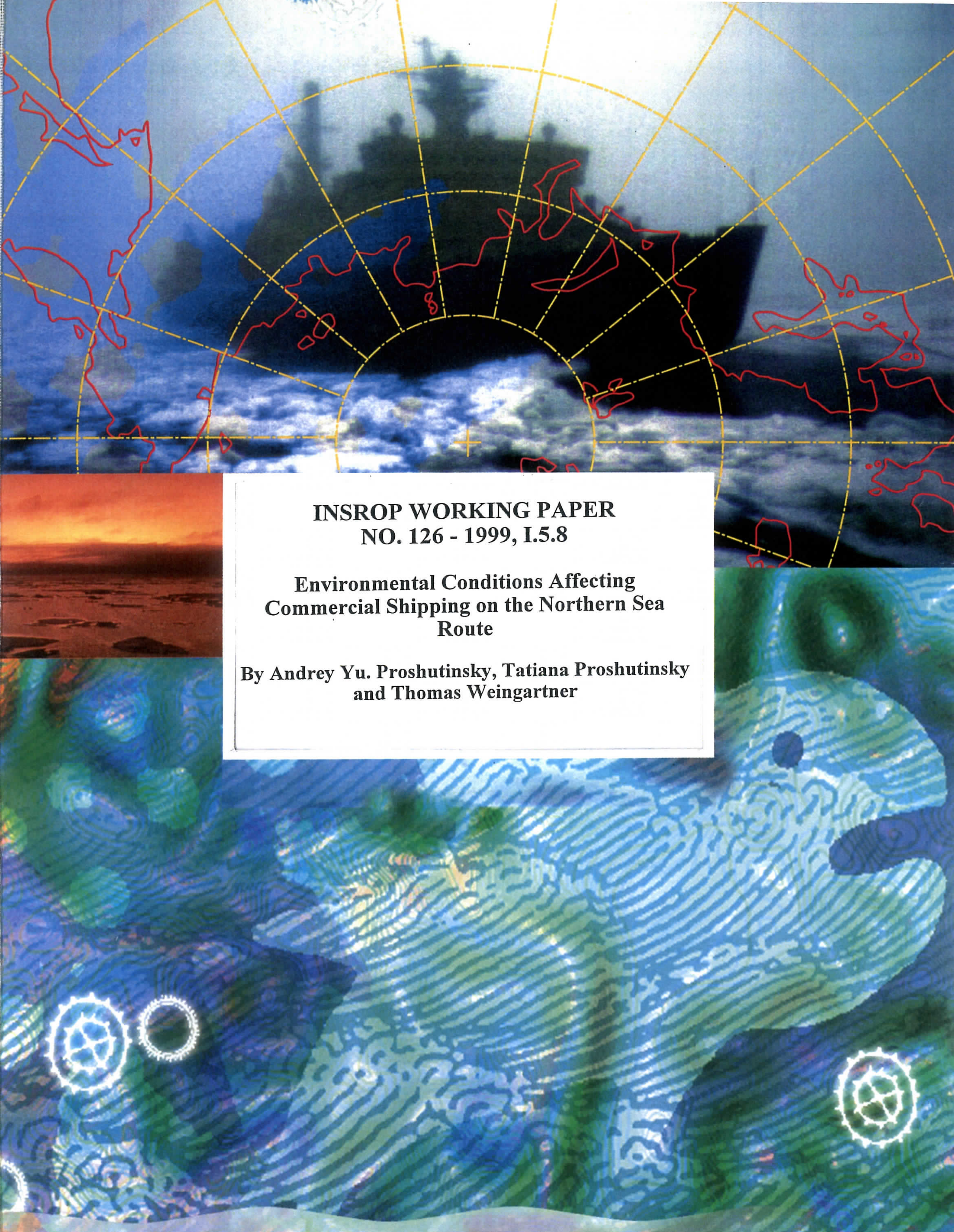

INSROP WORKING PAPER
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Environmental Conditions Affecting Commercial Shipping on the Northern Sea Route

By Andrey Yu. Proshutinsky, Tatiana Proshutinsky
and Thomas Weingartner

INSROP International Northern Sea Route Programme

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Title:	**Environmental Conditions Affecting Commercial Shipping on the Northern Sea Route**
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What is an INSROP Working Paper and how to handle it:

FOREWORD - INSROP WORKING PAPER

INSROP is a five-year multidisciplinary and multilateral research programme, the main phase of which commenced in June 1993. The three principal cooperating partners are **Central Marine Research & Design Institute (CNIIMF)**, St. Petersburg, Russia; **Ship and Ocean Foundation (SOF)**, Tokyo, Japan; and **Fridtjof Nansen Institute (FNI)**, Lysaker, Norway. The INSROP Secretariat is shared between CNIIMF and FNI and is located at FNI.

INSROP is split into four main projects: 1) Natural Conditions and Ice Navigation; 2) Environmental Factors; 3) Trade and Commercial Shipping Aspects of the NSR; and 4) Political, Legal and Strategic Factors. The aim of INSROP is to build up a knowledge base adequate to provide a foundation for long-term planning and decision-making by state agencies as well as private companies etc., for purposes of promoting rational decisionmaking concerning the use of the Northern Sea Route for transit and regional development.

INSROP is a direct result of the normalization of the international situation and the Murmansk initiatives of the former Soviet Union in 1987, when the readiness of the USSR to open the NSR for international shipping was officially declared. The Murmansk Initiatives enabled the continuation, expansion and intensification of traditional collaboration between the states in the Arctic, including safety and efficiency of shipping. Russia, being the successor state to the USSR, supports the Murmansk Initiatives. The initiatives stimulated contact and cooperation between CNIIMF and FNI in 1988 and resulted in a pilot study of the NSR in 1991. In 1992 SOF entered INSROP as a third partner on an equal basis with CNIIMF and FNI.

The complete series of publications may be obtained from the Fridtjof Nansen Institute.

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1998 FINAL REPORT, INSROP PHASE 2 PROJECTS

Project group, number and title: Natural Conditions and Ice Navigation,
Project 2, Box C: The Simulation Study of NSR Commercial Shipping,
1.5.8 Environmental Conditions Affecting Commercial Shipping

Supervisor: Dr. Andrey Yu. Proshutinsky
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ABSTRACT

This report focuses on the climatology of environmental conditions affecting commercial navigation along the Northern Sea Route (NSR). Statistical characteristics (minimum, maximum, average, and probability of occurrence) are presented for major meteorological and oceanographic parameters that can limit navigation in the Kara, Laptev, East Siberian, and Chukchi seas. This information is available at http://www.ims.alaska.edu/8000/insrop-2.

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1. INTRODUCTION

Commercial navigation along the NSR can produce financial benefits only if ship speeds are high enough and ship transit is saved. The navigation season along the NSR usually begins in June and ends in October. Commercial navigation during the earliest and latest portions of the navigation season is most difficult. The ice cover present on different segments of the NSR during the entire year (even in summer) is a major factor limiting commercial navigation. Other adverse conditions are meteorological (wind, visibility), oceanographic (waves, currents, sea level), and a combination of meteorological and oceanographic phenomena (icing).

This report contains a statistical description of environmental conditions affecting commercial navigation for the entire year. We used this information to develop Monte Carlo model for numerical simulations of commercial voyages along the NSR. Our goal for these simulations is that they be used as an aid in projecting transportation costs for commodities shipped via the NSR, and to enable due allowance for risks and uncertainties associated with seasonal and geographical variations in environmental conditions. The basic knowledge for this project was accumulated in a previous report, Climatology of Environmental Conditions Affecting Commercial Navigation Along the Northern Sea Route by Proshutinsky et al. (1994) published in the Cold Regions Research and Engineering Laboratory (CRREL) report, Development and Results of a Northern Sea Route Transit Model by Mulherin et al. (1996). Additional information was adapted from several sources including climatological atlases, agency reports, reference books, journal articles, and national databases. These sources are listed in the References section of this report.

We have provided a description of the climatology along the NSR for 335 points on the coastal transit route, the high-latitude transit route, and a transitional part of the high-latitude route via the Vilkitskogo Strait (Figure 1). The information source for route-point coordinates with a 20-mile interval is from the INSROP-2 report, Routes and Associated Operational Infrastructure by Baskin et al. (1998). These data are presented in Appendix 1.

Major statistics of environmental parameters characterizing meteorological, oceanographic, and ice conditions are presented at http://www.ims.alaska.edu/8000/insrop-2. This information supplements the text of this report, and represents the major contribution of this work.

2. METEOROLOGICAL CONDITIONS

There are three major climatic regions along the Northern Sea Route (Figure 2):

- Atlantic or Western region which includes the Barents Sea and the western and southern parts of the Kara Sea,
- Siberian or Central region which extends from the Kara Sea to the western East-Siberian Sea,
- Pacific or Eastern region which includes the eastern part of the East-Siberian Sea and the Chukchi Sea.

This subdivision of the Arctic seas is based on the climatic regime related to influence of the Atlantic Ocean, Siberian mainland and the Pacific Ocean (Sovetskaia Arktika, 1970). Three major factors are related to meteorological phenomena that impede commercial

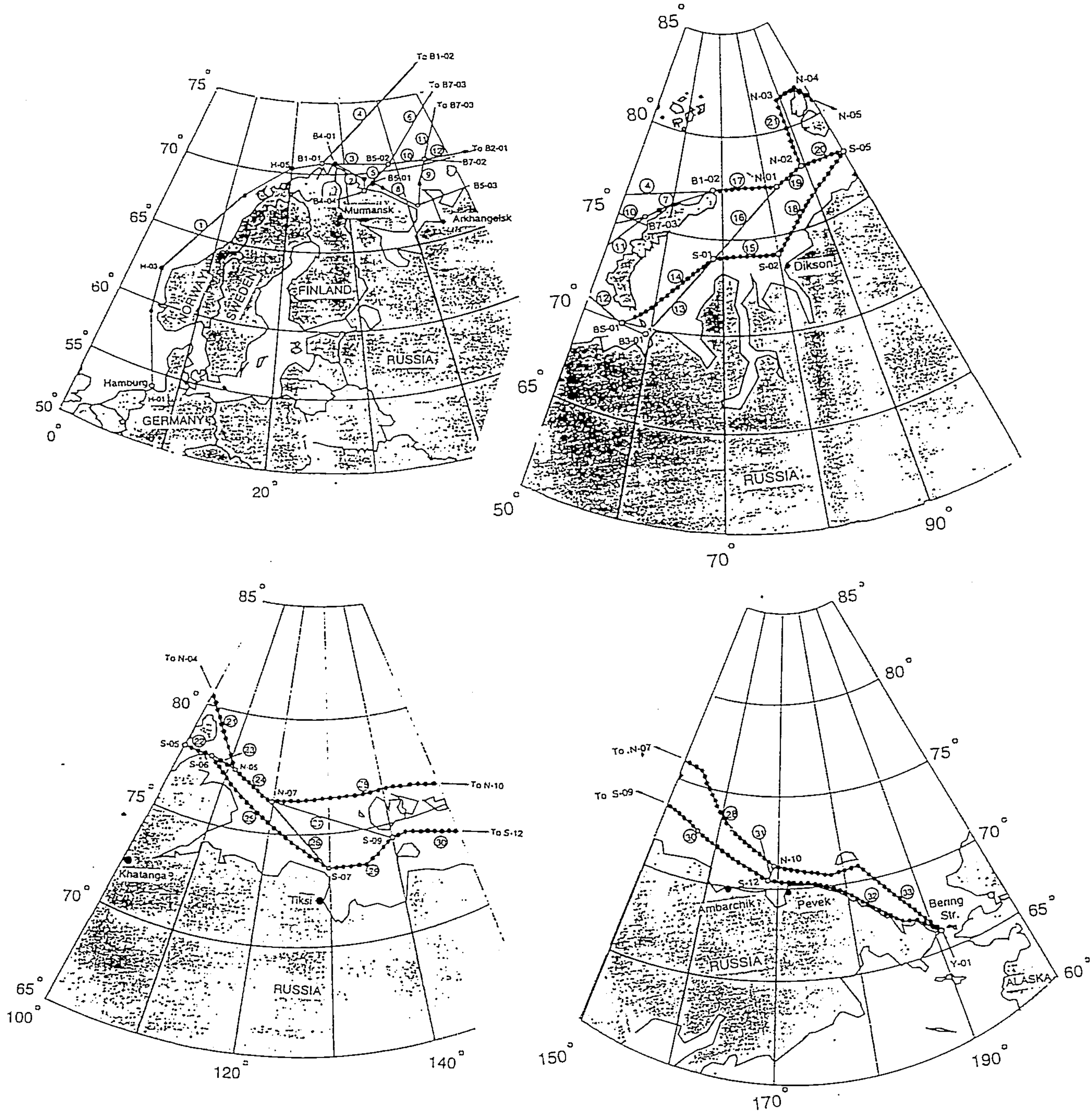


Figure 1. Fragments of the Northern Sea Route (NSR), in the Barents and Kara (A), Laptev (B), East-Siberian (C) and Chukchi (D) seas. Modified after Mulherin et al., 1998.

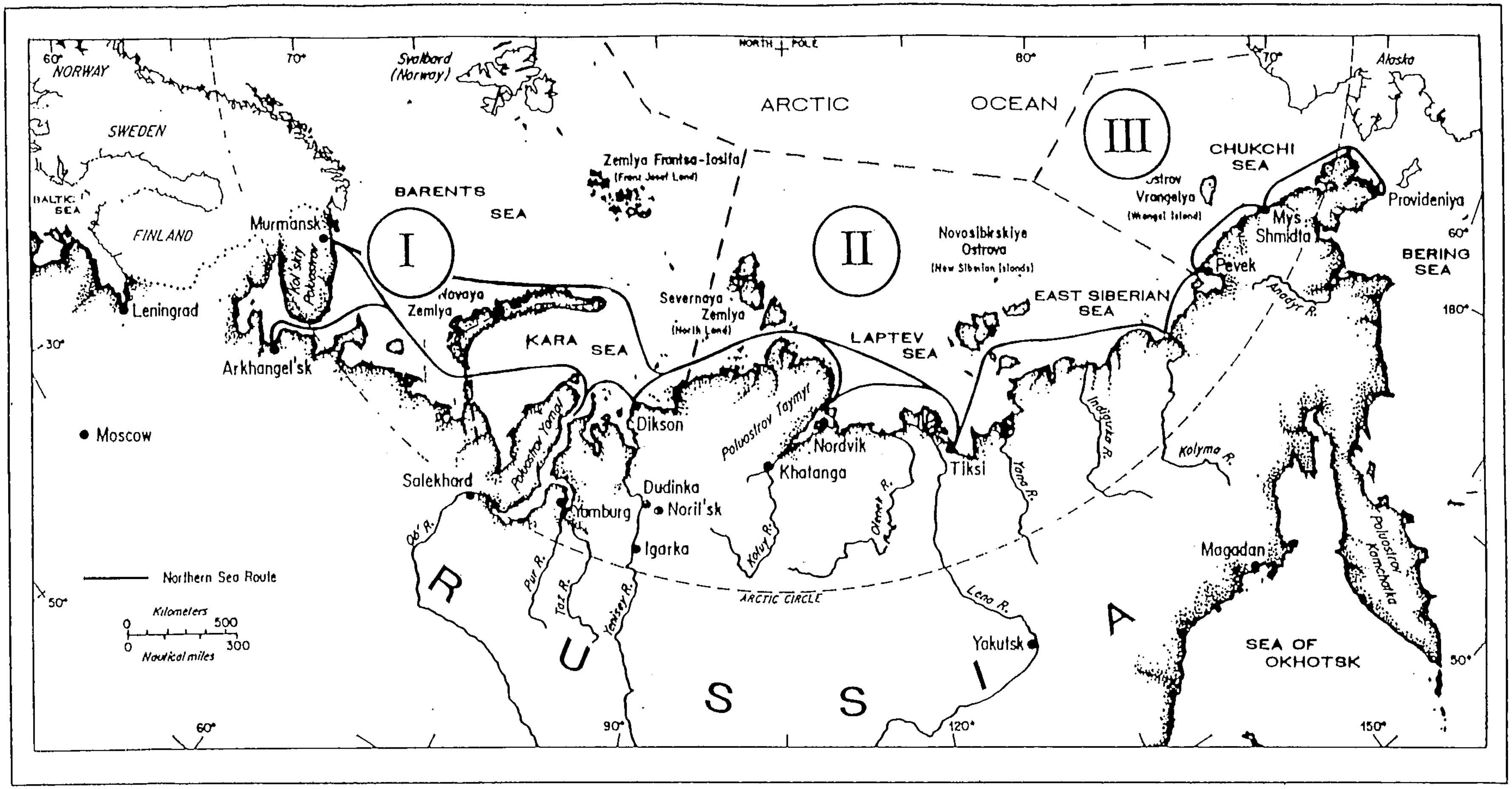


Figure 2. Climatic regions of the Northern Sea Route.
I -- Atlantic (western), II -- Siberian (central), III -- Pacific (eastern).
-- boundaries between regions.
Modified after Brigham, 1991.

navigation. They are: horizontal visibility (related to fog, rain, snowstorm and duration of daylight), direct influence of wind speed and wind direction, and icing (from the combined influence of air and water temperatures, direction and speed of wind, direction and speed of ship, and state of the sea).

2.1 Visibility

Lack of visibility slows speed when a vessel is operating in conditions where the ice concentration is greater than 30%. Darkness, fog, and snowstorm are the defining factors for horizontal visibility in arctic waters. Major peculiarities of the climate of the NSR are related to its high-latitude location.

Absolute air humidity in the Arctic is very low. Over the sea surface along the NSR it ranges from 2 to 3 mbar in winter, and in summer, it increases two to six times. The maximum mean monthly relative humidity is observed in summer (85–95%). The minimum is observed in winter (75–85%). Fogs in the Arctic are related to high relative humidity. In winter, in spite of oversaturation of the air by water vapor, the frequency of fogs is small because of low absolute humidity of water masses and a low number of condensation particles. In places where enough particles of condensation (smoke, vehicle exhaust) occur, one can observe frost fogs.

In summer, over the northern arctic seas, the air is very close to a point of saturation by water vapor, and a small decrease in temperature is enough for fog formation. The fogs in the Arctic very often correlate with wind direction. This relationship is most visible in summer when advective fogs prevail and the temperature difference between land and open sea is large. In coastal regions, the fogs correlate with winds from the open sea. For example, on the west coast of Novaya Zemlia all fogs are brought in by west winds. There are no fogs when east winds blow. The opposite phenomenon is observed on the east coast of Novaya Zemlia. The same relationship between wind and fog is observed in the region of Mys Shmidta and Poseloc Uelen. On the islands of the northeast Kara Sea, the frequency of fog is a direct reflection of wind direction.

For most regions of the Arctic, there is an inverse relationship between fog and wind velocity. Maximum fog events are observed with small or regular wind velocities (0–7 m/s). But in the regions of Ostrov Dikson, Amderma, and Mys Shelagskii fog is followed by storm wind. There is a very strong relationship between fogs and ice edge location in the arctic seas. One can see a maximum frequency of fog occurrence in the northern parts of the seas where ice massifs are usually located. The frequency of occurrence increases with increasing ice concentration. But this relationship is observed only for ice concentrations, which are less than 80–90%. Above these concentrations the frequency of occurrence decreases. Over ice with a concentration of 100%, the number of days with fog is equal to the number of days with fog over a sea with an ice concentration of 40–50%. The maximum duration of fog that creates the lowest visibility is observed in summer at coastal regions and around islands in the western part of the Barents Sea, where warm currents meet cold arctic air masses. This is the so-called spot character of fogs.

Fogs caused by evaporation frequently occur in Kola Bay. From December to February in Kola Bay and other bays of the Barents Sea, there are about 11–13 days with fog from evaporation. Sometimes there are 22–24 days per month (about 100 days per year). In Murmansk, 50% of the fog events are regular or strong fogs and about 20% are very strong fogs with visibility of less than 50 m. The duration of fogs in February may reach 415–425 hours. An example of fog statistics (probability of fog occurrence) along the NSR is presented in Table 1 of Appendix 2. The complete version of these data (for all 335 points) is available at our database at http://www.ims.alaska.edu/8000/insrop-2. These data were obtained from AARI (1985), Vanda (1994), and Proshutinsky (1995). Figure 3 shows the probability of occurrence of fog in the Kara Sea.

A snowstorm is defined as an event where wind velocity is greater then 8 m/s, air temperature is less than 0° C, and visibility as a result of snowstorm is less than 2.5 km. Along coastal regions, the period of snowstorms is usually October through May. In the northern regions this period is generally September through June. Snowstorms are observed at the beginning of the winter (November, December) when strong winds prevail and new snow can float in the air. Snow is usually transported in the direction of prevailing wind flow. Mean annual number of days with snowstorm is about 100–120 days in the Barents, Kara, and Chukchi seas, and 60–80 days in the East Siberian and Laptev seas.

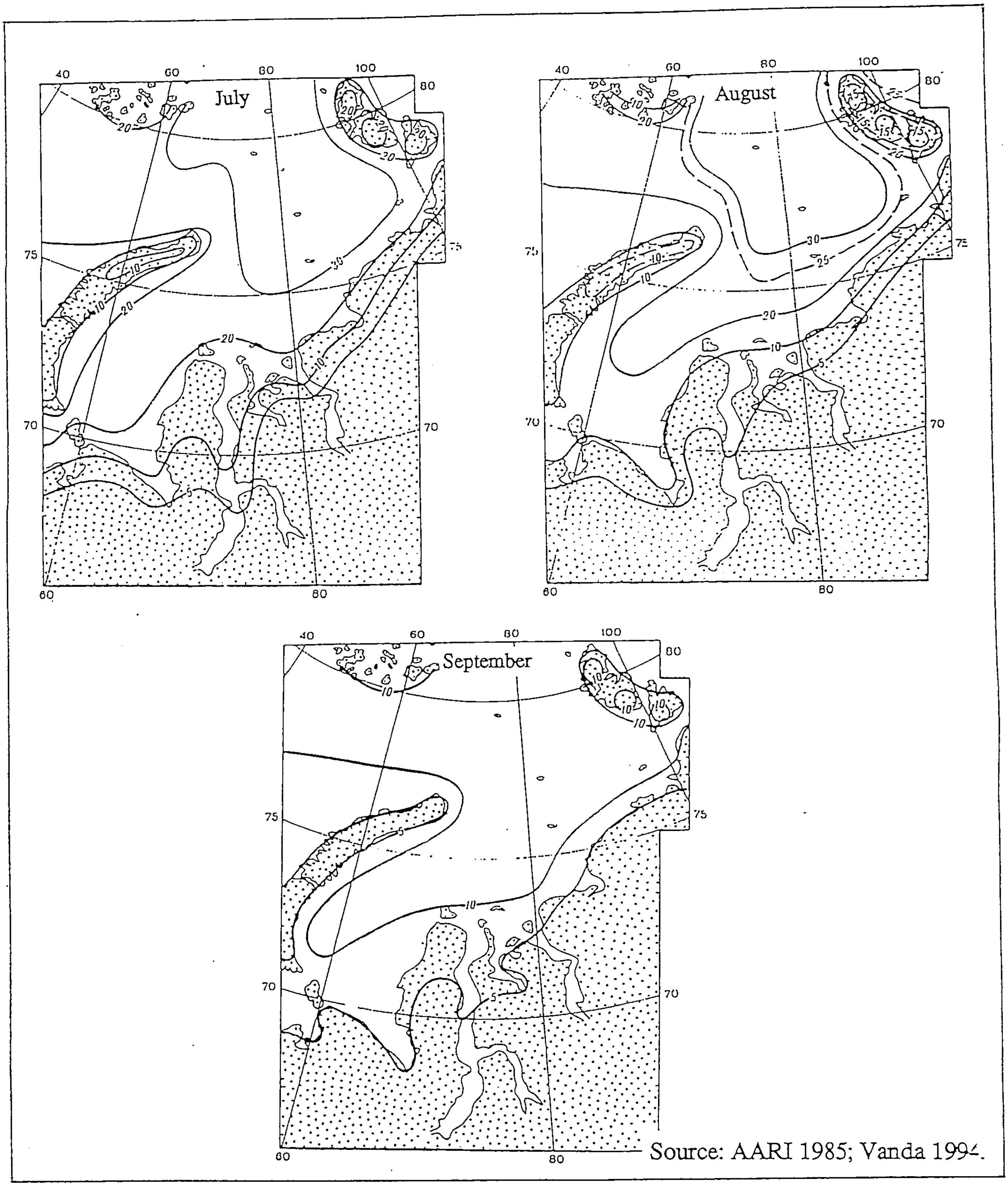
In winter, in the Bering, Kara, and Chukchi seas, snowstorms are present for half of each month, but in some places this value reaches 17–20 days per month. In the Laptev and East Siberian seas, the number of days with snowstorms ranges from 36 per month, while in regions with orographic increasing of wind velocities, 12–15 snowstorms occur per month (Tiksi, Ambarchik).

In the Barents Sea, frequency of snowstorms is 20–25% of the time with a maximum in the vicinities of Novaya Zemlia, the Russkaia Gavan region, and at the Karmakula station. Over the Kara Sea the frequency of snowstorms is 15–25% of time of the cold season. The lowest number of snowstorms is observed in the north and northeast part of the sea. Maximum frequency of snowstorms (20–25%) is observed along the east coast of Novaya Zemlia, in the Karskie Vorota, at Yugorskii Shar straits, at the west coast of Baidaratskaia Guba, north of the Ob-Yenisey region, and at the Proliv Vilkitskogo strait. In the Laptev Sea, the frequency of snowstorms in winter is 10–15% of time and increases to 20% of time eastward from Vilkitskogo Strait.

In the East Siberian Sea, the frequency of snowstorms increases in the southeast and at the Ambarchik (15–20%). The frequency of snowstorms ranges 5–10% of time in the central part of the Laptev Sea and Chaunskaia Guba. In the Chukchi Sea, the frequency of snowstorms is about 10–15%.

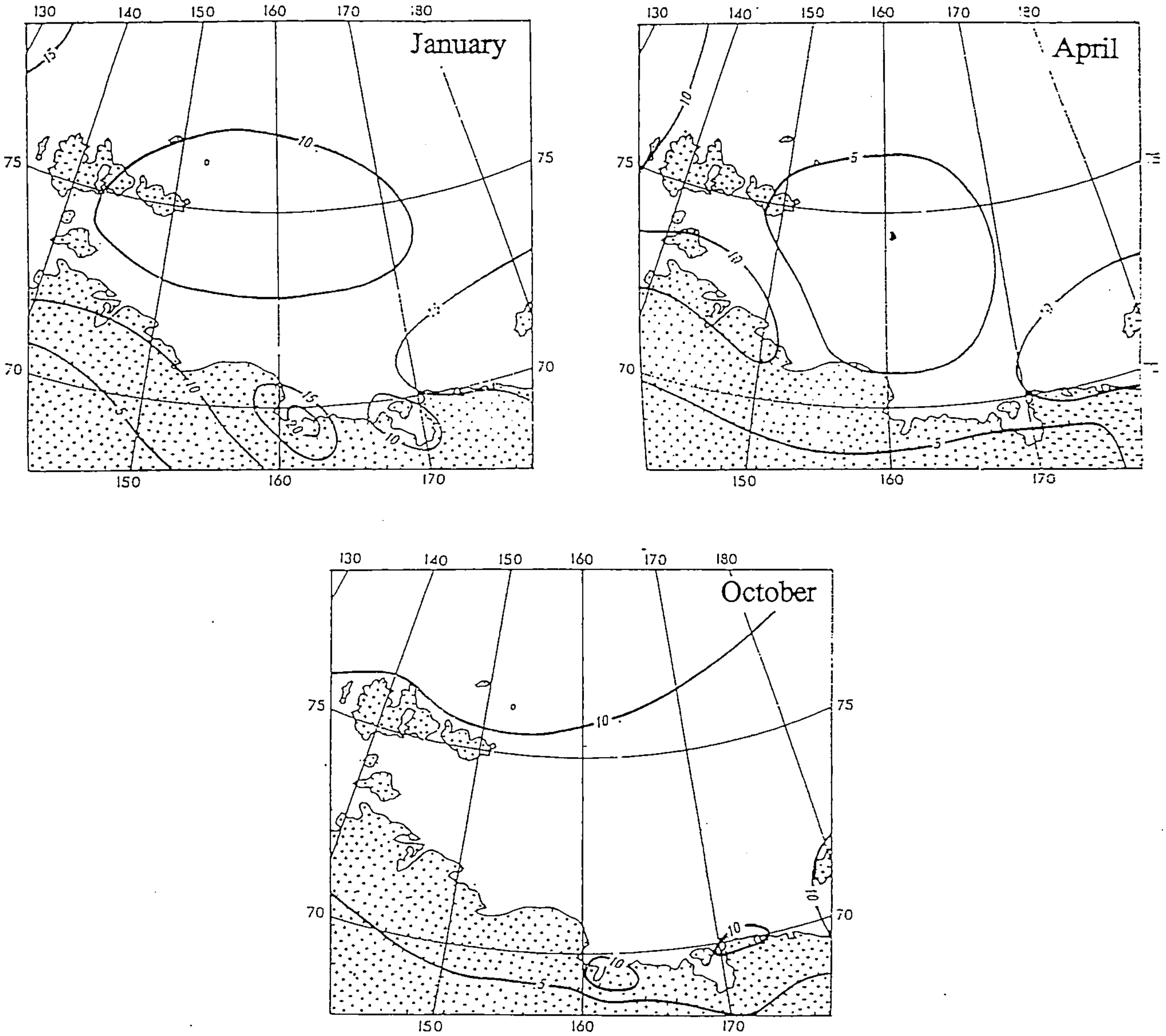
Mean duration of snowstorms in the Barents and Kara seas and northern Chukchi Sea range from 900–1100 hours, while at the Ambarchik and Valkarkai stations this value is about 800–900 hours. Over the East Siberian Sea and in the southern Chukchi Sea, annual snowstorm duration ranges from 400 to 500 hours. Probability of snowstorms is given only for the period from October through April because this phenomenon occurs very rarely in summer. An example of snowstorm statistics is given in Appendix 2, Table 2. The complete statistical information about this parameter can be found at http://www.ims.alaska.edu/8000/insrop-2. These data were obtained from AARI (1985), Vanda (1994), and Proshutinsky (1995). Figure 4 demonstrates an example of probability of occurrence of snowstorm in the East-Siberian Sea.

Fogs, rains, and snowstorms are dangerous weather phenomena that influence horizontal



Source: AARI 1985; Vanda 1994.

Figure 3. Probability of occurrence of fog in the Kara Sea (%)



Source: AARI 1985; Vanda 1994.

Figure 4. Probability of occurrence (%) of snowstorms in the East-Siberian Sea

visibility. Very low visibility (less than 1 km) has two minimums annually. The summer minimum is caused by a high frequency of fog; the winter minimum is caused by a high frequency of snowstorms. From June through August, the occurrence of low visibility in the open sea ranges from 25–30%. This value decreases toward the mainland coast (10%). During the central winter months, the occurrence of low visibility does not increase more than 10–15% because snowstorms causing visibility of less than 1 km are infrequent.

Decreased horizontal visibility is very important, especially in the autumn–winter period when limited visibility due to fog and snowstorm is combined with darkness. In conditions of limited visibility ships can lose a channel, get stuck in it, or break convoy motion. Release of stuck ships, and reformation of a convoy take time and decrease the efficiency of commercial navigation.

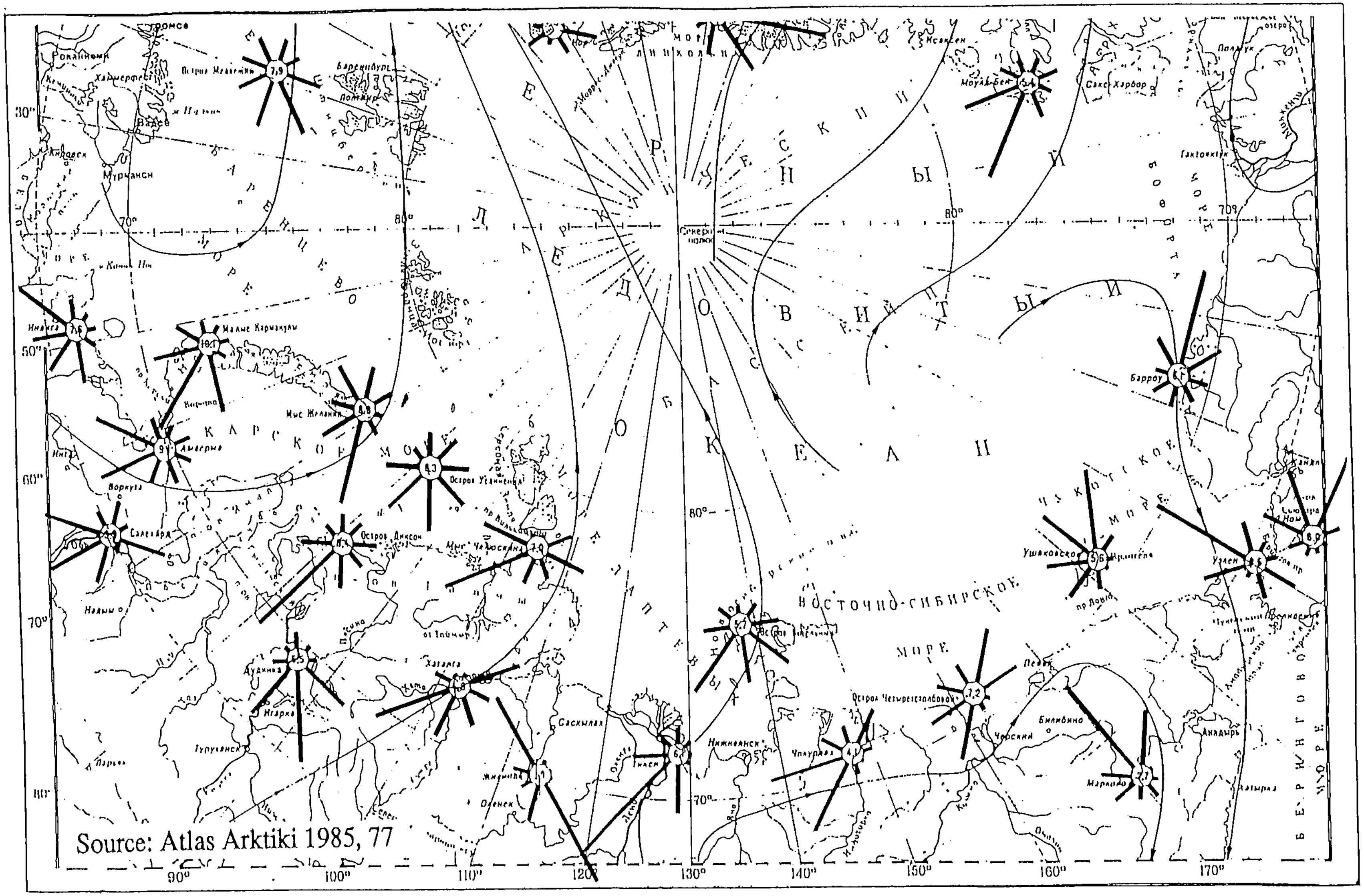
2.2 Wind regime

Atmospheric circulation patterns define the character of prevailing winds over the arctic seas. The direction of the prevailing wind changes significantly during the year. Depending on atmospheric conditions, a tendency toward a monsoon circulation is often observed; i.e., in winter winds are very often from a southern direction (the eastern parts of the East Siberian and Chukchi seas are exceptions to this general rule). Figure 5 shows wind roses for January. In summer, the opposite wind direction is observed.

In the northern coastal regions of the Bering and Kara seas, including a region of Franz Josef Land, prevailing southwest and south winds change directions toward the southeast and east, respectively. In the Laptev Sea, in winter, prevailing winds are from the south-southwest. Over the New Siberian Islands and the western part of the East Siberian Sea, the winds are more westerly. In the eastern part of the East Siberian Sea, where winds are unstable in character, winds from the west occasionally prevail. Northerly winds prevail in the Chukchi Sea with directions ranging from northwest in the western part of the sea to northeast in the eastern part. In the southeastern part of the Chukchi and Bering seas, winds prevail from the north in winter.

During the arctic summer, the atmospheric pressure is reversed relative to winter atmospheric pressure distribution. Over the Siberian continent and close to the North Pole atmospheric pressure is low while over the arctic seas it is relatively high. This atmospheric pressure distribution creates wind direction, which is the opposite of wind direction in winter. Occasionally, in the open sea, a small atmospheric pressure gradient leads to very weak prevailing winds. These are observed in the southwest part of the Kara Sea, in the central part of the Laptev Sea, and in the eastern part of the East Siberian Sea. The Chukchi Sea exhibits a more complicated wind regime with alternating north-south winds (Zavialova and Ukhanova, 1983).

Mean wind velocities are relatively small, about 4–5 m/s, and annual variability of mean wind velocities is different in every region. For example, in the west and east climatic regions, the velocities are higher than in the central part of the NSR. In winter, the highest mean monthly velocities are observed in the Barents Sea (8–9 m/s). In the Kara Sea they are 6–8 m/s. In the Laptev Sea and in the western part of the East Siberian Sea, they are less than 5 m/s. In the eastern part of the East Siberian Sea and in the Chukchi Sea, they increase again, reaching 5–7 m/s. Summer mean monthly wind velocities are more or less uniform along the entire Northern Sea Route and do not increase above 5–6 m/s.



Source: Atlas Arktiki 1985, 77

Figure 5. Wins roses, January
Numbers on circles show mean wind velocity (m/s);
length of rays represent probability of occurrence (%) of wind direction;
stream lines are direction of prevailing winds.

In winter and summer, wind velocities typically increase in proximity to capes, straits, and bays (e.g., coastal region of Kola Peninsula, north of the Novaya Zemlia, Vilkitskogo Strait, New Siberian straits, Proliv Longa and Bering Strait, Yenisey and Giganskii Bay, Pevek Bay, and some parts of the Chukchi Sea coastal region). Storm winds (with wind velocities of more than 15 m/s) are observed more often in winter than in summer. In the Barents Sea, there are about 6–8 storm days in January, while the Kara Sea has 4–6 storm days. However, in the northeastern part of these seas, there are 8–10 days with storm winds during the month. In the Laptev and East Siberian seas, the number of days with storm winds decreases, averaging 2–5 days per month. In the Chukchi Sea, 6–10 storm days occur per month.

In summer, an average 1-2 storms (maximum 3 storms) occurs along the NSR. However, there are sometimes 10–12 days with storm winds per month (for example, at near Muostakh Island, Kotelnii Island, and Uelen). The number of days with storms cannot completely characterize the storm-wind regime. Since the duration of storm winds is usually short, the probability of storm winds occurring even in the southern part of the Barents Sea is only 10–12%; in the Kara Sea about 5%; in the Laptev and East Siberian seas, ranges are from 2 to 3%; and in the Chukchi Sea 5–8%. The duration of storm winds for all the polar stations ranges from 6 to 24 hours in 70–90% of cases, but in winter, at Tiksi, Dikson, Amderma, Pevek, and Shmidta, stormy weather can last 8–14 days.

There are several places along the NSR where orographic conditions cause increased wind velocity (for example, the probability of storm winds in Malye Karmakuly increases to 23% in winter and to 21% north of Kola Peninsula). Maximum catabatic winds reach 50–56 m/s at Rudolpha Island, 70 m/s at the Karmakuly, 49 m/s at Mys Stolbovoy , and more than 80 m/s (Yuazhak) at Pevek. These winds most often blow in April through June, but they reach maximum velocities in autumn. In winter, these winds bring warm air and temperature increases of $20^o - 25^o$C per day (Anapolskaia and Zavyalova, 1969; Spravochnik po klimatu, 1968; Mozolevskaia, 1970; Dementev, 1985).

In the area of the NSR, wind is an important factor affecting ice conditions since wind drift of ice prevails in the arctic seas. According to their influence on drift ice, winds can be classified as pushing-off and pushing-to winds. Pushing-off winds are those favoring better ice conditions; i.e., they weaken or remove pressure in the close ice. Pushing-to winds influence the ice inversely. Along the NSR, unfavorable (pushing-to) winds are, with few exceptions, those blowing from the northern quarter. In the western NSR the occurrence rate of the pushing-to winds varies from 60–70% in June to 33–35% in August. In the eastern NSR (eastern East Siberian and Chukchi seas) the occurrence rate of the pushing-to winds increases towards the end of the navigation period. In the central NSR (Laptev Sea) the occurrence rate of pushing-to winds is about 50%. The percentage of pushing-to winds varies considerably from year to year. For instance, in August 1975 it was 39% in the area to the west of Proliv Vilkitskogo, and in August 1976 it was 81%. In the area of Novosibirskiye Ostrova the percentage of pushing-to winds in August 1979 was 20%, and in August of 1980 and 1981 it was 64% and 68%, respectively. Pushing-to winds usually are followed by pushing-off winds or by gentle winds normally lasting for three days; however, pushing-to winds may last as long as 8 days; and for more than 15 days in the areas to the west and east of Proliv Vilkitskogo and in the vicinity of Novosibirskie

Ostrova. The greatest duration of pushing-to winds (32 days) was observed in the western part of the Laptev Sea and in the area to the west of Proliv Vilkitskogo. The occurrence rate of winds with a speed of less than 12 m/s (up to 15 m/s in gusts) is greatest in the northernmost stretches of the NSR, especially at the end of the navigation season. In the rest of the NSR, the occurrence rate of winds with speeds up to 12 m/s is 10–19%. Strong winds normally last for only 1–3 days, although they may last up to six days in some sections.

Gales with wind speeds greater than 20 m/s normally last for one day. The western most part of the NSR is the exception, where gales may last for up to four days. In the area between Proliv Vilkitskogo and Proliv Longa the durations of gales with wind speeds of 20 m/sec and more did not exceed two days during the navigation period, and in the western East Siberian Sea such winds very rarely last for one day.

Existing wind regime information is not enough for a statistical description of wind speed and direction for the open sea. Because of this lack of data, we have used a geostrophic wind model with a space resolution of 50 km to simulate the wind regime over the Arctic Ocean (see Proshutinsky and Johnson [1997] for details). Simulations of wind were started from January 1, 1946, and run for 52 years, through December 31, 1997, using the daily surface atmospheric pressure (from National Center for Atmospheric Research (NCAR). The results of these calculations were used for statistical estimation of probability of occurrence of wind direction and wind speed for every point of our grid. This information is presented in Table 3 of Appendix 2. The original file with this information is located at http://www.ims.alaska.edu/8000/insrop-2 for all 335 points for every month. Results of simulated wind statistics were compared with observed data at the stations along the NSR, and a good agreement between observed and simulated data was demonstrated.

2.3 Icing

Icing on a structure at sea requires the several simultaneous conditions. The main element in the phenomenon of icing at sea is a supply of water or moisture at subfreezing temperatures on surfaces above sea level. This can be fresh water in the form of dry or wet snow, supercooled water droplets, or salt water in the form of sea spray overshipped water on deck.

There are two major types of sea icing: atmospheric and saltwater. Atmospheric icing is related to precipitation. Dry snow does not usually adhere to a surface so it poses no hazard. However, sea spray or sleet dampens the snow, and the wet snow freezes to the surface. The ice thus formed is porous, with low mechanical strength, so it can usually be removed.

Water that is supercooled freezes solid on contact with a cold surface. Supercooling occurs in its liquid phase at temperatures far below the freezing point. Supercooled droplets exist in the form of frost smoke, supercooled fog, or freezing rain and drizzle. These are the most common sources of atmospheric icing.

Opinions on the seriousness of atmospheric icing differ. In some reports this is scarcely mentioned, but in others it is referred to as the feared black frost. Atmospheric icing produces a uniform layer of ice on all surfaces. This may pose various problems in operations, communication, and navigation. For smaller vessels especially, black frost can cause a critical reduction of stability. If atmospheric icing occurs at the same time as sea spray icing, the increase beyond the amount caused by sea spray alone could be the decisive factor in an accident.

Saltwater icing (icing caused by sea spray) is the most frequent and most important form of icing in the sea. Another cause of saltwater icing is shipped water, which enters the deck of a vessel over the bow or sides. The latent heat content of this water, even if its temperature is near the freezing point, is sufficient to avoid freezing if it flows off the vessel quickly. This water will, in addition, contribute to the melting and flushing away of ice which has already formed on deck. But if the scuppers freeze or the railings are covered with ice, the waters may be trapped and frozen.

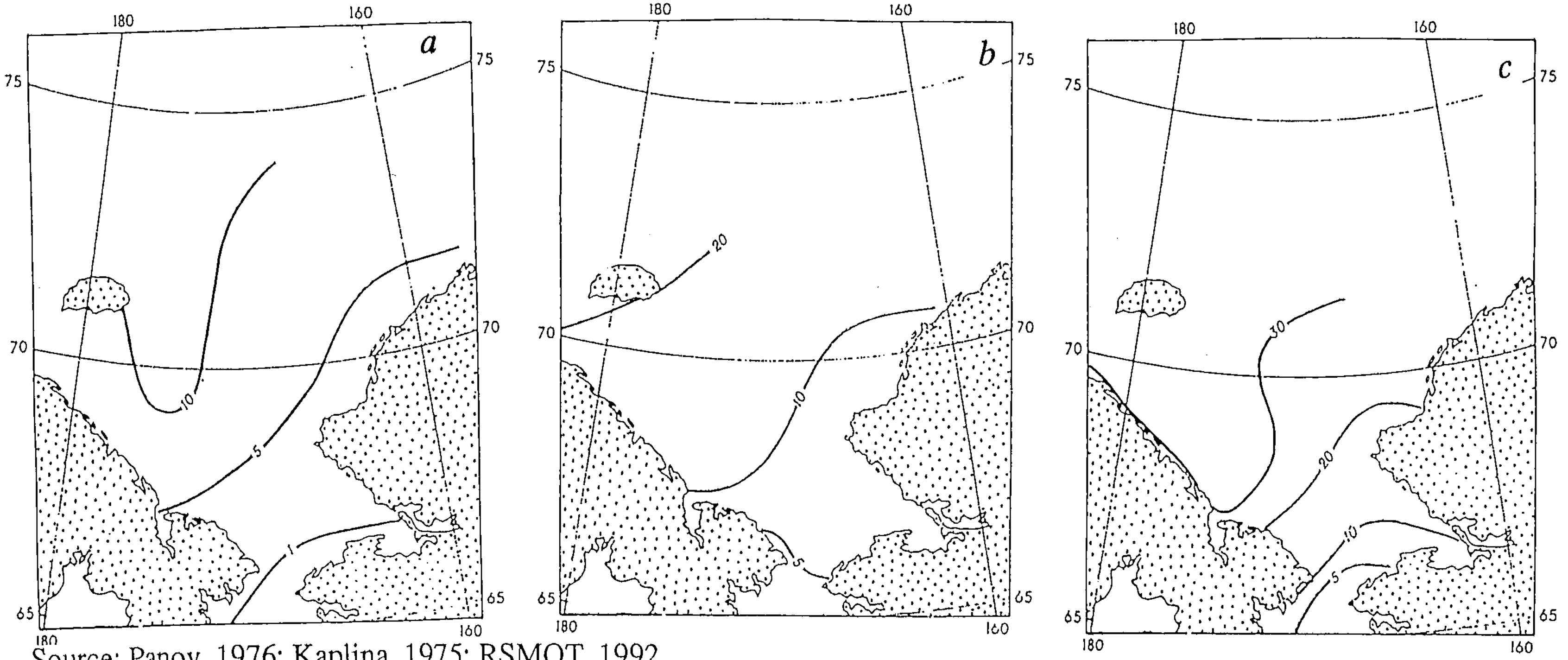
Sea spray icing accounts for by far the largest number of icing cases, and the most serious. Sea spray is formed in two ways. The most important with regard to icing is sea spray generated by the vessel or structure itself as it meets waves. The other type of sea spray is created when the wind blows droplets of water off the wave crests. This phenomenon depends on the form and steepness of the waves and wind speed. It begins to occur at speeds of 8–10 m/s. The stronger the wind, the higher the spray is lifted. Usually the height of sea spray icing is limited to 15–20 m above the sea surface; however, there have been reports of sea spray icing at up to 60 m above the sea surface.

A strong wind, cold air, and cold seawater all contribute to greater accumulations of ice on vessels. Icing along the NSR is generally not a serious problem for large cargo ships, but along some routes (Murmansk–Igarka, Murmansk–Dudinka) icing may be very dangerous, especially during a long cruise at the end of autumn or in winter when air temperatures are below zero and there is no ice cover on the sea surface. In arctic seas, icing of vessels may occur throughout the year. From December through June, only atmospheric icing is possible. From July through October marine icing accounts for 50% of all cases of icing; mixed icing for 45%; and atmospheric icing for 9%.

Atmospheric icing normally occurs when air temperature is between 0^o and -20^oC , wind speed is less than 10 m/s. As a result of atmospheric icing, higher parts of the ship get covered with 12 cm (rarely up to 6 cm) of thick ice. In cases of marine and mixed icing, ice thickness reaches 1 m in some cases.

Icing can be classed by its intensity as slow, fast, or very fast. Slow icing occur when the speed of ice accumulation is less than 1.5 ton per hour, or less than 1 cm/hour. It occurs when air temperature is between 0^o and -3^oC and at any wind speed, or with air temperatures of -3^o C or lower and a wind speed of less than 7 m/s. Fast icing in which speed of ice accumulation is 1.5 to 4 tons per hour, or 1 to 3 cm/hour occur with air temperatures of -3^o to -8^o C and wind speed of 7 to 15 m/sec. Very fast icing (speed of ice accumulation is more than 4 tons per hour, or more than 3 cm/hour) occurs with air temperatures of -8^o C or lower and wind speed of more than 15 m/sec.

This classification of icing intensity is applicable, in principle, to ships of large displacement, including icebreakers. However, ice accumulation speed varies from vessel to vessel in relation to the height above water. Duration of the icing phenomenon is 12 hours in 74% of cases; its maximum duration is seven days. In September the slow icing occurrence rate is 20–40% in the coastal areas, and 50–70% in the central parts of the arctic seas. The fast icing occurrence rate ranges from 15% in the southern parts; and up to 10% in the northern parts of the arctic seas. These values increase by about 10% in October.



Source: Panov, 1976; Kaplina, 1975; RSMOT, 1992.

Figure 6. Probability of occurrence (%) of very fast sea icing in the first (a), second (b), and the third (c) ten days of October in the Chukchi Sea.

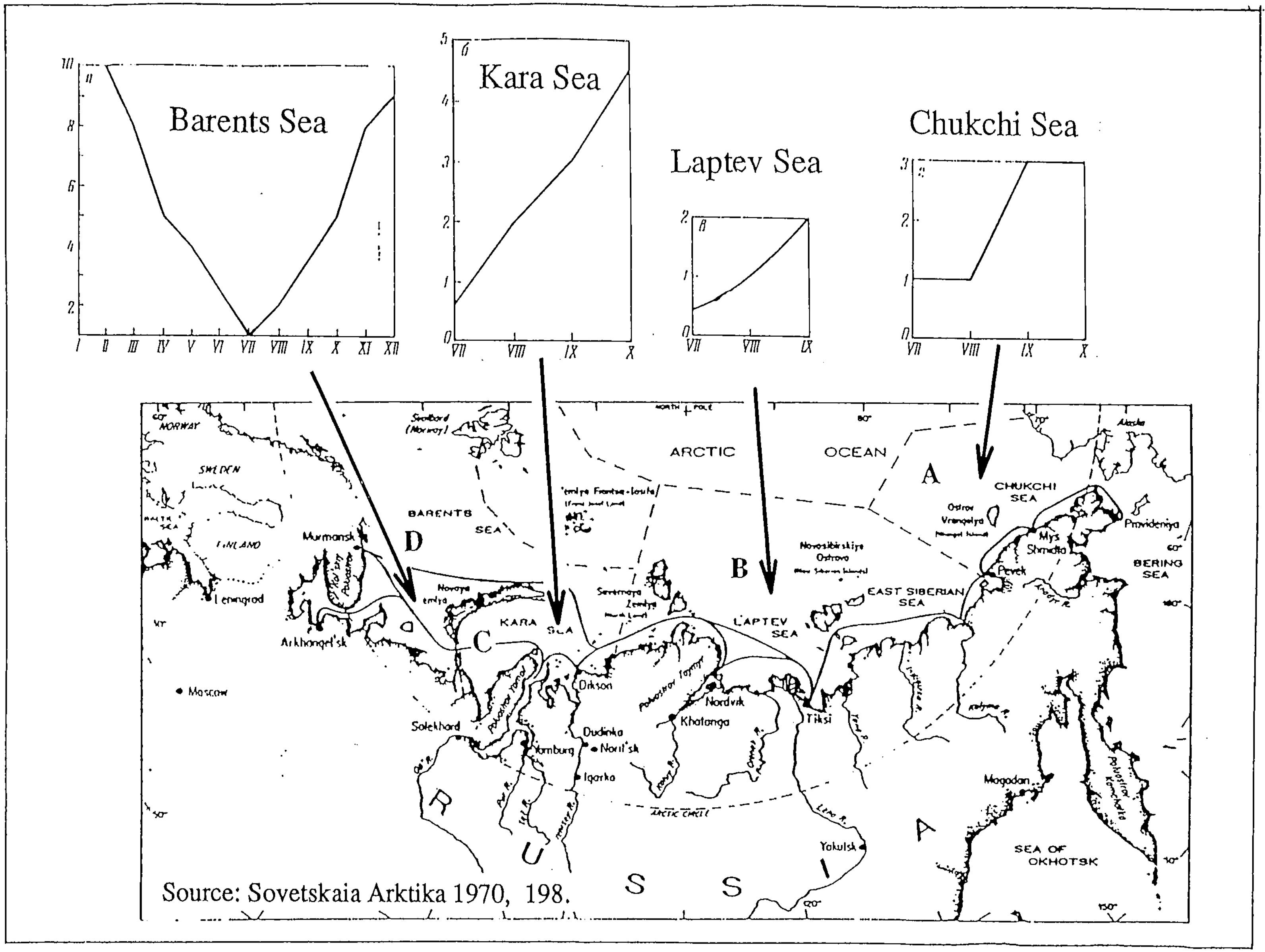
An example of empirical probability of occurrence of very fast icing in the Arctic is presented in Table 4 of Appendix 2. This information for all points of the NSR is presented at http://www.ims.alaska.edu/8000/insrop-2. These data is adapted from Panov (1976), Kaplina and Chukanin (1972), Kolosov (1972, 1975), AARI (1985), Vanda(1994), and Prohutinsky (1995). Figure 6 shows the probability of occurrence of very fast sea icing in October in the Chukchi Sea.

3. OCEANOGRAPHIC CONDITIONS

3.1. Waves

Wave parameters in the arctic seas are affected by both wind regime and ice conditions. While storm waves are very dangerous for small ships, they can also make the navigation of large ships difficult. Maximum waves are observed in the arctic seas in autumn. Strong waves and winds can generate a very dangerous phenomenon icing of ships and coastal constructions. (This phenomenon was discussed in Section 2.3). In open seas wave heights of 8 m are dangerous. For the coastal regions, heights of 5 m present a danger. Maximum wave height has a probability of occurrence of 0.1%. Maximum wind waves are observed in the Barents Sea in winter; the wind wave heights in the open part of the Barents Sea may reach 10–11 m. These waves are generated by stable west or southwest winds with velocities of about 20–25 m/s and duration of 16–18 hours. This happens, on average, ones or twice every five years. Wave heights of 7–8 m are developed by stable (16–18 hours) north and northwest storm winds. In the beginning of April, the intensity of waves in the Barents Sea notably decreases. The frequency of waves with heights of 5 m and more is about 4–5% at this time. In winter, this value is greater than 15%. In April–June, waves with heights of 3–9 m occur, on average, ones in five years. The calmest sea surface is observed in summer when the occurrence of waves with heights of more than 5 m is only 12%. Figure 7 presents the probability of occurrence of the wind waves with a height greater than 5 metes. In September, the intensity of waves increases. In November, in the Barents Sea, a wave regime similar to that in winter is established. Maximum wind waves are observed in the open sea (7–9 m). In the vicinity of the Murmansk shore, wind waves with heights of 7.5 m have been observed. In winter, well-developed swells are observed in the southern parts of the Barents Sea.

In the Kara Sea, in years with small amounts of ice, the fetch lengths range from 100–150 km in the beginning of July to 750–850 km and more, in September. In summer (July–August), the frequency of waves with heights of three or more m is about 8–10%. In autumn (September–October), it is about 12–15%. Strong wind waves are observed mostly in the southwest and northwest parts of the Kara Sea. In the southwest part of the sea, ice conditions usually do not influence the development of maximum wind waves, and waves can reach 8 m with wavelengths of 150–160 m and a period of 10 seconds. Strong wind waves are observed here, with winds coming from all directions. In summer, wind waves are more often generated by northeast winds. In the central Kara Sea, where depths and fetch lengths are small, insignificant waves develop. Sometimes, when strong waves penetrate this region from deep water, waves become shorter and steeper. In this case they can be dangerous for small ships navigating the NSR. Wind waves with heights of 1.5–2.5 m have a maximum frequency of occurrence in the Kara Sea. Frequency of wind



Source: Sovetskaia Arktika 1970, 198.

Figure 7. Probability of occurrence of the wind waves with a height greater than 5 meters

waves with heights of 5 m and more is at a maximum in October ranging from 45%.

In the Laptev Sea, wind waves with heights of more than 3 m are observed more frequently in September than in summer. Maximum wind waves are developed in the vicinity of west shores and in the central Laptev Sea. Wind waves with a height of 1.5 m have a maximum probability of occurrence in the Laptev Sea. In summer (July–August), in the central Laptev Sea, east storm winds generate maximum wave heights which may reach 5 m. In the southeastern Laptev Sea, maximum heights do not exceed 4 m. (Wind velocity ranges from 18 to 20 m/s.) In autumn, wind waves are at maximum heights of up to 6 m.

Because of the shallow depths and large areas with ice cover, wind waves are smallest in the East Siberian Sea. From July to September, the ice edge moves northward and the frequency of strong waves increases, reaching its maximum in September. In the middle of August, in the west part of the East Siberian Sea, a relatively large space of open water appears, and strong waves with heights of 4 m are generated by northwest winds with velocities of 20 m/s. East winds generate waves with heights of less than 2.5 m. In September, when the western part of the East Siberian Sea is almost ice free (from Novosibirskie Ostrova to the mouth of the Kolyma River), the maximum wave heights reach 5 m. While navigating to the north from the New Siberian Islands it is possible to meet with wind waves with heights of 5 m.

In the Chukchi Sea in July and August, weak wind waves prevail. High-pressure weather conditions and a large area of ice-covered sea favor this phenomenon. In September and October, wind waves reach 7-m heights. At the end of October, wave heights decrease due to the appearance of the ice cover. In the southern part of the Chukchi Sea, ice cover appears later, and strong wind waves may be generated even in November. In the southeast Chukchi Sea, strong waves are observed, with winds from all directions. Maximum wave heights here do not exceed 4.5 m. In the central and southwestern region of the sea, wave heights may reach 5 m.

North, northwest, and northeast storm winds are unfavorable for navigation in the Chukchi Sea. With north and northwest winds (velocity of about 20 m/s) ships may meet wave heights of 6.5-m in the Bering Strait, in the southern Chukchi Sea, and from Vankarem Mys to Serdtse-Kamen Mys. Wind waves here are less developed, with winds blowing from the south. However, along the coastal shipping route of the Chukchi Sea wave height may reach 6 m during the northern gales.

We have simulated wind waves in our Monte-Carlo model, taking into account wind speed, wind direction, and ice conditions at every time step. To calculate wave heights we have used the following relations (Tucker, 1991):

$$\mathbf{H} = 0.0163\mathbf{W}\mathbf{X}^{0.5} \tag{1}$$

$$\mathbf{H} = 0.21\mathbf{W}^{0.5}\mathbf{h}^{0.5}\mathrm{g}^{0.25} \tag{2}$$

where **H** is wave height, m; **X** is wind fetch, km; **W** is wind speed, m/s; **h** is sea depth, m; and g is gravity acceleration. Equation (1) is used for the deep sea ($\geq$ 40 m). Equation (2) is used for the shallow sea (less than 40 m). These formulas are applied if ice concentration is less than 30%. If it is higher we assume there is no waves. During summer, we estimate the wind fetch is 200 km; in winter it is only 100 km due to the location of the ice edge.

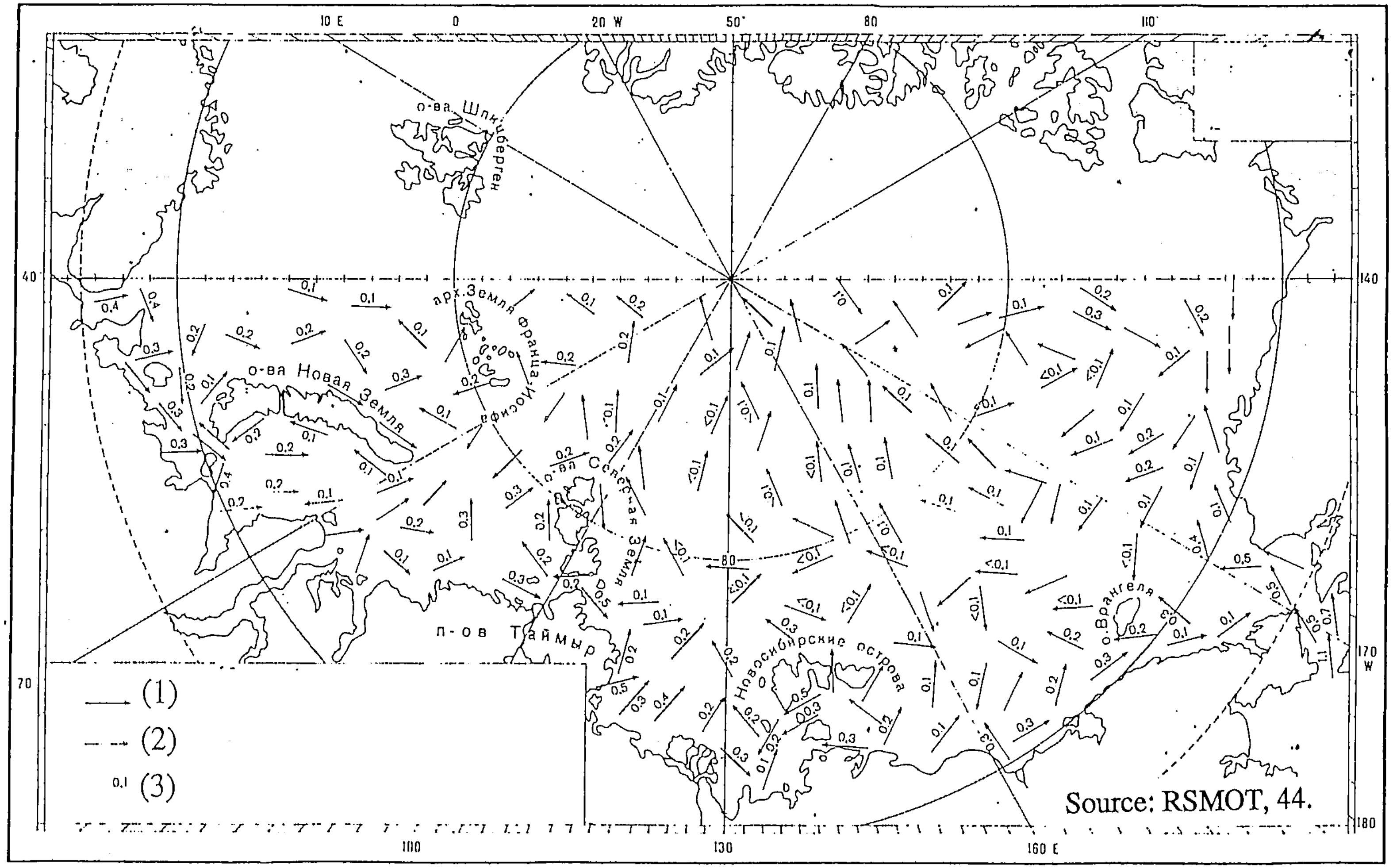
3.2 Currents

Summary currents in arctic seas are composed of permanent, wind-induced, and tidal currents. Permanent currents in the arctic seas are related to the general circulation of the Arctic Ocean and the general thermohaline structure of the region under consideration (Figure 8). In the Kara, East Siberian and Chukchi seas, permanent currents are formed as a result of fresh water inflow from rivers, and water exchange with adjacent areas. Permanent currents in the arctic seas have a relatively stable pattern. The rate of the constant currents is 0.1–0.3 knots in most of the NSR area. In some areas (mainly in straits and adjoining mouths of large rivers) the rate of the constant current increases to 0.4–1.2 knots. Permanent current velocities and directions for every point of the NSR are presented in Table 1 of Appendix 3, and in a more complete form, these data are at http://www.ims.alaska.edu/8000/insrop-2. These data were obtained from Proshutinsky (1995).

The Barents Sea circulation is very complicated; detailed scheme of its permanent currents was published by Polar Research Institute of Fishing Industry and Oceanography (PINRO), by Tantsiura (1959); Novitsky, (1961). Velocities of the surface currents were estimated by Potanin et al. (1989) using different methods of calculation. Results of observations of ship drifts demonstrate that the velocity of the North Cape current and its branches is about 1 knots. In the Karskie Vorota Strait, the permanent current from the Barents to the Kara Sea follows the coastline of Vaigatch Island at a velocity of 0.4 knots. Along Novaya Zemlia, a current with a velocity of 0.2 knots is directed from the Kara to the Barents Sea. In the Yugorskii Shar Strait, the permanent current is directed from the Barents to the Kara Sea.

The general circulation of the Kara Sea is cyclonic. The warm Novozemelskoye (of Novaya Zemlia) current flows from the Barents Sea, rounding Mys Zhelania to the Kara Sea. It sets southwest along the eastern coast of Ostrova Novaya Zemlia at a speed of 0.1–0.2 knots. In Proliv Karskiye Vorota a constant current (0.4 knots) goes along the shore of Ostrov Vaygach from the Barents Sea to the Kara Sea. Near the southern coast of Ostrova Novaya Zemlya there is a constant current with a speed of 0.2 knots which goes in the opposite direction. In Proliv Yugorskiy Shar a constant current with a mid-strait speed of 1.2 knots is directed from the Barents to the Kara Sea. In the southwest Kara Sea a constant current (speed approximately of 0.2 knots) flows northwest from the Barents Sea through Proliv Karskiie Vorota and Yugorskiy Shar. Waters from the Ob and Yenisey rivers spread fan-like into the Kara Sea. Part of these waters form a counter-clockwise rotating current in the southwest. Another part goes north and northeast, at a speed of 0.1–0.3 knots, toward Proliv Vilkitskogo.

In the Laptev and East Siberian Seas, the cyclonic system of circulation also prevails. In the Matisena strait a constant current with a speed 0.2–0.3 knots is directed to the east and northeast. In Proliv Lenina a constant current of the same speed goes to the southeast. The Vostochno-Taymyrskoye (of the east Taimyr) current goes from north to south along the eastern shores of Ostrova Severnaya Zemlya and near the shores of Poluostrov Taimyr with a speed 0.2 to 0.3 knots. Part of this current then sets out through Proliv Shokalskogo



Source: RSMOT, 44.

Figure 8. Surface currents in 0-10 m layer
1 - direction of a current; 2 - direction of a supposed current; 3 - velocity of a current, knots

and the northern part of Proliv Vilkitskogo to the Kara Sea. The main branch of this current continues to the south and is strengthened by waters coming from the Kara Sea through the southern part of Proliv Vilkitskogo at a current speed of 0.5 knots. At the approximate latitude of Bukhta Pronchishchevoy this current meets freshened waters from Khatangsky Zaliv, mixes, and continues to the east at a speed of 0.2 knots. In the southeast Laptev Sea, under the influence of an inflow from the Lena and Yana rivers, constant east and northeast currents form. These merge with currents setting west from Proliv Dmitriya Lapteva and Proliv Sannikova and continue to the north and northwest at a speed of 0.2 to 0.3 knots.

In the East Siberian Sea constant west and northwest currents prevail. Only in coastal areas does the current change direction to east-northeast. To the west of Ostrov Vrangelia a constant current with a speed of 0.1 to 0.2 knots sets northwest. This is an extension of the constant current coming from the Chukchi Sea through Proliv Longa. In Proliv Dmitriya Lapteva and Proliv Sannikova constant currents flow to the west at a speed of 0.2 to 0.3 knots. In the northern Proliv Longa a constant current sets west and in the southern part it sets east, both at a speed of 0.2 knots. The Indigirskoye (of Indigirka), a result of water inflow from the rivers Indigirka and Alazeia, goes north and northeast. Kolyma River waters form two branches of constant current, one of which sets north. The other sets east-northwest; both more at a speed of 0.3 knots.

Permanent currents of the Chukchi Sea are caused by a Pacific–Arctic Ocean interaction. Permanent currents may be described as inflow of Pacific waters through the Bering Strait; the East Siberian waters enter through the Longa Strait. In the Chukchi Sea, waters are divided into three branches: the Alaska, Gerald, and Longa currents. The Alaska current flows to the north and northeast with velocities ranging from 0.5 knots at Hope Cape to 0.2 knots at Barrow Cape. The Gerald current is directed from the Bering Strait to the north and flows around Gerald Island. The velocity of this branch ranges from 0.3 knots in the central part of the sea to 0.1 knots in the northern sea. The Longa branch leaves a major flow at parallel 68°N and turns northwest to the Longa Strait with velocity of 0.2 knots. The Chukotskoye current flows from Proliv Longa to the southeast, along the coast of Chukotskii Poluostrov. Its speed in Proliv Longa is 0.2 knots, and on the meridian of Kolyuchinskaya Guba it is 0.1 knots. This current does not usually reach the Bering Strait because in the vicinity of Kolyuchinskaya Guba it merges with the current flowing west-northwest.

Permanent currents are very important when there is no wind. In the narrow straits and bays they have to be taken into account by ships navigating along the NSR. In coastal areas with complicated shoreline configurations, current direction may either coincide with the wind direction or deviate from it. Northeast winds with speeds of 10 m/s drive, in general, currents flowing west and northwest at a magnitude of 0.4–0.8 knots. In the Laptev, East Siberian and Chukchi seas, southeast winds with speeds of 10 m/s drive a current flowing mainly northwest at a magnitude of 0.4–0.8 knots. In the Kara Sea similar winds drive a current flowing mainly northeast at a magnitude of 0.4–0.8 knots. In Proliv Matisena, during winds from the southeast and west, the current moves mainly northeast at 0.5 knots. In Proliv Dmitriya Lapteva, Proliv Sannikova, and Proliv Longa currents flow west and in Proliv Karskiye Vorota and Bering Strait they flow northeast. In the

Bering Strait, current velocity ranges from 1–1.2 knots. In Proliv Vilkitskogo, southwest winds drive currents, flowing east and northeast, at 1.3 knots.

Southwest winds with speeds of 10 m/s drive currents flowing predominantly to the east and northeast. Current speed in the open sea ranges from 0.3–0.8 knots, 1.7 knots in the Bering Strait; 2.1 knots in Proliv Sannikova; 2 knots in Proliv Yugorskiy Shar. In Proliv Vilkitskogo this wind drives a current east at 1.3 knots. In the Laptev, East Siberian and Chukchi seas, northwest winds with speed of 10 m/s drive currents flowing southeast at 0.4–0.6 knots. In the Kara Sea, similar winds drive currents flowing south and southwest at 0.2–0.5 knots. In Bering Strait, the current moves south reaching a speed of 1.1 knots.

Maximum speed of the wind currents is generally 1.5–2 knots, in some places reaching 2.5–3 knots, and as much as 5–6 knots in Proliv Matochkin Shar, Proliv Yugorskiy Shar, and Proliv Matisena. High-speed currents such as these are usually observed during winds of 20 m/s and greater.

Wind-induced currents near the sea surface are generally in the direction of the wind and equal to 2.5–3% of the wind's speed (Zubov, 1945). Using this algorithm, the model calculates a wind- induced current based on statistics of wind speed and wind direction.

Tidal currents in the arctic seas are dominantly semidiurnal. In the narrow straits and bays they have a reverse character; i.e., they change direction 180^o every 6 hours. In the open seas they have a rotational character. Maximum spring tide currents are usually observed 2.5–3 days after the new moon and the full moon, and the minimum neap tide currents are observed 2.5–3 days after the first and third quarters of the moon. Spring tidal currents are 2–2.5 times larger than neap tide currents. Velocities of tidal currents in the arctic seas vary widely from region to region. The information about tidal currents in the Arctic Ocean and arctic seas (space resolution is 14 km) can be found at http://www.ims.alaska.edu/8000. These data, which are in a good agreement with measurements, are the result of numerical simulation of the tides in the Arctic Ocean (Kowalik and Proshutinsky, 1994, 1995).

In the open regions of the Kara and western Laptev seas, the spring tide velocities range from 0.4 to 0.8 knots. In the eastern Laptev and the East Siberian seas, tide currents are about 0.2–0.4 knots and in the Chukchi Sea velocities range from 0.4–0.6 knots. In several regions of the arctic seas tidal currents reach extremum and have velocities of over 1.5–2.0 knots. For example, measurements show velocities of 1.5–1.8 knots in the Baidaratskaia Bay, to the north of Belii Island, in the Obskaia Guba, and in the region of Khatanga Bay. In the straits of Karskie Vorota, Yugorskii Shar, Malygina Strait, and Nordvik Bay, they reach 2–2.8 knots.

3.3 Sea ice conditions

Ice concentration, thickness, and pressure are the major direct factors influencing ship speed. Ice concentration was extracted from AARI 10-day Arctic Ocean EASE-Grid Sea Ice Observations (Figure 9). These gridded ice charts represent a reformatting by the National Snow and Ice Data Center (NSIDC), of information contained in Russian Arctic and Antarctic Research Institute (AARI) digital sea ice charts. AARI digitized arctic sea ice concentrations and stages of development from original source charts as part of an international data exchange program. The AARI source charts were developed from aircraft

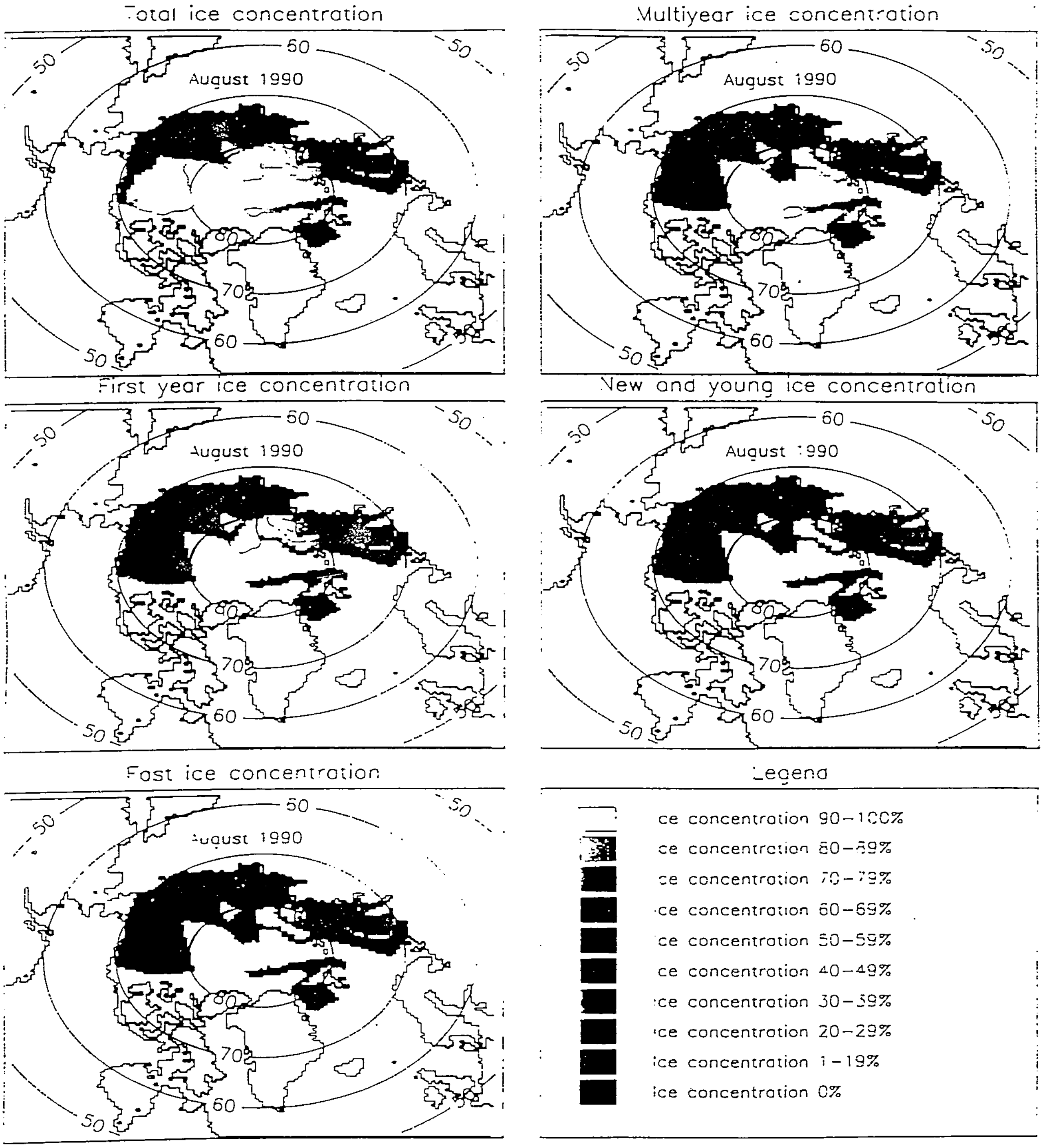


Figure 9 . Sea ice concentration from the AARI 10-Day Arctic Ocean EASE-Grid Sea Ice Observations Data Base (1954-1990)

and satellite observations made for shipping purposes; they provide extremely detailed information. AARI encoded these paper charts in digital Sea Ice Grid (SIGRID) format. But due to the difficulties of visualizing, extracting, and working with data in SIGRID, NSIDC is now providing AARI data in NSIDC's Equal Area SSM/I Earth (EASE) Grid. The EASE-Grid format makes it easier to compare observed ice concentration or ice types with the same parameters derived from satellite data. AARI sea ice data in the EASE-Grid North azimuthal projection are gridded at a 12.5-km resolution, for both western (24°W to 110°E) and eastern (105°E to 130°W) sectors. Data extend from 1953 through 1990, and are available via ftp (http://www-nsidc.colorado.edu/NSIDC/CATALOG/ENTRIES/nsi-0050.html in compressed tar format. In the EASE-Grid presentation, the original SIGRID data have been condensed to five layers: total sea ice concentration, multi-year ice concentration, first-year ice concentration, and new ice concentration. The fast-ice area is also shown in the fifth layer. We have processed this information and extracted ice concentrations for each point along the transitional routes. To define the ice thickness of different ice age categories for each grid point and each month we have used Tables 1.11.5 from the INSROP-2 report Natural Conditions Along the Selected Routes by Ashik et al., 1998. Examples of resulting ice statistics, which are used in the transit navigation model (see INSROP-2 report by Sadhi et al., 1998), is presented in Tables 1-3 of Appendix 4. Table 1 shows probability of occurrence of five ice categories for different ice concentration. It includes total ice concentration, multi-year, first-year, thin, and fast ice. Table 2 shows probability of occurrence of ice thickness for each point of the NSR. The information presented in this table is a combination of the data given in Table 1 and the data presented in Tables 1.11.5 of the INSROP-2 report Natural Conditions along the Selected Routes by Ashik et al., 1998. The complete data set of ice concentration statistics can be found at http://www.ims.alaska.edu/8000/insrop-2.

Ice pressure is one of the most important factors in slowing ship speed or even stopping an icebreaker. Ice compression and its probability along the NSR was simulated based on atmospheric pressures from 1946 through 1997. Assuming that the ice drifts along isobars (Zubov, 1945 Doronin, Kheysin, 1977) we can calculate ice drift velocities using geostrophic relationships, and after that to calculate divergence of the ice drift velocities. The ice pressure can be calculated as follows:

$$\begin{aligned} p &= -A_p \nabla \mathbf{u}_i \quad \text{if} \quad \nabla \mathbf{u}_i < 0 \\ p &= 0 \quad \text{if} \quad \nabla \mathbf{u}_i \geq 0 \end{aligned} \tag{3}$$

P is ice pressure; A_p is coefficient of ice compression. Simulated ice pressure was ranged in four groups: No ice pressure (when $\nabla \mathbf{u}_i \geq 0$), low, medium, and high ice pressure. It is important that sea ice drift at the land points is zero, and therefore the conditions of pushing-to and pushing-off winds are taken into account automatically. An example of this information is presented in Table 3 and the complete data file for each month and each point of the NSR can be found at http://www.ims.alaska.edu/8000/insrop-2.

Sea ice greatly affects navigation in the Arctic Ocean. Due to large interannual variability of ice cover along the Siberian coast, the arctic seas some years are fully free of ice in summer, while some have ice running just to the coastal edge, making navigation possible with the assistance of large icebreakers. In the early 1940s a natural phenomenon large settled assemblages of close sea ice was revealed by air reconnaissance data obtained by M.M. Somov and I.G. Ovchinnikov in the Kara Sea, and by P.A. Gordienko in the Laptev, East Siberian, and Chukchi seas. These close sea ice assemblages, which present significant obstacles to navigation, are called sea ice massifs. General ice cover distribution (for summer and winter) is presented on Figures 10 and 11. Sixteen sea ice massifs have now been found in the Arctic Ocean: nine in the Russian marginal arctic seas, six in the Arctic Ocean; and one with the largest area and thickest sea ice, in the Central Arctic Basin. Specialists distinguish between local sea ice massifs that, in the navigation period, alternate with open water and open sea ice, and those that branch from the Central Arctic Sea Ice Massif. The latter are formed by sustained outflow of settled sea ice from the Basin to the marginal seas.

There are two major ice massifs of about 1600–2500 km horizontal dimension in the Arctic Ocean. The first, a region with quasistationary ice rotation, is located between the Canadian Archipelago and a line following the 0–180° meridian. In this area, multi-year ice with a limited amount of variability in compression and concentration prevails. The second, an area with transit ice motion, is located between the area north of the arctic seas and 180° meridian. Ice thickness, concentration, and ice floe dimensions are smaller here. This area also has a permanent outflow of ice into the Greenland Sea. These two major areas can be subdivided into subregions with more or less uniform ice characteristics. For example, in the first area, it is possible to define four local regions with different ice characteristics. Their dimensions range from 450–500 km to 600–800 km. In the second area, which includes the NSR, the following well-investigated ice formations are found:

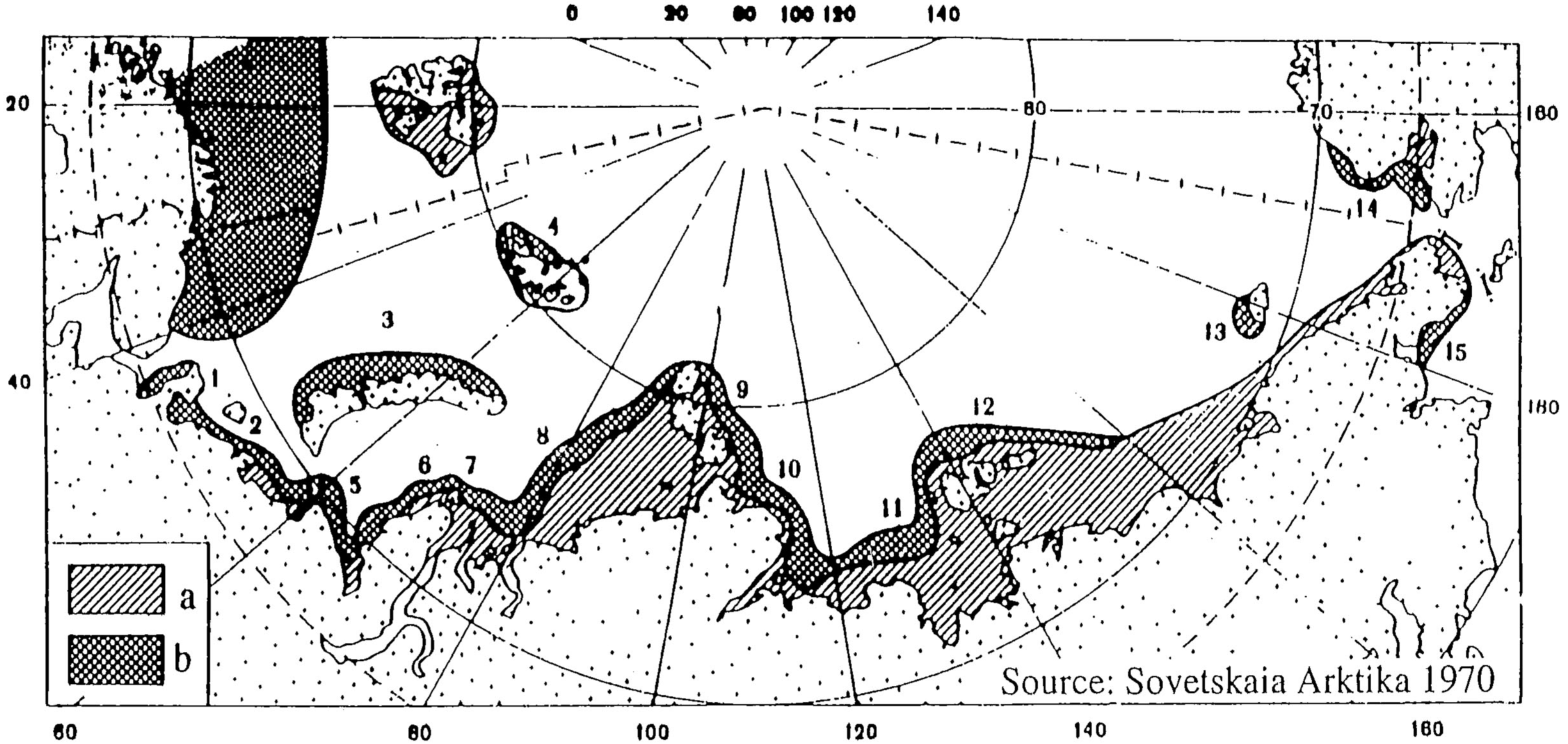
a) Ice massifs of ocean origin: Spitsbergenovskii, Karskii, Taimyrskii, Aionskii, and Chukotskii. In summer, ice destruction in these massifs is very slow. Massifs here are very often do not melt at all, but move northward under the influence of southern winds. In unfavorable years these massifs may block coastal waters with heavy, thick ice. In this event, navigation along the NSR is hazardous and sometimes impossible.

b) Local massifs of fast ice: Severozemelskii, Yanskii, and Novozemelskii. These massifs are generated in shallow-water regions with many islands and along very changeable coastlines.

c) Local massifs of pack ice: Novozemelskii, Wrangelevskii, and Anadirskii. These massifs are generated by wind and current conditions from other ice massifs. These massifs are less stable and have horizontal dimensions ranging from 250–400 km. In summer, every ice massif has a narrow periphery with a low ice concentration.

All of these ice massifs are characterized by annual and seasonal changes in area and location. Monitoring and forecasting of ice massifs are very important to navigation. Calculated variation of the range of the Alaska ice massif for September, based on 27 years of observations, is about 80%, or 1.6 times greater than the long-term mean value. This large variability of the branch massifs seems to be related to ice-drift variations in both speed and direction. The rate of the massif boundary shift varies greatly too. For instance, in the seas the daily average is 23 miles but may reach a 24-hour maximum of 10 miles.

The massifs tend to maintain their anomalous nature with regard to ice characteristics and location. If the Alaska ice massif, for instance, is located unfavorably (from the point

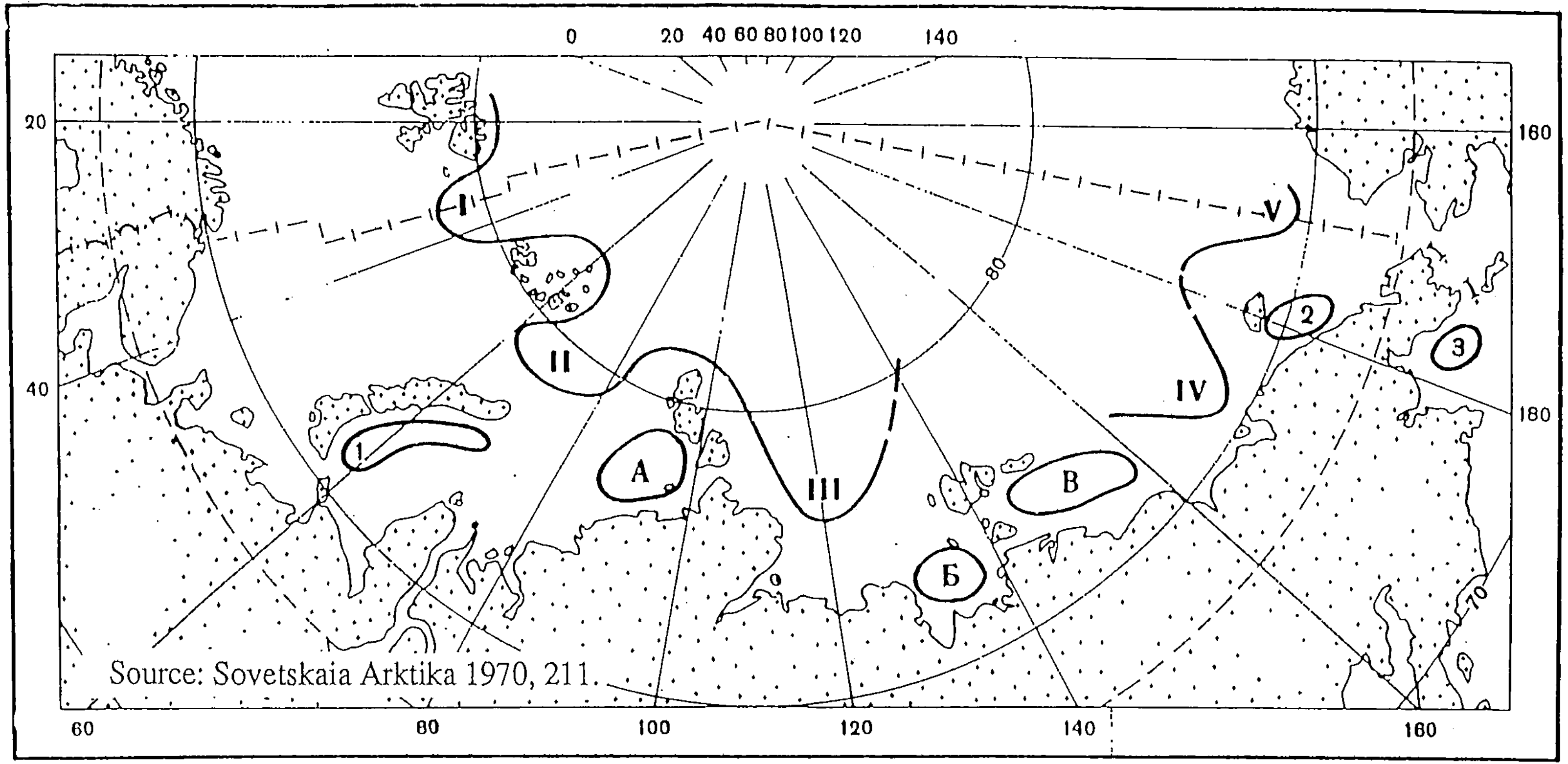


Source: Sovetskaia Arktika 1970

Figure 10. General ice cover distribution (winter)

a - fast ice;

b - polynias: 1 - Cheshskaya, 2 - Pechorskaya, 3 - Zapadno-Novozemelskaya, 4 - More Victorii, 5 - Amderminskaya, 6 - Yamalskaya, 7 - Ob'-Eniseyskaya, 8 - Zapadno-Severozemelskaya, 9 - Vostochno-Severozemelskaya, 10 - Taymirskaya, 11 - Lenskaya, 12 - Novosibirskaya, 13 - Zavrangelevskaya, 14 - Alaskinskaya, 15 - Anadirskaya.



Source: Sovetskaia Arktika 1970, 211.

Figure 11. General ice cover distribution (summer)

Major zones of high ice concentrations (ice massives) of the ocean origin:

I - Shpitsbergen, II - Karskii, III - Taymirskii, IV - Aionskii, V - Chukotskii.

Local massives of pack ice:

1 - Novozemelskii, 2 - Wrangelevskii, 3 - Anadirskii.

Local massives of the fast ice:

A - Severomorskii, B - Yanskii, C - Novosibirskii.

of view of ship navigation) at the start of the navigation season, in 80% of cases it will retain its ice characteristics and location for the entire first half of the season. The area of massif anomaly is usually stable for 13 months. In addition, certain teleconnections in the variability of the areas and the locations of certain ice massifs can be observed, and these may vary in response to a single factor. The ice massifs are known to interact, and in particular, to separate from each other in the spring-summer period. This is frequently due to the joining of polynyas, particularly stationary polynyas.

Starting in autumn, the fast ice is formed in the arctic seas. Maximum development of fast ice is observed in the shallow waters, with an external boundary of about 20–25 m depth. Close to coastlines with deeper waters, the width of fast ice is only about 10–20 km. The fast ice of the arctic seas usually consists of ice generated in autumn. But in the regions of Franz Josef Land, Spitsbergen, and the East Siberian Sea, two-year old ice may be encountered. Sometimes fast ice can persist during the summer and become two-year or multi-year fast ice.

There are many stamukhas in the landfast ice. They are predominant in the landfast ice of the East Siberian Sea, but separate stamukhas can be found near the landfast ice edge in the northeastern Kara Sea. In the arctic seas, two regions exhibit the greatest development of landfast ice. They are Severozemelskiy (of Severnaya Zemlia) and Novosibirskiy (of Novosibirskiye Ostrova). These two areas account for more than 4/5 of the total landfast ice area in the arctic seas. Landfast ice is usually 1.82 m thick, though near Proliv Karskiye Vorota and Bering Strait, it is 1.5–1.8 m. Wide leads with thinner ice, cracks, and hummocks, are frequently observed in the landfast ice. Landfast ice hummocking averages 1 to 2 points. When pushing-off ice drift prevails during autumn and winter seasons, landfast ice hummocking is about 1 point less than mean hummocking and 1 point greater than the average if pushing-to ice drift prevails. The most hummocked (2 to 3 points) are the narrow strips of landfast ice in the southwestern Kara Sea and along the coast of Chukotskiy Poluostrov.

Very often narrow polynyas or passageways exist between the fast ice and the pack ice. They usually appear for a short period of time under the influence of wind conditions. They can be very long, and they are always narrow. During pushing-off winds, flaw zones of thin ice are formed beyond the landfast ice and may exist for a long time as clear water polynyas, or as local ice formations up to 70 cm thick. Thin ice zones with a width greater than 35 miles have an occurrence rate which exceeds 50% in the Kara Sea and in areas to the west and north of Novosibirskie Ostrova. Such zones are less developed in the East Siberian and Chukchi seas where the width is less than 15 miles and the occurrence rate is less than 50%. Simultaneous occurrence of thin ice zones in all seas is a very rare phenomenon. Most probable is the occurrence of through zones of thin ice in the southwestern Kara Sea, in the vicinity of Ostrova Severnaya Zemlia and in areas to the west and north of Novosibirskie Ostrova. The occurrence rate of such zones decreases considerably from February through May. In the East Siberian and Chukchi seas, through zones of thin ice, even of 1-month duration, are highly improbable.

The drift ice area is located immediately beyond the zone of thin ice. Thick one-year ice occupies 2/3 of the drift ice area. About 60% of the area of the thick one-year ice is occupied by autumn 1.62 m thick ice, and about 40% by winter 1.2–1.6 m thick ice.

Perennial ice of the Arctic Basin enters into seas as ice massifs. Such ice is 2 to 3 m thick and is characterized by higher strength. Almost 3/4 of the total sea area occupied by perennial ice is concentrated in the East Siberian Sea where such ice occupies 15–20% of that area. In other arctic seas this ice normally occupies less than 5% of the areas.

Wind-driven ice drift prevails. Ice drift direction coincides with wind direction within 3 to 6 hours of the starting of wind. Ice drift results in ice exchange between the arctic seas and the Arctic Basin. In winter the ice is carried out of the Kara and Laptev seas and into the Chukchi Sea. Ice drift weakens in the arctic seas in May. Ice movement out of the northeastern Kara Sea and from the western Laptev Sea prevails, and ice movement to the Chukchi Sea continues. Ice movement from the southwestern Kara Sea almost stops, and the amount of ice carried from the northwest to the East Siberian Sea increases.

By the end of winter a large number of ice breccia, which include ice up to 1 m thick, have formed. In May their rotting goes on in all arctic seas. Ice cover consists mainly of big ice floes and their fragments. Fracture widths increase and the distance between fractures approaches less than one mile. In the East Siberian and Chukchi seas, ice cover fragmentation averages 6 to 7 points, and in the Kara and Laptev seas 5 to 6 points. The least fragmentation, 4 points, persists only in the northwestern Laptev Sea near Ostrov Severnaya Zemlia. Hummocked formations in the arctic seas are mainly separate hummock ridges crossing the floes and following their edge-lines. Drift ice hummocking of 2 points prevails in the Kara and Laptev Seas, and hummoks of 3 points are found in the East Siberian and Chukchi seas. Zones of higher hummocking (3 points and more) usually are observed in the Kara Sea to the south of parallel 73°N and to the north of parallel 78°N, and in the Laptev Sea along its W coast. Ice hummocking near the coast of Chukotskiy Poluostrov reaches 4 points due to ice carried from other areas, and the hummocks make ice barriers. Year-to- year variability of drift ice hummocking does not exceed one point.

The amount of snow on ice is assessed according to a 3-point scale, and averages 2 points, e. g, 5–10 cm thick, with small sastrugi.

Icebergs are rare in the shallow arctic seas. Small icebergs and their fragments can be met in the northern part of the Kara Sea and in the vicinity of Mys Zhelania. Their occurrence rate is 10%. Icebergs have not been observed in summer.

The major features of the ice distribution in the arctic seas, are caused by the monsoon character of atmospheric circulation. In summer, ice melting and decay begin to influence ice massif development. Long-time existing of polynyas leads to an increase in their water temperature and to ice melting at the side and bottom surfaces. When this happens, polynyas become the centers of ice melting in the seas. Winds can close the polynyas with ice cover if there is insufficient heat for self support.

Generation, development, and decay of ice cover are the major processes that define conditions of the NSR for commercial navigation. It is well known that the Arctic Basin is covered with pack ice year round. Because polynyas and passageways appearing between ice floes and ice massifs are unstable and of short duration, they do not play a role in the process of heating arctic waters. Therefore, only stable cooling leads to initial generation and formation of young ice. In the Arctic Ocean, this process usually has a stable development beginning about the middle of August. In early September, the process of ice growth propagates in the northern Arctic seas if residual ice is present. In the Barents

Sea the difference between earliest and latest dates of beginning ice generation may reach 3 months, while in the other seas it averages 2 months.

At the beginning of October, new ice generation begins in the shallow coastal regions of the arctic seas. As a rule, the arctic seas are covered with young ice at the end of October. Only in the southern Barents and in the southeastern Chukchi seas can one meet ice-free waters. Information about the dates of the beginning stable ice generation at stations along the NSR is presented in Proshutinsky et al., 1995. In November, young ice in the arctic seas reaches its maximum thickness and becomes one-year ice with a thickness of 30–70 cm. The intensity of ice growth from the Laptev to the Barents and Chukchi seas slowly decreases. This phenomenon is caused by warming of the Atlantic and the Pacific Oceans. At the middle of February the thickness of the ice cover reaches that of one-year-thick ice (more than 120 cm). The maximum ice distribution in the Northern Hemisphere occurs in March.

Ice growth continues until May in the arctic seas and in the Arctic Basin. With new ice generation and growth, the ice cover begins to change its shape under the influence of wind and currents. Young, thin ice under stress from blocks and ice floes disintegrates, forming areas with open water and generating ice ridges and zones with strong compressions. The strongest zones of ridging are observed at a distance of about 50 km from a shore or along a fast-ice edge. The ice ridges reach 45 m in height in the open sea with maximum height of 10 m. At the coastal regions and at the edge of fast ice, ridge barriers having heights of 18–20 m are very often generated.

Ice melt and decay are caused by direct solar radiation and the presence of warm air masses. There is enough heat to decay and break fast-ice formations, and to melt natural ice growing throughout the arctic seas. But in real conditions ice melting is a function of many factors, and ice cover very often remains for a second year in areas along the NSR. The Barents, Kara, Laptev, and Chukchi seas are ice-free only in years with very favorable conditions.

4. SUMMARY

Russian researches have collected weather, ice, and oceanographic data in the arctic seas for many decades and they have developed different methods for estimation and prediction of environmental parameters for polar navigation and shipping along the NSR. These extensive data, published in atlases, monographes, reference books, and articles were the cornerstone of our project. However, more information is needed on the ice thickness, ocean currents, and meteorological conditions in the Arctic. Existing sources of information contain multi-year mean environmental variables; however, uncertainties sometimes result from the existing atlases because they do not take into account climate change and climate variability. Recent findings of two climate states of the Arctic described by *Proshutinsky and Johnson* [1997] demonstrate that seasonal variations in the ice, weather and oceanic conditions are very different for cyclonic and anticyclonic arctic climate states. Therefore a major goal of future research is to document the atmospheric, ice, and oceanic signals showing seasonal variability of environmental parameters during different climate states. This will significantly improve data quality for the purposes of shipping simulation along the NSR.

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Appendix 1.

Table 1 Coordinates of the routes

Point		Latitude			Longitude		
1	B2-04	70	32	0	58	15	0
2		70	46	30	58	56	30
3		71	1	0	59	38	30
4		71	15	30	60	21	6
5		71	30	0	61	4	6
6		71	44	30	61	47	48
7		71	59	0	62	31	54
8		72	13	30	63	16	42
9		72	28	0	64	2	6
10		72	42	30	64	48	0
11		72	57	0	65	34	36
12		73	11	30	66	21	48
13		73	26	0	67	9	42
14		73	40	30	67	58	18
15	S-01	73	50	0	68	30	0
16		73	50	0	69	41	48
17		73	50	0	70	53	42
18		73	50	0	72	5	30
19		73	50	0	73	17	18
20		73	50	0	74	29	12
21		73	50	0	75	41	0
22		73	50	0	76	52	48
23		73	50	0	78	4	42
24		73	50	0	79	16	30
25	S-02	73	50	0	80	10	0
26		74	5	12	80	57	12
27		74	20	18	81	45	6
28		74	35	30	82	33	42
29		74	50	36	83	23	12
30		75	5	48	84	13	24
31		75	20	54	85	4	30
32		75	26	6	85	56	30
33		75	51	12	86	49	18
34	S-03	76	0	0	87	20	0
35		76	11	6	88	29	12
36		76	22	12	89	39	18
37		76	33	18	90	50	18
38		76	44	24	92	2	18
39		76	55	24	93	15	18
40		77	6	30	94	29	18
41		77	17	36	95	44	24
42	S-04	77	20	0	96	0	0
43		77	27	36	97	24	42
44		77	35	18	98	50	12
45		77	42	54	100	16	36
46		77	50	30	101	43	48
47	S-05	77	52	0	102	0	0
48		77	51	12	103	35	0
49		77	50	24	105	9	54
50	S-06	77	50	0	106	0	0
51		77	38	6	107	15	48
52		77	26	18	108	30	30
53		77	14	24	109	44	0
54		77	2	36	110	56	24
55		76	50	42	112	7	42
56		76	38	54	113	18	0
57		76	27	0	114	27	18
58		76	15	6	115	35	30
59		76	3	18	116	42	54
60		75	51	24	117	49	18
61		75	39	36	118	54	42
62		75	27	42	119	59	18
63		75	15	54	121	3	6
64		75	4	0	122	6	0
65		74	52	12	123	8	6
66		74	40	18	124	9	30
67		74	28	24	125	10	0
68		74	16	36	126	9	48
69		74	4	42	127	8	54
70		73	52	54	128	7	18
71		73	41	0	129	5	0
72	S-07	73	32	0	129	50	0
73		73	32	0	131	0	36
74		73	32	0	132	11	6
75		73	32	0	133	21	42
76		73	32	0	134	32	12
77		73	32	0	135	42	48
78	S-08	73	32	0	136	0	0
79		73	46	0	136	50	48
80		73	59	54	137	42	18
81		74	13	54	138	34	30
82	S-09	74	22	0	139	5	0
83		74	29	12	140	14	24
84	S-10	74	34	0	141	0	0
85		74	30	30	142	13	48
86		74	27	0	143	27	24
87		74	23	30	144	40	42
88		74	20	0	145	53	48
89	S-11	74	18	0	146	38	0
90		74	7	36	147	40	54
91		73	57	18	148	43	6
92		73	46	54	149	44	36
93		73	36	30	150	45	30
94		73	26	12	151	45	48
95		73	15	48	152	45	30
96		73	5	24	153	44	36
97		72	55	0	154	43	6
98		72	44	42	155	41	0
99		72	34	18	156	38	24
100		72	23	54	157	35	12
101		72	13	36	158	31	30
102		72	3	12	159	27	18
103		71	52	48	160	22	30
104		71	42	30	161	17	12
105		71	32	6	162	11	30
106		71	21	42	163	5	12
107		71	11	18	163	58	30
108		71	1	0	164	51	18
109		70	50	36	165	43	36
110		70	40	12	166	35	30
111		70	29	54	167	26	54
112	S-12	70	17	0	168	32	0
113		70	15	0	169	30	54
114		70	13	0	170	29	42
115		70	10	54	171	28	24
116		70	8	54	172	27	0
117		70	6	54	173	25	30
118		70	4	54	174	23	54
119		70	2	48	175	22	12
120	S-13	70	1	0	176	19	0
121		69	51	6	177	9	36
122		69	41	12	177	59	54
123		69	31	18	178	49	42
124		69	21	24	179	39	12

Point		Latitude			Longitude		
125		69	11	30	180	28	12
126	S-14	69	11	0	180	31	0
127		68	57	24	181	12	6
128		68	43	54	181	52	48
129		68	30	18	182	33	6
130		68	16	42	183	13	0
131		68	3	6	183	52	24
132		67	49	30	184	31	30
133		67	36	0	185	10	12
134		67	22	24	185	48	36
135	S-15	67	12	0	186	18	0
136		67	7	18	187	8	6
137		67	2	36	187	57	54
138	S-17	67	0	0	188	26	0
139		66	45	36	189	1	24
140		66	31	18	189	36	30
141		66	16	54	190	11	18
142	S-18	66	10	0	190	28	0
143	B1-02	77	11	0	68	0	0
144		77	11	0	69	30	12
145		77	11	0	71	0	18
146		77	11	0	72	30	30
147		77	11	0	74	0	36
148		77	11	0	75	30	48
149		77	11	0	77	1	0
150		77	11	0	78	31	6
151		77	11	0	80	1	18
152		77	11	0	81	31	24
153	N-01	77	11	0	82	30	0
154		77	20	48	83	49	6
155		77	30	30	85	9	18
156		77	40	18	86	30	24
157		77	50	0	87	52	42
158	N-02	77	58	0	89	0	0
159		78	18	0	89	0	0
160		78	38	0	89	0	0
161		78	58	0	89	0	0
162		79	18	0	89	0	0
163		79	38	0	89	0	0
164		79	58	0	89	0	0
165		80	18	0	89	0	0
166		80	38	0	89	0	0
167		80	58	0	89	0	0
168		81	18	0	89	0	0
169	N-03	81	20	0	89	0	0
170		81	21	18	91	12	36
171		81	22	30	93	25	30
172		81	23	48	95	38	48
173	N-04	81	24	0	96	0	0
174		81	7	54	97	17	48
175		80	51	42	98	33	18
176		80	35	36	99	46	36
177		80	19	24	100	57	48
178		80	3	18	102	7	6
179		79	47	6	103	14	36
180		79	31	0	104	20	24
181		79	14	48	105	24	30
182		78	58	42	106	27	0
183		78	42	30	107	28	0
184		78	26	24	108	27	42
185		78	10	12	109	25	54
186		77	54	6	110	22	54
187	N-05	77	47	0	110	48	0
188		77	32	6	111	50	18
189		77	17	6	112	51	24
190		77	2	12	113	51	18
191	N-06	76	55	0	114	20	0
192		76	47	18	115	41	6
193		76	39	30	117	1	18
194		76	31	48	118	20	54
195	N-07	76	26	0	119	20	0
196		76	26	54	120	45	12
197		76	27	42	122	10	30
198		76	28	36	123	35	48
199		76	29	30	125	1	18
200		76	30	18	126	26	48
201		76	31	12	127	52	30
202		76	32	6	129	18	12
203		76	32	54	130	44	0
204		76	33	48	132	9	54
205		76	34	42	133	35	54
206		76	35	30	135	2	0
207		76	36	24	136	28	12
208		76	37	18	137	54	30
209		76	38	6	139	20	48
210		76	39	0	140	47	18
211	N-08	76	40	0	142	0	0
212		76	33	54	143	22	18
213		76	27	54	144	44	6
214		76	21	48	146	5	12
215		76	15	42	147	25	42
216		76	9	42	148	45	42
217		76	3	36	150	5	6
218		75	57	36	151	23	54
219		75	51	30	152	42	12
220		75	45	24	153	59	54
221	N-09	75	44	0	154	20	0
222		75	27	48	155	7	0
223		75	11	30	155	53	12
224		74	55	18	156	38	36
225		74	39	6	157	23	12
226		74	22	54	158	7	0
227		74	6	36	158	50	6
228		73	50	24	159	32	30
229		73	34	12	160	14	6
230		73	18	0	160	55	12
231		73	1	42	161	35	36
232	N-10	72	58	0	161	45	0
233		72	45	48	162	38	42
234		72	33	36	163	31	48
235		72	21	18	164	34	24
236		72	9	6	165	16	18
237		71	56	54	166	7	42
238		71	44	42	166	58	30
239		71	32	24	167	48	42
240		71	20	12	168	38	24
241		71	8	0	169	27	36
242	N-11	71	0	0	170	0	0
243		70	56	18	171	0	12
244		70	52	36	172	0	18
245		70	48	54	173	0	12
246		70	45	12	173	59	48
247		70	41	30	174	59	18
248		70	37	42	175	58	36
249		70	34	0	176	57	48
250		70	30	18	177	56	42
251	N-12	70	30	0	178	4	0
252		70	33	30	179	3	6
253		70	36	54	180	2	18
254		70	40	18	181	1	42
255		70	43	48	182	1	12
256	N-13	70	45	0	182	21	0
257		70	28	12	182	53	48
258		70	11	24	183	26	6
259		69	54	36	183	57	54
260		69	37	48	184	29	24

Point		Latitude			Longitude		
261		69	21	6	185	0	24
262		69	4	18	185	31	0
263		68	47	30	186	1	18
264		68	30	42	186	31	6
265		68	13	54	187	0	36
266		67	57	6	187	29	48
267		67	40	18	187	58	36
268		67	23	30	188	27	0
269		67	6	42	188	55	6
270		66	49	54	189	22	54
271		66	33	6	189	50	24
272		66	16	24	190	17	30
273	Y-01	66	10	0	190	28	0
274	N-02	77	58	0	89	0	0
275		77	57	18	90	35	48
276		77	57	18	90	35	48
277		77	56	30	92	11	30
278		77	55	48	93	47	6
279		77	55	0	95	22	36
280		77	54	12	96	58	0
281		77	53	30	98	33	18
282		77	52	42	100	8	30
283		77	52	0	101	43	36
284	S-05	77	52	0	102	0	0
285		77	51	12	103	35	0
286		77	50	24	105	9	54
287	S-06	77	50	0	106	0	0
288		77	49	0	107	34	42
289		77	48	0	109	9	18
290		77	47	0	110	43	42
291	N-05	77	47	0	110	48	0
292	H-01	54	0	0	7	30	0
293	H-02	59	0	0	4	30	0
294	H-03	61	50	0	4	0	0
295	H-04	68	20	0	12	30	0
296	H-05	70	45	0	20	0	0
297	B1-01	71	20	0	25	50	0
298	B1-02	77	11	0	68	0	0
299	B2-01	70	0	0	56	0	0
300	B2-02	70	17	0	57	56	0
301	B2-03	70	23	24	57	58	0
302	B2-04	70	32	0	58	15	0
303	B3-01	69	37	0	59	35	0
304	B3-03	69	38	54	60	11	54
305	B3-04	69	38	36	60	19	36
306	B3-05	69	40	48	60	30	0
307	B3-06	69	42	54	60	33	54
308	B3-07	70	0	0	60	44	0
309	B4-01	71	15	0	28	0	0
310	B4-02	69	59	0	33	34	0
311	B4-03	69	35	0	33	34	0
312	B4-04	69	25	0	33	45	0
313	B5-01	69	47	0	34	46	0
314	B5-02	70	48	0	38	22	0
315	B5-03	76	7	0	59	0	0
316	B6-01	69	20	0	36	30	0
317	B6-02	67	50	0	41	10	0
318	B6-03	67	30	0	41	24	0
319	B7-01	69	0	0	43	0	0
320	B7-02	70	30	0	45	35	0
321	B7-03	75	20	0	55	30	0
322	N1-01	77	11	0	82	30	0
323	N1-02	77	58	0	89	0	0
324	N1-03	81	20	0	89	0	0
325	N1-04	81	24	0	96	0	0
326	S-01	73	50	0	68	30	0
327	S-02	73	50	0	80	10	0
328	S-03	76	0	0	87	20	0
329	S-04	77	20	0	96	0	0
330	S-05	77	52	0	102	0	0
331	S-06	77	50	0	106	0	0
332	S-07	73	32	0	129	50	0
333	S-08	73	32	0	136	0	0
334	S-09	74	22	0	139	5	0
335	S-10	74	34	0	141	0	0

Appendix 2.

Table 1. Probability of occurrence (%) of fog*

Point	Latitude			Longitude			April	May	June	July	August	Sept.	Oct.
1	70	32	0	58	15	0	2	7	12	11	10	6	3
2	70	46	30	58	56	30	2	7	12	12	12	7	3
3	71	1	0	59	38	30	2	7	12	13	14	8	3
4	71	15	30	60	21	6	2	7	13	14	15	9	3
5	71	30	0	61	4	6	2	7	13	14	16	9	3
6	71	44	30	61	47	48	2	7	13	15	18	10	3
7	71	59	0	62	31	54	2	8	14	16	19	11	3
325	81	24	0	96	0	0	1	10	20	20	20	11	3
326	73	50	0	68	30	0	2	8	15	18	21	12	4
327	73	50	0	80	10	0	1	6	12	11	10	7	4
328	76	0	0	87	20	0	1	8	15	22	30	17	4
329	77	20	0	96	0	0	1	5	10	20	30	16	3
330	77	52	0	102	0	0	40	25	10	15	20	11	2
331	77	50	0	106	0	0	1	5	10	17	25	13	1
332	73	32	0	129	50	0	2	7	12	13	15	8	1
333	73	32	0	136	0	0	2	7	12	13	15	8	2
334	74	22	0	139	5	0	1	8	15	19	23	12	1
335	74	34	0	141	0	0	1	8	15	19	23	12	1

* Data are presented for several nodes, the rest of data is available at http://www.ims.alaska.edu/insrop-2

Table 2. Probability of occurrence (%) of snowstorms*

							Month						
Point	Latitude			Longitude			10	11	12	1	2	3	4
1	70	32	0	58	15	0	10.	9.	8.	8.	7.	6.	5.
2	70	46	30	58	56	30	10.	9.	8.	8.	7.	6.	5.
3	71	1	0	59	38	30	10.	9.	9.	8.	7.	7.	6.
4	71	15	30	60	21	6	11.	10.	9.	8.	8.	7.	6.
5	71	30	0	61	4	6	11.	10.	10.	9.	8.	8.	7.
6	71	44	30	61	47	48	12.	11.	10.	10.	9.	8.	7.
7	71	59	0	62	31	54	12.	11.	11.	10.	9.	9.	8.
325	81	24	0	96	0	0	10.	11.	12.	12.	13.	14.	15.
326	73	50	0	68	30	0	15.	14.	14.	13.	12.	12.	11.
327	73	50	0	80	10	0	15.	14.	13.	12.	12.	11.	10.
328	76	0	0	87	20	0	15.	15.	15.	15.	15.	15.	15.
329	77	20	0	96	0	0	15.	15.	15.	15.	15.	15.	15.
330	77	52	0	102	0	0	15.	13.	12.	10.	8.	7.	5.
331	77	50	0	106	0	0	15.	14.	13.	12.	12.	11.	10.
332	73	32	0	129	50	0	10.	10.	10.	10.	10.	10.	10.

* Snowstorm is defined as an event where wind velocity is greater or equal to 8m/s, air temperature is less than 0°, and visibility as a result of snow is less than 2.5 km. Data are presented for several nodes, the rest of data is available at http://www.ims.alaska.edu/insrop-2

Appendix 2.

Table 3. Probability of occurrence (%) of wind speed and wind direction, January*

DIR - wind direction; N - probability of the wind direction; MAX - maximum simulated wind speed, m/s; MEAN - mean wind speed, m/s; 0-5, 5-10 etc. - wind speed, m/s.

DIR	N	MAX	MEAN	0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40	40-45
1 B2-04	(point number)											
000-045	6.9	25.4	7.3	2.3	3.2	1.1	0.3	0.0	0.1	0.0	0.0	0.0
045-090	6.0	22.0	7.8	1.8	2.4	1.3	0.3	0.1	0.0	0.0	0.0	0.0
090-135	11.2	25.1	9.0	1.9	5.2	2.4	1.3	0.1	0.1	0.0	0.0	0.0
135-180	16.7	25.9	10.1	2.4	6.2	4.8	2.5	0.6	0.1	0.0	0.0	0.0
180-225	24.3	36.1	12.3	2.8	6.4	6.6	5.9	1.9	0.5	0.1	0.1	0.0
225-270	16.9	29.1	11.5	2.8	5.0	4.0	2.8	2.0	0.4	0.0	0.0	0.0
270-315	10.7	26.2	9.0	2.5	4.3	2.2	1.2	0.5	0.1	0.0	0.0	0.0
315-360	7.3	21.7	7.9	1.9	3.7	1.0	0.7	0.1	0.0	0.0	0.0	0.0
2												
000-045	6.6	23.0	7.7	1.7	3.4	1.0	0.4	0.1	0.0	0.0	0.0	0.0
045-090	6.2	23.2	7.6	1.8	2.8	1.1	0.5	0.1	0.0	0.0	0.0	0.0
090-135	11.9	28.3	8.5	2.8	5.4	2.6	0.9	0.1	0.1	0.0	0.0	0.0
135-180	18.9	26.7	10.9	2.5	6.6	5.1	3.5	1.0	0.2	0.0	0.0	0.0
180-225	22.8	35.4	12.1	2.2	6.8	6.2	5.4	1.6	0.5	0.1	0.1	0.0
225-270	14.5	24.6	10.9	2.7	5.3	1.9	3.3	1.3	0.0	0.0	0.0	0.0
270-315	10.2	23.6	8.5	2.8	4.1	2.0	0.9	0.3	0.0	0.0	0.0	0.0
315-360	8.9	24.4	7.4	2.9	4.2	1.1	0.5	0.2	0.0	0.0	0.0	0.0

*Data are presented for two nodes (1 B2-04 and 2), the rest of data is available at http://www.ims.alaska.edu/insrop-2

Table 4. Probability of occurrence (%) of very fast icing*

Point		Latitude			Longitude			Aug.	Sep.	Oct.
1	B2-04	70	32	0	58	15	0	1	3	5
2		70	46	30	58	56	30	1	3	5
3		71	1	0	59	38	30	1	3	6
4		71	15	30	60	21	6	1	4	7
5		71	30	0	61	4	6	1	4	8
6		71	44	30	61	47	48	1	5	9
7		71	59	0	62	31	54	2	6	10
8		72	13	30	63	16	42	2	7	12
9		72	28	0	64	2	6	2	7	12
10		72	42	30	64	48	0	2	7	13
11		72	57	0	65	34	36	2	7	13
12		73	11	30	66	21	48	3	8	14
13		73	26	0	67	9	42	3	8	14
14		73	40	30	67	58	18	4	9	15
15	S-01	73	50	0	68	30	0	4	9	15
16		73	50	0	69	41	48	5	10	16
17		73	50	0	70	53	42	5	10	16
18		73	50	0	72	5	30	6	11	17
19		73	50	0	73	17	18	7	12	17
20		73	50	0	74	29	12	8	13	18
21		73	50	0	75	41	0	8	13	18

- Very fast icing is defined as an event where speed of ice accumulation is greater than 4 tons/hour or 3 cm/hour.
- Data are presented for several nodes, the rest of the data can be found at http://www.ims.alaska.edu/insrop-2

Appendix 3.

Table 1.Permanent currents along the NSR (knots)*

								Currents	
								Dir.	Speed
Point		Latitude			Longitude				knots
1	B2-04	70	32	0	58	15	0	45	0.2
2		70	46	30	58	56	30	45	0.2
3		71	1	0	59	38	30	45	0.2
4		71	15	30	60	21	6	45	0.2
5		71	30	0	61	4	6	45	0.2
6		71	44	30	61	47	48	45	0.2
7		71	59	0	62	31	54	45	0.2
8		72	13	30	63	16	42	45	0.2
9		72	28	0	64	2	6	45	0.2
10		72	42	30	64	48	0	225	0.1
11		72	57	0	65	34	36	225	0.1
12		73	11	30	66	21	48	225	0.1
13		73	26	0	67	9	42	225	0.1
14		73	40	30	67	58	18	225	0.1
15	S-01	73	50	0	68	30	0	225	0.1
16		73	50	0	69	41	48	0	0.1
17		73	50	0	70	53	42	0	0.1
18		73	50	0	72	5	30	0	0.1
19		73	50	0	73	17	18	0	0.1

- Data are presented for several nodes, the rest of data is available at
- http://www.ims.alaska.edu/insrop-2

Appendix 4.

Table 1. Ice concentration statistics

Probability of occurrence (%) of ice concentrations for different ice categories (layers): total ice concentration, multi-year ice, first-year ice, thin ice, and fast ice. 10-30, 40-60, 70-80, 90-100 are the rates of expected ice concentration

Point = 1

Layer=1 (Probability of occurrence of total ice concentration)

month:	1	2	3	4	5	6	7	8	9	10	11	12
ice free	0.	3.	0.	2.	2.	32.	65.	73.	91.	90.	43.	13.
10-30	0.	0.	0.	0.	2.	12.	10.	11.	6.	0.	3.	0.
40-60	0.	0.	2.	0.	2.	6.	4.	9.	0.	0.	5.	3.
70-80	0.	0.	0.	2.	4.	3.	3.	1.	0.	5.	3.	11.
90-100	100.	97.	98.	96.	91.	47.	19.	6.	3.	5.	46.	74.

Layer = 2 (Probability of occurrence of concentration of multi-year ice)

month:	1	2	3	4	5	6	7	8	9	10	11	12
ice free	100.	100.	98.	100.	100.	100.	96.	99.	100.	95.	97.	100.
10-30	0.	0.	2.	0.	0.	0.	4.	0.	0.	0.	3.	0.
40-60	0.	0.	0.	0.	0.	0.	0.	0.	0.	5.	0.	0.
70-80	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
90-100	0.	0.	0.	0.	0.	0.	0.	1.	0.	0.	0.	0.

Layer = 3 (Probability of occurrence of concentration of first-year ice)

month:	1	2	3	4	5	6	7	8	9	10	11	12
ice free	25.	22.	12.	6.	6.	35.	65.	74.	91.	100.	95.	82.
10-30	11.	3.	0.	0.	4.	10.	10.	11.	6.	0.	0.	5.
40-60	4.	0.	2.	0.	4.	6.	4.	9.	0.	0.	0.	3.
70-80	36.	19.	13.	14.	15.	1.	6.	1.	0.	0.	3.	8.
90-100	25.	57.	73.	80.	72.	47.	15.	4.	3.	0.	3.	3.

Layer = 4 (Probability of occurrence of concentration of new ice)

month:	1	2	3	4	5	6	7	8	9	10	11	12
ice free	11.	16.	44.	47.	49.	95.	100.	100.	100.	90.	46.	13.
10-30	50.	62.	42.	49.	45.	5.	0.	0.	0.	0.	5.	11.
40-60	4.	0.	4.	0.	2.	0.	0.	0.	0.	5.	5.	5.
70-80	11.	3.	0.	0.	0.	0.	0.	0.	0.	5.	3.	16.
90-100	25.	19.	10.	4.	4.	0.	0.	0.	0.	0.	41.	55.

Layer = 5 (Probability of occurrence of concentration of fast ice)

month:	1	2	3	4	5	6	7	8	9	10	11	12
ice free	100.	97.	83.	86.	87.	95.	99.	100.	100.	100.	95.	100.
10-30	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
40-60	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
70-80	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
90-100	0.	3.	17.	14.	13.	5.	1.	0.	0.	0.	5.	0.

* Data are presented only for node 1, the rest of data can be found at http://www.ims.alaska.edu/insrop-2

Appendix 4.

Table 2. Probability of occurrence (tenth) of ice thickness
Month = 1

					Thickness, cm			
Point	Max Cm	Min cm	Mean cm	None	<120	120-180	180-240	>240
1	100.	28.	67.	0.00	1.00	0.00	0.00	0.00
2	126.	28.	73.	0.00	0.96	0.04	0.00	0.00
3	120.	30.	92.	0.00	1.00	0.00	0.00	0.00
4	120.	30.	89.	0.00	1.00	0.00	0.00	0.00
5	120.	30.	89.	0.00	1.00	0.00	0.00	0.00
6	120.	30.	99.	0.00	1.00	0.00	0.00	0.00
7	120.	30.	103.	0.00	1.00	0.00	0.00	0.00
8	120.	30.	106.	0.00	1.00	0.00	0.00	0.00
9	120.	30.	106.	0.00	1.00	0.00	0.00	0.00
10	120.	30.	107.	0.00	1.00	0.00	0.00	0.00
11	120.	30.	107.	0.00	1.00	0.00	0.00	0.00
12	120.	30.	104.	0.00	1.00	0.00	0.00	0.00
13	120.	102.	110.	0.00	1.00	0.00	0.00	0.00
14	120.	102.	109.	0.00	1.00	0.00	0.00	0.00
15	116.	30.	104.	0.00	1.00	0.00	0.00	0.00
16	116.	30.	90.	0.00	1.00	0.00	0.00	0.00
17	120.	24.	79.	0.00	1.00	0.00	0.00	0.00
18	116.	24.	89.	0.00	1.00	0.00	0.00	0.00
19	120.	30.	85.	0.00	1.00	0.00	0.00	0.00
20	120.	30.	77.	0.00	1.00	0.00	0.00	0.00
21	120.	30.	93.	0.00	1.00	0.00	0.00	0.00
22	120.	30.	70.	0.00	1.00	0.00	0.00	0.00
23	120.	30.	65.	0.00	1.00	0.00	0.00	0.00

* Data are presented for several nodes, the rest of data can be found at http://www.ims.alaska.edu/insrop-2

Table 3. Probability of occurrence (%) of ice pressure

		Pressure			
Point		No press.	LIGHT	MEDIUM	HIGH
1	B2-04	66.3	14.4	17.7	1.5
2		97.0	3.0	0.0	0.0
3		97.0	2.9	0.1	0.0
4		97.2	2.8	0.0	0.0
5		97.2	2.8	0.0	0.0
6		96.3	3.6	0.1	0.0
7		95.5	4.3	0.2	0.0
8		93.4	6.2	0.3	0.0
9		93.4	6.2	0.3	0.0
10		92.5	7.1	0.5	0.0
11		92.9	6.7	0.4	0.0
12		93.6	6.0	0.3	0.0
13		94.8	5.1	0.1	0.0
14		94.8	5.1	0.1	0.0
15	S-01	95.6	4.4	0.0	0.0
16		96.4	3.6	0.0	0.0
17		81.7	8.9	8.9	0.5
18		96.4	3.6	0.0	0.0
19		96.4	3.6	0.0	0.0
20		96.4	3.6	0.0	0.0
21		95.6	4.4	0.1	0.0
22		95.6	4.4	0.1	0.0

*Data are presented or several nodes, the rest of the data is available at http://www.ims.alaska.edu/insrop-2

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26 November 1998

Review of the INSROP Paper Box C/Project 2/1.5.8: "Environmental Conditions Affecting Commercial Shipping"

Claes Ragner
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Dear Claes

I have reviewed this key paper by A. Proshutinsky, T. Proshutinsky and T. Weingartner, all of the University of Alaska - Fairbanks. As they mentioned in the introduction, some of this material was previously used in a 1994 CRREL report. However, I see that the authors have since added a substantial number of references relevant to the simulation study. I have also looked over the extensive data files, all of which will be quite valuable to many INSROP users. Here are several highly recommended changes:

1) **Comment on data availability** — Somewhere in the report (front page or in a summary) mention should be made how to obtain this data set. I highly recommend that it be placed on the INSROP web site once any known errors are corrected. The discs of data can be maintained at FNI, but it would be best to have the data in the INSROP GIS and on the INSROP web site.

2) **Appendix captions/headings** — Each appendix and table requires some explanation. Obviously, some of these tables are only "samples" of the entire data set. One should be able to look at a table caption and have an idea of what the data is without referring back to the text.

3) **Map** — As this is a stand alone INSROP Working Paper, it would be useful to include a locator map of the ice massifs, seas and other geographical points mentioned in the text. A map from one of the references might suffice.

4) **Summary** — A summary would be useful at the end of the text. Perhaps comment might be made regarding the general quality of the data. How to obtain the data set might also be included.

Overall, the paper is an important contribution to the INSROP data base and should be published as an INSROP Working Paper. I believe the recommended changes/additions would enhance the use of the report.

Respectfully

Lawson W. Brigham

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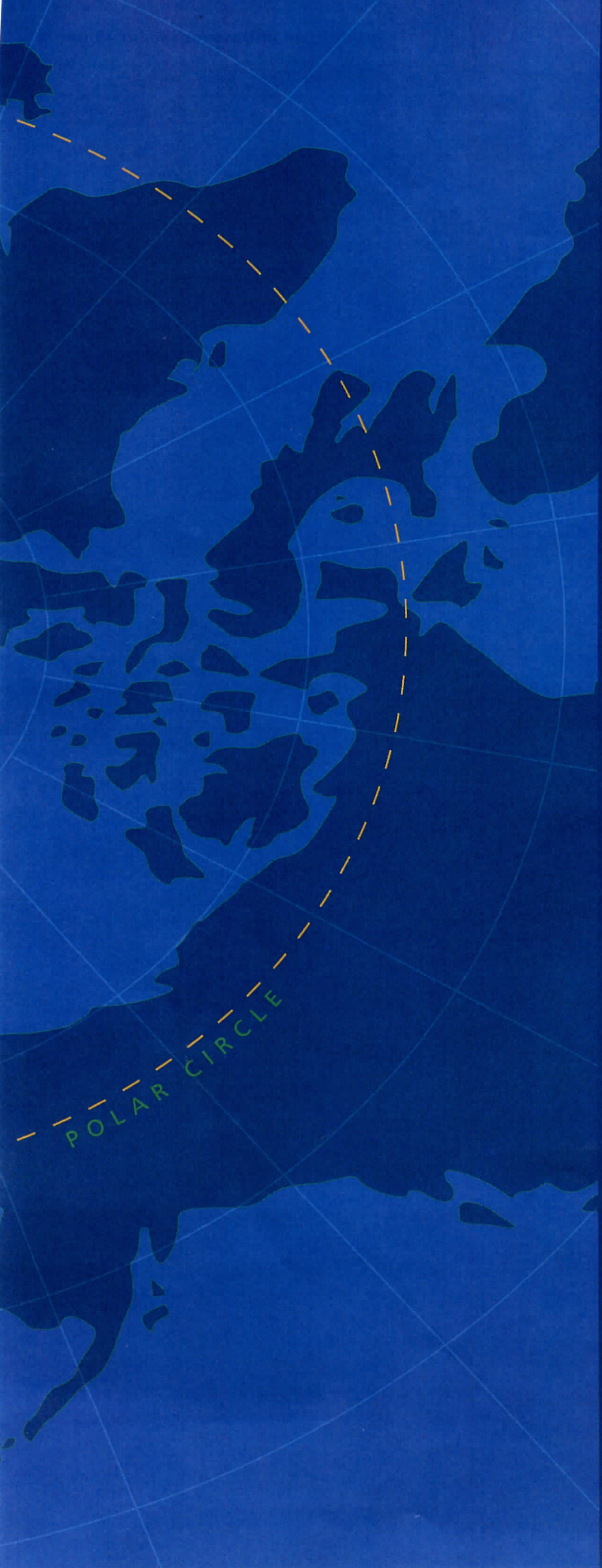
Captain, U.S. Coast Guard (Ret.)
Scott Polar Research Institute



The three main cooperating institutions of INSROP

Ship & Ocean Foundation (SOF), Tokyo, Japan.
SOF was established in 1975 as a non-profit organization to advance modernization and rationalization of Japan's shipbuilding and related industries, and to give assistance to non-profit organizations associated with these industries. SOF is provided with operation funds by the Sasakawa Foundation, the world's largest foundation operated with revenue from motorboat racing. An integral part of SOF, the Tsukuba Institute, carries out experimental research into ocean environment protection and ocean development.

Central Marine Research & Design Institute (CNIIMF), St. Petersburg, Russia.
CNIIMF was founded in 1929. The institute's research focus is applied and technological with four main goals: the improvment of merchant fleet efficiency; shipping safety; technical development of the merchant fleet; and design support for future fleet development. CNIIMF was a Russian state institution up to 1993, when it was converted into a stockholding company.

The Fridtjof Nansen Institute (FNI), Lysaker, Norway.
FNI was founded in 1958 and is based at Polhøgda, the home of Fridtjof Nansen, famous Norwegian polar explorer, scientist, humanist and statesman. The institute spesializes in applied social science research, with special focus on international resource and environmental management. In addition to INSROP, the research is organized in six integrated programmes. Typical of FNI research is a multidisciplinary approach, entailing extensive cooperation *with other research institutions* both at home and abroad. The INSROP Secretariat is located at FNI.