higher access in summer (40% / 40% / 40%; 60% / 60% / 61% July-October) (Figure 3.7). Late-century year-round access rises to 52% / 61% / 81% on average and approaches maximum in summer under RCP 8.5 (96%, July-October). Navigation season length at early-century is brief in Parry Channel and in the northern CAA (< 30 days) (Figure 3.6). The Arctic Ocean north of the CAA remains reliably inaccessible (average < ~10 days; σ < ~10). However, navigation season in lower-latitude straits such as Davis Strait and M'Clintock Channel is substantially longer with moderate variability (average ~90-120 days; σ ~5-20). The southeastern Beaufort Sea is highly variable (σ ~27-50). In general, PC6 access is limited to southern regions of the CAA with brief, highly variable navigation seasons, even in summer.

Canadian OW vessel access is severely limited and restricted to summer months. Year-round access is low at baseline (21%) and early-century (24% / 24% / 24%) on average, owing to near-zero access from January-May in every forcing scenario (Figure 3.7). Summer (July-October) access is limited by early-century (55% / 55% / 55%) but rises substantially by late-century and achieves near-maximum under RCP 8.5 (64% / 74% / 94%). Navigation season at early-century is very short in the northern CAA (average < 10 days) (Figure 3.6). However, variability is moderate (σ ~25 days) in some high-latitude straits (e.g. M'Clure Strait, Lancaster Sound), suggesting navigation seasons of less than a month may be possible in limited areas of the CAA at early-century. Navigation season in Baffin Bay and Foxe Basin is considerably longer with moderate variability (average ~70-110 days; σ ~5-20). The Hudson Bay and Hudson Strait are reliably accessible from July-October (average > 120 days; σ ~0), while the southeastern Beaufort Sea remains unreliable (average ~80-110 days; σ ~30-50). Overall results

suggest limited, marginal 21st-century access for OW vessels in Canada's EEZ, and widespread summer access possible only under highest climate forcing and by century's end.

3.4.3 Regional results: Greenlandic coastal seas

PC3 vessel access is somewhat limited at early-century but increases steadily throughout the century. Baseline year-round access averages 57%, while roughly two-thirds of Greenland's EEZ is accessible at early-century (63% / 57% / 66% annual average; 71% / 65% / 76% July-October) (Figure 3.8). However, by mid-century access increases (77% / 79% / 86% annual average; 84% / 86% / 91% July-October), and approaches maximum potential by late-century (86% / 89% / 96% annual average; 90% / 93% / 97% July-October). Navigation season at early-century is reliably long along Greenland's west and southeast coasts (average > ~120 days, Baffin Bay; > ~110 days, north Atlantic west of Iceland) but extremely short along the northern coast (average ~0-30 days, Nares Strait and Arctic Ocean; Figure 3.6). Navigation season variability at these higher latitudes is high in some areas (northwest coast and southern Nares Strait: σ ~20-30) and low in others (northern Nares Strait: σ ~0). The northeast coast is moderately accessible (average ~60-90 days) but is highly variable (σ ~30-40). Excluding these northern regions, Greenland's EEZ is highly accessible to PC3 vessels by mid-century.

PC6 vessels are restricted to less than half of Greenland's EEZ at baseline (42% annual average) and early-century (46% / 47% / 48% annual average) with nearly two-thirds of the EEZ accessible in summer (63% / 64% / 66% July-October) (Figure 3.8). By late-century, average year-round access approaches maximum under RCP 8.5 (89%), but remains moderate under RCP 4.5 and RCP 6.0 (65% / 72%). As with PC3 vessels, navigation season at early-century is longer along the west and southeast coasts than along the northeast coast and in the Arctic Ocean (Figure 3.6). Baffin Bay and the southeast are accessible nearly all summer (average ~110-120

days; $\sigma \sim 5-15$). Navigation season is short in the Nares Strait (average $\sim 10-20$ days), however, and near zero along the northern coast. Greenland's east coast is moderately navigable, but highly unreliable (average $\sim 25-60$ days; $\sigma \sim 30-40$). These results suggest limited summer access for PC6 vessels at early-century, primarily along the western coast, and widespread summer access by late-century.

OW vessels have limited access at baseline (31% annual average) and early-century (34% / 35% / 35% annual average), driven mainly by summer (59% / 59% / 61% July-October) (Figure 3.8). Access is generally higher in Greenland than in Canada due to the southwest coast remaining largely ice-free in winter. Late-century access is similarly limited year-round (45% / 50% / 63%) but is comparable to that of PC3 and PC6 vessels in summer under RCP 8.5 (94%). Navigation season at early-century is longest in Baffin Bay and the Davis Strait (average $\sim 90-110$ days) with moderate variability ($\sigma \sim 10-25$ days) (Figure 3.6). Navigation season is brief to nonexistent along the north (average $\sim 0-10$ days) and northeast ($\sim 10-30$ days) coasts, with high variability in the northeast ($\sigma \sim 20-35$). In general, OW vessels are limited mainly to Greenland's west and southeast coasts in summer for the first half of the 21st century, with widespread summer access by late-century under the highest forcing (RCP 8.5).

3.4.4 Regional results: Svalbard and Jan Mayen (Norway)

PC3 vessels have access to the vast majority of Norway's Arctic EEZ in every scenario. Baseline year-round access averages 72%, and increases by early-century (89% / 92% / 97% annual average; 94% / 95% / 99% July-October). By mid-century, average year-round access increases nearly to maximum regardless of forcing scenario (99% / 99% / 99%) (Figure 3.9). Navigation season at early-century is long compared to other regions within the IMO Guidelines Boundary, but can be highly variable (Figure 3.6). Seas south of Svalbard and surrounding Jan

Mayen are reliably accessible throughout summer (average > 120 days; $\sigma \sim 0$). Navigation season is shorter and highly variable in the Arctic Ocean north of Svalbard (average ~60-100 days; $\sigma > 40$). The north Barents Sea east of Svalbard is accessible for most of summer (average > 110 days) but is more variable ($\sigma \sim 5-25$) than the south Barents Sea ($\sigma \sim 0$). In general, PC3 vessels may navigate freely in Norway's Arctic EEZ throughout the 21st century.

PC6 vessels have access to nearly two-thirds of Norway's Arctic EEZ at baseline (64% annual average) with marginally higher access at early-century (68% / 71% / 76% annual average; 76% / 77% / 88% July-October) (Figure 3.9). By late-century, PC6 vessels gain access to nearly the entire EEZ (92% / 95% / 100% annual average; 99% / 100% / 100% July-October). Like PC3 vessels, PC6 vessels may navigate for long seasons in the seas surrounding Jan Mayen and south of Svalbard at early-century (average > 120 days; $\sigma \sim 0$) (Figure 3.6). In contrast, navigation season north of Svalbard is brief and highly variable, ranging from ~10 days near the central Arctic Ocean to ~80 days near Svalbard's northern coast ($\sigma \sim 35-40$). Navigation season east of Svalbard is longer (average ~80-110 days) with fairly high variability ($\sigma \sim 15-38$). In general, all but the northernmost portions of the EEZ are accessible to PC6 vessels by mid-century, with near-maximum access year-round by late-century.

OW vessels may access the majority of Norway's EEZ at baseline (57% annual average) and early-century (60% / 63% / 65% annual average; 70% / 71% / 77% July-October) (Figure 3.9). By mid-century, OW vessels gain near-maximum access in August (95%) and September (99%) under RCP 8.5. By late-century, summer access approaches maximum in all forcing scenarios (91% / 95% / 100% July-October) and remains high in November (100%) and December (97%) under RCP 8.5. Navigation season at early-century is reliably long near Jan Mayen and south of Svalbard (average > 120 days; $\sigma \sim 0$) and much shorter north of Svalbard

(average ~0-60 days) (Figure 3.6). Navigation season variability generally decreases with latitude, as variability is relatively high near Svalbard (σ ~25-35) and low adjacent to the central Arctic Ocean (σ ~5-10). Like PC6 vessels, navigation season length in the north Barents Sea is moderate with high variability (average ~70-110 days; σ ~18-40). Overall, OW vessels have access to a greater percentage of Norway's EEZ than any other Arctic EEZ throughout the 21st century.

3.4.5 Regional results: Russian maritime Arctic

Russia's EEZ, the largest of the Arctic Ocean, is largely accessible to PC3 vessels in every scenario. Access is roughly two-thirds at baseline (63% annual average) and increases substantially by early-century (89% / 89% / 95% annual average; 98% / 98% / 99% July-October) (Figure 3.10). By mid-century, nearly the entire EEZ is accessible year-round on average (97% / 97% / 99%). Navigation season at early-century is reliably long in the eastern (Chukchi: average > 110 days; σ ~0-10) and western (Barents and western Kara: average > 110 days; σ ~0-5) seas of Russia's EEZ (Figure 3.6). Navigation season east of Novaya Zemlya and west of the New Siberian Islands is generally shorter and highly variable. These areas include the eastern Kara (average ~80-110 days; σ ~10-40), Laptev (average ~70-115 days; σ ~20-43), and East Siberian Seas (average ~90-120 days; σ ~6-35). Overall, these central coastal seas constitute a region of relatively marginal shipping potential, whereas the rest of Russia's EEZ remains relatively accessible to PC3 vessels year-round throughout the 21st century.

While Russia's EEZ is largely inaccessible to PC6 vessels at baseline (38% annual average), a majority is accessible by early-century (56% / 55% / 63% annual average), with considerably higher access in summer (84% / 84% / 92% July-October) (Figure 3.10). Access is near-maximum in summer by mid-century under all forcing scenarios (95% / 97% / 99% July-

October) and year-round by late-century under RCP 8.5 (97%). As with PC3 vessels, PC6 vessel navigation season at early-century is longest and least variable in the Barents, Chukchi, and western Kara Seas (average ~110-120 days; σ ~0-15) (Figure 3.6). Navigation season is significantly shorter and highly variable in the eastern Kara (average ~65-105 days; σ ~10-45), Laptev (average ~60-105 days; σ ~25-50) and East Siberian Seas (average ~80-110 days; σ ~16-45). Variability in these seas is highest in the northernmost areas adjacent to the central Arctic Ocean. In general, PC6 vessels may access the majority of Russia's coastal seas in summer by mid-century, with widespread access six months of the year by late-century.

OW vessel access throughout Russia's EEZ is limited to a brief period in summer. At baseline, only 21% of Russia's EEZ is accessible year-round on average, while roughly a third of the EEZ (primarily the western end) is accessible by early-century (34% / 33% / 38% annual average) driven largely by summer access (69% / 68% / 75% July-October) (Figure 3.10). Late-century access is sharply higher under RCP 8.5 (70% annual average) and is near-maximum in summer under all forcing scenarios (93% / 94% / 99% July-October). As with polar-classed vessels, navigation season at early-century is relatively long in the Barents, western Kara and southern Chukchi Seas (average ~115-120 days) with fairly low variability (σ ~0-18) (Figure 3.6). Navigation season is shorter and highly variable in the eastern Kara (average ~40-110 days; σ ~12-40), Laptev (average ~25-90 days; σ ~25-42), and East Siberian Seas (average ~30-105 days; σ ~22-44). Variability decreases with latitude, as northern seas adjacent to the central Arctic Ocean are more reliably inaccessible to OW vessels. These central coastal seas are among the most variable zones within the IMO Guidelines Boundary for this vessel type. Overall, OW vessels gain substantial access in summer by late-century, especially under high forcing, while winter access remains low throughout the 21st century.

3.4.6 Regional results: U.S. maritime Arctic

PC3 vessels have access to nearly the entire U.S. maritime Arctic in every scenario. Baseline access is high (95% annual average) and increases further by early-century (99% / 98% / 99% annual average) (Figure S8). Similarly, navigation season is reliably long for PC3 vessels (Figure 3.11). The Alaskan Beaufort Sea (average >115 days), Chukchi Sea, Bering Strait and Bering Sea (average > 120 days) are accessible for nearly a full summer. Navigation season variability is generally very low ($\sigma \sim 0$), though modestly higher near the northern Alaskan coast ($\sigma \sim 4-15$) (Figure 3.6).

Nearly three-quarters of the U.S. EEZ is accessible to PC6 vessels at baseline (74% annual average). By early-century, access is marginally higher year-round but nearly maximum in summer (83% / 79% / 79% annual average; 99% / 99% / 99% July-October) (Figure 3.11). Furthermore, access remains at least 97% through January in every forcing scenario. By late-century, nearly the entire EEZ is accessible in every forcing scenario (96% / 98% / 99% annual average). Navigation season at early-century for PC6 vessels is long with low to moderate variability (Figure 3.6). PC6 vessels may navigate for a full summer in the Chukchi Sea, Bering Strait and Bering Sea (average > 120 days) and slightly less than a full summer in the Beaufort Sea (average > 110 days). Navigation season variability is moderate in the Beaufort and Chukchi Seas ($\sigma \sim 5-16$), higher near the Alaskan coast ($\sigma \sim 20$), and very low elsewhere ($\sigma \sim 0-2$). In general, PC6 vessels have widespread access to the U.S. EEZ by mid-century for nine months of the year.

While low access from November-June limits OW vessels to approximately two-thirds of the U.S. EEZ year-round by early-century (64% / 60% / 62% annual average; up from 53% at baseline), these vessels have nearly full access in summer (98% / 98% / 98% July-October)

(Figure 3.11). By late-century, access approaches maximum under RCP 8.5 year-round (91%), and under every forcing scenario in summer (99% / 99% / 99% July-October). Navigation season at early-century is near maximum in the Bering Strait and Bering Sea with very low variability (average > 120 days; $\sigma \sim 0$) (Figure 3.6). Navigation season is shorter and more variable in the Beaufort (average ~105-115 days; $\sigma \sim 13$ -28) and Chukchi (average ~105-120 days; $\sigma \sim 0$ -15) Seas, particularly where adjacent to the Arctic Ocean (average ~90-100 days; $\sigma \sim 22$ -25). Except for these high-latitude areas, OW vessel access in summer at early-century is comparable to that of polar-classed vessels. Overall, however, access for OW vessels remains seasonal at early-century with eight months remaining ice-covered.

3.4.7 Regional results: international high seas

PC3 vessel access to the international high seas (central Arctic Ocean) grows dramatically by mid-century. While very low at baseline (18%), access increases over threefold by early-century (64% / 56% / 76% annual average), and increases nearly to maximum in every forcing scenario by mid-century (97% / 99% / 100% annual average) (Figure 3.12). Access is at least 90% in every month in all scenarios at mid-century, except in May under RCP 4.5 (89%). Navigation season at early-century is short near the CAA and Greenland (average ~16-20 days) and grows longer and less variable with proximity to the Bering Strait (average ~105-120 days; west of Banks Island) (Figure 3.6). Navigation season is somewhat shorter near the archipelagoes of the Russian maritime Arctic (average 90-110 days; north of Severnaya Zemlya and the New Siberian Islands). Excluding the region north of the Beaufort and Chukchi Seas ($\sigma \sim 0$ -7), navigation season in the central Arctic is highly variable, especially north of Svalbard near the Russian boundary ($\sigma \sim 40$ -50) and north of Greenland and the CAA ($\sigma \sim 30$ -37). In general,

results suggest moderate navigation potential in the high seas at early-century, but significantly greater access year-round by mid-century.

PC6 vessels have limited summer access to the high seas in most scenarios. Access is near zero at baseline (4% annual average) and low at early-century (15% / 11% / 17% annual average; 32% / 24% / 38% July-October) (Figure 3.12). By mid-century, summer access is substantially higher (72% / 78% / 92% July-October), and is close to maximum by late-century in every forcing scenario (90% / 96% / 100% July-October). Under RCP 8.5, PC6 vessels have full access year-round by late-century (100%). However, winter and spring remain highly restricted under RCP 4.5 (49% December-March; 0% April/May) and RCP 6.0 (66% December-March; 4% April/May). Navigation seasons are very short at early-century (Figure 3.6). At the North Pole and near the CAA, PC6 vessels may navigate only sporadically or not at all (average ~0-15 days). Long navigation seasons (> ~110 days) are possible only immediately adjacent to the Beaufort and Chukchi Seas. Navigation season variability in the central Arctic Ocean is low (σ ~0-10 near the North Pole) owing to the persistent inaccessibility of this area to PC6 vessels. Variability increases with distance from the central Arctic and is very high north of the Beaufort and Chukchi Seas and adjacent to the Russian EEZ (σ ~30-45). In general, navigation potential in the high seas remains marginal for PC6 vessels by mid-century, but improves with proximity to the Bering Strait and the edge of the Russian EEZ.

OW vessel access in the international high seas is minimal in most scenarios. At early-century, access is near zero in all forcing scenarios (4% / 4% / 4% annual average; 1% at baseline), even in summer (12% / 10% / 12% July-October) (Figure 3.12). By mid-century, summer access is marginally higher under RCP 4.5 (29%) and RCP 6.0 (32%), but sharply higher under RCP 8.5 (53%). These forcing contrasts are even more apparent by late-century

(49% / 63% / 100% July-October) when the high seas remains nearly fully accessible through November (97%) under RCP 8.5. Not surprisingly, navigation season at early-century is very short or nonexistent for OW vessels (Figure 3.6). Navigation season length is near zero throughout the central Arctic Ocean with very low variability ($\sigma \sim 0$). Navigation season is somewhat longer and significantly more variable with eastward distance (average ~ 10 -25 days, $\sigma \sim 25$ -35, north of Laptev and East Siberian Seas). Similarly, navigation season length and variability increase with proximity to the Bering Strait. OW vessels can potentially navigate for up to 3 months north of the Beaufort and Chukchi Seas (average ~ 30 -95 days), though operation in this area is unreliable ($\sigma \sim 25$ -37). Overall, the high seas remain highly inaccessible to OW vessels in most scenarios.

3.4.8 Potential navigation routes: the Northwest Passage

By the early 21st century, navigation season length for PC3 vessels is severely shorter in the CAA than anywhere else along the NWP (Figure 3.6). While navigation season averages $\sim 105 - 120$ days at the eastern mouth of Lancaster Sound, pervasive ice to the west, in Parry Channel, limits PC3 vessels to <15 operating days. Variability is high at the eastern and western ends of Parry Channel ($\sigma \sim 25$ -43) and lower in the Barrow Strait ($\sigma \sim 0$ -25), indicating that while some sections of the Canadian NWP may be navigable in any given year, low-variability “choke points” will likely restrict full transits. Upon exiting the M’Clure Strait, navigation season length increases dramatically. PC3 vessels may navigate for nearly a full summer at the Bering Strait (average ~ 120 days). Variability is low in the northern Beaufort and Chukchi ($\sigma \sim 0$ -15) Seas and at the Bering Strait ($\sigma \sim 0$). Overall, summer navigation season grows by +20 / +10 / +37 days by mid-century and +15 / +20 / +38 days by late-century, under RCP 4.5 / 6.0 / 8.5, respectively (Table 3.5). The surprising finding that fewer days are accessible by late-century than by mid-

century could result from continued import of heavy ice from the central Arctic Ocean into Parry Channel (Melling, 2002; Howell and Yackel, 2004; Howell et al., 2008; Howell et al., 2009), as this result is not observed in other regions in this study.

Like PC3 vessels, PC6 vessels may only navigate for short periods along Parry Channel at early-century (Figure 3.6). Navigation season length is near zero west of Lancaster Sound, though access may be marginally higher in some sections of Parry Channel (e.g., Viscount Melville Sound, average ~10-30 days). Variability is relatively high at the eastern (σ ~12-40) and western (σ ~33-37) termini of Parry Channel and low in between (σ ~0 Barrow Strait). Navigation season is substantially longer west of the CAA with low to moderate variability (Beaufort Sea: average ~60-120 days, σ ~5-30; Chukchi Sea: 110-120 days, σ ~0-16). Overall, summer navigation season grows by +17 / +9 / +40 days by mid-century and +15 / +31 / +45 days by late-century (Table 3.5).

OW vessels may not navigate in the eastern NWP for more than 10 days in summer at early-century (Figure 3.6). Navigation season length is near zero in much of Parry Channel. Variability throughout the Parry Channel is low to moderate (σ ~0-25), suggesting a low likelihood of accessibility to OW vessels in any given year. The western mouth of the M'Clure Strait is the most variable portion of the NWP for OW vessels (σ ~30-38). Navigation season is relatively long west of the CAA with moderate variability (Beaufort Sea: average ~50-105 days, σ ~15-25; Chukchi Sea: average ~105-120 days, σ ~5-15). Navigation season variability decreases with proximity to the Bering Strait (σ ~0). Overall, summer navigation season grows by +14 / +7 / +39 days by mid-century and +15 / +28 / +50 days by late-century (Table 3.5). These short periods of navigation for OW ships represent a strong limitation to use of the NWP for trans-Arctic voyages.

3.4.9 Potential navigation routes: the Northern Sea Route

Navigation seasons along the NSR are the longest of the Arctic routes examined in this study. Because the NSR is almost entirely circumscribed within Russia's EEZ (Kara Gate to Bering Strait), NSR navigation season length parallels that of Russia's EEZ. At early-century, PC3 vessels may navigate reliably for nearly a full summer (average > 120 days; σ ~0-10) in the western (Kara Sea) and eastern (Chukchi Sea) portions of the NSR (Figure 3.6). Navigation season is shorter in the Laptev (average ~95-100 days) and East Siberian (average ~95-120 days) Seas. This central portion of the NSR tends to be highly variable, particularly in the eastern Kara Sea and Vilkitsky Strait (average ~95-105 days; σ ~40) and north of the New Siberian Islands (average ~70-80 days; σ ~40-45). The Laptev Sea portion of the NSR as a whole is slightly less variable than these "hotspots" of high variability (σ ~25-40). Overall, summer navigation season grows by +9 / +7 / +4 days by mid-century and +10 / +12 / +5 days by late-century (Table 3.5).

Like PC3 vessels, PC6 vessels may navigate for relatively long periods in summer along the NSR at early-century. Navigation season is longest in the Chukchi (average ~110-120 days; σ ~0-17) and western and central Kara (average ~100-120 days; σ ~3-20) Seas, with low to moderate variability (Figure 3.6). Navigation season is shorter and much more variable in the "interior" of the NSR from Vilkitsky Strait to Wrangel Island. The route passing through the Laptev Sea (average ~75-90 days; σ ~35-43) and north of the New Siberian Islands (average ~45-60 days; σ ~40-50) is especially unreliable. These portions of the NSR may be accessible for nearly a full summer in one year and wholly inaccessible the next. The Vilkitsky Strait is accessible for slightly longer (average ~85-90 days) but is similarly unreliable (σ ~45-50). Overall, summer navigation season grows by +15 / +9 / +10 days by mid-century and +19 / +21 / +13 days by late-century (Table 3.5).

OW vessel navigation along the NSR at early-century is generally limited to summer in the western and central Kara (average ~90-120 days) and Chukchi (average ~110-120 days) Seas (Figure 3.6). Navigation season is substantially shorter in the Laptev (average ~35-65 days) and East Siberian (average ~35-100 days) Seas, particularly north of the New Siberian Islands (average ~30-40 days). As with PC6 vessels, navigation season variability is high along the NSR from Vilkitsky Strait to Wrangel Island. Variability is especially high in the Vilkitsky Strait (σ ~40-48), in the Laptev Sea (σ ~40), and immediately east of the New Siberian Islands (σ ~40). Brief, highly variable navigation seasons in these areas suggest that interannual variability will largely determine whether the NSR is accessible to OW vessels for any length of time at early-century. Overall, summer navigation season grows by +20 / +12 / +15 days by mid-century and +28 / +30 / +24 days by late-century (Table 3.5).

3.4.10 Potential navigation routes: the Trans-Polar Route

By the early 21st-century, navigation season for PC3 vessels along the TPR is brief and highly variable from the Fram Strait to the North Pole, growing longer and less variable with proximity to the Bering Strait (Figure 3.6). While PC3 vessels may navigate in the Fram Strait for over two months in summer (average ~65-80 days), navigation season shrinks to approximately one month near the North Pole (average ~25-35 days). High variability in the central Arctic suggests that this portion of the route may be accessible for over two months in one year, and not at all the next (σ ~35-45). PC3 vessels may navigate reliably for nearly a full summer from the high seas north of the Chukchi Sea to the Bering Strait (average ~115-120 days; σ ~0-4). Overall, summer navigation season grows by +30 / +24 / +24 days by mid-century and +31 / +38 / +24 days by late-century (Table 3.5).

PC6 vessels may navigate along the TPR only sporadically at early-century (Figure 3.6). Navigation season length is less than one month in the Fram Strait (average ~10-28 days) and is near zero at the North Pole (average ~0-3 days). Navigation season is brief throughout the central Arctic Ocean (average < 30 days) with low to moderate variability (σ ~0-25). While navigation season grows longer with proximity to the Bering Strait, it also becomes more variable. Variability reaches a maximum in the high seas north of the Chukchi Sea (σ ~42). PC6 vessels may navigate reliably for nearly a full summer in the northern (average ~110-115 days; σ ~5-10) and southern (average > 120 days; σ ~0) Chukchi Sea. Overall, summer navigation season grows by +29 / +25 / +46 days by mid-century and +47 / +64 / +61 days by late-century (Table 3.5).

There is virtually no navigation season for OW vessels at early-century along the TPR (Figure 3.6). Navigation season length is less than 10 days from the Fram Strait to the high seas north of the Chukchi Sea, and reliably near zero throughout much of the central Arctic Ocean (average ~0-3 days; σ ~0). Variability increases from the central Arctic to the high seas north of the Chukchi Sea, peaking near the Russian EEZ Boundary (σ ~22-36). From the Chukchi Sea to the Bering Strait, seasons are markedly longer (average ~100-120 days) and less variable (σ ~0-15). Overall, summer navigation season grows by +9 / +8 / +30 days by mid-century and +24 / +37 / +74 days by late-century (Table 3.5).

3.5 Discussion

While ship-accessible area and navigation season length increase in all scenarios and share broadly similar geographic patterns, the choice of forcing scenario is important. In particular, the highest radiative forcing scenario (RCP 8.5) is a significant driver of access change, especially for the weaker vessel classes. By late century, PC6 and OW access is considerably higher for this scenario than either RCP 4.5 or 6.0 (Figure S3 B, C), with the IMO

Guidelines Boundary becoming over 90% accessible to OW vessels from July to November (four months longer than under RCP 6.0). Moreover, PC6 vessels gain access to at least 80% of the aggregate region in winter (February-June) under RCP 8.5, whereas less than half of the region becomes accessible under RCP 6.0. High forcing also results in large non-linear access gains at the margins of the summer navigation season (July and November) for OW vessels and in winter for PC6 vessels between mid-century and late-century (Figure 3.5 B,C). In contrast, access under medium-low forcing (RCP 4.5) is very similar to that under medium forcing (RCP 6.0): by mid-century, aggregate year-round access is no more than 3% greater under RCP 6.0 than under RCP 4.5 for any vessel class. This result reflects the trajectories described by van Vuuren (2011), which indicate similar radiative forcing for these scenarios (and slightly higher for RCP 4.5) until approximately 2060. These trajectories also explain the finding of greater access in aggregate at early-century (Table 3.4) and longer average navigation seasons by mid-century (Table 3.5) under RCP 4.5. However, even by late-century, differences between RCP 4.5 and RCP 6.0 are marginal in aggregate. Viewed collectively, these results suggest a non-linear response of technical ship access to climate forcing, by which access increases sharply under the warmest climate forcing scenario.

Large disparities in access due to vessel class are evident in all scenarios. It is generally recognized in policy circles that ice-capable ships will continue to be necessary for Arctic navigation in the near term as ice recedes (IMO, 2002; Arctic Council, 2009). However, recent projections of an ice-free summer before 2050 (Holland et al., 2006; Wang and Overland, 2009) may engender the notion that ice-capable ships will diminish in strategic importance. While the results presented here indeed indicate increasing future access for all vessel types (Figure 3.3), the differences due to vessel class are striking and often exceed the impacts of climate forcing

alone. For example, at mid-century, PC3 vessels have access to the vast majority of the IMO Guidelines Boundary area year-round, whereas for PC6 vessels, January access is less than two-thirds of the September maximum (RCP 6.0). By late-century in winter, the IMO Guidelines Boundary area is fully accessible to PC3 vessels save for the northern CAA and western central Arctic, whereas OW vessels are restricted to portions of the Bering, Barents, Chukchi and Greenland Seas only. In general, PC3 vessels are able to navigate relatively freely in all forcing scenarios with relatively minor seasonal fluctuation, while weaker vessels (especially OW) are comparatively more subject to differences in climate forcing and the intra-annual timing of ice retreat.

Aggregate totals for the IMO Guidelines Boundary region are useful for general summarization but obscure strong geographic variations in projected ship-accessible area and navigation season length. By late-century, the EEZs of Norway and the U.S. are projected to be nearly fully accessible year-round to polar-classed vessels (98% and 96% to PC6; 99% and 100% to PC3, respectively; three-forcing average), with marginally lower figures for the Russian maritime Arctic (85% PC6; 99% PC3). In contrast, access to the Greenlandic EEZ is lower (75% PC6; 90% PC3), and lower still for the Canadian EEZ (65% PC6; 87% PC3). Perhaps the most striking change occurs in the international high seas, where access increases from 4% (PC6) / 18% (PC3) in the late 20th century to 73% (PC6) / 100% (PC3) by late-century. Of the Arctic Ocean coastal states, Russia (36% / 47% / 35%) is projected to gain access to the greatest percentage of its EEZ by late-century (PC3 / PC6 / OW, 3-forcing average), followed by Greenland/Denmark (34% / 33% / 22%), Norway (27% / 32% / 23%), Canada (31% / 26% / 17%), and the U.S. (4% / 24% / 27%). That all Arctic coastal states stand to gain access to

significant portions of previously inaccessible EEZ underscores the pervasive effect of climate change at the circumpolar scale even while absolute access varies widely within the region.

Of the three navigation routes examined here, the NSR is most robustly accessible throughout the 21st century under all forcing scenarios. By mid-century, PC3 and PC6 vessels may access the entire NSR nearly all summer, and OW vessels may navigate for over three months (Table 3.5). In contrast, the NWP and TPR remain less accessible, especially to weaker vessel types, until the latter half of the century. Note, however, that these findings are spatial averages, and that individual portions of routes may be significantly less accessible and/or more variable than the route average. In most cases, some portions are reliably accessible for a full summer (e.g., Beaufort Sea, Kara Sea) while other portions are accessible only briefly or not at all (e.g., Parry Channel, Laptev Sea). Nevertheless, these results suggest that the NSR remains the most viable option for Arctic navigation in the near term. By late-century, however, the TPR is projected to become viable for polar-classed vessels, suggesting that routing decisions may increasingly be made to maximize distance savings rather than ice avoidance in the long term. Even so, trans-Arctic navigation is likely to remain a summertime phenomenon, as illustrated by stark contrasts in navigation season length (Figure 3.6).

Despite our projections of widespread increases in technically accessible marine area, numerous challenges continue to constrain Arctic navigation. One key finding is that voyages in the near term are likely to be unreliable due to highly variable navigation seasons in much of the region (Figure 3.6). In general, this study finds high interannual variability for all vessel classes where average season length is intermediate, and low variability where average season length is high or low. This finding has important implications for trans-Arctic shipping in particular because most trans-Arctic routes pass through at least one zone of intermediate season length.

For example, early-century variability for PC3 vessels is highest in the high seas and central seas of the Russian EEZ that comprise critical portions of the TPR and NSR, respectively. Likewise, navigation seasons for PC6 and OW vessels are most variable in a zone encircling the central Arctic Ocean, encompassing much of the NSR and extending to the Beaufort and Greenland Seas. Thus, while the NSR may be accessible for limited periods at early-century, its access is unpredictable from year to year for all vessel classes. Ice forecasting and monitoring systems, such as satellite-borne synthetic aperture radar (SAR), may mitigate short-term unpredictability by providing daily to weekly estimates of ice concentration and type characteristics, though such techniques have yet to be implemented extensively throughout the Arctic (Johannessen et al., 2007; Sakov et al., 2012). The NWP is similarly variable along Parry Channel, though its average access is much lower than that of the NSR. The early-century projections of short seasons for all vessel classes in Parry Channel suggest that “choke points” and MYI invasions will continue to pose a hazard along the NWP in the near future (Howell et al., 2009). However, the coarse spatial resolution of CCSM4 (1°) limits the utility of sea ice projections in geographically complex regions such as the CAA; thus, results presented for the Canadian maritime Arctic are less reliable than those of other regions. While the TPR holds limited promise for PC3 vessels in summer at early-century, high variability from the Fram Strait to the pole illustrates the impracticality of the TPR for strategic planning in the near term.

It is important to note that because this study uses one simulation from one model, its results reflect only the scenario-based uncertainty between the RCPs. This study aims to quantify the uncertainty arising from external climate forcing in order to assess the impact of anthropogenic greenhouse gas emissions on marine access. An alternative analysis might also explore variability between models using a multi-model approach, as demonstrated by Khon et al.

(2010) who found significant differences among the CMIP3 models in their ability to represent ice season length in the NWP and NSR. As CCSM4 reaches its minimum downward trend in September sea ice extent somewhat later than the mean of CMIP5 models (Massonnet et al., 2012), access might be expected to increase somewhat faster if driven by an ensemble of models. Furthermore, these results may be conservative since ice extent is greater in CCSM4 than the CMIP5 29-model mean through most of the 21st century (Massonnet et al., 2012). Other approaches might investigate intra-model variability by comparing several simulations of the same model initialized from different historical conditions. While inter- and intra-model uncertainty remain important constraints on attempts to visualize plausible Arctic futures, forcing scenario-based uncertainty represents a compelling starting point from which to study human impacts on the Arctic environment owing to its strong policy relevance. Future studies might combine this emphasis on human impacts with the multi-model approach of Khon et. al to further refine projections of future Arctic marine access.

Several factors constrain the results of these projections and provide opportunities for further research. This study examined technical access in sea ice only and did not consider the effect of ice on ship speed, an important constraint on the cruising speed of all vessel classes. The coarse spatial resolution of CCSM4 (1°) limits the utility of sea ice projections at finer scales, particularly in geographically complex regions such as the CAA. Thus, results presented for the Canadian maritime Arctic and the NWP are less reliable than those of other regions and are intended to provide only a general picture of future marine access. Ice ridging and ice decay processes are not currently included in climate model simulations, yet are known significantly impact ship access. The circulation of the Arctic Ocean is another important consideration, as the location of thick ice is dependent on ice drift. It is unclear how well ice drift is modeled in many

climate models (Kwok, 2011), leading to uncertainty in the distribution of thick ice each summer. In addition, while this study explicitly examined the interannual variability of sea ice in CCSM4, the results provide only a broad picture of circumpolar variability as a component of multidecadal projections. High spatial and temporal-resolution ice forecasts and satellite data will be required for operational and tactical navigation in ice at regional and local scales. Finally, this study did not address the economic viability of navigation routes, which depend on numerous factors other than sea ice.

3.6 Conclusion

Based on CCSM4-projected trends in sea ice concentration and thickness, this study projects robust, widespread increases in Arctic marine access during summer (July-October) for a range of vessel classes. The two polar-classed vessels examined here (PC3 and PC6) gain technical access to up to 96% (PC3) and 91% (PC6) of the aggregate IMO Guidelines Boundary region in summer by the middle of this century, rising to 98% and 98%, respectively by late-century, under the highest radiative forcing scenario (8.5 W/m^2). Even for the lowest forcing scenario (4.5 W/m^2), we estimate 93% and 82% summer access by mid-century, and 95% and 90% by late-century, respectively. These circumpolar averages mask strong regional contrasts, in which these overall trends are manifested differently within the exclusive economic zones of Canada, Greenland/Denmark, Norway, Russia and the U.S.; the high seas; and the NWP, NSR, and TPR. In general, Russia, Greenland/Denmark, and Norway should experience the greatest increases in marine access, and Canada and the U.S. should experience the least owing to continued persistence of ice in the CAA and relatively high access in the U.S. EEZ today. Furthermore, these results are very likely conservative, owing to overestimation of sea ice extent in CCSM4 relative to other CMIP5 models (Massonnet et al., 2012). However, it is important to

realize that in the near term, access will be mainly confined to summer months only. The Arctic marine environment is likely to be fully or partially ice-covered 6-8 months each year for the first half of the century, and no climate model projects an ice-free Arctic in winter by 2100 (ACIA, 2004a; Stroeve et al., 2012a).

This study represents a first attempt to project future access to the Arctic marine environment for a spectrum of vessel classes and climate change scenarios. For the near future, polar classed ships will remain more important for Arctic operations than open-water ships. Ongoing projections should assist national governments, regulatory and environmental agencies, and the global maritime industry in strategic planning efforts to better understand the range of plausible futures for Arctic marine operations. Furthermore, this work illustrates the usefulness of merging climate model simulations with future Arctic marine regulatory frameworks (i.e. Polar Class vessels as defined by the IMO) to enhance the policy relevance of climate science. While marine access is projected to increase for all climate scenarios, a wide range of futures is possible, and technology (i.e. vessel class) figures importantly – often more importantly – than climatic forcing scenario alone. Therefore, a central conclusion is that Arctic marine access depends strongly upon capital investment and infrastructure in addition to geophysical considerations of sea ice. In this sense, it is a unifying, interdisciplinary concept determined by both the physical environment and human socioeconomic systems.

3.7 Figures



Figure 3.1: Selected navigation routes used in this analysis (NWP, NSR, TPR), international high seas, and marine EEZs (dashed lines) of Canada, Greenland, Norway, Russia, and the U.S. within the IMO Arctic Ship Guidelines Boundary (thick black border).

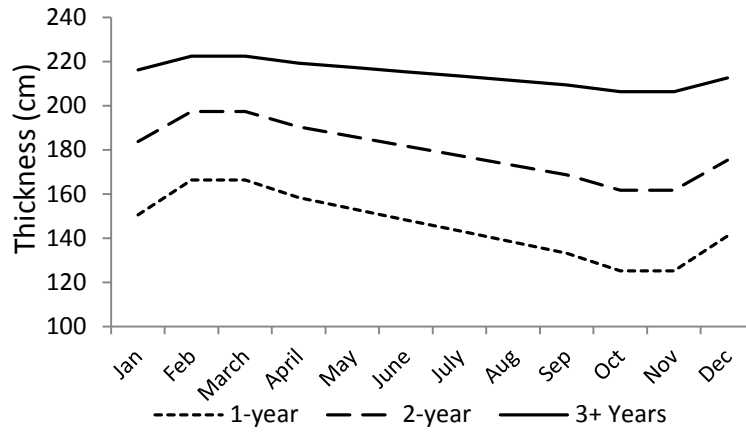
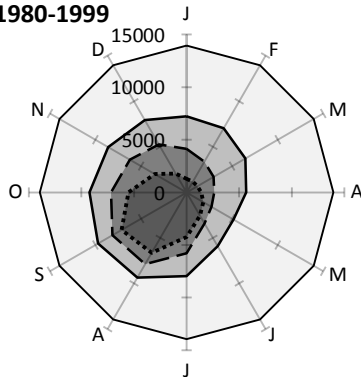


Figure 3.2: Seasonal change in ice thickness by age class, derived from observed ice thickness (Kwok et al., 2007) and age (Maslanik et al., 2007) for February-March (2004-2008) and October-November (2003-2007). Thickness values for April-September and December-January were interpolated linearly from February-March maxima and October-November minima.

Figure 3.3: Total ship-accessible marine area in the aggregate IMO Arctic Ship Guidelines Boundary region (1000 km²) as driven by climate forcing scenario (RCP 4.5, 6.0, 8.5), time-averaging window (2011-2030, 2046-2065, 2080-2099), and vessel class (PC3, PC6, OW). Outer circles signify 100% year-round access. For reference, baseline late-20th-century historical values (1980-1999) are also shown.

20th-century baseline

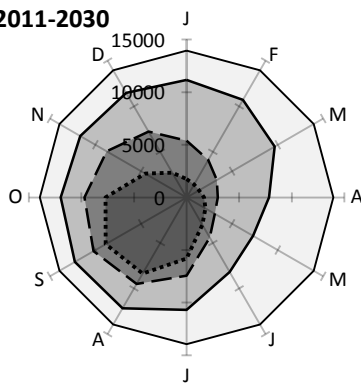
1980-1999



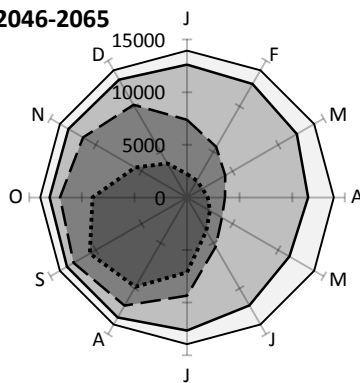
RCP 4.5

□ 100% ■ PC3 ■ PC6 〰 OW

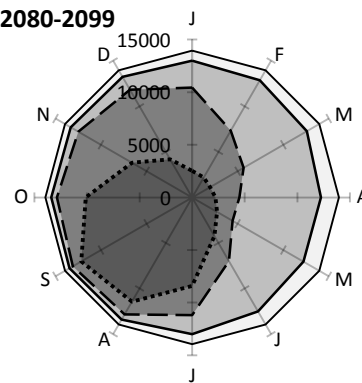
2011-2030



2046-2065



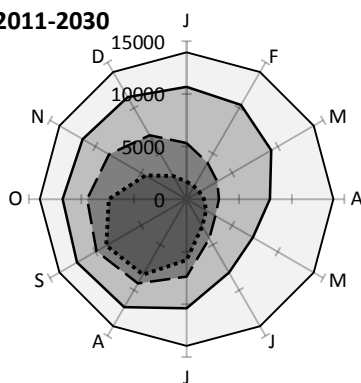
2080-2099



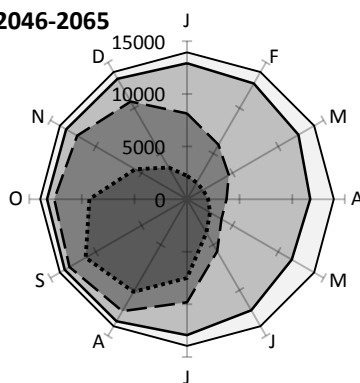
RCP 6.0

□ 100% ■ PC3 ■ PC6 〰 OW

2011-2030



2046-2065



2080-2099

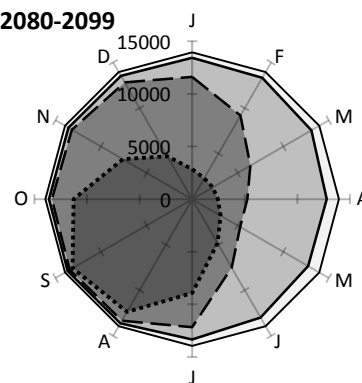
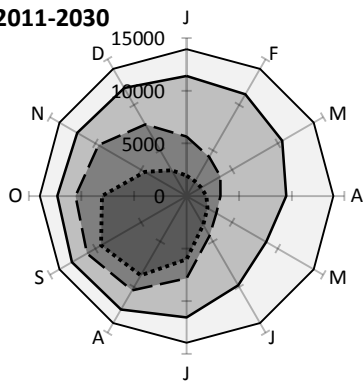


Figure 3.3, continued

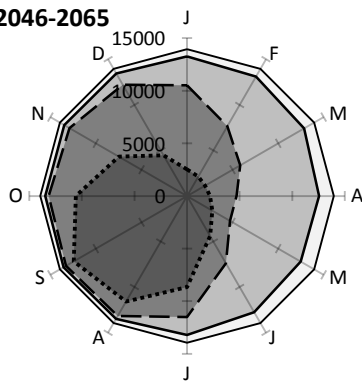
RCP 8.5

□ 100% ■ PC3 ■ PC6 ▤ OW

2011-2030



2046-2065



2080-2099

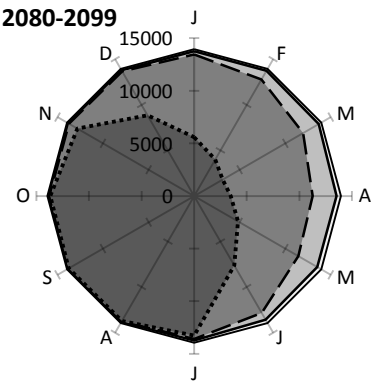


Figure 3.4: Monthly changes in total ship-accessible area (1000 km², left vertical axis and % total, right vertical axis) by vessel class and climate forcing scenario, from early-century to mid-century (“Early”) and mid-century to late-century (“Late”). PC3 vessels gain the most access in the first half of the century while PC6 and OW vessels gain substantial access in the latter half of the century.

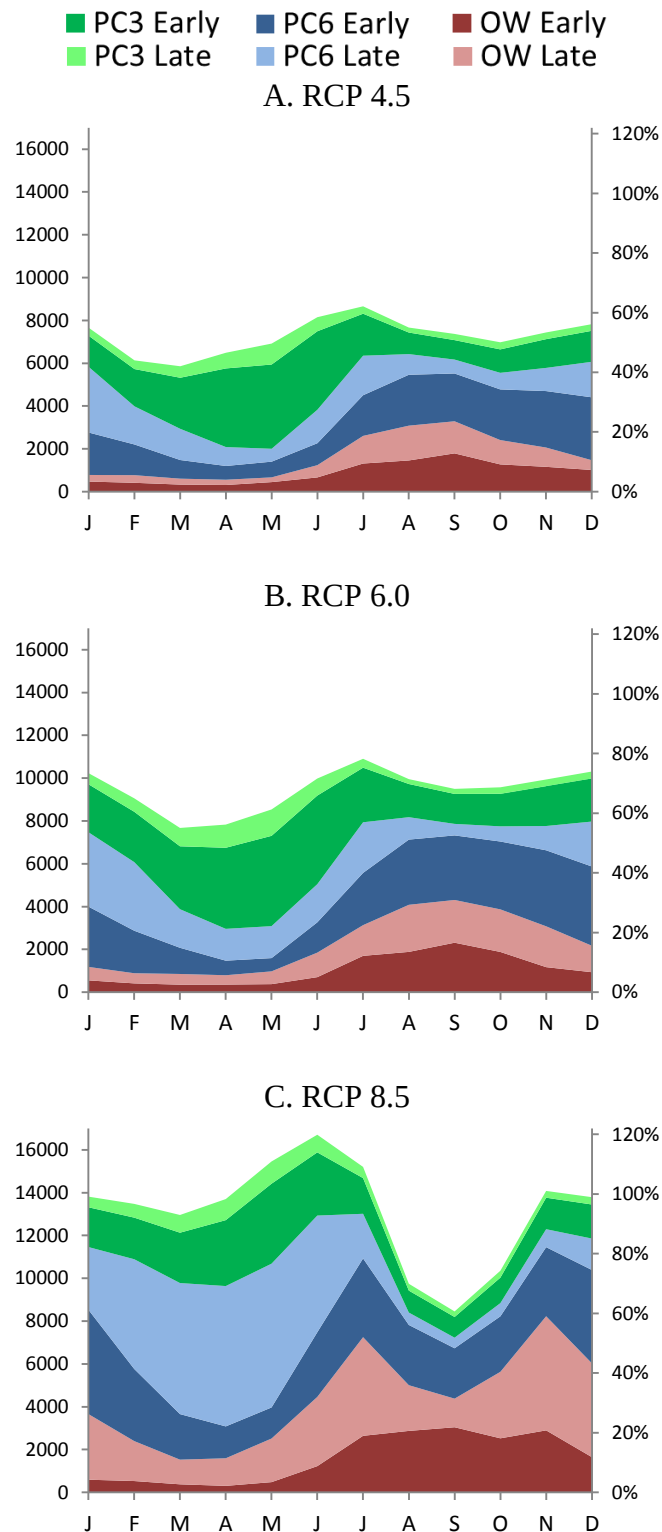
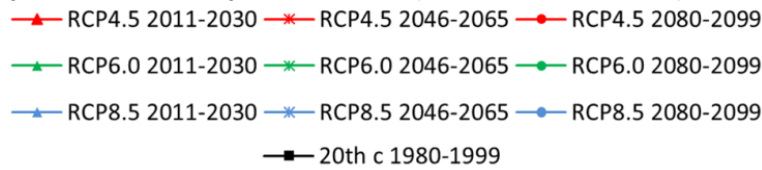
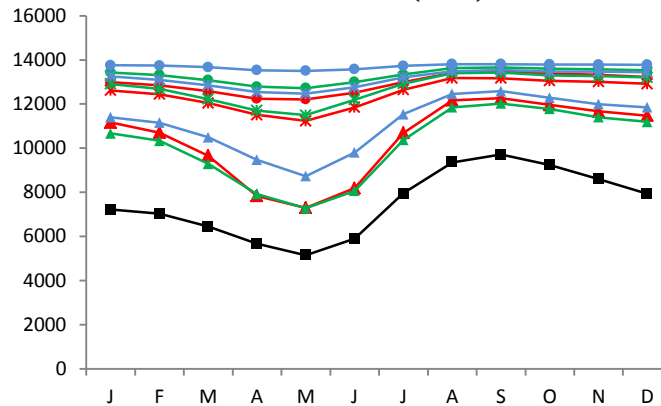


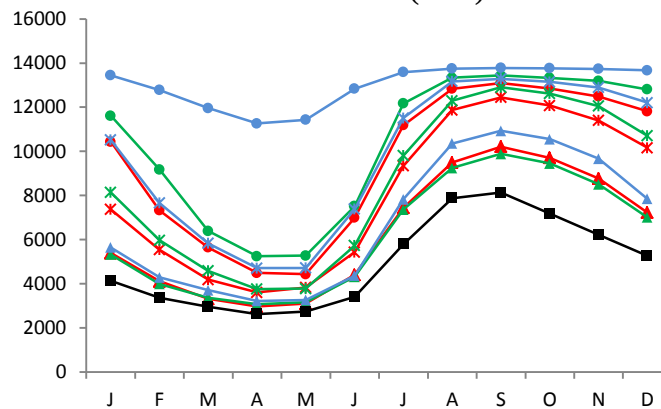
Figure 3.5: Monthly variations in total ship-accessible marine area (1000 km²) as a function of vessel class and climate forcing scenario. Red/green/blue lines indicate RCP 4.5/RCP 6.0/RCP 8.5 forcing scenarios, respectively. Triangle/star/circle symbols indicate early-century/mid-century/late-century time windows, respectively. Late-20th-century baseline data (1980-1999; black line) shown for reference.



A. Polar Class 3 (PC3)



B. Polar Class 6 (PC6)



C. Open-Water (OW)

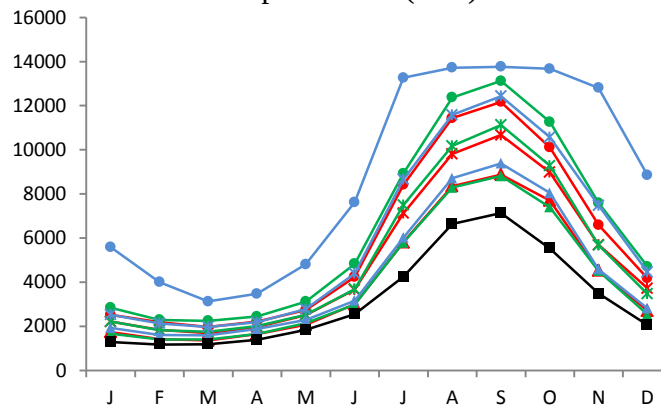


Figure 3.6: Number of ship-accessible days in summer (July-October, left) and winter (December-March, second page) for PC3, PC6, and OW vessels (red: average; blue: standard deviation) at early-century (2011-2030) under medium forcing (RCP 6.0).

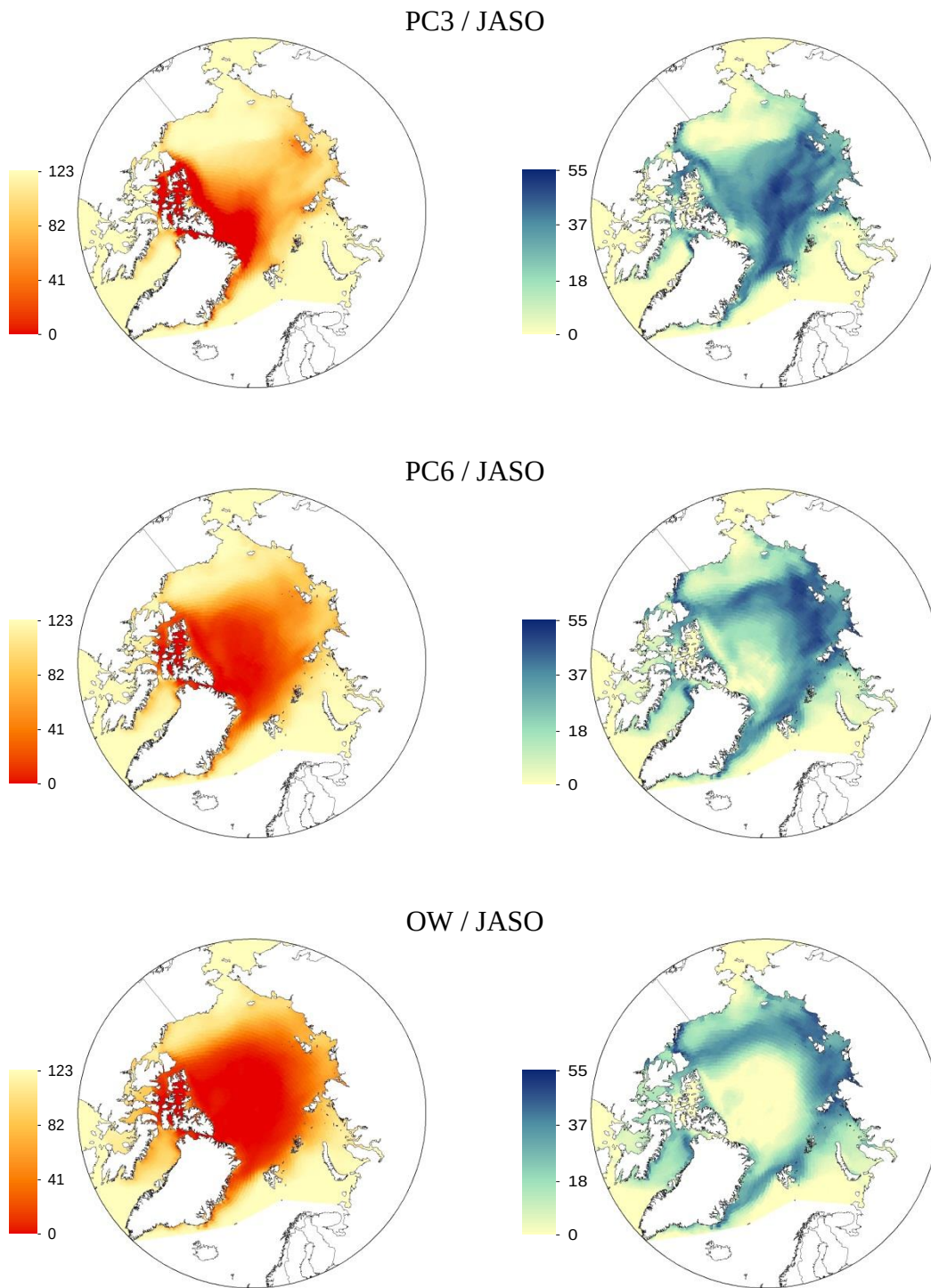


Figure 3.6, continued

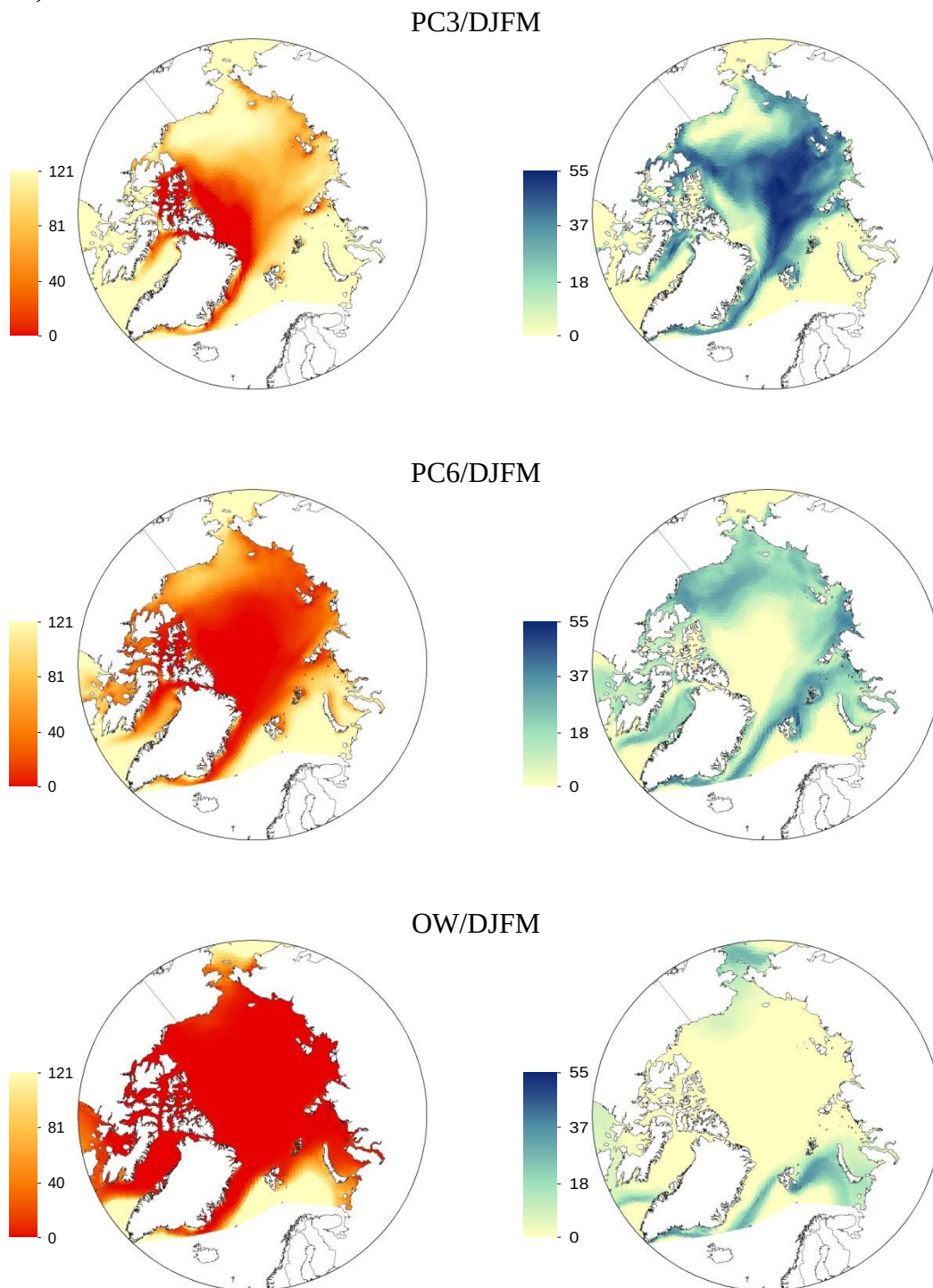
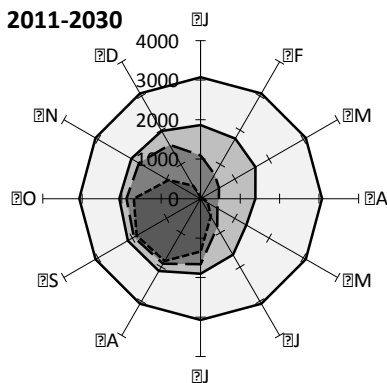


Figure 3.7: Total ship-accessible marine area in the Canadian maritime Arctic (1000 km²) as driven by climate forcing scenario (RCP 4.5, 6.0, 8.5), time-averaging window (2011-2030, 2046-2065, 2080-2099), and vessel class (PC3, PC6, OW). Outer circles signify 100% year-round access.

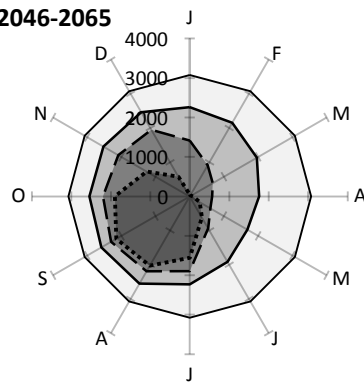
RCP 4.5

□ 100% ■ PC3 ■ PC6 ■ OW

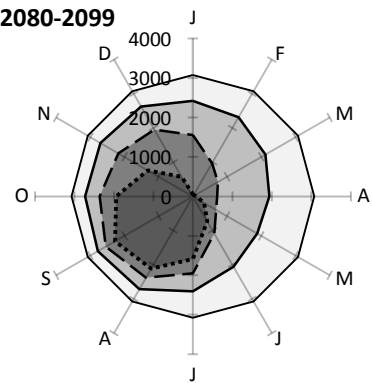
2011-2030



2046-2065



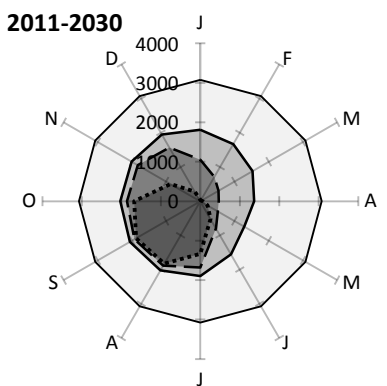
2080-2099



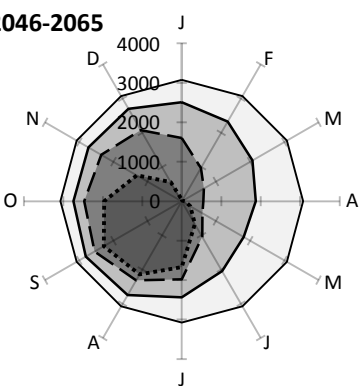
RCP 6.0

□ 100% ■ PC3 ■ PC6 ■ OW

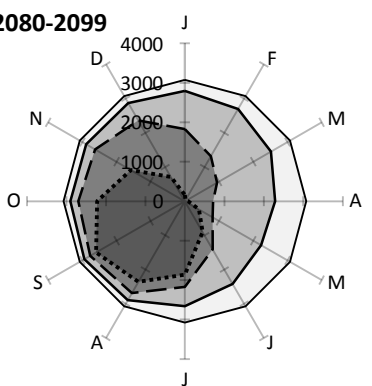
2011-2030



2046-2065



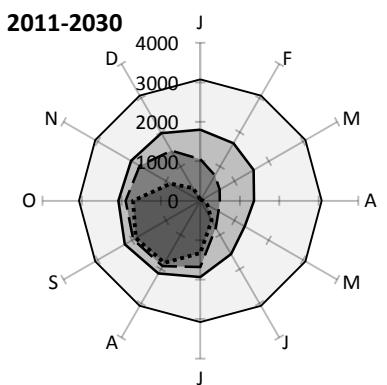
2080-2099



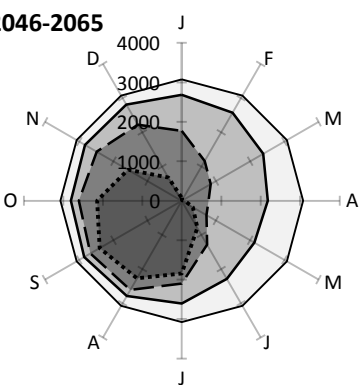
RCP 8.5

□ 100% ■ PC3 ■ PC6 ■ OW

2011-2030



2046-2065



2080-2099

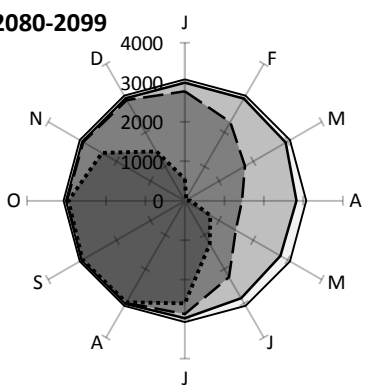
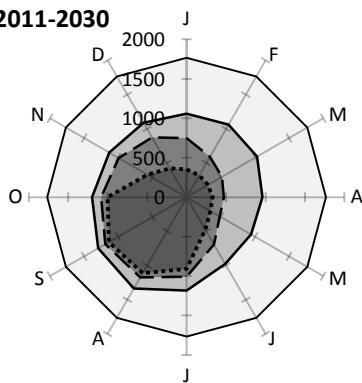


Figure 3.8: Total ship-accessible marine area in the Greenlandic coastal seas (1000 km²) as driven by climate forcing scenario (RCP 4.5, 6.0, 8.5), time-averaging window (2011-2030, 2046-2065, 2080-2099), and vessel class (PC3, PC6, OW). Outer circles signify 100% year-round access.

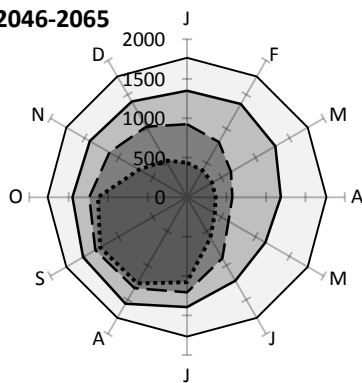
RCP 4.5

□ 100% ■ PC3 ■ PC6 ■ OW

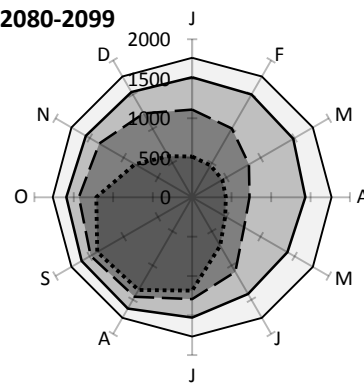
2011-2030



2046-2065



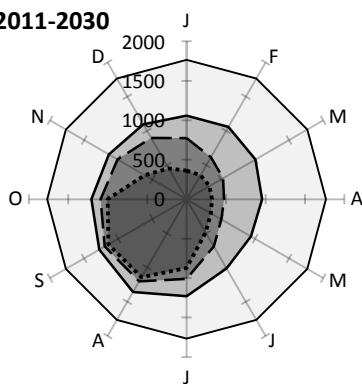
2080-2099



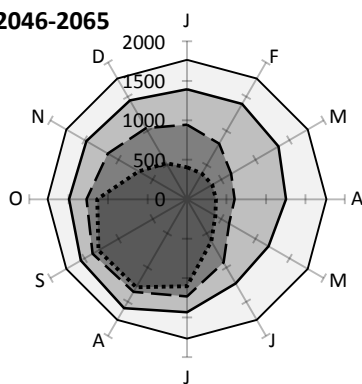
RCP 6.0

□ 100% ■ PC3 ■ PC6 ■ OW

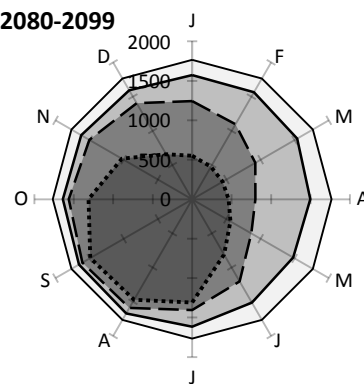
2011-2030



2046-2065



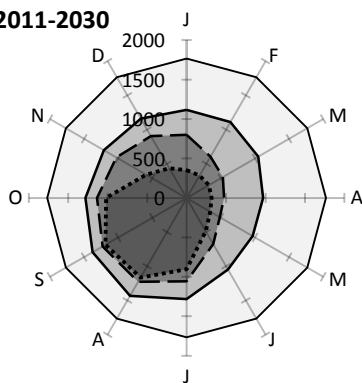
2080-2099



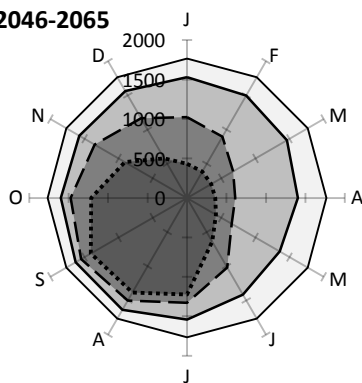
RCP 8.5

□ 100% ■ PC3 ■ PC6 ■ OW

2011-2030



2046-2065



2080-2099

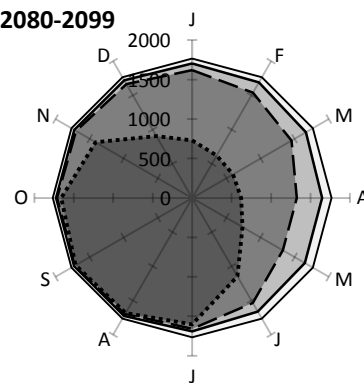
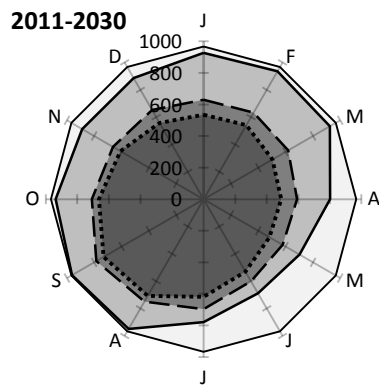
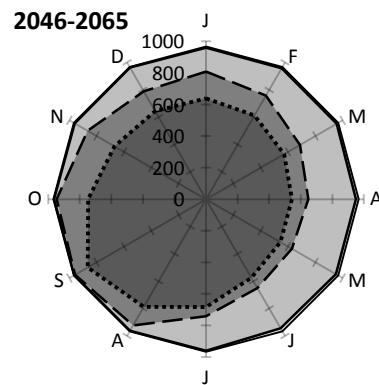
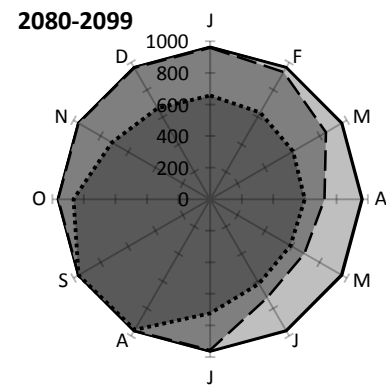


Figure 3.9: Total ship-accessible marine area in Norway's Arctic EEZ (Svalbard and Jan Mayen) (1000 km²) as driven by climate forcing scenario (RCP 4.5, 6.0, 8.5), time-averaging window (2011-2030, 2046-2065, 2080-2099), and vessel class (PC3, PC6, OW). Outer circles signify 100% year-round access.

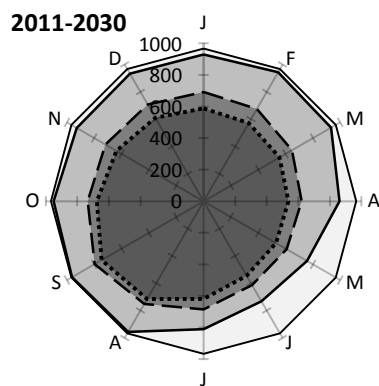
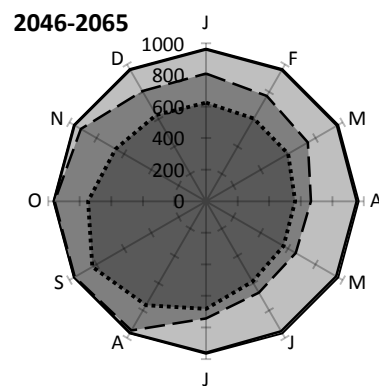
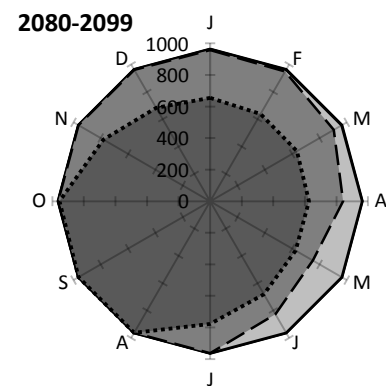
RCP 4.5

□ 100% ■ PC3 ■ PC6 ■ OW



RCP 6.0

□ 100% ■ PC3 ■ PC6 ■ OW



RCP 8.5

□ 100% ■ PC3 ■ PC6 ■ OW

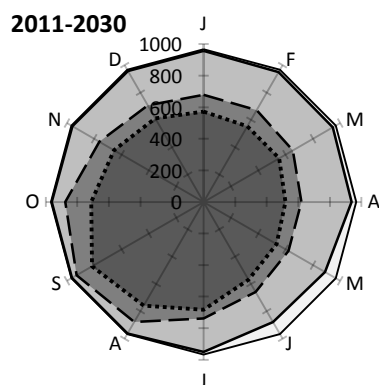
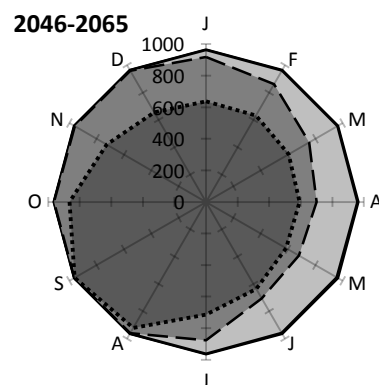
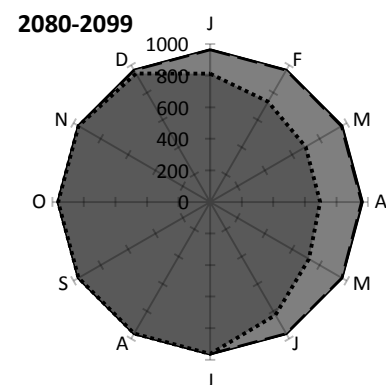
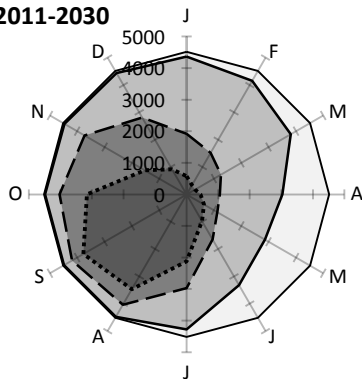


Figure 3.10: Total ship-accessible marine area in the Russian maritime Arctic (1000 km²) as driven by climate forcing scenario (RCP 4.5, 6.0, 8.5), time-averaging window (2011-2030, 2046-2065, 2080-2099), and vessel class (PC3, PC6, OW). Outer circles signify 100% year-round access.

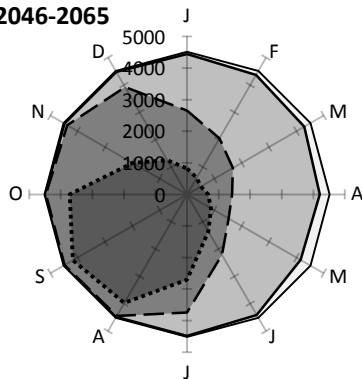
RCP 4.5

□ 100% ■ PC3 ■ PC6 ■ OW

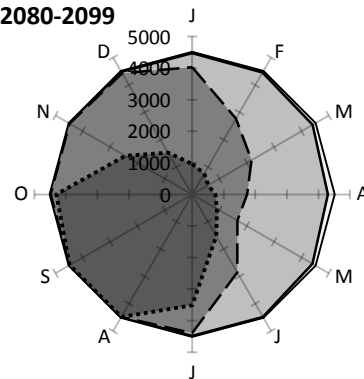
2011-2030



2046-2065



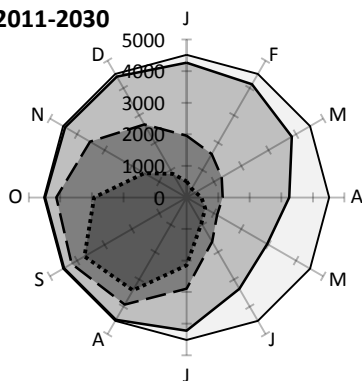
2080-2099



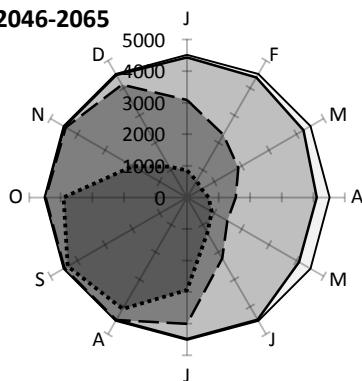
RCP 6.0

□ 100% ■ PC3 ■ PC6 ■ OW

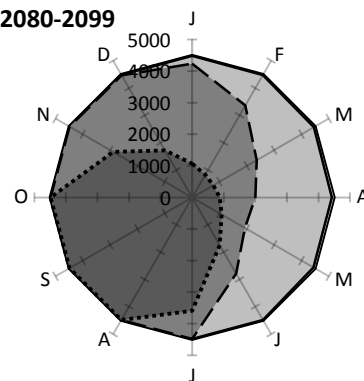
2011-2030



2046-2065



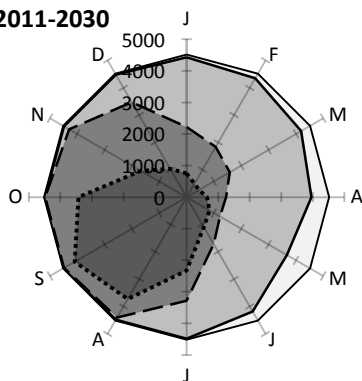
2080-2099



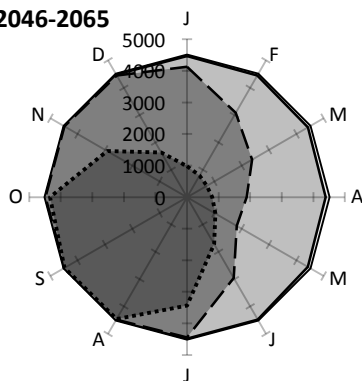
RCP 8.5

□ 100% ■ PC3 ■ PC6 ■ OW

2011-2030



2046-2065



2080-2099

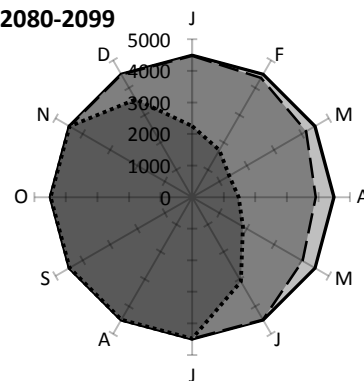
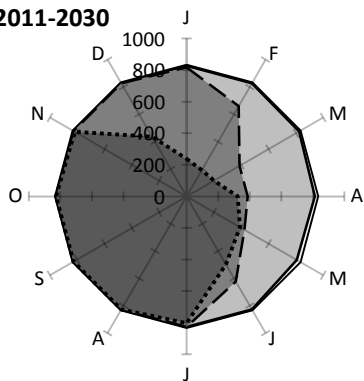


Figure 3.11: Total ship-accessible marine area in the U.S. maritime Arctic (1000 km²) as driven by climate forcing scenario (RCP 4.5, 6.0, 8.5), time-averaging window (2011-2030, 2046-2065, 2080-2099), and vessel class (PC3, PC6, OW). Outer circles signify 100% year-round access.

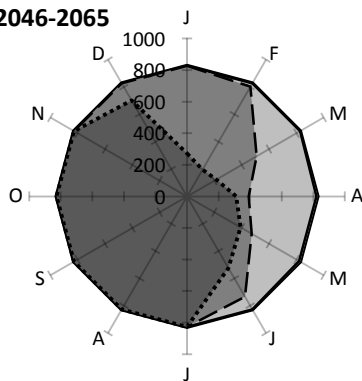
RCP 4.5

□ 100% ■ PC3 ■ PC6 ■ OW

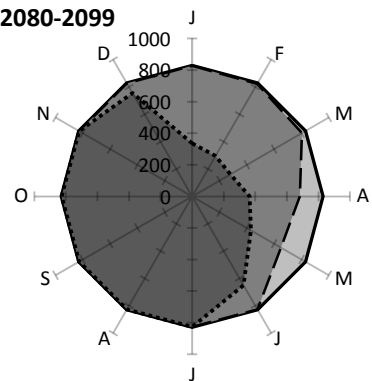
2011-2030



2046-2065



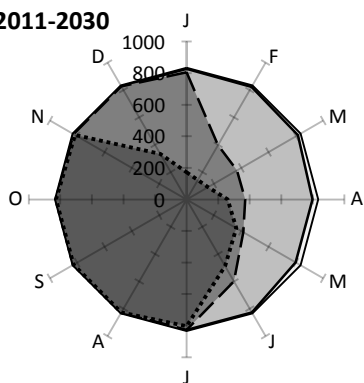
2080-2099



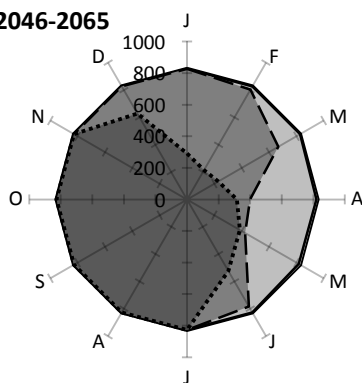
RCP 6.0

□ 100% ■ PC3 ■ PC6 ■ OW

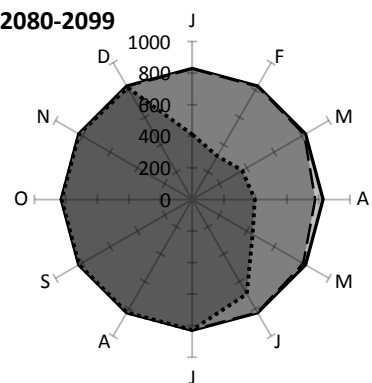
2011-2030



2046-2065



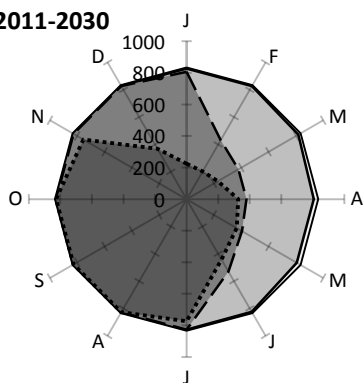
2080-2099



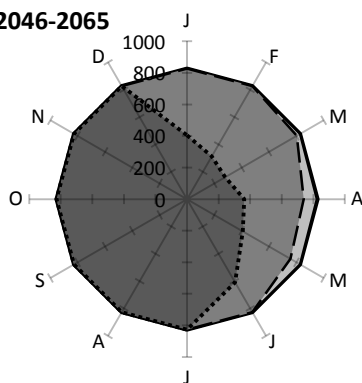
RCP 8.5

□ 100% ■ PC3 ■ PC6 ■ OW

2011-2030



2046-2065



2080-2099

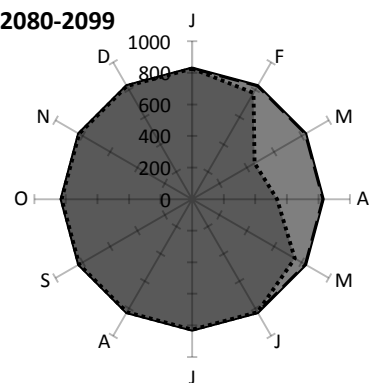
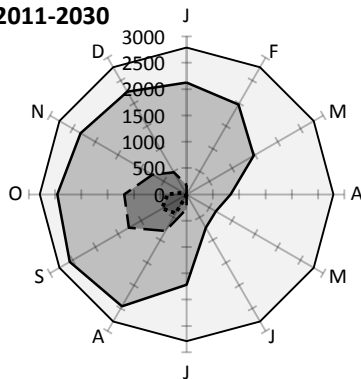


Figure 3.12: Total ship-accessible marine area in the international high seas (1000 km²) as driven by climate forcing scenario (RCP 4.5, 6.0, 8.5), time-averaging window (2011-2030, 2046-2065, 2080-2099), and vessel class (PC3, PC6, OW). Outer circles signify 100% year-round access.

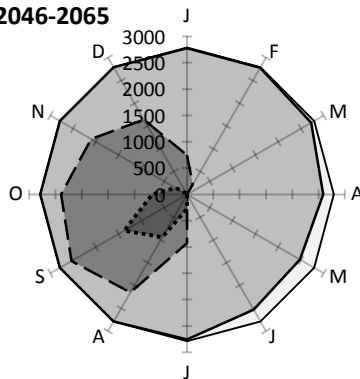
RCP 4.5

□ 100% ■ PC3 ■ PC6 ■ OW

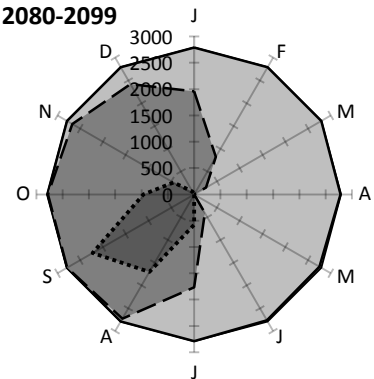
2011-2030



2046-2065



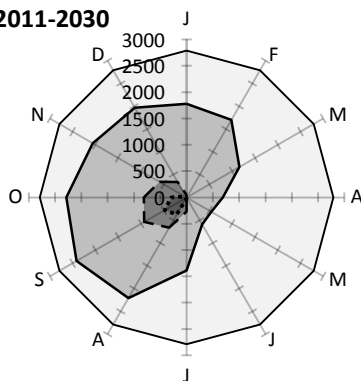
2080-2099



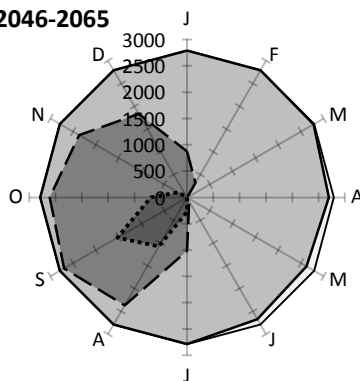
RCP 6.0

□ 100% ■ PC3 ■ PC6 ■ OW

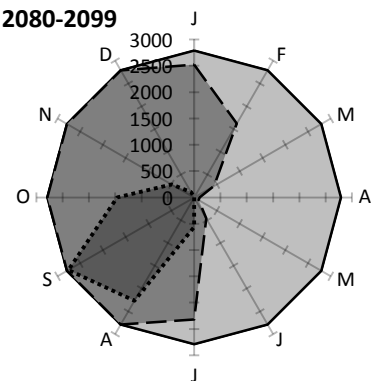
2011-2030



2046-2065



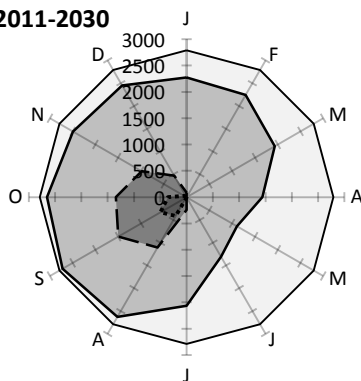
2080-2099



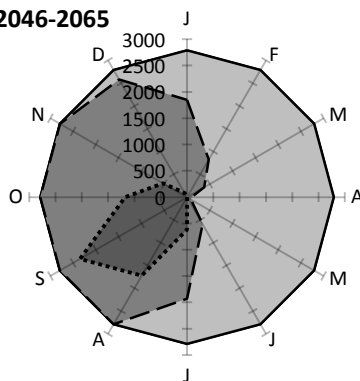
RCP 8.5

□ 100% ■ PC3 ■ PC6 ■ OW

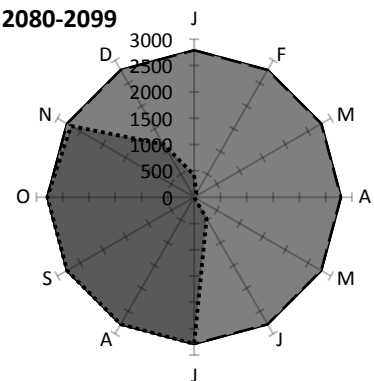
2011-2030



2046-2065



2080-2099



3.8 Tables

Table 3.1: Median ice thickness (cm) per age class. February-March (2004-2008) and October-November (2003-2007) ICESat ice thickness grids (Kwok et al., 2007) were combined with 12.5-km² ice age grids (Maslanik et al., 2007) to obtain the median of thickness values spatially coincident with a given age class.

Year	First-year ice		Second-year ice		Third-year ice	
	Feb/Mar*	Oct/Nov	Feb/Mar	Oct/Nov	Feb/Mar	Oct/Nov
2003	n/a	127.6	n/a	183.5	n/a	225.5
2004	157.0	117.5	206.1	180.0	271.7	254.3
2005	169.1	118.0	215.4	139.6	244.9	204.7
2006	163.6	126.4	178.7	131.6	209.9	164.4
2007	181.9	136.6	187.1	174.1	198.3	183.1
2008	159.7	n/a	199.2	n/a	187.2	n/a
5-year mean	166.3	125.2	197.3	161.8	222.4	206.4

*February-March figures calculated by Maslanik (2007)

Table 3.2: Intra-annual second-year and multi-year minimum ice thickness (cm) derived from linearly interpolated mean thickness (Figure 3.2). Minimum thickness was defined as the middle value between the mean thickness values of adjacent age classes.

Month	Second-year	Multi-year
Jan	167	200
Feb	182	210
March	182	210
April	174	205
May	170	202
June	165	199
July	160	195
Aug	156	192
Sep	151	189
Oct	143	184
Nov	143	184
Dec	158	194

Table 3.3: Ice Multipliers for selected vessel classes

Ice Type	PC3	PC6	OW
Open water	2	2	2
Gray	2	2	1
Gray-white	2	2	-1
Thin first-year, first stage	2	2	-1
Thin first-year, second stage	2	2	-1
Medium first-year	2	1	-2
Thick first-year	2	-1	-3
Second-year	1	-3	-4
Multi-year	-1	-4	-4

Adapted from Transport Canada (1998)

Table 3.4: Average annual, summer (JASO) and winter (DJFM) ship-accessible area within the IMO Guidelines Boundary (1000 km² and % of total) accessible to PC3, PC6, and OW vessels by early- (2011-2030), mid- (2046-2065), and late- (2080-2099) 21st century under medium-low (RCP 4.5), medium (RCP 6.0), and high (RCP 8.5) climate forcing. Historical late 20th century values (1980-1999) are also shown.

Polar Class 3												
	1980-1999			2011-2030			2046-2065			2080-2099		
	Annual	JASO	DJFM	Annual	JASO	DJFM	Annual	JASO	DJFM	Annual	JASO	DJFM
20th c.	7518 (54%)	9064 (65%)	7161 (51%)	-	-	-	-	-	-	-	-	-
RCP 4.5	-	-	-	10422 (75%)	11770 (84%)	10750 (77%)	12474 (89%)	13014 (93%)	12508 (90%)	12933 (93%)	13313 (95%)	12915 (93%)
RCP 6.0	-	-	-	10181 (72%)	11508 (82%)	10371 (74%)	12729 (91%)	13264 (94%)	12758 (91%)	13306 (95%)	13558 (97%)	13340 (95%)
RCP 8.5	-	-	-	11148 (79%)	12217 (87%)	11225 (80%)	13134 (94%)	13429 (96%)	13161 (94%)	13708 (98%)	13784 (98%)	13738 (98%)
Polar Class 6												
	1980-1999			2011-2030			2046-2065			2080-2099		
	Annual	JASO	DJFM	Annual	JASO	DJFM	Annual	JASO	DJFM	Annual	JASO	DJFM
20th c.	4974 (36%)	7245 (52%)	3929 (28%)	-	-	-	-	-	-	-	-	-
RCP 4.5	-	-	-	6344 (45%)	9213 (66%)	5009 (36%)	8105 (58%)	11432 (82%)	6815 (49%)	9466 (68%)	12492 (90%)	8805 (63%)
RCP 6.0	-	-	-	6224 (44%)	8987 (64%)	4921 (35%)	8529 (61%)	11905 (85%)	7352 (52%)	10290 (73%)	13069 (93%)	9997 (71%)
RCP 8.5	-	-	-	6806 (48%)	9918 (71%)	5371 (38%)	9752 (69%)	12777 (91%)	9053 (64%)	13000 (93%)	13721 (98%)	12964 (92%)
Open-Water												
	1980-1999			2011-2030			2046-2065			2080-2099		
	Annual	JASO	DJFM	Annual	JASO	DJFM	Annual	JASO	DJFM	Annual	JASO	DJFM
20th c.	3208 (23%)	5884 (42%)	1425 (10%)	-	-	-	-	-	-	-	-	-
RCP 4.5	-	-	-	4103 (29%)	7688 (55%)	1808 (13%)	4989 (36%)	9145 (66%)	2364 (17%)	5731 (41%)	10534 (76%)	2714 (19%)
RCP 6.0	-	-	-	4047 (29%)	7573 (54%)	1749 (12%)	5102 (36%)	9518 (68%)	2314 (16%)	6313 (45%)	11422 (81%)	3023 (22%)
RCP 8.5	-	-	-	4336 (31%)	8039 (57%)	1987 (14%)	5931 (42%)	10810 (77%)	2774 (20%)	8726 (62%)	13606 (97%)	5391 (38%)

Table 3.5: Spatial averages of early- (2011-2030), mid- (2046-2065) and late-century (2080-2099) days accessible (average and standard deviation [italics] of navigation season length) in summer (July-October) to PC3/PC6/OW vessels along selected navigation routes, under RCP 4.5/RCP 6.0/RCP 8.5 climate forcing.

	Northwest Passage (NWP)						Northern Sea Route (NSR)						Trans-Polar Route (TPR)					
	PC3		PC6		OW		PC3		PC6		OW		PC3		PC6		OW	
RCP 4.5																		
2011-2030	89	19	79	19	69	19	111	18	98	26	81	27	91	21	59	16	39	11
2045-2065	109	13	96	18	83	18	120	6	113	13	101	21	121	4	88	21	48	13
2080-2099	104	17	94	18	84	17	121	4	117	9	109	15	122	2	106	13	63	18
RCP 6.0																		
2011-2030	86	15	76	16	67	15	110	18	99	24	85	26	85	24	49	14	36	8
2045-2065	96	16	85	17	74	15	117	11	108	19	97	23	109	17	74	28	44	13
2080-2099	116	10	107	15	95	16	122	3	120	6	115	10	123	1	113	10	73	19
RCP 8.5																		
2011-2030	84	16	75	15	66	13	118	11	109	20	97	26	99	23	62	20	40	9
2045-2065	121	4	115	8	105	12	122	3	119	8	112	13	123	1	108	11	70	18
2080-2099	122	1	120	4	116	6	123	1	122	1	121	3	123	0	123	0	114	6

4. Marine Accessibility Along Russia's Northern Sea Route

A version of: Stephenson, S.R., Brigham, L.W., Smith, L.C. (2013). Marine accessibility along Russia's Northern Sea Route. Polar Geography, 37: 111-133.

4.1 Abstract

Recent Arctic sea ice retreat indicates that the Russian coastal seas encompassing the Northern Sea Route (NSR) will be among the first marine environments to transition to a summer ice-free state. 46 voyages carrying 1.26 million tons of cargo in 2012 suggest increasing economic viability of the NSR for eastward transport of natural resources from northern Norway and Russia. However, considerable uncertainty remains about the near-term length and variability of the navigation season, and shelf bathymetry presents a critical constraint limiting vessel draft and cargo capacity. This paper aims to quantify the length and variability of the NSR navigation season as constrained by both sea ice and bathymetry over the next 15 years. We present simulations of accessibility to the Russian maritime Arctic by Polar Class and non-ice strengthened vessels, as based on CCSM4 daily projections of sea ice concentration and thickness averaged for 2013-2027. Results indicate strong navigation uncertainties in the Kara, Laptev, and East Siberian Seas, while destination shipping to the Barents and Chukchi Seas will be relatively unencumbered by ice. Shallow-draft ships may be required for maximum utilization of the navigation season for full NSR transits. This study can be viewed as support to strategic planning in identifying key navigational challenges and opportunities along the NSR.

4.2 Introduction

The Northern Sea Route (NSR) has recently undergone an evolution in economic function and popular conception. After decades of use primarily as a Russian national

transport artery servicing local settlements and the domestic resource industry, the NSR is now being recast as an international seaway for export of Arctic petroleum and mineral resources to world markets and a potential alternative pathway for global trade. Following its official opening to the international community in 1991, the NSR failed to attract significant attention as a transport corridor due to its challenging physical environment, marginal economic potential, and uncertain political climate (Brubaker and Ragner, 2010). However, recent dramatic sea ice reductions have ignited vigorous discussion over the technical and economic viability of the route (Smith, 2010; The Economist, 2012b). While some researchers and political figures have proclaimed the arrival of a new global trade space (Borgerson, 2008; Bryanski, 2011), other analyses have noted significant constraints to future Arctic trade routes (Arctic Council, 2009; Brigham, 2010; Carmel, 2013). Recent media coverage also provides a more realistic view of the NSR as a seasonal complement, rather than a rival, to the Suez Canal (The Moscow Times, 2013).

A review of the NSR during the Soviet era helps to place this resurgence in proper context. The modern development of NSR operations during the 1950s to the end of the USSR represents a remarkable achievement, and huge capital investment, of the Soviet Union (Brigham, 1991). Then, as today, the primary reason to build an Arctic marine transportation system was to support development of Siberia's vast natural resources. The peak of annual traffic on the NSR was reached in 1987 with 6,579 million tons of cargo carried by 331 ships on an extraordinary number of 1306 voyages (Brigham and Ellis, 2004). A large fleet of nuclear and diesel-electric powered icebreakers escorted icebreaking carriers in convoy. Year-round navigation to the port of Dudinka on the Yenisey River was achieved during the 1978-79 navigation season; this allowed uninterrupted service to the industrial complex at Norilsk and carriage of ore to smelters on the Kola Peninsula. Most

of the voyages were internal to the Soviet Arctic but some icebreaking carriers did venture into the Pacific; for example, sailing to western Canada to bring grain cargoes back to the USSR along the NSR during the summer navigation season. Convoys escorted by icebreakers remain a primary mode of operation for the length of the NSR. The primary focus today in summer is on the carriage of natural resources from the Russian Arctic to markets in Asia, principally China.

The decline in Arctic ice extent and volume has been well documented (Comiso et al., 2008; Stroeve et al., 2012b). September sea ice extent has decreased 13% per decade since satellite observations began in 1979 (NSIDC, 2012b), while ice volume has decreased 36% in autumn and 9% in winter in the last decade (Laxon et al., 2013). Record lows in September ice extent in 2007 and 2012 signal a transition from an Arctic Ocean dominated by thick perennial multi-year ice (MYI) toward thinner, seasonal first-year ice (FYI) (Maslanik et al., 2011; Comiso, 2012; Polyakov et al., 2012). This ice is likely to remain seasonal, as thinner ice delays freeze-up by allowing increased penetration of solar radiation to the ocean in summer (Hudson et al., 2013), and is more vulnerable to storm fracturing, accelerating melt by exposing greater ice surface area to warm seas (Parkinson and Comiso, 2013). General circulation models project robust continued decline toward an eventual ice-free state in summer with the disappearance of MYI, though with significant timing differences ranging from 10 to 80 years (Boe et al., 2009; Wang and Overland, 2009; Overland and Wang, 2013).

These trends, coupled with growing interest in Arctic shipping and resource exploitation, have incited numerous feasibility studies of shipping along the NSR (ACIA, 2004b; Verny and Grigentin, 2009; Det Norske Veritas, 2010; Khon et al., 2010; Liu and Kronbak, 2010; Schøyen and Bråthen, 2011; Stephenson et al., 2011; Arbo et al., 2012;

Smith and Stephenson, 2013; Stephenson et al., 2013b). Such studies often aim to determine the conditions under which various types of shipping along the NSR will be technically and/or economically viable. Today, shipping throughout the Arctic consists mainly of oil and liquefied natural gas (LNG) tankers, bulk carriers, fishing vessels, cruise ships, and smaller cargo vessels mostly operating in summer; container shipping is regional and usually for summer supply. Icebreaking cargo carriers and polar icebreakers continue year-round operations where sea ice regimes permit (Brigham and Ellis, 2004; Arctic Council, 2009). In the Russian Arctic, vessel shuttle systems operate year-round from both Dudinka (nickel) and the Varandey offshore terminal (oil) to Murmansk. In contrast, trans-Arctic voyages in summer treat the NSR as a seaway linking northern Norway and northwest Russia with Pacific ports, or enabling shorter, seasonal connections between global trade hubs in Europe and Asia. These voyages comprise a relatively small percentage of NSR traffic today, though the technical feasibility of such voyages is likely to increase substantially in the coming decades (Smith and Stephenson, 2013). 46 transit voyages transporting 1.26 million tons of cargo occurred in 2012, up from 34 in 2011 and 4 in 2010 (Pettersen, 2012). At the end of August 2013, nearly 500 vessels had obtained permission to sail the route, though only 20 had completed the transit (NSR Information Office, 2013).

These vessel transits, while miniscule in number compared to those through the Suez or Panama Canals, demonstrate a growing focus on connections to global commodities markets, particularly to East Asia (Blunden, 2012; Hong, 2012). Several key voyages illustrate these connections (Brigham, 2013): a Suezmax-class supertanker (*Vladimir Tkhnov*) carrying 120,000 tons of gas condensate from Murmansk to Bangkok in August 2011; a bulk carrier (*Sanko Odyssey*) transporting 66,000 tons of iron ore from

Murmansk to Beilun, China in September 2011; and an ice-classed tanker (*Ob River*) carrying over 66,000 tons of LNG from Hammerfest, Norway to Tobata, Japan in November 2012, the first-ever shipment of LNG. This latter voyage was also notable for occurring relatively late in autumn, facilitated by a record minimum ice extent. Of the 15 largest cargo-carrying (non-ballast) full transits of the NSR in 2012, 14 carried petroleum or mineral cargoes to or from east Asian ports, all of which exceeded 60,000 dwt (Table 4.1).

All shipping in the NSR is constrained to some degree today by sea ice and bathymetry. Three distinct climatic regions encompass the Russian Arctic coastal seas, leading to an uneven distribution of ice along the NSR. In the west, the Barents and western Kara Seas are characterized by marine climatic conditions owing to relatively warm current from the Atlantic Ocean (Brigham et al., 1999). This has facilitated continuous year-round transport of nickel from Dudinka to Murmansk since 1979 (Arctic Council, 2009; Humphreys, 2011). The southern Kara Sea also receives significant runoff from the Yenisey and Ob rivers, which can hasten ice disappearance by over two weeks near river mouths (Frey et al., 2003). The Chukchi Sea at the eastern terminus of the NSR has a similar marine climate influenced by north Pacific current through the Bering Strait. In contrast, the climate of the “interior” region encompassing the eastern Kara, Laptev, and East Siberian Seas is much colder, dominated by continental air masses and the adjacent Arctic Ocean. While the Kara Sea is often sheltered from heavy ice to the north by the Novaya Zemlya and Franz Josef Land archipelagos, the interior seas experience significant ice transport from the central Arctic Ocean, including some MYI floes (Brigham et al., 1999; Brubaker and Ragner, 2010). Historically, the navigation season has been limited to

approximately July through October in every region east of the port of Dikson, and the East Siberian Sea has rarely been more than 50% ice-free in a typical year (Ivanov et al., 1998).

Bathymetry represents a second key constraint on navigation in specific areas of the NSR. The continental shelves of the Russian Arctic are unusually broad and shallow, creating draft limitations that restrict NSR route choice. The Dmitry Laptev and Sannikov Straits in the New Siberian Islands (Figure 4.1) are especially shallow (6.7 m and 13 m, respectively), preventing transit by medium and larger cargo ships, and all of Russia's nuclear icebreakers (Sakhuja, 2012). In general, ships calling at ports along coastal routes in this region may have up to 9 m of draft (~20,000 dwt cargo, assuming 30 m beam) whereas voyages directly north of the New Siberian Islands may have up to 12.5 m draft and carry ~50,000 dwt (Brigham et al., 1999). Bathymetry in other large straits, such as Kara Gate (~10-40 m), Vilkitsky Strait (100-200 m), and Long Strait (33 m) generally does not restrict transit for most vessels. Even so, vessels must proceed with caution, particularly in the Laptev and East Siberian Seas where depths are often less than 20 meters and occasionally less than 15 meters. While depth generally increases with northward distance from the coast, sea ice conditions also tend to be more severe at higher latitudes. A synthesis of INSROP data concluded that bathymetry and severe ice conditions together contribute to making the NSR east of the Kara Sea a "complicated and even extreme system...one of the most difficult anywhere to conduct marine operations" (Brigham et al., 1999).

Considerable uncertainty remains regarding the length and variability of the navigation season for all vessels operating in the NSR in the near term. Even under the most aggressive climate warming scenarios, the Arctic Ocean is projected to be mostly ice-covered in winter throughout the 21st century (Vavrus et al., 2012). Shipowners are keenly

aware of the uncertainties: a survey of 98 shipping companies conclusively found no interest in trans-Arctic container or roll-on roll-off shipping (Lasserre and Pelletier, 2011). September ice extent may vary extensively interannually due to natural variability in cloud cover, atmospheric circulation, local surface winds, and ocean temperature (Polyakov et al., 2004; L'Heureux et al., 2008; Ogi and Wallace, 2012; Kapsch et al., 2013), suggesting large and unpredictable fluctuations in NSR navigability from year to year even when ice extent is at minimum. Moreover, the navigation season in the Russian maritime Arctic is highly spatially heterogeneous, compounding uncertainties for full transits of the NSR. Few studies (Khon et al., 2010; Stephenson et al., 2011; Stephenson et al., 2013b) have attempted to model the future navigation season of the NSR using GCM sea ice projections, and none have accounted for the additional constraint of bathymetry on marine accessibility. This paper aims to quantify the length and variability of the NSR navigation season as constrained by both sea ice and bathymetry over the next 15 years. Simulations of marine accessibility are presented for ice capable (Polar Class 3) and non-ice strengthened (open water) vessels based on daily sea ice projections from 2013-2027 under medium climate forcing (RCP 6.0). The plausible scenarios and case studies developed in this research can support near-term planning by many stakeholders who are making decisions about marine operations along the NSR.

4.3 Methods

4.3.1 Study area

By federal law, the Russian Federation formally defines the NSR from Kara Strait eastward to the Bering Strait (Russian Federation, 2012) and traverses four coastal seas of Arctic Russia (Kara, Laptev, East Siberian, Chukchi) (Figure 4.1). This study also includes

the eastern Barents Sea for analysis since it is seasonally ice-covered. The optimal navigation route varies with ice conditions, bathymetry, vessel size, and voyage purpose. The NSR currently receives traffic originating from Russian and Norwegian ports, such as Kirkenes and Murmansk, in the adjacent Barents Sea. 58 straits created by three archipelagos (Novaya Zemlya, Severnaya Zemlya, and the New Siberian Islands) and Wrangel Island introduce numerous alternatives to a single major route, though in practice, sea ice conditions and bathymetry constrain voyages to a small number of route variants. For example, most ships pass Severnaya Zemlya either at the Vilkitsky Strait or divert north of the archipelago to avoid pack ice, and continue north of the New Siberian Islands to avoid shallow bathymetry unless calling at coastal ports (Brigham et al., 1999).

This study defines the NSR region as the area of Russia's Exclusive Economic Zone (EEZ) from the eastern Barents Sea (40°E) to the Bering Strait (190°E), excluding the Bering Sea south of 65.66°N (Figure 4.1). A state EEZ is defined as ocean beyond a territorial sea extending up to 200 nautical miles from the coast (UNCLOS, 1982b). The study area includes the International Maritime Organization (IMO) Guidelines Boundary area (IMO, 2002) defining "Arctic ice-covered waters" in the zone north of 60°N excluding portions of the north Atlantic, Norwegian and Barents Seas in which sea ice concentrations of 10% or greater are present and which pose a structural risk to ships (see IMO, 2002 for a detailed definition). This region, encompassing approximately 4.1 M km² over 151 degrees of longitude, is subdivided into five marginal seas: Barents (40-58°E; ~824,000 km²), Kara (58-100°E; ~1.18 M km²), Laptev (100-140°E; ~782,000 km²), East Siberian (140-177°E; ~951,000 km²), and Chukchi (177-190°E; ~363,000 km²).

4.3.2 Marine access 2013-2027

Projected NSR navigation season over the years 2013-2027 was calculated using the methodology detailed in Stephenson et al. (2011; 2013) and briefly summarized here.

Safe navigation in ice-covered waters depends on both the severity of ice conditions and the structural properties of ships. The ability of a ship to safely enter an ice-covered area is given by the Ice Numeral:

$$IN = (C_a * IM_a) + (C_b * IM_b) + \dots + (C_n * IM_n)$$

where C_a/C_b is the sea ice concentration in tenths of ice type a/b and IM_a/IM_b is the Ice Multiplier of ice type a/b (Transport Canada, 1998). A negative Ice Numeral signifies that the ice regime presents a significant hazard and should be avoided. The Ice Multiplier is a non-zero integer variable (ranging from -4 to 2) indicating the risk presented by a particular ice type to a given vessel class, with lower Ice Multipliers denoting greater risk. Ice type is closely related to ice age: older ice tends to be thicker and stronger than younger ice due to annual accretion of ice layers and reduced brine inclusions (Bjerkelund et al., 1985; Johnston and Timco, 2008).

Ice type/age classes were approximated by ice thickness ranges. While this method does not account for thickness variations within age classes, ice age and thickness are generally well correlated for a given time of year (Fowler et al., 2004; Hunke and Bitz, 2009). Six classes were defined according to Transport Canada guidelines: “gray” (10-15 cm), “gray-white” (15-30 cm), “thin first-year first stage” (30-50 cm), “thin first-year second stage” (50-70 cm), “medium first-year” (70-120 cm), “thick first-year” (first-year ice over 120 cm). Ice with thickness greater than 0 cm and less than 10 cm was classified as “gray ice.” Thickness ranges for second-year ice and MYI were derived from observed age and thickness data. Maslanik et al. (2007) calculated median “proxy” ice thicknesses for

age classes in February-March from 2004-2008 by combining ICESat-derived ice thickness measurements (Kwok et al., 2007) with 12.5-km² ice age grids obtained from Lagrangian drift tracking. Their methodology was repeated in this study using October-November ICESat data from 2003-2007. Mean ice age in October-November was calculated by averaging age grids from weeks 41-48. The median of ICESat thickness values spatially coincident with a given age class was calculated for each year, and these medians were averaged over the 2003-2007 period to obtain proxy thicknesses for second-year ice and MYI (3+ years old). Age-thickness relationships for months other than February-March and October-November were obtained from linear interpolation.

Ice Multiplier values were selected for two vessel classes representing high and low navigation capability in ice: Polar Class 3 (PC3), capable of “year-round operation in second-year ice which may include multi-year ice inclusions” (IMO, 2002) and open-water (OW) ships with no ice strengthening. Polar Class refers to a ship’s ability to resist ice loads and maintain stability in ice with strengthened hulls and rudders; thus Polar Class vessels are built to survive ice encounters but may not be able to move through ice at high speed. However, some Polar Class ships have improved propulsion systems capable of limited ramming over short distances (Mulherin et al., 1994; Germanischer Lloyd Aktiengesellschaft, 2008). For Ice Numeral calculations, Canadian “CAC3” class is assumed to be equivalent to Polar Class 3, while the weaker “Type E” class is defined here as “open water” vessels intended for ice-free operation (IMO, 2002; Transport Canada, 2009b). Using the described procedures, Ice Multipliers were derived for PC3 (IM_{PC3}) and OW (IM_{OW}) vessel classes from ice thickness (T ; in centimeters) as follows:

$$\begin{aligned} IM_{PC3} &= 2; \text{ if } 0 \leq T < T_{SYI}; \\ &1; \text{ if } T_{SYI} \leq T < T_{MYI}; \\ &-1; \text{ if } T \geq T_{MYI} \end{aligned}$$

$$\begin{aligned}
IM_{OW} &= 2; \text{ if } T = 0; \\
&1; \text{ if } 0 < T < 15; \\
&-1; \text{ if } 15 \leq T < 70; \\
&-2; \text{ if } 70 \leq T < 120; \\
&-3; \text{ if } 120 \leq T < T_{SYI}; \\
&-4; \text{ if } T \geq T_{SYI}
\end{aligned}$$

where T_{SYI} and T_{MYI} represent month-specific thickness of second-year ice and multi-year ice, respectively.

Daily averages of ice concentration and thickness output were obtained from one 21st-century simulation (identified as the “MOAR” run) of the Community Climate System Model 4.0 (CCSM4) for a 15-year period (2013-2027) representing near-term conditions (NCAR, 2012). CCSM4 is an improvement on CCSM3 with major enhancements in all component models, and captures well the observed 20th-century sea ice climatology over seasonal, interannual and decadal timescales (Gent et al., 2011; Jahn et al., 2012; Stroeve et al., 2012a). Jahn et al. (2012) found the average ensemble-mean September ice extent in CCSM4 from 1981-2005 to be in good agreement with satellite passive microwave observations. In addition, the interannual variability of September ice extent from individual ensemble members exhibits a magnitude similar to that of observations. Ensemble-mean ice thickness in CCSM4 agrees well with ICESat average ice thickness (2003/2004 – 2007/2008), with most of the differences between the thickness distributions falling within the error bars on the ICESat retrievals. Ice recedes in CCSM4 somewhat slowly compared with other models from the Coupled Model Intercomparison Project Phase 5 (CMIP5), as the trend in September sea ice extent reaches its minimum near 2060 in CCSM4 compared with 2050 for the 29-model mean (Massonnet et al., 2012). This point represents the year in which sea ice recession is most rapid before slowing toward an ice-free state. CCSM4 and the 29-model mean both reach ice-free conditions in September

(defined as less than 1 million km²) by approximately 2070; however, like most global climate models, CCSM4 does not reproduce the rapid decline from 2007-2012 (Stroeve et al., 2012a). Biases in CCSM4 are mainly limited to the western Arctic (Beaufort Sea, Baffin Bay, and north of Greenland and the Canadian Archipelago) and parts of the north Pacific, Norwegian Sea, and central Arctic Ocean (Jahn et al., 2012).

Projections in this study assume a medium climate warming scenario (RCP 6.0), specified by a stabilized radiative forcing of 6.0 W/m² by 2100 (van Vuuren et al., 2011). CCSM4 output at 1° resolution (NCAR, 2012) for the region north of 60° N was converted to a 20-km² Lambert Azimuthal Equal-Area grid using nearest-neighbor interpolation. Ice Numeral grids from 2013-2027 were calculated for PC3 and OW vessels using one ice concentration and thickness value per grid cell. Locations were considered accessible where the Ice Numeral was non-negative. For each year, annual and monthly “navigation season length” grids were created through raster addition to determine the number of days each grid cell was accessible to a given vessel class. Raster values were spatially averaged within 151 zones of 1° longitude in the study area (40-190°E). These values were averaged over the years 2013-2027 to obtain period-mean and standard deviation of navigation season length for each longitudinal zone.

4.3.3 Bathymetry of the New Siberian Islands

Because severe ice conditions are generally more likely at higher latitudes, large deep-draft ships sailing north of the New Siberian Islands may experience shorter navigation seasons than shallow-draft vessels plying the Sannikov and Dmitry Laptev Straits. It is therefore of interest to mariners to understand the tradeoff between vessel size and navigation season in this region. The relationship between ocean depth and navigation

season length was obtained via linear regression. Ocean depth was obtained from the International Bathymetric Chart of the Arctic Ocean, the highest resolution (500 m) bathymetric dataset available for the region north of 64° N (Jakobsson et al., 2012). Annual navigation season length (2013-2027 average) and depth were overlaid on a 20-km grid comprising 585 locations within the region north of the New Siberian Islands, defined as the marine area bounded by latitude/longitude to the west (131° E), east (155° E), and south (75° N), and to the north by the 100 m isobath (Figure 4.1). Locations were excluded where depth was less than four meters and in the inlet separating Faddeyevski Island from Bunge Land. Regression of accessibility and depth variables at 585 point locations was performed in order to assess the direction and extent of the relationship between marine accessibility and vessel draft.

4.4 Results and discussion

4.4.1 Results

Figures 4.2 and 4.3 and Table 4.2 illustrate and summarize our near-term projections of navigation potential along the NSR. Results reflect the overall longitudinal distribution of sea ice in the Russian maritime Arctic, with relatively long navigation seasons at the western and eastern ends of the NSR and shorter, highly variable seasons in the Laptev and East Siberian seas. The Barents Sea is navigable by OW vessels for nearly four months (July-October) and by PC3 vessels year-round despite being partially ice-covered in winter. Variability is very low, suggesting reliable navigation seasons moderated by the relatively warm Gulf Stream current in the north Atlantic. The Chukchi Sea is less accessible than the Barents year-round but is nearly ice-free in summer, allowing both vessel classes to navigate freely from July-October and for limited periods in November

and June. These projections suggest that destination shipping to these seas, such as fishing and tourism vessels originating from the north Atlantic and Bering Sea, will be relatively unencumbered by ice in the near term.

Navigation is considerably more challenging and less reliable in the Laptev, East Siberian, and eastern Kara Seas. In summer, PC3 vessels are likely to navigate freely through these seas in an average year, but may be limited to less than 15 days in some years due to strong interannual variability (Figure 4.3). Unescorted OW vessels may navigate for short periods ($< \sim 20$ days per month) but are unlikely to have unfettered continuous access for a full month. In winter, navigation is less reliable for Polar Class vessels and effectively impossible for non-ice strengthened ships. For PC3 vessels, portions of the interior seas may fluctuate from fully accessible (but not ice-free) in one year to fully inaccessible the following year. As ice typically covers the entire NSR east of the Barents Sea from December to May, OW vessels have virtually no ability to navigate in these seas in winter, and are likely to encounter ice in low concentrations year-round in the near term. Ice often covers the Kara Sea in late fall and extends into the Barents Sea in winter. As most summer ice in the NSR is first-year ice with relatively low thickness ($< \sim 1.2$ m), Polar Class 3 vessels may have little difficulty navigating such areas of relatively low ice concentration. Nevertheless, there will be a continued need for year-round icebreaker escort of non-ice strengthened vessels attempting full transits of the NSR.

We also observe a robust inverse relationship between navigation season length of OW vessels and ocean depth in the region north of the New Siberian Islands (Figure 4.4; adjusted $r^2 = .56$). Owing to heavier and more persistent ice at higher latitudes, deep-draft routes adjacent to the Arctic Ocean are accessible for shorter periods on average than are shallower routes (~ 12.5 m) near the northern edge of the archipelago. This finding

underscores a key tradeoff between vessel draft and navigation potential in the eastern NSR. In the near term, smaller ships may be required for maximum utilization of the navigation season for full transits of the NSR. Conversely, vessels carrying larger cargoes (> 50,000 dwt) will be limited to fewer days of operation, with fewer accessible days projected as requirements for deeper draft increase.

4.4.2 Full NSR transit case studies for 2013-2027

Here we examine two hypothetical “case studies” of full NSR transits (September and December) to illustrate how our results could be used for planning of near-term Arctic marine operations. In each case, we consider transits from west to east by unescorted PC3 and OW cargo vessels with draft exceeding 10 meters.

First we consider transits in September, when navigation season is longest (Figures 4.3, 4.5). Both vessels encounter minimal ice resistance in the Barents and western Kara Seas, with only a small disparity in operating capability (~3-5 days) between the classes. In the eastern Kara Sea, ice build-up near Severnaya Zemlya reduces navigation potential for both classes, with more severe limits on operating days OW vessels (< 15 days). PC3 vessels then move freely from the Vilkitsky Strait to the Bering Strait, as infrequent MYI encounters hinder navigation on only ~5 days on average. However, OW vessels may only operate for 15-20 days on average in the Laptev and East Siberian Seas. These periods are highly variable, as OW ships may be limited to 5 days of navigation in one year, and may operate freely for nearly a full month the following year. Both ships must sail north of the New Siberian Islands to avoid shallow bathymetry in the Sannikov (13 m) and Dmitry Laptev (6.7 m) Straits. For PC3 vessels, this northern route is accessible only 3-5 days fewer than the southern straits, as these ships may sail into the central Arctic Ocean (>80°

N) with only a minor reduction in navigation season. In contrast, OW vessels encounter significant ice hazards in these northern routes, which become increasingly inaccessible at higher latitudes (Figure 4.4). At the 100 m isobath, these vessels may operate for 10 days or fewer during the month. East of the New Siberian Islands, navigation season increases gradually to a maximum of 30 days of operation in the Chukchi Sea.

A December case study serves to illustrate the feasibility of making a full transit in late-season conditions (Figures 4.3, 4.6). Both vessels may operate for long periods in the southern Barents Sea owing to low ice concentrations west of Novaya Zemlya. As in September, PC3 vessels may navigate freely to the Bering Strait with relatively lower accessibility and higher variability east of the Vilkitsky Strait. Navigation season is somewhat shorter (~5 days) along a route 200 km north of the New Siberian Islands. Overall, PC3 vessels may operate for marginally shorter periods in December than in September on average with similar spatial variation in the eastern coastal seas. However, unlike in September, PC3 vessels must operate at reduced speed owing to high ice concentration throughout the eastern NSR. While relatively thin at this stage (< 1 m), ice cover is sufficiently widespread as to prevent passage by OW vessels east of Kara Strait in December. Navigation season is near zero along the vast majority of the NSR with very low variability, indicating low likelihood of passage in any given year. These results suggest some potential for an expansion of the navigation season into early winter for ice-capable ships, but not for unescorted non-ice strengthened vessels.

4.4.3 Discussion

Despite the distance advantage of the NSR relative to established global trade routes, utilization of the NSR will be prudent only if the business case is viable under the condition

of limited (summer) and unpredictable navigation periods. Our results show that the NSR navigation season is likely to be limited to an extended period in summer for most vessels during the early part of this century; navigation seasons that extend to early spring and late autumn will be unpredictable even for Polar Class 3 vessels. Today, summer NSR shipping is feasible only for Polar Class vessels, which comprise a small percentage of the global fleet and are designed for carrying natural resources (tankers and bulk carriers) rather than containers. While our work compares independently operated icebreaking carriers (PC3) with non-ice strengthened ships (OW), it is unlikely that the Russian authorities will permit unescorted non-ice strengthened ships in the NSR in the foreseeable future. Mandatory icebreaker escort remains the Russian mode of NSR operations, which skews the length of the operating season for OW vessels.

Our findings have important strategic implications for vessel capacity and disaster response. Much of the near-future increase in full transits of the NSR is expected to come from bulk transport of oil and gas from northwest Russia or refined petroleum products (e.g. jet fuel) from East Asia (Arctic Council, 2009). Excluding ships calling at intermediate ports, many of these voyages will minimize transport costs by utilizing large-capacity ships, such as Panamax (65,000 - 80,000 dwt; 12.04 m max draft) and Suezmax (120,000 - 200,000 dwt; 20.1 m max draft) classes (Panama Canal Authority, 2005; Suez Canal Authority, 2010; Maritime Connector, 2013). Of the 46 full transits of the NSR in 2012, 17 were by ships carrying cargoes in excess of 50,000 tonnes, most of which were petroleum products (Rosatomflot, 2012). Draft restrictions required these ships to utilize northerly routes near the New Siberian Islands, which are not only more ice-prone than southern routes but also farther from coastal support bases. Thus, we note that the New Siberian Islands may be an expedient location for the siting of search and rescue and disaster

response stations. Oil spill response efforts in the Arctic are complicated by numerous factors including ice cover, adverse weather, cold temperature, and remoteness of shore-based support infrastructure. With an expanding proportion of NSR traffic driven by petroleum demand, capacity for timely response to environmental disasters in this remote region becomes increasingly critical.

Our findings also suggest strong uncertainties regarding the potential of the NSR for container shipping and other time-sensitive cargoes. Container trade is largely driven by “just-in-time” delivery models for the global supply chain, which are based on economies of scale and reliable delivery schedules in addition to transport costs (Levinson, 2006). Scale economies are constrained by shallow draft in key straits, precluding transit by the largest tanker classes (VLCC and ULCC; > 180,000 dwt) thus requiring more vessels to transport a given quantity of product. Interannual ice variability makes prediction of route opening and closing dates highly uncertain, complicating delivery schedules which are typically fixed weeks in advance. Furthermore, the limited, seasonal availability of the NSR requires companies to change schedules at least twice a year, creating additional costs and the possibility of errors leading to delivery delays (Lasserre and Pelletier, 2011). Given that bulk commodities such as oil and gas are less sensitive to arrival dates and may be transported below deck, one might expect the trans-Arctic shipping potential of these commodities via the NSR to be higher. While the voyage of the *Yong Sheng* in August 2013 was historic for being the first NSR transit by a commercial Chinese vessel, the ship was designed for multiple uses and cargo types rather than large-volume container shipping, which remains untested via the NSR.

Significant environmental and economic challenges besides sea ice and bathymetry constrain the development of Arctic shipping (Arctic Council, 2009; Brigham, 2010). As

receding ice exposes larger areas of open water and wind fetch, storm surges will present an increasing environmental hazard, particularly to container vessels carrying above-deck stacked cargoes. Even in low concentrations, ice can cause significant hull damage. Ships navigating in mostly open water are especially vulnerable to “growlers” (small blocks of hard MYI) as these ships are likely to be operating at higher speeds. Furthermore, ice drift speed is likely to trend upward where MYI concentrations are low (Kwok et al., 2013). Initial capital investment in Polar Class vessels may be prohibitive for many shipping companies, and insurance rates for non-Polar Class vessels are likely to be costly or impossible to obtain (Lasserre and Pelletier, 2011). Operating costs of Polar Class 3 vessels are likewise significant owing to reduced fuel efficiency and specialized training for crew members (Mulherin et al., 1996; Tamvakis et al., 1999; Det Norske Veritas, 2010). Port facilities, monitoring stations, salvage, and search and rescue facilities are sparse relative to lower latitudes. Expansion and maintenance of port infrastructure is expensive due to remoteness, cold climate, permafrost and coastal erosion (ACIA, 2004b). Economic issues specific to the NSR include transit fees and the lack of coastal markets and transshipment ports.

Because this study is based on one ensemble member (#6) of CCSM4, results based on other ensemble members will differ due to internal model variability, especially on sub-20 year timescales (Figure 4.7). In 20th-century simulations, ensemble member 6 shows less ice loss than other ensemble members with a statistically insignificant negative trend in September ice extent from 1981-2005 (Kay et al., 2011). Thus our results may be somewhat conservative in comparison to those obtained from other ensemble members. However, we expect that differences in accessibility arising from internal variability in ice extent will be limited mainly to open water vessels, as these vessels are sensitive to changes

in concentration of first-year ice whereas Polar Class 3 vessels are not. In addition, the negative trend in sea ice area (as opposed to extent) is significant for all ensemble members, due to the fact that ice extent is a summation of all areas with an ice concentration of 15% or more and does not account for decrease in overall sea ice concentration (Jahn et al., 2012). Ice area is a better indicator of marine accessibility than extent because large areas of open water may exist within the defined ice extent margin, and thus may be navigable depending on the thickness of ice present. Therefore we expect results from any of the six ensemble members to be broadly representative of navigation potential in the near term. Over longer timescales, the effect of internal variability is reduced as all ensemble members demonstrate significant negative trends in September ice extent from 1952-2005 (Kay et al., 2011).

Our study is subject to several limitations. The coarse spatial resolution of global climate models such as CCSM4 ($\sim 1^\circ$) limits the utility of these projections in straits and other narrow marine spaces. However, as the majority of the Russian maritime Arctic is open to atmospheric and oceanic circulation from the Arctic Ocean, GCM data are better suited to our study area than to more complex geographies such as the Northwest Passage. A similar analysis of NSR navigation season based on GCM ice concentration appeared in the Arctic Climate Impact Assessment (2004). In addition, our results are likely conservative in comparison to recent observed sea ice loss. September ice extent in CCSM4 from 2013-2027 ($\sim 5.5\text{-}6.5 \text{ M km}^2$) (Massonnet et al., 2012) is greater than the record minima in 2007 (4.17 M km^2) and 2012 (3.41 M km^2). Few individual model simulations show trends in sea ice decline comparable to recent observations (Stroeve et al., 2007; Winton, 2011), suggesting a failure of models as a whole to account for the physical mechanisms behind rapid decline, such as ice drift acceleration (Rampal et al., 2011). As

model simulations are based in part on an understanding of thermodynamics and mass balance obtained from MYI observations (Hudson et al., 2013), a transition to a seasonal FYI-dominated ice cover suggests that model projections may continue to lag behind observations. Analysis of more aggressive warming scenarios (e.g., RCP 8.5) may provide insight on how marine accessibility responds to faster-than-predicted ice melt. However, even the most aggressive climate models and warming scenarios project widespread ice cover in winter throughout the 21st century.

4.5 Conclusion

The NSR is emerging as a seasonal trade route for shipping Arctic natural resources to global markets. This study focuses on the critical issue of changing marine access given the extraordinary retreat of Arctic sea ice during the past three decades. Our findings support the following broad conclusions:

1. Arctic sea ice in the Russian maritime Arctic remains a key constraint to the operation of non-ice strengthened or open water ships during the period of study, 2013-2027. There remains limited accessibility for non-ice strengthened ships in select coastal seas from July to October, if the Russian authorities even allow seasonal navigation of such ships east of Vilkitsky Strait.
2. Ships may operate in the western NSR for substantially longer seasons, including year-round navigation (with appropriate ice-class vessels), compared with more limited accessibility remaining in the eastern NSR (Laptev, East Siberian and Chukchi seas).
3. While Polar Class 3 (PC3) vessels may technically navigate along the NSR in winter for short periods, marine access is highly variable leading to large

uncertainties in the plausibility of year-round operation across the whole of the NSR.

4. Bathymetry around the New Siberian Islands presents a significant constraint for deeper draft vessels, forcing ships northward into more challenging sea ice for Polar Class ships.

4.6 Figures

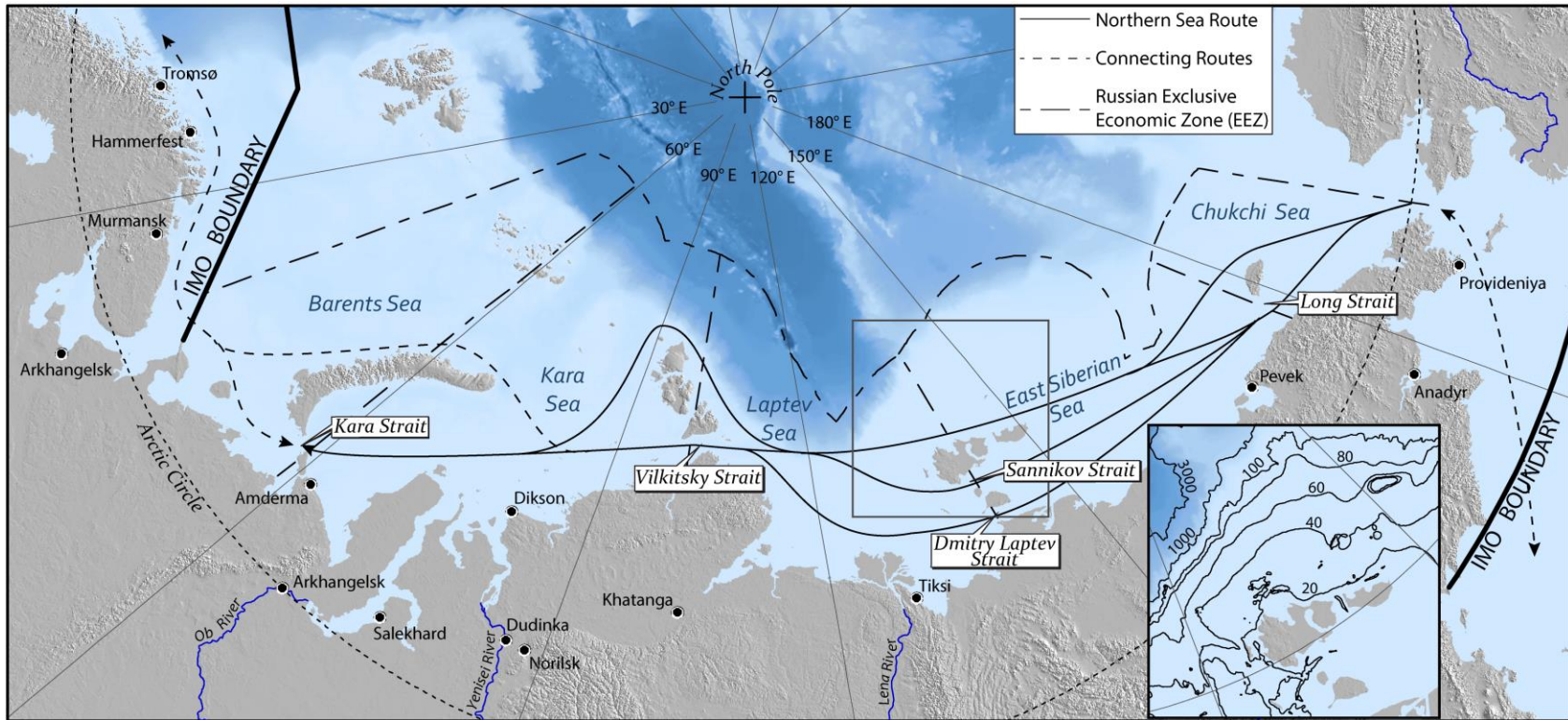


Figure 4.1: Summary map of the Russian maritime Arctic. Includes the NSR. Bathymetric contours shown in meters.

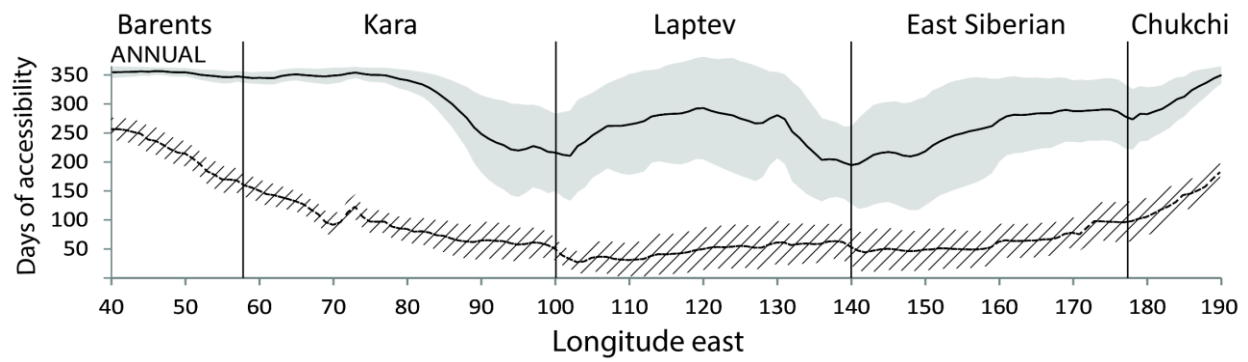


Figure 4.2: Annual days accessible to Polar Class 3 (solid) and non-ice strengthened (“open water;” dashed) vessels in the study area, 2013-2027 average (line) and standard deviation (envelope) under medium forcing (RCP 6.0). Results are averages of all grid cells within 1-degree zones of longitude from 40-190°E.

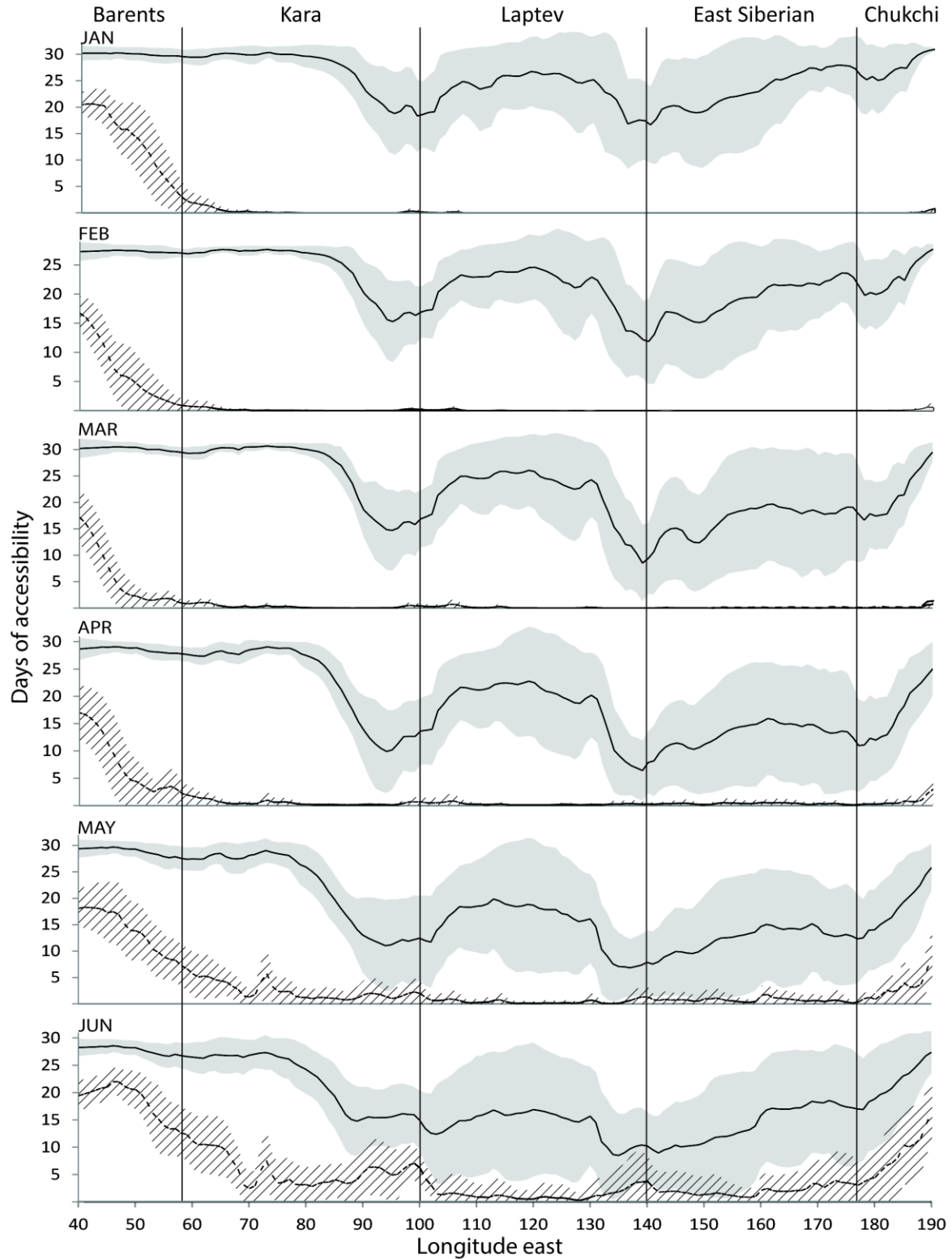


Figure 4.3: Monthly days accessible to Polar Class 3 (solid) and non-ice strengthened (“open water;” dashed) vessels in the study area, 2013-2027 average (line) and standard deviation (envelope) under medium forcing (RCP 6.0) (July-December appears on a second page). Results are averages of all grid cells within 1-degree zones of longitude from 40-190°E.

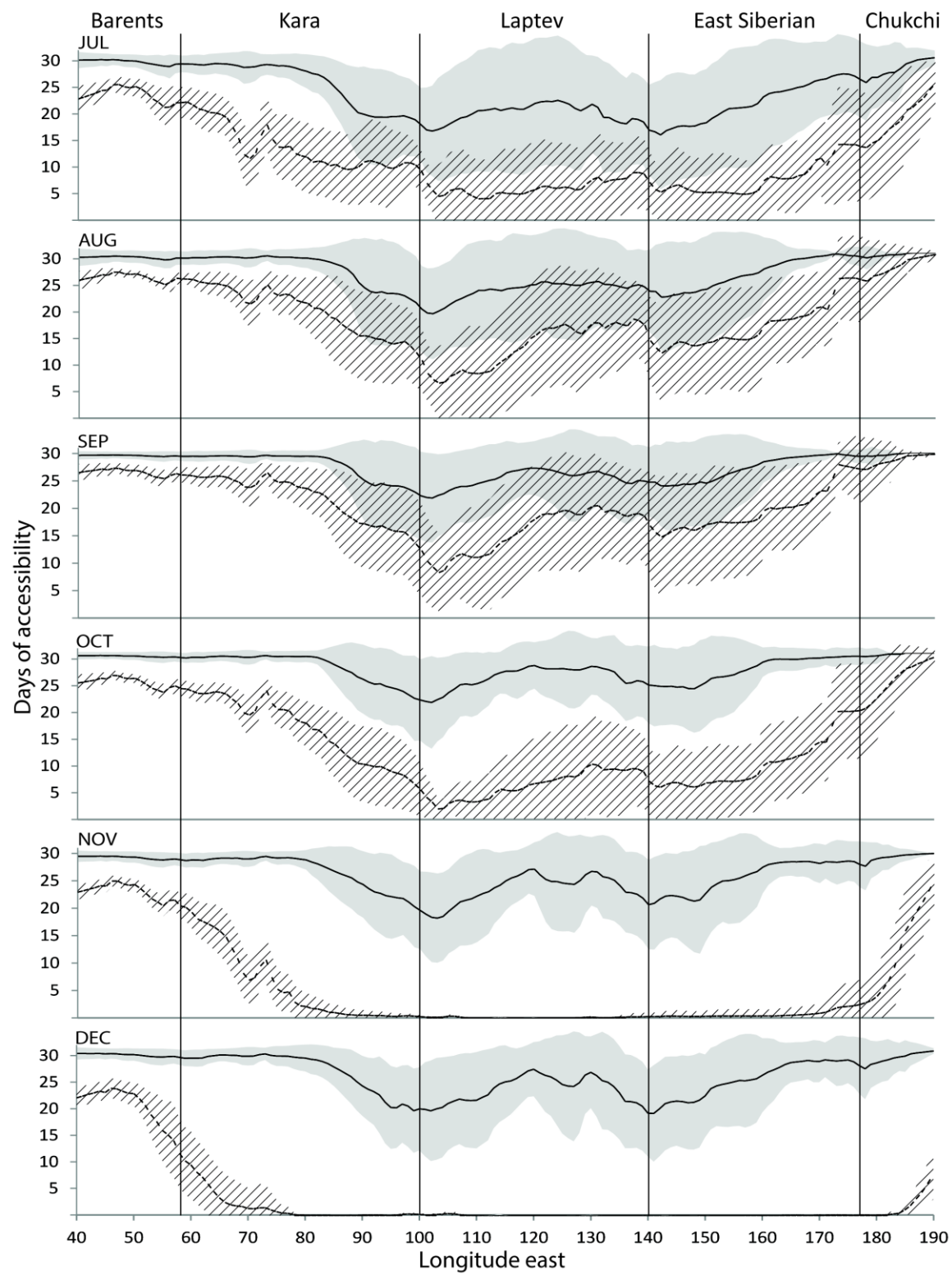


Figure 4.3 (continued)

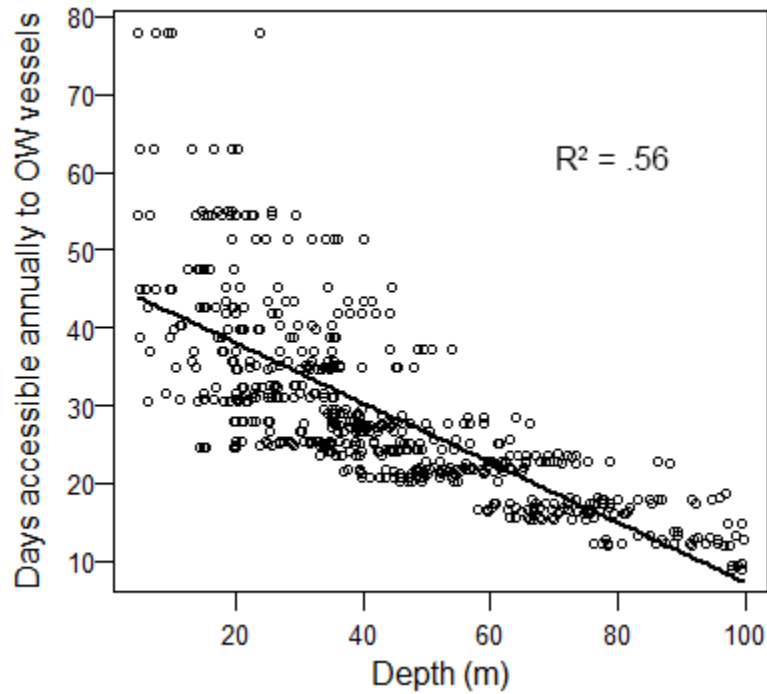


Figure 4.4: Relationship of navigation season (open water vessels) to bathymetry near the New Siberian Islands. Annual accessible days and ocean depth (Jakobsson et al., 2012) values were obtained for 585 locations within the marine area bounded by latitude/longitude to the west (131° E), east (155° E), and south (75° N), and to the north by the 100 m isobath (Figure 3.1), excluding depths less than four meters and the inlet separating Faddeyevski Island from Bunge Land.

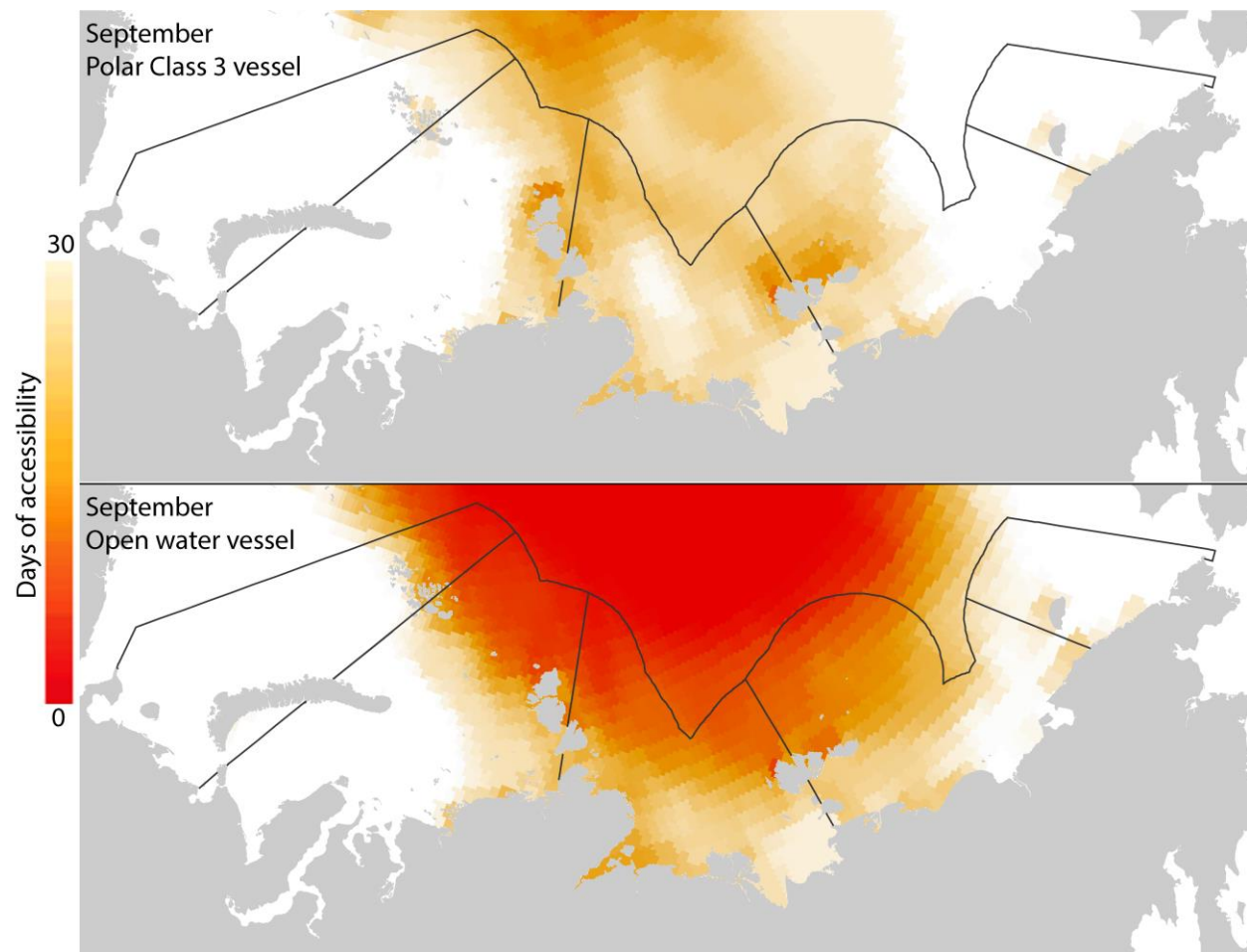


Figure 4.5: Case Study 1: Accessible days in September, 2013-2027 average.

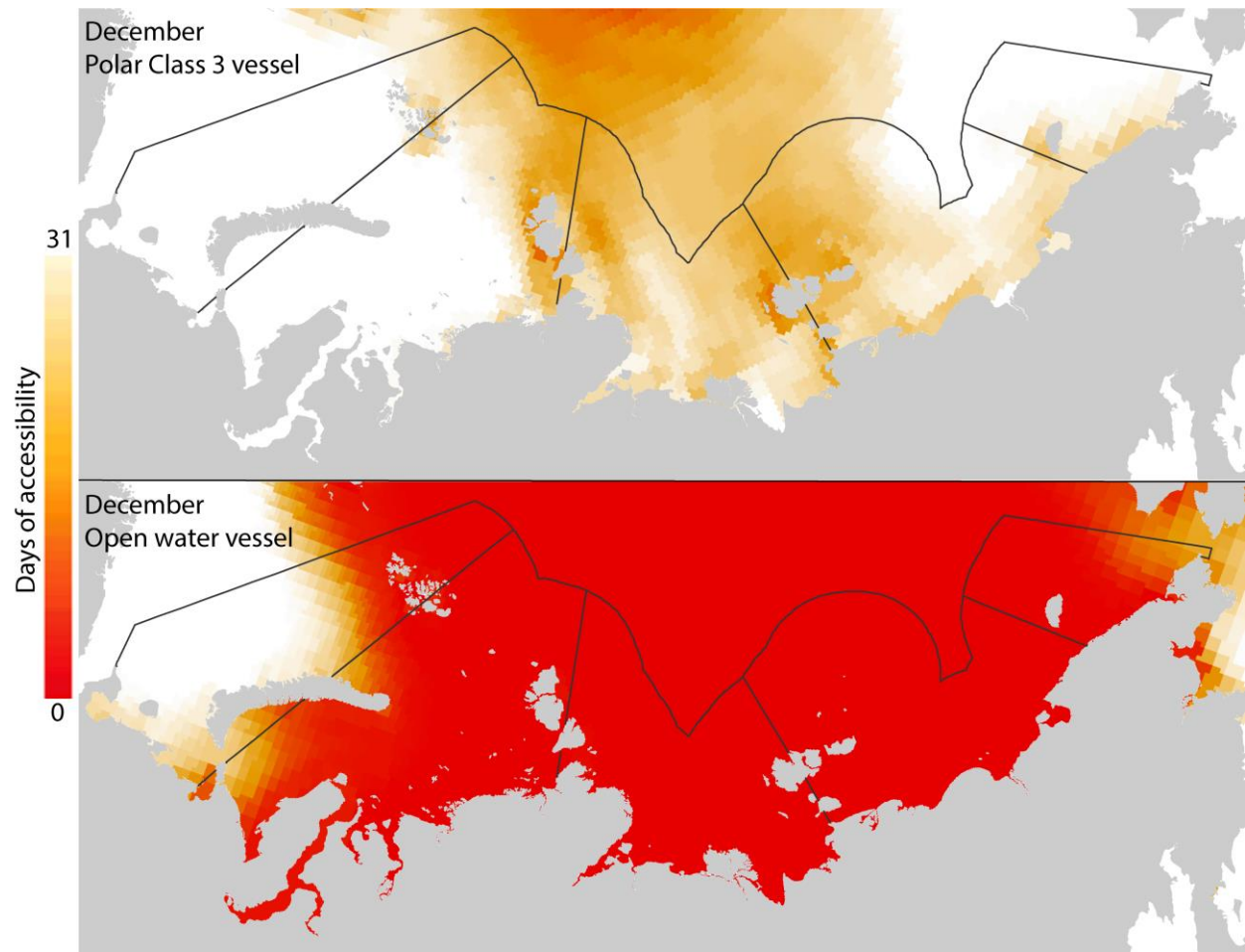


Figure 4.6: Case Study 2: Accessible days in December, 2013-2027 average.

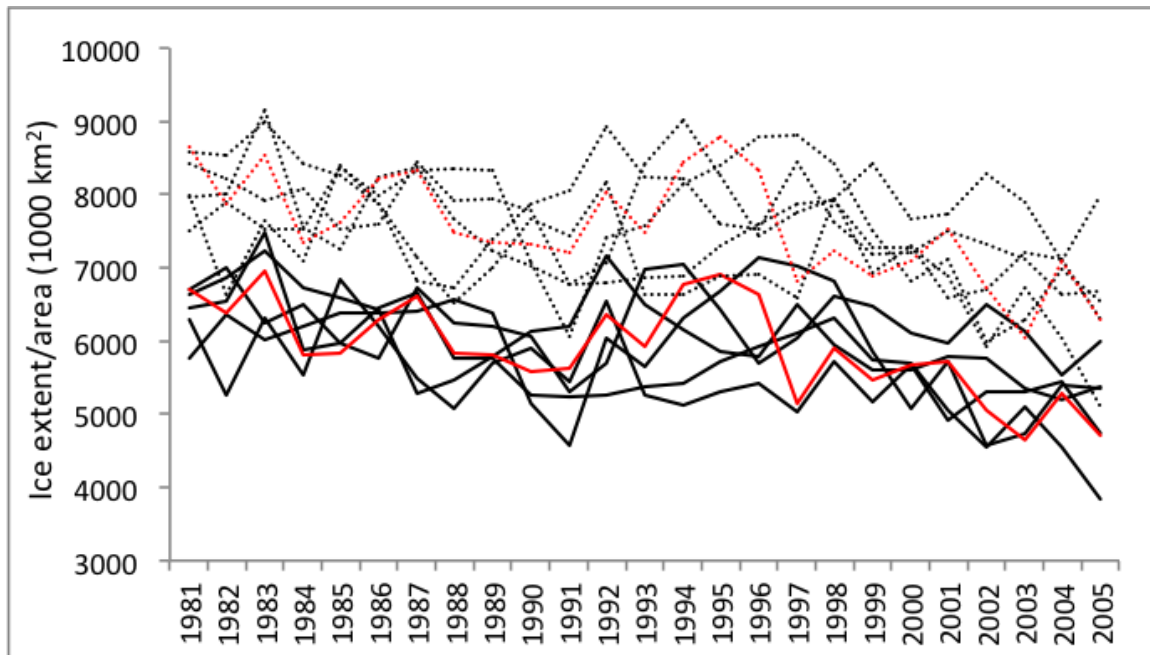


Figure 4.7: September ice extent (dashed lines) and ice area (solid lines) for the six ensemble members of CCSM4 from 1981-2005. On average, ensemble member #6 (shown in red) projects more ice cover than other ensemble members, though annual differences are greater for ice extent ($\sim 12,000 \text{ km}^2$) than ice area ($\sim 6,000 \text{ km}^2$).

4.7 Tables

Table 4.1: Top 15 full NSR transits in 2012 by tonnage (Rosatomflot, 2012)

Vessel (Flag)	Shipowner / Operator	Cargo Type	Cargo Tonnage	Origin	Destination	Date of Sail	Time on NSR (days)	Average speed (kn)
Nordic Odyssey (Panama)	Nordic Bulk Carriers	Coal	71786	Vancouver	Hamburg	26.10.12	10	10.4
Nordic Odyssey (Panama)	Nordic Bulk Carriers	Iron ore	67520	Murmansk	China	10.07.12	11.2	9.7
Marika (Norway)	MARINVEST	Jet fuel	66552	Yosu, Korea	Porvoo, Finland	11.08.12	10.2	10.2
Stena Poseidon (Finland)	Neste Oil	Jet fuel	66416	Yosu, Korea	Porvoo, Finland	30.06.12	11.5	9.4
Ob River (Marshall Islands)	LANCE SHIPPING S.A	LNG	66342	Hammerfest	Tobata, Japan	07.11.12	9	12.5
Palva (Finland)	Neste Oil	Jet Fuel	66275	Yosu, Korea	Porvoo, Finland	05.09.12	8.5	11.8
Nordic Odyssey (Panama)	Nordic Bulk Carriers	Iron ore	66000	Murmansk	Huanghua, China	09.09.12	7.4	13.5
Nordic Orion (Panama)	Nordic Bulk Carriers	Iron ore	65937	Murmansk	Huanghua, China	10.08.12	8.5	12.3
Nordic Orion (Panama)	Nordic Bulk Carriers	Iron ore	62806	Murmansk	Huanghua, China	02.10.12	7.5	13.3
STI Harmony (Marshall Islands)	Scorpio Ship Management	Gas condensate	61496	Murmansk	Zhenjiang, China	23.08.12	8.1	12.9
Marika (Norway)	MARINVEST	Gas condensate	61266	Murmansk	Korea	30.09.12	8.6	11.6
Maribel (Norway)	MARINVEST	Gas condensate	61138	Murmansk	Daesan, Korea	17.10.12	7.8	12.8
Marinor (Norway)	MARINVEST	Gas condensate	60992	Murmansk	Daesan, Korea	30.08.12	8.4	12.4
Two Million Ways (Cyprus)	Nagilo shipping Company Ltd	Gas condensate	60841	Murmansk	Incheon, Korea	26.09.12	8	12.5
Marilee (Norway)	MARINVEST	Gas condensate	60505	Murmansk	Incheon, Korea	10.07.12	11.3	9.6

Table 4.2: Accessibility Summary

2013-2027 mean (standard deviation) annual and monthly days accessible to Polar Class 3 and open water vessels under medium forcing (RCP 6.0) in the study area. Results are averages of all grid cells in the respective coastal seas defined by longitudinal ranges in Section 4.3.1.

Polar Class 3

	Barents	Kara	Laptev	E. Siberian	Chukchi
January	30 (1)	28 (2)	23 (7)	24 (7)	28 (3)
February	27 (1)	26 (2)	21 (5)	20 (7)	24 (3)
March	30 (1)	28 (1)	22 (6)	17 (10)	23 (5)
April	29 (1)	25 (2)	18 (7)	13 (9)	18 (6)
May	29 (2)	24 (3)	15 (8)	13 (9)	19 (7)
June	28 (1)	24 (3)	14 (9)	14 (9)	23 (6)
July	30 (1)	27 (3)	20 (10)	22 (9)	29 (4)
August	30 (1)	29 (3)	24 (8)	27 (5)	31 (0)
September	30 (1)	29 (2)	26 (6)	27 (4)	30 (0)
October	31 (1)	29 (2)	27 (5)	28 (4)	31 (0)
November	29 (1)	28 (2)	24 (6)	26 (5)	29 (1)
December	30 (1)	28 (2)	24 (7)	26 (5)	30 (2)
Annual	353 (8)	324 (21)	258 (75)	258 (68)	314 (31)

Open water

	Barents	Kara	Laptev	E. Siberian	Chukchi
January	14 (4)	0 (0)	0 (0)	0 (0)	0 (0)
February	7 (4)	0 (0)	0 (0)	0 (0)	0 (0)
March	6 (3)	0 (0)	0 (0)	0 (0)	0 (0)
April	8 (4)	0 (0)	0 (0)	0 (0)	1 (1)
May	14 (5)	3 (2)	0 (0)	1 (1)	4 (3)
June	19 (3)	6 (3)	1 (2)	2 (3)	9 (6)
July	24 (2)	15 (4)	6 (6)	8 (7)	20 (8)
August	27 (1)	22 (3)	14 (9)	17 (8)	29 (3)
September	27 (1)	23 (4)	16 (8)	20 (8)	29 (2)
October	26 (1)	19 (3)	7 (7)	10 (7)	27 (5)
November	23 (1)	8 (2)	0 (0)	1 (2)	14 (6)
December	21 (3)	2 (3)	0 (0)	0 (0)	2 (1)
Annual	214 (19)	98 (16)	46 (30)	59 (29)	136 (26)

5. The Network Allure: Spatial Embeddedness in Arctic Extractive Industries

A version of: Stephenson, S.R., Agnew, J.A. (in review). The network allure: spatial embeddedness in Arctic extractive industries.

5.1 Abstract

The “network” has gained widespread acceptance within economic geography as a metaphor for the complex inter-firm relations that constitute modern industrial production systems. Taken to an extreme, however, networks may reinforce assumptions that technology has demoted or rendered obsolete the effect of distance and the unique physical and sociopolitical context of specific places. We aim to articulate a nuanced picture of economic networks as an alternative to the totality and fetishism of an entirely networked world through analysis of extractive industries in the Arctic and sub-Arctic. Consistent with a global production network (GPN) approach, extractive activities are deeply embedded in political structures, physical infrastructure, and environmental conditions, causing different kinds of networks to be realized at different stages of the extractive value chain. Using examples of transport infrastructure and state ownership in the oil and gas industry, we show how extractive networks are shaped not only by exogenous market pressures but also local conditions and path-dependent connections to other places. Framed in this way, networks may be invoked to explain why extractive development occurs in some places and not in others. The network concept in the extractive sector is deconstructed to establish the concrete linkages between firms that collectively manifest as networks, followed by an examination of place embeddedness in northern extractive industries with particular attention to Arctic and sub-Arctic Russia.

5.2 Introduction

The network remains a powerful and pervasive image of economic relations. Long before the telecommunications and logistics innovations of the late 20th century heralded the modern “shrinking” of the world, networks were invoked qualitatively as didactic illustrations of economic internationalization, depicting world trade as a system of interdependencies across national boundaries and at great distance (Hilgerdt, 1943; Hansson, 1952; Saul, 1954). These ideas were later buttressed by an expansion of quantitative network-analytic methods enabling complex analysis of the topology and spatial organization of economic relations (Wasserman and Faust, 1994; Serrano and Boguña, 2003; Fagiolo et al., 2008), leading to widespread acceptance of a network basis for world trade. This formulation has continued to gain currency as trade has become increasingly globalized: two hallmarks of contemporary globalization, the functional integration of internationally dispersed activity and the vertical disintegration of transnational corporations (TNCs), are often conceived as network-building processes at divergent scales (Gereffi et al., 2005). The salience of the global production network (GPN) in modern economic discourse attests to its rise to dominance as a mode of transnational production and organization.

The allure of the network metaphor in economic geography is perhaps understandable given the myriad spatial interdependencies of modern industrial production. However, if networks are actually analytical tools rather than concrete spatialities, then recent focus on networks of distinct spatio-scalar units such as cities (Sassen, 2001; Taylor, 2004) and firms (Coe et al., 2004; Gereffi et al., 2005) may be viewed as products of a search for an appropriate geographic form on which the “explanatory weight” of networks must rest (Jones et al., 2011). In this regard, it becomes analytically convenient to describe cities and firms as discrete nodes of activity separated by “empty” space in which relatively little happens. This is Castells’ (2000)

“space of flows” in which anything can be located anywhere, with little regard for the peculiarities of places or the materiality of connections between them. Similarly, attempts to orient thinking in human geography away from a hierarchical scalar ontology (Amin, 2002; Marston et al., 2005) risk advancing notions of limitless, unmediated interconnectivity (Friedman, 2005) even as they (rightly) draw attention to specious attributions of agency according to hierarchy. Taken to an extreme, this “network ideology” reinforces the modern myth that technology has demoted or rendered obsolete the effect of distance and embeddedness of place. The danger in such conceptual exclusivity is that places become defined solely in relation to each other, neglecting their unique territorial and sociopolitical context. As Sunley (2008) points out, a territorial/relational dichotomy is artificial and misleading, as relations crossing boundaries may reinforce the significance of those boundaries rather than undermine them. Just as a narrow territorial worldview fails to account for the growing economic interdependence of places, exclusively relational thinking is too abstract to explain how economic processes actually work. This overreliance on the network metaphor obscures the still essential role of states and other non-networked social structures, creating a false impression of analytical precision based on a single concept (Joseph, 2010; Erickson, 2012).

Captivation with the flat ontology of the network has historical roots in the early nineteenth century utopian thinking of Saint Simon. This was the time when the physiological conception of social life he sponsored began to replace the more politicized approaches of the early Enlightenment (Wokler, 1987). “Network” is not simply an innocent technical term invented alongside the Internet. Though we might all agree that there are concrete networks of all sorts that have been around for time immemorial, from that of blood circulation in animals to those involving transport and communication in the world economy, the idea of the world in its

entirety becoming organized *solely* on a networked basis is qualitatively different. The implication is that a new networked world is the emerging foundation for a social transformation in which place-to-place differences in economic or other activities will cease to matter. In a merging of Saint Simonian with neo-Marxist thinking, Manuel Castells (2000), for example, claims that the reticular and non-hierarchical character of networks, particularly that of the Internet, provides the material base to a totally new type of society. This of course not only simplifies the idealized network as egalitarian, democratic, and relational when, as is well known, actual networks are as often as not hierarchical instruments of power, it also privileges technical change over political decision as the driver of history, fetishizes deterritorialization over its historical partner reterritorialization (in the dialectical formulation of Deleuze), and normalizes the present day world of neo-liberal capitalism associated as it is with the “world that no knows no boundaries” over other possibilities. At its extreme, therefore, it is an “ideology” in the sense of the term used by Pierre Musso (2003), a discourse combining a geopolitical imagination of the future with normative roots in nineteenth century utopianism and vast empirical overstatement of the role of networks in contemporary life. This history of “network” as a utopian project and teleological myth needs to be carefully distinguished from the uses of the term as a concept helpful in understanding economic and political organization.

We argue for a nuanced economic geography that forges an alternative between the “territorial trap” (Agnew, 1994) and the totality and fetishism of an entirely networked world. While we do not believe that theorists such as Castells explicitly advocate for a Saint Simon-esque vision, we contend that such an understanding of economic relations may proliferate if not countered by discussion of local embeddedness and connectivities. Our attempt to reconcile the encompassing structure of networks with a territorially-bounded world parallels numerous efforts

to illuminate the evolving geographies of communication in the context of globalization (Cox, 1997; Yeung, 1998; Ó Tuathail, 2000; Agnew, 2009a). That economic power now flows from the complex interrelationships of “body, neighborhood, state, region and globe” (Dicken et al., 2001) (pp. 95) is a clear departure from the strict territorial ontology of long ago. At the same time, networks cannot be extricated from territory completely because every network element is situated within a specific political, social, and cultural context. Our view is comparable to that of Dicken et al. (2001) who, while elevating the network to the “foundational unit of analysis for our understanding of the global economy” (pp. 91), also call attention to the structural power relations constituted by networks and the distinct time- and space-specific contexts in which networks are realized (pp. 94). Massey (2004) makes a similar argument by emphasizing that global spaces are constituted by “power geometries” representing the politics of relations and practices in local places. Perhaps most concretely, Coe et al. (2008) assert that “every element in a GPN—every firm, every function—is, quite literally, grounded in specific locations. Such grounding is both material (the fixed assets of production), and also less tangible (localized social relationships and distinctive institutions and cultural practices)” (pp. 279). The key point these authors make is that the functioning of the global economy depends critically on networks, and that these networks are inextricably embedded in non-network structures.

We aim to articulate a spatial context for economic networks through analysis of extractive industries in the Arctic and sub-Arctic regions. Our arguments build upon foundational work by Bridge (2005; 2008; 2010; 2013) that articulate both the commodity chain structure and the intrinsic geographic specificity of natural resource extraction. Although natural resources have not been central to most studies of global commodity chains and production networks (Smith, 2005; Bridge, 2008), recent work by De Graaf (2011) illustrates how

quantitative network-analytic techniques may be applied to study evolving relations among extractive firms. Her work reveals that the global oil industry is becoming increasingly transnationalized through integration of national and private companies, while omitting extensive discussion of the physical and social structures underlying inter-firm relations. In this paper we expand on such inquiries to illustrate how networks are necessary but not sufficient descriptors of the complex relations underpinning the global economy. First, we deconstruct the network concept in the extractive sector to establish the concrete linkages between firms that collectively manifest as networks, followed by an examination of place embeddedness in northern hydrocarbon industries. While many aspects of embeddedness can be found in extractive projects throughout the northern high latitudes, we focus on Russia as its relatively advanced infrastructural development and unique ownership regime present an especially instructive case.

5.3. Deconstructing the network in the extractive sector

5.3.1 Networks and chains

Today most industrial sectors operate according to a logic of local production and global coordination. Firms are located in specific places and form the basis for local economies, and are also integrated within larger networks of firms whose activities are driven by global markets. The primacy of transnational corporations (TNCs) as agents of economic change stems from their power to coordinate and control operations among these often distant and disparate firms without direct ownership, allowing them to outsource generic functions in order to focus on core competencies not easily replicated by other firms (Penrose, 1959; Prahalad and Hamel, 1990; Sturgeon, 2002). These complex circuits involve specialized technological and service inputs, which enable TNCs to control processes of production and to choose which firms participate (Rabach and Kim, 1994). TNCs thus determine which cities, countries and regions become

connected to the network (Dicken, 2011). The type of coordination by lead firms determines the nature of each subsidiary firm's role within the network, creating power asymmetries that belie presumptions of a flat world.

These differential power relations are critical to thinking about economic networks not as a dimensionless, freely flowing marketplace, but as a series of functionally integrated chains in which lead firms exercise enormous influence. The work of Gereffi (1994; 1996) and Gereffi et al. (2005) is fundamental in highlighting not only the networked structure of global commodity chains but also the social relations that govern each stage of the chain. For example, the size and reach of distribution networks influence the degree of control lead firms exercise over production and marketing operations through value-added services, reflected in the recent reformulation of commodity chains as global *value* chains (Gereffi et al., 2005; Dicken, 2011). The bidirectional flow of information between stages of a value chain makes possible the functional fragmentation and spatial dispersion of production. This governance structure has critical implications for economic development, as when producers in developing countries are denied network access because the value chains for their products are governed by few lead firms with ties elsewhere (Dolan and Humphrey, 2000; Humphrey and Schmitz, 2001). The power to include or exclude firms from productive processes in this way is characteristic of the role of TNCs as principal agents in economic networks.

Analysis at the level of the value chain serves a critical purpose in establishing economic relations as concrete processes with vital physical and sociopolitical dimensions. Here, Sturgeon's (2001) discussion of chains and networks is useful in illustrating the distinction and complementarity of the two concepts. Whereas chains describe the sequence of activities leading to the production, delivery and consumption of goods and services and the set of actors involved

at each stage, networks highlight the relationships that bind firms into larger economic groups (Sturgeon, 2001). Implicit in this distinction is a particular analytical focus related to scale: chains emphasize relations between individual firms in a linear industrial process, while networks highlight the myriad inter-firm relations comprising diverse chains from multiple sectors (Coe et al., 2008). However, value chains are not merely the local building blocks of global networks. Sturgeon points out that reliance on local-scale analysis overlooks broader regional and global dynamics occurring across local boundaries, and conversely, that macro-level statistics often miss essential details of how firms operate in practice. Recognizing the shortcomings of each approach on its own reveals the falsehood of the global/local dichotomy; rather, the local is situated within the global, as demonstrated by the rise of industrial clusters, existing simultaneously in local places and in the global marketplace. Value chains enable analysis of both global linkages and the empirical reality of individual firms and their specific roles in a sequence of production. Accordingly, one of the key insights from a value chain-oriented approach is that the different ways firms are organized internally and in relation to each other has vital implications for the overall structure of industries.

Transportation is an excellent example of the simultaneously global and local dimensions of value chains. As a mechanism for moving labor and product, transportation serves to maintain the cohesion of GPNs in light of increasing functional fragmentation and geographic dispersion of production services (Rodrigue, 2006). At the same time, transportation systems are the (often literally) concrete structures underlying GPNs and are themselves examples of networks with material meaning. While transportation, logistics and distribution have often been ignored in mainstream econometrics and characterized as mere derived demand, they are actually value-added activities that both enable and constitute the flows supporting GPNs (Hesse and Rodrigue,

2006). Falling transport costs enabled by technological innovations and low fuel prices have driven a significant share of world trade growth over the past several decades, though income growth and tariff-rate reductions remain the primary drivers (Baier and Bergstrand, 2001). At a local scale, port characteristics such as berth dimensions and intermodal connectivity are critical in determining where and how firms will conduct operations (Bird, 1971; Stopford, 1997). That most goods are now transported in standardized containers requiring specialized cranes and delivery mechanisms underscores the indispensable role of modern logistics in the world economy (Levinson, 2006).

Many factors besides transportation combine to create the specific geography of production underlying economic networks. Rather than locating randomly or as prescribed by normative rules, firms choose to locate in places with specific contextual advantages tied to infrastructure and state regulation. Why industries become established in some areas and not in others is the subject of a lively and contested development literature and remains one of the central research topics in economic geography (Storper, 1997; Scott and Storper, 2003; Jofre-Monseny et al., 2014). Analysis of industry clusters has revealed that locating near strategic suppliers often confers competitive advantages that outweigh the cost savings and flexibility of a global-sourcing approach (Steinle and Schiele, 2008). Identifying such locational advantages focuses attention on production and service activities in the specific places in which they are performed. For example, a firm providing management consulting services may derive an advantage from locating near its client firms with access to a skilled workforce, despite the availability of telecommunications technologies allowing client meetings at a distance and relatively high mobility of skilled labor. A key attribute of TNCs as lead firms is their ability to exploit geographical differences that advantage firms in some places and not in others, such as

differential regulations and resource endowments. This geographic unevenness underscores the role of non-network factors such as state policies and the physical environment in determining the spatial organization of value chains. Even as they promote an integrative and transnational view of economic relations, networks are highly territorial (Coe et al., 2004; Coe et al., 2008).

5.3.2 Extractive chains

While geographic context shapes network-building processes in all economic sectors, it is especially important to extractive industries. The extractive sector encompasses all firms involved in the extraction, processing (refining), and delivery of renewable and non-renewable natural resources, including but not limited to energy hydrocarbons (coal, oil and natural gas), biomass (food, timber, and other non-food crops), and minerals (metals and other naturally occurring abiotic substances). Owing to the need for raw materials in all manner of production circuits, extractive industries occupy the initial stage of value chains in nearly every non-service sector of the global economy. Despite accounting for only a small share of world production and trade, minerals remain essential building blocks for all modern economies to the extent that national strategic priorities are often oriented toward their acquisition and control (UNCTAD, 2007). Oil and other fossil fuels are particularly indispensable, satisfying 87% of total energy demand worldwide and nearly all demand in the transportation sector (BP, 2012). The robust inverse relationship between global GDP and oil price underscores the profound dependence of the world economy on the widespread provision of a few relatively homogenous commodities. However, extractive industries and raw materials have largely been absent in analysis of value chains, with disproportionate emphasis placed instead on later stages of production (Bunker and Ciccantell, 2005; Smith, 2005). Likewise, most studies of extractive development have avoided

transnational and network-based approaches in favor of a narrower focus on the role of the state in achieving development goals (Bridge, 2008).

The work of Gavin Bridge (2005; 2008; 2010; 2013) has been instrumental in uniting the territorial and networked dimensions of extractive industries. Despite the relative neglect of the extractive sector in the GPN literature, Bridge (2008) points out that many issues germane to natural resources such as geographical shifts in demand, new “extractive frontiers,” and power shifts between global oil majors and states are compatible with a GPN agenda. The structure of value chains in the extractive sector likewise shares much in common with that of other sectors commonly associated with a GPN mode of production, such as manufacturing. As in many sectors, production circuits in the extractive sector comprise a diverse typology of firms reflecting varying degrees of functional integration and geographic dispersion. The international oil companies (IOCs) that currently dominate the private oil sector (e.g. “supermajors” ExxonMobil, BP, Royal Dutch Shell, Total, Chevron) and many large state-owned national oil companies (NOCs, e.g., Saudi ARAMCO, China’s CNPC, Iran’s NIOC) retain the characteristics of vertically integrated companies in their engagement with all segments of the oil value chain: upstream (exploration, production), midstream (transport, refining), and downstream (distribution, retailing) (Bridge, 2008; Dicken, 2011). At the same time, these large firms promote the growth of global extractive production networks by coordinating the activities of smaller companies specializing in a limited number of functions. These firms typically specialize in either upstream (independent producers, e.g. Apache, Eurogas) or midstream/downstream functions (independent transporters, refiners and distributors, e.g. HollyFrontier, TransCanada), or provide field services such as drilling and logistics to other producing firms (e.g. Parker Drilling; Baker Hughes). Upstream activities often require the

services of multiple firms, whose interactions are sufficiently complex as to be understood as a networked project in itself (Bridge, 2008). Focusing on a single midstream activity such as refining also allows independent operators to invest in additional capacity that would have been neglected by integrated firms due to higher returns on investment in exploration and production assets (Pfeifer, 2013). In these service firms we see something of the semi-independent “turn-key” suppliers found in many industrial sectors, so named because they provide multiple related services with relatively little input by lead firms (Sturgeon, 2001), with some such firms (e.g. Halliburton) offering an array of extractive services in order to position themselves as a “total solution” capable of occupying multiple functional roles. As in other sectors, lead firms in the extractive sector obtain increased flexibility and returns to scale from adopting a modular, vertically disintegrated production strategy. Of course, such a strategy carries risks as well as benefits, exemplified in the extreme by the functional disengagement between BP and its partner service firms (rig operator Transocean and contractor Halliburton) preceding the Deepwater Horizon disaster (BOEMRE, 2011).

Despite these similarities, production networks in the extractive sector differ from those of other sectors in several important ways. Of particular importance to the structure of extractive industries is the role of the state in both creating the institutional context for and directly participating in extractive activities. States are intimately involved in production networks in many sectors by enforcing regulations, encouraging the growth of specific industrial sectors, investing in education and infrastructure, and competing and collaborating with other states to attract foreign investment and capture value from international trade (Knox et al., 2008; Agnew, 2009b; Dicken, 2011). Bridge’s depiction of a generalized production network for oil (2008, pp. 399) illustrates the capacity of states in extractive networks to enact health, safety and

environmental regulations, collect taxes, and grant exploration licenses. But the state also extends beyond these functions to act as resource producer by controlling the activities of its national oil companies (NOCs). These firms are increasingly taking the role of lead firms traditionally held by IOCs by acquiring or entering into partnerships with independent producers and service firms (The Economist, 2013). Such direct market involvement by the state is especially important in the oil and gas sector as these resources comprise a majority of the state revenues of several key exporters, such as Russia, Norway, Saudi Arabia, and Venezuela. Figure 5.1 expands upon the upstream and midstream elements of Bridge's diagram to include this critical state capacity while also highlighting the sub-national spaces in which extractive activities occur. These spaces constitute critical elements of the spatial context underlying networks in ways the state alone cannot. For example, while states have authority to grant exploration licenses, they may have little influence over the local political environment at drilling sites. Resistance from local populations and court injunctions may prevent or delay drilling even when projects have state support. Such site-specific factors are critical in the extractive sector as resources are necessarily found in specific places. Production costs vary widely from project to project as resources are highly heterogeneous in their materiality—a product of their specific geology, chemistry, and physical accessibility. Oil and gas must be transported to midstream processing facilities (e.g. refineries; mills) and/or markets via specialized, capital-intensive infrastructure (e.g. pipelines; ports; tanker vessels) often requiring substantial foreign investment. Furthermore, the routes these infrastructures take are often politically contested and constrained by biophysical factors such as distance, climate, terrain, and wildlife distribution.

These elements of finance, infrastructure, physical environment and local politics reveal that different stages of the value chain are differentially embedded in or across different places. While they are often omitted from simple formulations of GPNs, they actually constitute different kinds of networks that act at different stages of the value chain. Abstracting beyond the particulars of the value chain to which “the network” nominally applies thus suggests that there is a qualitative continuity across the network in how it operates. Yet, in fact, and specifically in the case of the oil-gas value chain, the precise economic processes driving the different stages or links in the chain are distinctive. So, if at one stage the economic process is primarily about localization economies at the source between firms intimately involved in exploration and extraction, at subsequent stages so-called network externalities associated with transportation agents and mechanisms (pipelines, ships) and full-blown agglomeration economies (mixes of localization and urbanization economies) are crucial (Figure 5.1). Localization economies are the returns to firms from locating close to firms in the same sector that they operate in, while agglomeration economies are the combination of localization economies and those economies produced by urbanization (affiliated services, training programs, deep labor pools, attractions, etc.) associated with urban centers (Jofre-Monseny et al., 2014). Network externalities are returns to connectivity across physical networks such as pipeline and other transport infrastructure that determine where and how much product is delivered. The functioning of these networks are themselves influenced by factors of place such as climate and environmental change (Stephenson et al., 2011; Stephenson et al., 2013a; Stephenson et al., 2013b). Clearly, there is no singular economic process at work across the entire production chain or “network” in the overblown sense. Overuse of the term “network” thus risks conflation of several complementary but distinct ideas, unless effort is made to identify which networks are operating

where. Thus, it is instructive to think of Bridge's "generalized production network" as a value chain composed of different types of networks at different stages. Describing the whole value chain as a network and implying that the economic processes associated with the chain as a whole are all based in a uniquely networked ontology are not fruitful in characterizing how chains such as those bringing oil and gas to global markets actually operate. This is not to dismiss the value of GPNs as a way of thinking about relations and flows in the extractive sector, but rather to suggest that the differential embeddedness of the chain is crucial to understanding its workings, and the manifold variety of meanings inherent in the term "network" demands precise articulation and careful elaboration.

The finiteness of non-renewable resources imposes pressure on firms to continually invest in exploration with no guarantee of success, and increasingly with diminishing returns as cheaper, relatively accessible deposits become scarcer over time. Thus, firms must operate in diverse, continually evolving spatial contexts in a context of shifting political attitudes and environmental change. While crude oil itself is a largely homogeneous commodity varying mainly by sulfur content, oil extraction is a highly diverse enterprise involving a multitude of actors, capital endowments, technologies, physical environments, and regulatory regimes. Places with a history of drilling are likely to have extant infrastructure and institutional frameworks that facilitate further drilling, while development in remote areas may be hindered by lack of the same. The opposite is also true, as past experience with the negative environmental and social impacts of extractive industries may impel communities to mobilize against new extractive projects. Local dynamics may strengthen or mitigate external drivers such as market demand and national strategic objectives, revealing the specific positionality of places within broader regional and global contexts (Sheppard, 2002). It is thus necessary to elevate geographical particularities

above mere “local messiness” to form the basis of understanding of resource economies (Barnes and Hayter, 2005). Framed in this way, networks are a useful way of conceptualizing the myriad relationships that promote extractive development in specific places.

5.4 Place embeddedness in northern resource peripheries

5.4.1 Tapping the Arctic

The Arctic and sub-Arctic are an instructive setting for examining the context dependence of oil and gas networks. The region is host to diverse and numerous state and private actors whose activities are both driven by external market pressures and constrained by local political and environmental factors. The extractive history of northern states is marked by differences between market-oriented resource capitalism in the US and Canada and autarkic state-directed development in the former Soviet Union, setting the stage for the present collection of actors dominated by IOCs in North America and state-controlled firms in Russia. The networks in which these firms operate also encompass numerous small producers operating independently and under contract with larger firms, as well as states with unique regulatory and development agendas. Conventional oil extraction began in the 1960s in both Alaska (Prudhoe Bay) and west Siberia, and production declines from these mature fields have led companies in both regions to expand northward into more remote and environmentally challenging areas, including offshore in the Pechora, Kara, and Chukchi Seas. Such exploration is critical for Russia, whose oil production is projected to decline by 1 million barrels per day by 2020 without Arctic drilling (Kramer, 2013). In contrast, aggressive exploration in Alaska is not critical for the US, which is currently enjoying a boom in domestic energy production in the contiguous states.

Recently the notion of the Arctic as a new global extractive frontier and resource “El Dorado” has gained traction with the continued retreat of summer sea ice, which reached a

record minimum extent in 2012. This rapid decline coincided with the 2008 USGS release of estimates of undiscovered and technically recoverable conventional oil and gas in the region, fueling speculation that Arctic resources would become increasingly accessible (Bird et al., 2008; Gautier et al., 2009; Stephenson et al., 2013b). The oft-cited report estimated that 90 billion barrels of oil and 1669 trillion cubic feet of gas lie north of the Arctic Circle, 84% of which is offshore and concentrated mainly within the exclusive economic zones (EEZ) of Russia (west Siberian Basin, east Barents Basin) and Alaska (Beaufort Sea). Despite their unambiguous ownership, these reserves have occasionally been at the center of media tropes predicting an imminent “Arctic rush” for resources and geopolitical advantage, underpinned by neorealist accounts of the state within international relations (Bridge, 2013; Klare, 2013). Apart from a few minor territorial disputes between historically amicable allies (Byers, 2009), the Arctic as a region has experienced little territorial competition between states, and most experts agree that continued ice melt is unlikely to impel states toward a geopolitically-motivated “resource grab” (Young, 2009; Keil, 2013). Rather, the eight Arctic states (Canada, Finland, Greenland/Denmark, Iceland, Norway, Russia, Sweden, and the US) are pursuing various development strategies aligned with distinct national priorities. The resolution of the Barents Sea delimitation dispute between Norway and Russia in 2010 demonstrated a willingness to cooperate even in regions of high oil and gas potential as part of a broader strategy to strengthen international law in the region (Moe et al., 2011).

The so-called “rush” for Arctic resources makes more sense from the perspective of IOCs motivated by dwindling access to inexpensive hydrocarbons at lower latitudes (Maugeri, 2013). Since the 2008 USGS report, numerous global majors including Eni, ExxonMobil, Shell, Statoil and Total have undertaken Arctic drilling projects or have formed joint ventures with NOCs to

do so, underscoring a trend of expanding reserves through relatively high-cost production methods. Conventional hydrocarbons in the Arctic and other remote areas, along with unconventional resources such as bitumen, tight oil and shale gas, are occupying an increasingly large share of the asset portfolios of IOCs as states reserve access to cheaper conventional fields for NOCs. Extraction of unconventional oil and gas requires sophisticated methods involving specialized equipment and manpower at considerable expense (IEA, 2013), and so far has not been sufficient to offset production declines at mature conventional fields. In 2012, the European majors reported a reserve replacement ratio of only 92%, while returns on capital employed in exploration and production fell (Pfeifer and Chazan, 2013). While proliferation of hydraulic fracturing technology has dramatically increased the supply base of IOCs in North America, it has also put downward pressure on gas prices, diminishing returns further as more companies enter the market (EIA, 2012) . Sustained high oil prices, exceeding \$100/barrel on average since 2010, have encouraged pursuit of high-cost strategies despite considerable uncertainty about long-term price projections (Cobb, 2013; Saefong and Sjolín, 2013). Arctic and other “new frontier” plays such as Brazil’s offshore pre-salt fields are thus touted as opportunities for IOCs to diversify assets, increase global reach and close reserve deficits using conventional drilling methods in a relatively unexplored supply base.

Recent Arctic ventures by IOCs have not been encouraging, however. Cold climate, infrastructural scarcity, permafrost terrain, and remoteness from supply routes present common obstacles to extractive development throughout the region. Shell’s nearly \$6 billion Arctic campaign was stymied when its Kulluk offshore drilling rig ran aground the Gulf of Alaska in December 2012. The company has since suspended its plans to drill in the Beaufort and Chukchi Seas and will not return to the offshore Arctic before 2014. Perhaps seeking to avoid similar

mistakes in an uncertain regulatory environment, ConocoPhillips has postponed all drilling in the Chukchi Sea in 2014. Cairn Energy's \$1.2 billion bid to drill in offshore Greenland has yet to produce oil. Partnerships with Russian firms have been mixed, with ExxonMobil and Rosneft moving forward on a Kara Sea joint venture while BP and Rosneft have discontinued the Sakhalin-4 project due to disappointing hydrocarbon potential. Even where exploration is successful, extraction costs will be high. The IEA estimates that Arctic oil will be profitable only if extraction costs remain below \$60/barrel, while actual cost estimates range from \$40-100. Coupled with environmental risks, these costs are likely to stifle exploration and limit production from the entire region to approximately 200,000 barrels of oil per day by 2035, complicated further by lead times of 10-25 years from lease to production (IEA, 2006; IEA, 2013). The Arctic may indeed contain vast quantities of oil and gas, but without a viable business case, the resources will stay in the ground.

The significant potential of Arctic resources coupled with their relative inaccessibility and high operating costs illustrate the evolving roles of NOCs and IOCs in extractive networks. The rise of NOCs in the 1960s and 1970s catalyzed a series of shifts in power between state-owned and international oil companies (UNCTAD, 2007), such that 90% of total global reserves are controlled by NOCs today (IEA, 2012). While NOCs have the advantage of preferred access to resources owned by the controlling state, the majors have generally retained an advantage in technology and expertise. Expansion of Arctic operations, particularly offshore, has increased demand for cold-weather equipment and specialized services such as iceberg management. This has led NOCs to partner with IOCs where resources are remote and/or offshore, as Russia's Rosneft has done with ExxonMobil, Statoil, and ENI. Such deals make sense for majors facing dwindling reserves in mature fields with increased pressure to explore in relatively inaccessible

places. BP, for example, will receive all of its production growth in the medium term from its Russian holdings (Financial Times, 2014). Recent political agreements such as the Norway-Russia Barents Sea boundary resolution in 2011 suggest that technology-access partnerships between IOCs and NOCs will continue to be a primary *modus operandi* in the Arctic (Stephenson, 2012). However, NOCs are increasingly utilizing expertise at various stages of the value chain to close the technology gap while consolidating control over greater quantities of reserves. NOCs often have access to capital from their home states on favorable terms, strengthening their ability to both invest at home and acquire new assets in foreign markets. Furthermore, the proliferation of global oil and gas service firms has meant that the majors are no longer the sole holders of advanced drilling technology. For example, Halliburton is consulting with both Rosneft and ExxonMobil in preparation for the 2014 drilling season (Kramer, 2013). By partnering with oil service firms, state-controlled companies are able to reduce their dependence on the majors for development of their own fields as well as compete with them on projects outside their home markets (The Economist, 2013). Russian NOCs are also forging partnerships beyond this cluster of oil service firms by working with Korean shipbuilding specialists to bolster tanker capacity along the Northern Sea Route (Bennett, 2014). By inserting itself into multiple international networks of specialized expertise, the Russian state is thus attempting to manage the environmental challenges of Arctic drilling while retaining its role as lead firm.

However, knowledge diffusion and the functional fragmentation of production have not made it easy for new firms to enter the market, or for local economies in resource peripheries to benefit equally from oil and gas activities. The capital intensity of oil and gas creates high barriers to entry that reinforce the position of established firms. While specialist firms and

independents now operate globally in both partnership and competition with the majors, these firms are highly concentrated in industrial clusters (e.g. Houston, Aberdeen) that may have been located near extraction sites at one time but remain distant from most resource peripheries today. With its divisible production process, transportable product, coordinated actors with distinct competencies, focus on innovation, and volatile market, the oil and gas industry exemplifies an industry with a high propensity to cluster (Steinle and Schiele, 2002). The inter-firm relations developed in geographical clusters are often replicated in other regions with limited involvement by local actors. Steen and Underthun (2011) observe that most of the key capabilities involved in the development of the Snøhvit natural gas complex were brought by established extra-local foreign and Norwegian firms and subcontractors, despite the intentions of the Norwegian state to use the project to stimulate growth of local firms in Hammerfest. While this may appear to downgrade the importance of local context in shaping production at Snøhvit, these contracts were enabled by state anti-discrimination legislation allowing lead firms to retain the services of their preferred (extra-local) partners. In this way, the institutional embeddedness of the GPN at Snøhvit was as essential to its operation as its networked character.

5.4.2 Ownership, infrastructure, and the Russian state

Arctic resource optimism and uncertainty both stem in part from a romanticization of the region as an untapped “treasure trove” which the state may decide to either exploit or leave for future generations. Northern resource development has long been directed by market demand and political decision-making from southern population centers (Innis, 1930; Jensen et al., 1983; Bone, 1992; Southcott, 2010), highlighting the central role of the state as resource owner as well as producer (Coe, 2011). Decisions about whether to open lands to extraction are often framed as efforts to realize the value of “buried treasure” with the (sometimes implicit) rationale that the

economic benefits will be shared by all (Bridge, 2004). Alaska's Permanent Fund and Norway's Government Pension Fund are examples of public resource revenue sharing, though both funds distribute benefits statewide rather than proportionally to communities most directly involved in and impacted by extractive activity. That oil and gas resources are nonrenewable and tied to specific territorial spaces further enhances their perceived value as strategic national assets.

The notion of collective national resource ownership can lead to anxiety about opening extraction to foreign firms, especially if the firms can leverage an advantage in technology or other capital toward favorable terms. China's strategy of pursuing long-term dominance in the international oil market through diplomacy and investment in Africa exemplifies a sort of de-facto resource ownership resulting from such uneven bargaining positions (Taylor, 2006).

Ownership of transportation and support infrastructure is nearly as important as ownership of the resources themselves due to investment requirements often amounting to billions of dollars for a single project (UNCTAD, 2007). Costs are especially high in the Arctic and sub-Arctic due to lack of connections to existing road, rail and pipeline networks (ACIA, 2004b). If funding for pipelines is unavailable, firms must rely on multimodal transfers over winter roads and railways, as Gazprom Neft has done with oil from its Novoportovskoye field (Staalesen, 2013). Initially, states may be reluctant to pursue such investments without contractual guarantees from TNCs, which have flexibility to relocate operations to take advantage of differential regulatory or tax regimes. Once infrastructure is in place, however, these investments become "sunk costs" affording the state a stronger bargaining position for both attracting the business of TNCs and controlling the direction and magnitude of export flows. Permanent pipeline and road infrastructure are also more reliable than winter roads and marine transport, as winter roads are likely to become unusable in the future due to climate warming (Stephenson et al., 2011) while

shipping seasons along the Northern Sea Route are highly variable from year to year (Stephenson et al., 2013a).

State control of both upstream and midstream operations is a cornerstone of Russia's hydrocarbon development strategy. During the 2000s, Gazprom acquired the majority of gas assets in east Russia, including the East Siberian Chayanda and Kovykta fields which are expected to form the basis for pipeline exports to China (Henderson and Stern, 2014). Nearly 70% government-owned Rosneft controls 40% of Russia's crude oil production following a series of takeovers of former rivals beginning in 2004 (Reznik et al., 2014). In total, state-owned enterprises account for more than half of Russian GDP. While seeking to position itself as a global player by acquiring stakes in foreign projects, Russia has been cautious about involving foreign firms in its domestic activities, selling limited minority ownership mainly where its state-controlled firms lack required technology or expertise. Russian firms likewise have been reluctant to engage in production sharing agreements with foreign firms despite the fact that the state would retain resource ownership under such agreements (Hober, 2013). The government also controls over 10,000 kilometers of pipeline transporting 88% of the oil produced in Russia through its controlled company Transneft, the largest such network in the world (EIA, 2013a). Ownership of these pipelines enables Russia to adjust export volumes with its state objectives, including pressuring European customers to accept high gas prices pegged to the price of oil. However, Russia's transport networks do not extend everywhere it sells gas. By October 2014, new EU rules aimed at increasing competition in the energy sector will force Gazprom to sell its minority stake in Lithuania's national pipeline company (Chazan and Buckley, 2013). The move will allow Lithuania to reduce its dependence on Russian energy and seek cheaper alternatives, such as North American LNG through its planned Baltic Sea import terminal. In order to retain

its core business in the EU, Gazprom will need to reform its pricing scheme to adapt to a new transport regime of limited ownership. Gazprom has hinted it may be willing to do so, but continues to use geopolitical threats to obtain leverage in the negotiations, most recently by announcing plans to bypass Lithuania's pipeline by shipping LNG to its Kaliningrad enclave via the Baltic Sea.

The challenges Russia faces in supplying oil and gas to Europe contrast sharply with those it faces in East Asia. Russia supplies gas to Europe via a robust network of 6 oil pipelines (Druzhba, Baltic 1 & 2, North-West, Caspian, Baku-Novorossiysk) and 5 gas pipelines with a combined capacity of nearly 170 billion cubic meters per day (Northern Lights, Yamal-Europe I, Soyuz, Bratstvo, and Nord Stream) (EIA, 2013a) (Figure 5.2). However, European demand for Russian hydrocarbons has flagged in recent years due to slow economic growth and competition from LNG and coal. Conversely, demand for oil and LNG is high in East Asia, but these markets are served by only one oil pipeline (East Siberia-Pacific Ocean [ESPO]), one LNG plant (Sakhalin-2) and no gas pipelines. The ESPO pipeline enabled Rosneft to strike several supply agreements with China in 2013 including one for \$270 billion over 25 years (Rudnitsky and Kravchenko, 2013). Fulfilling these agreements will require Transneft to more than double the capacity of the current pipeline to 1.6 million barrels per day at a cost of \$4.9 billion. Gazprom made a similar pivot toward Asia by signing a 30-year MOU with China to supply at least 38 billion cubic meters of gas per year from new fields in eastern Siberia starting in 2018 (Chazan and Buckley, 2013). However, the deal is contingent upon Gazprom completing the so-called "Power of Siberia" pipeline, which will connect remote gasfields in Yakutia with Vladivostok and several entry points into China. For now, Gazprom is moving ahead with nearly \$40 billion in investments despite uncertainty over its ability to budget for the pipeline before securing a

pricing agreement with China (Soldatkin, 2013). Whereas in Europe, excess transport capacity and political squabbles are hindering the efficiency of Russia's petroleum network, in Asia, both production and transport capacity are limiting factors.

The divergent trajectories of these markets raise questions about the future direction and economic viability of Russian Arctic gas. Gazprom has already shelved development of the immense Shtokman field in the Barents Sea, citing high infrastructure costs and reduced US demand due to plentiful domestic shale gas. The pace of development of its Yamal Peninsula fields is likewise uncertain. Falling domestic demand prompted Gazprom in October 2013 to revise downward its growth projections at the Bovanenkovskoye field and delay some pipeline construction. However, one week later it announced the opening of 13 new wells at the field, and began production at the nearby northeast Urengoy field later in the month (Arctic Info, 2013b; Arctic Info, 2013a; Arctic Info, 2013c). These conflicting actions suggest that the company is still determining the precise role of Arctic gas in its reserve portfolio despite needing new resources to replace declining production at its mature fields. Thus far, Russian companies have been able to secure foreign investment for pipelines in eastern Siberia as an advance against future production without ceding majority control of any project. However, distances between fields and destination markets severely constrain the geographic distribution of such investments. While eastern Siberian oil fields with close proximity to the ESPO pipeline make likely investment targets for Asia, Yamal gas pipelines make sense only as a conduit to Europe. Gazprom plans to continue westward transport of Yamal gas by expanding capacity of the Bovanenkovo-Ukhta pipeline, linking up with the Yamal-Europe and Northern Lights pipelines. This makes sense in the context of leveraging existing infrastructure, but further commits Gazprom to a waning and increasingly politically volatile demand market.

In parallel with Gazprom's pipeline projects, the Russian state has turned to LNG as a way to deliver its Arctic gas to high-demand markets. While oil shipping from the Arctic has been ongoing via the Varandey terminal on the Pechora Sea since 2008, gas shipping from the region will be led by Yamal LNG, Russia's second LNG plant and first in the Arctic. The project, majority-owned by independent producer Novatek with minority partners Total and CNPC, is planned for completion in 2016 with a total liquefaction capacity of 37 million cubic meters (EIA, 2013a). Recognizing the potential of persistent high future LNG prices in Japan and Korea, Putin ordered the government in October 2013 to increase tax incentives for gas production on the nearby Gydan peninsula if the gas produced there is sent to Yamal LNG. The tax breaks are estimated to save Novatek over \$4 billion while significantly boosting its resource base (Sladkova, 2013). Even more significant was the decision two months later to liberalize exports of LNG, ending Gazprom's long-standing monopoly on gas exports. The move followed a series of signals of strong government support for Yamal LNG despite the fact that foreign firms own 40% of the project and Russian state-controlled companies hold no stake.

Yamal LNG illustrates how Russian gas depends on the intersection of the physical environment, state objectives, and connections to global transport systems. Because LNG cannot be transported by pipeline, it must be shipped along the adjacent Northern Sea Route in specialized tankers designed to maintain gas in a liquid state. Eastward passage is limited to summer as the route is seasonally ice-covered nine months of the year. Russian law requires vessels to be escorted by icebreaker when ice is severe, effectively allowing the government to act as regional logistic gatekeeper through its state-owned icebreaker company, Rosatomflot. The company recently placed an order for its eighth nuclear icebreaker and is expected to sign a 40-year contract to provide icebreaker services to Yamal LNG in early 2014. Enabling regular

passage along the Northern Sea Route will not only generate greater tax revenues from more frequent shipments, but will also demonstrate the feasibility of the route for transit shipping from outside the region. This has the potential to generate substantial revenues from transit fees, depending on the type and quantity of cargo (Stephenson et al., 2013a). The state may adjust its escort fee structure with its economic priorities, either to raise revenues or encourage greater transport volume. Thus, transport of Yamal LNG depends greatly on local ice conditions and state strategic objectives, both of which may seem to reduce opportunities for involvement by foreign actors. However, the reverse is true. Transporting LNG outside of the summer ice-free period requires considerable investments in the form of ice-class vessels capable of clearing paths through young ice. Yamal LNG project managers estimate that 16 such vessels will be needed for regular year-round shipments to Europe, for which the first contract was won by Korean shipbuilder DSME amid bids by numerous international consortia. While the state stood to benefit from a closer business relationship with Yamal LNG through contracts with its controlled shipping company Sovcomflot, Yamal LNG's imperative to quickly ramp up logistical support demanded engagement with international shipbuilding networks. Furthermore, transport to distant markets will involve transfer of LNG from ice-class vessels to ordinary tankers, requiring transfer contracts with foreign ports such as France's Dunkirk and Belgium's Zeebrugge (Paris, 2014). In this way, developing Yamal LNG as an export commodity engages numerous international networks of logistics, technology, and specialized manufacturing, which project leaders recognize are essential for ensuring reliable and cost-effective deliveries.

5.5 Conclusion

The Arctic remains one of the most significant regions of untapped oil and gas. Unlike in many extractive peripheries, resource ownership is unambiguous and the likelihood of political

conflict in the foreseeable future is low despite increasing offshore activity in newly ice-free waters. Yet unique environmental, infrastructural, and logistic challenges preclude the possibility of a rapid infusion of Arctic hydrocarbons into global value chains. Arctic extractive industries will respond slowly to changes in the energy economy due to high costs and long lead times of connecting remote supplies with preferred markets. Once built, infrastructure may not be quickly redeployed to accommodate shifts in the political and economic landscape. In the Russian case, high pipeline capacity and falling demand in Europe contrast sharply with sparse infrastructure and high demand in East Asia. Resolving this mismatch will be critical to determining the role of Arctic resources in the future global energy mix.

Our aim has been to highlight the simultaneously local and global dependencies of northern development as a counterweight to the mantra of “locating anywhere” that pervades much discussion of global production networks. While natural resources are commoditized according to global standards and prices, the activities leading to their extraction and conveyance are also deeply embedded in national political structures and local environmental conditions. The point is not that networks do not exist in this sector, but rather that contextual embeddedness causes different kinds of networks to be realized at different stages of the extractive value chain. Neglecting place-to-place differences obscures the concrete actors and relations that give network flows meaning, leading to idealized visions of a “world without boundaries” that leave little room for a nuanced account of how the global economy actually works. Conceived in this way, the concept of the network can be potentially misleading as it brings with it notions of a flat, deterritorialized world.

The Arctic, with its rapidly changing physical environment, concentration of resource ownership and means of transport, and distance from refineries and destination markets, offers

an instructive case of a region with numerous opportunities and obstacles for global extractive networks. The pace of oil and gas extraction in this region will depend substantially on how states adapt their development objectives to accommodate IOCs and service firms capable of operating in cold climates with highly variable sea ice conditions. More so than other industrial sectors, natural resources are deeply tied to specific spaces of production and transportation. Where and how resources are extracted, where they will go once extracted, and how they will get there are decisive questions that make or break the viability of a project. For these most basic building blocks of the global economy, spatial embeddedness matters enormously.

5.6 Figures

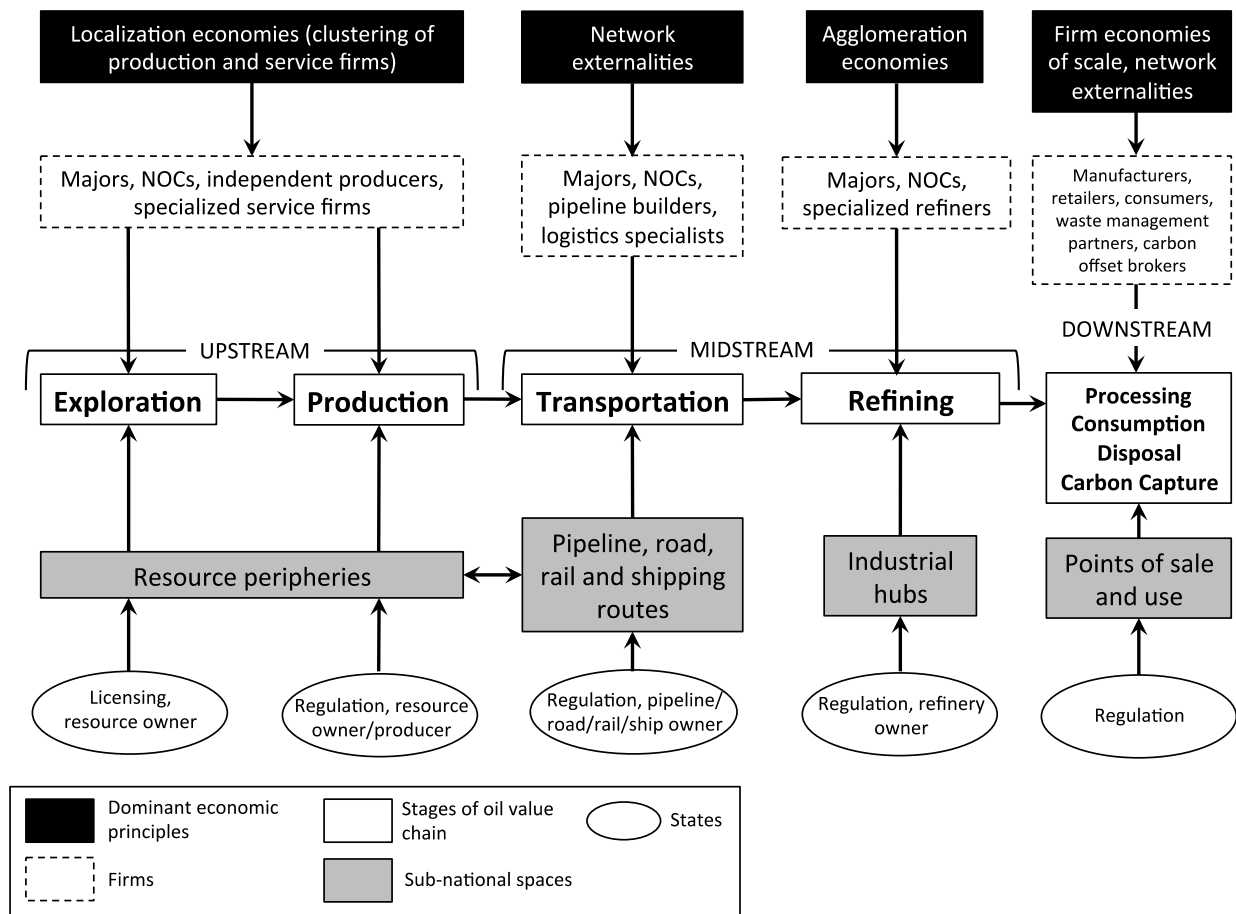


Figure 5.1: Generalized production network for oil, adapted from Bridge (2008).

6. Conclusion

Transportation systems in the Arctic will undergo profound changes in the coming decades. Observed and projected trends in sea ice recession have signaled that marine access will continue to rise for most vessel types in summer, while vessels with some icebreaking capability will have expanded access year-round. However, considerable uncertainties remain about the economic impacts of these changes. Resource extraction and transit shipping are risky and expensive enterprises in the Arctic, owing to high infrastructural costs, commodity price fluctuations, navigation season uncertainty, and potentially severe environmental impacts. Resource development and shipping will require considerable investments in infrastructure in order to operate safely and adapt to a changing global economy. In particular, transit shipping will require significant overhaul of port facilities to accommodate cargo transfer between ordinary freighters and ice-capable vessels. While shipping is likely to continue to increase in the near term, it may be many years before Arctic cities become fully integrated within global resource and transportation networks.

Given the climatic and economic uncertainties, one might envision several contrasting scenarios of future urban development. Taking Russia as an example, in one scenario, persistent and unpredictable ice conditions and rising global oil and gas supplies stymie the creation of an Arctic marine transit network based on the NSR. An opposing scenario sees rapid decline in ice extent and attendant expansion of the navigation season combined with high oil prices precipitating large investments in port infrastructure, accelerating expansion of oil and gas activities. In this latter scenario, investment will occur where economic incentives are present and where new infrastructure complements existing facilities and supply lines in fulfilling a strategic or commercial objective. It is thus plausible that Naryan Mar, situated on the seasonally

ice-free Pechora Sea with close proximity to the Varandey oil terminal and Prirazlomnoye offshore oil field, will be a target of future investment while Tiksi, located far from planned hydrocarbon projects and potential NSR transshipment hubs, will not. Whereas NSR infrastructure in the Soviet period was developed to be independent of international commodity flows, new infrastructure will be built to capitalize on opportunities created by these same flows. Russian Arctic development will thus proceed as a series of targeted investments that favor coastal settlements in areas of high resource potential.

History suggests that national development priorities, rather than retreating sea ice, will continue to be a primary driver of these investments. As in the Soviet era, current resource projects are being driven by policy, exemplified by government investments exceeding 47 billion RUB to expedite construction of the Yamal LNG export facility even though ice is present most of the year in the Ob Bay. Such decisions are ultimately the primary determinants of shipping, reducing sea ice to a mitigating factor. Absent of such targeted investments, cities hoping to capture revenue from petroleum and transit activities must adjust expectations toward a reality of persistently high operating costs and an uncertain pace of development. Likewise, claims that the NSR will soon rival the Suez Canal as a global shipping corridor are exaggerated. In the near term, transit shipping will continue to be viable for bulk commodities, but the potential for large-scale container shipping remains very much in doubt. To paraphrase Norwegian Vice Admiral Haakan Bruun-Hanssen (Bennett, 2013), the economic future of the Arctic will be driven by “profit, safety, and reliability” rather than circumpolar resource appraisals and melting ice.

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