Projected 21st-century changes to Arctic marine access

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Introduction

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.

Methods

Study area

The area of analysis covers approximately 14 M km^2 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)[1] (Figure 1). The IMO Guidelines Boundary is intended to delineate area with potentially hazardous ice conditions 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, 1982). 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).

[1] 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 67º03'9 N, longitude 026º33'4 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 60º North as far as Il'pyrskiy 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 60º North and thence eastward to the southern tip of Greenland."

Three potential trans-Arctic navigation routes were also analyzed, namely the Northwest Passage (NWP), Northern Sea Route (NSR) and Trans-Polar route (TPR) (Figure 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 1).

Sea ice data – CCSM4

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., 2012). 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).

Ice thickness ranges

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) (Transport Canada, 1998). 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).

Ice type

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.

Thickness and age of multi-year ice (MYI) and second-year ice

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-km^2 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 S4). 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 S1). 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 S5).

Vessel class

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, 2009). The “Type E” class includes vessels intended for ice-free operation only and is defined here as “open-water” (OW).

Results

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 2; Table S1). 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 S2). On average, annual accessible area increases +2.1 M / +2.5 M / +1.9 M km^2 between early-century and mid-century, and +4.6 K / +5.8 K / +5.7 K km^2 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 S3A). 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 2; Table S1). 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 km^2 between early-century and mid-century; +1.4 M / +1.8 M / +3.3 M km^2 between mid-century and late-century; Figure S2). In contrast to PC3 vessels, PC6 vessels exhibit a strong seasonal pattern marked by substantially higher access in summer than in winter (Figure S3B). 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 2; Table S1). 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 S2). Between mid-century and late-century under the highest forcing (RCP 8.5), access gains are sharply higher in July (+4.6 M km^2) and November (+5.3 M km^2). 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 S3C). 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.

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 S4). 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). 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; σ ~15-40), whereas southerly regions such as Hudson Bay and Victoria Strait are nearly fully accessible in summer (average ~110-120 days). Navigation season variability is higher in some straits than others (e.g. M'Clure Strait with σ > 40, vs. Hudson Strait with σ ~0). Variability is particularly high along the eastern rim of the Beaufort Sea (σ ~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 S4). 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). 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 S4). 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). 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 hand

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.

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 S5). 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). 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 S5). 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). Baffin Bay and the southeast are accessible nearly all summer (average ~110-120 days; σ ~5-15). Navigation season is short in the Nares Strait (average ~10-20 days), however, and near zero along the northern coast. Greenland's east coast is moderately navigable, but highly unreliable (average ~25-60 days; σ ~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 S5). 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 ~90-110 days) with moderate variability (σ ~10-25 days) (Figure 3). Navigation season is brief to nonexistent along the north (average ~0-10 days) and northeast (~10-30 days) coasts, with high variability in the northeast (σ ~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).

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 S6). Navigation season at early-century is long compared to other regions within the IMO Guidelines Boundary, but can be highly variable (Figure 3). Seas south of Svalbard and surrounding Jan Mayen are reliably accessible throughout summer (average > 120 days; σ ~0). Navigation season is shorter and highly variable in the Arctic Ocean north of Svalbard (average ~60-100 days; σ > 40). The north Barents Sea east of Svalbard is accessible for most of summer (average > 110 days) but is more variable (σ ~5-25) than the south Barents Sea (σ ~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 S6). 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; σ ~0) (Figure 3). 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 (σ ~35-40). Navigation season east of Svalbard is longer (average ~80-110 days) with fairly high variability (σ ~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 S6). 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; σ ~0) and much shorter north of Svalbard (average ~0-60 days) (Figure 3). 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.

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 S7). 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). 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 S7). 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). 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 S7). 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). 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.

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). 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 (σ ~0), though modestly higher near the northern Alaskan coast (σ ~4-15).

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 S8). 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). 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 (σ ~5-16), higher near the Alaskan coast (σ ~20), and very low elsewhere (σ ~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 S8). 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; σ ~0) (Figure 3). Navigation season is shorter and more variable in the Beaufort (average ~105-115 days; σ ~13-28) and Chukchi (average ~105-120 days; σ ~0-15) Seas, particularly where adjacent to the Arctic Ocean (average ~90-100 days; σ ~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.

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 S9). 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). 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 (σ ~0-7), navigation season in the central Arctic is highly variable, especially north of Svalbard near the Russian boundary (σ ~40-50) and north of Greenland and the CAA (σ ~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 S9). 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). 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 S9). 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). Navigation season length is near zero throughout the central Arctic Ocean with very low variability (σ ~0). Navigation season is somewhat longer and significantly more variable with eastward distance (average ~10-25 days, σ ~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 (σ ~25-37). Overall, the high seas remain highly inaccessible to OW vessels in most scenarios.

Potential Navigation Routes: The Northwest Passage (NWP)

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). While navigation season averages ~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 (σ ~25-43) and lower in the Barrow Strait (σ ~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 (σ ~0-15) Seas and at the Bering Strait (σ ~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 S2). 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). 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 S2).

OW vessels may not navigate in the eastern NWP for more than 10 days in summer at early-century (Figure 3). 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 S2). These short periods of navigation for OW ships represent a strong limitation to use of the NWP for trans-Arctic voyages.

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). 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 S2).

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). 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 S2).

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). 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 S2).

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). 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 S2).

PC6 vessels may navigate along the TPR only sporadically at early-century (Figure 3). 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 S2).

There is virtually no navigation season for OW vessels at early-century along the TPR (Figure 3). 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 S2).

Limitations

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.

Figures S1-S9

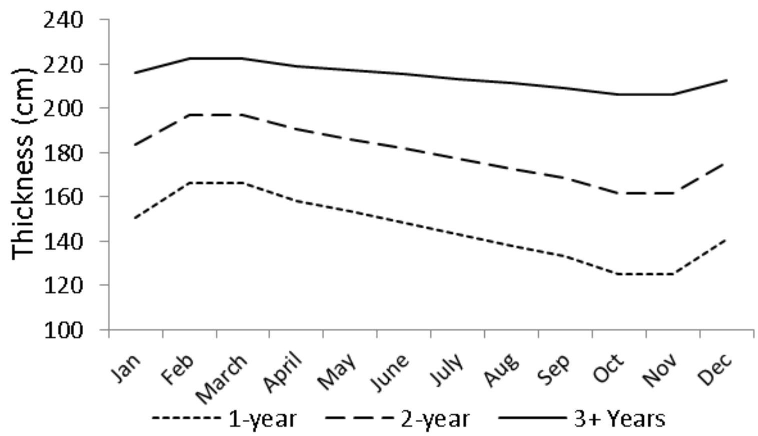


Figure S1: Seasonal change in ice thickness by age class, derived from observed ice thickness (Kwok et al., 2007) and age (Maslanik et al., 2007) for February-March (2004-2008) and October-November (2003-2007). Thickness values for April-September and December-January were interpolated linearly from February-March maxima and October-November minima (see Table S4).

Figure S2: Monthly changes in total ship-accessible area (1000 km^2, left vertical axis and % total, right vertical axis) according to 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.

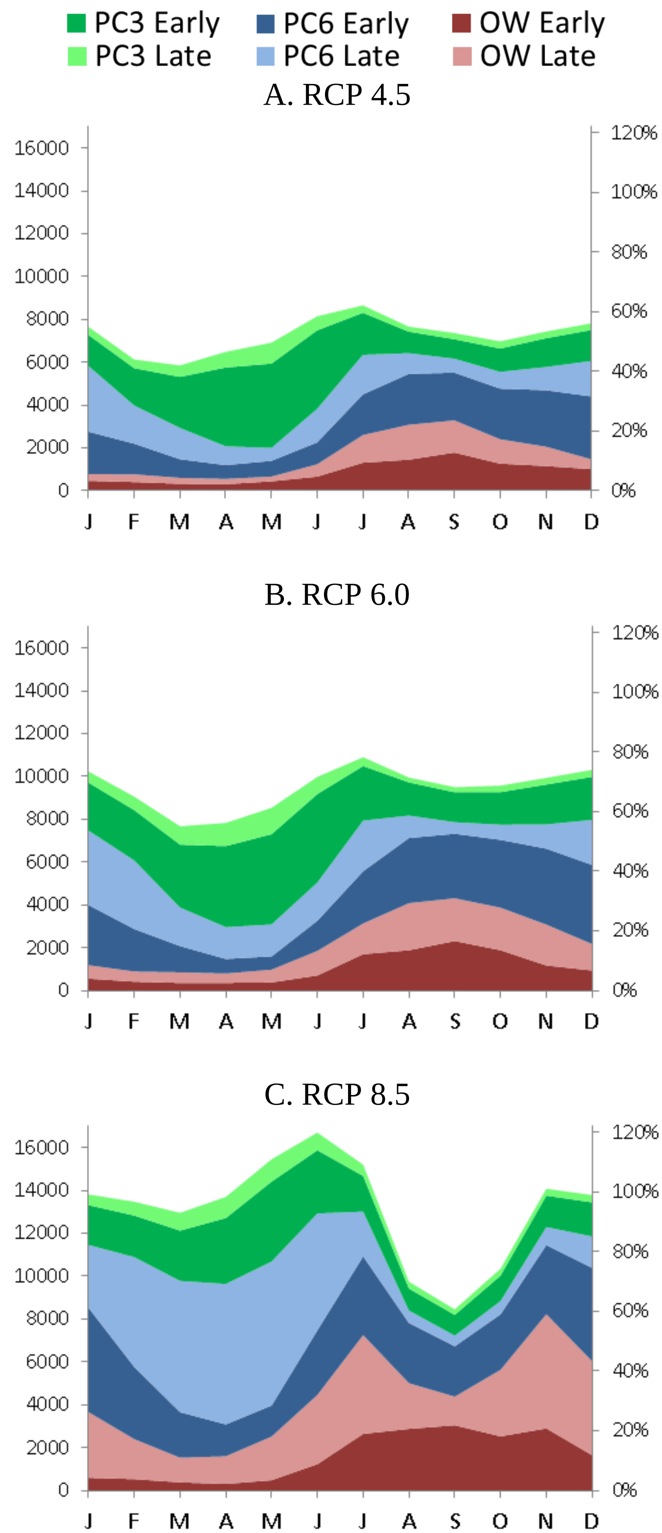


Figure S3: Monthly variations in total ship-accessible marine area (1000 km^2) as a function of vessel class and climate forcing scenario. Red/green/blue lines indicate RCP 4.5/RCP 6.0/RCP 8.5 forcing scenarios, respectively. Triangle/star/circle symbols indicate early-century/mid-century/late-century time windows, respectively. Late-20th-century baseline data (1980-1999; black line) shown for reference.

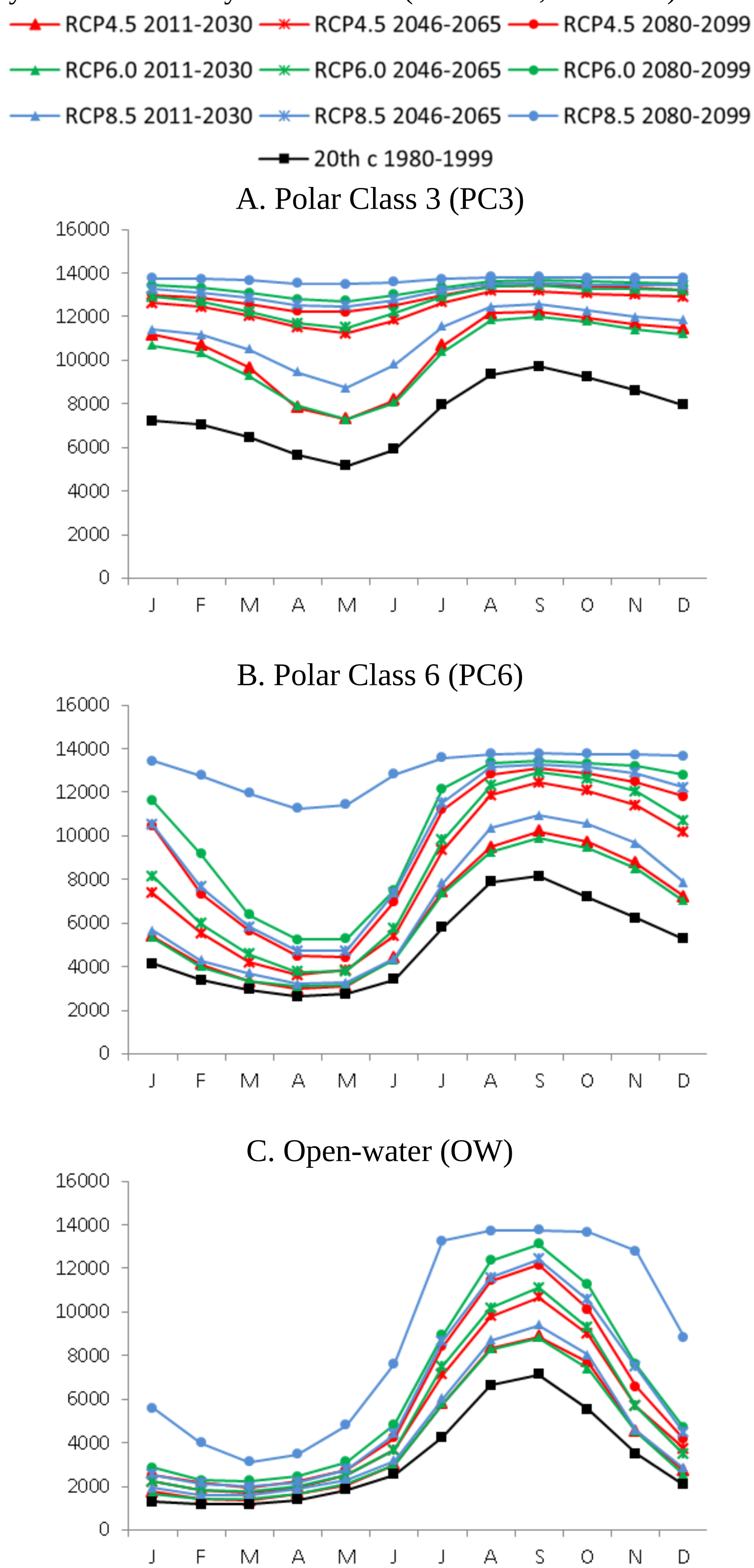
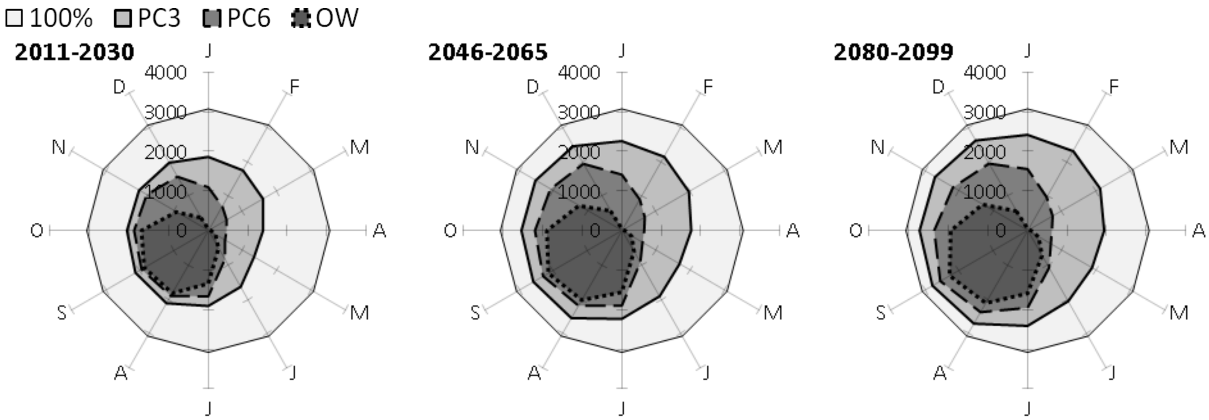
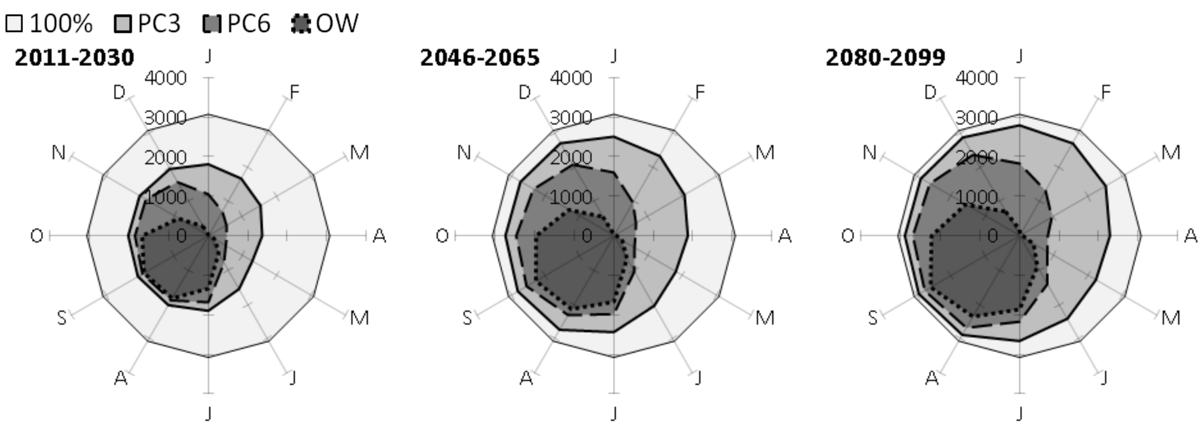


Figure S4: Total ship-accessible marine area in the Canadian maritime Arctic (1000 km^2) as driven by climate forcing scenario (RCP 4.5, 6.0, 8.5), time-averaging window (2011-2030, 2046-2065, 2080-2099), and vessel class (PC3, PC6, OW). Outer circles signify 100% year-round access.

RCP 4.5



RCP 6.0



RCP 8.5

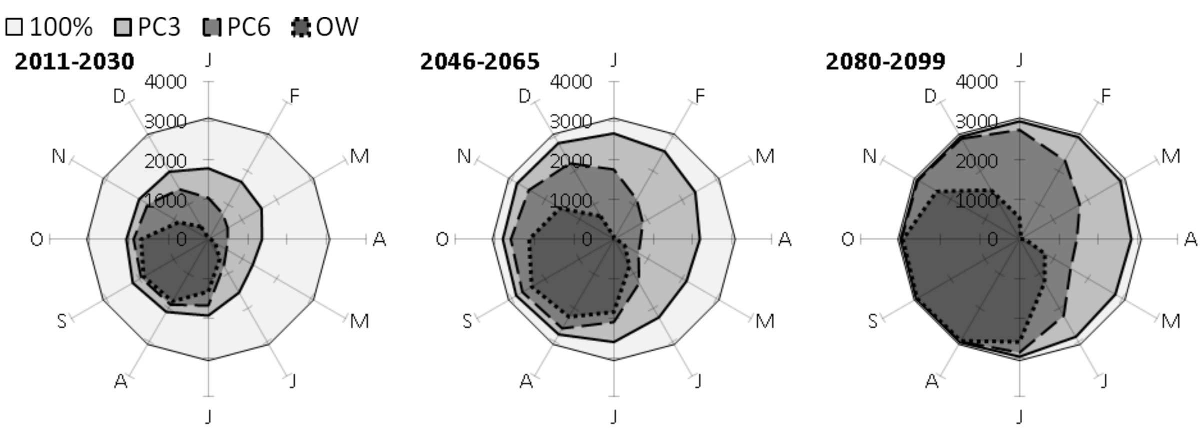


Figure S5: Total ship-accessible marine area in the Greenlandic coastal seas (1000 km^2) as driven by climate forcing scenario (RCP 4.5, 6.0, 8.5), time-averaging window (2011-2030, 2046-2065, 2080-2099), and vessel class (PC3, PC6, OW). Outer circles signify 100% year-round access.

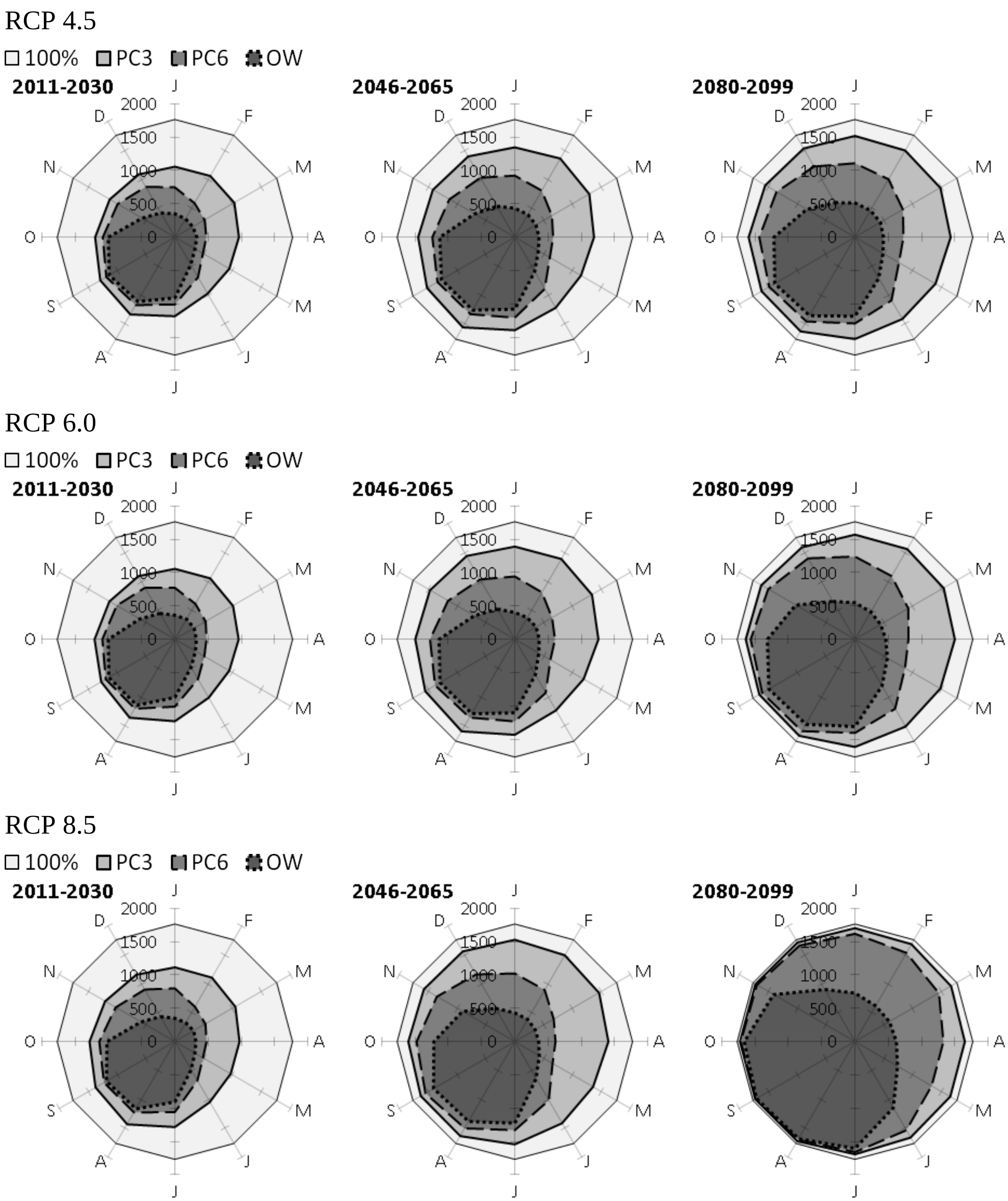
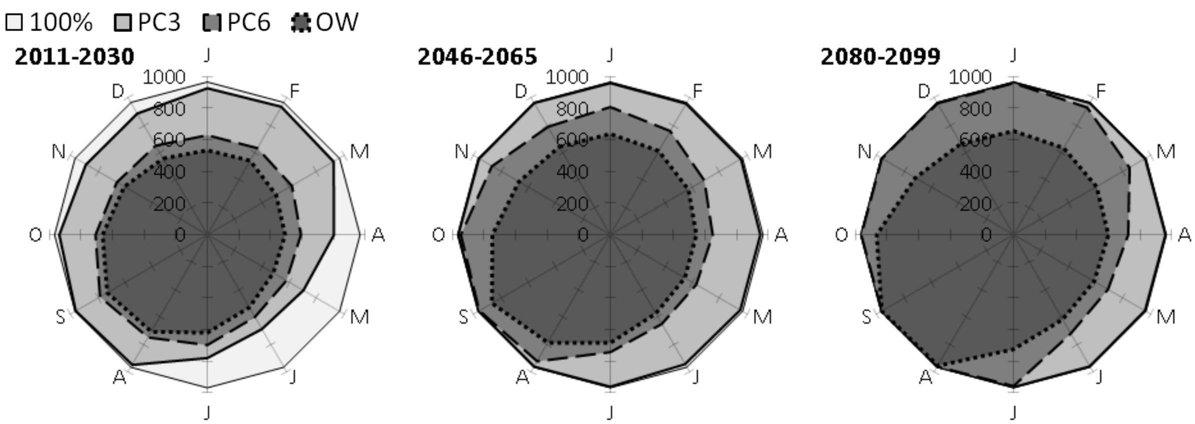
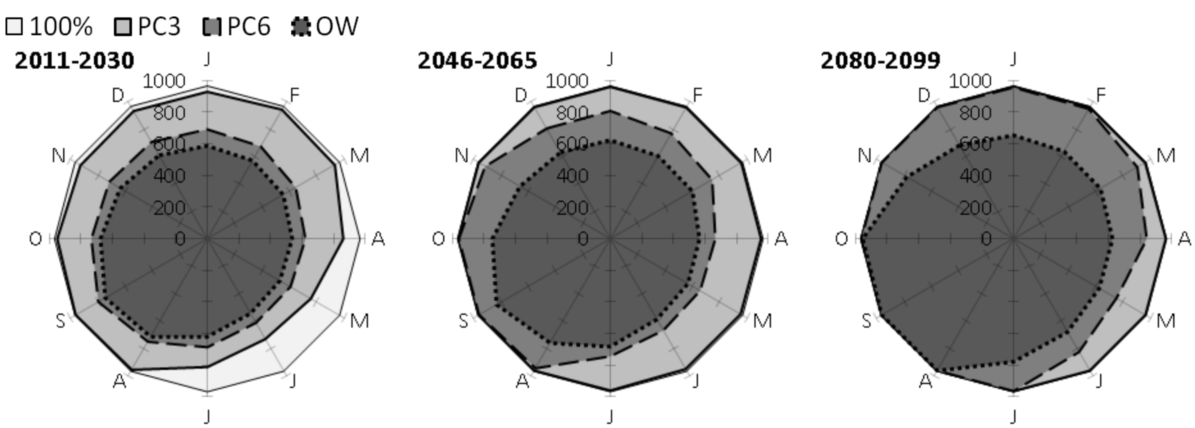


Figure S6: Total ship-accessible marine area in Norway's Arctic EEZ (Svalbard and Jan Mayen) (1000 km^2) as driven by climate forcing scenario (RCP 4.5, 6.0, 8.5), time-averaging window (2011-2030, 2046-2065, 2080-2099), and vessel class (PC3, PC6, OW). Outer circles signify 100% year-round access.

RCP 4.5



RCP 6.0



RCP 8.5

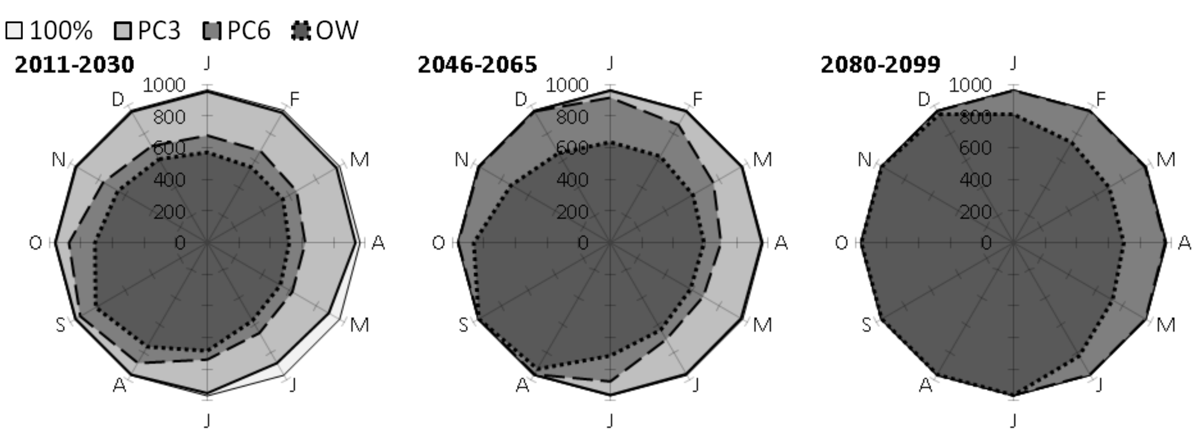
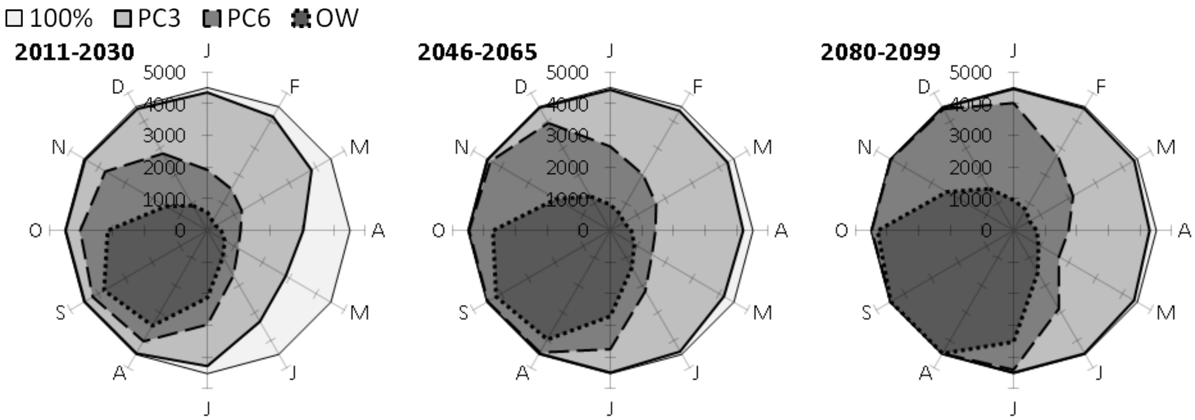
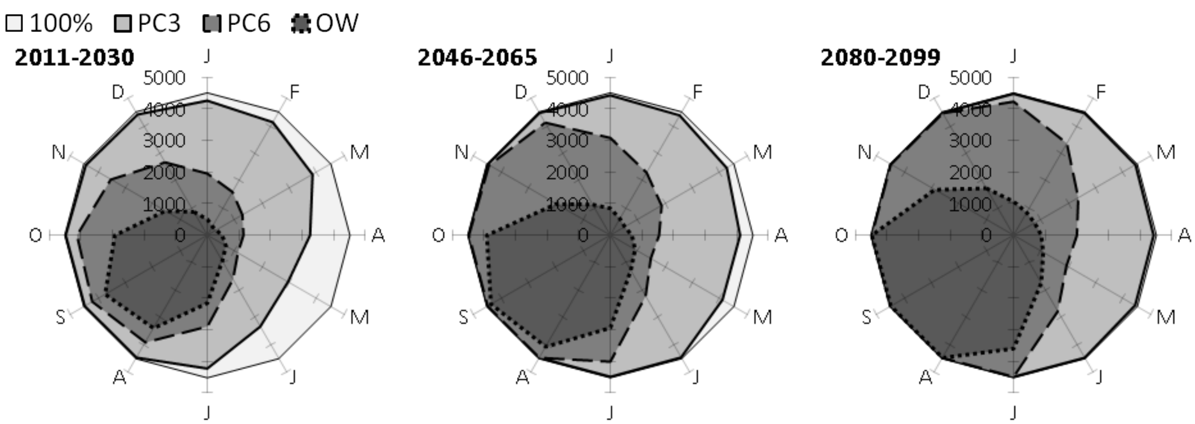


Figure S7: Total ship-accessible marine area in the Russian maritime Arctic (1000 km^2) as driven by climate forcing scenario (RCP 4.5, 6.0, 8.5), time-averaging window (2011-2030, 2046-2065, 2080-2099), and vessel class (PC3, PC6, OW). Outer circles signify 100% year-round access.

RCP 4.5



RCP 6.0



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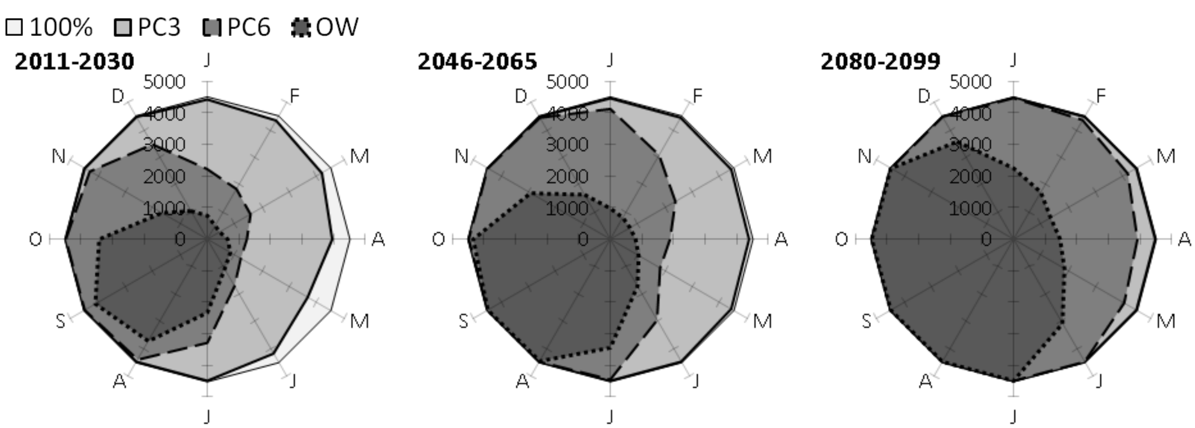
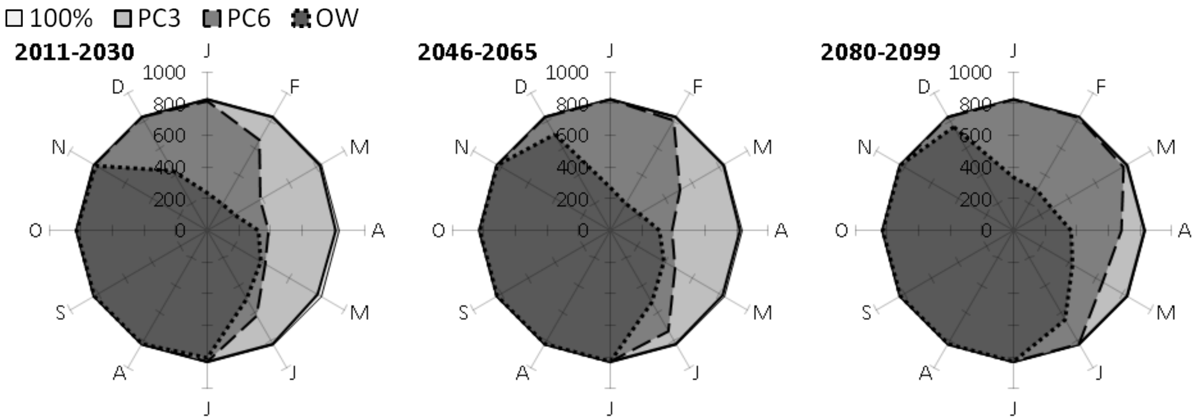
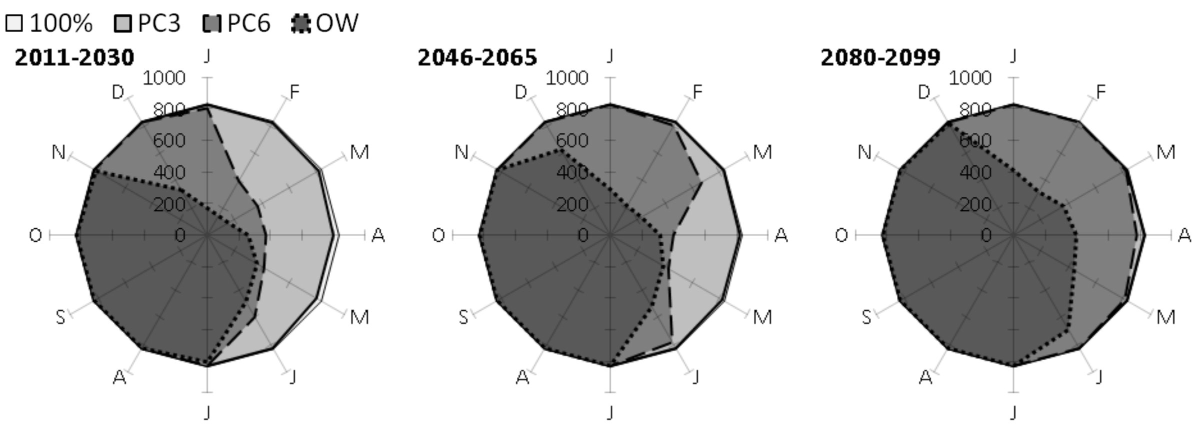


Figure S8: Total ship-accessible marine area in the U.S. maritime Arctic (1000 km^2) as driven by climate forcing scenario (RCP 4.5, 6.0, 8.5), time-averaging window (2011-2030, 2046-2065, 2080-2099), and vessel class (PC3, PC6, OW). Outer circles signify 100% year-round access.

RCP 4.5



RCP 6.0



RCP 8.5

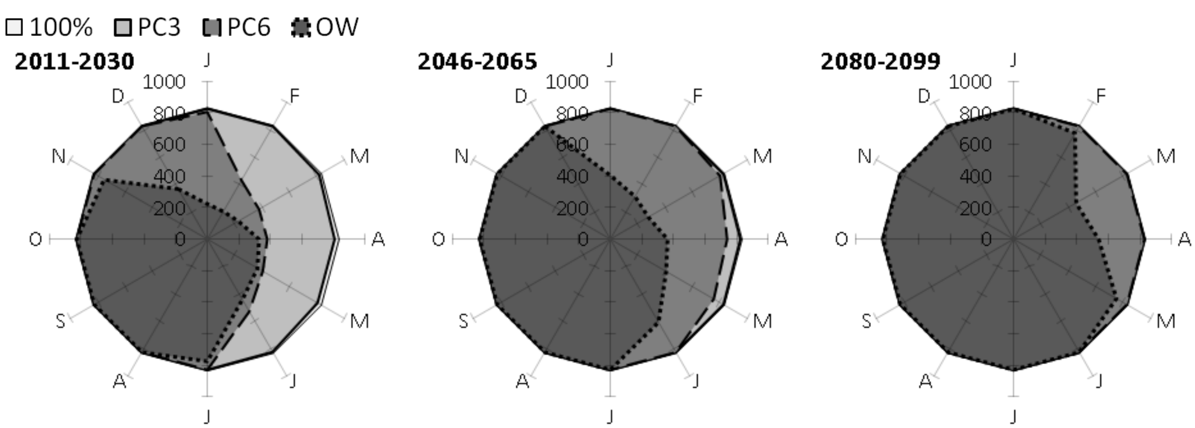
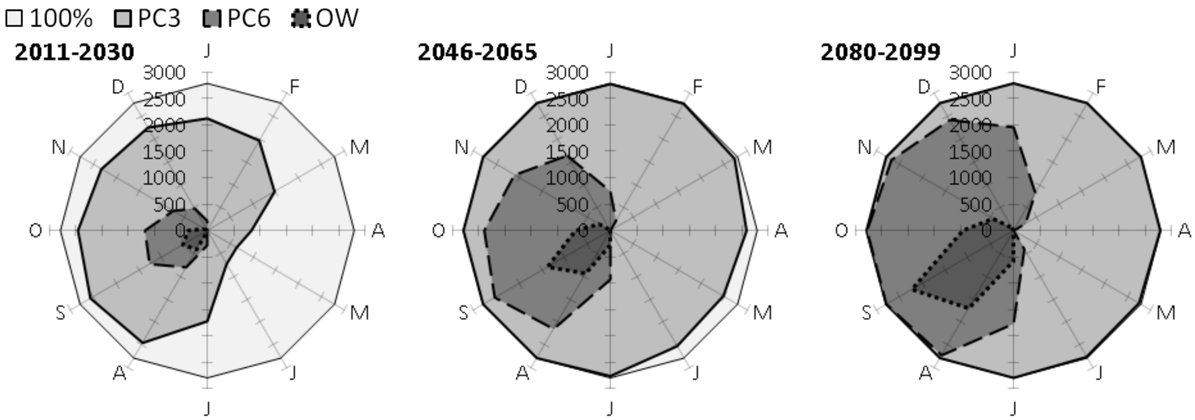
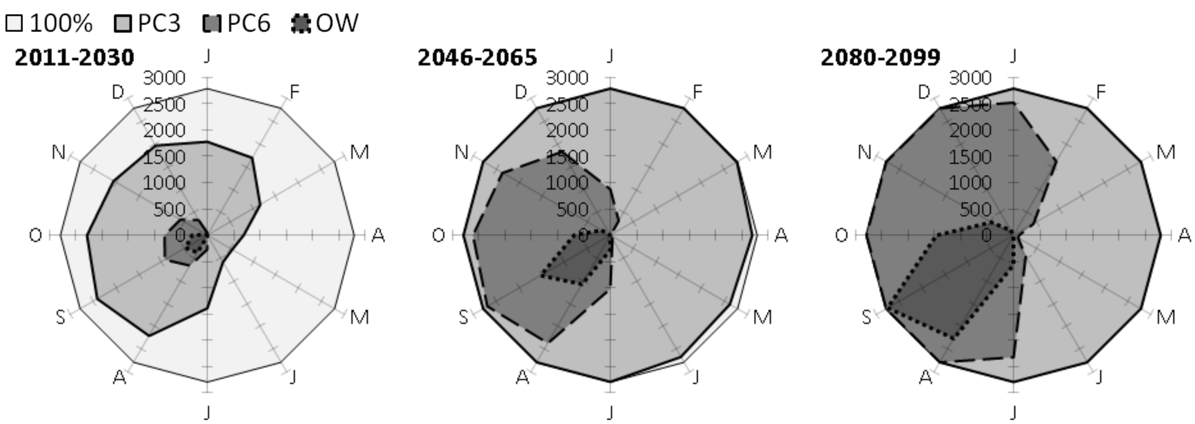


Figure S9: Total ship-accessible marine area in the international high seas (1000 km^2) as driven by climate forcing scenario (RCP 4.5, 6.0, 8.5), time-averaging window (2011-2030, 2046-2065, 2080-2099), and vessel class (PC3, PC6, OW). Outer circles signify 100% year-round access.

RCP 4.5



RCP 6.0



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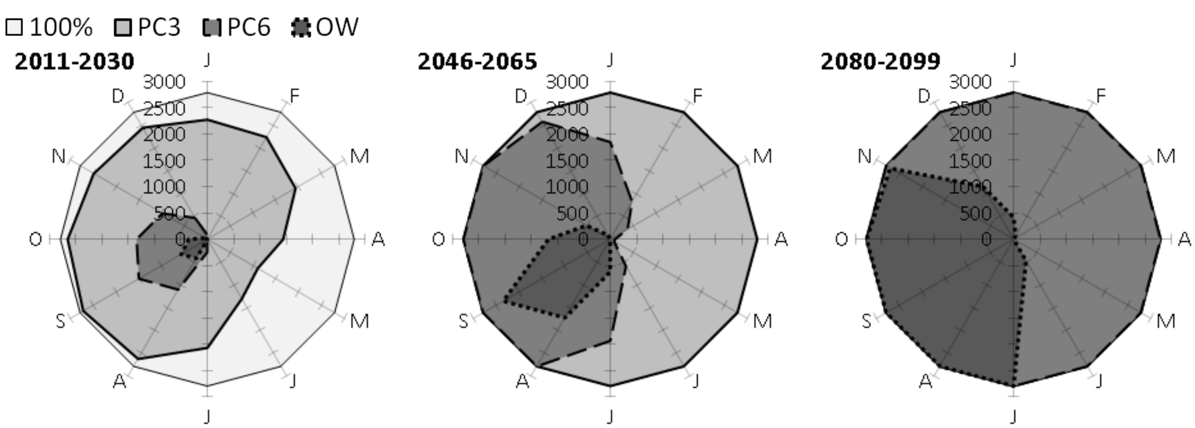

Tables S1-S5

Table S1: Average annual, summer (JASO) and winter (DJFM) ship-accessible area within the IMO Guidelines Boundary (1000 km^2 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 S2: 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

Table S3: 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 S4: 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-km^2 ice age grids (Maslanik et al., 2007) to obtain the median of thickness values spatially coincident with a given age class.

	First-year ice		Second-year ice		Third-year ice	
Year	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 S5: Intra-annual second-year and multi-year minimum ice thickness (cm) derived from linearly interpolated mean thickness (Figure S1). 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

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