United States Arctic Research Commission

THE ARCTIC OCEAN AND CLIMATE CHANGE: A SCENARIO FOR THE US NAVY

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United States Arctic Research Commission

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ARCTIC OCEAN CLIMATE CHANGE

Preface

At a meeting held at the Naval Ice Center on 7 July, 2000 with representatives from the National/Naval Ice Center, the Oceanographer of the Navy (N096), the Office of Naval Research (ONR), MEDEA, the Arctic Research Commission, and U.S. Coast Guard the national and strategic issues surrounding operations in an ice-free, or ice-diminished Arctic were framed. It was recommended that a forum be established to evaluate the Naval implications of operating in an ice-free Arctic. In order for this forum to succeed it was deemed essential that the views of nationally recognized experts on Arctic climate change be presented to the Navy in order to assure a sound scientific basis for future planning. The US Arctic Research Commission undertook to survey the community of experts in the field and to present their views to the Navy as a basis for further planning. The following is an edited compilation of the views of that panel of experts convened by the United States Arctic Research Commission to assist the Navy in considering the effects of climate change on their operations in and around the Arctic Ocean in the mid to late Twenty First Century.

Summary:

- The climate of the Arctic responds to short-term variations on a roughly decadal scale known as the Arctic Oscillation (AO) and the North Atlantic Oscillation (NAO), which are closely coupled and may be features of the same phenomena observed in different regions. These decade long oscillations will continue to add variability to Arctic climate.

- Model studies indicate that temperatures in the Arctic region will increase by mid-century with summer temperature (Jun-Aug) increasing by 1-2 deg. C, autumn (Sep-Nov) by 7-8 deg. C, winter (Dec-Feb) by 8-9 deg. C and spring (Mar-May) by about 5 deg. C. Variations between model predictions are of the order of 1-2 deg. C in summer and 5-6 deg. C in winter.

- In the winter the entire Arctic Basin will be ice covered. Model studies suggest that summer ice extent will decrease by roughly 30% and ice volume by roughly 40%. A conservative consideration of model results suggests summer ice extent will decrease by only 15% and that ice volume will decrease by 40% leading to an increase in the relative abundance of thin, first-year ice.

- The Sea of Okhotsk and the Sea of Japan will remain ice-free throughout the year. The Russian coast and the Canadian Archipelago will be ice free and open to navigation by non-ice-strengthened ships in summer.

- In the atmosphere, the Arctic boundary layer will be warmer and wetter. Cloudiness will increase, extending the summer cloudy regime into earlier onset and later decline. The likelihood of freezing mist and drizzle will increase as a result.

- Polar low pressure systems will become more common and boundary layer forced convection will increase mixed phase (ice-water) precipitation. Vessel and aircraft icing will be more common.

- Arctic warming will affect permafrost. The active (seasonally melted) layer will thicken and permafrost extent in the discontinuous permafrost region (along the borders of permafrost stability) will decrease. The inner and outer boundaries of the discontinuous zone will move to the North.

- Changes in timing and composition of river runoff will affect surface seawater. Increased sediment loads in spring runoff will spread out at sea affecting optical transparency.

- Soils will be drier and more susceptible to tundra fires. Local optical properties may change affecting energy balances and local weather.

- Declines in traffic on the Northern Sea Route (NSR) may continue in concert with Russian economic difficulties. But climate induced increases in trafficability in the NSR may cause increased use for Atlantic-Pacific transportation.

- Both Russia and Canada assert policies holding navigable straits in the NSR and the Northwest Passage under their exclusive control. The US differs in their interpretation of the status of these straits. As these routes become more available for international traffic, conflicts are likely to arise.

- Ships that can expect contact with even minor abundances of sea ice require increases in stiffeners and plate thickness in the affected region. Underwater installations including propellers, rudders, fin stabilizers, sea chests and especially thin-skinned sonar installations must be redesigned for Arctic operations.

- Icing of ships and aircraft will require accommodation in ship/aircraft design and operation. Weapons systems will also be affected by icing conditions.

- Sonar operations in the Arctic will experience increased ambient noise levels and the surface duct will be diminished or lost. Ice keels will be shallower and less abundant and the area in which they can be expected to occur will be reduced. Active sonar detection of submarines will become more feasible.

- Russian economic levels have resulted in the reduction of the Russian Arctic's European population. Operation of the expensive and difficult logistics pipeline to Arctic communities may be further reduced leading to a return to subsistence living by native populations.

- The Russian Arctic is a storehouse of natural resources. Changing climate may spur an increase in exploitation of energy, mineral and forest resources, especially by or for the benefit of resource poor Asian nations.

- The response of marine resources to changing climate is very difficult to predict but northward migrations are likely. In particular, northward movement of Bering Sea species into the Beaufort/Chukchi Sea region north of Bering Strait is likely. Climate warming is likely to bring extensive fishing activity to the Arctic, particularly in the Barents Sea and Beaufort/Chukchi region where commercial operations have been minimal in the past. In addition, Bering Sea fishing opportunities will increase as sea ice cover begins later and ends sooner in the year.

- Ecological disruption due to climate-induced separation of essential habitats can be expected with particular effects on marine mammal populations.

- The exploration, development, production and transportation of petroleum in the Arctic will expand with or without climate change as prices continue to rise due to the decreasing rate of discovery of reserves elsewhere. Climate warming and reduction in ice cover will facilitate and perhaps accelerate the process.

I. *Modeling recent and future changes in the Arctic Ocean environment*

Understanding of global and regional components of the earth's physical environment and its short-to-long term variability is one of the main requirements for realistic forecasts of weather and climate. Both global climate models and recent observations suggest that the Arctic Ocean is the region where an amplified response to global climate change might be taking place. In addition, changes in the Arctic Ocean and sea ice circulation are important to dispersion of nuclear contamination, biological productivity, and navigational forecasts.

Some models predict that the Arctic ice will significantly reduce in area and volume or possibly disappear during summer months as a result of increased greenhouse gases. The sea-ice albedo feedback is used to explain such a scenario. It implies that at warmer temperatures there will be less sea ice in the Arctic, which will allow an increased absorption of solar radiation due to decreased albedo, which will result in even warmer temperatures, and so on. The only immediate stabilizing effect (or negative feedback) comes from more rapid radiative cooling of the sea ice surface at warmer temperatures. On the other hand, other stabilizing effects are possible over longer times. For example, warmer air temperatures may lead to enhanced hydrological cycle and greater moisture convergence into the Arctic Ocean providing increased stratification in the upper ocean. Melting of large amounts of sea ice must also lead to dramatic increases in the fresh water flux out from the Arctic Ocean. The Great Salinity Anomaly of the late 1960s and 1970s is a good example of such an extreme event. An excess of fresh water exported from the Arctic into the Nordic and Labrador seas can alter or stop convection there, thus strongly affecting the formation of North Atlantic Deep Water and the global thermohaline circulation. A favorable scenario of Arctic climate change is one with a shorter-term (years to decades) natural variability superimposed on the long term warming trend due to greenhouse gas and other human-related emissions. Such a scenario is at least partly in agreement with time series of the Arctic Oscillation (AO) and the North Atlantic Oscillation (NAO), which are often used as indices of Arctic climate variability.

Over the last few decades, general circulation models (GCMs) have made significant advancements in representation of physical processes determining oceanic regimes and their variability and in use of modern high performance computers to solve complex oceanographic problems. Regional models of the Arctic Ocean have increased their spatial resolution by an order of magnitude, from the order of 100 km to 10 km, during the last decade. As a result, many important (and commonly neglected) small-scale bathymetric and geographic features have been included in such models. This allows more realistic representation of circulation and water mass and properties exchanges within the Arctic Ocean and its interactions with the global ocean. High model resolution also allows to better address new tactical requirements of operational ice prediction models, such as ice edge position, lead orientation, and sea ice thickness and concentration.

Improved regional models can successfully simulate recent regime shift in the sea ice and ocean circulation between the 1970s / 1980s and the early 1990s. Model results are in qualitative agreement with hydrographic measurements (suggesting recent changes) from the SCICEX submarine cruises and from icebreaker expeditions in the early 1990s. One of the conclusions from those models is that changes in the sea ice and ocean circulation and properties are at least partly in response to larger scale variability in the Northern Hemisphere weather patterns, such as AO or NAO. The shelf circulation and shelf-basin communication changes significantly between different regimes. The large scale drift of sea ice and its properties as well as the fresh water export from the Russian shelves and the Atlantic Water circulation within the Eurasian and Canadian Basins change in the early 1990s. Largest changes associated with this shift take place in the Eurasian and Makarov basins, over the Chukchi/Beaufort shelves and slopes and in the Canadian Archipelago. Information about spatial distribution of recent changes is crucial as it provides guidance for future field campaigns and potential future tactical operations, not available otherwise. Results from both observations and models indicate that a continuation of large scale measurements including repeated basin-wide hydrographic transects and focused process studies in the above mentioned regions should be of highest priority. This would allow evaluation of what may be an inherent cyclicity in Arctic climate and understanding and possibly more reliable predictions of future climate change in the Arctic Ocean.

II. *Climate Model Projections for the Mid-21st-Century Arctic*

The global climate models used by the Intergovernmental Panel on Climate Change (IPCC) project a stronger warming over the Arctic Ocean than over any other area of the Northern Hemisphere. However, the Arctic warming is highly seasonal, and it varies widely among the nine models used by the IPCC. Relative to the 1961-1990 baseline climatology, the central Arctic Ocean is projected to be warmer in the 2030-2060 period by 1-2 deg. C in summer (Jun-Aug), by 7-8 deg. C in autumn (Sep-Nov), by 8-9 deg. C in winter, and by approximately 5 deg. C in spring (Mar-May). The across-model standard deviation of the projected warming is nearly as large as the warming itself, ranging from 1-2 deg. C in the summer months to 5-6 deg. C in the winter months. The spatial pattern of warming over the subpolar seas and the Arctic Ocean is closely tied to the retreat of sea ice. Adjacent land areas are projected to warm more than the ocean areas in summer, but less than the ocean areas in winter.

Projected annual mean precipitation rates for 2030-2060 are generally higher than at present by about 1 cm per month, although the changes tend to be smaller in summer and larger in autumn. While there is a tendency for the largest precipitation changes to occur over the subArctic (50 deg.-70 deg. N), the spatial pattern of the projected change in precipitation is noisier than the pattern of temperature changes. The model-to-model scatter of precipitation change is even greater than the scatter of the temperature changes. Changes in evapotranspiration have yet to be evaluated.

Sea level pressure is projected to decrease by 1-2 mb over much of the Arctic. The largest projected decreases of pressure are in autumn and winter, and on the Eurasian side of the Arctic Ocean. While lower mean pressures may imply more cyclone activity, there has not yet been a systematic evaluation of daily model output to determine whether synoptic (i.e., storm) activity shows a significant increase in the climate scenarios. To our knowledge, there have been no evaluations of changes in cloudiness and radiative fluxes over the Arctic in the climate projections of global models.

Observed Climate Change in the Arctic: Records for 1961-1990 over the central Arctic Ocean, collected as part of the Russian "North Pole" drifting station program, show statistically-significant increases in temperature of 0.89 deg. C and 0.43 deg. C per decade for May and June, respectively. Temperature increases during this period are also significant for summer as a whole. A different analysis for the period 1979-1997, based on a combination of temperature data from the North Pole program, drifting buoys and land stations, reveals statistically significant trends over most of the Arctic Ocean in spring, locally exceeding 2.5

deg. C per decade. This is consistent with indications based on satellite passive microwave records of an earlier onset of spring melt over the sea ice cover and is likely also related to reductions in sea ice extent of about 3% per decade since 1979 as assessed from satellite records.

Temperature trends over the Arctic Ocean are broadly consistent those over land. Land records show pronounced warming from about 1970 onwards (mostly in winter and spring), over Siberia and Northwestern North America. The general pattern of warming is partly compensated by cooling trends over eastern Canada and the northern North Atlantic. It is important to note that in terms of 55-85 deg. N zonal averages, temperatures around 1970 were below average. Hence, what we've really seen is (in part) a recovery from anomalously cold conditions. It also appears that from 1920-1940, Arctic temperatures rose even more sharply than in the past several decades. On the other hand, the paleo-climate records suggests that today's Arctic temperatures are the highest of at least the past 400 years, possibly longer.

Since 1900, there has been a general increase in precipitation for the 55-85 deg. N latitude band, largest during autumn and winter. There have been pronounced recent increases in the past 40 years over northern Canada. Changes over the Arctic Ocean are unknown due to the paucity of data.

The general pattern of recent Arctic temperature change and (at least to some extent) changes in precipitation appear to be related to shifts in the large-scale atmospheric circulation, reflected in generally positive modes of the Arctic Oscillation (AO) and North Atlantic Oscillation (NAO). Changes in the AO and NAO are also reflected in observed decreases on sea level pressure over the central Arctic, as well as a tendency for more frequent high-latitude cyclone activity. Recent modeling experiments indicate that anthropogenic forcing may modulate the intensity and frequency of modes of variability such as the AO and NAO.

In summary, observed changes in temperature, precipitation and atmospheric circulation are broadly in accord with climate model projections. However, attribution of change is complicated by the wide scatter between projections from different models.

III. *A Scenario for Arctic Ocean Sea Ice in the Year 2050*

Predicting the future climate is risky. Climate is known to be variable on "all time scales." Trends that appear for, say, a decade may or may not persist into the next decade. Climate models make predictions based on an insufficient representation of important physics and chemistry. With this disclaimer, we construct a scenario for Arctic Ocean ice conditions in the year 2050. Our approach is this. We examined the changes predicted by four reputable global climate models. We compare these with extrapolated trends that have been observed over the last several decades. We then suggest a conservative interpretation of both types of evidence for what to expect by 2050. For both models and observations, we deal with end-of-summer minimal extent, volume and thickness which have decreased more than winter maximums.

Model evidence: Four global climate models predict reductions in ice extent and thickness in the Arctic. The models all show a continually decreasing ice cover. A middle-of-the-road estimate from models is that by 2050, ice extent will be down about 30% (to 3.5 million sq. km).

Models also predict a declining ice volume. A moderate model estimate is that by 2050, ice volume will decrease some 40% to 5400 cubic km. Models are not fully credible. When run to "predict" past observations, different models show different biases, so their projections into the future are of uncertain validity. But they all predict a diminishing ice cover.

The 4-model average decrease by 2050 is 30% in summer minimum ice extent and 40% in summer minimum ice volume.

Observational evidence: The 100-year historical record from ships and settlements going back to 1900 shows a decline in ice extent starting about 1950 and falling below pre-1950 minima after about 1975. This decline is better documented by satellites during the last 20 years. The rate of decline is about 3% per decade.

The record of submarine ice draft data shows that the ice draft at the end of summer has declined by about 40% over a time interval of about thirty-five years, or about 11% per decade. There are few data from the intervening years, so it is difficult to assess "normal" climatic variability, even over the 35 years of submarine data, much less over a longer period.

Future scenario: A conservative scenario is that by 2050 the observed trend will reduce summer minimum ice extent by 15%; this is an extrapolation of the satellite observations which are quite reliable and are not contradicted by climate model forecasts. For volume and thickness, a conservative estimate is obtained by extrapolating model forecasts which are not contradicted by sparse observations. By 2050, the end-of-summer volume can be expected to be down by about 40%, of which about 15% would be due to decreased extent and the remaining 25% would be seen in an end-of-summer thickness reduced by 25% to about 1.5 m.

What does this mean in terms of various regions of the Arctic? During winter, the central Arctic and all peripheral seas including the Greenland Sea, Bering Sea, and Gulf of St. Lawrence will continue to have significant ice cover. Extent and, in most areas, ice thickness will be reduced. The Sea of Okhotsk and Sea of Japan will be ice-free for the entire year. In late summer, the entire Russian coast will be ice free, allowing navigation through the Barents, Kara, Laptev and East Siberian Seas along the entire Northern Sea Route. The Northwest Passage through the Canadian Archipelago and along the coast of Alaska will be ice free and navigable every summer by non-icebreaking ships. Ice will be present all year along the eastern and northern coasts of Greenland. Ice will also remain throughout the summer within and adjacent to the northern Canadian Archipelago. Significant ice will remain in the central Arctic Ocean, though the mean thickness will be about 1.5 m, and it will be less compact.

IV. *Changes in Weather Patterns in the Arctic under Assumed Global Warming*

Recent scenarios of climate change in the Arctic produced by state-of-the-art global climate models (GCMs) suggest that the Arctic/subArctic will see substantial warming over the current state. The cold season in particular in many models sees a 6-8 deg. C warming over the ocean, with a less dramatic change in terrestrial regions. Associated with many of these is the prediction of an ice- free or nearly ice-free ocean state, at least seasonally if not throughout the entire year. It is certainly plausible that the marginal ice zone will migrate considerably poleward throughout the year in a warmer climate.

A discussion of how weather (vs. the cumulative effects of weather we call climate) is difficult to predict based on a broadly defined seasonal mean state. That being the case, it *is* possible to speculate on how weather as currently understood might be impacted by changes in a background "mean" state. Given the nature of Naval operations, this discussion will focus on marine weather

A more ice-free ocean and/or longer ice-free season would clearly lead to much greater latent and sensible surface heat fluxes into the Arctic boundary layer (BL). A warmer and moister BL would most likely produce greater BL cloudiness, perhaps extending the current observed summer cloud fractional coverage maximum on both ends of the warm season. This would result in poorer surface visibility for a greater portion of the year, and in the winter could also increase the likelihood of freezing mist and drizzle

Since the temperature of the continental Arctic away from the coastal regions will continue to be modulated largely by radiative energy loss (assuming that seasonal snow cover still pertains), the temperature differences between land and ocean will likely be more pronounced, creating more localized baroclinicity to the coastal regions in the cold season. Given the ingredients of greater baroclinicity, a BL environment with significantly enriched latent energy, and the strong planetary vorticity implicit in the high latitude setting, it seems reasonable for Arctic cyclogenesis of so-called polar lows to be more common than currently observed during much of the year.

BL-forced convection would be more likely with these systems, much of it being from mixed-phase clouds, particularly in the warm sector with higher precipitation rates and more localized precipitation. Vessel icing could be a prime concern, especially in the vicinity of cold Arctic continental air masses where over-running is likely to occur. With the likelihood of more mixed-phase precipitation through a much greater portion of the year, the threat of aircraft icing would also be greatly enhanced.

Under the ice-free ocean scenario, the equator-to-pole temperature gradient will be diminished over current values perhaps weakening the magnitude of the polar jet. However, as stated above, the increased heterogeneity of surface heating in the lower troposphere may act as more of an "anchor" to the long wave pattern producing preferred regions of cyclonic storm activity and cyclogenesis.

Finally, the current tendency of poleward-propagating extratropical cyclones to decay in cooler subArctic waters (for example as currently happens in the Aleutians/Bering Sea and the 'coffin corner" of the Gulf of Alaska near Yakutat) might be diminished, causing stronger and more frequent activity in the subArctic coastal margins.

V. *The Response of Arctic Hydrological Processes to a Changing Climate*

The effects of a warming climate on the terrestrial regions of the Arctic are already apparent; some subsequent impacts to the hydrologic system are also evident. It is expected that the effects and consequences of a warming climate will become even more pronounced within the next 10 to 50 years, at first primarily through atmospheric and near-surface processes and later through geomorphological evolution and hydrological responses to permafrost degradation.

These changes will affect the Naval Mission in the Arctic Basin through impacts on regional weather, oceanic circulation patterns, salinity and temperature gradients, sea ice formation, and water properties. It is difficult to quantify the long-term effects of a changing climate, but it is possible to envision many of the changes that we should expect.

The broadest impacts to the terrestrial Arctic regions will result through consequent effects of changing permafrost structure and extent. As the climate differentially warms in summer and winter, the permafrost will become warmer, and the active layer (the layer of soil above the permafrost that annually experiences freeze and thaw) will become thicker. These simple structural changes will affect every aspect of the surface water and energy balances. As the active layer thickens, there is greater storage capacity for soil moisture, and greater lags and decays are introduced into the hydrologic response times to summer precipitation events. When the frozen ground is very close to the surface, the stream and river discharge peaks are higher and the baseflow (low discharge rates that occur in rivers between storms or in winter) is lower. As the active layer thickens and the moisture storage capacity increases, the lag time of runoff also increases. This has significant impacts on large and small scales. The timing of stream runoff will change, reducing the percentage of continental runoff released during the summer and increasing the proportion of winter runoff. This is already becoming evident in Siberian Rivers. As permafrost becomes thinner and is reduced in spatial extent, the proportions of groundwater in stream runoff will increase as the proportion of surface runoff decreases, increasing river alkalinity and electrical conductivity. This could impact mixing of fresh and saline waters, formation of the halocline, and seawater chemistry.

Other important impacts will occur due to changing basin geomorphology. Currently the drainage networks in Arctic watersheds are quite immature as compared to the more well-developed stream networks of temperate regions. These stream channels are essentially frozen in place because the major flood events (predominantly snowmelt) occur when the soils and streambeds are frozen solid. As the active layer becomes thicker, there will be significantly increased sediment loads delivered to the ocean. Presently, the winter ice cover on the smaller rivers and streams (<~10,000 km^2) are completely frozen from the bed to the surface when spring melt is initiated. However, in lower sections of the rivers there are places where the channel is deep enough to prevent complete winter freezing. Break-up of the rivers differs dramatically in these places where the ice is not frozen fast to the bottom. Huge ice chunks are lifted by the flowing water, chewing up channels bottoms and sides and introducing massive sediments to the spring runoff. Such increased sediment loads may affect coastal water properties with consequent impacts on sound transmission, estuary productivity, contaminant transport, and a host of other marine processes.

As the air temperatures become higher, the active layer becomes thicker. Even if precipitation increases, we have reason to believe the surface soils will become drier. The Arctic is described in many basic geography textbooks as a desert due to the low precipitation rates; however, it is a desert that frequently looks like a bog as the ice-rich permafrost near the surface prevents infiltration of surface soil moisture to deeper groundwater. If the active layer thickens to the point where a talik (an unfrozen layer above the permafrost, but below the seasonally frozen soil) forms, then soils may drain internally throughout the winter leaving the surface significantly drier. As the surface soils dry, the feedbacks to local and regional climate will change dramatically, with particular emphasis upon sensible and latent heat flux. Drier soils will also influence the rate and intensity of tundra fires, providing more positive feedback mechanisms by creating darker surfaces that absorb more solar radiation and through releasing large quantities of carbon from peat soils. This may impact recycling of precipitation, military capabilities to predict weather and may indeed increase variability of many processes and variables, including convective storms.

These changes in the hydrological regime should improve productivity of terrestrial aquatic and marine ecosystems. Increases in winter baseflow will markedly improve winter habitat in streams and rivers for freshwater and anadromous fishes. There is a possibility that these rivers could eventually support commercial fishing industries. There are numerous economic and natural barriers constraining potential marine industrial development, however if the sea ice degradation does allow civilian vessels to work in the Arctic Ocean during at least the summer months, then we should expect a fishing industry will develop. As pressure on fishing resources continues to intensify throughout the North Pacific and North Atlantic, the fishing industry may indeed “push these limits” and attempt to establish market influence sooner than natural conditions permit. Consequently, Naval and Coast Guard rescues of vessels trapped in sea ice may become routine long before sea ice degradation allows extensive civil transport of the Arctic Ocean.

VI. *Arctic Environmental Change and the Northern Sea Route*

Recent Arctic environmental changes, in particular changes in the area and thickness of sea ice, can fundamentally impact Arctic marine transportation. Longer melt seasons, thinning ice covers, and reductions in multiyear ice have key operational implications (for example, greater access and longer navigation seasons) for shipping around the Arctic basin. Notably the Northeast Passage, or the Northern Sea Route (NSR) from a more formal Russian perspective, across the north of Eurasia has experienced reductions in the sea ice cover. In addition, the administration, regulation and overall operation of Russia’s NSR have undergone considerable changes during the past decade following the end of the Soviet Union. The combination of regional environmental change and new management of the NSR and Russia’s Arctic fleet pose potential implications for the United States and naval operations.

The end of the USSR has brought great change to all aspects of the NSR. Total cargo tonnage along the NSR has been reduced to less than 2.0 million tons, less than a third of what it reached during the heyday of the Soviet Union. This reduction in cargo and ship traffic is primarily a consequence of changes in the industrial complex at Noril’sk. However, year-round marine operations across the Kara Sea to Dudinka (port city for Noril’sk) were maintained throughout the 1990's. This was accomplished using the capable, but aging icebreaker fleet (nuclear and non-nuclear) of Murmansk Shipping Company (MSC). In November 1998 controlling interest in MSC was acquired by the Russian oil company, Lukoil; fresh capital from Lukoil has allowed the recent buildup of a domestic Arctic tanker fleet. Comprehensive and official regulations for navigation along the NSR remain in effect; navigation control, mandatory pilotage, mandatory icebreaker escort (in Vilkitskiy, Dmitry Laptev, Sannikov and Shokalskiy straits) and rules for escort represent a considerable effort to control domestic and foreign shipping along the NSR. Recent papers have highlighted the continued differences between the US and Russia concerning the NSR. The US continues to assert that the ice-covered straits of the NSR are international and subject to the right of transit passage; Russia continues to claim the straits as internal waters. This is likely to remain a contentious political issue between the US and Russia despite future access to the Russian Arctic under more favorable climatic conditions.

A comprehensive study of the NSR - the International Northern Sea Route Programme (INSROP) - was conducted during 1993-99 and funded primarily by Norwegian and Japanese interests. Three principal partners were involved: the Ship & Ocean Foundation (Tokyo), the Central Marine and Design Institute (St. Petersburg), and the Fridtijof Nansen Institute (Oslo), the key coordinator. The project produced 167 peer-reviewed working/technical papers (involving 318 researchers at 50 institutions in 10 countries; a handful of US researchers participated) and a comprehensive reference volume. Significant Russian information on the NSR environment, Arctic ship technology, legal positions, commercial shipping, navigation regulations, and regional (Russian Arctic) economies is now available outside Russia within the INSROP reports. The proceedings of an INSROP summary conference held in Oslo 18-20 November 1999 (The Northern Sea Route User Conference) have now been published. Included are several conclusions drawn from the conference and overall INSROP effort: the NSR's technological and environmental challenges are no longer absolute obstacles to commercial shipping; the EU and oil/gas interests are conducting pilot studies for Arctic marine routes between the Kara Sea and Europe; Russia needs to better accommodate the concerns and requirements of international shipping (NSR tariffs require considerable adjustment); and, the NSR's physical and operational infrastructure must be further developed to attract increased commercial use. Discussed during the workshop were the impacts of future reductions of sea ice along the NSR on extending the navigation seasons and future requirements for icebreaker support. One significant question remains unresolved: will future Arctic commercial ships navigate along the NSR independently (without icebreaker support) if ice conditions continue to improve?

Recent evidence from satellite observations confirms that the areal extent of Arctic sea ice has decreased approximately 3 % per decade. The largest decrease derived from historical records has been recorded for summer since 1950, a key observation for seasonal shipping along the NSR and other Arctic marginal seas. The Siberian Arctic has experienced sea ice reductions during the last decades of the twentieth century. Parkinson has shown regional sea ice reductions in the NSR area for 1978-1996: a 17.6 % decrease per decade in summer for the Barents and Kara seas, and a 3.7% decrease per decade for a large Arctic Ocean area including the Chukchi, East Siberian and Laptev seas. Record summer sea ice reductions in the Russian Arctic for 1990, 1993 and 1995 have also been identified; a record sea ice retreat was observed in 1998 for the Beaufort and Chukchi seas. The area of winter fast ice in the Russian Arctic (Kara Gate to Long Strait) decreased by 11.3% for 1975-93 and there have been reductions in total and old ice areas in the East Siberian Sea during 1972-94. Johannessen has observed a 14% decrease in winter multiyear ice in the central Arctic Ocean for 1978-98 and Rothrock has calculated ice thickness reductions (40%) from submarine data across the Arctic Ocean. These significant transformations and the regional trends noted for the Siberian Arctic, if continued, portend improved conditions for Arctic navigation along the NSR.

Several implications for the US/USN are apparent with regard to the changing nature of Russia's Northern Sea Route:

- Potential greater marine access along the Russian Arctic coast for domestic and international commercial shipping;
- Continued US and Russian differences in the application of the LOS to the Arctic and NSR;

- Closer collaboration between the EU and Russia in development of Western Siberia by oil/gas interests and use of the NSR as a regional marine route (between the Kara Sea and Europe);

- Potential use of the NSR for through transit (Atlantic to Pacific and return) of hazardous wastes and other sensitive cargoes;

- Lukoil's dominant position as owner of both icebreakers and Arctic tankers, and the exclusion of other domestic & foreign competitors (for example Finnish tankers);

- The continued exclusion of US research ships from operating in the Russian Arctic for collaborative science.

VII. *Surface Ship Design Requirements for Arctic Operations*

Background: The U. S. Navy has not recently designed surface ships, other than ice breakers, to operate in the Arctic. The problems of ice damage and topside icing when surface ships were operated in high latitudes were handled on an ad hoc basis. From time to time during the design of a new class of surface ships, the issue of ice hardening has arisen. One example was during the design of the Perry (DDG-7) class guided missile frigates. While high latitude operations were envisioned, these ships were heavily cost constrained and the ice hardening characteristic was dropped from consideration during cost tradeoffs.

The Navy and Coast Guard, however, have designed icebreakers, as have commercial interests. Other commercial ships have been designed for ice hardening. Most major classification societies who govern the details of commercial ship hull design have established rules for the design of ship hulls for operations in ice. The American Bureau of Shipping (ABS) would be the relevant classification society for U. S. ship design.

The ABS rules for design and construction of ships for "navigation in ice" have evolved over a period of many years and are part of a multi-volume set entitled Rules for Building and Classing Steel Vessels. This document could provide the basis for design of a warship that was to "navigate in ice".

There is provision to tailor the hardening of the design to operate in "multi-year" or "first year" ice, in company with an ice breaker or independently, in what thickness of ice, and in the area of ice cover it might be expected to encounter.

Assumptions: The likely operation of surface warships in the Arctic considering the effects of climate change could be in an area of "first year" open ice, less than one meter thick, covering no more than 60% of the total area of operations.

Discussion: With the above assumptions, ABS Rules require strengthening of the bow and stern areas. Since current surface ships have not considered strengthening for ice operations, Future designers must carefully analyze the ABS Rules in selecting plating and stiffener configuration in the bow and stern areas. Of course, independent finite element analysis, taking into account the dynamic and static loads caused by encountering the ice, can also provide the designer with the structural design configuration.

Bow mounted sonar domes and arrays in particular would require careful attention. Propellers, rudders, fin stabilizers, and sea chests are also affected by ice operation. The effect of topside icing and a provision to de-ice must also be considered. While straightforward in a new design, modifications of existing ships could be a costly process

VIII. *CLIMATE CHANGE IN THE ARCTIC: Effects on Sonar Performance*

Background: Recent reports indicate a dramatic decrease, over the past several years, in sea ice thickness and extent in the Arctic. If this trend continues, significant areas of the Arctic Ocean may become permanently ice-free in the future. The entire area may become seasonally ice-free. The presence of sea ice has great impact on Naval operations. In particular, it affects the performance of sonars, and it makes the region a parochial submarine operating area.

Discussion - The present situation: Near-surface sound propagation paths in the central Arctic are typically upward refracted, due to a positive sound velocity gradient; such upward refraction traps acoustic energy near the surface, and results in abnormally low long-range propagation losses at low frequencies (below 50 Hz.) The presence of ice cover causes the sound propagation to be dispersive; higher frequencies suffer greater losses due to multiple reflections off the rough under side of the ice.

- Ambient noise in the Arctic can be extremely low (lower than sea state zero) in the central Arctic under solid ice cover; or extremely high in marginal ice zones, where the noise of collisions from moving ice can exceed that of wave noise in the open sea.

- Ice keels, created as sea ice is compacted by wind and currents, present large acoustic reflectors to active sonars; they can easily equal or exceed the acoustic target strength of a large submarine.

- The geographic proximity of the Arctic Ocean to North America, Europe, and Asia makes it a particularly attractive area for the stationing of strategic (ballistic missile) submarines. Transiting submarines may be detected at long range by surveillance sensors, but the ice canopy makes deployment of surveillance systems costly and difficult. Stationary submarines can take refuge near the ice, where they are virtually undetectable and invulnerable to attack; or in the marginal ice zones, where environmental noise masks their presence.

- Operation of submarines in shallow ice-covered seas is especially difficult and hazardous due to the need for the submarine to operate close to the ice where ice keels present collision hazards. Active sonar must be used continuously in such environments (contrary to the instincts of submariners) in order to assess ice hazards ahead of the ship. ASW operations, concurrent to a shallow under-ice transit, are impossible as the ship is fully engaged in navigating the ice hazards.

Probable changes due to climate change: Melting of Arctic sea ice will expose the sea surface to winds, which will significantly change both ambient noise and acoustic propagation. Wind-generated waves will make ambient noise in the central Arctic more typical of temperate oceans (i.e., increase). Wind-generated mixing of near surface water, combined with warmer air temperatures, will diminish or eliminate the surface duct, increasing low frequency propagation loss.

Disappearance of the ice canopy will also eliminate the haven now provided to stationary submarines by ice keels. Active sonar detection of submarines, both by ASW sonars and by acoustic torpedoes, will become feasible.

In summary, melting of sea ice in the Arctic will turn it into a conventional open-ocean ASW environment, with none of the advantages it now affords to an adversary strategic submarine.

In spite of the increased vulnerability to a strategic submarine positioned in the Arctic, because of its geographic location it will still be a prime location for stationing such forces. And, perhaps significantly, absence of sea ice will render the ocean both accessible to and a viable operating area for any submarine force B ice strengthened or not; nuclear or conventional.

IX. *Socio-economic Change in the Arctic*

As climate changes in the Arctic, socio-economic conditions will change as well. Additional changes are also imposed by factors external to climate change. The diminution of summer ice cover will permit a more active use of the Northern Sea Route (see above). On the other hand, recent population trends in the Russian Arctic indicate that a rapid decline in the population of European Russians is underway now and that the demand for the logistics pipeline provided to communities in the Russian Arctic by the NSR may decline. On the other hand, the Russian Arctic is a resource rich region and continued and expanding exploitation of energy, mineral and forest resources may be expected. In particular the interests of China and Japan in the abundant resources of the Russian Far East appear to be kindling renewed interest in the region in these countries. Russia has recently commenced the construction of a fleet of eleven ice capable tankers for oil transport in the Arctic.

A further consequence of changes in summer ice extent as well as changes in the oceanography of the region will be changes in fisheries. Already, commercial species are recording sightings well north of their usual ranges. Salmon have been seen in rivers near Barrow, AK, well north of their normal range. Marine mammals will respond to these changes as well. Walrus require the opportunity to haul out on ice floes near their feeding grounds. As the ice edge retreats walrus populations will be required to adapt new strategies for calving and feeding.

Among indigenous people in Alaska approximately 50% of the calories consumed come from "country" foods. The seal, walrus, whale and fish components of the subsistence harvest will change as the climate changes (as will the terrestrial component of wildfowl, caribou and moose). These changes may be accompanied by the growth of commercial harvesting in the region by fishing vessels from farther south. In the Russian Arctic, subsistence hunting and fishing at sea may well expand due to the retreat of the European population and the consequent reduction in the supply both of food staples and of the cash economy necessary for the purchase of imported food.

In addition to changes at sea, climate change will affect marine infrastructure in the coastal zone. Permafrost degradation, increases in sea level (due to thermal expansion as deep water warms and to the melting of Arctic and Antarctic glaciers) changes in river flood patterns and timing can be expected to have negative effects on port structures such as docks, bulkheads, cargo handling facilities, airports and roads in the Arctic. If resource exploitation in the Russian Arctic increases, greater demands for sea lift may occur as new and replacement facilities are required for resource acquisition, processing and transportation.

In addition to these potential changes, the search for and development of offshore petroleum resources is bound to come to the Arctic. Climate warming can only accelerate the process. The petroleum industry is already moving into deeper water in other regions. A decrease in the problems associated with drilling and producing oil offshore as sea ice extent and thickness diminishes will expand exploration and production opportunities in the Arctic. Plans are already being made for offshore drilling for oil in the US Arctic. The Russian and Canadian sectors are also strong potential sites for offshore development. These developments will bring seismic exploration ships, mobile drilling platforms of various types and offshore supply vessels into the region with the concomitant development of shore-based facilities.

X. *Acknowledgements*

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