Arctic Environmental Assessment and Outlook Report

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Executive Summary

In 2009, President George W. Bush, signed National Security Presidential Directive – 66/Homeland Security Presidential Directive – 25. These established requirements for the U.S. to develop greater capabilities and capacity to protect United States air, land, and sea borders in the Arctic region. These directives also aim to increase Arctic maritime domain awareness and global mobility, requiring the U.S. to ensure a sovereign maritime presence in the Arctic. In May 2010 the U.S. Navy released its "Strategic Objectives for the Arctic" in order to meet these national goals.

To assess the impact of a changing climate on naval operations, Chief of Naval Operations Admiral Gary Roughead, created Task Force Climate Change in May 2009. The first goal of the task force was to develop and implement the Navy's Arctic Roadmap, a five-year plan to guide Navy policy, investment and actions. This report addresses Action Item 5.7 of the U.S. Navy Arctic Roadmap - to produce an Arctic Environmental Assessment and Outlook Report. This first biennial report provides a comprehensive assessment of the state of the Arctic environment, including the oceanography, hydrography, meteorology, fisheries, ice-extent, and climatic trends. This is important because the IPCC refresh rate is too long to meet the budget POM cycle, so this assessment will periodically synthesize existing scientific reports to inform POMs, specifically POM-14; this allows the Navy's decisions to be based on sound science, and not use one source only, but a consensus of accepted sources.

Some of the key environmental findings are as follows:

Sea Ice Extent: The areal sea ice extent has decreased 2.7% per decade, with larger decreases of 7.4% for the summer minima. The years 2007-2010 witnessed the four lowest minima of sea ice extent in the satellite record.

Sea Ice Thickness: Since the 1970s, sea ice thickness has been on the decline. As of summer 2010, sea ice volume was 70% below the mean since 1979. Current projections indicate that the Arctic Ocean may experience ice free summers by the late 2030s.

Atmosphere: Atmospheric temperatures in the Arctic over the last twenty years have been increasing at a rate eight times the global average. Precipitation in the Arctic has increased 1% per decade due to warmer air absorbing more moisture into the atmosphere.

Permafrost: Some models predict that almost half of the area covered by permafrost could be thawed by 2050.

Fisheries: Fish continue to move poleward into Arctic waters due to increasing water temperatures.

As the Arctic environment continues to change and human activity increases, the U.S. Navy must be prepared to operate in this region. It is important to note that even though the Arctic is opening up, it will continue to be a harsh and challenging environment for the foreseeable future due to hazardous sea ice, freezing temperatures and extreme weather. Although the Navy submarine fleet has decades of experience operating in the Arctic, the surface fleet, air assets, and U.S. Marine Corps ground troops have limited experience there. The Navy must now consider the Arctic in terms of future policy, strategy, force structure, and investments.

1.0 Introduction

In May 2009, the Chief of Naval Operations (CNO) staff examined Navy issues and concerns due to global climate change. This examination resulted in the CNO's decision to establish Task Force Climate Change (TFCC) under the direction of the Oceanographer of the Navy. TFCC's first task was to make recommendations to Navy leadership regarding policy, strategy, force structure and investments relating to the changing Arctic. To help accomplish this task, TFCC developed the Navy Arctic Roadmap. The Roadmap laid out timelines for several actions over the next few years. This report addresses Action Item 5.7 - to produce an Arctic Environmental Assessment and Outlook Report - to inform Navy policy, strategy, and investment decisions. This is the first biennial report that provides a comprehensive assessment of the state of the Arctic environment, which includes the oceanography, hydrography, meteorology, fisheries, ice-extent, and climatic trends. It also includes projections based upon the latest scientific studies, research, and modeling efforts regarding future Arctic environmental conditions. It has particular emphasis on the time-frame in which ice extent and thickness will allow for trans-Arctic shipping and significant increases in intra-Arctic shipping, resource extraction and ecotourism.

Scientific evidence indicates that the Earth's climate is changing, with the most rapid changes occurring in the Arctic. While there is uncertainty about Arctic ice extent, the current scientific consensus indicates the Arctic may experience nearly ice free summers as early as the 2030s. This opening in the Arctic may lead to increased resource development, research, tourism, and could reshape the global transportation system. Because the Arctic is primarily a maritime environment, the Navy must consider the changing Arctic in developing future policy, strategy, force structure and investments.

2.0 Environmental Assessment

As the Earth's atmosphere continues to warm, it creates a unique environmental chain reaction in the Arctic. As the Arctic's ice melts it reveals more water hastening further warming of the Arctic's atmosphere that then warms the frozen land masses melting the permafrost. The receding ice is also opening more navigable waterways for surface vessels, and revealing Arctic resources that were previously inaccessible. This section discusses the environmental trends broken down into three separate mediums: Climate or atmosphere, the ocean and the land mass.

2.1 Climate Trends

During the 20th century, air temperatures over Arctic land areas increased by up to 5°C; sea ice thinned and declined in extent; Atlantic water flowing into the Arctic Ocean warmed; and terrestrial permafrost and Eurasian spring snow decreased in extent.[1] Substantial environmental impacts of climate change show profound regional differences both within and between the Polar Regions, and enormous complexity in their interactions.[2] For example, while warming trends persist throughout the Arctic, the Antarctic shows localized cooling trends over the high continental interior but substantial warming (the largest rate of warming on the Earth) over the Antarctic Peninsula. These climate trends, while seemingly different between Polar Regions, are ultimately related to a mechanism common to both Polar Regions. This mechanism is a gradual shift in the Northern and Southern Annular Modes, which are major patterns of atmospheric variability in the Polar Regions that govern the strength and location of the prevailing westerlies. This trend in both polar Annular Modes is related to increasing greenhouse gas (GHG) concentrations. Observational knowledge of the climate system together with global climate model (GCM) simulations confirm that past changes in GHG concentrations will lead to future climate change.[3]

Recently, there has been an unprecedented effort to validate and create better models in order to advance climate change projections. In doing so, many model results have been made available for prompt scrutiny by researchers outside of the modeling centers. 14 modeling groups from 10 countries using 23 models performed a set of coordinated, standard experiments. The resulting multi-model database of outputs, analyzed by hundreds of researchers worldwide, forms the basis for much of this assessment of model results.[4]

2.1.1 Arctic Climate

The climate within the Arctic Region is largely influenced by ocean currents and seasonal high and low-pressure systems generated by the prevailing mid-troposphere westerly winds. The forcing function for these winds is shown in Figure 1.

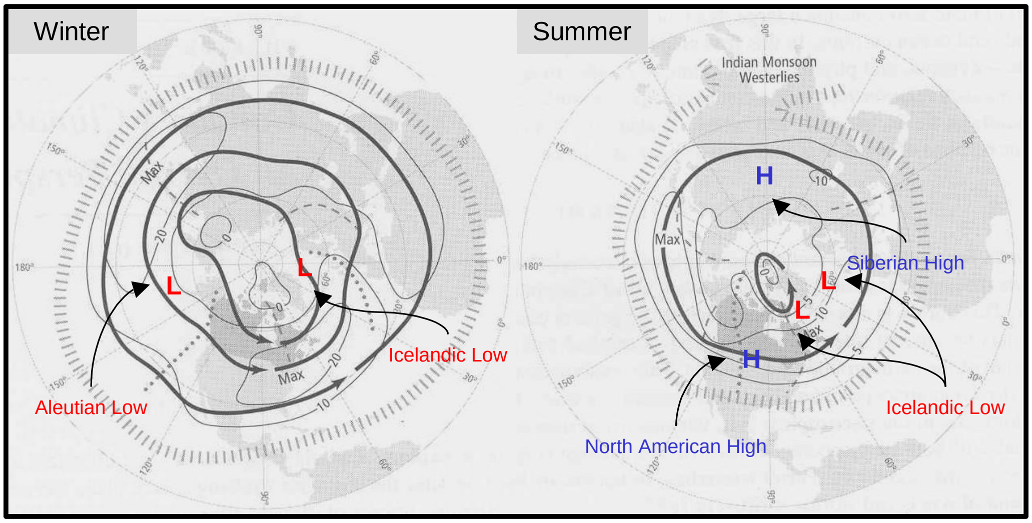


Figure 1: Arctic Atmospheric Circulation[5]

2.1.2 Low and High Pressure Systems

Figure 1 illustrates the controlling feature of the westerlies, which typically generate a ridge of high pressure over Canada in the summer and the East Pacific in winter. The Aleutian Low is a semi-permanent low-pressure center located near the Aleutian Islands, which is most intense in winter and generates numerous strong cyclones. The Icelandic Low, usually located between Iceland and southern Greenland, is also typically most intense during winter.

In summer the Icelandic Low weakens and splits into two centers, one near Davis Strait and the other west of Iceland. The Siberian High is an intense, cold anticyclone that forms over Eastern Siberia in winter. Prevailing from late November to early March, it is associated with frequent cold air outbreaks over East Asia. The Beaufort High (not shown) is a high-pressure center or ridge over the Beaufort Sea, present mainly in winter. The North American High (not shown) is a relatively weak area of high pressure that covers most of North America during winter. This pressure system tends to be centered over the Yukon Territory, but is not as well defined as its continental counterpart, the Siberian High.[6]

2.1.3 Air Temperature

Temperatures in the Arctic continue to rise more rapidly than the global average. Average Arctic temperatures have increased at almost twice the global average rate in the past 100 years[7] and eight times the global average in the last 20 years.[8]

According to the recent Intergovernmental Panel on Climate Change (IPCC) report, the mean global surface temperature has increased by 0.74ºC over the last 100 years (1906-2005) (Figure 2).[9] Eleven of the 12 warmest years have been recorded in the past 12 years.[10]

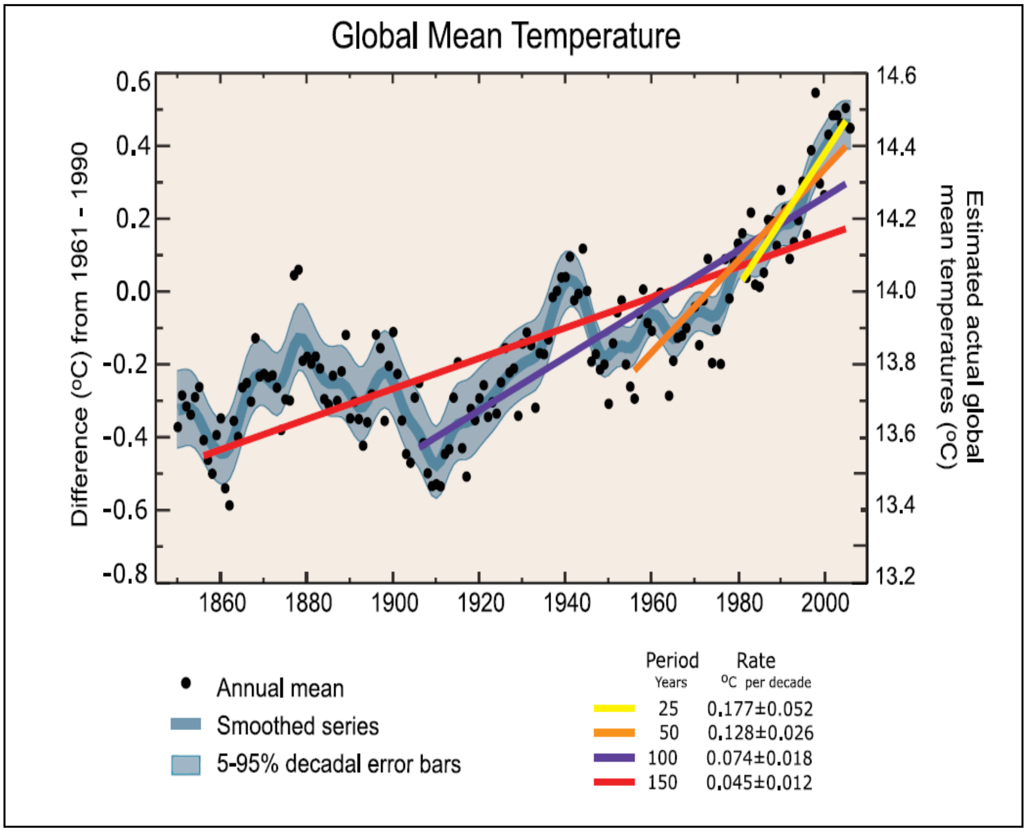


Figure 2: Global Mean Temperature

Warming in the Arctic is projected to range from +2°C to +9°C from current level by the year 2100, depending on the model and forcing scenario. The projected warming is largest in the northern autumn and winter, and is largest over the polar oceans in areas of sea-ice loss.[11]

2.1.4 Precipitation

Precipitation in the Arctic has slightly increased over the past century (about 1% per decade). To reduce uncertainty in precipitation estimates there needs to be less deficiencies in the precipitation measurement network more accurate measurements of rain and snow in windy polar regions. There is not yet any direct observation of systematic increases in intense storms in the Arctic although coastal vulnerability to storms is increasing with the retreat of sea ice.[12]

The simulated monthly precipitation varies substantially among the Global Climate Models (GCMs) throughout the year but the ensemble mean monthly means are within the range of different observational data sets.[13] There is a very strong correlation between the temperature and precipitation changes (approximately a 5% precipitation increase per degree Celsius warming) across the model ensemble. The percentage precipitation increase is largest in winter and smallest in summer, consistent with the projected warming.[14]

The dark green color on Figure 3 represents increased precipitation.

Global precipitation is projected to increase during the 21st century by 10 to 20 percent.[16] Many processes involving Arctic cloud physics and precipitation are still poorly understood and thus continue to pose a challenge for climate models. In addition, evaluating simulations of the Arctic is challenging because of the uncertainty in the observations. The few available observations are unevenly distributed in space and time and various data sets often differ considerably. This holds especially for reports of precipitation measurements, which can be problematic in cold environments due to multiple types of commonly occurring precipitation year-round.[17]

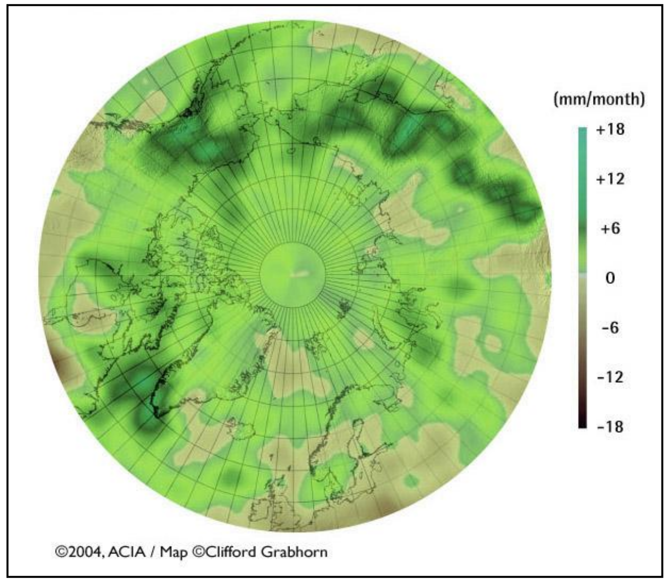


Figure 3: Projected Precipitation Change from 1980-1999 to 2070-2089 in mm/month (Aug)[15]

2.1.5 Winds

The Arctic winter is prone to high winds and intense storms that deposit significant amounts of snow in sheltered areas. Arctic surface wind speeds tend to be even higher in summer due to the frequent occurrence of inversions (when warm air tops a surface cold layer).

2.1.6 Albedo Feedback Loop

Sea ice plays a crucial role in the arctic climate. The amplified warming of the Arctic has been explained as being due, in part, to a positive albedo feedback loop: as the air temperature increases, the sea ice cover (which presents a bright, white, highly reflective surface) melts and reveals the darker ocean surface. This dark surface absorbs more solar energy during the summer season when the sun never sets. This causes more heating, which causes more melting, creating a cycle that helps perpetuate warming conditions (Figure 4).

By combining computer models and meteorological observations scientists have found that over the last five years air temperatures have been warming near the Earth's surface more than they have been at higher altitudes. The phenomenon is strongest in autumn and over areas of open water that would have in the past been iced over. A darker pole absorbs more solar energy and sea water stores that energy, which is later released into the atmosphere.

This means that the shrinking ice cap is playing a triple role in warming the Arctic. The diminished ice is reflecting less solar energy, the open water is storing more energy that is released back to the atmosphere. This open water is also supplying greenhouse gas to the atmosphere in the form of water vapor. Those three factors combine to produce a strong regional greenhouse over the Arctic.[18]

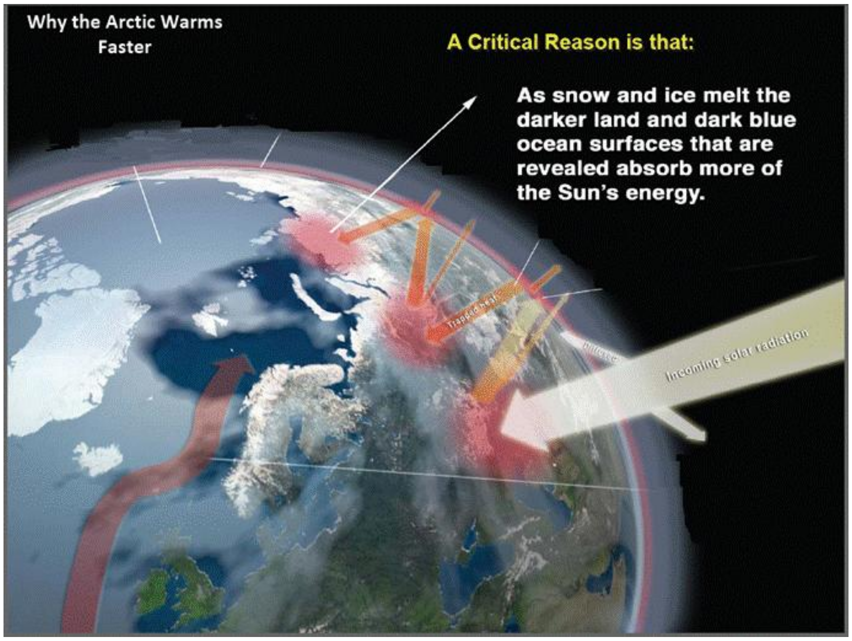


Figure 4: Albedo Feedback

2.2 Ocean Trends

As the Earth's atmosphere warms, the Arctic Ocean will physically change in its ice extent, circulation, and ice movement. One example involves changes in high latitude atmospheric circulation related to climactic warming. The Northern Annular Mode (NAM), also known as the Arctic Oscillation (AO), is a persistent mode of atmospheric variability in the Arctic. In a warming climate, the AO shifts to a pattern characterized by a positive index, whereby the prevailing westerlies strengthen and shift poleward. This in turn leads to significant changes in sea ice motion from Ekman transport that ultimately cause faster sea ice advection from the central Arctic Ocean to the Fram Strait, and thinning of the Arctic sea ice cover in general.[19]

2.2.1 Ocean Currents

Ocean currents contribute significantly to the Arctic climate, which in turn impact global climate systems. Figure 5 shows the North Atlantic and Arctic Ocean circulation. The red arrows represent relatively warm water from lower latitudes entering the Arctic, while blue arrows represent the export of colder water from the Arctic. The shaded white shows the average area covered by sea ice.[20]

As depicted in Figure 5, ocean currents bring warm water from low latitudes to the northeastern part of the Atlantic Ocean reducing the full severity of an arctic climate in many areas such as Norway. In some parts of the Arctic, warm ocean currents bring heat and moisture in the air and frontal activity, which results in increased precipitation. For instance, southern Iceland, southern Alaska, and parts of the Norwegian coast receive in excess of 11 inches of precipitation per year. In contrast, inland areas of the Arctic with continental climate and lower temperatures receive less than six inches of precipitation per year. Snow accumulation on ice can significantly alter the physical behavior of the sea ice cover and introduce appreciable modifications in the exchanges of heat, momentum, freshwater, and salt between the ocean, sea ice, and atmosphere. An albedo feedback loop may develop and thus raise or lower temperatures.

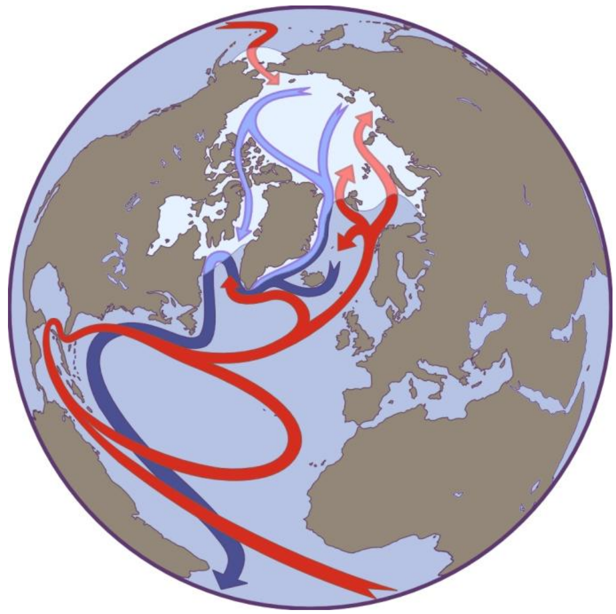


Figure 5: Ocean Current Circulation In and Out of the Arctic[21]

2.2.2 Sea Ice Extent

The Arctic is typically covered with about 14 to 16 million square kilometers of sea ice in late winter, which is reduced to about seven to nine million square kilometers by the end of summer.[22]

The most complete record of sea ice extent is provided by passive microwave data from satellites that are available since the early 1970s. Prior to that, aircraft, ship and coastal observations were available at certain times and in certain locations. The accuracy of satellite derived ice concentration is usually 5% or better, although errors of 10 to 20% can occur during the melt season. The accuracy of the ice edge (relevant to estimating ice extent) is largely determined by the spatial resolution of the satellite radiometer, and is of the order of 25 km (recently launched instruments provide improved resolution of about 12.5 km).[23]

Data from satellites indicates that the sea ice is retreating at a pace exceeding even the most dramatic predictions of scientists. Figure 6 shows the downward trend from 1979 until 2010 in the sea ice extent in the Arctic. There are yearly fluctuations in coverage, but the overall pattern (blue line) clearly descends up to 2007 when, as the graph shows, a radical drop in the extent of sea ice occurs, putting that year in record books. The 2010 Arctic Report Card from NOAA indicates this downward trend in average Arctic sea-ice extent to be -11.6% per decade. The receding Arctic sea-ice extent was lowest in the summer of 2007 (1980: 3 million square miles, 2007: 1.6 million square miles.) and second lowest in 2008. Figure 7 shows a satellite image of the 2007 recession. The last four summers (2007 -2010) have experienced the four lowest minimums in the satellite record, and eight of the ten lowest minimums have occurred during the last decade. While significant uncertainty exists in projections for Arctic ice extent, the current scientific consensus indicates the Arctic may experience nearly ice free summers sometime in the 2030s. Models predict Arctic summer ice will decrease by 15-30 percent (3 percent per decade) and ice volume by 40 percent.

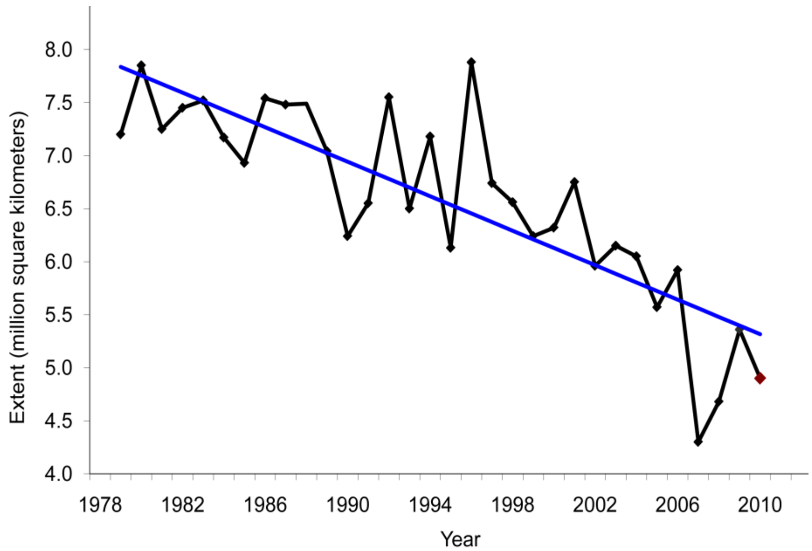


Figure 6: Average Monthly Arctic Sea Ice Extent September 1979 to 2010
(National Snow and Ice Data Center)

Figure 7: This image shows the minimum sea ice extent that occurred on 14 September, 2007
(Goddard Space Flight Center Scientific Visualization Studio)

Observed decreases in the overall sea ice extent are also consistent with the 1980: 7.8 million sq km, to 2007: 4.2 million sq km.

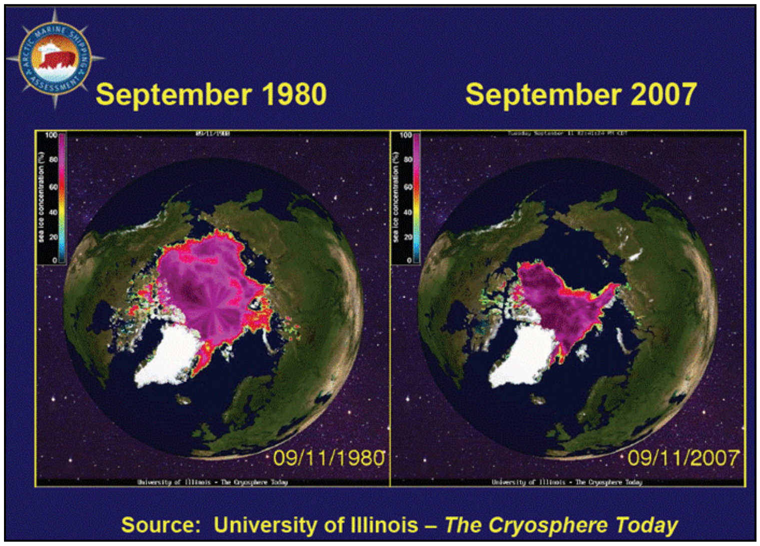


Figure 8: Comparison of Ice Extent between 1980 and 2007

In addition to the overall decrease in summer Arctic sea ice cover, there is notable variability in average Arctic sea ice cover both regionally and seasonally. Table 1 below shows the average Arctic Sea Ice Coverage from 1979 through 2002 which illustrates this type of variation.

Table 1: Average Arctic Sea Ice Coverage from 1979 through 2002[1]

Month	Bering Sea	Hudson Bay	Baffin Bay	Greenland Sea	Kara-Barents Seas	Arctic Ocean	Canadian Archipelago	Total Arctic
JUN	27,601	410,035	324,716	280,472	558,800	2,679,822	277,478	4,608,562
JUL	2,256	188,102	182,971	211,618	369,886	2,541,241	259,314	3,755,388
AUG	6	53,622	55,572	140,043	185,656	2,268,791	198,117	2,901,807
SEP	2,677	22,743	34,183	128,987	126,055	2,162,631	167,712	2,644,986

In the winter, the entire Alaskan northern coast and a substantial portion of the Alaskan western coast is ice-covered. In the summer months, the Arctic sea ice margin retreats northward creating open waters around the entire Alaskan coastline for several weeks to several months. In September 2008, the Russian Northern Sea Route and Canadian Northwest Passage were simultaneously navigable for first time in recent history. These passages are shown in Figure 9. Arctic sea ice extent over the next several decades in early spring and late summer (shoulder seasons) is expected to be even further reduced, creating more broken ice along the Alaskan coastline. Greater spatial and temporal variability in sea ice extent and thickness throughout the Arctic is expected, which may influence the capability needed to break ice of differing thicknesses in certain regions of the Arctic.[24]

[1] All figures are in square miles. Source: http://polynya.gsfc.nasa.gov/datasets/Np_25yrs_78-03_mon.ext.txt.

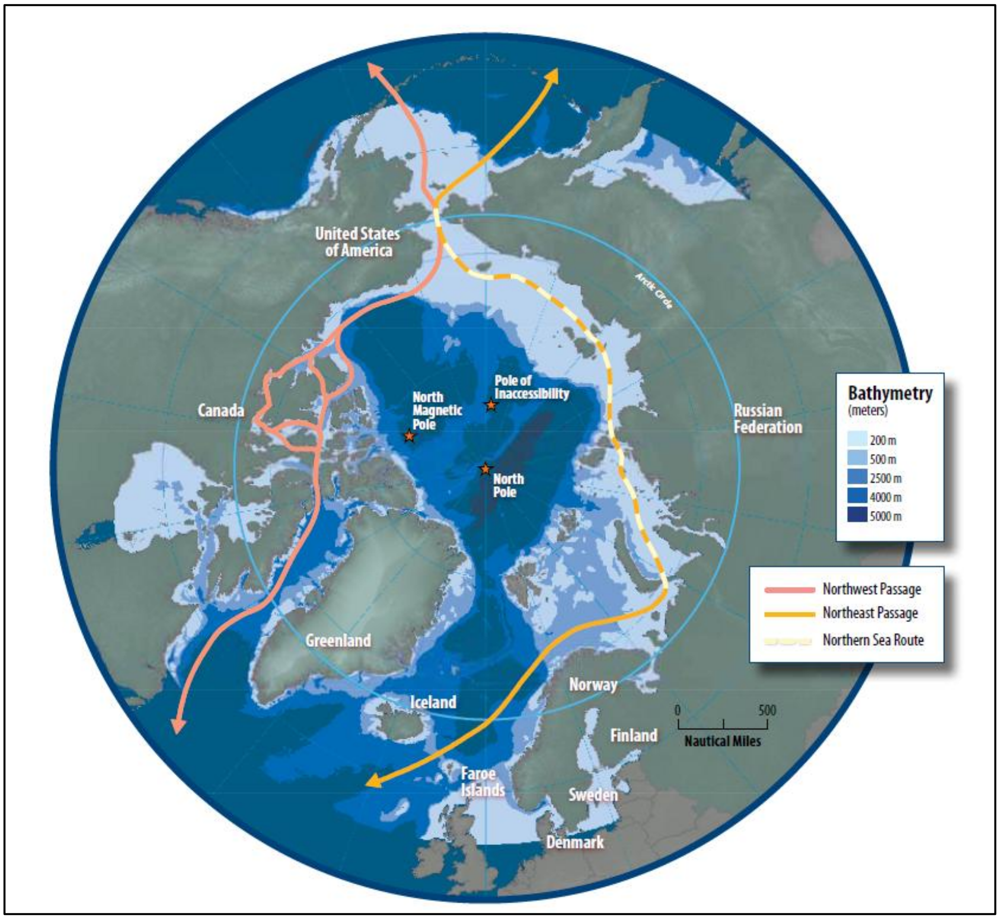


Figure 9: Northwest Passage and Northern Sea Route[25]

The reduction of summer sea ice is accelerated by a number of positive feedbacks in the climate system (see paragraph 2.1.6). The ice-albedo feedback allows open water to receive more heat from the sun during summer, the insulating effect of sea ice is reduced and the increase in ocean heat transport to the Arctic further reduces ice cover. Model simulations indicate that the late-summer sea ice cover decreases substantially and generally evolves over the same time scale as global warming.[26] The global impacts may also be significant as absorption of solar radiation increases, and could lead to changes in the world ocean circulation (see section 2.1.6).[27]

From a practical maritime perspective, the significance of this physical change in the Arctic Ocean will be the disappearance of multiyear ice, ice that survives the summer melt for one year or longer. It is this older sea ice that is more difficult to break, and its presence makes it more challenging to operate in the Arctic offshore. Its potential disappearance could in future decades make this ocean significantly more navigable.[28] Access to newly opened waters is creating new economic opportunities for the fishing, energy, shipping, and tourism industries, which are expected to expand in both scope and intensity in the Arctic and could reshape the global transportation system.

The melting of summer ice will have major direct impacts on indigenous people and Arctic wildlife such as polar bears and seals, and will also open the region to increased development pressure as access by sea to valuable natural resources becomes easier.

2.2.3 Sea Ice Thickness

Sea ice is not only measured by coverage but also by thickness or draft (the thickness of ice below the surface). The thickness of sea ice is a consequence of past growth, melt and deformation, and so is an important indicator of climatic conditions. Thickness is related to age. Thin, single year ice melts annually, while thick multi-year ice tends to survive the summer melt season. The loss of multi-year ice is considered a much more important metric than ice extent for climate change characterization. Ice thickness is also closely connected to ice strength, and so changes in thickness are important to navigability by ships, to the stability of the ice as a platform for use by humans and marine mammals, and to light transmission through the ice cover.

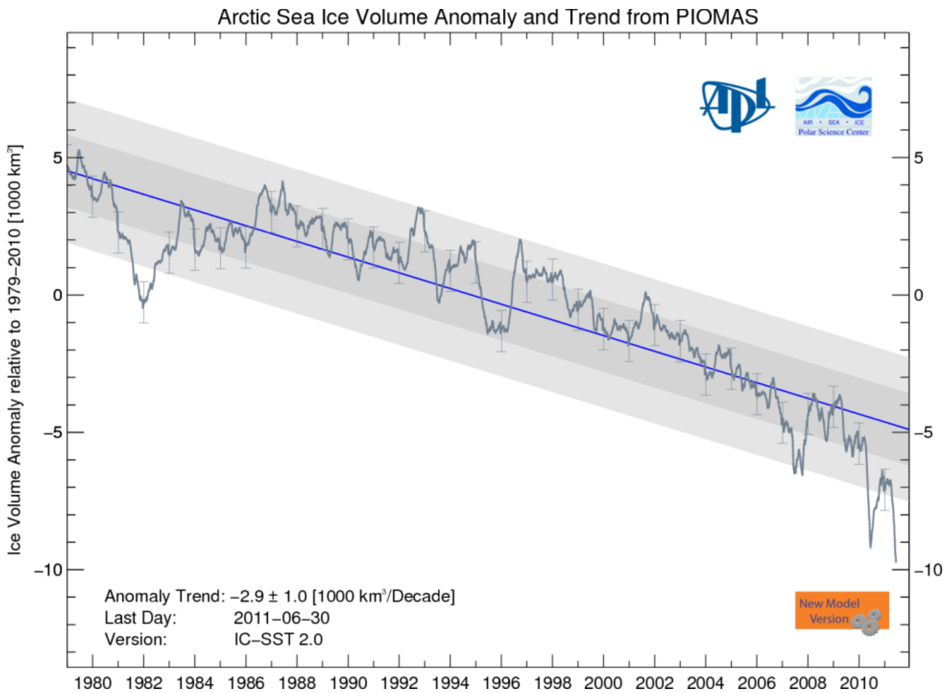


Figure 10**:** Arctic Sea Ice Volume Anomaly and Trend (University of Washington Applied Physics Laboratory).

Ocean warming causes a thinner volume of ice in the Arctic that is more susceptible to future decline. Figure 10 shows this volumetric decline of Arctic sea ice. This figure also reflects that Arctic summer sea ice volume in the last decade reached a record minimum in 2010.

Sea ice increases in thickness as bottom freezing balances heat conduction through the ice to the surface (heat conduction is strongly influenced by the insulating thickness of the ice itself and the snow on it).[29] Some records indicate that the average thickness of year round sea ice is around 9.8 feet, but areas as thick as 23 feet are present due to ridging.[30]

Most of the inhomogeneity in the pack results from deformation of the ice due to differential movement of individual pieces of ice (called 'floes').[31] Under convergence, thin ice sheets may 'raft' on top of each other, doubling the ice thickness, and under strong convergence (for example, when wind drives sea ice against a coast), the ice buckles and crushes to form sinuous 'ridges' of thick ice. In the Arctic, ridges can be tens of meters thick, account for nearly half of the total ice volume and constitute a major impediment to transportation on, through, or under the ice.[32] The keels of some sea ice ridges extend downward up to 60 meters. The latter pose navigational hazards for submarines.

The limited data available is from submarine transects of the Arctic Region and more recently from projects such as the Arctic Sea Ice Thickness Observing Network. Between 1995 and 1999, the U.S. Navy carried out five nuclear submarine research cruises through the Arctic Ocean, known as the Scientific Ice Expeditions (SCICEX) program. The SCICEX program facilitated research in many disciplines, including ice thickness studies as sea ice draft data was gathered for the region.[33]

A 'basin-scale' analysis found that ice draft in the mid-1990s was less than that measured between 1958 and 1977 at every available location (including the North Pole).[34] The change was least (–0.9 m) in the southern Canada Basin and greatest (–1.7 m) in the Eurasian Basin (with an estimated overall error of less than 0.3 m). The decline averaged about 42% of the average 1958 to 1977 thickness. Ice thickness varies considerably from year to year at a given location (see Figure 11).

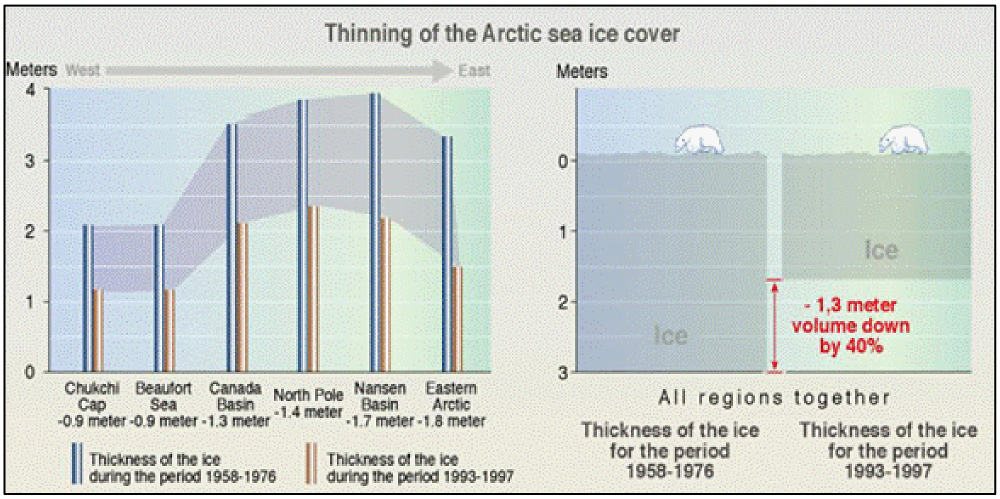


Figure 11: Changing Arctic Sea Ice Thickness[35]

On the basis of submarine sonar data and interpolation of the average sea ice thickness in the Arctic Basin from a variety of physics based sea ice models, it is very likely that the average sea ice thickness in the central Arctic has decreased by up to 1 m since the late 1980s, and that most of this decrease occurred between the late 1980s and the late 1990s. The steady decrease in the area of the summer minimum arctic sea ice cover since the 1980s, resulting in less-thick multiyear ice at the start of the next growth season, is consistent with this. This recent decrease, however, occurs within the context of longer-term decadal variability, with strong maxima in arctic ice thickness in the mid-1960s and around 1980 and 1990, due to both dynamic and thermodynamic forcing of the ice by circulation changes associated with low-frequency modes of atmospheric variability.[36]

Until recently there have been no satellite remote sensing techniques capable of mapping sea ice thickness, and this parameter has primarily been determined by drilling or by under-ice sonar measurement of draft (the submerged portion of sea ice). Upward-looking sonar has been on submarines operating beneath arctic pack ice since 1958. Ice draft measurement by moored ice-profiling sonar, electromagnetic induction sounders deployed on the ice surface, ships or aircraft, or airborne laser altimetry to measure freeboard (the portion of sea ice above the waterline), indirect estimates, based on measurement of surface gravity waves, are available in some regions for the 1970s and 1980s, but the accuracy of these estimates is difficult to quantify.[37]

An emerging new technique, using satellite radar or laser altimetry to estimate ice freeboard from the measured ranges to the ice and sea surface in open leads (and assuming an average floe density and snow depth), offers promise for future monitoring of large-scale sea ice thickness. Scientists estimated average arctic sea ice thickness over the cold months (October–March) for 1993 to 2001 from satellite-borne radar altimeter measurements. Their data reveal a realistic geographic variation in thickness (increasing from about 2 m near Siberia to 4.5 m off the coasts of Canada and Greenland) and a significant (9%) interannual variability in winter ice thickness, but no indication of a trend over this time.[38]

2.2.4 Ice Movement

The perennial sea ice cover is not attached to land and moves as illustrated in Figure 12. Approximately 14% of the sea ice mass is exported each year through Fram Strait.[39]

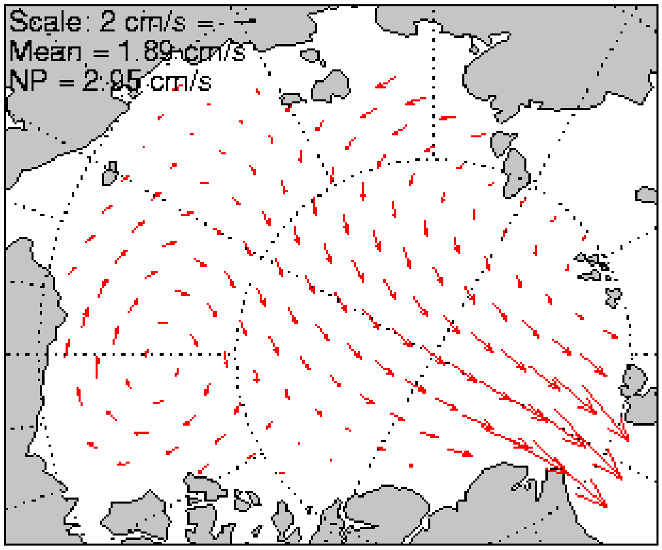


Figure 12: Ice Circulation in the Arctic

Arctic ocean-sea ice models, and GCMs with the most current physical representations of sea ice, are increasingly capable of reproducing the known features of the Arctic Ocean circulation and observed sea ice drift patterns under realistic atmospheric forcing.[40]

2.2.5 Cryosphere and Sea Level

Changes in the cryosphere will continue to affect sea level rise during the 21st century. During 2000 to 2020, some scenarios project the rate of thermal expansion due to warming of the ocean to be 1.3 ± 0.7 mm yr–1.[41] Glaciers, ice caps and the Greenland Ice Sheet are projected to lose mass in the 21st century because increased melting will exceed increased snowfall.[42]

Recent analysis of airborne data, satellite data and seismic data indicate thinning around the periphery of the Greenland ice sheet, where summer melt has increased during the past 20 years, while there is evidence of slower rates of thickening further inland.[43] Where snow cover or snowpack decreased, temperature often dominated; where snow increased, precipitation almost always dominated.[44]

Fresh water and ice flowing into polar oceans have a direct impact on sea level and (in conjunction with the melt of sea-ice) are important in maintaining the thermohaline circulation. Changes in the cryosphere will continue to affect sea level rise during the 21st century. From 2000 to 2020, some scenarios project the rate of thermal expansion due to warming of the ocean to be 0.5 ± 0.03 inches per year. Dynamical processes related to ice flow could increase the vulnerability of the ice sheets to warming, increasing future sea level rise. Figure 13 illustrates the increase in Eurasian river discharge to the Arctic Ocean.[45] The increase in river discharge corresponds with declines in the ice volume of Arctic and sub-Arctic glaciers and the Greenland ice sheet.[46]

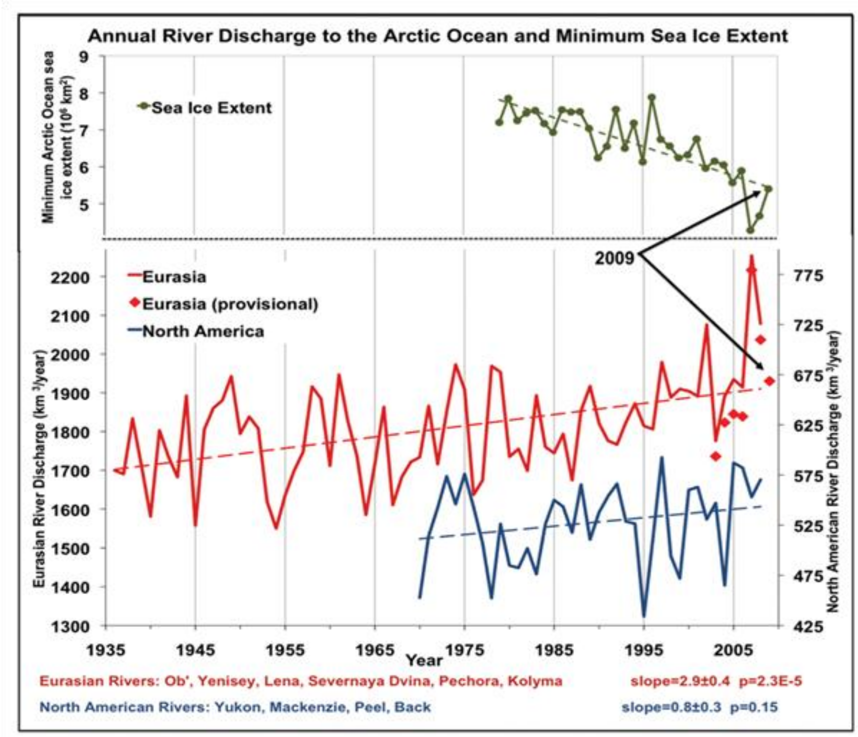


Figure 13: Total annual river discharge to the Arctic Ocean[2]

In September 2003, scientists from the United States and Canada announced that the largest ice shelf in the Arctic had broken up. The Ward Hunt ice shelf to the north of Canada's Ellesmere Island split into two main parts, with other large blocks of ice also pulling away from the main sections. Knowledge about these processes is limited and there is not yet a consensus on their magnitude.[47]

2.2.6 Salinity

Some ocean areas— most notably the high northern latitudes of the Atlantic—may also have reduced salinity in the upper layer due to freshwater input from melting land-ice and from higher than average precipitation and runoff into rivers.[48]

2.3 Hydrography and Land Mass Trends[49]

Permafrost regions occupy approximately 24% of the terrestrial surface of the Northern Hemisphere. The effects of climatic warming on permafrost and the seasonally thawed layer above it (the active layer) can severely disrupt ecosystems and human infrastructure such as roads, bridges, buildings, utilities, pipelines, and airstrips. Reduced sea ice allows higher storm surges to reach shore and thawing permafrost makes the shoreline more vulnerable to erosion. As the waves erode the bluffs, the permafrost emerges, melts, and collapses the cliffs above it. Whole sections of beachfront can fail catastrophically.

The U.S. Arctic Research Commission in 2002 chartered a task force on climate change. The task force found evidence of widespread warming of permafrost and observations of thawing —both conditions have serious, long-term implications for Alaska's transportation network, for the Trans-Alaska Pipeline, and for the nearly 100,000 Alaskan citizens living in areas of permafrost. Climate research and scenarios for the

[2] From the six largest rivers in the Eurasian Arctic for the observational period 1936-2008 (updated from Peterson et al., 2002) (red line) and from the four large North American pan-Arctic rivers over 1970-2(red line) and from the four large North American pan-Arctic rivers over 1970-2008 (blue line).

21st century also indicate that major settlements (such as Nome, Barrow, Inuvik, and Yakutsk) are located in regions of moderate or high hazard potential for thawing permafrost. Climate models predict that over half of the area covered by permafrost now could thaw by 2050, and as much as 90 percent could thaw by 2100.

Figure 14 shows a typical temperature profile through permafrost, from the ground surface to the base of the permafrost. This profile is often called a ‘trumpet curve’. Higher temperatures are to the right and lower to the left; 0°C is represented as a dashed vertical line. The heavier curves show current conditions. The summer profile curves to the right side of the ‘trumpet’, indicating above-freezing temperatures near the ground surface. The winter profile curves to the left, indicating that the lowest temperatures are experienced at the surface, with higher temperatures deeper in the permafrost. The summer and winter profiles intersect at depth; below this point, temperatures are not affected by the seasonal fluctuations at the surface. The ground warms gradually with depth in response to the geothermal gradient.

The base of the permafrost is situated where the temperature profile crosses 0°C. The *active layer* is the layer of earth material between the ground surface and the permafrost table that freezes and thaws on an annual basis. In its simplest approximation, climate warming can be envisioned as a shift of the temperature profile to the right, as shown by the gray curves. The surface temperatures in summer and winter are higher, the active layer is thicker, and the mean annual temperature at the thermal damping depth is higher. Over time the base of the permafrost thaws and moves toward the surface. Thus, the permafrost body warms and thins as thaw progresses both above and below.

Thickening of the active layer has two immediate effects. First, the decomposed plant material frozen in the upper permafrost thaws, exposing the carbon to microbial decomposition, which can release carbon dioxide and methane to the atmosphere. Second, the ice in the upper permafrost is converted to water. In coarse materials such as sand and gravel, this is not necessarily a problem. However, fine-grained sediments often contain excess ice in the form of lenses, veins, and wedges. When ice-rich permafrost thaws, the ground surface subsides; this downward displacement of the ground surface is termed *thaw settlement* (Figure 14). Typically, thaw settlement does not occur uniformly over space, yielding a chaotic surface with small hills and wet depressions known as *thermokarst terrain*; this is particularly common in areas underlain by ice wedges. When thermokarst occurs beneath a road, house, pipeline, or airfield, the structural integrity is threatened. If thermokarst occurs in response to regional warming, large areas can subside and, if near the coast, can be eroded by encroaching seas.

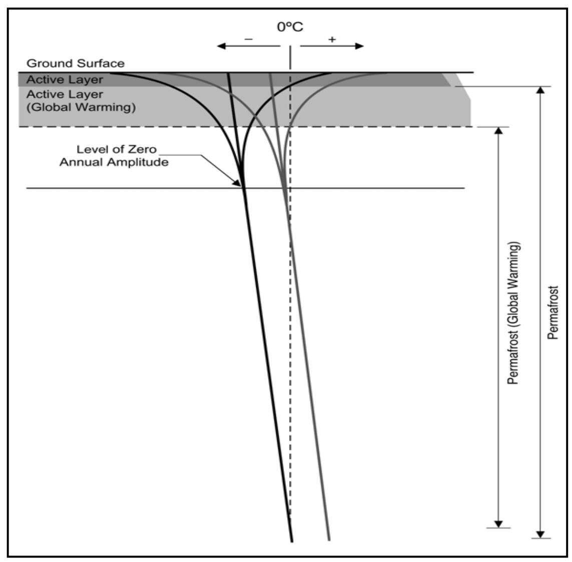


Figure 14: Ground temperature profile

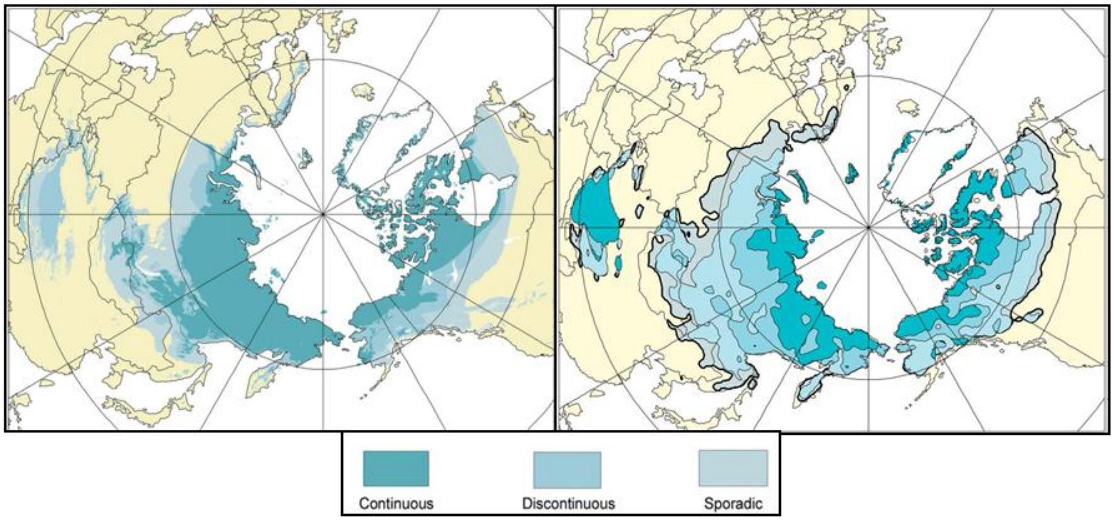


Figure 15: Permafrost zonation in the Northern Hemisphere[4]

Figure 16: Distribution of permafrost in 2050[3]

The 1997 map on which Figure 15 is based is the first detailed document to show permafrost distribution in the Northern Hemisphere based on standardized mapping criteria.[50] Figure 16 shows the distribution of permafrost in 2050 according to the United Kingdom Transient Run (UKTR) GCM, based on calculations by Ansimov and Nelson (1997).[51] Zonal boundaries were computed using criteria for the "surface frost number," a dimensionless index based on the ratio of freezing and thawing degree-days (Nelson and Outcalt, 1987).[52] The solid line shows the approximate southern limit of contemporary permafrost as presented in Figure 16. Areas occupied by permafrost have been adjusted slightly from those in the original publication to account for marginal effects.

Figure 17 shows the relative changes in active-layer thickness in 2050 according to the UKTR general circulation model.

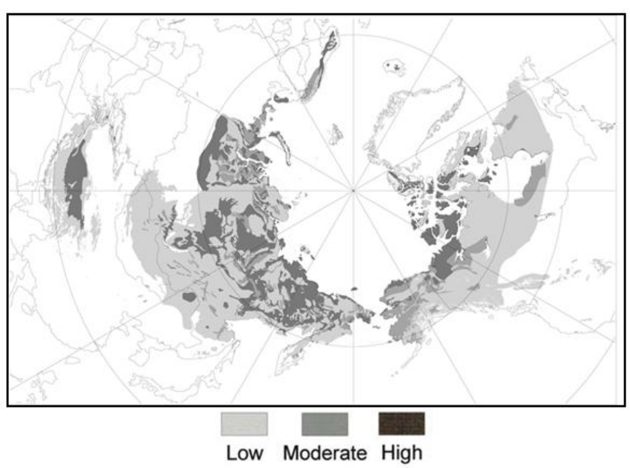


Figure 17: Relative changes in active-layer thickness in 2050[5]

[3] According to the UKTR general circulation model, based on calculations by Ansimov and Nelson (1997).
[4] Zones are defined on the basis of percentage of land surface underlain by permafrost: continuous zone, 90–100%; discontinuous zone, 50–90%; sporadic zone, 10–50%; isolated patches, 0–10%.
[5] According to the UKTR general circulation model, reclassed from Ansimov et al. (1997): low: 0–25%; medium: 25–50%; high: >50%.

The following three figures show areas at risk for infrastructure damage as a result of thawing of permafrost for population centers (Figure 18), transportation facilities (Figure 19), and electrical transmission lines and pipelines (Figure 20).

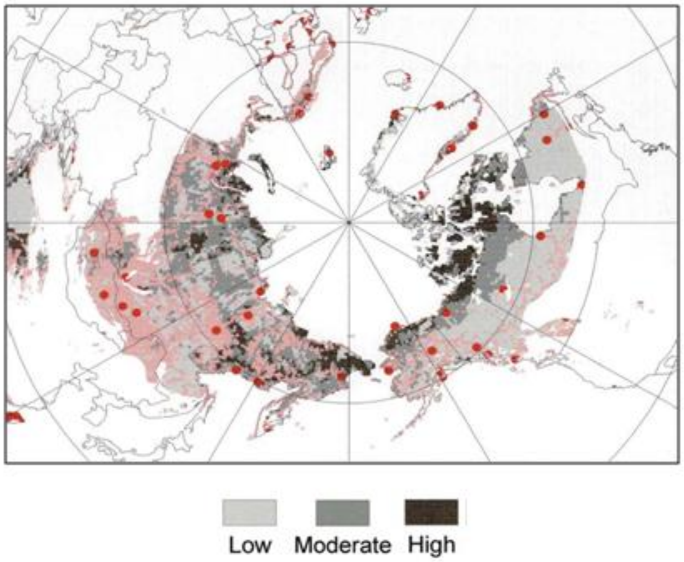


Figure 18: Risk to infrastructure

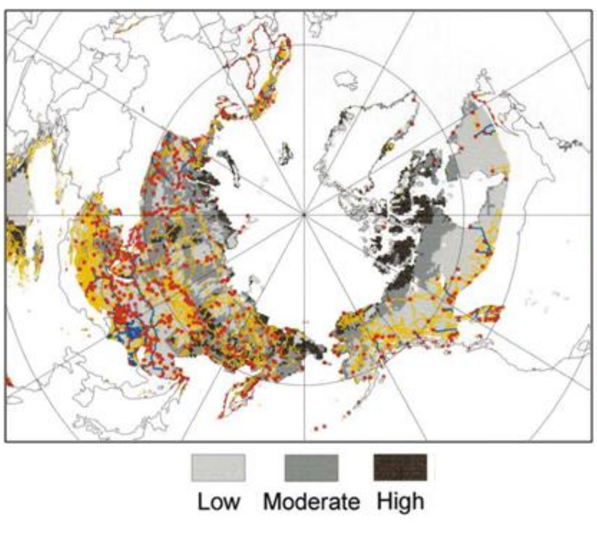


Figure 19: Risk to transportation facilities

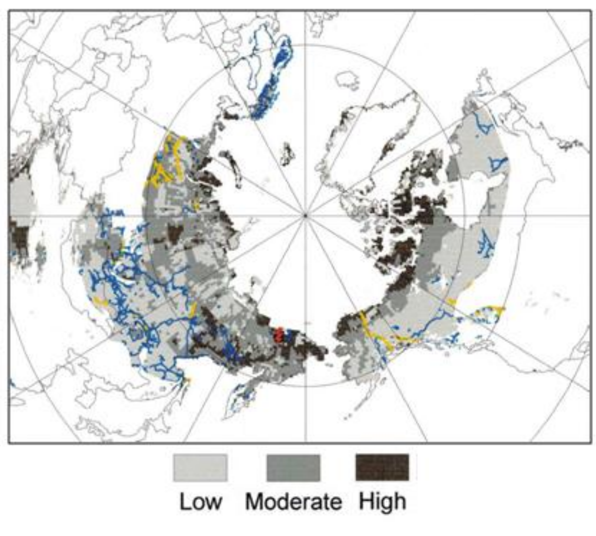
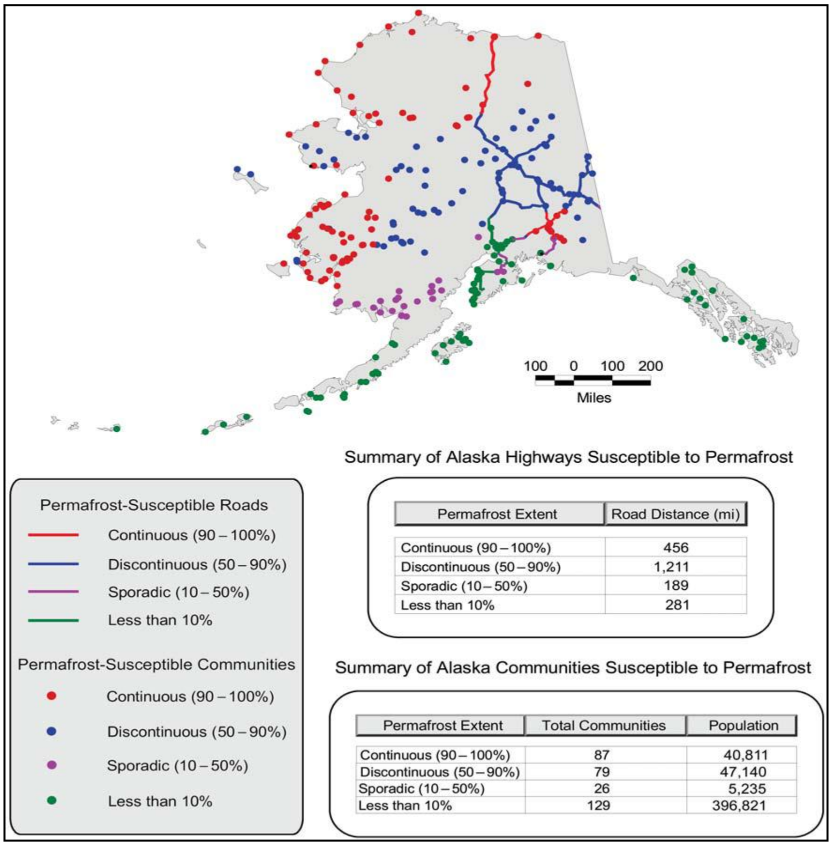


Figure 20: Risk to major electrical transmission lines and pipelines

In Figure 18, the red dots indicate population centers; the pink shading indicates areas of human settlement. In Figure 19, the yellow lines indicate winter trails, the blue lines indicate railroads, and the red dots indicate airfields. Lastly, in Figure 20, the blue lines indicate electrical transmission lines, the yellow lines indicate pipelines (yellow), and the black dot with red lightning is the location of the Bilibino nuclear power plant in Russia.

Figure 21 below shows the major road routes of the state of Alaska and the locations of communities, shaded to indicate whether they are situated in areas of continuous, discontinuous, or sporadic permafrost. Sizeable towns and settlements are located in areas that are susceptible to permafrost degradation; nearly 100,000 Alaskans live in areas vulnerable to permafrost degradation. Moreover, many of the state's highways traverse areas underlain by permafrost. Roads in the interior, particularly north of Fairbanks (i.e., the gravel Dalton Highway), traverse areas underlain by ice-rich permafrost and may require substantial rehabilitation or relocation if thawing occurs. The Alaska Railroad extends from Seward to Fairbanks, crosses permafrost terrain, and has been affected by differential frost heave and thaw settlement in places (Ferrians et al., 1969).[53] A significant number of airstrips in communities of southwest, northwest, and interior Alaska are built on permafrost and will require major repairs or complete relocation if their foundations thaw.



Summary of Alaska Highways Susceptible to Permafrost

Permafrost Extent	Road Distance (mi)
Continuous (90 – 100%)	456
Discontinuous (50 – 90%)	1,211
Sporadic (10 – 50%)	189
Less than 10%	281

Summary of Alaska Communities Susceptible to Permafrost

Permafrost Extent	Total Communities	Population
Continuous (90 – 100%)	87	40,811
Discontinuous (50 – 90%)	79	47,140
Sporadic (10 – 50%)	26	5,235
Less than 10%	129	396,821

Figure 21: Exposure of communities and major roads in Alaska to permafrost.[6]

Alaska has four large military bases, two of which must contend with discontinuous permafrost. Alaska also has 600 former defense sites. Russia has an even greater problem, with a significant number of population centers, industrial complexes (including one nuclear power plant), and military bases in permafrost areas (Ershov et al., 2003).[54] The continuous permafrost in the far north forces essentially all facilities to be constructed on permafrost. Farther south, in areas of discontinuous permafrost, land ownership and needs often force facilities to be developed on permafrost.

The permafrost underlying most of the state is the key reason why Alaskan infrastructure will be affected by a warming climate far greater than any other region of the U.S. Thawing permafrost poses several types of risks to community infrastructure. Most are associated with the thawing of ice-rich permafrost,

[6] Source data: U.S. Geological Survey, International Permafrost Association, and Alaska Department of Natural Resources GIS database.

which, when thawed, loses strength and volume. The most basic risk is caused by the loss of mechanical strength and eventually thaw settlement or subsidence. Thaw settlement causes the failure of foundations and pilings, affecting all types of community infrastructure. Bond strengths between permafrost and piles are greatly reduced by rising temperatures. Increases in the thickness of the active layer can cause frost heaving of pilings and structures. Warming will also accelerate the erosion of shorelines and riverbanks, threatening the infrastructure located on eroding shorelines. Thawing of permafrost or increasing the thickness of the active layer can also mobilize pollutants and contaminants that are presently confined (Snape et al., 2003).[55]

3.0 Outlook - Resource Exploration Assessment

The receding Arctic ice and milder climate will soon reveal resources previously inaccessible. These resources will certainly benefit those nations that can harvest them but this competition for resources will also present political friction between states.

3.1 Fisheries

Many factors will affect Arctic marine ecosystems, such as warmer Arctic surface and water temperatures, reductions in sea ice coverage and thickness, reduced salinity, increasing acidification and other oceanographic and meteorological changes. However, the cumulative effect of these factors on fisheries does not yet have a consensus. The composition of Arctic marine ecosystems will undoubtedly change; qualitatively, quantitatively, spatially and temporally. Where new fishing opportunities will occur (on the high seas and within coastal state maritime zones) and with respect to which species or category of species (e.g. shared, anadromous, straddling or highly migratory) is also difficult to predict. Similarly, it remains difficult to predict which states - Arctic Ocean coastal states or other states - will benefit or suffer and how subsistence fishing will be affected, among other things by competition with commercial fisheries. Finally, as reduced ice coverage and thickness enables increases in human activities - most importantly shipping and offshore hydrocarbon activities - these activities may compete with fishing in a spatial sense or affect them by pollution and other impacts.

While warmer areas of the Arctic Ocean have supported commercial fishing activities for decades, until recently, there had been little or no major fishing activity in the colder areas of the Arctic, with ice-covered regions completely cutting off access to fishing. The retreat of Arctic sea ice is opening up new parts of the Arctic Ocean to fishing vessels, and there are already signs that certain marine species are migrating north at a rapid rate.[56]

The impact of current and future Arctic fisheries on the marine environment and marine biodiversity in the Arctic is not likely to be fundamentally different from impacts to the marine environment and biodiversity in other parts of the globe. However, the challenge in enforcing fishing regulations is much different due to the harsh nature of the Arctic environment. Increased access to Arctic fisheries could lead to over-exploitation of target species and a variety of impacts on non-target species, for instance on dependent species due to predator-prey relationships, on associated species due to by-catch and on benthic species due to bottom fishing techniques.[57]

3.2 Gas, Oil, Hydrates

Though the Arctic holds a significant share of the world‘s oil and gas reserves, there is no instrument providing comprehensive global regulation of offshore hydrocarbon activities, nor is there any global regulatory or governance body with such a mandate. UNCLOS sets out the basic rules on access to and control over offshore hydrocarbon resources and the mandate of the International Seabed Authority (ISA). Other instruments with more limited applicability to offshore hydrocarbon activities include Maritime Pollution (MARPOL), the Oslo/Paris (OSPAR) Convention, Oil Pollution Preparedness, Response, and Cooperation (OPRC), and the Espoo Convention. There are also multilateral and bilateral agreements that deal with offshore oil and gas activities, yet none of them are comprehensive in their coverage. Nor are these specifically tailored to address the unique circumstances of the Arctic.[58]

The existing Arctic Council's Arctic Offshore Oil and Gas Guidelines could go a long way toward addressing the current regulatory gaps if put into practice by the Arctic states. The Guidelines were adopted by the Arctic Council in 1997 and then revised in 2002. A third revision was released in 2008, and adopted in the Ministerial meeting in April 2009. The guidelines provide recommendations on standards, technical and environmental best practices, management policy, and regulatory control for Arctic offshore oil and gas operations. The Guidelines also recommend that regulation of offshore hydrocarbon activities utilize the precautionary approach, the polluter-pays principle and the principle of sustainable development. Although providing an important step in the creation of a comprehensive regulatory regime, the Guidelines are not legally binding and leave the coastal states with a wide margin of discretion in their implementation.[59]

3.3 Minerals

Exploration of minerals and precious metals will continue to increase as the Arctic environment becomes more accessible and hospitable. Multi-billion dollar estimates of untapped minerals, ranging from gold and diamonds to potash and zinc, have many countries hoping to mine the Arctic seafloor. Complicating this landscape are Arctic nations rushing to justify the extension of their continental shelf claim beyond the 200 mile EEZ. Arctic nations are also surging further north, mining today what was hidden a decade ago. For example, in worldwide diamond production over the past decade, Canada has surged from 8th place (at 2 million carats per year) to 3rd (now at 18 million carats per year).

3.4 Trans and Intra-Arctic Shipping

Using the Northwest Passage (NWP) could save international shipping companies an estimated 35% on a voyage between Europe and Asia compared to taking the Panama Canal or going around Cape Horn. However, ice melt patterns are not uniform and shippers face considerable uncertainty regarding the timely delivery of their shipments. For instance, regional variations in increases or decreases of sea-ice concentration have important implications for ship operations because certain routes may be subject to heavier than normal ice conditions as a result of ice movement. This highlights the major hazard for ships navigating the Northwest Passage. In the NWP, multi-year ice floes from the Canadian Basin or the Queen Elizabeth Islands, or both, meander southward into the lower reaches of the archipelago where they block passages and create choke points. Multi-year ice is thicker, stronger, and takes longer to break up than seasonal first-year ice and thus presents a serious navigation threat to transiting ships. Despite the Arctic warming trend and reduced ice cover, navigation in the NWP will remain hazardous. Ice in the eastern Arctic is melting more slowly than in the western Arctic.[60]

Vessels without ice hardening can already pass through the Northern Sea Route for part of the year. By 2025, it is even possible that ice-hardened vessels will be able to travel directly across the North Pole in the summer, circumventing the Northern Sea Route entirely. More conservative estimates suggest such an outcome is possible by 2050.[61] A major growth in Arctic shipping would directly affect the U.S. Navy because it would be the Navy's responsibility to ensure additional sea-lanes remain free and safe.

3.5 Tourism, Recreation and Adventure Activity

Both human-induced and natural events are making the Polar Regions increasingly accessible. Vastly improved geographic and hydrographic knowledge; advancements in transport and navigational technologies; more comfortable clothing; more durable recreational equipment; significant reductions in the amount, extent and duration of sea ice; and a relatively more tolerable climate are all contributing to growing access to the Polar Regions. The cumulative impacts of these events are larger numbers of polar tourists spending more time in more locations. During the period from 1968 to 2005, 25 June to 15 October represented the optimal navigation season for cruise ships.[62]

The transport of tourists to the Arctic, in itself, increases the volume of ship and airplane traffic. In addition to the impacts on climate by long distance air and water traffic, increased ship traffic in these waters could lead to increased risks of groundings and other accidents, the results of which can include oil spills and other environmental consequences.

The number of cruise ships visiting the Canadian Arctic has steadily increased since 1984. In 2006, the number of cruise ships doubled to 22 ships, up from 11 ships in the previous season (Buhasz, 2006),[63] confirming observations from elsewhere that the ocean environment has become one of the fastest growing areas of the world's tourism industry (Miller and Auyong, 1991; Orams, 1999; Hall, 2001; Dowling, 2006).[64]

A key concern in what seems to be the most likely scenario of increased cruise traffic, combined with increased interannual variability in sea-ice hazards, is the availability of short-term and long-range sea-ice forecasts to aid in safe vessel transits, route planning, and long-term planning. The U.S. National/Naval Ice Center and the Canadian Ice Service are the government departments responsible for relaying ice information to the public. Both the National Ice Center and the Canadian Ice Service have begun to look more closely at seasonal forecasting to ensure safe passage. Since the current state of the Earth's climate is to some degree a function of past climate states, relatively simple statistical models that exploit this "interseasonal memory" in the climate system have successfully predicted the length of the shipping season along the northern coast of Alaska (Drobot, 2003, 2005) and the start date of the shipping season in Hudson Bay (Tivy et al., in press).[65] Further research would be required to adapt these models to meet the specific needs of the tourism industry. In general, the current state of short-term and long-range sea-ice forecasting is insufficiently advanced to deal with a major increase in ship traffic in Canada's ice-infested waters, particularly through the narrow channels of the Canadian Arctic Archipelago.

Although there has been an increase in open water in the Arctic, this does not mean that there is safe passage. In many cases, the navigable areas through the Northwest Passage actually have exhibited increases in hazardous ice conditions. For example, the influx of multi-year ice into the channels of the Northwest Passage has created many navigation choke points. Thus, cruise operators working in the Canadian Arctic face considerable uncertainty in the future: rather than widespread accessibility, as some have claimed, there is likely to be much more variability of ice conditions across this region.[66]

Cruise operators may be forced to reduce their activities in the Northwest Passage and to focus more heavily on the Eastern Canadian Arctic, where ice conditions are likely to continue to be more favorable for safe navigation. This focus is starting to be seen around Baffin Island, where communities such as Pond Inlet are emerging as favored destinations for cruise operators.[67]

Cruise tourism inevitably will continue to increase. Visitors on more traditional cruises are becoming more adventurous, seeking out more challenging, more remote locations to add to their global cruise list (Marsh and Staple, 1995).[68] Latent demand and the propensity for an increasing number of cruise visitors to become return patrons is important: even in the early days of Arctic cruising, 30% of tourists indicated that they would return to the Arctic (Marsh and Staple, 1995).[69] Research in Antarctica confirms that people who have visited "one polar region are also likely to want to experience the other"[70], and with the number of tourists visiting Antarctica growing dramatically in recent years[71], a potentially sizeable market exists for Arctic regions. All of these trends suggest the prospect of continued growth in Arctic cruise tourism.

4.0 Tactical, Operational and Strategic Implications for the Navy of an Opening Arctic

Estimates vary as to when the Arctic is likely to be ice free during the summer. The National Snow and Ice Data Center suggests a seasonally ice-free Arctic by 2060. A National Science Foundation report suggests that the Arctic Ocean could be devoid of ice in the summertime by 2040. The two most important implications of an opening Arctic Ocean are improved access to likely vast energy and mineral resources and potentially shorter maritime shipping routes. Transiting the Northern Sea Route above Russia between the North Atlantic and the North Pacific would trim about 5,000 nautical miles and a week's sailing time off a trip compared with use of the Suez Canal. Voyaging between Europe and Asia through Canada's Northwest Passage would trim some 4,000 nautical miles off of a trip using the Panama Canal. Resource and shipping benefits are unlikely to materialize by 2025. The U.S. National Petroleum Council has said that some of the technology to exploit oil from the heart of the Arctic region may not be ready until as late as 2050. Nonetheless, these potential riches and advantages are already perceptible to the United States, Canada, Russia, Denmark, and Norway—as evidenced by the emergence of competing territorial claims, such as between Russia and Norway, and Canada and Denmark.[72]

4.1 Operational Challenges

Operational challenges in the Arctic are legion: from temperatures below -55 degrees Celsius, to vast, uninhabited expanses, to months-long darkness. The Arctic environment—essentially maritime in nature—precludes most of the usual support militaries take for granted in more moderate or overland climes, such as navigation aids, communications, logistics and maintenance infrastructure, and even search and rescue (SAR) services. Communications, never perfect even in ideal conditions, are extremely limited. Satellite connectivity is rare, GPS coverage is marginal, and long-haul high-frequency communications are unreliable.[73]

Surface vessels are especially challenged in the Arctic. Free-drifting icebergs and shifting pack ice can hole all but the heartiest icebreakers. Twenty-four-hour winter darkness increases watch manning and reduces morale. Extreme cold threatens both humans and machinery; icing on ships' equipment and superstructures can pose a capsizing threat. Typically icing occurs in the range of +2 degrees to – 10 degrees Celsius; in colder temperatures icing doesn't occur. Warmer air temperatures will increase the amount of suspended moisture in the atmosphere and facilitate the development of weather events, thus increasing the potential for icing hazards. Equipment and personnel casualties can quickly become emergencies in the Arctic. Polar conditions transform sophisticated weapons and sensors rendering them useless. Arctic surface operations require herculean efforts just to remain within safety margins.[74]

Navy mission elements likely to be affected by the projected environmental conditions include launch and recovery operations from aircraft carriers and other ships, Arctic air navigation, weapons systems employment, personnel performance, sustainment factors and command and control considerations. Rapidly changing ice and weather conditions will limit ship maneuverability. Icy deck surfaces on aircraft carriers will increase the risk to crews for handling aircraft. Aircraft launch and recovery and close ship maneuvering will be made more difficult due to poor visibility.

There are limitations and uncertainties in current computer models that forecast Arctic conditions. Example, the 2007 IPCC reports did not capture the accelerated changes observed in the behavior of sea ice and ice sheets. Weather observing stations and field research will increase the empirical base for scientific modeling. Indigenous observers and their traditional knowledge is an underutilized asset in evaluating and understanding the processes contributing to rapid environmental change.

Temperature and salinity profiles can change very rapidly (within a day) in the Arctic surface waters creating the need for more robust acoustic forecast models. Warming of the upper layers of the ocean produces downward-refracting acoustical conditions. These conditions normally produce shorter acoustic detection ranges. Some ocean areas— most notably the high northern latitudes of the Atlantic—may also have reduced salinity in the upper layer due to freshwater input from melting land-ice and from higher than average precipitation and runoff into rivers. This reduced salinity may also affect acoustical propagation conditions.[75]

A list of additional Arctic environment impacts follow:

- Radar ranges degraded by EM effects
- Comms antennae impacted by ice accretion
- Radios degraded in icy conditions
- Frozen VLS launchers degrade TLAM quick strike capability
- Human fatigue in cold weather
- Frozen gun turrets
- Decreased navigation capabilities

- Fog 100 days/year
- 24 hours of darkness in winter
- Haze in late winter, early spring
- Limited available high resolution satellite imagery
- 80% cloud cover
- Ceiling below 1000 ft
- EM effects of aurora borealis
- Impact on aircraft operations
- Icy deck landings
- 30-40 kt winds
- Snow 160 days/year
- Forward logistics capability not available

Most of these impacts will exist even as the Arctic warms over the next 30 years. Though Naval activities in the Arctic are expected to increase, the Arctic will still remain a difficult and dangerous operating theater of operations.

5.0 Summary

With the Arctic environment changing faster than any place on earth, this is cause for immediate attention. Although the projections vary, scientists agree that the Arctic is headed toward ice-free summers, which in turn poses numerous challenges and opportunities for the U.S. Navy. An opening ocean in the near future may increase water traffic, create boundary disputes, and raise questions over sea sovereignty. It is for these reasons and others that it is important to study the Arctic now so that the U.S. Navy is better prepared to operate there in the future. Though it is doubtful that the Arctic will shift much of Navy's attention from current deployment patterns, the Navy must be prepared to respond to any location when called. Just as the Coast Guard is expected to maintain an icebreaking capability to support our national interests, so must the Navy be able to operate in this heretofore inhospitable ocean.

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