



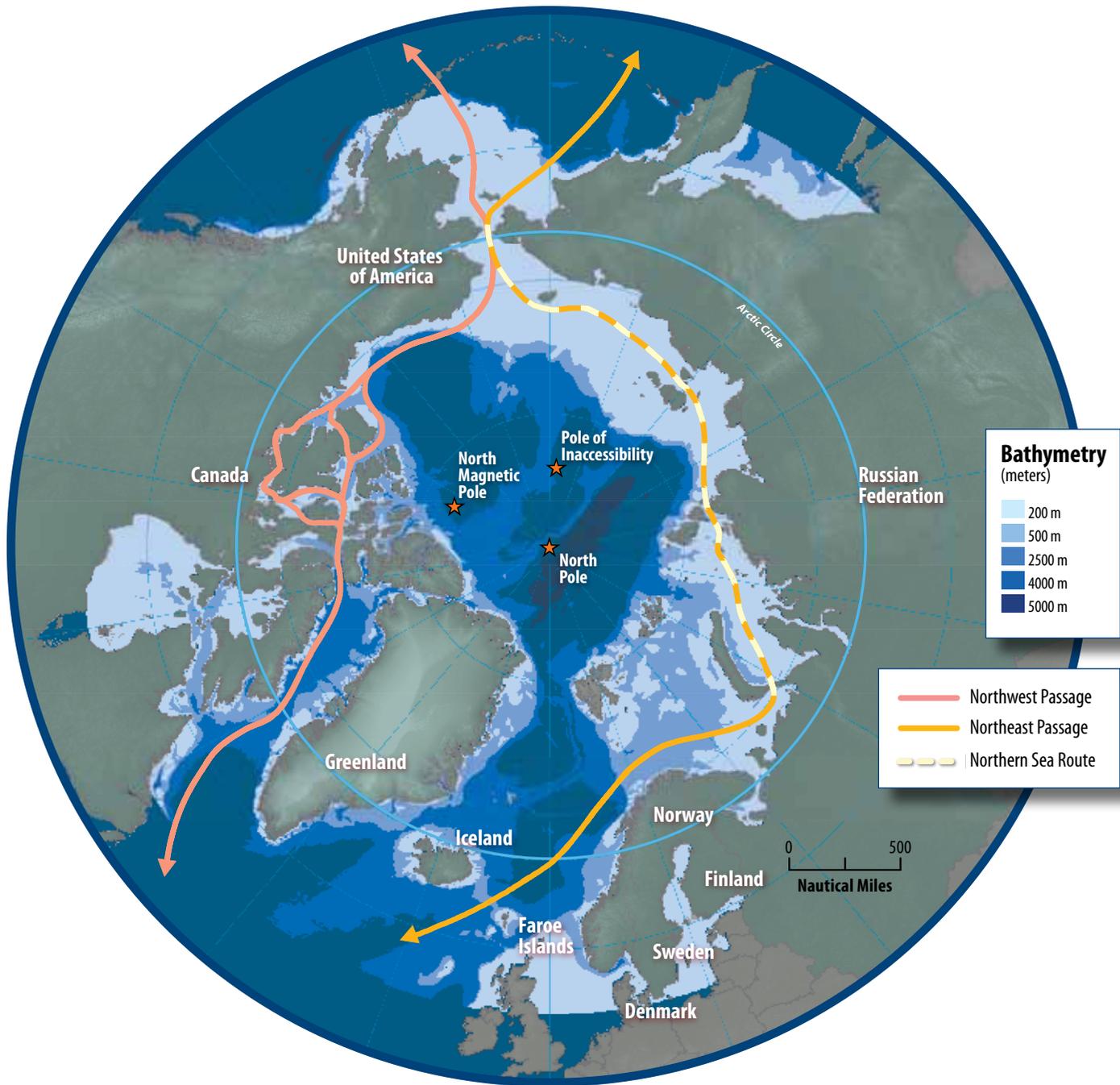
ARCTIC MARINE GEOGRAPHY, CLIMATE AND SEA ICE

Arctic Marine Geography

Our Earth has two polar regions, each with a large marine environment, that are vital to the well-being of the planet: Antarctica and the Arctic. Unlike Antarctica, though, which is a continent surrounded by an ocean, the Arctic is an ocean surrounded by continents. The Arctic Ocean, at 14.056 million km², is the smallest of the world's five oceans (Table 2.1). It is mostly an enclosed sea that has limited exchange of deep water with other oceans. Compared to the Mediterranean Sea, the Arctic has a much greater exchange of water, and it is more than 5.6 times larger. Consequently, the International Hydrographic Organization along with the International Maritime Organization recognizes the Arctic Ocean as one of the five major components of the world ocean that covers almost 71 percent of the Earth's surface. More importantly, the Arctic Ocean is the least sampled of the world's oceans and many areas remain where few, if any, soundings have been recorded. The implications of this lack of basic marine information are profound for charting hydrography and for basic Arctic navigation.

The Arctic is bordered by numerous coastal seas, all of which are seasonally covered with sea ice. Working from Greenland eastwards, the waters adjacent to the Arctic basin itself are Greenland Sea, Norwegian Sea, Barents Sea, White Sea, Kara Sea, Laptev Sea, East Siberian Sea and Chukchi Sea - all fronting on the Eurasia continental land mass. The Bering Sea, the Beaufort Sea, the waters within the Canadian Archipelago including those of the Northwest Passage, Hudson Bay and Hudson Strait, Lincoln Sea, Baffin Bay, Davis Strait and Labrador Sea are all bordering on the North American continent. Most Arctic marine activity, such as fishing, offshore hydrocarbon development and ship transits, takes place in these coastal seas.

Bathymetrically, the Arctic marine area is relatively shallow (Map 2.1) with broad continental shelves. The shelf extends 100 to 200 kilometers from the United States and Canada, and more than 1,000 kilometers in places extending north from the Russian Federation. Depths over the shelves average between 100 and 200 meters but are variable, especially as the continental landmasses and islands are approached. At the continental slopes, the break between the shelf and the deep ocean basin, depths are between 300 and 500 meters.



Map 2.1 The Arctic marine area. Source: AMSA

4,000 meters +
The depth of the Arctic Ocean at the North Pole.

	Size (million km ²)	Percentage of Earth's Total Surface	Greatest Depth (m)	Average Depth (m)
Pacific	155.557	30.5	10,911	4,300
Atlantic	76.762	20.8	8,605	3,300
Indian	65.556	14.4	7,258	3,900
Southern	20.327	4.0	7,235	4,000-5,000
Arctic	14.056	2.8	5,160	1,050

■ **Table 2.1** Arctic Ocean compared to other oceans. *Source: AMSA*

Country	Closest Point to the North Pole	Distance to Pole (km)
Greenland (Denmark)	Kaffeklubben Island, Perry Land	707
Iceland	Kolbeinsey, Eyjafjorour	2552
Norway	Rossoya Sjuoyane, Svalbard	1024
Russian Federation	Cape Fligely, Rudolf Island, Franz Josef Land	911
USA	Point Barrow, Alaska	2078
Canada	Cape Columbia, Ellesmere Island	769

■ **Table 2.2** Distances from nearest land of Arctic states to the North Pole. *Source: AMSA*

There are two major deep basins - the Eurasia and Amerasia - separated by the Lomonosov Ridge stretching from the East Siberian Sea to the Lincoln Sea. The ridge is an underwater mountain chain rising, on average, 3,000 meters above the abyssal plain. On the Eurasian side of the Lomonosov Ridge, the basin is again split into two by the Nansen-Gakkel Arctic Mid-Ocean Ridge. Between the Lomonosov and Nansen-Gakkel Ridges lies the Pole Abyssal Plain in which is found the geographical North Pole at 90 degrees north. The depth of water at the pole is well over 4,000 meters. On the Amerasia side of the Lomonosov Ridge there are also two basins - the Makarov and Canada - separated by the Alpha and Mendeleev ridges. Of the two basins, the Canada Basin is the largest.

Major islands and island archipelagos fringe the Arctic marine area and they help frame the marine routes, legal regimes and navigational options in the Arctic Ocean. The largest island is Greenland at 2,166,086 km². The largest archipelago is the Canadian Archipelago with more than 36,000 islands including Baffin (507,451 km²), Victoria (217,291 km²) and Ellesmere (196,236 km²), which are among

the world's largest 10 islands. The next largest single island fringing on the Arctic marine area is Iceland (103,000 km²). On the west, the Arctic Ocean is bounded by Svalbard (Norway) of which Spitsbergen is the largest island; Franz Josef Land (Russian Federation) with 191 islands; Novaya Zemlya (Russian Federation) with two major islands (Severny at 47,079 km² and Yuzhny at 33,246 km²); Severnaya Zemlya (Russian Federation) consisting of four major islands and 70 smaller ones; and New Siberian Islands (Russian Federation) with the Anzhu Islands and the Lyakhovskiy Islands. Between the New Siberian Islands group and the Bering Strait lies Wrangel Island (7,300 km²). Given these fringing islands, the distance from the nearest land to the North Pole is as little as 707 kilometers (382 nautical miles) (Table 2.2), but this distance is different for each Arctic nation. Of interest to the marine world is the approximate 2,100 nautical mile (1134 kilometer) distance (direct) from the Bering Strait to the North Pole to Fram Strait (between Greenland and Svalbard). All other distances along the coastal routes within the Arctic basin are longer.

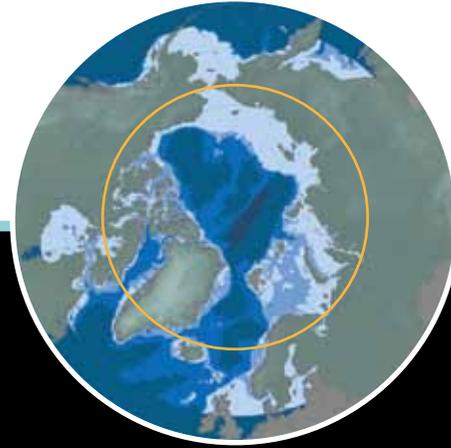
Although technically not on the edge of the Arctic Ocean, the Aleutian Islands in the Pacific Ocean provide the southern limit of the Bering Sea, which links through the Bering Strait into the Chukchi Sea and the Arctic Ocean. A global maritime trade route - the North Pacific's Great Circle Route - intersects with the Aleutian Islands and thousands of large ships pass north and south of these islands on voyages between the west coast of North America and Asian ports each year.

The water connections linking the Arctic and the Pacific and Atlantic oceans are limited. The narrow and shallow Bering Strait (85 kilometer width; 30-50 meter depth) is the only link between the Arctic and the Pacific. There are more and wider passages between the Arctic and the Atlantic. Davis Strait between Canada and Greenland links Baffin Bay with the Labrador Sea and the North Atlantic. At its narrowest point Davis Strait is about 300 kilometers wide; at its widest it is over 950 kilometers. Between Greenland and Iceland lies Denmark Strait (290 kilometers wide at its narrowest). The widest passage is the Norwegian Sea at about 1,100 kilometers separating Iceland from Norway.

These water passages between the Arctic Ocean and its northern coastal seas allow exchanges of water vital to the Arctic's climate and marine ecosystems. By far the greatest exchange of water takes place between the Arctic and the Atlantic. Relatively warm dense salty water, as part of the North Atlantic Current originating in the Gulf of Mexico and Caribbean Sea, enters the Norwegian Sea continuing into the Barents Sea. This warmer water means that the Southern Barents Sea is not generally ice-covered, a significant factor in the regulation and control of marine traffic in this northwest

corner of Europe that is by latitude located in the Arctic region. After much mixing and cyclonic (counter-clockwise) circulation, cold, less salty water exits between Svalbard and Greenland and Greenland and Iceland. This exiting water consists not only of the modified North Atlantic waters but, more importantly, continental river water from Eurasia, especially from the Ob', Yenisei and Lena rivers of the Russian Federation; freshwater from the Mackenzie River in Canada; and Pacific water which entered through the Bering Strait. The driving engine conveying the Pacific water and the river waters eastward is the Beaufort Gyre north of Alaska and western Canada. This gyre - a clockwise circulation of relatively fresh, less dense water - is driven by prevailing winds. When winds shift and the current lessens some water escapes and is caught up in the Trans Polar current, eventually linking with the outflow water into the Atlantic Ocean. Cold waters also exit from the Arctic to the Atlantic through Baffin Bay, Davis Strait and Hudson Strait.

An important geographical limit and a defining line is the Arctic Circle (66 degrees 33 minutes north). At this latitude places receive continuous light for 24 hours per day once a year and as one moves poleward the number of days of continuous light increases until at the North Pole continuous light is experienced for six months



Arctic Circle

The Arctic Circle is the circle of latitude at 66 degrees 33 minutes N (2606 kilometers/1619 miles from the North Pole) that encloses a northern area about 8 percent of Earth's surface. The Arctic Circle is the southern limit of the midnight sun, where north of the circle there is at least one day each year when the sun does not set.



between the Vernal (March 21) and Autumnal equinoxes (September 21). Conversely, continuous dark is experienced at the pole for the other six months and decreasingly in time as one moves south. Significant for marine operations is that much of the central Arctic Ocean is shrouded in winter darkness with very low temperatures for half the year. This seasonal or diurnal cycle in the polar environment, while highly influential in the rhythmic behavior and adaptation of Arctic communities and animal populations, has broad implications for maritime use throughout the Arctic Ocean and its coastal seas.

The Canadian Maritime Arctic and Northwest Passage

The Canadian maritime Arctic is located across the north of Canada from the Beaufort Sea in the west to Baffin Bay in the east, and south to 60 degrees north latitude. The Canadian Arctic Archipelago stretches longitudinally about 1,900 kilometers from mainland Canada to the northern tip of Ellesmere Island. From west to east, it covers a distance of about 2,400 kilometers from Banks Island (west side) to Baffin Island (east side). The size of this roughly triangular area, including land and ocean, is approximately 2.1 million km², about the size of Greenland. As mentioned previously, it comprises approximately 36,000 islands, making it one of the most complex geographies on Earth. The area is sparsely populated along the coastline. The largest settlement is Iqaluit, Baffin Island, at 6,100 people; the entire Baffin region includes most of the eastern and northern portion of the Archipelago including all of Baffin Island. The most northern settlement is Grise Fjord on Ellesmere Island. Resolute on Cornwallis Island and the shores of Barrow Strait are an important staging area for air and marine traffic.

The Archipelago serves as a major impediment to shippers seeking a link between the Atlantic and Pacific oceans or for internal shipment of resources or community supplies. There are five recognized routes or passages, with variations, through the Archipelago (Table 2.3). They make up the much searched for Northwest Passage, which occupied European adventurers for more than 400 years. The NWP is the name given to the various marine routes between the Atlantic and Pacific oceans along the northern coast of North America that span the Canadian Arctic Archipelago. The



Northwest Passage (NWP)

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first complete ship transit of the NWP took place from 1903-06 by Norwegian explorer Roald Amundsen following Route 3b (Table 2.3). In 1940-42 the first eastward passage, using Route 4, was made by the *St. Roch* commanded by RCMP Sergeant Henry Larsen. This trip was followed in 1944 by a westward passage following Route 1, marking the first time the Northwest Passage had been navigated in a single season.

All passages have common eastern and western approaches. In the east, ships must proceed through the Labrador Sea, Davis Strait and Baffin Bay - the exception is for Route 5, which requires a transit through Hudson Strait. In the western approaches ships proceed through the Bering Sea, Bering Strait, the Chukchi Sea and the Beaufort Sea before deciding which route to follow. In general, the operating season is short - from late July to mid-October - depending on the route and year. Of the various passages, routes 1 and 2 are considered deep water ones, while the others have limiting shoals and rocks restricting the draft of vessels to less than 10 meters.

The Arctic Ocean is the least sampled of the world's oceans and many areas remain where few, if any, soundings have been recorded.

Water Routes of the Northwest Passage

Route	Routing (East to West)	Physical Description	Of Note
1	Lancaster Sound – Barrow Strait – Viscount Melville Sound – Prince of Wales Strait – Amundsen Gulf.	<p>Lancaster Sound: 80 km wide, 250 km long, deep at over 500 m.</p> <p>Barrow Strait: 50 km wide, 180 km long, deep, string of islands west of Resolute disrupts clear navigation.</p> <p>Viscount Melville Sound: 100 km wide, 350 km long, experiences multi-year ice from M'Clure Strait.</p> <p>Prince of Wales Strait: minimum width of less than 10 km about half way through the Strait, 230 km long, limiting depth of 32 m.</p> <p>Amundsen Gulf: irregular shape, 90 km wide entrance, approximately 300 km long.</p>	Suitable for deep draft navigation; the route followed by <i>St. Roch</i> in 1944 on westerly transit and the <i>SS Manhattan</i> in 1969.
2	Same as 1 but substitute M'Clure Strait for Prince of Wales Strait and Amundsen Gulf. Collectively Lancaster Sound – Barrow Strait – Viscount Melville Sound is known as Parry Channel.	<p>M'Clure Strait: 120 km wide at east end, 275 km long to Beaufort Sea, deep at over 400 m, experiences multi-year ice from Arctic Ocean.</p>	<p><i>SS Manhattan</i> attempted this route in 1969 but was turned back.</p> <p>Russian icebreaker <i>Kapitan Klebnikov</i> succeeded in a passage in 2001.</p> <p>In September 2007 was clear of Arctic pack ice for a limited time since satellite photos have been available; there was more ice in 2008.</p>
3A	Lancaster Sound – Barrow Strait – Peel Sound – Franklin Strait – Larsen Sound – Victoria Strait – Queen Maud Gulf – Dease Strait – Coronation Gulf – Dolphin and Union Strait – Amundsen Gulf.	<p>Lancaster Sound and Barrow Strait: see Route 1.</p> <p>Peel Sound: 25 km wide, deep at over 400 m at south end.</p> <p>Franklin Strait: 30 km wide.</p> <p>Larsen Sound: depths vary between 30 and 200 meters.</p> <p>Victoria Strait: 120 km wide, at southern end is blocked by Royal Geographical Society Islands, worst ice conditions along the mainland coast of Canada.</p> <p>Queen Maud Gulf: eastern entrance 14 km wide, but widens into an irregular area with width of up to 280 km before narrowing to 14 km at entrance to Dease Strait; numerous islands, reefs and shoals.</p> <p>Dease Strait: 14 – 60 km wide, 160 km long.</p> <p>Coronation Gulf: over 160 km long, many islands.</p> <p>Dolphin and Union Strait: 80 km wide at Amundsen Gulf, 150 km long, caution should be exercised in passage, several soundings of less than 10 m have been recorded.</p> <p>Amundsen Gulf: see Route 1.</p>	Of the 3A, 3B and 4 routes, this is considered the best option but with a draft limit of 10 m.
3B	A variation of 3A. Rather than following Victoria Strait on the west side of King William Island, the route passes to the east of the island following James Ross Strait – Rae Strait – Simpson Strait.	<p>James Ross Strait: 50 km wide, but restricted by islands, extensive shoaling.</p> <p>Rae Strait: 20 km wide, with limiting depths of between 5-18 m in mid channel.</p> <p>Simpson Strait: about 3 km wide at narrowest point, most hazardous navigation area in 3B route.</p>	<p>The route of Roald Amundsen.</p> <p>Also route of the <i>MS Explorer</i>, in 1984, the first cruise ship to navigate the Northwest Passage.</p>
4	Similar to 3A. Rather than following Peel Sound on the west side of Somerset Island, the route passes to the east of the island through Prince Regent Inlet and Bellot Strait.	<p>Prince Regent Inlet: 80 km wide, free of islands, deep.</p> <p>Bellot Strait: short and very narrow, strong currents, limiting depth of 22 m.</p>	Route of <i>St. Roch</i> in 1940-42 on easterly transit.
5	Hudson Strait – Foxe Channel – Foxe Basin – Fury and Hecla Strait – Gulf of Boothia – Bellot Strait – remainder via routes 3A, 3B or 4.	<p>Hudson Strait: 100 km wide, 650 km long, deep, also serves as entrance to Hudson Bay and Churchill port.</p> <p>Foxe Channel: 130 km wide, deep, with limiting shoal in the middle that can be avoided.</p> <p>Foxe Basin: very large, many islands in northern end.</p> <p>Fury and Hecla Strait: 160 km long, very narrow with fast current.</p> <p>Gulf of Boothia: very large waterway connecting to Prince Regent Inlet to the north (see route 4). No problems for navigation except at exit of Fury and Hecla Strait where Crown Prince Frederick Island is to be avoided.</p>	Not generally considered a viable commercial passage for moderate to deep draft ships.

■ **Table 2.3** Adopted from Pharand (1988) with additional material from Sailing Directions, Arctic Canada, Vol. 3, 5th edition, 1994 and Canadian Arctic Shipping Assessment, Transport Canada, 2007.

The Nature of Ice at Sea

Several forms of floating ice may be encountered at sea. The most extensive is that which results from the freezing of the sea surface, namely sea ice; but mariners must also be concerned with "ice of land origin" - icebergs, ice islands, bergy bits and growlers. Both icebergs and sea ice can be dangerous to shipping and always have an effect on navigation.

- Young ice: newly formed sea ice less than 30 centimeters thick. It forms extensively in the autumn as ocean surface temperatures fall below freezing and on leads that open in mid-winter due to shifts in the pack ice. It is not a significant safety hazard for most Arctic vessels although, when placed under pressure by winds or currents, it can impede progress.
- First-year ice: can easily attain a thickness of 1 meter but rarely grows beyond 2 meters by the end of the winter. It is relatively soft due to inclusions of brine cells and air pockets and will not generally hole an ice-strengthened ship operated with due caution. Under pressure from winds or currents, first-year ice can impede progress to the point where even powerful vessels can become beset for hours or even days.
- Old ice: If first-year ice survives the summer melt season, it is then classified as old ice (subdivided into second-year and multi-year ice). It is typically 1 to 5 meters thick and is extremely hard. During the summer melt process, the brine cells and air pockets that characterize first-year ice drain out the bottom of the ice, leaving a clear, solid ice mass that is harder than concrete. Even ice-strengthened vessels are at risk of being holed by old ice. When under pressure, old ice can stop the most powerful icebreakers.
- Icebergs: are large masses of floating ice originating from glaciers. They are very hard and can cause considerable damage to a ship in a collision. Ice islands are vast tabular icebergs originating from floating ice shelves. Smaller pieces of icebergs are called bergy bits and growlers and are especially dangerous to ships because they are extremely difficult to detect.

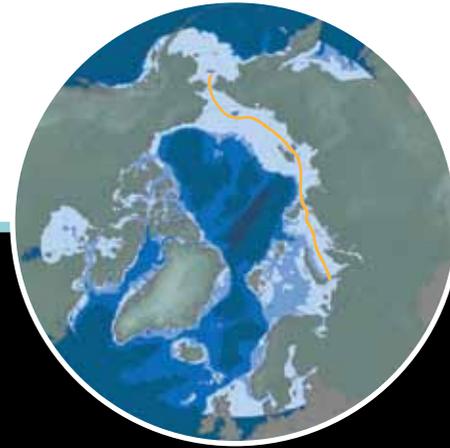


The Russian Maritime Arctic and Northern Sea Route

The physical environment of the northern coast of Eurasia - the Russian maritime Arctic - presents unique challenges to the mariner and to modern ship technology and systems. Shallow waters generally characterize the length of the coastline from the Norwegian-Russian border in the west (in the Barents Sea) to the Bering Strait. The average depths of the East Siberian and Chukchi seas are 58 meters and 88 meters respectively, making the entire coastal region in the east quite shallow for all marine operations. The average depth of the Laptev Sea is 578 meters (its northern limit extends into the Arctic Ocean basin); however, 66 percent of its area along the coast is in depths of 100 meters or less. The Kara Sea has an average depth of 90 meters and the Barents Sea is relatively shallow along the coast (10-100 meters) in the southeastern region and slopes to depths of 200-300 meters to the northwest. From the early years of exploration in the 17th century to today's offshore development and use of shipping routes, the consistently shallow bathymetry of this broad Arctic coast has been a key facet in all maritime affairs.

The Northern Sea Route is defined in Russian law as the set of Arctic marine routes between Kara Gate in the west and the Bering Strait. A number of narrow straits represent a significant constraint to navigation along the NSR. Yugorskiy Shar Strait is located along the south coast of Vaygach Island and is the southernmost entrance from the Barents to Kara seas (21 nautical miles long, 13-30 meters deep). Kara Gate is the main shipping strait between the Barents and Kara seas (18 nautical miles long, minimum depth of 21 meters) and shipping uses an established traffic separation scheme. Vilkitskiy Strait separates Severnaya Zemlya from the northernmost extremity of the Eurasian land mass, Cape Chelyuskin. This is a key NSR strait between the Kara and Laptev seas (60 nautical mile length, 100-200 meter depths), but it is ice-covered except for a short period in some summer seasons. Shokalskiy Strait is located in Severnaya Zemlya north of Vilkitskiy Strait and is a second possible shipping route between the Kara and Laptev seas (80 nautical miles long, minimum depth of 37 meters).

In the eastern reaches of the NSR, Dmitry Laptev Strait, oriented east-west, is the southernmost passage between the New Siberian Islands and the Russian mainland, linking the Laptev and East Siberian seas. This strait is 63 nautical miles long and has depths of 12-15 meters; however, the eastern approach has only depths of 10 meters or less, restricting traffic to ships with less than a 6.7 meter draft. Sannikov Strait is a second passage through the New Siberian Islands linking the Laptev and East Siberian seas (160 nautical miles long, minimum depths of 13 meters). From a navigation

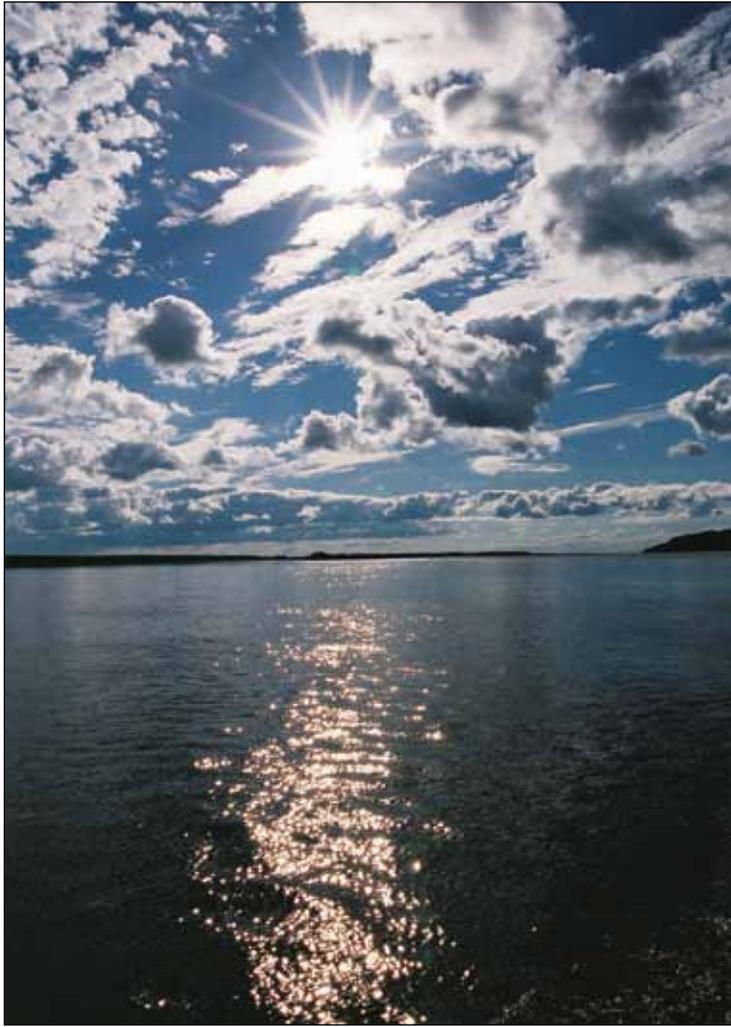


Northern Sea Route (NSR)

The NSR is defined in Russian Federation law as a set of marine routes from Kara Gate (south of Novaya Zemlya) in the west to the Bering Strait in the east. Several of the routes are along the coast, making use of the main straits through the islands of the Russian Arctic; other potential routes run north of the island groups.

perspective, the low surrounding New Siberian Islands make visual and radar observations difficult to obtain, especially during long periods of reduced visibility. Long Strait separates Wrangel Island from the Russian mainland and links the East Siberian and Chukchi seas (a 120-nautical mile southern route along the coast with 20 meter minimum depths; a 160-nautical mile northern route with 33 meter minimum depths).

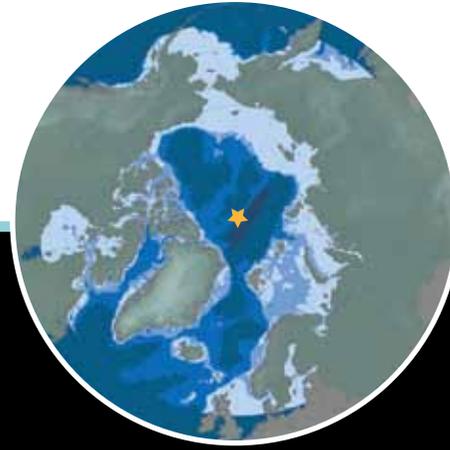
Several marine route distances are notable: from Murmansk to the Bering Strait is 3,074 nautical miles; and the Northern Sea Route from Kara Gate to the Bering Strait is 2,551 nautical miles. The Dudinka to Murmansk marine route that is maintained year-round is 1,343 nautical miles, while it is approximately 500 nautical miles between the offshore region of the Pechora Sea (site of new oil terminals) in the southeast corner of the Barents Sea and Murmansk. Compared with the Canadian Arctic, the Russian maritime Arctic has many more viable ports located along the length of the NSR. Primary NSR ports from west to east include: Amderma, Dikson, Yamburg (Ob' Gulf), Dudinka (north Yenisei River), Igarka (south Yenisei River), Khatanga (Khatanga River on the Laptev Sea), Tiksi (Tiksi Gulf near the Lena River), Zeleny Mys (Kolyma River) and Pevek.



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Arctic Climatology

One defining threshold of the Arctic environment that is often used is set by the 10°C July isotherm. This isotherm marks the southern Arctic boundary where the monthly mean temperature in July is below 10°C. This limit also closely corresponds to the northern limit of the treeline. Because of the mix of landmasses, water and ice in the northern latitudes the isotherm pushes north above the Arctic Circle in all of Eurasia, but is south of the Arctic Circle in much of central and eastern Canada, southern Greenland and the Aleutian Islands. For example, the mean monthly July temperature at Honningsvåg, Norway (latitude 70° 58' N) is 10.3°C; at Murmansk, Russia (latitude 68° 58' N) it is 13.4°C. However, at Inukjuak, Quebec, Canada on the east side of Hudson Bay (58° 27' N) the average July temperature is only 9.4°C; at Paamiut, Greenland on the south west coast (62° 00' N) it is 5.5°C.



Geographic North Pole

The Geographic North Pole, the Earth's northernmost point, is located at the northern end of the Earth's axis of rotation. The latitude of the Geographic North Pole is 90 degrees N and it is the point where all the meridians of longitude and all 24 of the world's time zones converge.

In January, mean temperatures everywhere within the Arctic Circle are all below 0°C, varying from about -5°C along the north coast of Norway to greater than -35°C in central Greenland, the northern part of the Canadian Archipelago and in northern Siberia. The average January temperature at the North Pole is estimated at between -30 and -35° C; however, this is difficult to know given that no permanent recording station exists at the pole. Over virtually all of the Arctic Ocean mean winter air temperatures are not as cold as they are in fringing continental land masses in Siberia, Alaska and Canada.

Precipitation, generally, is light within the Arctic at less than 250 millimeters per annum. Only along exposed coastal regions in southern Baffin Island, western Greenland and northern Scandinavia are amounts greater than this regularly experienced. The main component of the precipitation in the central and high Arctic is snow, but it too is light, at less than 25 centimeters per annum. Although light, snow tends to be blown in all regions and accumulates in drifts and around structures; in marine environments drifting snow accumulates along ice edges and other features on the sea ice creating considerable additional barriers to normal navigation. Almost all snow disappears nearly everywhere in the summer, except in glacier areas.

One of the factors explaining the climatic patterns and annual weather events in the Arctic is the distribution of high and low pressure systems through the year. In winter two semi-permanent low pressure areas set up in the region: one over Iceland and the

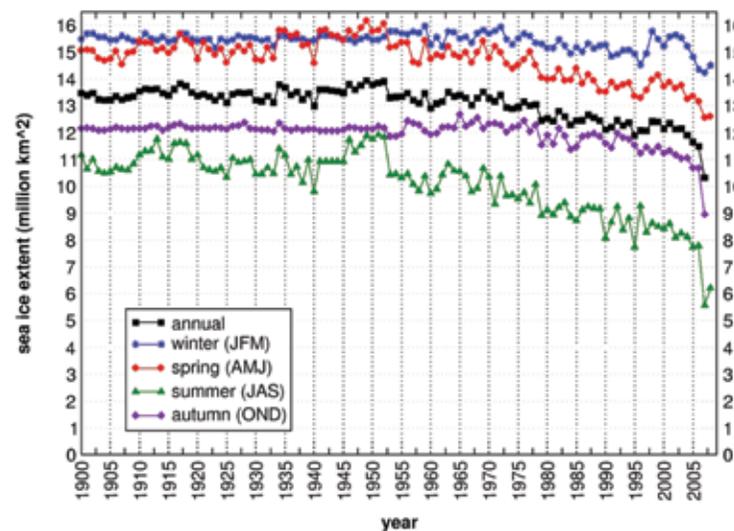
North Atlantic extending into the Barents Sea, the other over the Gulf of Alaska in the North Pacific. In contrast, high pressure areas are established over Siberia and the Yukon in Canada. The pressure differences bring about frequent and intense cyclonic storms moving generally from west to east. In summer, the lows weaken, the Siberian high disappears and the Canadian high shifts north over the Canadian Archipelago. As a result, pressure gradients are less and cyclonic activity declines, providing a fairly benign Arctic marine environment for voyages and regional operations. By October, the winter configuration begins to take effect and storminess increases with declining temperatures. Again, the seasonality of the polar environment, in this case the overall annual weather patterns over the Arctic Ocean, is a critical, strategic aspect for planning current and future marine transport systems throughout the Arctic basin.

Arctic Sea Ice: Changing Operating Conditions in the Arctic Ocean

Introduction

The Arctic sea ice cover is undergoing an extraordinary transformation that has significant implications for marine access and shipping throughout the Arctic basin. The Arctic Climate Impact Assessment, released by the Arctic Council at the Iceland Ministerial meeting in November 2004, documented that Arctic sea ice extent has been declining for the past five decades. Research has also

■ **Graph 2.1** Northern Hemisphere sea ice extent. *Source: J. Walsh, W. Chapman*



Future Arctic navigation and all marine activity will depend on more frequent, reliable and near real-time sea ice thickness measurements.

indicated that sea ice thickness has been decreasing during the same period, and the area of multi-year ice has also been declining in the central Arctic Ocean.

Global Climate Models used in the ACIA and the Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC AR4 released in 2007) simulate a continuous decline in sea ice coverage through the 21st century. One ACIA model showed it is plausible that during mid-century, the entire Arctic Ocean could be ice-free for a short period in the summer, a finding that garnered significant media attention.

Recent research (2006-2008) has indicated this plausible ice-free state of the Arctic sea ice cover may occur as early as 2040, if not sooner. It is important to note that despite the remarkable, ongoing changes in Arctic sea ice and some uncertainty surrounding the output of the GCMs, no research and none of the GCM simulations have indicated that the winter sea ice cover of the Arctic Ocean will disappear during this century.

This fact alone - that there will always be an Arctic sea ice cover to contend with - has important implications for all future Arctic marine activity and for the development of ship standards and measures to enhance Arctic marine safety and environmental protection. The resulting sea ice conditions for future Arctic marine operations will be challenging and will require substantial monitoring and improved regional observations. This new Arctic Ocean of increasing marine access, potentially longer seasons of navigation and increasing ship traffic requires greater attention and stewardship by the Arctic states and all marine users.

In assessments of ongoing and projected climate change, Arctic sea ice is a critical and highly visible element. Observed sea ice extents derived from satellite passive microwave data for 1979-2006 indicate a decrease or annual loss of 45,000 km² of ice (3.7 percent decrease per decade). The same data analysis shows negative ice extent trends for each of the four seasons and each of the 12 months; the decline in summer extent (6.2 percent decrease per decade) is larger than in winter (2.6 percent decrease per decade).

Interestingly, the five smallest September ice-covered areas for the Arctic Ocean during the modern satellite record (1979-2008) have occurred in the five most recent seasons (2004-2008). Map 2.2 shows the sea ice coverage derived from satellite at the time of minimum extent of Arctic sea ice on September 16, 2007.

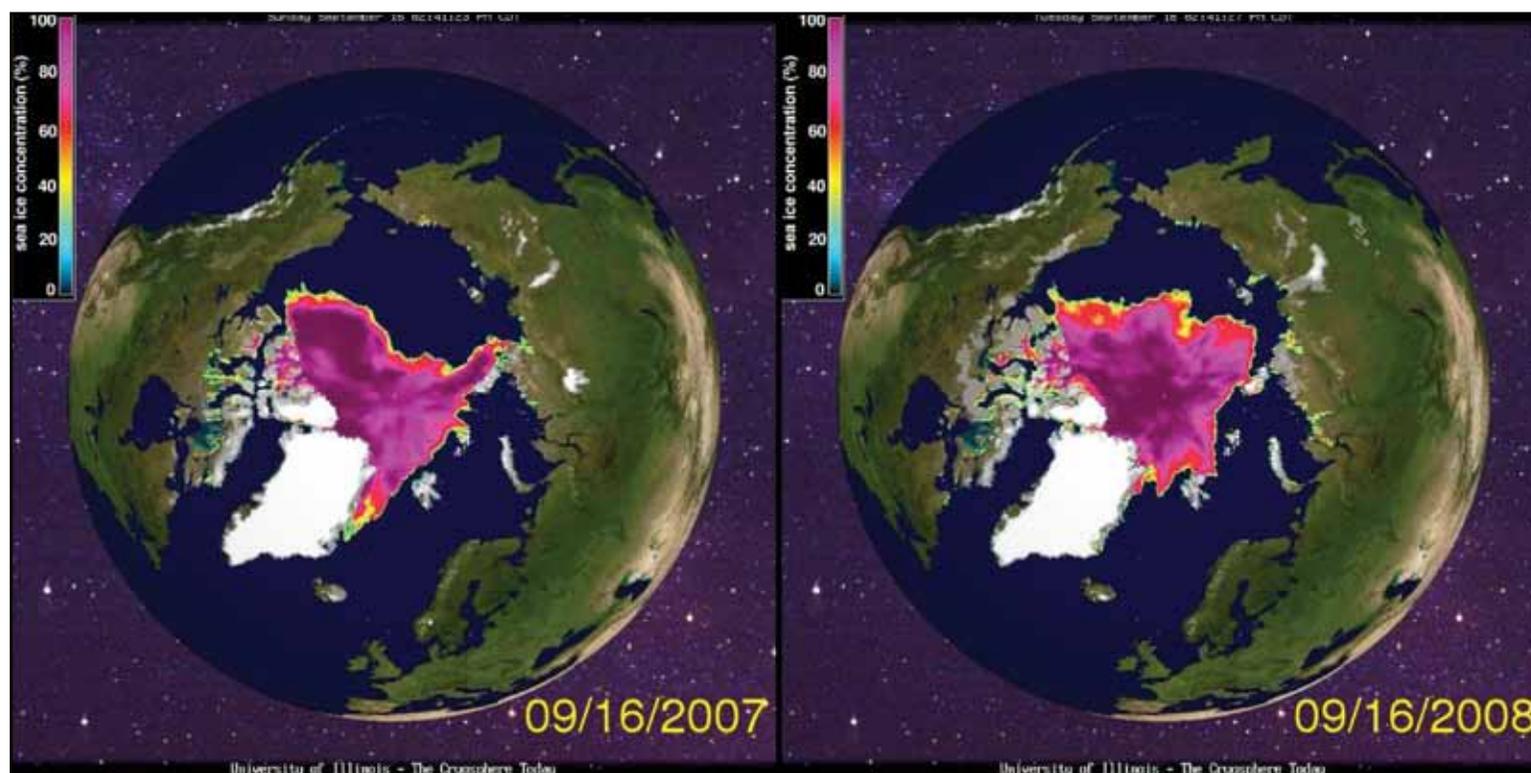
This snapshot represents the minimum coverage of Arctic sea ice in the satellite era of observations. Striking are several notable features: the largely ice-free areas across the Russian Arctic coastal seas (north of the Eurasian coast), except for a small region in the western Laptev Sea; an ice edge that has retreated north of Svalbard and well north in the Beaufort and Chukchi seas; several ice-free passages through the Canadian Archipelago; and a large area of the central Arctic Ocean that previously has not been observed open or without even a thin ice cover.

These extraordinary changes in the summer ice cover of the Arctic Ocean, represented by a single, iconic satellite image for September 16, 2007, are major factors in the potential lengthening of the navigation season in regional Arctic seas, particularly in the summer. It should be noted though that during the same timeframe, the Fram Strait contained more ice than normal, underscoring the regional variability of sea ice extent.

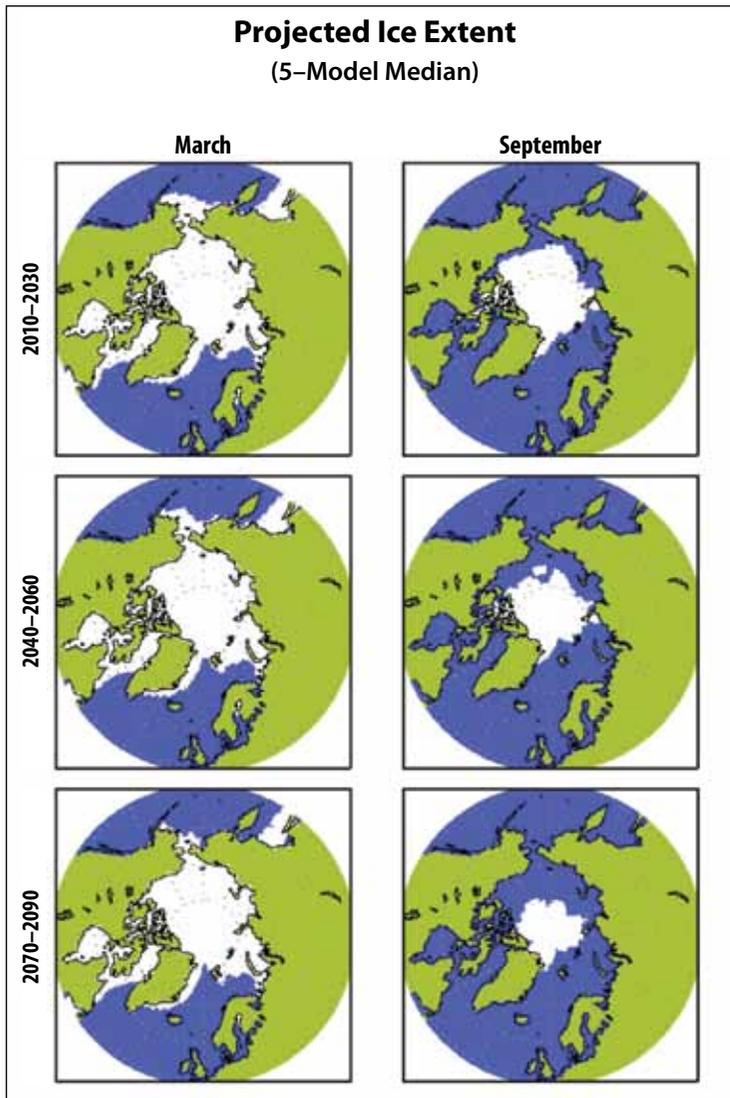
Arctic Climate Impact Assessment

The ACIA, approved by the eight Arctic countries, was called for by the Arctic Council and the International Arctic Science Committee. The assessment found that the Arctic is extremely vulnerable to observed and projected climate change and its impacts. The Arctic is now experiencing some of the most rapid and severe climate change on earth. During the 21st century, climate change is expected to accelerate, contributing to major physical, ecological, social and economic changes, many of which have already begun. Changes in Arctic climate will also affect the rest of the planet through increased global warming and rising sea levels. Of direct relevance to future Arctic marine activity, and to the AMSA, is that potentially accelerating Arctic sea ice retreat improves marine access throughout the Arctic Ocean.

The assessment confirmed, using a wealth of current Arctic research, that declining Arctic sea ice is a key climate change indicator. During the past five decades the observed extent of Arctic sea ice has declined in all seasons, with the most prominent retreat in summer. While the ACIA models have now been surpassed by more capable GCMs, each of the five GCMs used in the ACIA did project a continuous decline in Arctic sea ice coverage throughout the 21st



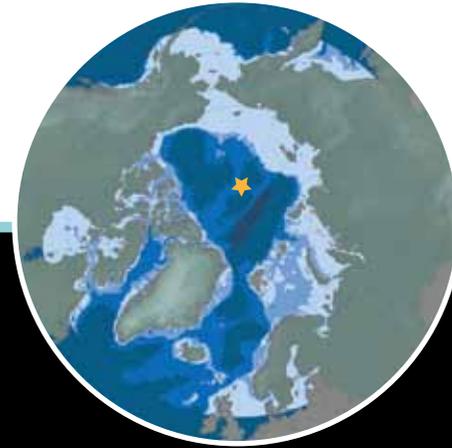
Map 2.2 Satellite images of summer sea ice cover. Source: University of Illinois – The Cryosphere Today



Map 2.3 Arctic sea ice simulations for the 21st century.
Source: Arctic Climate Impact Assessment

century (Map 2.3). From a strategic planning perspective, this is a key factor for evaluating future Arctic marine transport systems. As noted previously, one of the models simulates a summer ice-free Arctic Ocean by 2050, a future scenario of great significance for Arctic shipping and offshore development. Such a physical occurrence would mean that multi-year ice could possibly disappear in the Arctic Ocean. All of the next winter's ice would be first-year: no ice will have survived a winter season (and be able to gain strength and thickness).

GCM projections to 2100 suggest that in the summer the Arctic sea ice will retreat further and further away from most Arctic coasts, potentially increasing marine access and extending the season of



Northern Pole of Inaccessibility

Located at 84 degrees 3 minutes N, 174 degrees fifty-one minutes W, the Pole of Inaccessibility is the point farthest from any Arctic coastline, making it the most difficult to attain.

navigation in nearly all Arctic regional seas. One critical limitation of the GCMs is that they are not useful for determining the state of sea ice in the Northwest Passage region. Their spatial resolution is much too coarse to be applied to the complicated geography of the Canadian Arctic Archipelago.

In the ACIA, the only reliable observed data for the region comes from the Canadian Ice Service and this information, archived since the late 1960s, shows a mean negative trend of sea ice coverage in the Canadian Arctic, but very high year-to-year variability. The ACIA models, however, could be applied very crudely to the more open coastal seas of the Russian Arctic. The ACIA sea ice projections for Russia's Northern Sea Route indicated longer periods of ice-free conditions which could translate into a longer navigation season throughout the 21st century.

The ACIA confirms that the observed retreat of Arctic sea ice is a real phenomenon. The GCM projections to 2100 show extensive open water areas during the summer around the Arctic basin. Thus, it is highly plausible there will be increasing regional marine access in all the Arctic coastal seas. However, the projections show only a modest decrease in winter Arctic sea ice coverage; there will always be an ice-covered Arctic Ocean in winter although the ice may be thinner and may contain a smaller fraction of multi-year ice. The very high, inter-annual variability of observed sea ice in the Northwest Passage and non-applicability of the GCMs to the region prevent an adequate assessment of this complex region.

It is important to note that despite the remarkable, ongoing changes in Arctic sea ice and some uncertainty surrounding the output of the GCMs, no research and none of the GCM simulations have indicated that the winter sea ice cover of the Arctic Ocean will disappear during this century.

Although the ACIA projections indicate an increasing length of the navigation season for the Northern Sea Route (20-30 days per year in 2004, to 90-100 days by 2080), detailed quantification of this changing marine access also tested the limitations of the ACIA GCMs. Since the work of the ACIA, advances and refinements in the models may allow them to provide more robust strategic information on the length of time regions remain ice-free and year-to-year regional sea ice variabilities. There is a definite need for improved Arctic regional models to adequately assess future changes in sea ice extent and thickness, and their considerable implications for expanded marine use of the Arctic Ocean. And, there is a significant need for more sea ice observations to improve the calibration and validation of the GCMs.

The final ACIA report lists 10 major findings that are essentially the key impacts of climate change on Arctic people and the environment. The ACIA key finding #6 states, "Reduced sea ice is very likely to increase marine transport and access to resources." One of the follow-on Arctic Council activities addressing this ACIA finding is the AMSA.

Intergovernmental Panel on Climate Change Fourth Assessment and Beyond

The Intergovernmental Panel on Climate Change (IPCC) was established in 1988 by the World Meteorological Organization of the United Nations Environment Programme. IPCC is an intergovernmental body



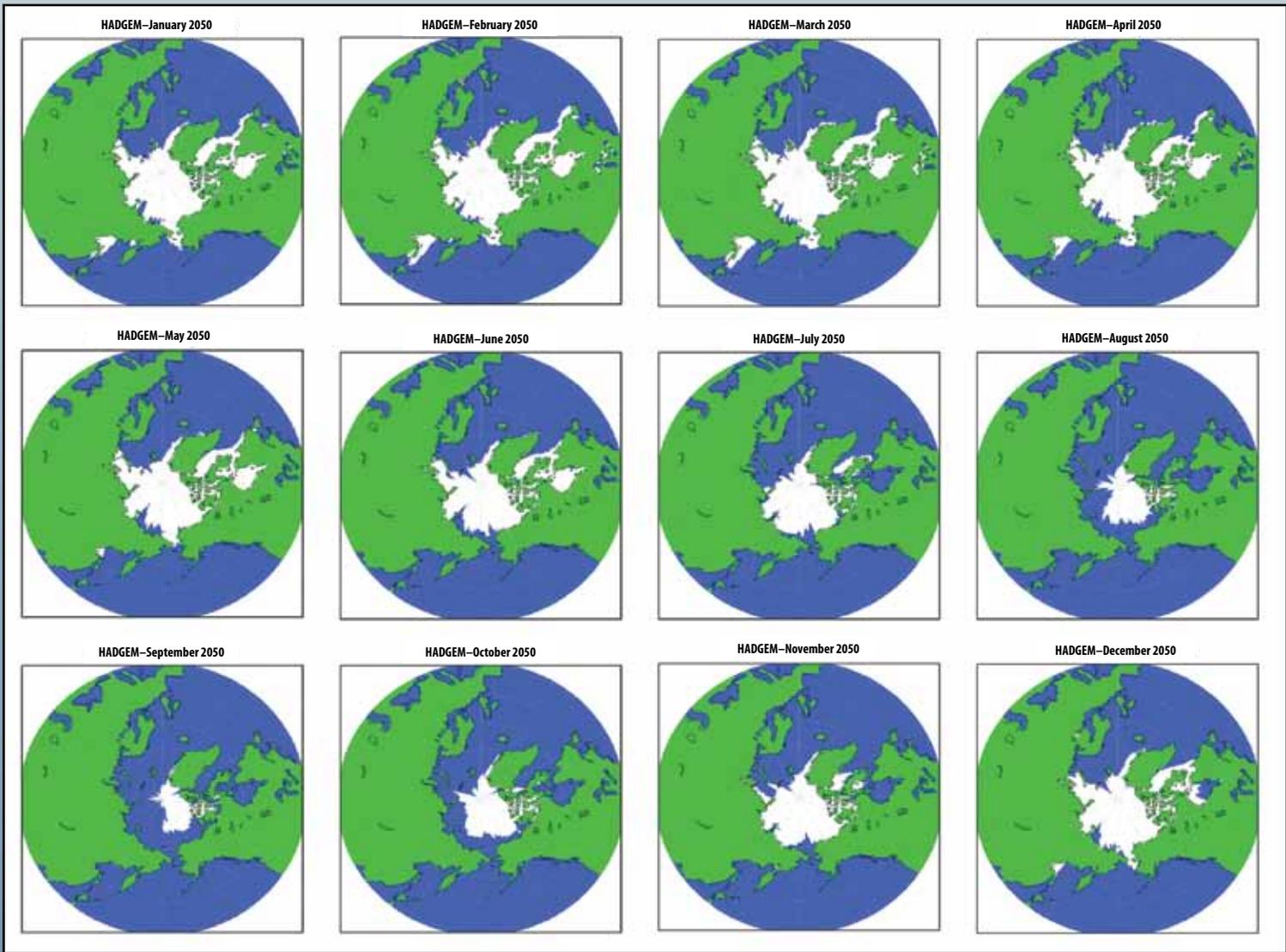
North Magnetic Pole

The North Magnetic Pole is a non-stationary pole in the Arctic to which compass needles point from any direction. The magnetic field at this point points straight down or is at right angles to the Earth's surface. The position of the Pole continues to wander and is currently northwest of the Canadian Arctic.

that provides scientific and technical information to policy makers. The 2007 IPCC 4th Assessment report indicated the lack of comprehensive sea ice data prior to the satellite era. However, observed data analyses have been able to confirm a sustained decline in Arctic sea ice since the early 1970s, notably during the summer melt season. The report also comments that the accuracy of satellite-derived ice concentration is usually 5 percent or better; errors of up to 10-20 percent can occur during the melt season as the passive microwave sensors measure the thin surface layers of melt water on the sea ice surface. Of critical importance to future navigation, the assessment also summarizes the information on the remarkable decrease in multi-year ice throughout the Arctic Ocean.

The possibility of an ice-free Arctic Ocean, even for a brief period, was advanced as an intriguing outcome of the ACIA. Recent analyses of GCM sea ice simulations using models from the IPCC AR4 (applying global warming scenarios) show near-complete loss of Arctic sea ice in September for 2040 to beyond 2100. However, additional research also indicates abrupt reductions in sea ice coverage during the 21st century are a common feature in many of the GCM simulations. Whether these periods of accelerated summer sea ice retreat might provide windows of opportunity for improved marine navigation is unknown. However, these research results and recent model inter-comparisons show the many uncertainties that remain in simulating the future ice cover of the Arctic Ocean.

Map 2.4 Hadley Centre Arctic Sea Ice Simulations, 2050. Source: IPCC4 - 2050

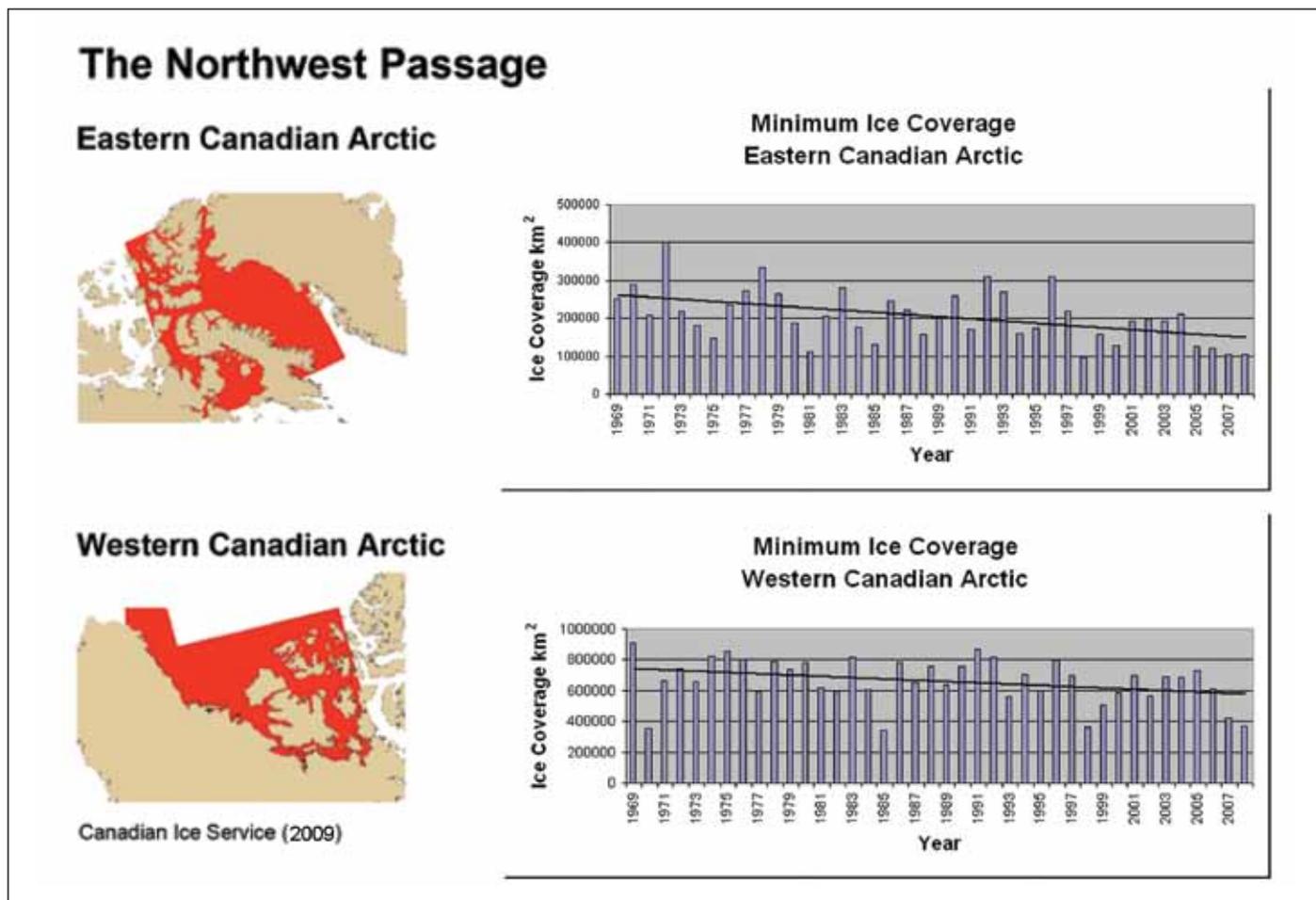


Further research on the performance of the IPCC AR4 models (Map 2.4) reveals that none of the GCMs have negative trends for sea ice as large as the observed sea ice coverage trend for the period 1953-2006 (7.8 percent per decade reduction). The observed trend is three times larger than the multi-model mean of a 2.5 percent per decade loss. This is an extraordinary development that also means the current summer sea ice minima are as much as 30 years ahead of the mean of the model simulations. With continued greenhouse gas emissions, it is highly plausible that the Arctic Ocean could become completely ice-free for a short summer period much earlier than 2040.

Just as important to ship navigation, these simulations indicate large areas of the coastal Arctic seas to be ice-free for longer periods in the spring and autumn months. Arctic marine access continues to increase in nearly all the scenarios posed by the ACIA and the more recent IPCC assessments.

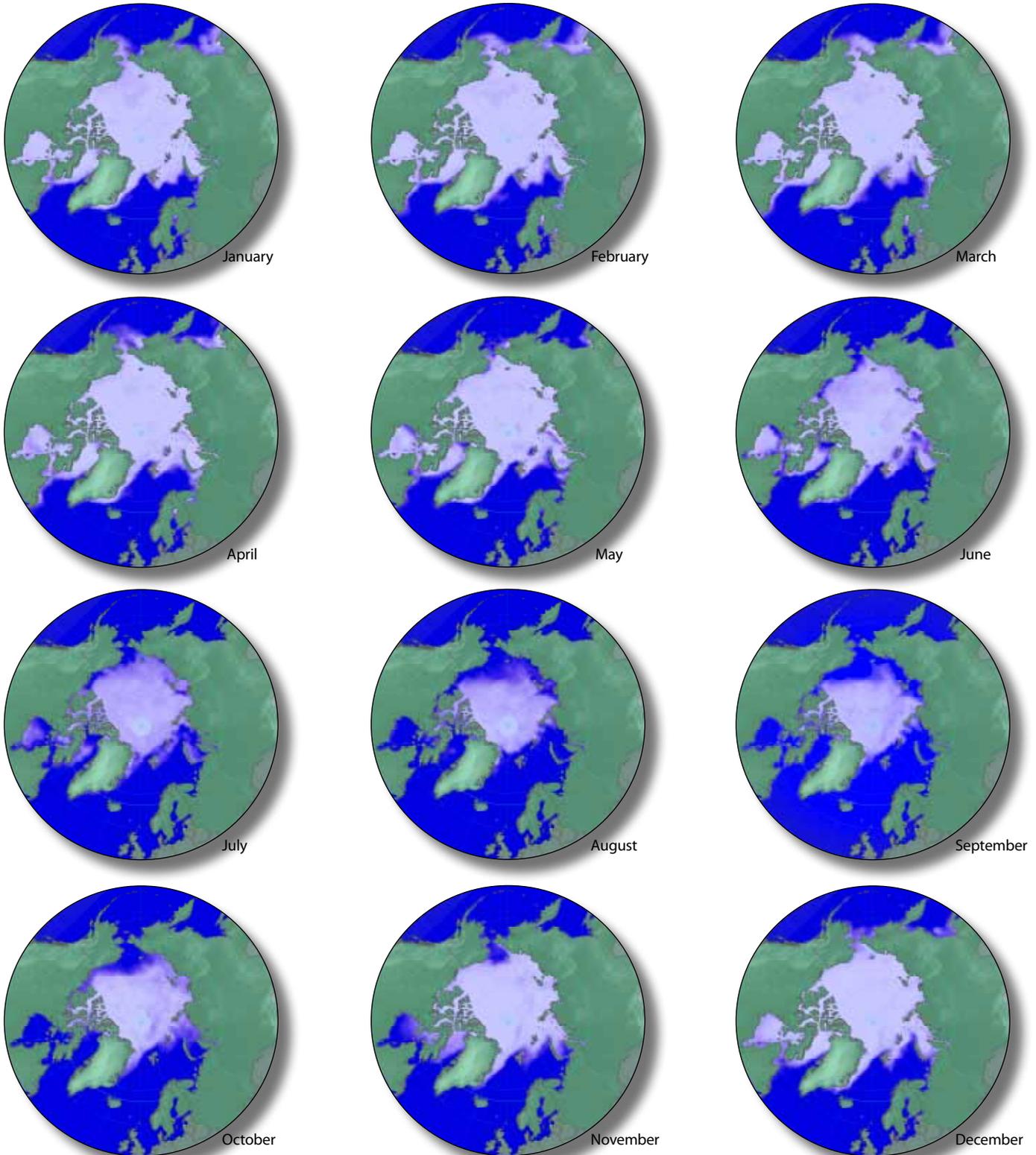
Additional Sea Ice Trends and Research

Earlier observations from aircraft and ships, and three decades of daily satellite observations, suggest that the September 2007 minimum sea ice extent (Map 2.2) was the lowest since the early 1950s; however, the September 2008 minimum extent indicated a slightly larger area of sea ice coverage. The Arctic sea ice cover is at a maximum extent in March and this maximum coverage has also been observed to decrease at approximately 2 percent per decade during the period 1979-2008. These extent reductions have been observed in all seasons of a year, but perhaps more significant have been observations of a rapid decline of thick, multi-year sea ice in the central Arctic Ocean. A study of satellite data for winter during 1978-1998 revealed that the multi-year sea ice cover had declined by 7 percent per decade. A second trend analysis for 25 years of summer ice minima (1978 to 2003) reports a decline of multi-year sea



Graph 2.2 Sea ice variability in the Canadian Arctic and Northwest Passage. Source: Canadian Ice Service

Monthly Arctic Sea Ice Extent and Coverage, 2004



Map 2.5 Sea ice depictions for the AMSA shipping survey year of 2004. Source: AMSA



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ice as high as 9.2 percent per decade. One important result of these trends should be a decrease in the presence of multi-year ice in the Arctic's coastal seas where seasonal navigation and marine activity are highest.

Arctic sea ice thicknesses have been much more difficult to monitor and evaluate during recent decades. Direct measurements of first-year sea ice in the Arctic coastal seas by the Arctic and Antarctic Research Institute in St. Petersburg, the Russian Federation, along the Russian Arctic, generally yield 1-2 meter thicknesses. For the central Arctic Ocean, thicknesses of multi-year sea ice can be as high as 4-5 meters. One pioneering study using sea ice draft data acquired on submarine cruises (data from 1958-1976 compared with cruise data for 1993-1996) indicated a decrease in thickness at the end of the melt season for the central Arctic Ocean from 3.1 to 1.8 meters. This represented a volume decrease of 40 percent and a widespread decrease in sea ice draft. This 40 percent reduction was adjusted to 32 percent in a subsequent study once additional submarine tracks were added.

One key issue is that future sampling of Arctic sea ice thickness requires enhanced monitoring systems for more effective spatial and temporal measurements. Modern measurement systems such as electromagnetics, upward looking sonars and satellites have been developed that are improving thickness observations. Future Arctic navigation and all marine activity will depend on more frequent, reliable and near real-time sea ice thickness measurements.

Sea Ice Regional Trends

Canadian Maritime Arctic and Northwest Passage

The observed record of minimum sea ice extent for the eastern and western regions of the Canadian Arctic is illustrated in Graph 2.2. Although the observations for both regions show negative trends for the period 1969-2008, the year-to-year variability in coverage is quite extreme. Both regions also exhibit large differences for a given year; for example, in 1991 the western Canadian Arctic showed one of the highest or largest ice coverage areas, while in the eastern region a more normal coverage area at the summer minimum was observed. These regional variabilities create a challenge for seasonal operations. While these observations indicate an overall decrease in the ice cover of the waterways that comprise the Northwest Passage, the two key variabilities - year-to-year and spatial - create challenges for planners judging risk and the reliability of an Arctic marine transportation system for the long-term.

The five models used in the ACIA revealed that the last regions of the Arctic Ocean with sea ice coverage in summer would be in the northern waterways of the Canadian Archipelago and along the northern coast of Greenland. The flow of more mobile multi-year ice through these waterways presents another potential challenge to marine operations. Enhanced satellite monitoring (with high resolution imagery) of this complex region will be a necessity if expanded marine operations beyond summer are to be realized.

The five models used in the ACIA revealed that the last regions of the Arctic Ocean with sea ice coverage in summer would be in the northern waterways of the Canadian Archipelago and along the northern coast of Greenland.

Research Opportunities

- ❑ Research to improve regional models for increased understanding and enhanced forecasting of regional Arctic sea ice variability. New regional models should include ice thickness, snow cover and ice ridging, all key parameters of importance to Arctic navigation.
- ❑ Comprehensive analyses of current and future Global Climate Model simulations of Arctic sea ice extent to quantitatively assess the range of plausibly ice-free and partially ice-covered conditions.
- ❑ Considering the ongoing development of the Sustained Arctic Observing Network (SAON), develop and contribute a set of parameters to be observed and more observations that will be relevant to enhancing marine safety and marine environmental protection.
- ❑ Continued data analysis and updating of the International Bathymetric Chart of the Arctic Ocean (IBACO) with a long-term goal to create a comprehensive, integrated digital database of all bathymetric information for the Arctic Ocean.

The physical environment of the northern coast of Eurasia - the Russian maritime Arctic - presents unique challenges to the mariner and to modern ship technology and systems.

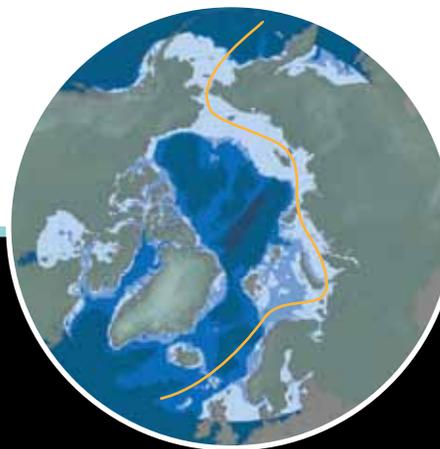
Russian Maritime Arctic and Northern Sea Route

Map 2.2 indicates that a nearly ice-free summer passage could have been made in 2007 and 2008 from Kara Gate through to the Bering Strait along the length of the Northern Sea Route except for sea ice in the western Laptev Sea. Passive microwave satellite observations of sea ice in the Russian Arctic seas from 1979 to the present show large reductions in sea ice extent in summer and reductions in winter extent in the Barents Sea. All of the ACIA model simulations and more recent IPCC AR4 model simulations confirm that large summer ice edge retreats should occur in the Laptev, East Siberian and western Chukchi seas. With a continued shrinkage of the fraction of multi-year sea ice in the central Arctic Ocean, it is plausible that fewer multi-year ice floes may be observed along the navigable eastern passages of the Northern Sea Route.

Long-term fast ice thickness measurements of the four Russian marginal seas (Kara, Laptev, East Siberian and Chukchi seas) have been analyzed for trends using 65-year observational records (1930s to 1990s). Long-term trends are small and inconclusive: the trends are small (approximately 1 centimeter per decade); the trends for the Kara and Chukchi seas are positive and the trends for the Laptev and East Siberian seas negative.

A review of recent assessments, observations and studies indicate that there remains much to understand about the present and future trends in Arctic sea ice. The operating conditions for Arctic ships will remain challenging, particularly in winter. It is also highly plausible that Arctic sea ice will be more mobile, particularly in spring, summer and autumn, as the cover continues to retreat from Arctic coastlines. Arctic coastal seas may experience increased ridging of seasonal sea ice, potentially creating more difficult operating conditions for marine navigation. The observed records of sea ice extent in the Canadian and Russian Arctic areas display high inter-annual variabilities. Such year-to-year variability poses a serious challenge to risk and the overall reliability of Arctic marine transport systems. Three key conclusions with direct relevance to Arctic shipping include:

- Arctic sea ice has been observed to be diminishing in extent and thinning for five decades. Also, model simulations indicate a continuing retreat of Arctic sea ice throughout the 21st century. However, no research indicates Arctic sea ice will disappear completely and a substantial winter sea ice cover will remain.
- Even a brief ice-free period in summer for the Arctic Ocean would mean the disappearance of multi-year sea ice in the central Arctic Ocean. Such an occurrence would have significant implications for design, construction and operational standards of all future Arctic marine activities.
- Observed sea ice trends and GCM simulations show coastal Arctic regions to be increasingly ice-free, or nearly ice-free, for longer summer and autumn seasons. Longer open water seasons



Northeast Passage (NEP)

The NEP is defined as the set of sea routes from northwest Europe around North Cape (Norway) and along the north coast of Eurasia and Siberia through the Bering Strait to the Pacific.

increase the potential for greater coastal erosion, which can impact support infrastructure for Arctic development and marine transportation.

Regarding future needs, a key requirement is the development of high resolution, regional sea ice models that can provide more robust and realistic forecasting of marine operating conditions. There is also a critical requirement for more real-time sea ice observations, especially ice thickness measurements, to support all future Arctic marine uses. The national ice centers and ice services are critical providers of such sea ice information and greater international collaboration among the centers will enhance the development of more integrated products. New satellite sensors hold the promise of providing greater, near real-time ice thickness information for Arctic ships that are underway on future voyages. ☀

A global maritime trade route - the North Pacific's Great Circle Route - intersects with the Aleutian Islands and thousands of large ships pass north and south of these islands on voyages between the west coast of North America and Asian ports each year.

Findings

- 1] Arctic sea ice coverage (extent) has been decreasing since the 1950s in all seasons. Observations of sea ice in the central Arctic Ocean have also indicated thinning during the past four decades. However, there remains a significant, year-to-year variability in regional sea ice coverage.
- 2] Global Climate Model simulations indicate a continuing “retreat” of Arctic sea ice through the 21st century. Observed sea ice trends and GCM simulations show coastal Arctic regions to be increasingly ice-free or nearly ice-free for longer summer and autumn seasons. Importantly, all simulations indicate that an Arctic sea ice cover remains in winter.
- 3] Recent sea-ice model simulations indicate the possibility of an ice-free Arctic Ocean for a short period of time in summer by earlier than mid-century. The key implication for this physical change will be the near (or complete) disappearance of multi-year sea ice.
- 4] Future sea ice conditions remain uncertain. It is highly plausible that Arctic sea ice will be more mobile in partially ice-covered coastal seas, particularly in spring, summer and autumn. Coastal seas may experience an increase and greater frequency of ice ridging and shorter periods of coastal fast ice.
- 5] The resolutions of GCM simulations are much too coarse for adequate coverage of the complex geographies of the Canadian and Russian Arctic. GCM Arctic sea ice simulations also lack robustness to provide detailed information on future marine operating conditions such as the length of the navigation season, “residence time” of ice-free conditions, frequency of leads and ridges and more.
- 6] Recent GCM Arctic sea ice simulations have not replicated the observed sea ice reductions from the 1950s to today. For example, the model simulations have not shown the drastic decrease of observed sea ice extent during recent years.
- 7] Climate change as indicated by Arctic sea ice retreat is a facilitator of marine access. It is highly plausible there will be greater marine access and longer seasons of navigation, except perhaps during winter, but not necessarily less difficult ice conditions for marine operations.