ICE AND POLAR NAVIGATION

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CHAPTER 32

ICE NAVIGATION

INTRODUCTION

3200. Ice and the Navigator

Sea ice has posed a problem to the navigator since antiquity. During a voyage from the Mediterranean to England and Norway sometime between 350 B.C. and 300 B.C., Pytheas of Massalia sighted a strange substance which he described as "neither land nor air nor water" floating upon and covering the northern sea over which the summer sun barely set. Pytheas named this lonely region Thule, hence Ultima Thule (farthest north or land's end). Thus began over 20 centuries of polar exploration.

Ice is of direct concern to the navigator because it restricts and sometimes controls vessel movements; it affects dead reckoning by forcing frequent changes of course and speed; it affects piloting by altering the appearance or obliterating the features of landmarks; it hinders the establishment and maintenance of aids to navigation; it affects the use of electronic equipment by affecting propagation of radio waves; it produces changes in surface features and in radar returns from these features; it affects celestial navigation by altering the refraction and obscuring the horizon and celestial bodies either directly or by the weather it influences, and it affects charts by introducing several plotting problems.

Because of this direct concern with ice, the prospective polar navigators must acquaint themselves with its nature and extent in the area they expects to navigate. In addition to this volume, books, articles, and reports of previous polar operations and expeditions will help acquaint the polar navigator with the unique conditions at the ends of the Earth.

3201. Formation of Sea Ice

As it cools, water contracts until the temperature of maximum density is reached. Further cooling results in expansion. The maximum density of fresh water occurs at a temperature of 4.0°C, and freezing takes place at 0°C. The inclusion of salt lowers both the temperature of maximum density and, to a lesser extent, that of freezing. These relationships are shown in Figure 3201. The two lines meet at a salinity of 24.7 parts per thousand, at which maximum density occurs at the freezing temperature of –1.3°C. At this and greater salinities, the temperature of maximum density of sea water is coincident with the freezing point temperature, i.e., the density increases as the temperature gets colder. At a salinity of 35 parts per thousand, the approxi-

mate average for the oceans, the freezing point is –1.88°C.

As the density of surface seawater increases with decreasing temperature, convective density-driven currents are induced bringing warmer, less dense water to the surface. If the polar seas consisted of water with constant salinity, the entire water column would have to be cooled to the freezing point in this manner before ice would begin to form. This is not the case, however, in the polar regions where the vertical salinity distribution is such that the surface waters are underlain at shallow depth by waters of higher salinity. In this instance density currents form a shallow mixed layer which subsequently cannot mix with the deep layer of warmer but saltier water. Ice will then begin forming at the water surface when density currents cease and the surface water reaches its freezing point. In shoal water, however, the mixing process can be sufficient to extend the freezing temperature from the surface to the bottom. Ice crystals can, therefore, form at any depth in this case. Because of their lower density, they tend to rise to the surface, unless they form at the bottom and attach themselves there. This ice, called anchor ice, may continue to grow as additional ice freezes to that already formed.

3202. Land or Glacial Ice

Ice of land origin is formed on land by the freezing of freshwater or the compacting of snow as layer upon layer adds to the pressure on that beneath.Under great pressure, ice becomes slightly plastic, and is forced downward along an inclined surface. If a large area is relatively flat, as on the Antarctic plateau, or if the outward flow is obstructed, as on Greenland, an **ice cap** forms and remains essentially permanent. The thickness of these ice caps ranges from nearly 1 kilometer on Greenland to as much as 4.5 kilometers on the Antarctic Continent. Where ravines or mountain passes permit flow of the ice, a **glacier** is formed. This is a mass of snow and ice which continuously flows to lower levels, exhibiting many of the characteristics of rivers of water. The flow may be more than 30 meters per day, but is generally much less. When a glacier reaches a comparatively level area, it spreads out. When a glacier flows into the sea, sections will break off an float away as **icebergs**. Icebergs may be described as tabular or non-tabular. Non-tabular icebergs can be further described as domed, pinnacled, tabular (Figure 3202a) and (Figure 3202b), wedged, drydocked, or as an ice island. A floating iceberg seldom
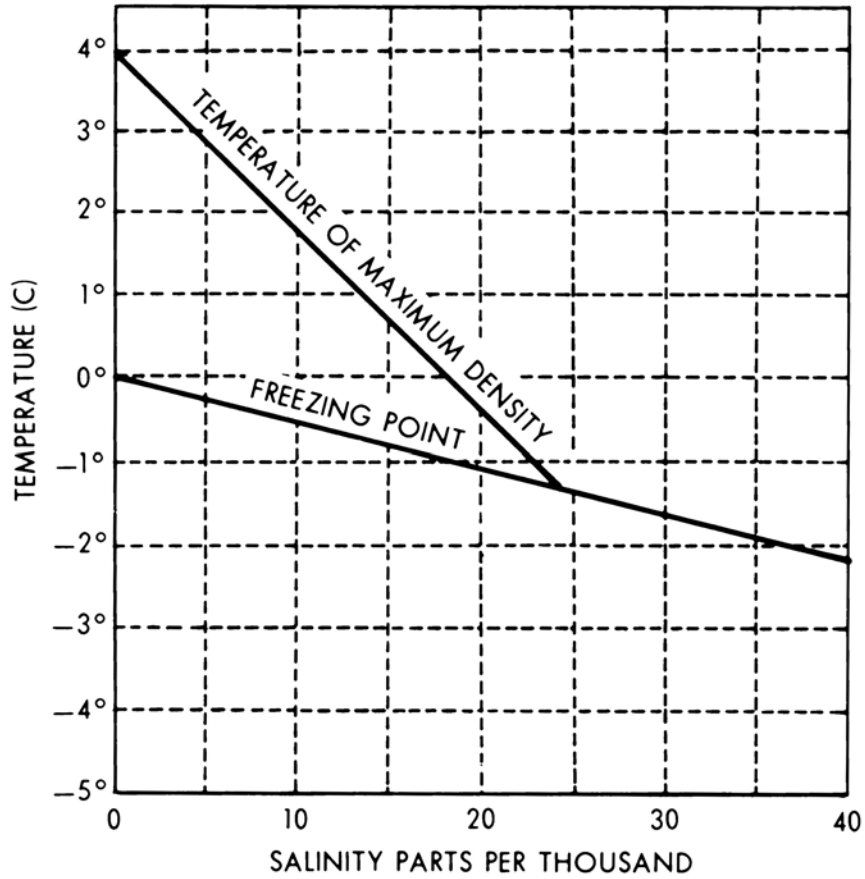
Figure 3201. Relationship between temperature of maximum density and freezing point for water of varying salinity.

Figure 3202a. A tabular iceberg. Photographer: Lieutenant Elizabeth Crapo, NOAA Corp.

melts uniformly because of lack of uniformity in the ice itself, differences in the temperature above and below the waterline, exposure of one side to the sun, strains, cracks, mechanical erosion, etc. The inclusion of rocks, silt, and other foreign matter further accentuates the differences. As a result, changes in equilibrium take place, which may

cause the berg to tilt or capsize. Parts of it may break off or **calve**, forming separate smaller bergs. A relatively large piece of floating ice, generally extending 1 to 5 meters above the sea surface and 5 to 15 meters length at the waterline, is called a **bergy bit**. A smaller piece of ice large enough to inflict serious damage to a vessel is called a **growler** because of the noise it sometimes makes as it bobs up and down in the sea. Growlers extend less than 1 meter above the sea surface and about a length or about 5 to 15 meters. Growlers can be greenish or have semi-transparent blue tones that blend into the seawater and make them particularly difficult to detect visually. Bergy bits and growlers are usually pieces calved from icebergs, but they may be the remains of a mostly melted iceberg. The population of Antarctic icebergs includes many icebergs in the larger size classes compared to the Arctic population. Tabular icebergs can have linear dimensions of many kilometers, and for the very largest, up to in excess of a hundred kilometers.

Figure 3202b. Pinnacled iceberg. Photographer: Lieutenant Philip Hall, NOAA Corp.

One danger from icebergs is their tendency to break or capsize. Soon after a berg is calved, while remaining in high latitude waters, 60-80% of its bulk is submerged. But as the berg drifts into warmer waters the underside begins to melt, and as the berg becomes unstable, it can sometimes roll over. Eroded icebergs that have not yet capsized have a jagged and possibly dirty appearance. A recently capsized berg will usually be smooth, clean, and curved in appearance. Previous waterlines at odd angles can sometimes be seen after progressive tilting or one or more capsizings.

The stability of a berg can sometimes be noted by its

reaction to ocean swells. The livelier the berg, the more unstable it is. It is extremely dangerous for a vessel to approach an iceberg closely, even one which appears stable, because in addition to the danger from capsizing, unseen cracks can cause icebergs to split in two or calve off large chunks. These sections can be many times the size of a vessel and displace huge volumes of water as they break away or turn over, inducing an immense swell.

Another danger is from underwater extensions, called **rams**, which are usually formed due to melting or erosion above the waterline at a faster rate than below. Rams may also extend from a vertical ice cliff, also known as an **ice front**, which forms the seaward face of a massive ice sheet or floating glacier; or from an **ice wall**, which is the ice cliff forming the seaward margin of a glacier which is aground. In addition to rams, large portions of an iceberg may extend well beyond the waterline at greater depths.

Strangely, icebergs may be helpful to the mariner in some ways. The melt water found on the surface of icebergs is a source of freshwater, and in the past some daring seamen have made their vessels fast to icebergs which, because they are affected more by currents than the wind, have proceeded to tow them out of the ice pack.

Icebergs can be used as a navigational aid in extreme latitudes where charted depths may be in doubt or non-existent. Since an iceberg (except a large tabular berg) must be at least as deep in the water as it is high to remain upright, a grounded berg can provide an estimate of the minimum water depth at its location. Water depth will be at least equal to the exposed height of the grounded iceberg. Grounded bergs remain stationary while current and wind move sea ice past them. Drifting ice may pile up against the up current side of a grounded berg.

3203. Iceberg Drift

Icebergs extend a considerable distance below the surface and have relatively small "sail areas" compared to their underwater body. Therefore, the near-surface current is primarily responsible for drift; however, observations have shown that wind can govern iceberg drift at a particular location or time.

The relative influence of currents and winds on the drift of an iceberg varies according to the direction and magnitude of the forces acting on its sail area and subsurface cross-sectional area. The resultant force therefore involves the proportions of the iceberg above and below the sea surface in relation to the velocity and depth of the current, and the velocity and duration of the wind. Studies tend to show that, generally, where strong currents prevail, the current is dominant. In regions of weak currents, however, winds that blow for a number of hours in a steady direction materially affect the drift of icebergs.

As icebergs deteriorate through melting, erosion, and calving, observations indicate the height to draft ratio may approach 1:1 during their final stage of decay, when they are

referred to as a dry dock, winged, horned, or pinnacle iceberg. The height to draft ratios found for icebergs in their

Iceberg type	Height to draft ratio
Blocky or tabular	1:5
Rounded or domed	1:4
Picturesque or Greenland (sloping)	1:3
Pinnacled or ridged	1:2
Horned, winged, dry dock, or spired (weathered)	1:1

Table 3203a. Height to draft ratios for various types of icebergs.

tends to have a greater effect on shallow than on deep-draft icebergs, the wind can be expected to exert increasing influence on iceberg drift as the iceberg deteriorates.

Simple equations that approximate iceberg drift have been formulated. However, there is uncertainty in the water and air drag coefficients associated with iceberg motion. Values for these parameters not only vary from iceberg to iceberg, but they probably change for the same iceberg over its period of deterioration. Further, the change in the iceberg shape that results from deterioration over time is not well known.

various stages are presented in Table 3203a. Since wind

Present investigations utilize an analytical approach, facilitated by computer modeling, in which the air and water drag coefficients are varied within reasonable limits. Combinations of these drag values are then used in several increasingly complex water models that try to duplicate observed iceberg trajectories. The results indicate that with a wind-generated current, Coriolis force, and a uniform wind, but without a gradient current, small and medium icebergs will drift with the percentages of the wind as given in Table 3203b. The drift will be to the right in the Northern Hemisphere and to the left in the Southern Hemisphere.

Wind Speed (knots)	Ice Speed/Wind Speed (percent)		Drift Angle (degrees)	
	Small Berg	Med. Berg	Small Berg	Med. Berg
10	3.6	2.2	12°	69°
20	3.8	3.1	14°	55°
30	4.1	3.4	17°	36°
40	4.4	3.5	19°	33°
50	4.5	3.6	23°	32°
60	4.9	3.7	24°	31°

Table 3203b. Drift of iceberg as percentage of wind speed.

The movement of icebergs can be counter-intuitive. In the Antarctic an example is provided by the massive iceberg B15A (length 150 km) when it was located adjacent to Ross Island in the Southern Ross Sea. Its presence had a huge impact on wild life in the area and on access to McMurdo Sound and the McMurdo station. The prevailing wind in its locality is typically offshore from the ice shelf. When the winds are light the berg can be observed to drift slowly away from the edge of the shelf. But when the wind strengthened, the berg suddenly moved quickly south (i.e. upwind) to collide with the sea floor. A possible explanation of such behavior can be found in likely changes in the sub-surface ocean currents. While the wind was strong, surface water was advected away from the shelf, to be replaced by water drawn in from the north at greater depths. The iceberg would then be driven south by the increased velocity of the sub-surface current which would have acted on its sides for a large fraction of its depth and on the basal surface of the berg.

It is important to note that iceberg drift is frequently influenced by the presence of eddies and meanders of mean ocean currents. These oceanic features make iceberg trajectory predictions challenging. For example, eddies and meanders are frequently found in the North Atlantic where the Labrador Current meets the North Atlantic Current near

the tail of the Grand Banks. In the Southern Hemisphere, predicting iceberg and sea ice drift is affected by the Southern Orkney islands. Careful attention to near real time observations from satellite imagery and drifting buoys can help improve the understanding of iceberg drift in these complex oceanographic environments.

3204. Icebergs in the North Atlantic

Sea level glaciers exist on a number of landmasses bordering the northern seas, including Alaska, Greenland, Svalbard (Spitsbergen), Zemlya Frantsa-Iosifa (Franz Josef Land), Novaya Zemlya, and Severnaya Zemlya (Nicholas II Land). Except in Greenland and Franz Josef Land, the rate of calving is relatively slow, and the few icebergs produced melt near their points of formation. Many of those produced along the western coast of Greenland, however, are eventually carried into the shipping lanes of the North Atlantic, where they constitute a major menace to ships. Those calved from Franz Josef Land glaciers drift southwest in the Barents Sea to the vicinity of Bear Island.

Generally the majority of icebergs produced along the east coast of Greenland remain near their source. However, a small number of bergy bits, growlers, and small icebergs are transported south from this region by the East Green-

land Current around Kap Farvel at the southern tip of Greenland and then northward by the West Greenland Current into Davis Strait to the vicinity of 67°N. Relatively few of these icebergs menace shipping, but some are carried to the south and southeast of Kap Farvel by a counterclockwise current gyre centered near 57°N and 43°W.

The main source of the icebergs encountered in the North Atlantic is the west coast of Greenland between 67°N and 76°N, where approximately 10,000–15,000 icebergs are calved each year. In this area there are about 100 low-lying coastal glaciers, 20 of them being the principal producers of icebergs. Of these 20 major glaciers, 2 located in Disko Bugt between 69°N and 70°N are estimated to contribute 28 percent of all icebergs appearing in Baffin Bay and the Labrador Sea. The West Greenland Current carries icebergs from this area northward and then westward until they encounter the south flowing Labrador Current. West Greenland icebergs generally spend their first winter locked in the Baffin Bay pack ice; however, a large number can also be found within the sea ice extending along the entire Labrador coast by late winter.

During the next spring and summer they are transported farther southward by the Labrador Current. The general drift patterns of icebergs that are prevalent in the eastern portion of the North American Arctic are shown in Figure 3204a. Observations over a 117-year period (1900-2016) show that an average of 486 icebergs per year reach latitudes south of 48 N; approximately 10 percent of this total will be carried south of the Grand Banks (43 N) before they melt. Icebergs may be encountered during any part of the year, but in the Grand Banks area they are most numerous during spring. The maximum monthly average of iceberg sightings below 48 N occurs during April, May and June, with May having the highest average of 151. The distribution of the Davis Strait-Labrador Sea pack ice appears to influence the melt rate of the icebergs as they drift south. Sea ice decreases iceberg erosion by damping waves and holds surface water temperatures below 0 C, so as the extent of the sea ice increases the icebergs will tend to survive longer. Stronger than average northerly or northeasterly winds during late winter and spring will accelerate sea ice drift to the south, which also may prolong an iceberg's survival. The large inter-annual variations in the number of icebergs calved from Greenland's glaciers, makes forecasting the length and severity of an iceberg season very challenging.

The variation from average conditions is considerable. More than 2,202 icebergs have been sighted south of latitude 48 N in a single year (1984), while in 1966 and 2006 not a single iceberg was encountered in this area. In 1940, 1958, and 2010, only one iceberg was observed south of 48 N. More recently, within the two-year period from 2013-2014, the number of icebergs south of latitude 48 N varied from 13 in 2013 to 1546 in 2014. The variability of the iceberg population in the transatlantic shipping lanes is related to environmental conditions. Average iceberg and pack ice limits in this area during May are shown in Figure 3204b. Beyond these average limits, icebergs have been reported in the vicinity of Bermuda, the Azores, and within 500 kilometers of Great Britain.

Pack ice may also be found in the North Atlantic, some having been brought south by the Labrador Current and some coming through Cabot Strait after having formed in the Gulf of St. Lawrence.

3205. Sea Ice

Sea ice forms by the freezing of seawater and accounts for 95 percent by area of all ice encountered. The first indication of the formation of new sea ice (up to 10 centimeters in thickness) is the development of small individual, needle-like crystals of ice, called **spicules**, which become suspended in the top few centimeters of seawater. These spicules, also known as **frazil ice**, give the sea surface an oily appearance. **Grease ice** is formed when the spicules coagulate to form a soupy layer on the surface, giving the sea a matte appearance. Calm wind conditions are favorable for initial sea ice growth but sea ice can form in most wind conditions given sufficiently cold water temperatures. The next stage in sea ice formation occurs when **shuga**, an accumulation of spongy white ice lumps a few centimeters across, develops from grease ice. Upon further freezing, and depending upon wind exposure, sea state, and salinity, shuga and grease ice develop into **nilas**, an elastic crust of high salinity, up to 10 centimeters in thickness, with a matte surface, or into **ice rind**, a brittle, shiny crust of low salinity with a thickness up to approximately 5 centimeters. A layer of 5 centimeters of freshwater ice is brittle but strong enough to support the weight of a heavy man. In contrast, the same thickness of newly formed sea ice will not support more than about 10 percent of this weight, although its strength varies with the temperatures at which it is formed; very cold ice supports a greater weight than warmer ice. As it ages, sea ice becomes harder and more brittle.

New ice may also develop from slush which is formed when snow falls into seawater which is near its freezing point, but colder than the melting point of snow. The snow does not melt, but floats on the surface, drifting with the wind into beds. If the temperature then drops below the freezing point of the seawater, the slush freezes quickly into a soft ice similar to shuga.

Sea ice is exposed to several forces, including currents, waves, tides, wind, and temperature variations. In its early stages, its plasticity permits it to conform readily to virtually any shape required by the forces acting upon it. As it becomes older, thicker, more brittle, and exposed to the influence of wind and wave action, new ice usually separates into circular pieces from 30 centimeters to 3 meters in diameter and up to approximately 10 centimeters in thickness with raised edges due to individual pieces striking against each other. These circular pieces of ice are called **pancake ice** (Figure 3205) and may break into smaller pieces with
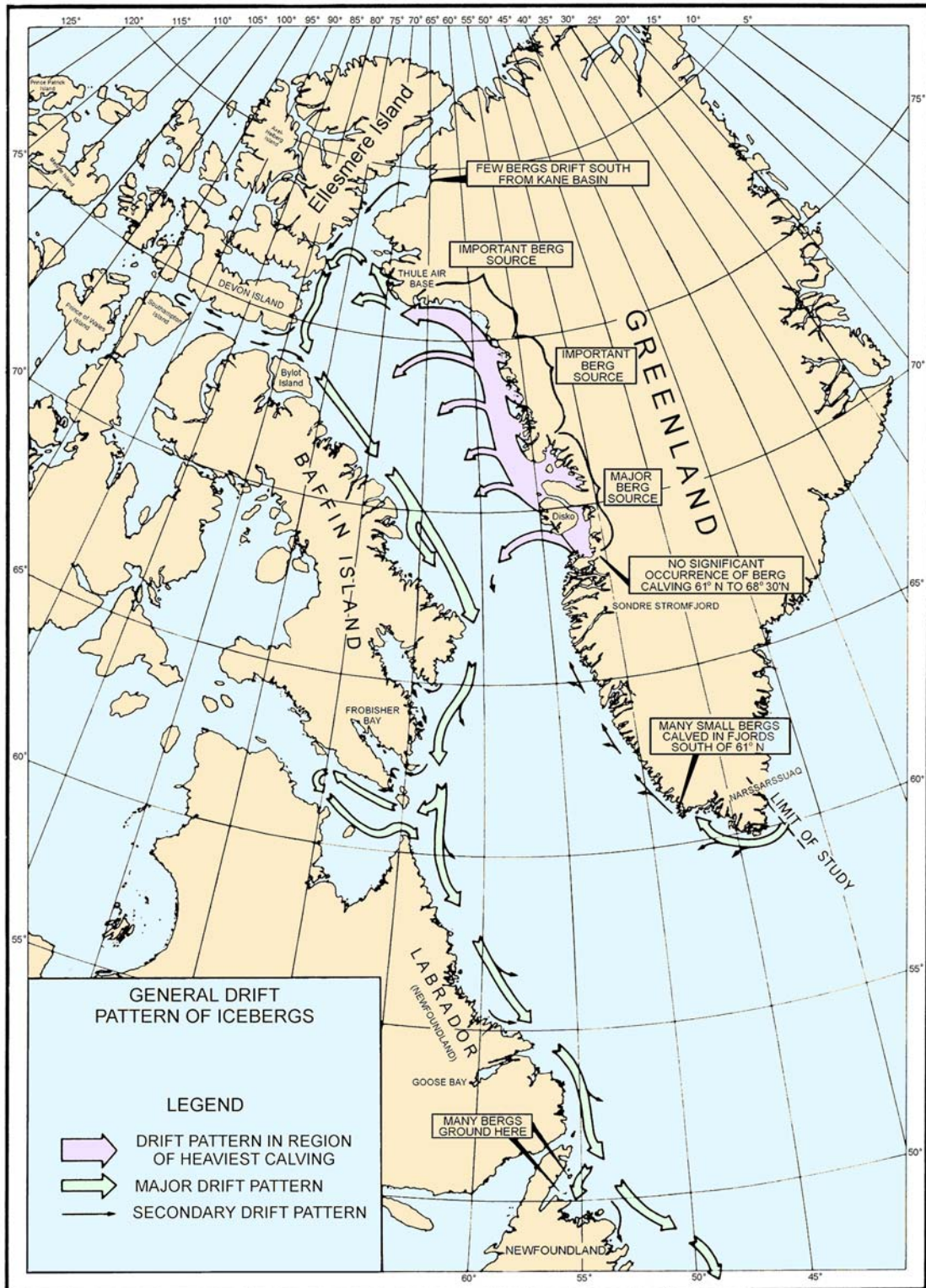
Figure 3204a. General drift patterns of icebergs in Baffin Bay, Davis Strait, and Labrador Sea.

strong wave motion. Any single piece of relatively flat sea ice less than 20 meters across is called an **ice cake**. With continued low temperatures, individual ice cakes and pan-

cake ice will, depending on wind or wave motion, either freeze together to form a continuous sheet or unite into pieces of ice 20 meters or more across. These larger pieces
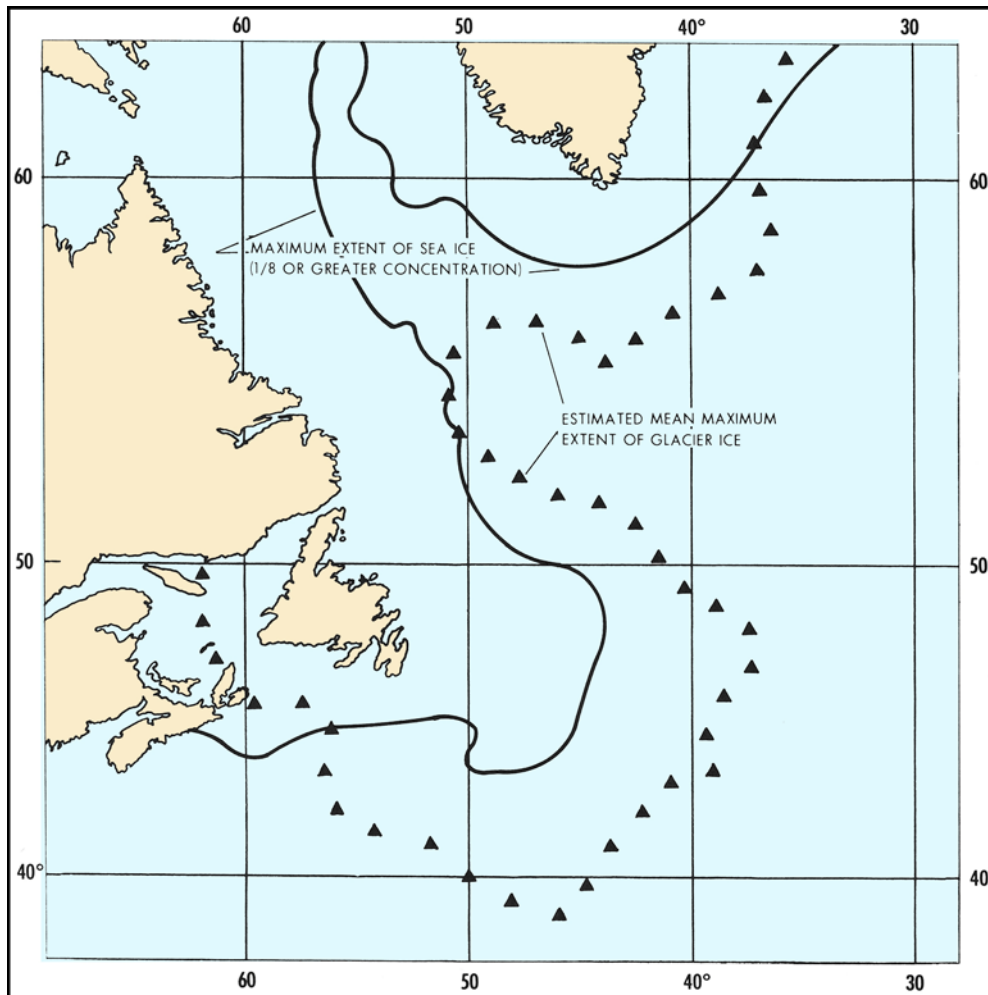
Figure 3204b. Average iceberg and pack ice limits during the month of May.

Figure 3205. Pancake ice. Image courtesy of John Farrell, U.S. Arctic Commission, Healy 1202.

are then called **ice floes**, which may further freeze together to form an ice covered area greater than 10 kilometers across known as an **ice field**. In wind sheltered areas thick-ening ice usually forms a continuous sheet before it can develop into the characteristic ice cake form. When sea ice reaches a thickness of between 10 to 30 centimeters it is referred to as **gray** and **gray-white ice**, or collectively as **young ice**, and is the transition stage between nilas and **first-year ice**. Sea ice may grow to a thickness of 10 to 13 centimeters within 48 hours, after which it acts as an insulator between the ocean and the atmosphere progressively slowing its further growth. Sea ice may grow to a thickness of between 2 to 3 meters in its first winter. Ice which has survived at least one summer's melt is classified as **old ice**. If it has survived only one summer's melt it may be referred to as **second-year ice**, but this term is seldom used today. Old ice which has survived at least two summers' melt is known as **multiyear ice** and is almost salt free. This term is increasingly used to refer to any ice more than one season old. Old ice can be recognized by a bluish tone to its surface color in contrast to the greenish tint of first-year ice; both first year and multiyear ice is often covered with snow. Another sign of old ice is a smoother, more rounded appearance due to melting/refreezing and weathering by

wind-driven snow and spray

Greater thicknesses in both first and multiyear ice are attained through the deformation of the ice resulting from the movement and interaction of individual floes. Deformation processes occur after the development of new and young ice and are the direct consequence of the effects of winds, tides, and currents. These processes transform a relatively flat sheet of ice into pressure ice which has a rough surface. **Bending**, which is the first stage in the formation of pressure ice, is the upward or downward motion of thin and very plastic ice. Rarely, **tenting** occurs when bending produces an upward displacement of ice forming a flat sided arch with a cavity beneath. More frequently, however, **rafting** takes place as one piece of ice overrides another. When pieces of first-year ice are piled haphazardly over one another forming a wall or line of broken ice, referred to as a **ridge**, the process is known as **ridging**. Ridges on sea ice are generally about 1 meter high and 5 meters deep, but under considerable pressure may attain heights of 20 meters and depths of 50 meters in extreme cases. Pressure ice with topography consisting of numerous mounds or hillocks is called hummocked ice, each mound being called a hummock. The corresponding underwater feature is known as a bummock. In the Antarctic **Seasonal Sea Ice Zone (SSIZ),** rafting makes an important contribution to the growth of the thickness of the ice. One immediate danger of rafting occurs when the thickness of the rafted ice is double that of its constituent pieces. This process shifts the distribution of ice thickness classes to thicker ice. Another major contributor to the growth in thickness of Antarctic ice is accumulation of snow on the upper surface. In addition the added weight of snow can depress the surface of the underlying ice to below the level of the sea water. Sea water can then infiltrate the snow to form snow-ice. Sea water will find a path into the snow from the outer edges of floes and from underneath the floe via cracks in the ice.

The motion of an individual floe is driven by its interaction with the ocean current and wind, as well as with adjacent floes or obstacles such as a coastline, or icebergs. Momentum is transferred from the wind and current to the floe through their interaction with the roughness of the upper and lower surfaces at various scales, and the "sail" effect of the upper ridges, sub-surface keels, and the outer edges of a floe. The motion of adjacent floes is seldom equal. Some ice floes are in rotary motion as they tend to trim themselves into the wind. Since ridges extend below as well as above the surface, the deeper ones are influenced more by currents at those depths. When a strong wind blows in the same direction for a considerable period so that there is a net convergence in the motion of a field of sea ice floes, each floe exerts pressure on the next one, and as the effect accumulates over time, the pressure becomes tremendous.

The alternate melting and growth of sea ice, combined with the continual motion of various floes that results in separation as well as consolidation, causes widely varying conditions within the ice cover itself. The mean areal density, or concentration, of pack ice in any given area is expressed in tenths. Concentrations range from:

Open water (total concentration of all ice is < one tenth)
Very open pack (1-3 tenths concentration)
Open pack (4-6 tenths concentration)
Close pack (7-8 tenths concentration)
Very close pack (9-10 to <10-10 concentration)
Compact or consolidated pack (100% coverage)

The extent to which an ice cover of varying concentrations can be penetrated by a vessel varies from place to place and with changing weather conditions. With a concentration of 1 to 3 tenths in a given area, an unreinforced vessel can generally navigate safely, but the danger of receiving heavy damage is always present. When the concentration increases to between 3 and 5 tenths, the area becomes only occasionally accessible to an unreinforced vessel, depending upon the wind and current. With concentrations of 5 to 7 tenths, the area becomes accessible only to ice strengthened vessels, which on occasion will require icebreaker assistance. Navigation in areas with concentrations of 7 tenths or more should only be attempted by icebreakers.

Sea ice which is formed in situ from seawater or by the freezing of pack ice, of any age, to the shore and which remains attached to the coast, to an ice wall, to an ice front, or between shoals is called **fast ice**. The width of this fast ice varies considerably and may extend for a few meters or several hundred kilometers in bays and other sheltered areas. Fast ice, often augmented by annual snow accumulations, may attain a thickness of over 2 meters above the sea surface.

An **ice shelf** forms where land ice flows across the coastline and becomes afloat. Ice shelves are comprised primarily of meteoric ice, ice formed from densification of precipitated snow. These shelves are typically formed by the coalescence of ice flow from multiple ice streams. Where a main ice stream / glacier contributes to the shelf, they may be called glacier tongues. Some sections of some Antarctic ice shelves may also have a considerable fraction of the thickness comprised of marine ice which has accreted to the base of the meteoric ice either by direct freezing of sea water or by accumulation of frazil ice formed in the water column beneath the ice shelf. There may also be a net input to the thickness by accumulation of snow on the upper surface. Massive ice shelves, where the ice thickness reaches several hundred meters, are found in both the Arctic and Antarctic.

Within the ice cover, openings may develop resulting from a number of deformation processes. Long, jagged cracks may appear first in the ice cover or through a single floe. When these cracks open and reach lengths of a few meters to many kilometers, they are referred to as **fractures**. If they widen further to permit passage of a ship,

they are called **leads**. In winter, a thin coating of new ice may cover the water within a lead, but in summer the water usually remains ice-free until a shift in the movement forces the two sides together again. A lead ending in a pressure ridge or other impenetrable barrier is a **blind lead**.

A lead between pack ice and shore is a **shore lead**, and one between pack and fast ice is a **flaw lead**. Navigation in these two types of leads is dangerous, because if the pack ice closes, the ship can be caught between the two, and driven aground or caught in the shear zone in between.

A **polynya** is an area within pack ice where there is: open water; or ice concentration lower than in the surrounding pack. There are two types of polynya: **sensible-heat polynya**, and **latent-heat polynya**. "Sensible-heat" polynyas occur where there is an upwelling of relatively warmer water that melts the sea ice or prevents it forming in that area. "Latent-heat" polynyas are caused by motion of the pack ice relative to something. Thus they may result from motion of the ice away from an obstacle, such as a coastline or grounded iceberg which acts as a barrier against incursion of pack ice into the area from elsewhere, or even by divergence of the pack ice. The name comes from the process whereby latent heat released by the freezing of water is lost to the atmosphere. **Recurring polynyas** are located where the required conditions regularly occur.

In the Arctic, sensible-heat polynyas are often the site of historical native settlements, where the open water of the polynya allows fishing and hunting at times before the regular seasonal ice breakup. Thule, Greenland is an example. The presence of a sensible heat polynya can also ameliorate the local climate.

In both polar regions, latent-heat polynyas occur at various locations around the coast, where prevailing off-shore wind sweeps the area clear of newly formed ice. They can be very large in area and typically produce very large amounts of sea ice. This happens through the loss of heat from the water surface to the atmosphere and rapid freezing of the surface water. The freezing of the water and export of the relatively fresh ice also leaves excess salt in the water column which increases the salinity and thus density of the water. This cold dense water sinks to the bottom and may eventually contribute to the generation of "bottom-water" and to the deep over-turning circulation of the world's oceans.

The majority of icebergs found in the Antarctic origi-nated from the massive ice shelves and glacier tongues that fringe the continental ice sheet. Most of the ice discharged from the Antarctic ice sheet passes through those regions of floating ice, which together comprise about 40% of the coastline. The icebergs have either calved directly from those ice margins or from the resultant icebergs. Icebergs formed in this manner are called **tabular icebergs,** having a box like shape with horizontal dimensions measured in ki-lometers. The thickness of icebergs can range up to several hundred meters. In the Antarctic, the thickness is typically 200-300 m, and in extreme cases can be 500 m or more,

with heights above the sea surface of 25-40 meters and ap-proaching 60 meters. See Figure 3202a. The largest Antarctic ice shelves are the Ross Ice Shelf at the southern boundary of the Ross Sea and the Filchner-Ronne Ice Shelf in the Weddell Sea.

The expression "tabular iceberg" is generally not ap-plied to icebergs which break off from Arctic ice shelves; similar formations there are called **ice islands.** These origi-nate when shelf ice, such as that found on the northern coast of Greenland and in the bays of Ellesmere Island, breaks up. As a rule, Arctic ice islands are not as large as the tabular icebergs found in the Antarctic. They attain a thickness of up to 55 meters and on the average extend 5 to 7 meters above the sea surface. Both tabular icebergs and ice islands possess a gently rolling surface. Because of their deep draft, they are influenced much more by current than wind.

3206. Thickness of Sea Ice

Sea ice has been observed to grow to a thickness of almost 3 meters during its first year. However, the thickness of first-year ice that has not undergone deformation does not generally exceed 2 meters. In coastal areas where the melting rate is less than the freezing rate, the thickness may increase during suc-ceeding winters, being augmented by compacted and frozen snow, until a maximum thickness of about 3.5 to 4.5 meters may eventually be reached. Old sea ice may also attain a thick-ness of over 4 meters in this manner, or when summer melt water from its surface or from snow cover runs off into the sea and refreezes under the ice where the seawater temperature is below the freezing point of the fresher melt water.

The growth of sea ice is dependent upon a number of meteorological and oceanographic parameters. Such pa-rameters include air temperature, initial ice thickness, snow depth, wind speed, seawater salinity and density, and the specific heats of sea ice and seawater. Investigations, how-ever, have shown that the most influential parameters affecting sea ice growth are air temperature, wind speed, snow depth and initial ice thickness. Many complex equa-tions have been formulated to predict ice growth using these four parameters. However, except for air temperature and wind speed, these parameters are not easily observed for remote polar locations.

Field measurements suggest that reasonable growth es-timates can be obtained from air temperature data alone. Various empirical formulae have been developed based on this premise. All appear to perform better under thin ice con-ditions when the temperature gradient through the ice is linear, generally true for ice less than 100 centimeters thick. Differences in predicted thicknesses between models gener-ally reflect differences in environmental parameters (snowfall, heat content of the underlying water column, etc.) at the measurement site. As a result, such equations must be considered partially site specific and their general use ap-proached with caution. For example, applying an equation derived from central Arctic data to coastal conditions or to
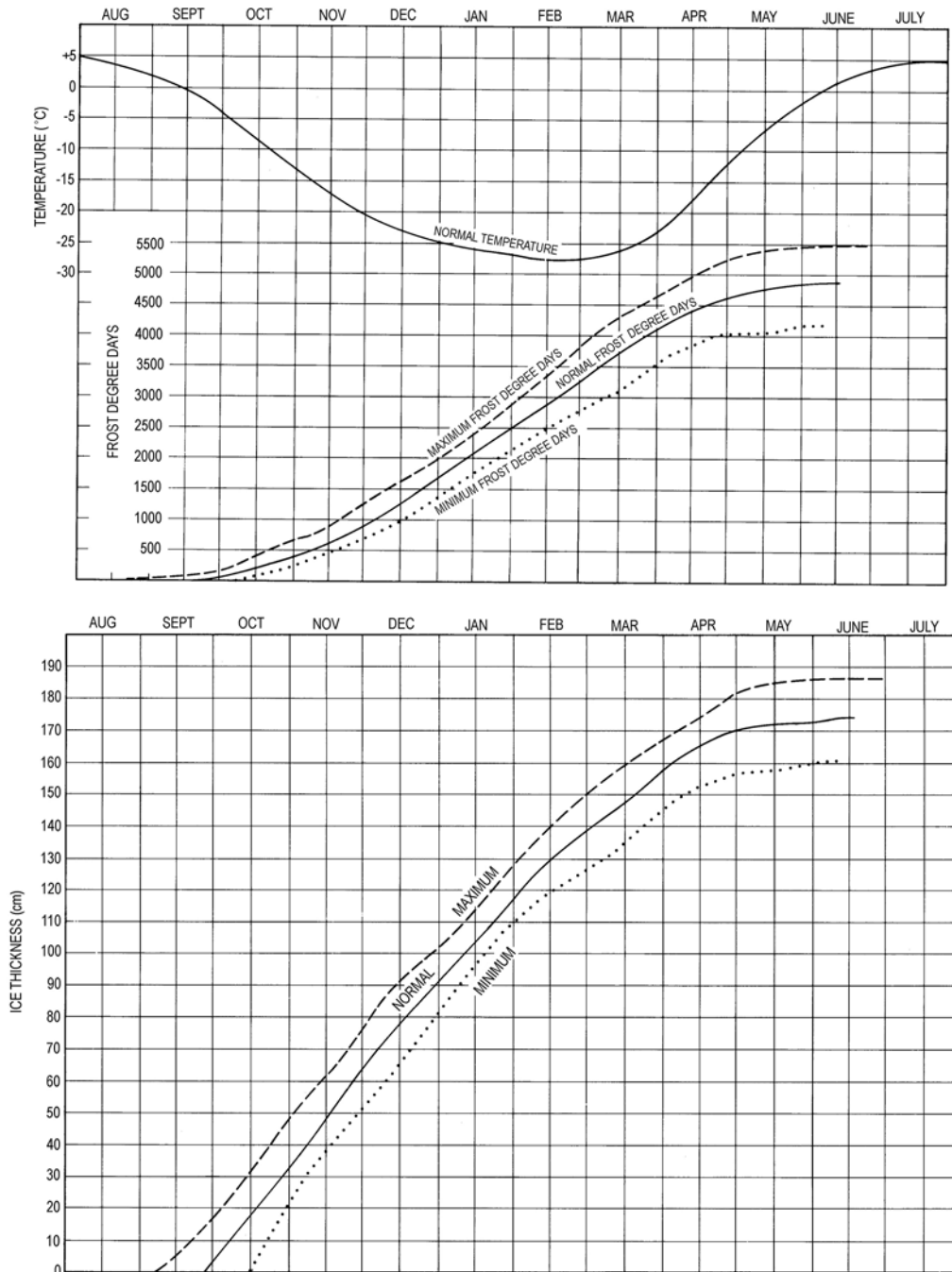
Figure 3206a. Relationship between accumulated frost degree days and theoretical ice thickness at Point Barrow, Alaska.

Antarctic conditions could lead to substantial errors. For this reason Zubov's formula is widely cited as it represents an average of many years of observations from the Russian Arctic:

$$h^2 + 50h = 8\phi$$

where h is the ice thickness in centimeters for a given day and ϕ is the cumulative number of frost degree days in degrees Celsius since the beginning of the freezing season.

A **frost degree day** (or **freezing degree day**) is defined as a day with a mean temperature of 1 below freezing. The base most commonly used is the freezing point of freshwater (0° C). If, for example, the mean temperature on a given day is 5 below freezing, then five frost degree days are noted for that day. These frost degree days are then added to those noted the next day to obtain an accumulated value, which is then added to those noted the following day. This process is repeated daily throughout the ice growing season.
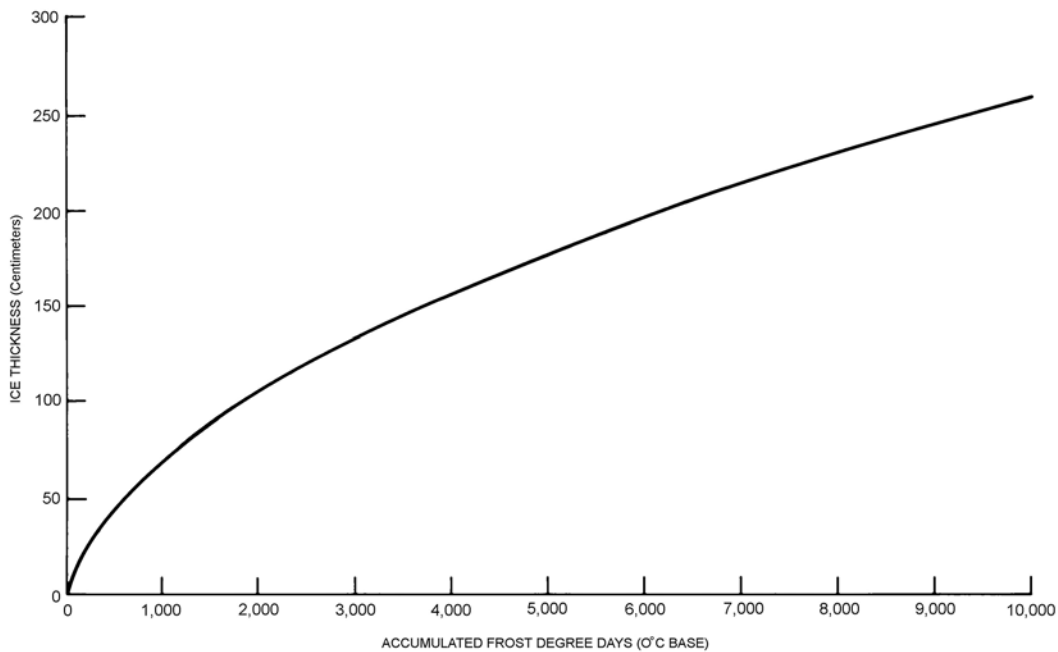
Figure 3206b. Relationship between accumulated frost degree days (°C) and ice thickness (cm).

Temperatures usually fluctuate above and below freezing for several days before remaining below freezing. Therefore, frost degree day accumulations are initiated on the first day of the period when temperatures remain below freezing. The relationship between frost degree day accumulations and theoretical ice growth curves at Point Barrow, Alaska is shown in Figure 3206a. Figure 3206b graphically depicts the relationship between accumulated frost degree days (°C) and ice thickness in centimeters.

During winter, the ice usually becomes covered with snow, which insulates the ice beneath and tends to slow down its rate of growth. This thickness of snow cover varies considerably from region to region as a result of differing climatic conditions. Its depth may also vary widely within very short distances in response to variable winds and ice topography. While this snow cover persists, up to 90% of the incoming radiation is reflected back to space. Eventually, however, the snow begins to melt, as the air temperature rises above 0 C in early summer and resulting freshwater forms puddles on the surface. These puddles absorb the incoming radiation and rapidly enlarge as they melt the surrounding snow or ice. Eventually the puddles penetrate to the bottom surface of the floes forming **thawholes**. This slow process is characteristic of ice in the Arctic Ocean and seas where movement is restricted by the coastline or islands. Where ice is free to drift into warmer waters (e.g., the Antarctic, East Greenland, and the Labrador Sea), decay is accelerated in response to wave erosion as well as warmer air and sea temperatures.

3207. Salinity of Sea Ice

When sea ice crystals first form, the salt collects into brine droplets. The brine is normally expelled back into the ocean water. Some of the droplets can be trapped in the pockets between ice crystals and, because it would take much colder temperatures to freeze, the liquid brine droplets remain trapped in the pockets between the ice crystals. As the freezing process continues, some brine drains out of the ice, decreasing the salinity of the sea ice. At lower temperatures, freezing takes place faster, trapping a greater amount of salt in the ice.

Depending upon the temperature, the trapped brine may either freeze or remain liquid, but because its density is greater than that of the pure ice, it tends to settle down through the pure ice, leaching into the sea. As it does so, the ice gradually freshens, becoming clearer, stronger, and more brittle. By the time sea ice survives multiple melt seasons, much of the brine has been expelled, and may be suitable to replenish the freshwater supply of a ship. Even though the brine has been expelled, other contaminants may be present that would prevent the meltwater from being consumable. Icebergs, having formed from precipitation, contain no salt, and uncontaminated melt water obtained from them is fresh.

The settling out of the brine gives sea ice a honeycomb structure which greatly hastens its disintegration when the temperature rises above freezing. In this state, when it is called **rotten ice**, much more surface is exposed to warm air and water, and the rate of melting is increased. In a day's time, a floe of apparently solid ice several inches thick may disappear completely.

3208. Density of Ice

The density of freshwater ice at its freezing point is 0.917gm/cm^3. Newly formed sea ice, due to its salt content, is more dense. The density decreases as the ice freshens. By the time it has shed most of its salt, sea ice is less dense than freshwater ice, because ice formed in the sea contains voids left by brine leaching. Ice having no salt but containing air to the extent of 8 percent by volume (an approximately maximum value for sea ice) has a density of 0.845 gm/cm^3.

The density of land ice varies over even wider limits. Most land ice is formed by compacting of snow. This results in the entrapping of relatively large quantities of air. **Névé**, a snow which has become coarse grained and compact through temperature change, forming the transition stage to glacier ice, may have an air content of as much as 50 percent by volume. By the time the ice of a glacier reaches the sea, its density approaches that of freshwater ice. A sample taken from an iceberg on the Grand Banks had a density of 0.899gm/cm^3.

When ice floats, part of it is above water and part is below the surface. The percentage of the mass below the surface can be found by dividing the average density of the ice by the density of the water in which it floats. Thus, if an iceberg of density 0.920 floats in water of density 1.028 (corresponding to a salinity of 35 parts per thousand and a temperature of -1 C), 89.5 percent of its mass will be below the surface.

3209. Drift of Sea Ice

In 1893, Fridtjof Nansen, a 32-year old Norwegian explorer aboard the vessel Fram noted that floes of sea ice did not drift directly downwind. He documented this phenomenon and shared the observations with his colleague Vagn Walfrid Ekman. In his 1902 doctoral thesis, Ekman mathematically described the wind forcing on surface waters. The result is described as **Ekman Transport**, and was further refined a various depths as the **Ekman Sprial**.

Although in some cases, surface currents have some effect upon the drift of pack ice, the principal factor is wind. As described above, the earth's rotation imparts an apparent force (Coriolis force) such that ice does not drift directly downwind, but varies from this direction, depending upon the force of the surface wind and the ice thickness. The force is a consequence of physics related to the rotation of the earth about its axis. The force is zero at the equator and increases with increasing latitude. In the Northern Hemisphere, this drift is to the right of the direction toward which the wind blows, and in the Southern Hemisphere it is to the left. The relationship between surface wind speed, ice thickness, and drift angle was derived theoretically for the drift of consolidated pack under equilibrium (a balance of forces acting on the ice) conditions, and shows that the drift angle increases with increasing ice thickness and decreasing surface wind speed. See Figure 3209. A slight increase also occurs with higher latitude.

In the Antarctic, these effects on the movement of pack ice about the continent contribute to the pattern of spatial distribution of the ice and the direction of the drift of the ice. Near to the coast the drift is from east to west, and further out the drift is from the west to the east. The effect of the Coriolis force is to keep the pack ice in the near coastal drift belt close to the coast. The passage of storms modifies this overall movement pattern. In very general terms, when a low pressure system passes north of an area, the easterly component of the wind strengthens which can lead to ice being moved south towards the coast compacting into a belt locked against the coast.

In the Arctic, a comparable situation with a storm passing to the south of an area, would result in pack ice at the outer margins of the Arctic Ocean moving away from the coast and compacting seawards.

Since the cross-isobar deflection of the surface wind over the oceans is approximately 20°, the deflection of the ice varies as much as 70° to the right of the isobars, with low pressure on the left and high pressure on the right in the Northern Hemisphere. The positions of the low and high pressure areas are, of course, reversed in the Southern Hemisphere.

The rate of drift depends upon the roughness of the surface and the concentration of the ice. Percentages vary from approximately 0.25 percent to almost 8 percent of the surface wind speed as measured approximately 6 meters above the ice surface. Low concentrations of heavily ridged or hummocked floes drift faster than high concentrations of lightly ridged or hummocked floes with the same wind speed. Sea ice of 8 to 9 tenths concentrations and six tenths hummocking or close multiyear ice will drift at approximately 2 percent of the surface wind speed. Additionally, the response factors of 1/10th and 5/10ths ice concentrations, respectively, are approximately three times and twice the magnitude of the response factor for 9 tenths ice concentrations with the same extent of surface roughness. Isolated ice floes have been observed to drift as fast as 10 percent to 12 percent of strong surface winds.

The rates at which sea ice drifts have been quantified through empirical observation. The drift angle, however, has been determined theoretically for 10 tenths ice concentration. This relationship presently is extended to the drift of all ice concentrations, due to the lack of basic knowledge of the dynamic forces that act upon, and result in redistribution of sea ice, in the polar regions.

3210. Extent of Ice in the Sea

When an area of sea ice, no matter what form it takes or how it is disposed, is described, it is referred to as **pack** ice. In both polar regions the pack ice is a very dynamic feature, with wide deviations in its extent dependent upon changing oceanographic and meteorological phenomena. In winter the Arctic pack extends over the entire Arctic Ocean, and for a varying distance outward from it; the lim-
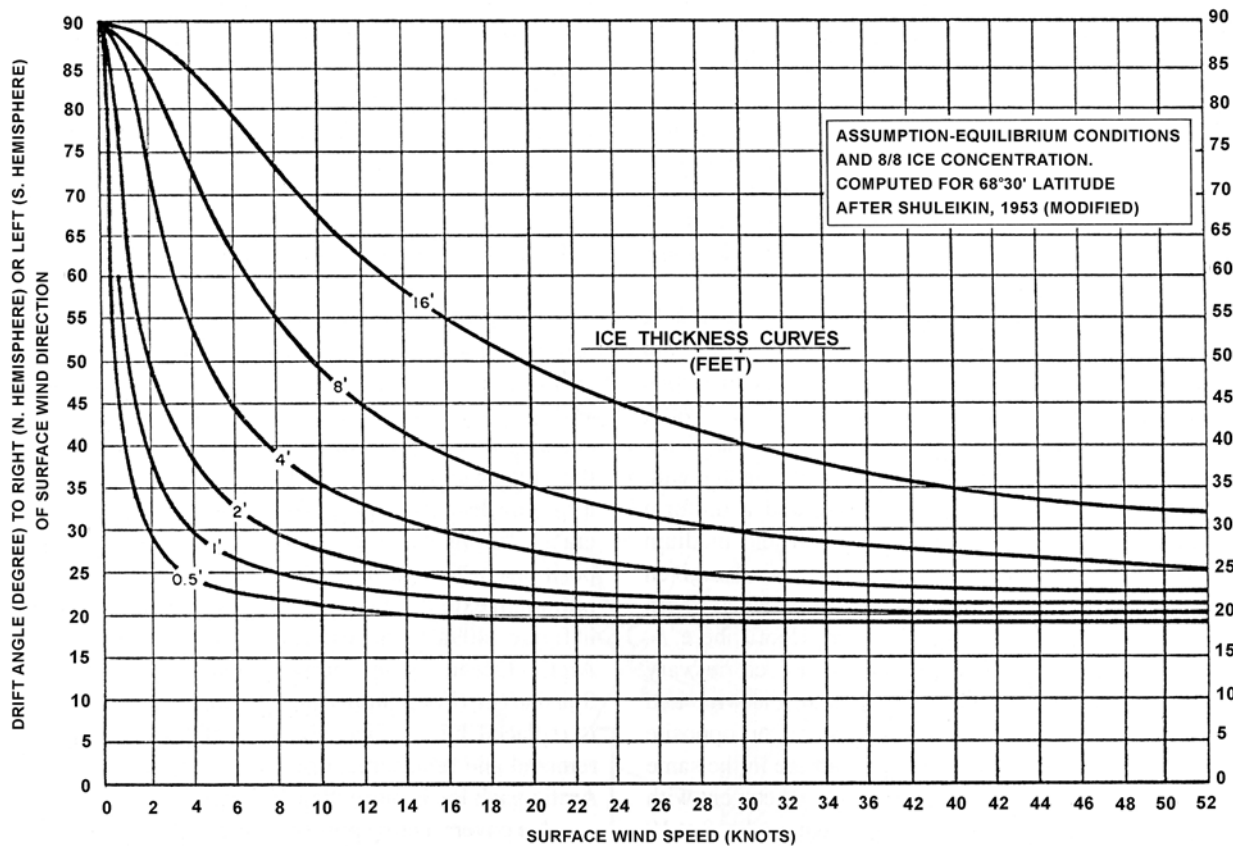
Figure 3209. Ice drift direction for varying wind speed and ice thickness.

its recede considerably during the warmer summer months. The average positions of the seasonal absolute and mean maximum and minimum extents of sea ice in the Arctic region are plotted in Figure 3210a. Each year a large portion of the ice from the Arctic Ocean moves outward between Greenland and Spitsbergen (Fram Strait) into the North Atlantic Ocean and is replaced by new ice. Because of this constant annual removal and replacement of sea ice, relatively little of the Arctic pack ice is more than 10 years old.

The average monthly Arctic sea ice extent for August has been decreasing dramatically over the last several decades as reflected in Figure 3210b. The phenomenon is discussed in more detail in Chapter 33.

Ice covers a large portion of the Antarctic waters and is probably the greatest single factor contributing to the isolation of the Antarctic Continent. The total area of sea ice varies between about 3 million square kilometers at its minimum and 19-20 million square kilometers at its maximum extent. The seasonal absolute and mean maximum and minimum positions of the Antarctic ice limit are shown in Figure 3210c. The overall minimum extent occurs in approximately February and maximum extent usually occurs in late September / early October. The extent progressively expands from its minimum with the onset of the colder months and waning sun-light. The distribution results from the increase in area where freezing is occurring together

with a net advection north of the sea ice. The northern limit in particular regions is influenced by wind and its variability. The extent can also be influenced by the total area and distribution of ice remaining from the previous winter. The pack ice completely surrounds the continent, forming an almost impassable barrier that extends northward on the average to about 54°S in the Atlantic and to about 62°S in the Pacific. As the ice retreats in the warmer months, opening up and disintegration of the pack ice allows navigation access to some coastal areas of the Antarctic. The date at which a particular area can be accessed depends on the local ice conditions. In some areas access to the fast ice edge can be attained early in the season, such as November, but access to the coast may not occur until January or February. In other areas, access to a region may not occur until later in the season. Access also depends very much on the capability of the vessel. In some seasons the coastal fast ice in front of some coastal stations has not broken out for one or more seasons preventing ship-access to those stations.

The **National Snow and Ice Data Center (NSIDC)**, located at the University of Colorado in Boulder, maintains data sets comprised of Arctic sea ice concentration climatology derived from the **U.S. National Ice Center's (USNIC)** weekly or biweekly operational ice-chart time series. The charts used in the climatology are from 1972 through 2007; and the monthly climatology products are
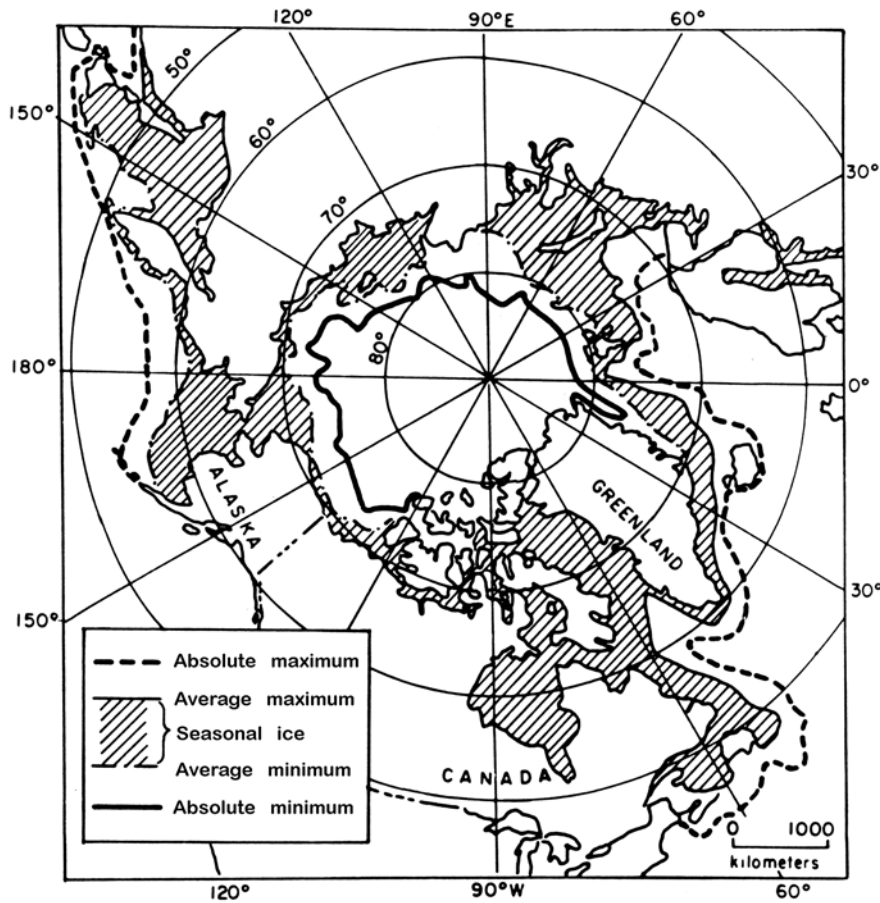
Figure 3210a. Average maximum and minimum extent of Arctic sea ice.

median, maximum, minimum, first quartile, and third quartile concentrations, as well as frequency of occurrence of ice at any concentration for the entire period of record as well as for 10-year and 5-year periods. These climatologies and the charts from which they are derived are provided in the 25-km Equal-Area Scalable Earth Grid (EASE-Grid) binary (.bin) format. The USNIC climatologies are also available in ArcGIS geodatabases (.mdb), and GIF format browse files (.gif) are also provided.

USNIC charts are produced through the analyses of available in situ, remote sensing, and model data sources. They are generated primarily for mission planning and safety of navigation. USNIC charts generally show more ice than do passive microwave derived sea ice concentrations, particularly in the summer when passive microwave algorithms tend to underestimate ice concentration. The record of sea ice concentration from the USNIC series is believed to be more accurate than that from passive microwave sensors, especially from the mid-1990s on, but it does not maintain the consistency of some passive microwave time series. NSIDC hosts numerous passive microwave and other sea ice data information useful to mariners planning voyages in or near areas affected by sea ice. These data sets are available through the link provided in Figure 3210d.

Daily sea ice edge analysis is available online via the link provided in Figure 3210e.

Additionally, the National Geospatial Agency's (NGA) **Arctic GEOINT Services portal** that includes nautical charts, sailing directions, shape files and infographics for the Arctic that allow the user to focus on specific data layers. The link is provided in Figure 3210f.

3211. Ice Detection

Safe navigation in ice infested waters depends on a number of factors, not the least of which is accurate knowledge of the location and amount of sea ice that lies between the mariner and his destination. Sophisticated electronic equipment, such as radar, sonar, and the visible, infrared, and microwave radiation sensors on board satellites, have added to our ability to detect and avoid ice.

Depending on the geographic location, as a ship proceeds into higher latitudes, the first ice encountered is likely to be in the form of icebergs, because such large pieces require a longer time to break up and melt. Icebergs can be avoided if detected early. The distance at which an iceberg can be seen visually depends upon meteorological visibility, height of the iceberg, source and condition of lighting, and
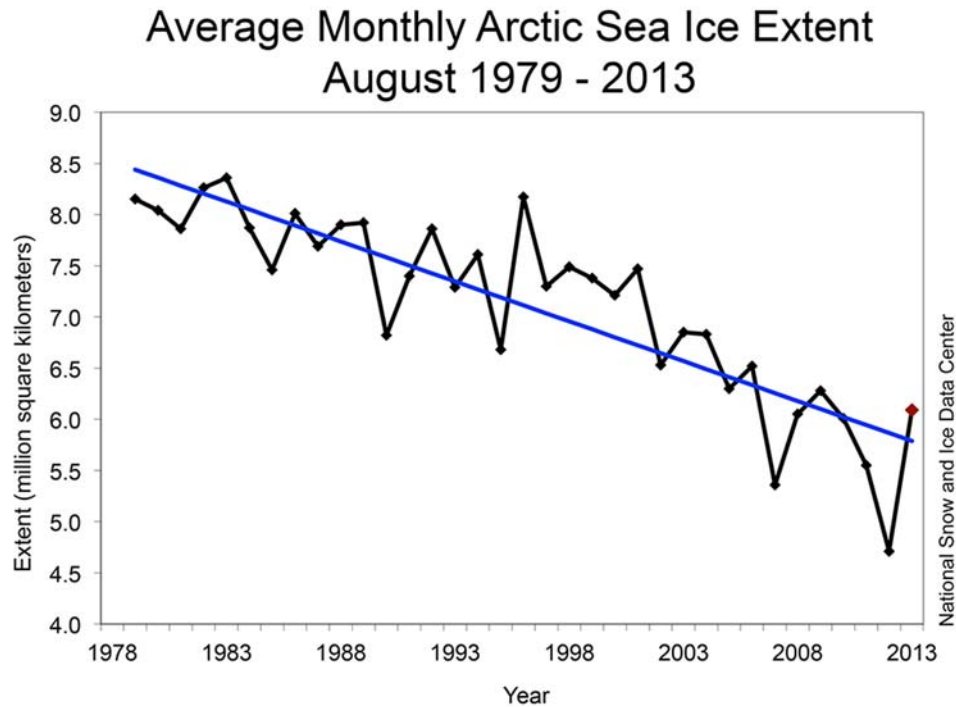
Average Monthly Arctic Sea Ice Extent
August 1979 - 2013

Figure 3210b. Average monthly Arctic sea ice extent August 1979 - 2013.

the observer. On a clear day with excellent visibility, a large iceberg might be sighted at a distance of 20 miles. With a low-lying haze around the horizon, this distance will be reduced. In light fog or drizzle this distance is further reduced, down to near zero in heavy fog.

In a dense fog an iceberg may not be perceptible until it is close aboard where it will appear in the form of a luminous, white object if the sun is shining; or as a dark, somber mass with a narrow streak of blackness at the waterline if the sun is not shining. If the layer of fog is not too thick, an iceberg may be sighted from aloft sooner than from a point lower on the vessel, but this does not justify omitting a bow lookout. The diffusion of light in a fog will produce a **blink**, or area of whiteness, above and at the sides of an iceberg which will appear to increase the apparent size of its mass.

On dark, clear nights icebergs may be seen at a distance of from 1 to 3 miles, appearing either as white or black objects with occasional light spots where waves break against it. Under such conditions of visibility, smaller growlers are more difficult to detect and pose a greater danger to vessels. The vessel's speed should be reduced and a sharp lookout maintained.

The moon may either help or hinder, depending upon its phase and position relative to ship and iceberg. A full moon in the direction of the iceberg interferes with its detection, while moonlight from behind the observer may produce a blink which renders the iceberg visible for a greater distance, as much as 3 or more miles. A clouded sky at night, through which the moonlight is intermittent, also renders ice

detection difficult. A night sky with heavy passing clouds may also dim or obscure any object which has been sighted, and fleecy cumulus and cumulonimbus clouds often may give the appearance of blink from icebergs.

If an iceberg is in the process of disintegration, its presence may be detected by a cracking sound as a piece breaks off, or by a thunderous roar as a large piece falls into the water. These sounds are unlikely to be heard due to shipboard noise. The appearance of small pieces of ice in the water often indicates the presence of an iceberg nearby. In calm weather these pieces may form a curved line with the parent iceberg on the concave side. Some of the pieces broken from an iceberg are themselves large enough to be a threat to shipping.

As the ship moves closer towards areas known to contain sea ice, one of the most reliable signs that pack ice is being approached is the absence of swell or wave motion in a fresh breeze or a sudden flattening of the sea, especially from leeward. The observation of icebergs is not a good indication that pack ice will be encountered soon, since icebergs may be found at great distances from pack ice. If the sea ice is approached from windward, it is usually compacted and the edge will be sharply defined. However, if it is approached from leeward, the ice is likely to be loose and somewhat scattered, often in long narrow arms.

Another reliable sign of the approach of pack ice not yet in sight is the appearance of a pattern, or **sky map**, on the horizon or on the underside of distant, extensive cloud areas, created by the varying amounts of light reflected
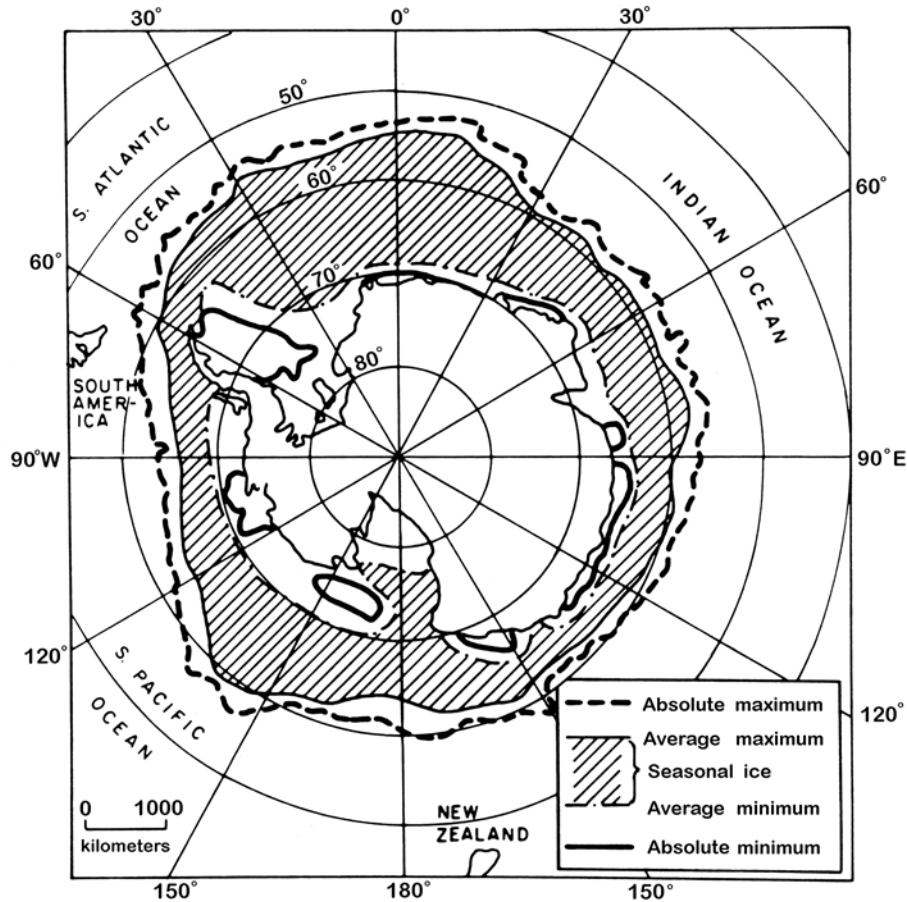
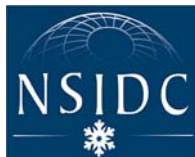*Figure 3210c. Average maximum and minimum extent of Antarctic sea ice.*

Figure 3210d. U.S. National Snow and Ice Data Center.
http://www.nsidc.org

Figure 3210e. U.S. National Ice Center.
http://www.natice.noaa.gov

from different materials on the sea or Earth's surface. A bright white glare, or **snow blink**, will be observed above a snow covered surface. When the reflection on the underside of clouds is caused by an accumulation of distant ice, the glare is a little less bright and is referred to as an **ice blink**. A relatively dark pattern is reflected on the underside of clouds when it is over land that is not snow covered. This is

known as a land sky. The darkest pattern will occur when the clouds are above an open water area, and is called a **water sky**. A mariner experienced in recognizing these sky maps will find them useful in avoiding ice or searching out openings which may permit the vessel to make progress through an ice field.

Figure 3210f. NGA Arctic Support.
http://nga.maps.arcgis.com/apps/MapSeries/index.html?a
ppid=cf2fba21df7540fb981f8836f2a97e25

Another indication of the presence of sea ice is the formation of thick bands of fog over the ice edge, as moisture condenses from warm air when passing over the colder ice. An abrupt change in air or sea temperature or seawater salinity is *not* a reliable sign of the approach of icebergs or pack ice.

The presence of certain species of animals and birds can also indicate that pack ice is in close proximity. The sighting of walruses, seals, or polar bears in the Arctic should warn the mariner that pack ice is close at hand. In the Antarctic, the usual precursors of sea ice are penguins, terns, fulmars, petrels, and skuas.

Due to the low profile and poor reflectivity, ice presents only about 1/60th of the radar return of a vessel of the same cross sectional area. It has a reflection coefficient of 0.33. Despite these limitations, a properly tuned radar can prove to be a valuable tool. Although many icebergs will be observed visually on clear days before there is a return on the radarscope, radar will detect the average iceberg at a range of about 8 to 10 miles.

The intensity of the return is a function of the nature of the ice's exposed surface (slope, surface roughness); however, it is unusual to find an iceberg which will not produce a detectable echo. Ice is not frequency-sensitive; both S- and X-band radars provide similar detectability. However, there is an advantage in using S-band radar in heavy precipitation since signal attenuation is less than X-band allowing better detection in these conditions.

While large icebergs will almost always be detected by radar in time to be avoided, a growler large enough to pose a serious danger to a vessel may be lost in the sea return and escape detection. Growlers cannot usually be detected at ranges greater than four miles, and are usually lost in seas greater than four feet. If an iceberg or growler is detected by radar, careful tracking is necessary to distinguish it from a rock, islet, or another ship.

Radar can be of great assistance to experienced radar observers. Smooth sea ice, like smooth water, returns little or no echo, but small floes of rough, hummocky sea ice capable of inflicting damage to a ship can be detected in a smooth sea at a range of about 2 to 4 miles. The return may be similar to sea return, but the same echoes appear at each sweep. A lead in smooth ice is clearly visible on a radarscope, even though a thin coating of new ice may have formed in the opening. A light covering of snow obliterating many of the features to the eye will have little effect on radar return.

Experience in interpretation is gained through comparing various radar returns with actual observations. The most effective use of radar in ice detection and navigation is constant surveillance by trained and experienced operators.

Experience in interpretation is gained through comparing various radar returns with actual observations. The most effective use of radar in ice detection and navigation is constant surveillance by trained and experienced operators.

In lieu of other means of detections, echoes from the ship's whistle or horn may sometimes indicate the presence of icebergs and indicate direction. If the time interval between the sound and its echo is measured, the distance in meters can be determined by multiplying the number of seconds by 168. However, echoes are unreliable because only ice with a large vertical area facing the ship returns enough echo to be heard. Once an echo is heard, a distinct pattern of horn blasts (not a Navigational Rules signal) should be made to confirm that the echo is not another vessel.

Ice in the polar regions is best detected and observed from high above, either from aircraft or by satellite. Fixed-winged aircraft have been utilized extensively for obtaining detailed aerial ice reconnaissance information since the early 1930's. Some ships, particularly icebreakers, proceeding into high latitudes carry helicopters, which are invaluable in locating leads and determining the relative navigability of different portions of the ice pack. Unmanned aerial systems are also used for ice reconnaissance. Ice reports from personnel at Arctic and Antarctic coastal shore stations can also prove valuable to the polar mariner.

The enormous ice reconnaissance capabilities of meteorological satellites were confirmed within hours of the launch by the **National Aeronautics and Space Administration (NASA)** of the first experimental meteorological satellite, TIROS I, on April 1, 1960. With the advent of the polar-orbiting meteorological satellites during the mid and late 1960's, the U.S. Navy initiated an operational satellite ice reconnaissance program which could observe ice and its movement in any region of the globe on a daily basis, depending upon solar illumination. Since then, improvements in satellite sensor technology have provided a capability to make detailed global observations of ice properties under all weather and lighting conditions. The current suite of airborne and satellite sensors employed by the USNIC and the International Ice Patrol include: aerial reconnaissance using a real aperture maritime search radar with visual observations, visual and infrared satellite sensors, and all-weather passive microwave. In addition, **synthetic aperture radar (SAR)** on various commercial and government satellite platforms provide all-weather, day/night ice information for both sea ice and iceberg detection. Commercial SAR systems in use today include the Canadian Radarsat-2, the
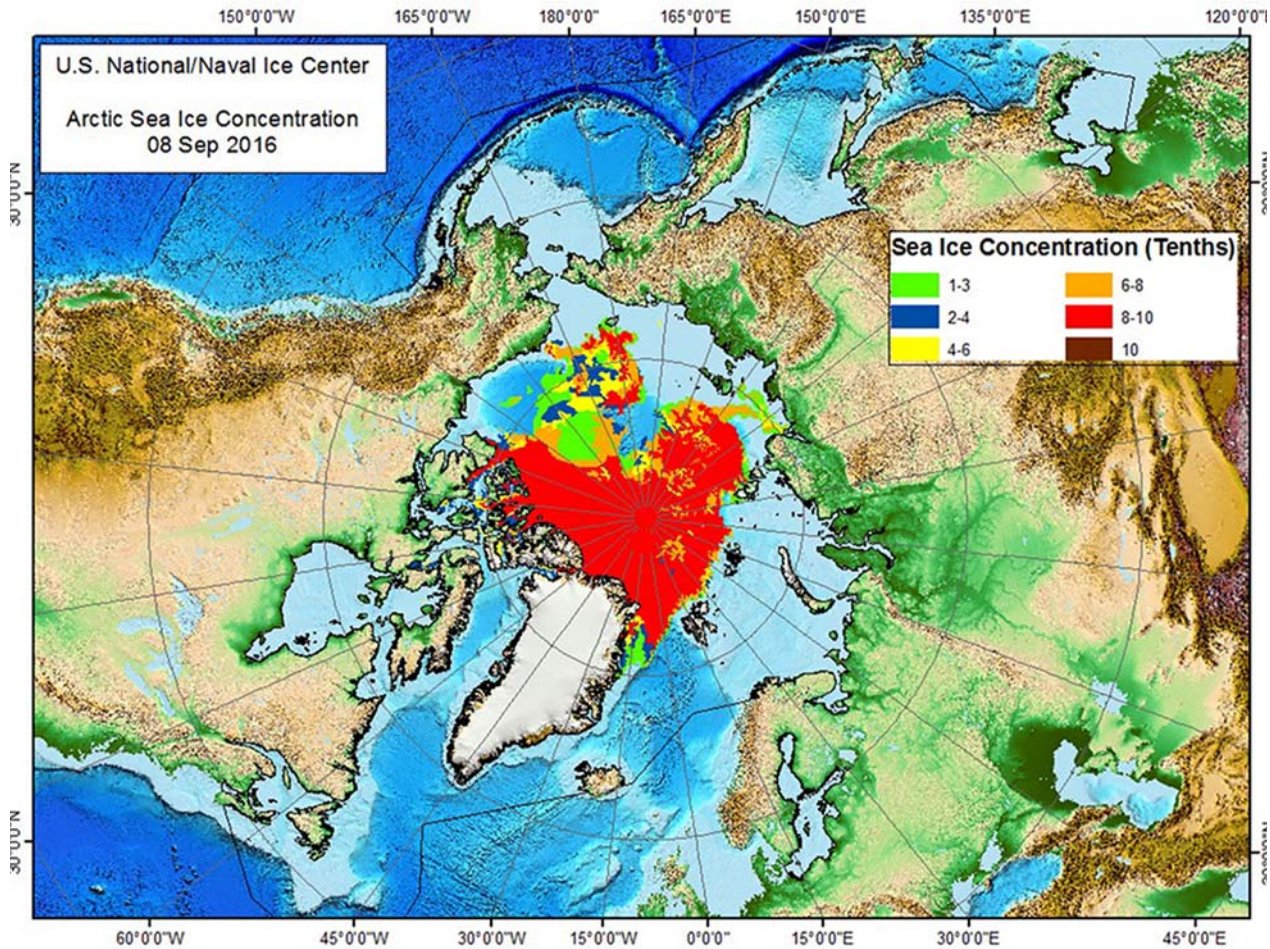
Figure 3211. Example of a USNIC Sea Ice Concentration Product derived from satellite imagery.

German TerraSAR-X, Italian COSMO-SkyMed, and the European Space Agency Sentinel-1 satellites. Operational ice services around the world have come to rely on SAR technology for ice monitoring and charting. A satellite-derived Sea Ice Concentration Product produced by the USNIC for 08 September 2016 is shown in Figure 3211.

3212. Operations in Ice

Operations in ice-prone regions necessarily require considerable advanced planning and many more precautionary measures than those taken prior to a typical open ocean voyage. The crew of a polar-bound vessel should be thoroughly indoctrinated in the fundamentals of polar operations, utilizing the best information sources available. The subjects covered should include training in ship handling in ice, polar navigation, effects of low temperatures on materials and equipment, damage control procedures, communications problems inherent in polar regions, polar meteorology, sea ice terminology, ice observing and reporting procedures (including classification and codes) and polar survival. Training materials

should consist of reports on previous Arctic and Antarctic voyages, sailing directions, ice atlases, training films on polar operations, and U.S. Navy service manuals detailing the recommended procedures to follow during high latitude missions.

The preparation of a vessel for polar operations is of extreme importance and the considerable experience gained from previous operations should be drawn upon to bring the ship to optimum operating condition. At the very least, operations conducted in ice-infested waters require that the vessel's hull and propulsion system undergo certain modifications.

The bow and waterline of the forward part of the vessel should be heavily reinforced. Similar reinforcement should also be considered for the propulsion spaces of the vessel. Cast iron propellers and those made of a bronze alloy do not possess the strength necessary to operate safely in ice. Therefore, it is strongly recommended that propellers made of these materials be replaced by steel. Other desirable features are the absence of vertical sides, deep placement of the propellers, a blunt bow, metal guards to protect propellers from ice damage, and lifeboats for 150 percent of

personnel aboard. The complete list of desirable features depends upon the area of operations, types of ice to be encountered, length of stay in the vicinity of ice, anticipated assistance by icebreakers, and possibly other factors. Strength requirements and the minimum thicknesses deemed necessary for the vessel's frames and additional plating to be used as reinforcement, as well as other procedures needed to outfit a vessel for ice operations, can be obtained from the American Bureau of Shipping. For a more definitive and complete guide to the ice strengthening of ships, the mariner may desire to consult the procedures outlined in Rules for Ice Strengthening of Ships, from the Board of Navigation, Helsinki, Finland. Further specifications have been published by the International Association of Classification Societies (IACS). These requirements are collectively known as **Polar Class**, and assess vessels from PC1 to PC5.

Equipment necessary to meet the basic needs of the crew and to insure the successful and safe completion of the polar voyage should not be overlooked. A minimum list of essential items should consist of polar clothing and footwear, 100% UV protective sunglasses, food, vitamins, medical supplies, fuel, storage batteries, antifreeze, explosives, detonators, fuses, meteorological supplies, and survival kits containing sleeping bags, trail rations, firearms, ammunition, fishing gear, emergency medical supplies, and a repair kit.

The vessel's safety depends largely upon the thoroughness of advance preparations, the alertness and skill of its crew, and their ability to make repairs if damage is incurred. Spare propellers, rudder assemblies, and patch materials, together with the equipment necessary to effect emergency repairs of structural damage should be carried. Examples of repair materials needed include quick setting cement, oakum, canvas, timbers, planks, pieces of steel of varying shapes, welding equipment, clamps, and an assortment of nuts, bolts, washers, screws, and nails.

Ice and snow accumulation on the vessel poses a definite capsize hazard. Mallets, baseball bats, ax handles, and scrapers to aid in the removal of heavy accumulations of ice, together with snow shovels and stiff brooms for snow removal should be provided. A live steam line may be useful in removing ice from superstructures.

Navigation in polar waters is at best difficult and, during poor conditions, impossible, except using satellite or inertial systems. Environmental conditions encountered in high latitudes such as fog, storms, compass anomalies, atmospheric effects, and, of course, ice, hinder polar operations. Also, deficiencies in the reliability and detail of hydrographic and geographical information presented on polar navigation charts, coupled with a distinct lack of reliable bathymetry, current, and tidal data, add to the problems of polar navigation. Much work is being carried out in polar regions to improve the geodetic control, triangulation, and quality of hydrographic and topographic information necessary for accurate polar charts. However, until this massive task is completed, the only resource open

to the polar navigator, especially during periods of poor environmental conditions, is to rely upon the basic principles of navigation and adapt them to unconventional methods when abnormal situations arise.

Upon the approach to pack ice, a careful decision is needed to determine the best action. If it is possible to go around the ice, rather than through it, do so. Unless the pack is quite loose, this action usually gains rather than loses time. When skirting an ice field or an iceberg, do so to windward, if a choice is available, to avoid projecting tongues of ice or individual pieces that have been blown away from the main body of ice.

When it becomes necessary to enter pack ice, a thorough examination of the distribution and extent of the ice conditions should be made beforehand from the highest possible location. Aircraft (particularly helicopters) and direct satellite readouts are of great value in determining the nature of the ice to be encountered. The most important features to be noted include the location of open water, such as leads and polynyas, which may be manifested by water sky; icebergs; and the presence or absence of both ice under pressure and rotten ice. Some protection may be offered the propeller and rudder assemblies by trimming the vessel down by the stern slightly (not more than 2–3 feet) prior to entering the ice; however, this precaution usually impairs the maneuvering characteristics of most vessels not specifically built for ice breaking.

Selecting the point of entry into the pack should be done with great care; and if the ice boundary consists of closely packed ice or ice under pressure, it is advisable to skirt the edge until a more desirable point of entry is located. Seek areas with low ice concentrations, areas of rotten ice or those containing navigable leads, and if possible enter from leeward on a course perpendicular to the ice edge. It is also advisable to take into consideration the direction and force of the wind, and the set and drift of the prevailing currents when determining the point of entry and the course followed thereafter. Due to wind induced wave action, ice floes close to the periphery of the ice pack will take on a bouncing motion which can be quite hazardous to the hull of thin-skinned vessels. In addition, note that pack ice will drift slightly to the right of the true wind in the Northern Hemisphere and to the left in the Southern Hemisphere, and that leads opened by the force of the wind will appear perpendicular to the wind direction. If a suitable entry point cannot be located due to less than favorable conditions, patience may be called for. Unfavorable conditions generally improve over a short period of time by a change in the wind, tide, or sea state.

Once in the pack, always try to work with the ice, not against it, and keep moving, but do not rush. Respect the ice but do not fear it. Proceed at slow speed at first, staying in open water or in areas of weak ice if possible. The vessel's speed may be safely increased after it has been ascertained how well it handles under the varying ice conditions encountered. It is better to make good progress in the

general direction desired than to fight large thick floes in the exact direction to be made good. However, avoid the temptation to proceed far to one side of the intended track; it is almost always better to back out and seek a more penetrable area. During those situations when it becomes necessary to back, always do so with extreme caution and *with the rudder amidships*. If the ship is stopped by ice, the first command should be "rudder amidships," given while the screw is still turning. This will help protect the propeller when backing and prevent ice jamming between rudder and hull. If the rudder becomes ice-jammed, man after steering, establish communications, and *do not* give any helm commands until the rudder is clear. A quick full-ahead burst may clear it. If it does not, try going to "hard rudder" *in the same direction slowly* while turning full or flank speed ahead.

Ice conditions may change rapidly while a vessel is working in pack ice, necessitating quick maneuvering. Conventional vessels, even if ice strengthened, are not built for icebreaking. The vessel should be conned to first attempt to place it in leads or polynyas, giving due consideration to wind conditions. The age, thickness, and size of ice which can be navigated depends upon the type, size, hull strength, and horsepower of the vessel employed. If contact with an ice floe is unavoidable, never strike it a glancing blow. This maneuver engages the ice with weaker parts of the hull, and may cause the ship to veer off in a direction which will swing the stern into the ice. If possible, seek weak spots in the floe and engage it head-on at slow speed. Unless the ice is rotten or very young, do not attempt to break through the floe, but rather make an attempt to swing it aside as speed is slowly increased. Keep clear of corners and projecting points of ice, but do so without making sharp turns which may throw the stern against the ice, resulting in a damaged propeller, propeller shaft, or rudder. The use of full rudder in non-emergency situations is not recommended because it may swing either the stern or mid-section of the vessel into the ice. This does not preclude use of alternating full rudder (**sallying** the rudder) aboard icebreakers as a technique for penetrating heavy ice.

Offshore winds may open relatively ice free navigable coastal leads, but such leads should not be entered without benefit of icebreaker escort. If it becomes necessary to enter coastal leads, narrow straits, or bays, an alert watch should be maintained since a shift in the wind may force drifting ice down upon the vessel. An increase in wind on the windward side of a prominent point, grounded iceberg, or land ice tongue extending into the sea will also endanger a vessel. It is wiser to seek out leads toward the windward side of the main body of the ice pack. In the event that the vessel is under imminent danger of being trapped close to shore by pack ice, immediately attempt to orient the vessel's bow seaward. This will help to take advantage of the little maneuvering room available in the open water areas found between ice floes. Work carefully through these areas, easing the ice floes aside while maintaining a close watch on the general movement of the ice pack.

If the vessel is completely halted by pack ice, it is best to keep the rudder amidships, and the propellers turning at slow speed. The wash of the propellers will help to clear ice away from the stern, making it possible to back down safely. When the vessel is stuck fast, an attempt first should be made to free the vessel by going full speed astern. If this maneuver proves ineffective, it may be possible to get the vessel's stern to move slightly, thereby causing the bow to shift, by quickly shifting the rudder from one side to the other while going full speed ahead. Another attempt at going astern might then free the vessel. The vessel may also be freed by either transferring water from ballast tanks, causing the vessel to list, or by alternately flooding and emptying the fore and aft tanks. A heavy weight swung out on the cargo boom might give the vessel enough list to break free. If all these methods fail, the utilization of deadmen (2- to 4-meter lengths of timber buried in holes out in the ice and to which a vessel is moored) and ice anchors (a stockless, single fluked hook embedded in the ice) may be helpful. With a deadman or ice anchors attached to the ice astern, the vessel may be warped off the ice by winching while the engines are going full astern. If all the foregoing methods fail, explosives placed in holes cut nearly to the bottom of the ice approximately 10 to 12 meters off the beam of the vessel and detonated while the engines are working full astern might succeed in freeing the vessel. A vessel may also be sawed out of the ice if the air temperature is above the freezing point of seawater.

When a vessel becomes so closely surrounded by ice that all steering control is lost and it is unable to move, it is **beset**. It may then be carried by the drifting pack into shallow water or areas containing thicker ice or icebergs with their accompanying dangerous underwater projections. If ice forcibly presses itself against the hull, the vessel is said to be **nipped**, whether or not damage is sustained. When this occurs, the gradually increasing pressure may be capable of holing the vessel's bottom or crushing the sides. When a vessel is beset or nipped, freedom may be achieved through the careful maneuvering procedures, the physical efforts of the crew, or by the use of explosives similar to those previously detailed. Under severe conditions the mariner's best ally may be patience since there will be many times when nothing can be done to improve the vessel's plight until there is a change in meteorological conditions. It may be well to preserve fuel and perform any needed repairs to the vessel and its engines. Damage to the vessel while it is beset is usually attributable to collisions or pressure exerted between the vessel's hull, propellers, or rudder assembly, and the sharp corners of ice floes. These collisions can be minimized greatly by attempting to align the vessel in such a manner as to insure that the pressure from the surrounding pack ice is distributed as evenly as possible over the hull. This is best accomplished when medium or large ice floes encircle the vessel.

In the vicinity of icebergs, either in or outside of the

pack ice, a sharp lookout should be kept and all icebergs given a wide berth. The commanding officers and masters of all vessels, irrespective of their size, should treat all icebergs with great respect. The best locations for lookouts are generally in a crow's nest, rigged in the foremast or housed in a shelter built specifically for a bow lookout in the eyes of a vessel. Telephone communications between these sites and the navigation bridge on larger vessels will prove invaluable. It is dangerous to approach close to an iceberg of any size because of the possibility of encountering underwater extensions, and because icebergs that are disintegrating may suddenly capsize or readjust their masses to new positions of equilibrium. In periods of low visibility the utmost caution is needed at all times. Vessel speed should be reduced and the watch prepared for quick maneuvering. Radar becomes an effective but not infallible tool, and does not negate the need for trained lookouts.

Since icebergs may have from eight to nine-tenths of their masses below the water surface, their drift is generally influenced more by currents than winds, particularly under light wind conditions. The drift of pack ice, on the other hand, is usually dependent upon the wind. Under these conditions, icebergs within the pack may be found moving at a different rate and in a different direction from that of the pack ice. In regions of strong currents, icebergs should always be given a wide berth because they may travel upwind under the influence of contrary currents, breaking heavy pack in their paths and endangering vessels unable to work clear. In these situations, open water will generally be found to leeward of the iceberg, with piled up pack ice to windward. Where currents are weak and a strong wind predominates, similar conditions will be observed as the wind driven ice pack overtakes an iceberg and piles up to windward with an open water area lying to leeward.

Under ice, submarine operations require knowledge of prevailing and expected sea ice conditions to ensure maximum operational efficiency and safety. The most important ice features are the frequency and extent of downward projections (bummocks and ice keels) from the underside of the ice canopy (pack ice and enclosed water areas from the point of view of the submariner), the distribution of thin ice areas through which submarines can attempt to surface, and the probable location of the outer pack edge where submarines can remain surfaced during emergencies to rendezvous with surface ship or helicopter units.

Bummocks are the subsurface counterpart of hummocks, and **ice keels** are similarly related to ridges. When the physical nature of these ice features is considered, it is apparent that ice keels may have considerable horizontal extent, whereas individual bummocks can be expected to have little horizontal extent. In shallow water lanes to the Arctic Basin, such as the Bering Strait and the adjoining portions of the Bering Sea and Chukchi Sea, deep bummocks and ice keels may leave little vertical room for submarine passage. Widely

separated bummocks may be circumnavigated but make for a hazardous passage. Extensive ice areas, with numerous bummocks or ice keels which cross the lane may effectively block both surface and submarine passage into the Arctic Basin.

Bummocks and ice keels may extend downward approximately five times their vertical extent above the ice surface. Therefore, observed ridges of approximately 10 meters may extend as much as 50 meters below sea level. Because of the direct relation of the frequency and vertical extent between these surface features and their subsurface counterparts, aircraft ice reconnaissance should be conducted over a planned submarine cruise track before under ice operations commence.

Skylights are thin places (usually less than 1 meter thick) in the ice canopy, and appear from below as relatively light translucent patches in dark surroundings. The undersurface of a skylight is usually flat; not having been subjected to great pressure. Skylights are called large if big enough for a submarine to attempt to surface through them; that is, have a linear extent of at least 120 meters. Skylights smaller than 120 meters are referred to as small. An ice canopy along a submarine's track that contains a number of large skylights or other features such as leads and polynyas, which permit a submarine to surface more frequently than 10 times in 30 miles, is called **friendly ice**. An ice canopy containing no large skylights or other features which permit a submarine to surface is called **hostile ice**.

3213. Great Lakes Ice

Large vessels have been navigating the Great Lakes since the early 1760's. This large expanse of navigable water has since become one of the world's busiest waterways. Due to the northern geographical location of the Great Lakes Basin and its susceptibility to Arctic outbreaks of polar air during winter, the formation of ice plays a major disruptive role in the region's economically vital marine industry. Because of the relatively large size of the five Great Lakes, the ice cover which forms on them is affected by the wind and currents to a greater degree than on smaller lakes. The Great Lakes' northern location results in a long ice growth season, which in combination with the effect of wind and current, imparts to their ice covers some of the characteristics and behavior of an Arctic ice pack.

Since the five Great Lakes extend over a distance of approximately 800 kilometers in a north-south direction, each lake is influenced differently by various meteorological phenomena. These, in combination with the fact that each lake also possesses different geographical characteristics, affect the extent and distribution of their ice covers.

The largest, deepest, and most northern of the Great Lakes is **Lake Superior**. Initial ice formation normally begins at the end of November or early December in harbors and bays along the north shore, in the western portion of the
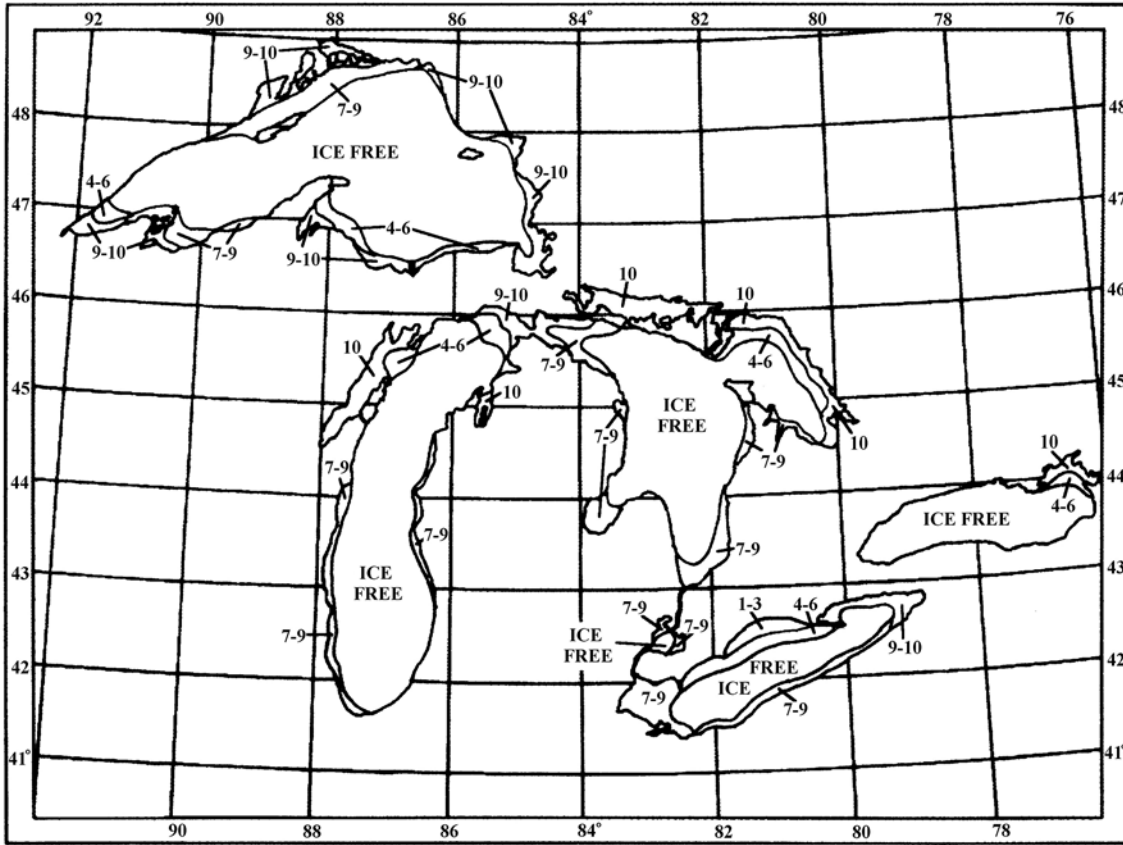
Figure 3213a. Great Lakes ice cover during a mild winter.

Figure 3213b. USCG cutters KATMAI BAY and MORRO BAY hold position as ice breaker MACKINAW works to find open water leads out of Whitefish Bay, Lake Superior, March 21-23, 2014. Credit: USCG Soo.

lake and over the shallow waters of Whitefish Bay (see Figure 3213b). As the season progresses, ice forms and thickens in all coastal areas of the lake perimeter prior to extending offshore. This formation pattern can be attributed to a maximum depth in excess of 400 meters and an associated large heat storage capacity that hinders early ice formation in the center of the lake. During a normal winter, ice not under pressure ranges in thickness from 45–85 centimeters. During severe winters, maximum thicknesses are reported to approach 100 centimeters. Winds and currents acting upon the ice have been known to cause ridging with heights approaching 10 meters. During normal years, maximum ice cover extends over approximately 75% of the lake surface with heaviest ice conditions occurring by early March. This value increases to 95% coverage during severe winters and decreases to less than 20% coverage during a mild winter. Winter navigation is most difficult in the southeastern portion of the lake due to heavy ridging and compression of the ice under the influence of prevailing westerly winds. Break-up normally starts near the end of March with ice in a state of advanced deterioration by the middle of April. Under normal conditions, most of the lake is ice-free by the first week of May.

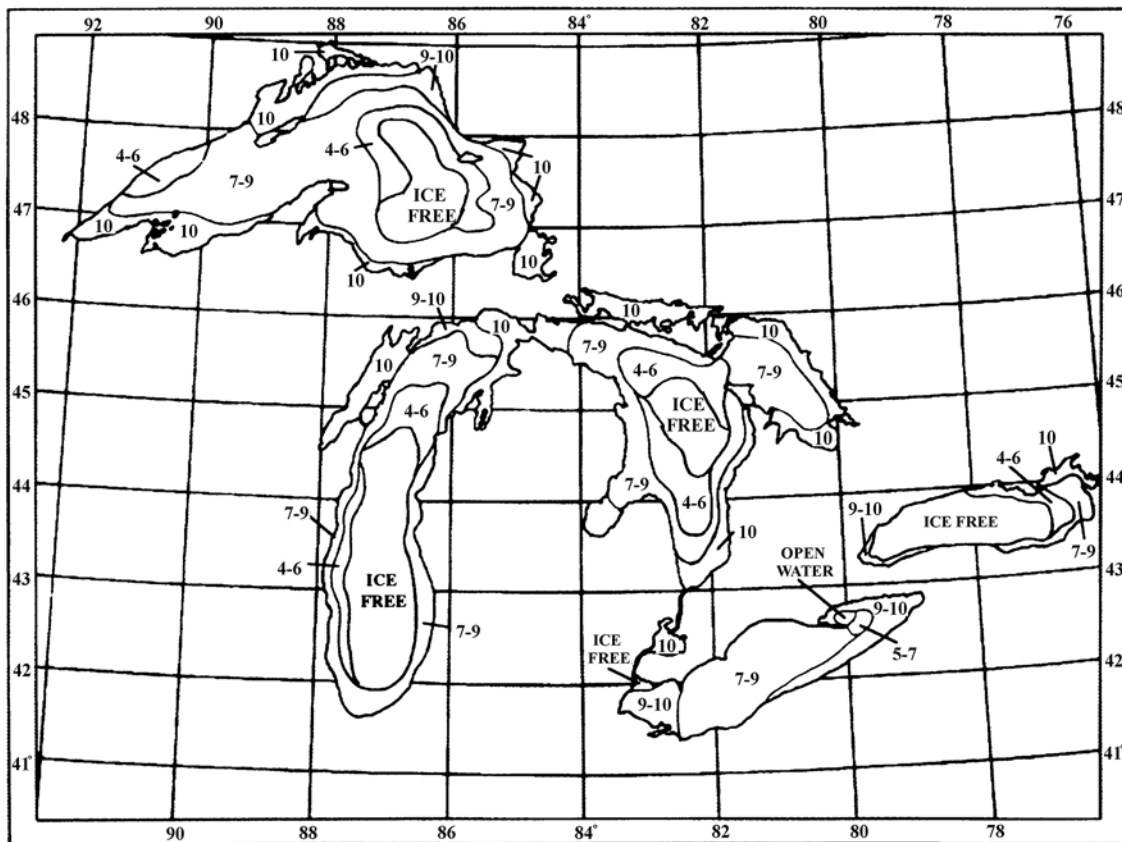**Lake Michigan** extends in a north-south direction over

Figure 3213c. Great Lakes ice cover during a normal winter.

490 kilometers and possesses the third largest surface area of the five Great Lakes. Depths range from 280 meters in the center of the lake to 40 meters in the shipping lanes through the Straits of Mackinac, and less in passages between island groups. During average years, ice formation first occurs in the shallows of Green Bay and extends eastward along the northern coastal areas into the Straits of Mackinac during the second half of December and early January. Ice formation and accumulation proceeds southward with coastal ice found throughout the southern perimeter of the lake by late January. Normal ice thicknesses range from 10–20 centimeters in the south to 40–60 centimeters in the north. During normal years, maximum ice cover extends over approximately 40% of the lake surface with heaviest conditions occurring in late February and early March. Ice coverage increases to 85–90% during a severe winter and decreases to only 10–15% during a mild year. Coverage of 100% occurs, but rarely. Throughout the winter, ice formed in mid-lake areas tends to drift eastward because of prevailing westerly winds. This movement of ice causes an area in the southern central portion of the lake to remain ice-free throughout a normal winter. Extensive ridging of ice around the island areas adjacent to the Straits of Mackinac presents the greatest hazard to year-round navigation on this lake. Due to an extensive length and north-south orientation, ice formation and deterioration often oc-

cur simultaneously in separate regions of this lake. Ice break-up normally begins by early March in southern areas and progresses to the north by early April. Under normal conditions, only 5–10% of the lake surface is ice covered by mid-April with lingering ice in Green Bay and the Straits of Mackinac completely melting by the end of April.

Lake Huron, the second largest of the Great Lakes, has maximum depths of 230 meters in the central basin west of the Bruce peninsula and 170 meters in Georgian Bay. The pattern of ice formation in Lake Huron is similar to the north-south progression described in Lake Michigan. Initial ice formation normally begins in the North Channel and along the eastern coast of Saginaw and Georgian Bays by mid-December. Ice rapidly expands into the western and southern coastal areas before extending out into the deeper portions of the lake by late January. Normal ice thicknesses are 45–75 centimeters. During severe winters, maximum ice thicknesses often exceed 100 centimeters with wind-

rows of ridged ice achieving thicknesses of up to 10 meters. During normal years, maximum ice cover occurs in late February with 60% coverage in Lake Huron and nearly 95% coverage in Georgian Bay. These values increase to 85–90% in Lake Huron and nearly 100% in Georgian Bay during severe winters. The percent of lake surface area covered by ice decreases to 20–25% for both bodies of water during mild years. During the winter, ice as a hazard to navigation is of greatest concern in the St. Mary's River/North Channel area and the Straits of Mackinac. Ice break-up normally begins in mid-March in southern coastal areas with melting conditions rapidly spreading northward by early April. A recurring threat to navigation is the southward drift and accumulation of melting ice at the entrance of the St. Clair river. Under normal conditions, the lake becomes ice free by the first week of May.

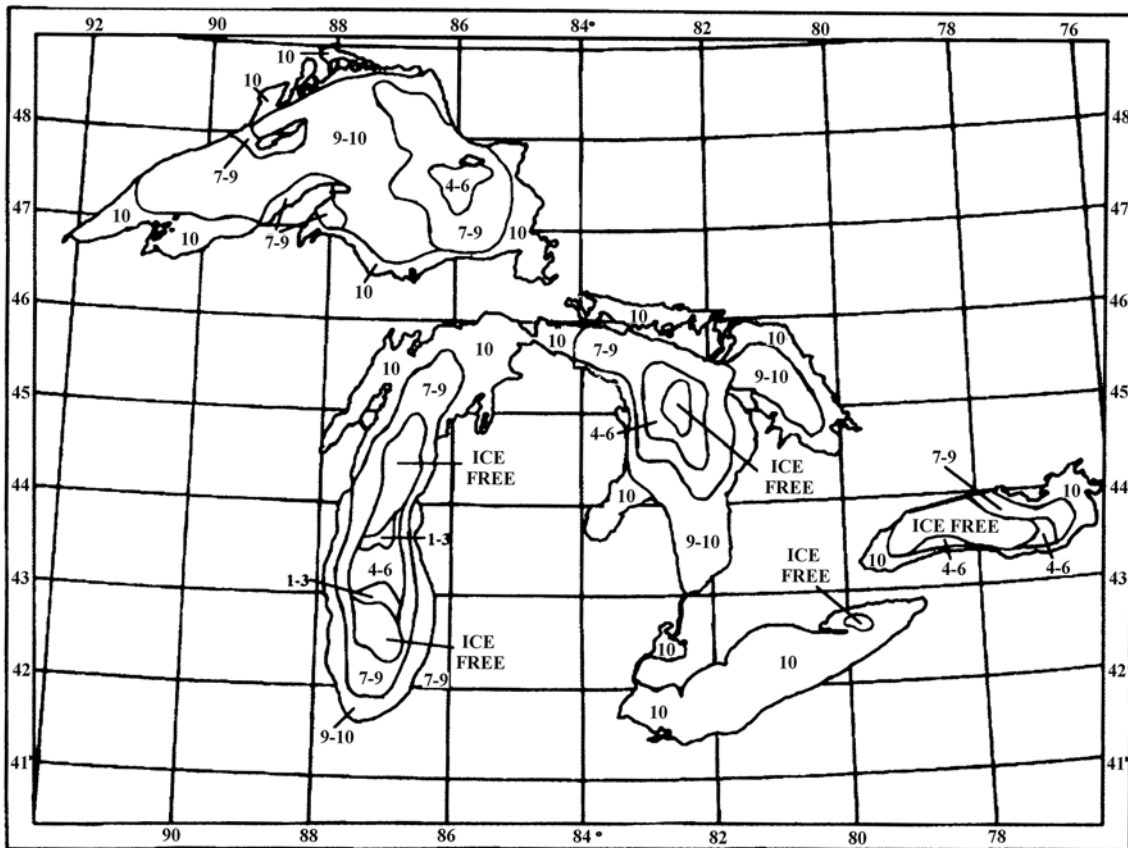The shallowest and most southern of the Great Lakes is

Figure 3213d. Great Lakes ice cover during a severe winter.

Lake Erie. Although the maximum depth nears 65 meters in the eastern portion of the lake, an overall mean depth of only 20 meters results in the rapid accumulation of ice over a short period of time with the onset of winter. Initial ice formation begins in the very shallow western portion of the lake in mid-December with ice rapidly extending eastward by early January. The eastern portion of the lake does not normally become ice covered until late January. During a

normal winter, ice thicknesses range from 25–45 centimeters in Lake Erie. During the period of rapid ice growth, prevailing winds and currents routinely move existing ice to the northeastern end of the lake. This accumulation of ice under pressure is often characterized by ridging with maximum heights of 8–10 meters. During a severe winter, initial ice formation may begin in late November with maximum seasonal ice thicknesses exceeding 70 centimeters. Since

this lake reacts rapidly to changes in air temperature, the variability of percent ice cover is the greatest of the five Great Lakes. During normal years, ice cover extends over approximately 90–95% of the lake surface by mid to late February. This value increases to nearly 100% during a severe winter and decreases to 30% ice coverage during a mild year. Lake St. Clair, on the connecting waterway to Lake Huron, is normally consolidated from the middle of January until early March. Ice break-up normally begins in the western portion of Lake Erie in early March with the lake becoming mostly ice-free by the middle of the month. The exception to this rapid deterioration is the extreme eastern end of the lake where ice often lingers until early May.

Lake Ontario has the smallest surface area and second greatest mean depth of the Great Lakes. Depths range from 245 meters in the southeastern portion of the lake to 55 meters in the approaches to the St. Lawrence River. Like Lake Superior, a large mean depth gives Lake Ontario a large heat storage capacity which, in combination with a small surface area, causes Lake Ontario to respond slowly to changing meteorological conditions. As a result, this lake produces the smallest amount of ice cover found on any of the Great Lakes. Initial ice formation normally begins from the middle to late December in the Bay of Quinte and extends to the western coastal shallows near the mouth of the St. Lawrence River by early January. By the first half of February, Lake Ontario is almost 20% ice covered with shore ice lining the perimeter of the lake. During normal years, ice cover extends over approximately 25% of the lake's surface by the second half of February. During this period of maximum ice coverage, ice is typically concentrated in the northeastern portion of the lake by prevailing westerly winds and currents. Ice coverage can extend over 50–60% of the lake surface during a severe winter and less than 10% during a mild year. Level lake ice thicknesses

normally fall within the 20–60 centimeter range with occasional reports exceeding 70 centimeters during severe years. Ice break-up normally begins in early March with the lake generally becoming ice-free by mid-April.

The maximum ice cover distribution attained by each of the Great lakes for mild, normal and severe winters is shown in Figure 3213a, Figure 3213c and Figure 3213d. It should be noted that although the average maximum ice cover for each lake appears on the same chart, the actual occurrence of each distribution takes place during the time periods described within the preceding narratives.

Analysis of the Great Lakes ice is done at the USNIC in conjunction with the Canadian Ice Service. This partnership - the North American Ice Service provides daily analysis of the Great Lakes ice throughout the season. Near real time lake ice products are publicly available at www.natice.noaa.gov. Additional information is available to the mariner from NOAA's **Great Lakes Environmental Research Laboratory (GLERL)** via the link provided in Figure 3213e.

Figure 3213e. NOAA - Great Lakes Environmental Research Laboratory. https://www.glerl.noaa.gov/

ICE INFORMATION SERVICES

3214. Importance of Ice Information

Advance knowledge of ice conditions to be encountered and how these conditions will change over specified time periods are invaluable for both the planning and operational phases of a voyage to the polar regions. Branches of the United States Federal Government responsible for providing operational ice products and services for safety of navigation include the Departments of Defense (U.S. Navy), Commerce (NOAA), and Homeland Security (U.S. Coast Guard). All of these agencies are part of the joint **U.S. National Ice Center (USNIC)**. The USNIC provides ice products and services to U.S. Government and maintains a public website for general ice conditions in the Arctic, Antarctic and Great Lakes. USNIC charts are produced through the analyses of available, near real time remote sensing, and model data sources. They are generated primarily for maritime domain awareness, and for U.S. government mission

planning and safety of navigation. The content of sea ice analyses is directly dependent upon the planned use of the product, the required level of detail, and the availability of on-site ice observations and/or remotely-sensed data. Ice analyses are produced primarily from satellite remote sensing data. Information from ship observations, aircraft reconnaissance, and buoy data are used when available.

The accurate interpretation of these data is critical to producing the USNIC's daily sea ice edge and the weekly Arctic and Antarctic hemispheric sea ice charts. Great Lakes ice analysis are done through the ice season; December through May.

3215. Ice Forecasts and Observations

Ice forecasting services are provided to U.S. Government agencies upon request for ongoing polar operations and operational planning. For government

entities, optimum track ship routing (OTSR) recommendations via the USN's Fleet Weather Center in Norfolk, VA will include sea ice edge information as applicable. Government units can request support via the USNIC website or by contacting the Command Duty Officer. Commercial operations interested in ice products may obtain routinely produced ice products from the public USNIC website and, in U.S. Alaska waters, from the **Alaska Sea Ice Program (ASIP)** sea ice desk in Anchorage, Alaska. They provide support to government and public users. Their products are available via the link provided in Figure 3215a.

The U.S. Coast Guard has an additional responsibility, separate from the USNIC, for providing icebreaker support for polar operations and the administration and operations of the **International Ice Patrol (IIP)**.

Figure 3215a Alaska Sea Ice Program.
https://www.weather.gov/afc/ice

Ice observation codes make use of special nomenclature which is precisely defined in several languages by the WMO publication *Sea Ice Nomenclature - WMO No. 259, TP 145*. This publication, available from the Secretariat of the WMO, contains descriptive definitions along with photography of most ice features. This publication is very useful for vessels planning to submit ice observations. The

Figure 3215b. WMO Sea-Ice Nomenclature.
http://www.jcomm.info/index.php?option=com_oe&task=
viewDocumentRecord&docID=14598

publication is available online via the link provided in Figure 3215b.

3216. The North Atlantic Ice Patrol

The North Atlantic Ice Patrol was established in 1914 by the International Convention for the Safety of Life at Sea (SOLAS), held in 1913 as a result of the sinking of the RMS TITANIC in 1912. The TITANIC struck an iceberg on its maiden voyage and sank with the loss of 1,513 lives. In accordance with the agreement reached at the SOLAS conventions of 1960 and 1974, the U.S. Coast Guard International Ice Patrol monitors the iceberg danger in the North Atlantic Ocean and to provide relevant iceberg warning products to the maritime community. Information on ice conditions for the Gulf of St. Lawrence and the coastal waters of Newfoundland and Labrador, including the Strait of Belle Isle, is provided by **ECAREG Canada** (Eastern Canada Traffic System), through any Coast Guard Radio Station, from the month of December through late June. Sea ice data for these areas can also be obtained from the Ice Operations Officer, located at St. Johns, Newfoundland, via Sydney, Halifax, or St. John's marine radio. The ice operations desk can be contacted at: iceatl.cggc@dfo-mpo.cg.ca

During the war years of 1916-18 and 1941-45, the Ice Patrol was suspended. Aircraft were added to the patrol force following World War II, and today perform the majority of the reconnaissance work. During each ice season, aerial reconnaissance surveys are made in the vicinity of the Grand Banks of Newfoundland and along the coast of Labrador to determine the southern, eastern, and western limit of the seaward extent of icebergs. The U.S. Coast Guard aircraft use the 360-degree ELTA radar to help detect and identify icebergs in this notoriously fog-ridden area. Reports of ice sightings are also requested and collected from ships transiting the Ice Patrol's operational area. Vessels are encouraged to report sightings of icebergs or stationary radar targets that may likely be icebergs to the nearest **Canadian Coast Guard Marine Communications and Traffic Services (MCTS)** station or the International Ice Patrol at: iipcomms@uscg.mil. Ice reports may also be sent at no charge using INMARSAT Code 42. The IIP implements a voluntary ice observation reporting system called the **Vessel of Opportunity Observation Program (VOOP)**. More information on the VOOP can be found at: http://www.navcen.uscg.gov/pdf/iip/VOOP.pdf.

International Ice Patrol activities are directed from an Operations Center in New London, Connecticut. The Ice Patrol gathers iceberg reports from all sources, including its own reconnaissance flights, commercial reconnaissance flights, and ships at sea and incorporates them into a computer database. An iceberg drift and deterioration model is then used to analyze and predict the movement and melt of the icebergs. Due to the large size of the Ice Patrol's operating area, some icebergs are seen only once. Model predictions are used to create iceberg warning products.

The results from the iceberg drift and deterioration model are used to compile bulletins that are issued once daily at

0000Z by radio communications. Bulletins are available over INMARSAT as a NAVAREA IV navigational warning. A bulletin and iceberg chart can also be found on the USCG Navigation Center webs portal via the link provided in Figure 3216.

Figure 3216. Products produced by the North American Ice Service (an international partnership between the International Ice Patrol, Canadian Ice Service and the National Ice Center) can be found via the following link: http://www.navcen.uscg.gov/?pageName=iipProducts

When icebergs are sighted outside the Iceberg Limit, **Notices to Shipping (NOTSHIP)** are issued by MCTS St. John's in between the regularly scheduled bulletins. Iceberg positions in the ice bulletins are updated for drift and deterioration at 12- hour intervals. A radio-facsimile chart is also broadcast once a day throughout the ice season.

A summary of broadcast times and frequencies can be found in Pub. 117, Radio Navigational Aids, and on the International Ice Patrol web site at: http://www.navcen.uscg.gov/?pageName=IIPHome.

Ice Patrol formed a partnership with the **Canadian Ice Service (CIS)** and the USNIC as the **North American Ice Service (NAIS)** with a goal to be the leading authority in ice information and services for the maritime interests of the Canadian and United States Governments in North America. IIP and CIS share a joint database of icebergs in the North Atlantic. Each organization produces the NAIS Iceberg Warning products at different times of the year. IIP is responsible for the products from January through September when icebergs typically threaten the transatlantic shipping lanes while CIS is responsible for the products during the remainder of the year when icebergs normally only threaten Canadian coastal waters. Both an English and a French version of the NAIS iceberg chart can be found on the CIS website at http://iceweb1.cis.ec.gc.ca/Prod/page2.xhtml?CanID=11091&lang=en&title=East+Coast.

3217. Ice Navigation in Canadian Waters

Ice Navigation in Canadian Waters is published by the Canadian Coast Guard and is intended to assist ships operating in ice in all Canadian waters, including the Arctic. This outstanding publication is available for free online through the link provided in Figure 3217 and provides vessels transiting Canadian ice-covered waters with the necessary understanding of the regulations, shipping support services, hazards and navigation techniques in ice.

Figure 3217 Ice Navigation in Canadian Waters. http://www.ccg-gcc.gc.ca/folios/00913/docs/ice-navigation-dans-les-galces-eng.pdf

3218. International Ice Information

The International Ice Charting Working Group (IICWG) was formed in October 1999 to promote cooperation between the world's ice centers on all matters concerning sea ice and icebergs. Members of this group are the world's experts in observing ice from satellites and aircraft, modeling ice, and preparing ice warning products for mariners to promote safe navigation. The group is dedicated to staying on top of emerging technologies in sea ice and iceberg detection by all means. Members share information on these technologies to benefit the ice services and mariners worldwide.

Contacting the ice services of the IICWG for accurate ice information will directly contribute to the protection of the marine environment by assisting with planning response efforts in the vicinity of the ice. The contact information, working hours, and internet addresses for each of the ice services, both in the Northern and Southern Hemispheres, are provided below.

International Ice Service Emergency Response Numbers

Argentina: http://www.hidro.gov.ar
Meteorology Department
Naval Hydrographic Service
Address: Av. Montes de Oca 2124 - Ciudad Autónoma de Buenos Aires. República Argentina. P.O. Box C1270AVB
Phone: (+54) 11 4317 2534 Spanish-speaking only

Hours: 24/7
E-mail: hydroshn@gov.ar

Australia: http://www.bom.gov.au/ant
Bureau of Meteorology Tasmania/Antarctica Region
Address: AACECRC Privatebag 80, HOBART Australia 7001
Phone: +61-3-62323642
Alternate Phone: +61-3-62323113
Hours: 24/7, Leave a message if no one answers, and response will be made within the hour
E-mail: season.ops@aad.gov.au, jan.lieser@acecrc.org.au
       Neal.young@acecrc.org.au

Brazil:
https://www.mar.mil.br/dhn/chm/meteo/indexing.htm
Navy Hydrography Center-Marine Meteorological Service
Address: Rua Barão de Jaceguay, s/n Ponta da Armação Niterói, RJ CEP. 24048-900
Phone: (+55) 21 2189-3275
Hours: 0830L-1630L, Monday thru Friday
Best Contact Number: (+55) 21 893-270, Available 24/7
E-mail: meteorologia-oceanografia@chm.mar.mil.br

Canada: http://ice-glaces.ec.gc.ca
Canadian Ice Service - Environment Canada
Address: 373 Sussex Drive, Block E, Ottawa, Ontario, Canada K1A 0H3
Phone: +1-800-668-6767
Hours: 0830L-1630L
E-mail: cis-scg.client@ec.gc.ca / enviroinfo@ec.gc.ca

Chile: http://www.shoa.cl/index.html
Chilean Navy Weather Service
Address: Errazuriz Echaurren 254 Playa Ancha, Valparaiso, Chile
Phone: +61 220 1161, Punta Arenas Duty Number
Hours: 24/7
E-mail: meteomag@directemar.cl

China: http://english.nmefc.gov.cn
National Marine Environment Forecast Centre
Address: 8, Dahuisi Rd., Haidian District, Beijing, 100081
Phone: Phone not available.
Hours: 0800L-1700L
E-mail: webmaster@nmefc.gov.cn

Denmark:
http://www.dmi.dk/en/groenland/hav/ice-charts
Danmark Meteorologiske Institut
Address: Lyngbyvej 100, DK-2100 Copenhagen
Phone: +45 39 15 72 45
Hours: 0800L-1700L
E-mail: iskort@dmi.dk

Estonia: http://www.emhi.ee

Estonian Meteorological and Hydrological Institute (EMHI)
Address: Rävala 8,EE-0001 Tallin, Estonia
Phone: TBD
Hours: 0800L-1700L
E-mail: mere@emhi.ee

Finland: http://en.ilmatieteenlaitos.fi/ice-conditions
Finnish Meteorological Institute, Ice Service
Address: P.O. Box 503, FIN-00101 Helsinki, Finland
Phone: +358 29 539 3464
Hours: 0800L-1700L
E-mail: iceservices@fmi.fi

Germany:
http://www.bsh.de/en/Marine_data/Observations/Ice/index.jsp
BSH-Eisdienst
Address: Neptunallee 5, 18069 Rostock, Germany
Phone: +49 381-4563780
Emergency Phone: +49 381-4563781 (with voice mail and contact information for off-office hours)
Hours: 0800L-1700L
E-mail: ice@bsh.de

Greenland: http://www.dmi.dk/vejr
Danish Meteorological Institute (DMI)
Ice Patrol Narsarsuaq
Address: PO Box 505, 3923 Narsarsuaq, Greenland
Phone: + 299 66 52 44 24/7 Emergency Representative
Hours: 0800L-1600L Monday thru Friday; 24/7 # always available
E-mail: icepatrol@dmi.dk

Iceland: http://www.vedur.is
Icelandic Meteorological Office
Address: Bustadavegur 9, IS-150 Reykjavik
Phone: + 354 522 6000 ** English recording, Can press 5 to access 24/7 Emergency Representative
Hours: 0830L-1600L Monday thru Friday; 24/7 response available
E-Mail: fyrirspurnir(at)vedur.is

Japan: http://www.jma.go.jp/jma/indexe.html
Japan Meteorological Agency
Address: 1-3-4 Otemachi Chiyoda-ku,Tokyo, 100-8122,Japan
Phone: Not Available
Hours: 0800L-1700L
E-Mail: seaice@climar.kishou.go.jp

Latvia: http://www.meteo.lv
Latvian Environment, Geology and Meteorology Centre
Address: 165 Maskavas Str, LV1019, Riga, Latvia
Phone: +371 67 032 609
Hours: 0800L-1700L (outside working hours - forecaster

on duty)
E-Mail: marine@meteo.lv

Lithuania: http://www.meteo.lt/english
Lithuanian Hydrometeorological Service
Address: Rudnios str 6, 09300 Vilnus, Lietuva
Phone: +3706 252247 voicemail not monitored
Hours: 0800L-1700L
E-Mail: lhmet@meteo.lt

Netherlands:
http://www.infocentrum_binnenwateren.nl.ijskaart
Rijkswaterstaat/Riza Centre for Water Management
Information and Warning Centre
Address: Infocentrum Binnenwateren, Postbox 17, 8200 AA Lelystad
Phone: +31-320 298 888
Hours: 24/7
E-mail: infocentrum@riza.rws.nl

Norway: http://polarview.met.no/
MET Norway
Norwegian Ice Service
Address: Vevarslinga for Nord-Norge, Postboks 6314 Langnes, NO-9293 Tromsoe
Phone: +47 7762 1300
Hours: 24/7
Norwegian Coastal Administration: +47 33 034800 (pollution cases), 24/7
Search and Rescue Coordination Center: +47 51 517000 (SAR cases), 24/7
E-Mail: istjenesten@met.no

Poland:
http://www.baltyk.pogodynka.pl//index.php?page=2&sub-page=64
Instytut Meteorologii i Gospodarki Wodnej - PIB (IMGW-PIB) - Oddzial Morski
Ice Service
Address: Waszyngtona 42, PL 81-342 Gdynia
Phone: +48-58 62 88 146 (Ice Team)
Hours: 0730L-1500L, Monday-Friday
Fax: +48 58 620 16 41
Emergency: +48-58 62 88 151, 24/7
E-mail: hydrologia.gdynia@imgw.pl

Russian Federation: http://www.aari.ru
Arctic and Antarctic Research Institute (AARI)
Address: 38, Bering Str., St.Petersburg, Russia 199397

Phone: +7 812 337-3168 (hours: 0900-1900UTC+0300)
Phone: +7 921 865-4056 (hours: 1900-0900UTC+0300)
Fax: +7 812 337-3241 (24/7)
E-mail: sat_info@aari.ru, service@aari.ru

Sweden: www.smhi.se
Swedish Meteorological and Hydrological Institute (SMHI)
Ice Service
Address: S-601 76 Norrkoping
Phone: +46-11 495 8533 ** Recorded message in Swedish and English
Hours: 0800L-1600L
E-mail: ice@smhi.se

United Kingdom: http://www.metoffice.gov.uk
Meteorological Office
Address: FitzRoy Road, Exeter, Devon EX1 3PB, United Kingdom
Phone: +44 1392 885680
Hours: 0800L-1700L
E-mail: enquiries@metoffice.gov.uk

United States

U.S. National Ice Center: http://www.natice.noaa.gov
Address: 4251 Suitland Road, NSOF, Washington, DC 20395
Phone: +301-943-6977
Hours: 0730L-1600L, Duty Officer - 24/7
E-mail: nic.cdo@noaa.gov

International Ice Patrol: http://www.navcen.uscg.gov/iip
Address: 1 Chelsea St., New London, CT 06320
Phone: +1-860 271 2626, Operations Center (forwarded to Watch Cell after hours)
Watch Cell Phone: 1 860 235 8171
Hours: 0730-1600 EST (Minimum); Watch phone - 24/7
E-Mail: iipcomms@uscg.mil

U.S._National_Weather_Service:
http://pafc.arh.noaa.gov/ice.php
Ice Desk-NWS Anchorage
Address: 6930 Sand Lake Road, Anchorage, AK 99502
Phone: (907) 266-5138
Emergency: (907) 271-6540, press 0 after hours for emergency
Hours: 0630L-1530L
E-Mail: nws.ar.ice@noaa.gov

CHAPTER 33

POLAR NAVIGATION

POLAR REGIONS

3300. Introduction

The complex challenge of clearly defining the limits of Earth's polar regions is problematic, yielding diverse conclusions determined by the different desires of interested parties. Astronomically, the parallels of latitude at which the sun becomes circumpolar (the Arctic and Antarctic Circles at about latitude 67.5°) are considered the lower limits. As of December 27, 2016, the lower limit runs 66°33'46.5" north of the Equator. Its latitude depends on the Earth's axial tilt, which fluctuates within a margin of 2° over a 40,000-year period, due to tidal forces resulting from the orbit of the Moon. Consequently, the Arctic Circle is currently drifting northwards at a speed of about 15 m (49 ft) per year.

Meteorologically, however, the limits are irregular lines which, in the Arctic, coincides approximately with the tree line. For general purposes, the navigator may consider polar regions as extending from the geographical poles of the earth to latitude 75° (in the Arctic coinciding approximately with the northern coast of Alaska). These areas are considered "high latitude" by the U.S. Navy. Transitional **subpolar regions** extending for an additional 10° (in the Northern Hemisphere extending to the southern tip of Greenland).

This chapter deals primarily with marine navigation in high latitudes.

3301. A Changing Landscape in the Arctic

Scientific research and projections of the changes taking place in the Arctic vary, but there is a general consensus that Arctic sea ice is diminishing. As recently as September 2011, scientists at the U.S. National Snow and Ice Data Center reported that the annual Arctic minimum sea ice extent for 2011 was the second lowest in the satellite record, and 938,000 square miles below the 1979 to 2000 average annual minimum. Much of the Arctic Ocean remains ice-covered for a majority of the year, but some scientists have projected that the Arctic may be ice-diminished for periods of time in the summer by as soon as 2040.

The environmental changes taking place in the Arctic are making maritime transit more feasible and are increasing the likelihood of further expansion of human activity, including tourism, oil and gas extraction, commercial ship-

ping, and fishing in the region. For example, in 2011, northern trans-shipping routes opened during the summer months, which permitted more than 40 vessels to transit between June and October. The Northern Sea Route opened in mid-August, and appeared to remain open through September, while the Northwest Passage opened for periods in the summer for the fifth year in a row. See Figure 3301 for locations of these shipping routes.

Despite these changes, several enduring characteristics still provide challenges to surface navigation in the Arctic, including large amounts of winter ice and increased movement of ice from spring to fall. Increased movement of sea ice makes hazard reporting less predictable, a situation that is likely to increase the risk for ships to become trapped or damaged by the ice. This chapter provides a description of these challenges to polar navigation.

3302. Polar Geography

The north polar region, the Arctic, consists of an elongated central water area slightly less than that of the United States, almost completely surrounded by land (Figure 3302a). Some of this land is high and rugged with permanent ice caps, but part of it is low and marshy when thawed. Underlying permafrost prevents adequate drainage, resulting in large numbers of lakes and ponds and extensive areas of muskeg, which is a soft spongy ground having a characteristic growth of certain types of moss and tufts of grass or sedge. There are also large areas of tundra, low treeless plains with vegetation consisting of mosses, lichens, shrubs, willows, etc., and usually having an underlying layer of permafrost. The northernmost point of land is Kap Morris Jessup, Greenland, about 380 nautical miles from the pole.

The central part of the Arctic Ocean, as the body of water is called, is a basin with about 12,000 feet average depth. However, the bottom is not consistent, having a number of seamounts and deeps. The greatest depth is probably a little more than 16,000 feet. At the North Pole the depth is 14,150 feet. Surrounding the polar basin is an extensive continental shelf, broken only in the area between Greenland and Svalbard (Spitsbergen). The many islands of the Canadian archipelago lie on this shelf. The Greenland Sea, east of Greenland, Baffin Bay, west of Greenland, and the Bering Sea, north of the Aleutians, each has its independent basin. In a sense, the Arctic Ocean is an arm of
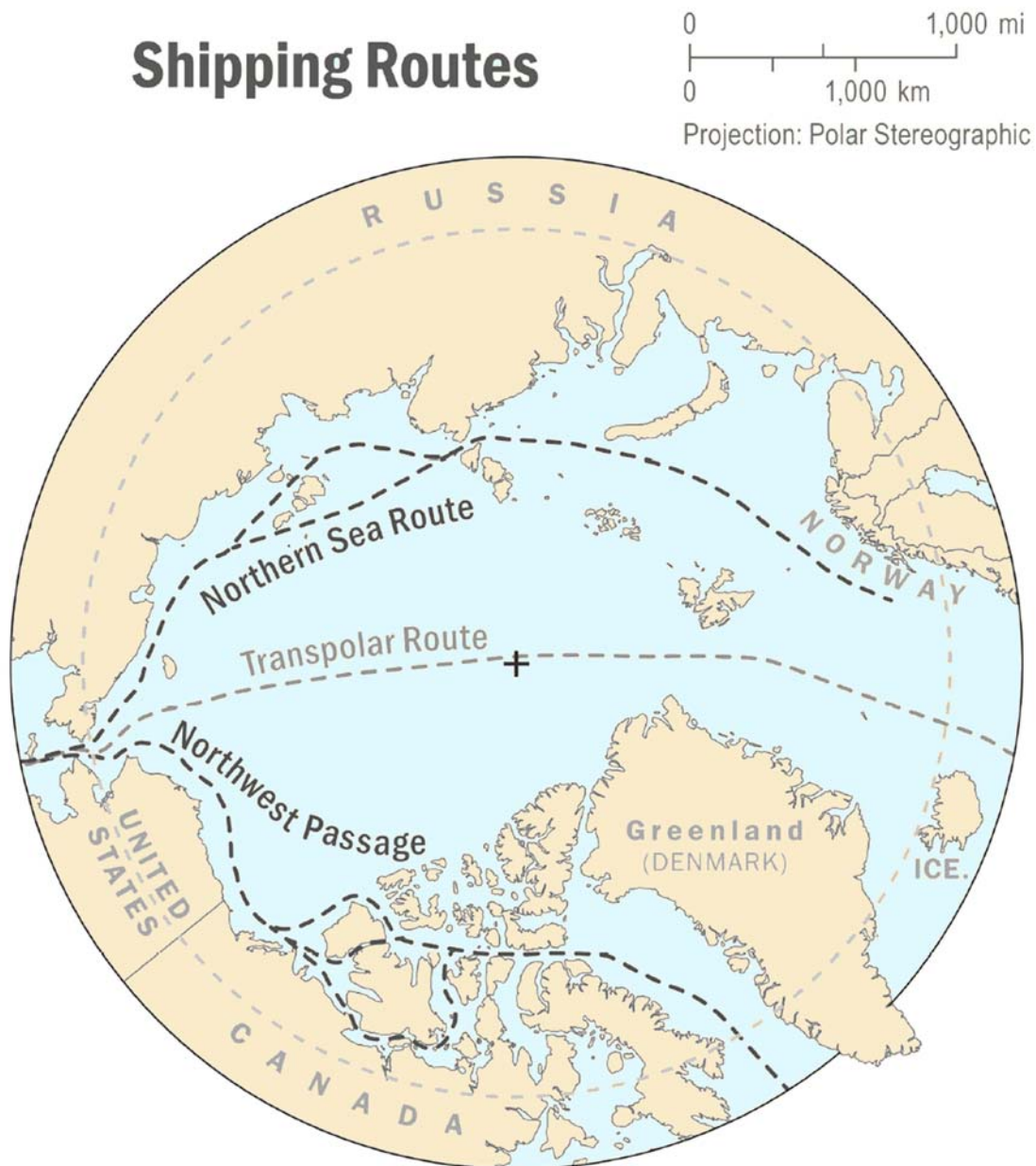
Figure 3301. Polar shipping routes.

the Atlantic.

The south polar region of the Antarctic is in marked contrast to the Arctic in physiographical features. Here a high, mountainous land mass about twice the area of the United States is surrounded by water (Figure 3302b). An extensive polar plateau covered with snow and ice is about 10,000 feet high. There are several mountain ranges with peaks rising to heights of more than 13,000 feet. The average height of Antarctica is about 6,000 feet, which is higher than any other continent. The height at the South Pole is about 9,500 feet. The barrier presented by land and tremendous ice shelves 500 to 1,000 feet thick prevent ships from reaching very high latitudes. Much of the coast of Antarctica is high and rugged, with few good harbors or anchorages.

3303. Shipping in Polar Waters

While there has historically been regular shipping, especially along the Russian coast in the summer seasons, the amount of shipping and traffic in the Arctic has increased substantially over the last decade. The increase is due to many factors, including interest in the arctic

The Arctic Ocean Floor

Figure 3302a. The Arctic Ocean floor and surrounding land masses.

environment, tourism, oil and gas exploration, and exploitation. This has been allowed by the overall reduction in sea ice for greater parts of the year, and the potential for reduced shipping costs using the arctic sea routes.

There are two major surface routes through the Arctic, the **Northwest Passage (NWP)** along the Canadian Archipelago, and the Russian Federation **Northern Sea Route (NSR)**. See Figure 3301.

All NWP passages have common eastern and western approaches. In the east, ships must proceed through the Labrador Sea, Davis Strait and Baffin Bay. In the western approaches ships proceed through the Bering Sea, Bering Strait, the Chukchi Sea and the Beaufort Sea before deciding which route to follow. In general, the operating season is

short (from late July to mid-October) depending on the route and year. Of the various passages listed below, routes 1 and 2 are considered deep water ones, while the others have limiting shoals and rocks restricting the draft of vessels to less than 10 meters.

Routes Through the NWP

1. Routing (East to West): Lancaster Sound - Barrow Strait - Viscount Melville Sound - Prince of Wales Strait - Amundsen Gulf.

2. Routing (East to West): Same as 1 but substitute M'Clure Strait for Prince of Wales Strait and Amundsen Gulf. Collectively Lancaster Sound -

Figure 3302b. A satellite composite image of Antarctica.

Barrow Strait - Viscount Melville Sound is known as Parry Channel.

3. Routing (East to West): Lancaster Sound - Barrow Strait - Peel Sound - Franklin Strait - Larsen Sound - Victoria Strait - Queen Maud Gulf - Dease Strait - Coronation Gulf - Dolphin and Union Strait - Amundsen Gulf.

4. Routing (East to West): A variation of 3. Rather than following Victoria Strait on the west side of King William Island, the route passes to the east of the island following James Ross Strait - Rae Strait - Simpson Strait.

5. Routing (East to West): Similar to 3. Rather than following Peel Sound on the west side of Somerset Island, the route passes to the east of the island through Prince Regent Inlet and Bellot Strait.

6. Routing (East to West): Hudson Strait - Foxe Channel - Foxe Basin - Fury and Hecla Strait - Gulf of Boothia - Bellot Strait - remainder via routes 3, 4 or 5.

The Russian Federation NSR is a shipping route officially defined by Russian legislation as lying east of Novaya Zemlya and specifically running along the Russian Arctic coast from the Kara Sea, along Siberia, to the Bering Strait. The entire route lies in Arctic waters and within Russia's Exclusive Economic Zone (EEZ). Parts are free of ice for only two months per year.

3304. Polar Code

To support increases in shipping traffic the International Maritime Organization (IMO) adopted the International Code for Ships Operating in Polar Waters (Polar Code) and related amendments to make it mandatory under both the International Convention for the Safety of Life at Sea (SOLAS) and the International Convention for the Prevention of Pollution from Ships (MARPOL). The Polar Code is intended to cover the full range of shipping-related matters relevant to navigation in waters surrounding the two poles including: ship design, construction and equipment; operational and training concerns; search and rescue; and, equally important, the protection of the unique environment and eco-systems of the polar regions. The Polar Code is available online via the link provided in Figure 3304.

3305. High-Latitude Effects

Special techniques have been developed to adapt navigation to the unique conditions of polar regions. These conditions are largely the result of high latitude, the environment and meteorological factors.

Figure 3304. The Polar Code
http://www.imo.org/en/MediaCentre/HotTopics/polar/Documents/POLAR%20CODE%20TEXT%20AS%20ADOPTED.pdf

Much of the thinking of the marine navigator is in terms of the "rectangular" world of the Mercator projection, on which the meridians are equally spaced, vertical lines perpendicular to the horizontal parallels of latitude. Directions are measured relative to the meridians, and are maintained by means of a magnetic or gyrocompass. A straight line on the chart is a rhumb line, the line used for ordinary purposes of navigation. Celestial bodies rise above the eastern horizon, climb to a maximum altitude often high in the sky as they cross the celestial meridian, and set below the western horizon. By this motion the sun divides the day naturally into two roughly equal periods of daylight and darkness, separated by relatively short transitional periods of twilight. The hour of the day is associated with this daily motion of the sun.

In polar regions conditions are different. Meridians all converge at the poles, which are centers of a series of concentric circles constituting the parallels of latitude. The rapid convergence of the meridians renders the usual convention of direction inadequate for some purposes. A rhumb line is a curve which differs noticeably from a great circle, even for short distances. Even visual bearings cannot adequately be represented as rhumb lines. At the pole all directions are south or north, depending upon the pole. Direction in the usual sense is replaced by longitude. The mariner must also remember that the geographic pole and the magnetic pole are not coincidental.

At the pole the **zenith** and **celestial pole** coincide. Hence, the celestial horizon and celestial equator also coincide, and declination and computed altitude are the same. Therefore, celestial bodies change computed altitude only by changing declination. Stars circle the sky without noticeable change in altitude. Planets rise and set once each sidereal period (12 years for Jupiter, 30 years for Saturn). At the North Pole the sun rises about March 21, slowly spirals to a maximum altitude of about 23°27' near June 21, slowly spirals downward to the horizon about September 23, and then disappears for another six months. At the South Pole, a similar cycle takes place, but during the opposite time of year. It requires about 32 hours for the sun to cross the horizon, during which time it circles the sky 1 and 1/3 times. The twilight periods following sunset and preceding sunrise last for several weeks. The moon rises and sets about once each month. Only celestial bodies of north declination are visible at the North Pole; only bodies of south declination are visible at the South Pole.

The long polar night is not wholly dark. The full moon at this time rises relatively high in the sky. Light from the **aurora borealis** in the Arctic and the **aurora australis** in the Antarctic is often quite bright, occasionally exceeding that of the full moon (see Figure 3305a). Even the planets and stars contribute an appreciable amount of light in this area where a snow cover provides an excellent reflecting surface.

Figure 3305a. Aurora borealis above Lyngenfjorden, Norway in March 2012. Image by Simo Räsänen, Wikimedia Commons.

All time zones, like all meridians, meet at the poles. Local time does not have its usual significance, since the hour of the day bears no relation to periods of light and darkness or to altitude of celestial bodies.

3306. Meteorological Effects

Polar regions are cold, but the temperature at sea is not as extreme as inland. The average winter temperature over

the Arctic Ocean is - 30°F to - 40°F, with an extreme low value near - 60°F. Colder temperatures have been recorded in Yellowstone National Park. During the summer the temperature remains above freezing over the ocean. Inland, extreme values are sometimes reached. At least one point on the Arctic Circle has experienced a temperature of 100°F. Few points on the Antarctic Continent have recorded temperatures above freezing, and the interior is probably the coldest part of the world.

Fog and clouds are common in polar regions, yet there is less precipitation than in some desert regions, since the cold air has small capacity for holding moisture. Very cold air over open water sometimes produces steaming of the surface, occasionally to a height of several hundred feet. This is called frost smoke or **sea smoke**. When there is no fog or frost smoke, the visibility is often excellent. Sounds can sometimes be heard at great distances.

Sharp discontinuities or inversions in the temperature lapse rate sometimes produce a variety of mirages and extreme values of refraction. The sun has been known to rise several days before it was expected in the spring. False horizons are not uncommon.

Strong winds are common in the subarctic and in both the Antarctic and subantarctic. The belt of water surrounding Antarctica has been characterized as the stormiest in the world, being an area of high winds and high seas. Strong winds are not encountered over the Arctic Ocean.

In the polar and subpolar regions the principal hazard to ships is ice, of which was both formed at sea or of land ice that flowed into the sea in the form of glaciers. Many low land areas are ice-free in summer. Ice is considered in more detail in Chapter 32.

When snow obliterates surface features, and the sky is covered with a uniform layer of cirrostratus or altostratus clouds, so that there are no shadows, the horizon disappears and earth and sky blend together, forming an unbroken expanse of white, without features. In these conditions landmarks cannot be distinguished, and with complete lack of contrast, distance is virtually impossible to estimate. This phenomenon is called arctic (or antarctic) **white out**. It is particularly prevalent in northern Alaska during late winter and early spring.

3307. Arctic Currents

The cold surface water of the Arctic Ocean flows outward between Greenland and Svalbard and is replaced by warmer subsurface water from the Atlantic. The surface currents depend largely upon the winds, and are generally quite weak in the Arctic Ocean. However, there are a number of well-established currents flowing with considerable consistency throughout the year. The general circulation in the Arctic is clockwise on the American side and around islands, and counterclockwise on the Asian side. Tidal ranges in this area are generally small. In the restricted waters of the upper Canadian-Greenland area

both tides and currents vary considerably from place to place. In the Baffin Bay-Davis Strait, the currents are strong and the tides are high, with a great difference between springs and neaps. In the Antarctic, currents are strong and the general circulation offshore is eastward or *clockwise* around the continent. Close to the shore, a weaker westerly, or *counterclockwise,* current may be encountered, but there are many local variations.

3308. Magnetic Poles

Since both magnetic poles are situated within the polar regions, the horizontal intensity of the earth's magnetic field is so low that the magnetic compass is of reduced value, and even useless in some areas.

The magnetic storms centered in the auroral zones disrupt radio frequency navigation and communications and alter magnetic compass sensibility. The frozen ground in polar regions is a poor conductor of electricity, another factor adversely affecting radio wave propagation.

3309. Summary of Conditions in Polar Regions

The more prominent characteristic features associated with large portions of both polar regions may be summarized as follows:

1. High latitude.
2. Rapid convergence of meridians.
3. Nearly horizontal diurnal motion of celestial bodies.
4. Long periods of daylight, twilight, and semidarkness..
5. Low mean temperatures.
6. Short, cool summers and long, cold winters.
7. High wind-chill factor.
8. Low evaporation rate.
9. Scant precipitation.
10. Dry air (low absolute humidity).
11. Excellent sound-transmitting conditions.
12. Periods of excellent visibility.
13. Extensive fog and clouds.
14. Large number and variety of mirages.
15. Extreme refraction and false horizons.
16. Winter freezing of rivers, lakes, and part of the sea.
17. Areas of permanent land and sea ice.
18. Areas of permanently frozen ground.
19. Large areas of tundra (Arctic).
20. Large areas of poor drainage, with many lakes and ponds (Arctic).
21. Large areas of muskeg (a grassy marsh when thawed) (Arctic).
22. Extensive auroral activity.
23. Large areas of low horizontal intensity of earth's magnetic field.
24. Intense magnetic storms.
25. Uncertain radio wave propagation.

26. Strong winds (Antarctic).

27. Frequent blizzards (Antarctic).

28. Large quantities of blowing snow.

CHARTS

3310. Projections

When navigating in polar regions, as elsewhere, charts are an indispensable component. Chart projections used for polar navigation are covered in Chapter 4, Sections 420 and 421. With the advent of modern electronic charting and voyage management systems, much of the traditional methods of positioning, such as manual computation and hardcopy plotting, are now reduced or eliminated through automation. Prudent mariners using electronic charting methods will familiarize themselves with their system's polar navigation modes prior to use, and will fully understand alternative program utilities and limitations per manufacturer specifications in order to guarantee system functionality in high latitudes.

For ordinary navigation the Mercator projection has long been the overwhelming favorite of marine navigators, primarily because a rhumb line appears as a straight line on this projection. Even in high latitudes the mariner has exhibited an understandable partiality for Mercator charts, which have been used virtually everywhere ships have gone.

However, as the latitude increases, the utility of the Mercator projection decreases, primarily because the value of the rhumb line becomes progressively less accurate. At latitudes greater than 60° the decrease in utility begins to be noticeable, and above latitude 70° it becomes problematic. In the clear polar atmosphere, visual bearings can be observed at great distances, sometimes 50 miles or more, but the use of a rhumb line to represent a bearing line introduces an error at any latitude, and at high latitudes errors become exaggerated.

Another objection to Mercator charts at high latitudes is the increasing rate of change of scale over a single chart. This results in distortion in the shape of land masses and errors in measuring distances.

At some latitudes the disadvantages of the Mercator projection outweigh its advantages. The latitude at which this occurs depends upon the physical features of the area, the configuration and orientation of land and water areas, the nature of the operation, and the experience and personal preference of the mariner. Because of differences of opinion on this matter, a transitional zone exists in which several projections may be encountered. The wise high-latitude navigator is prepared to use any of them, since coverage of the operating area may not be adequate on their favorite projection.

There are currently (2017) no standard projection recommended for polar marine operations, but this is expected to change in the near future with the increase in commercial activity in the Arctic. See Figure 3310 for link to more detailed information regarding suitable projections for navigation in the Arctic, including the use of ECDIS.

Figure 3310. Choosing Suitable Projections for Navigation in the Arctic by the National Technical University of Athens.
http://www.iho.int/mtg_docs/rhc/ArHC/ArHC3/ARHC3-3.2.7_Suitable_projections_for_the_Arctic.pdf

Projections commonly used for polar charts are the modified Lambert Conformal, the Gnomonic, the Stereographic and the Azimuthal Equidistant. These projections are similar near the pole. They are essentially conformal, and a great circle on each is nearly a straight line. As the distance from the pole increases, however, the distinctive features of each projection become apparent:

a. The modified Lambert conformal projection is conformal over its entire extent. The amount of scale distortion is comparatively small if it is carried only to about 25° or 30° from the pole. Beyond that, the distortion increases rapidly. A great circle is very nearly a straight line anywhere on the chart. Distances and directions can be measured directly on the chart in the same manner as on a Lambert conformal chart. However, because this projection is not strictly conformal, and on it great circles are not exactly represented by straight lines, it is not suited for highly accurate positioning.

b. The Polar Gnomonic projection is the one polar projection on which great circles are exactly straight lines. However, a complete hemisphere cannot be represented upon a plane because the radius of 90° from the center would become infinity.

c. The Polar Stereographic projection is conformal over its entire extent and a straight line closely approximates a great circle. The scale distortion is not excessive for a considerable distance from the pole, but it is greater than that of the modified Lambert conformal projection.

d. The Polar Azimuthal Equidistant projection is useful for showing a large area such as a hemisphere because there is no expansion along the meridians.

However, the projection is neither conformal nor equivalent and distances cannot be measured accurately in any but a north-south direction. Great circles other than the meridians differ somewhat from straight lines. The equator is a circle centered at the pole.

e. The two projections most commonly used for polar charts in traditional navigation are the modified Lambert Conformal and the Polar Stereographic. When a directional gyro is used as a directional reference, the track of the craft approximates a great circle. A desirable chart is one on which a great circle is represented as a straight line with a constant scale and with angles correctly represented. These requirements are not met entirely by any single projection, but they are approximated by the modified Lambert Conformal, the Polar Stereographic and the Azimuthal Polar Equidistant. The scale is more nearly constant on the Polar Equidistant, but the projection is not strictly conformal. The Polar Stereographic is conformal, and its maximum scale variation can be reduced by using a plane which intersects the earth at some parallel intermediate between the pole and the lowest parallel. The portion within this standard parallel is compressed and that portion outside is expanded.

3311. Adequacy

NOAA-provided charts and Coast Pilots are either unavailable or outdated for areas in the Arctic. Until recently, most of this region was relatively inaccessible by ship due to the presence of thick, impenetrable sea ice. Further, most Arctic waters that are charted were surveyed with imprecise technology, dating back to the 1800s. Most of the shoreline along Alaska's northern and western coasts has not been surveyed since 1960. As a result, confidence in the region's nautical charts is low. It is estimated by the Canadian Hydrographic Service (CHS) that less than 25% of the Arctic waters are surveyed to acceptable, modern standards. Much of the data is a collection of random vessel track soundings or over-ice spot soundings.

Modern U.S. navigational charts are a compilation of the best data available. Nevertheless, many of the soundings on the charts are from as early as the 1800s. Because transportation activities have increased in Arctic seaways, NOAA has been working to update outdated Arctic nautical charts to meet modern needs. In 2011, NOAA issued an *Arctic Nautical Charting Plan* after consultations with maritime interests and the public, as well as with other federal, state, and local governments. NOAA updated the plan in 2013, outlining the creation of 14 new charts to complement existing chart coverage. Since the update, NOAA released a new nautical chart for the Arctic, helping mariners navigate the Bering Strait. Chart 16190 (Bering Strait North) incorporates precise depth measurements acquired recently by NOAA Ship Fairweather hydrographic surveys.

On October 6, 2010, NOAA led a U.S. delegation that formally established a new Arctic Regional Hydrographic Commission (ARHC) with four other nations known (together with the U.S.) as "Arctic coastal states." The commission, which also includes Canada, Denmark, Norway, and the Russian Federation, promotes cooperation in hydrographic surveying and nautical charting. The Commission provides a forum for better collaboration to ensure safety of life at sea, protect the increasingly fragile Arctic ecosystem, and support the maritime economy.

Charts of most polar areas are generally inferior to those of other regions in at least three respects:

1. *Lack of detail*. Polar regions have not been surveyed with the thoroughness needed to provide charts with traditional detail. Relatively few soundings are available and many of the coastal features are shown by their general outlines only. Large areas are perennially covered by ice, which presents a changing appearance as the position and character of the ice changes. Heavy ice cover and snow prevent accurate determination of surface features of the earth beneath. Added to this is the similarity between adjacent land features where the hundreds of points and fiords in one rugged area or the extensive areas of treeless, flat coastal land in another look strikingly alike. The thousands of shallow lakes and ponds along a flat coastal plain also lack distinctive features.

2. *Inaccuracy*. Polar charts are based upon incomplete surveys and reports of those who have been in the areas. These reports are less reliable than in other areas because icebergs are sometimes mistaken for islands, ice-covered islands are mistaken for grounded icebergs, shorelines are not easy to detect when snow covers both land and attached sea ice, inlets and sounds may be completely obscured by ice and snow, and meteorological conditions may introduce inaccuracy in determination of position. Consequently, many features are inaccurately shown in location, shape, and size, and there are numerous omissions. Isogonic lines, too, are based upon incomplete information, resulting in less than desired accuracy.

3. *Coverage*. Relatively few nautical charts of polar regions are available, and the limits of some of these are not convenient for some operations. As in other areas, charts have been made as the need has arisen. Hence, large-scale charts of some areas are completely lacking. Aeronautical charts are sometimes quite helpful, as they often show more detail of land areas than do the nautical charts. However, aeronautical charts do not show soundings.

4. *Datum*. Since charts may have not be updated using

more modern methods (i.e. GPS) such that the chart datum may be a local one or one used by earlier cartographers (i.e. NAD27). Chart datum shifts may exceed as much as 1 km under worst case circumstances.

3312. Polar Grid

Because of the rapid convergence of the meridians in polar regions, the true direction of an oblique line near the pole may vary considerably over a relatively few miles. The meridians are radial lines meeting at the poles, instead of being parallel, as they appear on the familiar Mercator chart.

Near the pole the convenience of parallel meridians is attained by means of a **polar grid**. On the chart a number of lines are printed parallel to a selected reference meridian, usually that of Greenwich. On transverse Mercator charts the fictitious meridians may serve this purpose. Any straight line on the chart makes the same angle with all grid lines. On the transverse Mercator projection it is therefore a **fictitious rhumb line**. On any polar projection it is a close approximation to a great circle. If north along the reference meridian is selected as the reference direction, all parallel grid lines can be considered extending in the same direction. The constant direction relative to the grid lines is called **grid direction**. North along the Greenwich meridian is usually taken as grid north in both the Northern and Southern Hemispheres.

The value of grid directions is indicated in Figure 3312. In this figure A and B are 400 miles apart. The true bearing of B from A is 023°, yet at B this bearing line, if continued, extends in true direction 163°, a change of 140° in 400 miles. The grid direction at any point along the bearing line is 103°.

When north along the Greenwich meridian is used as grid north, interconversion between grid and true directions is quite simple. Let G represent a grid direction, T the corresponding true direction, λ is longitude and W is the Western Hemisphere. Then for the Arctic,

$$G = T + \lambda W$$

That is, in the Western Hemisphere, in the Arctic, grid direction is found by adding the longitude to the true direction. From this it follows that,

$$T = G - \lambda W$$

and in the Eastern Hemisphere,

$$G = T - \lambda E$$
$$T = G + \lambda E$$

In the Southern Hemisphere the signs (+ or -) of the longitude are reversed in all formulas.

If a magnetic compass is used to follow a grid direction, variation and convergency can be combined into a single correction called **grid variation** or **grivation**. It is customary to show lines of equal grivation on polar charts rather than lines of equal variation. **Isogrivs** are lines of equal grivation.

With one modification the grid system of direction can be used in any latitude. Meridians 1° apart make an angle of 1° with each other where they meet ' at the pole. The **convergency** is one, and the 360° of longitude cover all 360° around the pole. At the equator the meridians are parallel and the convergency is zero. Between these two limits the convergency has some value between zero and one. On a sphere it is equal to the sine of the latitude. For practical navigation this relationship can be used on the spheroidal earth. On a simple conic or Lambert conformal chart a constant convergency is used over the entire chart, and is known as the **constant of the cone**. On a simple conic projection it is equal to the sine of the standard parallel. On a Lambert conformal projection it is equal (approximately) to the sine of the latitude midway between the two standard parallels. When convergency is printed on the chart, it is generally adjusted for ellipticity of the earth. If K is the constant of the cone,

$$K = \sin 1/2(L_1 + L_2)$$

where L_1 and L_2 are the latitudes of the two standard parallels. On such a chart, grid navigation is conducted as explained above, except that in each of the formulas the longitude is multiplied by K:

$$G = T + K\lambda W,$$
$$T = G - K\lambda W$$
$$G = T - K\lambda E$$
$$T = G + K\lambda E$$

Thus, a straight line on such a chart changes its true direction, not by 1° for each degree of longitude, but by K°. As in higher latitudes, convergency and variation can be combined.

In using grid navigation one should keep clearly in mind the fact that the grid lines are parallel *on the chart*. Since distortion varies on charts of different projections, and on charts of conic projections having different standard parallels, t*he grid direction between any two given points is not the same on all charts*. For operations which are to be coordinated by means of grid directions, *it is important that all charts showing the grid be on a single graticule* (Section 403).

3313. Arctic Navigation Background
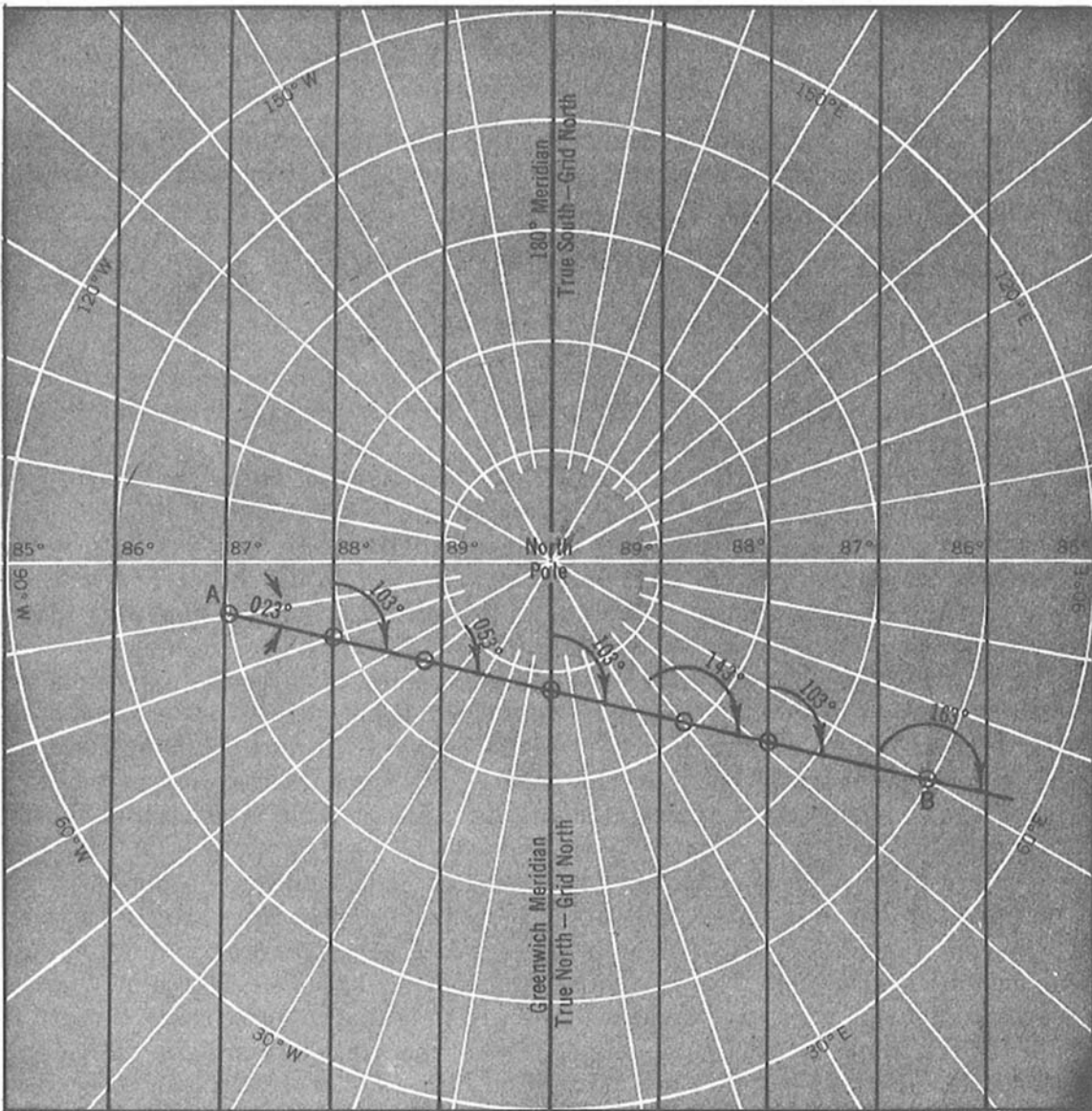
Navigation using an inertial navigation system (INS)

Figure 3312. Polar grid navigation.

utilizes a Local Level reference frame to represent heading and velocity quantities. The Local Level reference frame is an Earth-fixed frame, centered on the navigation system center, as in Figure 3313. The axes of the Level Frame are as follows:

Singularities arise as the vessel approaches the North pole, as the local North direction and the local East direction become undefined. (Navigation equations commonly use the tangent and secant trigonometric functions, which become indeterminate near 90°N (i.e., approach infinity)). To avoid this problem, a different coordinate system is required for operations near the North Pole.

3314. The Transverse Coordinate System

The singularity problem can be avoided by redefining the 'North' location when the vessel nears the poles. Nominally, North is equivalent to the $\hat{Z}$ axis in the Earth Centered, Earth Fixed (ECEF) coordinate system. If this coordinate system is rotated by -90 degrees about the $\hat{Y}$ axis, a new $\hat{Z}'$ axis is created that represents a new North, as shown in Figure 3314.

This new coordinate system is the Transverse Coordinate System. Fortunately, the transverse coordinate process has been automated in many electronic charting and voyage management systems, eliminating the need for the naviga-

$$\begin{bmatrix} \hat{N} \\ \hat{E} \\ \hat{D} \end{bmatrix} = \begin{matrix} \textit{Local North direction} \\ \textit{Local East direction} \\ \textit{Earth Center direction} \end{matrix}$$
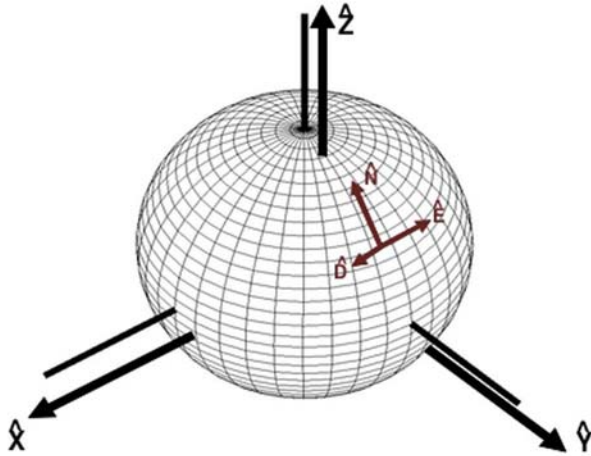

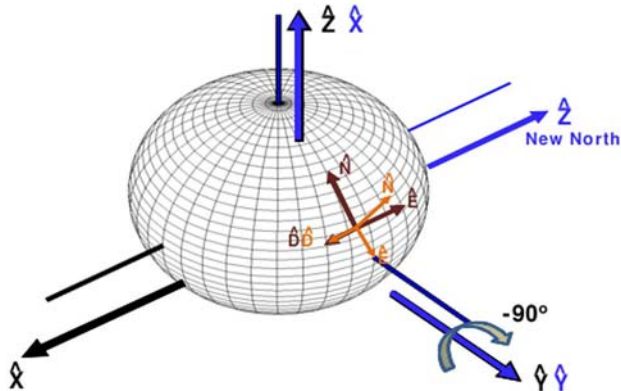*Figure 3313. Local Level and ECEF Frames.*

Figure 3314. Transverse and Transverse Local Level Frames.

tor to manually compute coordinate conversions. The following mathematical description of the Transverse Coordinate System is provided for completeness and to aid in understanding the processes that are occurring within the processor.

Ships equipped with INSs are required to switch to Transverse Mode to keep the INS solution from becoming unstable when tangents approach zero and to make heading

more useful. Modern INSs should have a Transverse Mode capability to generate navigation solutions in the Transverse Coordinate System. Heading, Velocity, and Position all change to Transverse Heading (THD), Transverse North and East Velocity (TNV/TEV), and Transverse Lat/Lon (TLT/TLN) when in a Transverse Mode. Chapter 20 Introduction to Intertial Navigation provides background on how INS works.

The Transverse Coordinate System and is created from the ECEF coordinate system through the following transformation: *Equation 1*

$$\begin{bmatrix} \hat{X}' \\ \hat{Y}' \\ \hat{Z}' \end{bmatrix} = T_E^T \begin{bmatrix} \hat{X} \\ \hat{Y} \\ \hat{Z} \end{bmatrix}$$

Where the ECEF to Transverse direction cosine matrix is: *Equation 2*

$$T_E^T = \begin{bmatrix} 0 & 0 & 1 \\ 0 & 1 & 0 \\ -1 & 0 & 0 \end{bmatrix}$$

A new Transverse Local Level frame is now defined as:

$$\begin{bmatrix} \hat{N}' \\ \hat{E}' \\ \hat{D}' \end{bmatrix} = \begin{matrix} \textit{Transverse North direction} \\ \textit{Transverse East direction} \\ \textit{Earth Center direction} \end{matrix}$$

3315. Position

The Transverse Latitude and Transverse Longitude position of the vessel needs to be computed in the new Transverse coordinate system, as North and the Prime Meridian are no longer in the same location. The position in ECEF can be computed from the nominal Latitude (L) and Longitude (λ) from the following: *Equation 3*

$$X = R_\varnothing \cos L \cos \lambda$$
$$Y = R_\varnothing \cos L \sin \lambda$$
$$Z = R_\varnothing \sin L$$

Likewise, the position in the Transverse coordinate system is: *Equation 4*

$$X' = R_\varnothing \cos L' \cos \lambda'$$
$$Y' = R_\varnothing \cos L' \sin \lambda'$$
$$Z' = R_\varnothing \sin L'$$

Where L' and λ' are the Transverse Latitude and Transverse Longitude, respectively, and are the values that need to be computed. $R_\varnothing$ is the Earth radius.

From equation 1, the following relationships hold: *Equation 5*

$$\widehat{X'} = \hat{Z}$$

$$\widehat{Y'} = \hat{Y}$$

$$\widehat{Z}' = -\hat{X}$$

Equating the two sides gives: *Equation 6*

$$R_\oslash \cos L' \cos \lambda' = R_\oslash \sin L$$

$$R_\oslash \cos L' \sin \lambda' = R_\oslash \cos L \sin \lambda$$

$$R_\oslash \sin L' = -R_\oslash \cos L \cos \lambda$$

Or, *Equation 7*

$$L' = \sin^{-1}(-\cos L \cos \lambda)$$

$$X' = \tan^{-1}\left(\frac{\sin \lambda}{\tan L}\right)$$

The equation for λ' comes from: *Equation 8*

$$\lambda' = \tan^{-1}\left(\frac{Z'}{X'}\right)$$

$$= \tan^{-1}\left(\frac{R_\oslash \cos L \cos \lambda}{R_\oslash \sin L}\right)$$

$$= \tan^{-1}\left(\frac{\sin \lambda}{\tan L}\right)$$

3316. Vector Transformation

Vectors in Local Level Frame can be represented in the Transverse Local Level frame through a series of transformation matrices: *Equation 9*

$$\begin{bmatrix} a' \\ b' \\ c' \end{bmatrix} = T_T^L T_E^T T_N^E \begin{bmatrix} a \\ b \\ c \end{bmatrix}$$

Where T_T^L and T_N^E are direction cosine matrices representing the transformation from Transverse Frame (T) to Transverse Local Level (L) and from Local Level (N) to ECEF (E) frame, respectively. These matrices are defined as: *Equations 10 & 11*

$$T_T^L = \begin{bmatrix} -\sin L' \cos \lambda' & -\sin L' \sin \lambda' & \cos L \\ -\sin \lambda & \cos \lambda' & 0 \\ -\cos L' \cos \lambda' & -\cos L' \sin \lambda' & -\sin L \end{bmatrix}$$

$$T_N^E = \begin{bmatrix} -\sin L \cos \lambda & -\sin \lambda & -\cos L \cos \lambda \\ -\sin L \sin \lambda & \cos \lambda & -\cos L \sin \lambda \\ \cos L & 0 & -\sin L \end{bmatrix}$$

The transformation matrix T_E^T is as defined in Equation 2.

3317. Velocity Transformation

Transforming a velocity from Local Level frame to Transverse Local Level is accomplished by transforming the velocity vector as previously described: *Equation 12*

$$\begin{bmatrix} V'_N \\ V'_E \\ V'_D \end{bmatrix} = T_T^L T_E^T T_N^E \begin{bmatrix} V_N \\ V_E \\ V_D \end{bmatrix}$$

3318. Heading Transformation

Heading in the Transverse Local Level frame is referenced to the Transverse North. As such, the nominal Local Level Heading must be transformed. This can be accomplished by creating a unit vector in local level frame as: *Equation 13*

$$\begin{bmatrix} H_N \\ H_E \\ H_D \end{bmatrix} = \begin{matrix} \cos \phi \\ \sin \phi \\ 0 \end{matrix}$$

Where ϕ is the heading.

This is now a vector that can be transformed into Transverse Local Level frame: *Equation 14*

$$\begin{bmatrix} H'_N \\ H'_E \\ H'_D \end{bmatrix} = T_T^L T_E^T T_N^E \begin{bmatrix} H_N \\ H_E \\ H_D \end{bmatrix}$$

The new Transverse Local Level Heading is: *Equation 15*

$$\phi' = \tan^{-1}\frac{H'_E}{H'_N}$$

3319. Plotting on Polar Charts

Plotting on polar charts, as on other charts, involves the measurement of distance and direction. Fortunately, the transverse coordinate process has been automated in many voyage management and charting systems, eliminating the need for mariner to manual compute and plot positions in

transverse coordinates on paper charts. The following information is provided on this manual process for completeness.

On a paper chart with converging meridians, as one on the Lambert conformal projection, distance is measured by means of the latitude scale, as on a Mercator chart, but this scale is so nearly constant that any part of it can be used without introducing a significant error. A mile scale is sometimes shown in or near the margin of such a chart, and can be used anywhere on that chart.

Since the meridians converge, a straight line makes a different angle with each meridian, as shown in Figure 3312. For this reason, compass roses are not customarily shown on such a chart. If they do appear, each one applies only to the meridian on which it is located. The navigator accustomed to using a Mercator chart can easily forget this point, and hence will do well to ignore compass roses. If a drafting machine is used, it should be aligned with the correct meridian each time a measurement is made. Since this precaution can easily be overlooked, especially by navigators accustomed to resetting their drafting machine only when the chart is moved, and since the resulting error may be too small to be apparent but too large to ignore, it is good practice to discard this instrument when the Mercator chart is replaced by one with converging meridians, unless positive steps are taken to prevent error.

The most nearly fool-proof and generally most satisfactory method of measuring directions on a paper chart with converging meridians is to use a protractor, or some kind of plotter combining the features of a protractor and straightedge (Figure 3319a).
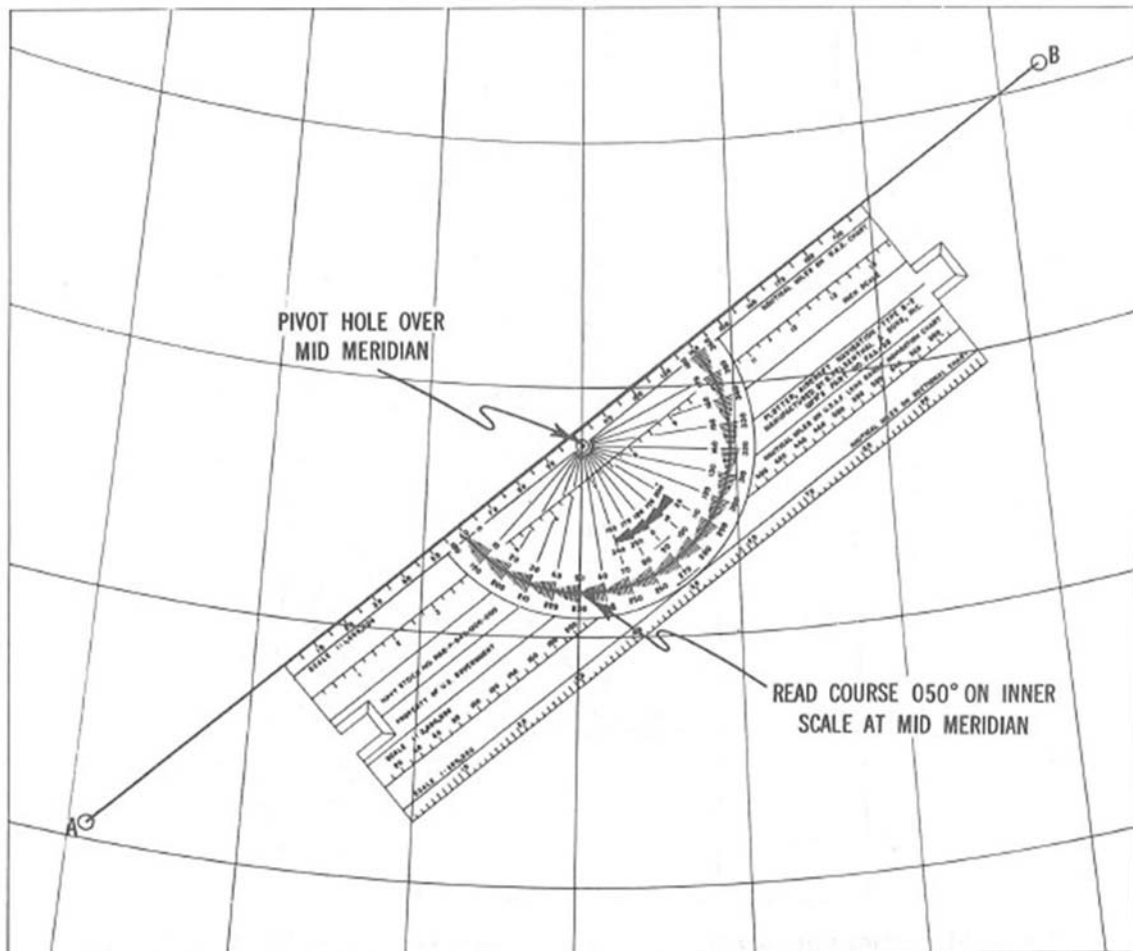

Figure 3319a. Measuring a course on a Lambert conformal chart. Note that the measurement is made at the mid meridian.

If a course is to be measured, the mid meridian of each leg should be used, as shown in Figure 3319a. If a bearing is to be measured, the meridian nearest the point at which the bearing was determined should be used, as shown in Figure 3319b. Thus, in the usual case of determining the bearing of a landmark from a ship, the meridian nearest the ship should be used. In using either of the plotters shown in Figure 3319a or Figure 3319b, note that the center hole is placed over the meridian used, the straightedge part is placed along the line to be drawn or measured, and the angle is read on the protractor at the same meridian which passes under the center hole. It is sometimes more conve-

nient to invert the plotter, so that the protractor part extends   on the opposite side of the straightedge.
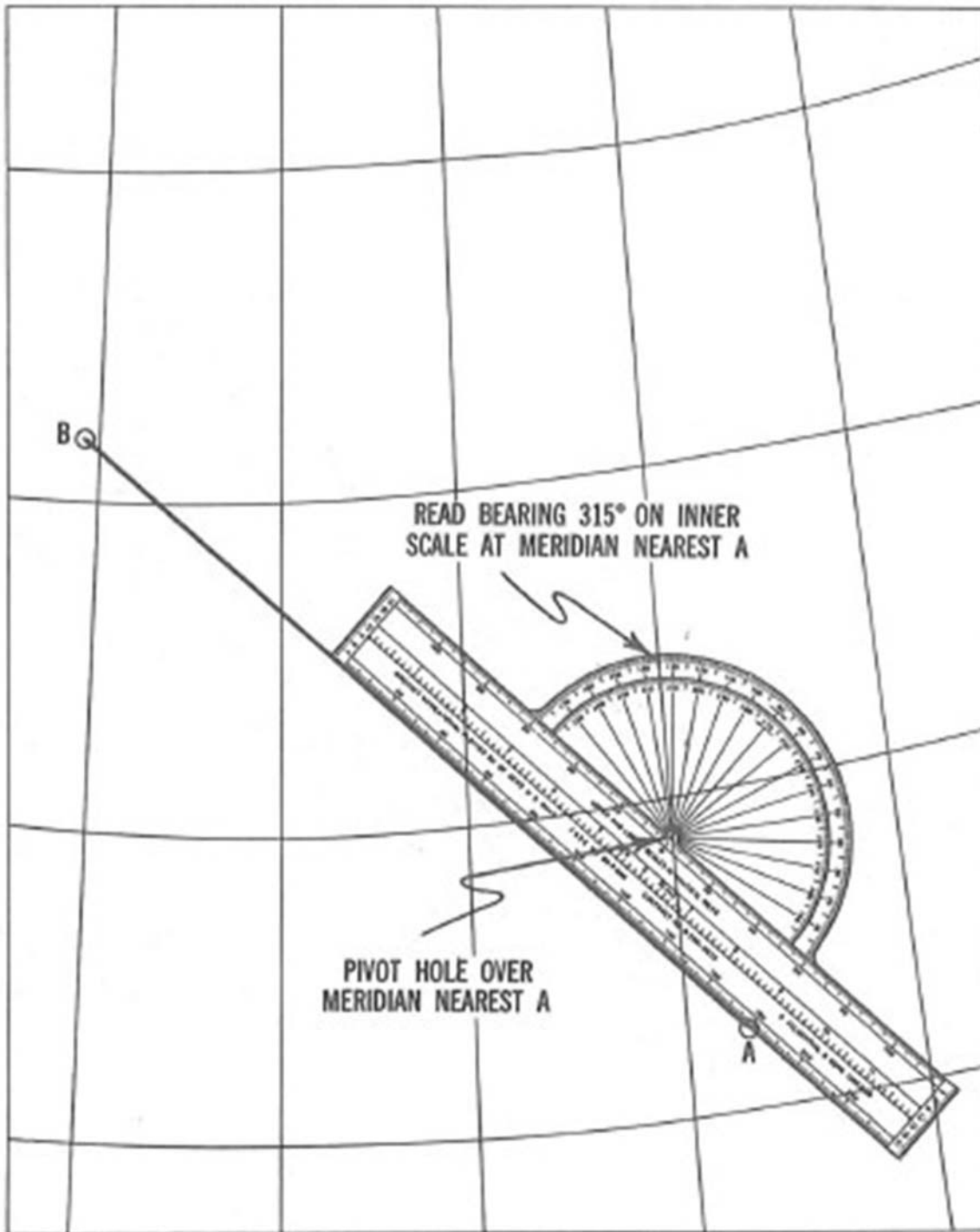
Figure 3319b. Measuring a bearing on a Lambert conformal chart. Note that the measurement is made at the meridian nearest the ship.

For plotting grid directions, angles are measured from grid north, using any grid meridian. Any convenient method can be used. If a protractor or plotter is being used for plotting grid directions, it is usually desirable to use the same instrument for plotting true directions. The distance is the same whether grid or true directions are used.

DEAD RECKONING

3320. Polar Dead Reckoning

In polar regions, as elsewhere, dead reckoning involves measurement of direction and distance traveled, and the use of this information for determination of position. Direction is normally determined by a compass (magnetic or gyrocompass), but in polar regions both magnetic and gyrocompasses are subject to certain limitations not encountered elsewhere. GNSS Global Navigation Satellite System can also provide an independent direction of movement using satellite signals and vessel motion, but this should not be confused with the actual ship orientation. However, the navigator who thoroughly understands the use of these instruments in high latitudes can get much useful information from them. The polar navigator should not overlook the value of radar tracking or visual tracking for determining direction of motion in the absence of a GNSS. This is discussed in Section 3323.

If GNSS is not available, speed or distance is normally measured by log or engine r evolution counter at normal latitudes. These backup speed measurement methods are not entirely suitable when the ship is operating in ice. The problem of determining speed or distance in ice without GNSS is discussed in Section 3323.

3321. Magnetic Compass

The magnetic compass directive force depends upon the horizontal intensity of the magnetic field of the earth. As the magnetic poles are approached, the opposing force on the compass card becomes progressively weaker until at some point the magnetic compass becomes useless as a direction-measuring device. In a marginal area it is good practice to keep the magnetic compass under almost constant scrutiny, as it will be somewhat erratic in dependability and its errors may change rapidly. Frequent compass checks by celestial observation or any other method available are wise precautions. A log of compass comparisons and observations is useful in predicting future reliability.

The magnetic poles themselves are somewhat elusive, since they participate in the normal diurnal, annual, and secular changes in the earth's field, as well as the more erratic changes caused by magnetic storms. Measurements indicate that the north magnetic pole moves within an elongated area of perhaps 100 miles in a generally north-south direction and somewhat less in an east-west direction. Normally, it is at the southern end of its area of movement at local noon and at the northern extremity twelve hours later, but during a severe magnetic storm this motion is upset and becomes highly erratic. Because of the motions of the poles, they are sometimes regarded as areas rather than points. There is some evidence to support the belief that

several secondary poles exist, although such alleged poles may be anomalies (local attractions), possibly of intermittent or temporary existence. Various severe anomalies have been located in polar areas and others may exist.

The continual motion of the poles may account, at least in part, for the large diurnal changes in variation encountered in high latitudes. Changes as large as 10° have been reported.

The decrease in horizontal intensity encountered near the magnetic poles, as well as magnetic storms, affects the magnetic deviation. Any deviating magnetic influence remaining after adjustment, which is seldom perfect, exerts a greater influence as the directive force decreases. It is not uncommon for residual deviation determined in moderate latitudes to increase 10- or 20-fold in marginal areas. Interactions between correctors and compass magnets exert a deviating influence that may increase to a troublesome degree in high latitudes. The heeling magnet, correcting for both permanent and induced magnetism, is accurately located only for one magnetic latitude. Near the magnetic pole its position might be changed, but this may induce sufficient magnetism in the Flinders bar to more than offset the change in deviation due to the change in the position of the heeling magnet. The relatively strong vertical intensity may render the Flinders bar a stronger influence than the horizontal field of the earth. When this occurs, the compass reading remains nearly the same on any heading.

Another effect of the decrease in the directive force of the compass is a greater influence of frictional errors. This combined with an increase in the period of the compass, results in greatly increased sluggishness in its return to the correct reading after being disturbed. For this reason the compass performs better in a smooth sea free from ice than in an ice-infested area where its equilibrium is frequently upset by impact of the vessel against ice.

Magnetic storms affect the magnetism of a ship as well as that of the earth. Changes in deviation of as much as 45° have been reported during severe magnetic storms, although it is possible that such large changes may be a combination of deviation and variation changes.

The area in which the magnetic compass is of reduced value cannot be stated in specific terms. A magnetic compass in an exposed position performs better than one in a steel pilot house. The performance of the compass varies considerably with the type of compass, sensibility and period, thoroughness of adjustment, location on the vessel, and magnetic properties of the vessel. It also varies with local conditions.

Based on the World Magnetic Model (WMM) 2015 coefficients the geomagnetic north pole is at 72.62°W longitude and 80.37°N latitude, and the geomagnetic south pole is at 107.38°E longitude and 80.37°S latitude. The axis

US/UK World Magnetic Model - Epoch 2015.0

Main Field Declination (D)

Main field declination (D)
Contour interval: 2 degrees, red contours positive (east); blue negative (west); green (agonic) zero line.
North Polar Region. Polar Stereographic Projection.
⚛ Position of dip poles

Map developed by NOAA/NGDC & CIRES
http://ngdc.noaa.gov/geomag/WMM
Map reviewed by NGA and BGS
Published December 2014

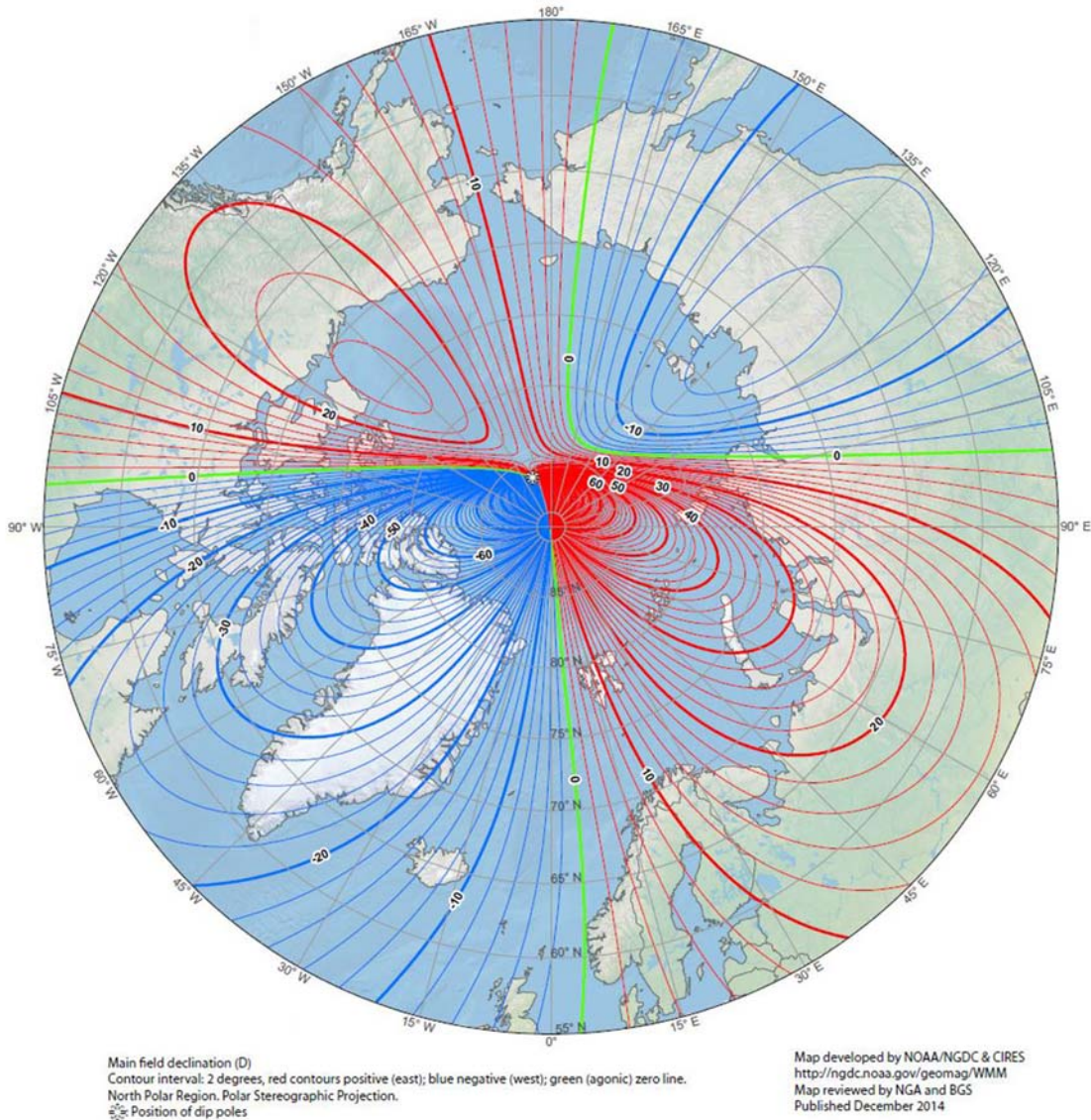*Figure 3321a. Main magnetic field declination for the North pole in 2015.*

of the dipole is currently inclined at 9.69° to the Earth's rotation axis. The WMM can also be used to calculate dip pole positions. These model dip poles are computed from all the Gauss coefficients using an iterative method. In 2015 the north dip pole computed from WMM2015 is located at longitude 159.18°W and latitude 86.27°N and the south dip pole at longitude 136.59°E and latitude 64.26°S.

In a very general sense the magnetic compass can be considered of *reduced* reliability when the horizontal intensity is less than 0.09 oersted, *erratic* when the field is less than 0.06 oersted, and *useless* when it is less than 0.03 oersted. Figure 3321a and Figure 3321b shows lines of equal

horizontal intensity in the north and south polar regions, respectively. However, the effectiveness of the magnetic compass is influenced also by local conditions. A compass on a vessel making a voyage through the islands of the Canadian archipelago has been reported to give fair indication of direction in certain small areas where the horizontal intensity is less than 0.02 oersted, yet to be useless at some places where the horizontal intensity is greater than 0.04 oersted.

Despite its various limitations, the magnetic compass is a valuable instrument in much of the polar regions, where the gyrocompass is also of reduced reliability. With careful
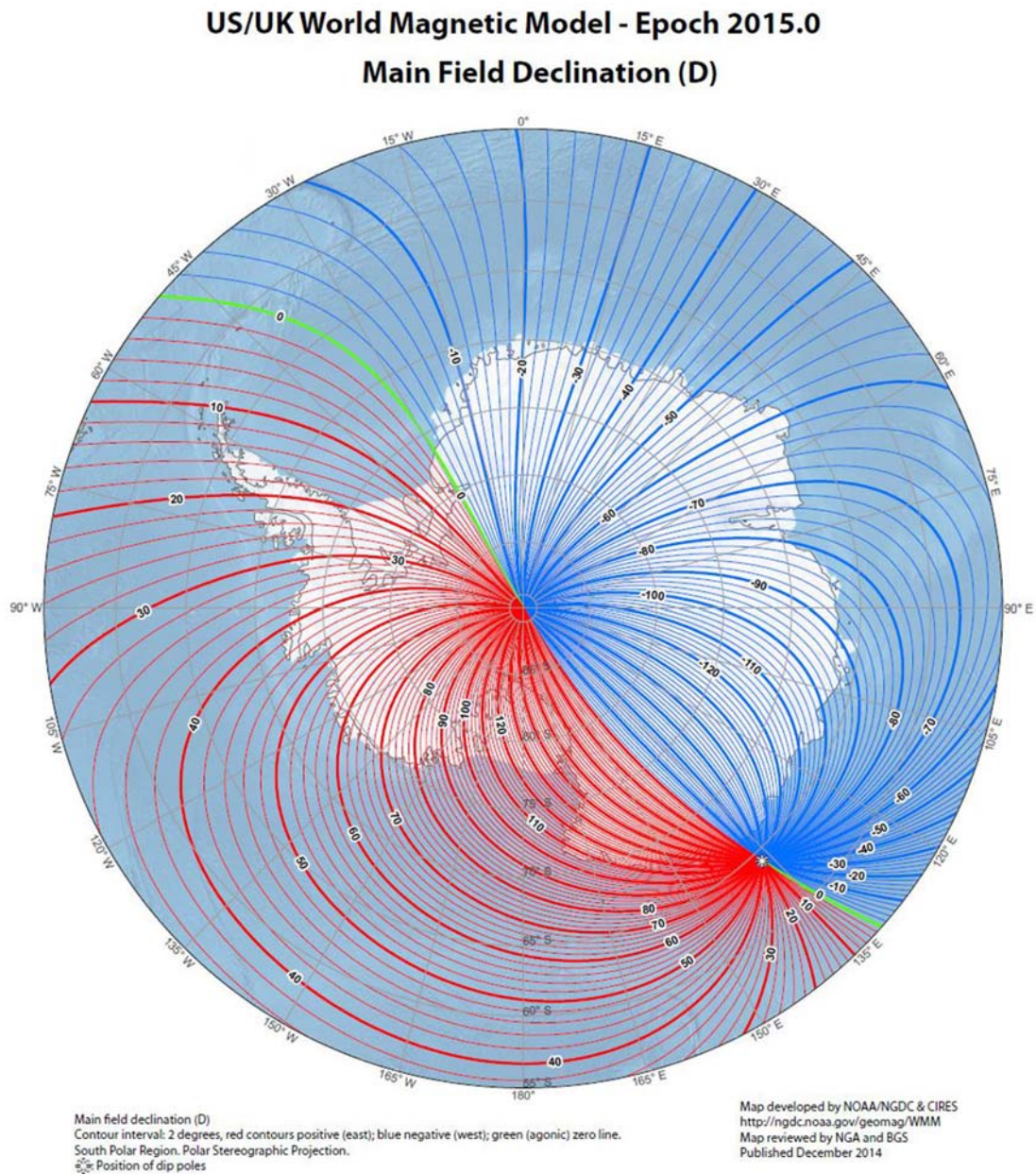
Figure 3321b. Main magnetic field declination for the South pole in 2015.

adjustment, frequent checks, and a record of previous be-
havior, polar navigators can get much useful service from
their instruments.

When a compass is subjected to extremely low tem-
peratures, there is danger of the liquid freezing. Sufficient
heat to prevent this can normally be obtained from the com-
pass light, which should not be turned off during severe
weather.

To learn more about the magnetic poles see the
NGA/NOAA World Magnetic Model (WMM) website and
model derivation report via the links provided in Figure and
Figure.

3322. Gyrocompass

The gyrocompass depends upon the rotation of the
earth about its axis. Its maximum directive force is at the
equator, where the axis of the compass is parallel to the axis
of the earth. As latitude increases, the angle between these
two axes increases. At the geographical poles the gyrocom-
pass has no directive force.

The common gyrocompass is generally reliable to lati-
tude 75°N. North of 75°N special care must be taken in
checking its accuracy. Even with the compensation given
by the latitude corrector on certain makes of compass, the

World Magnetic Model (WMM)

Figure 3321c. World Magnetic Model website
https://www.ngdc.noaa.gov/geomag/WMM/limit.shtml

Figure 3321d. Report on the US/UK World Magnetic Model for 2015-2020.
https://www.ngdc.noaa.gov/geomag/WMM/data/WMM2015/WMM2015_Report.pdf

gyro continues to lose horizontal force until, north of about 85°N, it generally becomes unusable. At higher latitudes the disturbing effect of imperfections in compass or adjustment is magnified. Latitude adjustment becomes critical. Speed error increases as the speed of the vessel approaches the rotational speed of the earth. Ballistic deflection error becomes large and the compass is slow to respond to correcting forces. Frequent changes of course and speed, often necessary when proceeding through ice, introduce errors which are slow to settle out. The impact of the vessel against ice deflects the gyrocompass, which does not return quickly to the correct reading.

Fiber optic gyros now have an accuracy of 1.5° at 75°N. At 85°N the accuracy is 4.5° and at 89°N the accuracy is 22° degrees. No gyro that measures the earth's rotation will work well at such high latitudes.

Gyrocompass error scales as a function of 1/cos (Latitude), so the error increases and becomes more erratic as the vessel proceeds to higher latitudes. At latitude 75° the gyro error should be determined frequently, perhaps every four hours, by means of celestial bodies when these are available. As the error increases and becomes more erratic, with higher latitude, it should be determined more frequently. In heavy ice at extreme latitudes an almost constant check is desirable. The gyro and magnetic compasses should be compared frequently and a log kept of the results of these comparisons and the gyro error determinations.

Most gyrocompasses may not be provided with a latitude correction setting above 70°N. Beyond this, correction can be made by either of two methods: (1) set the latitude and speed correctors to zero and apply a correction from a table or diagram obtainable from the manufacturer of the compass, or (2) use an equivalent latitude and speed setting. Both of these methods have proved generally satisfactory, although the second is considered superior to the first because it at least partly corrects for errors introduced by a change in course. In certain types of gyrocompasses, facilities for their operation in a high latitude mode, up to about 86°N, and as directional gyros, even to the poles, is provided.

The manual for the gyro compass should be consulted before entering higher latitudes. The numerous alterations in course and speed and collisions with ice can have an adverse effect on its accuracy. Therefore, when navigating in the Arctic:

- the ship's position should be cross-checked with other navigation systems, such as electronic position fixing devices, where course history could be compared with course steered (allowing for wind and current); and
- the gyro error should be checked whenever atmospheric conditions allow, by azimuth or amplitude.

Since most modern vessels use integrated digital navigation systems, an incorrect ship heading may cause erroneous position estimates if using radar fixes (with bearings having the same error as the gyrocompass). This was a factor in the *SS HANSEATIC* grounding in 1996 in the Canadian Arctic.

3323. Distance and Direction in Ice

In ice-free waters, distance or speed is determined by the installed GNSS and Electronic Chart Display and Information System (ECDIS), or Voyage Management System (VMS). As a backup, some form of log or engine revolution counter may be used as in non-polar operations, but there are some additional error sources. In the presence of ice, however, most logs are inoperative or inaccurate due to clogging by the ice. Engine revolution counters are not accurate speed indicating devices when a ship is forcing its way through ice. With experience, one can estimate the speed in relation to ice, or a correction can be applied to speed by engine revolution counter. However, these methods seldom provide desired accuracy.

If ranges and bearings of a land feature can be determined either visually or by radar, course and speed of the vessel ·or distance traveled over the ground can be determined by tracking the landmark and plotting the results. The feature used need not be identified. Ice can be used if it is grounded or attached to the shore. Course and speed or distance through the water can be approximately determined by tracking a floating iceberg or other prominent

floating ice feature. However, an error may be introduced by this method if the effect of wind and current upon the floating feature is different than upon the ship.

3324. Tide, Current and Wind

In general, tidal ranges are small, and the water in most anchorages is relatively deep, however, most tide tables do not extend into polar regions. NOAA manages a number of tide and current stations on the Alaskan coast. Information on Alaskan tides and currents is therefore available from the NOAA website.

Currents in many coastal areas are strong and somewhat variable. When a vessel is operating in ice, the current is often difficult to determine because of frequent changes in course and speed of the vessel and inaccuracies in the measurement of direction and distance traveled.

In the vicinity of land, and in the whole Antarctic area, winds are variable in direction, gusty, and often strong. Offshore, in the Arctic Ocean, the winds are not strong and are steadier, but ships rarely operate in this area. The wind in polar regions, as elsewhere, has two primary navigational effects upon vessels. First, its direct effect is to produce leeway. When a vessel is operating in ice, the leeway may be different from that in open water. It is well to determine this effect for one's own vessel. The second effect is to produce wind currents in the sea.

3325. Conclusion to Polar Dead Reckoning

Because of the potential for loss of GNSS or other aids for fixing the position of a vessel in polar regions, accurate dead reckoning as a backup is even more important than elsewhere. The problem is complicated by the fact that the elements of dead reckoning, direction and distance, are usually known with less certainty than in lower latitudes. This only heightens the need for keeping the dead reckoning with all the accuracy obtainable. This may usually be accomplished by careful hand plotting on the available paper charts or plotting sheets.

PILOTING

3326. Piloting in High Latitudes

Piloting is associated with proximity to land and shoal water, and is basically no different in high latitudes than elsewhere. Piloting is characterized by an alertness not required when a vessel is far from danger of grounding. Nowhere is this alertness more necessary than in polar regions. Added to the usual reasons for constant vigilance are the uncertainties of charted information and the lack of detail, as discussed in Section 3311. Navigators should review "Sailing Directions Pub 180 Planning Guide Arctic Ocean" for tide, current and other piloting information (see Section 3333), along with other nations' sailing directions if available.

3327. Landmarks

Natural landmarks are plentiful in some areas, but their usefulness is restricted by the difficulty in identifying them, or locating them on the chart. Along many of the coasts the various points and inlets bear a marked resemblance to each other. The appearance of a coast is often very different when many of its features are obfuscated by a heavy covering of snow or ice than when it is ice-free.

3328. Bearings

Bearings are useful, but have limitations. When bearings on more than two objects are taken, they may fail to intersect at a point because the objects may not be charted in their correct relation to each other. Even a point fix may be considerably in error geographically if all of the objects used are shown in correct relation to each other, but in the wrong position on the earth. However, in restricted waters it is usually more important to know the position of the vessel relative to nearby land and shoals than its latitude and longitude. The bearing and distance of even an unidentified or uncharted point are valuable.

When a position is established relative to nearby landmarks, it is good practice to use this to help establish the identity and location of some prominent feature a considerable distance ahead, so that this feature, in turn, can be used to establish future positions.

In high latitudes it is not unusual to make use of bearings on objects a considerable distance from the vessel. Because of the rapid convergence of the meridians in these areas, such bearings are not correctly represented by straight lines on a Mercator chart. Additionally, as previously noted, bearing accuracy may be degraded at higher latitudes. If this projection is used, the bearings should be corrected in the same manner that radio bearings are corrected (using table 1), since both can be considered great circles. Neither visual nor radio bearings are corrected when manually plotted on a Lambert conformal or polar stereographic chart.

3329. Soundings

Soundings are so important in polar regions that echo sounders are customarily operated continuously while the vessel is underway. It is good practice to have at least two such instruments, preferably those of the recording type and having a wide flexibility in the range of the recorder. Since depth of water is a primary consideration to avoid ground-

ing, a constant watch should be maintained to avoid unobserved shoaling.

Polar regions have relatively few shoals, but in some areas, notably along the Labrador coast, a number of pinnacles and ledges rise abruptly from the bottom. These constitute a real danger to vessels, since they are generally not surrounded by any apparent shoaling. In such an area, or when entering an unknown harbor or any area of questionable safety, it is good practice to send one or more small craft ahead with portable sounding gear.

In very deep water, of the order of 1,000 meters or more, the echo returned from the bottom is sometimes confused by the sound of ice coming in contact with the hull, but this is generally not a problem when the bottom is close enough to be menacing.

If a ship becomes **beset** by ice, so that steerage way is lost and the vessel drifts with the ice, it may be in danger of grounding as the ice moves over a shoal. Hence, it is important that soundings be continued even when beset. If necessary, a hole should be made in the ice and a hand lead used. A vessel with limited means for freeing itself may prudently save such means for use only when there is danger of grounding.

Useful information on the depth of water in the vicinity of a ship can sometimes be obtained by watching the ice. A stream of ice moving faster than surrounding ice, or a stretch of open water in loose pack ice often marks the main channel through shoal water. A patch of stationary ice in the midst of moving ice often marks a shoal.

Knowledge of earth formations may also prove helpful. The slope of land is often an indication of the underwater gradient. Shoal water is often found off low islands, spits, etc., but seldom near a steep shore. Where glaciation has occurred, the moraine deposits are likely to have formed a bar some distance offshore. Submerged rocks and pinnacles are more likely to be encountered off a rugged shore than near a low, sandy beach.

3330. Anchorage

Because good anchorages are not plentiful in high latitudes, there is an understandable temptation to be less demanding in their selection. This is dangerous practice, for in polar regions some of the requirements are accentuated. The factors to be considered are:

1. *Holding quality of the bottom*. In polar regions a rocky bottom or one with only fair to poor holding qualities is not uncommon. Sometimes the bottom is steep or irregular. Since the nature of the bottom is seldom adequately shown on charts, a wise precaution is to sample the bottom, and sound in the vicinity before anchoring.
2. *Adequate room for swing*. Because high winds are frequent along polar shores, sometimes with little or no warning, a long scope of anchor chain is customarily used. Some harbors are otherwise suitable, but allow inadequate room for swing of the vessel at anchor, or even for its yaw in a high wind. If a vessel is to anchor in an unsurveyed area, the area should first be adequately covered by small boats with portable sounding gear to detect any obstructions.
3. *Protection from wind and sea*. In polar regions protection from wind is probably the most difficult requirement to meet. Generally, high land is accompanied by strong wind blowing directly down the side of the mountains. Polar winds are extremely variable, both in direction and speed. Shifts of 180° accompanied by an increase in speed of more than 50 knots in a few minutes have been reported. It is important that ground tackle be in good condition and that maximum-weight anchors be used. All available weather reports should be obtained and a continuous watch kept on the local weather. Whenever a heavy blow might reasonably be anticipated, the main engines should be kept in an operating condition and on a standby status. Heavy seas are seldom a problem.
4. *Availability of suitable exit in event of extreme weather*. In ice areas it is important that a continuous watch be kept to prevent blocking of the entrance by ice, or actual damage to the vessel by floating ice. However, in an unsurveyed area it may be dangerous to shift anchorage without first sounding the area. It is a wise precaution to do this in advance. Unless the vessel is immediately endangered by ice, it is generally safer to remain at anchor with optimum ground tackle and use of engines to assist in preventing dragging, than to proceed to sea in a high wind, especially in the presence of icebergs and growlers, and particularly during darkness.
5. *Availability of objects for position determination*. The familiar polar problem of establishing a position by inaccurately charted or inadequately surveyed landmarks is accentuated when an accurate position is desired to establish the position of an anchor. Sometimes a trial and error method is needed, and it may be necessary to add landmarks located by radar or visual observation. Because of chart inadequacy, the suitability of an anchorage, from the standpoint of availability of suitable landmarks, cannot always be adequately predicted before arrival.

An unsurveyed harbor should be entered with caution at slow speed, with both the pilot house and engine room watch-standers alerted to possible radical changes in speed or course with little or no warning. The anchor should be kept ready for letting go on short notice and should be adequately attended. An engine combination providing full

backing power should be maintained.

3331. Sailing Directions

Sailing directions for high latitudes contain a wealth of valuable information acquired by those who have previously visited the areas. However, since high latitudes have not been visited with the frequency of other areas, and since these areas may have inadequate surveys, the sailing directions for polar areas are neither as complete nor as accurate as for other areas, and information on unvisited areas is completely lacking. Until traffic in high latitudes increases and the sailing directions for these areas incorporate the additional information obtained, unusual caution should accompany their use. Each vessel that enters polar regions can help correct this condition by recording accurate information and sending it to the National Geospatial-Intelligence Agency (NGA) or its counterpart in other countries. The latest edition of *Sailing Directions, Publication 180 Arctic Ocean*, should be on board for any mariners planning polar operations. *Sailing Directions* are available online via the link provided in Figure 3331a

For additional information on the Arctic and ice navigation in Canadian waters see the link provided in Figure 3331b.

Figure 3331a. Sailing Directions (Planning Guides)
https://msi.nga.mil/NGAPortal/MSI.portal?_nfpb=true&_pageLabel=msi_portal_page_62&pubCode=0011

Figure 3331b Ice Navigation in Canadian Waters.
http://www.ccg-gcc.gc.ca/folios/00913/docs/ice-navigation-dans-les-galces-eng.pdf

ELECTRONICS AND POLAR NAVIGATION

3332. Propagation

In general, radio wave propagation in high latitudes follows the same principles that apply elsewhere, as described in Chapter 21. However, certain anomalous conditions occur, and although these maybe imperfectly understood, and experience to date has not always seemed consistent, there is much information that has been established. An understanding of these conditions is important if maximum effective use is to be made of electronics in high latitudes. Such anomalous conditions are discussed in Chapters 21 and 24.

3333. Radar

In polar regions, where fog and long periods of continuous daylight or darkness reduce the effectiveness of both celestial navigation and visual piloting, and where other electronic aids are generally not available, radar is particularly valuable. Its value is further enhanced by the fact that polar seas are generally smooth, resulting in relatively little oscillation of the shipborne antenna. When ice is not present, relatively little sea return is encountered from the calm sea. In general, Arctic or cold conditions do not affect the performance of radar systems. Occasionally weather conditions may cause ducting, which is the bending of the radar beam because of a decline in moisture content in the atmo-

sphere. This effect may shorten or lengthen target detection ranges, depending on the severity and direction of the bending. A real problem with radar in the Arctic concerns interpretation of the screen for purposes of position fixing. Problems encountered with position fixing arise from either mistaken identification of shore features or inaccurate surveys. Low relief in some parts of the Arctic make it hard to identify landmarks or points of land. Additionally, ice piled up on the shore or fast ice may obscure the coastline. For this reason radar bearings or ranges should be treated with more caution than measurements in southern waters. Visual observations are always preferable. Sometimes it is possible to fix the position of grounded icebergs and then to use the iceberg for positioning further along the track, if performed with caution.

Large areas of the Arctic have not yet been surveyed to the same standards as areas further south, and even some of the more recently produced charts are based on aerial photography. To decrease the possibility of errors, three lines (range, or less preferably bearings) should always be used for positions. Fixes using both sides of a channel or lines from two different survey areas should be avoided. Because of potential problems, fixes in the Arctic should always be compared with other information sources, such as electronic positioning systems.

However, certain limitations affect the use of radar in polar regions. Similarity of detail along the polar shore is

even more apparent by radar than by visual observation. Lack of accurate detail on charts adds to the difficulty of identification. Identification is even more of a problem when the shoreline is beyond the radar horizon and accurate contours are not shown on the chart. When an extensive ice pack extends out from shore, accurate location of the shoreline is extremely difficult.

Good training and extensive experience are needed to interpret accurately the returns in polar regions where ice may cover both land and sea. A number of icebergs close to a shore may be too close together to be resolved, giving an altered appearance to a shoreline, or they may be mistaken for off-lying islands. The shadow of an iceberg or pressure ridge and the lack of return from an open lead in the ice may easily be confused. Smooth ice may look like open water. In making rendezvous, one might inadvertently close on an iceberg instead of a ship.

As with visual bearings, radar bearings need correction for convergency unless the objects observed are quite close to the ship.

3334. Electronic Charts

All United States chart now use the WGS-84 Datum and ellipsoid to match the output of the GPS system, so use of any voyage management product that employs both NGA chart products and GPS will not have a datum mismatch. The use of non-US government charts with GPS are a potential problem and the prudent navigator will ensure that the datums of the chart products match, as older products may still use local datums. Russian charts are based on the Krasovsky ellipsoid (Pulkova-42/SK-42). There are some reports that a 100-meter difference may exist in each axis between WGS-84 and Pulkova-42 along the Siberian coast.

3335. Inertial Navigation Systems

Modern military inertial navigation systems (INS) are designed to operate up to the North pole. The use of transverse coordinate systems (described in Section 3314) are typically required as the vessel reaches the very high latitudes, typically above about 85°N. Navigators must ensure that the INS is shifted to this mode and all understand the output of the information. Commercial INS may also function adequately at higher latitudes, but navigators should confirm their performance specification prior to entering the Arctic.

When operating in the Arctic, ships equipped with inertial navigation systems (INS) are required to switch to Transverse Mode to keep the INS solution from degrading when tangents approach zero and to make heading more useful. Transverse Mode is an alternative coordinate system which puts the virtual pole at the normal equator. Heading, Velocity, and Position all change to Transverse Heading (THD), Transverse North and East Velocity (TNV/TEV), and Transverse Lat/Lon (TLT/TLN) when in Transverse Mode.

Military marine INS are designed to function at 90° N. The AN/WSN-7A RLGN has been successfully operated in the Arctic, and at the North Pole (using transverse mode) under a variety of conditions without faults, and it is expected that all future military INS will have similar capabilities.

3336. Global Navigation Satellite Systems (GNSS)

Global satellite navigation systems (GPS, GLONASS, Gallileo, Beidu), are particularly useful in the Arctic because of the scarcity of aids of shorter range. Such short range aids as may be in existence are subject to damage or failure by ice or storms, or other causes. Ice and storm damage may be widespread and require considerable time to repair. Isolated damage may exist for a long time without being discovered and reported.

Some limitations of GNSS must be understood. Since the fielded GNSS are in orbit planes that are at an angle to the equator, GNSS will appear at reduced elevations. For example, GPS has 55 degree orbit planes, thus no satellite altitude higher than 35° degrees will be visible at the North pole. Galileo is similar at 56 degrees, but GLONASS is slightly better with a 65 degree orbit plane.

Because of GNSS receiver mask angles, lower altitude satellites may be removed from calculations; thus, there may be fewer satellites available to the navigator at any given time. Navigators may need to adjust altitude mask angle on receivers to increase number of available satellites, although this might add some increased uncertainty.

Low elevation angles in polar areas have the additional following impacts:

- low angles are good for the horizontal dilution of precision (HDOP), but bad for the vertical dilution of precision (VDOP)
- poorer altitude accuracy will be obtained
- Higher noise level in observations
- Larger ionospheric effects at lower elevation angles

Navigators must understand that there are sparse monitoring infrastructures by any of the GNSS or RF-based navigations systems including:

- Monitoring capability may be temporarily powered
- Poor real-time communication links
- Poor visibility of geostationary satellites
- Arctic area beyond reach of the Euro Geostationary Navigation Overlay Service (EGNOS) and the Wide Area Augmentation System (WAAS)
- GEO satellites low on horizon, visible only for brief periods

- No IALA differential beacons (300 kHz)
- Most RF communications are subject to ionosphere perturbations

If the datum used by the GPS receiver in calculating latitude and longitude is different from the datum of the chart in use, errors will occur when GPS derived positions are plotted on the chart. GPS receivers can be programmed to output latitude and longitude based on a variety of stored datums. The mariner must always ensure that the GPS position output is synchronized to the electronic or paper chart in use.

When GNSS satellite signals travel through the Earth's atmosphere, they are affected by the media of the RF transmission. In the ionosphere, the electromagnetic signals are affected mainly by free negatively charged electrons. The signals experience code delay and phase advance during the transition through the path.

The size of the effect on navigation is a function of the amount of electrons encountered by the signal, defined as the Total Electron Content (TEC). TEC is roughly correlated with the solar activity. The size of the signal delay is dependent on the frequency, i.e. different for GNSS frequencies. For example, it is reported that the typical signal delay causes an error on GPS L1 pseudo ranges of 5-15 meters during day time and 1-3 meters at night. These numbers are global averages with spatial and temporal variations dependent on the solar activity. In GNSS receivers and positioning algorithms the ionospheric effect should be handled by ionospheric models along with data collected from different frequencies and locations.

3337. GNSS Antennas

Antennas are another area of concern, as they can become ice fouled preventing reception, and should be deployed as high as possible to avoid multi-path RF reception problems. GNSS RF frequencies have reduced penetration power in water or ice.

3338. GPS Augmentation Systems

GPS receivers may have the ability to use augmentation systems, which can be either space-based augmentation systems (SBAS), such as Wide Area Augmentation System (WAAS), European Geostationary Navigation Overlay Service (EGNOS), and Multi-functional Satellite Augmentation System (MSAS), or terrestrial based augmentation systems like USCG's Differential GPS (DGPS).

For the SBAS systems, GPS correction data is transmitted to navigation users via geostationary satellites (GEO) which are located in the geostationary orbit at the Equator. Thus, the satellites are visible very low on the horizon at high latitudes. SBAS data reception can be often noisy and unreliable, and north of 81° N the satellites are not visible at all. The quality of the correction information is a function of the relative position of the reference station to the vessel used to calculate the corrections. Ground stations are being added. There are also ground stations for EGNOS at Jan Mayen Island and Svalbard Island, and corrections may be available in the Barents Sea from Eurofix. Mariners should consult the respective provides for reference station coverage and estimated accuracy for the intended area of operations.

SBAS suffer by the same limitations caused by ionospheric activity as satellite based positioning and navigation systems. In situations with increased ionospheric activity where ionospheric SBAS corrections really are needed for the EGNOS or WAAS user, the transmission of corrections might be disrupted by ionospheric perturbations.

It is reported that DGPS is also available along the Northern Sea Route (NSR), while there are no known DGPS stations along the Northwest Passage (NWP).

3339. Loran / CHAYKA

At present there is no LORAN coverage available in the Arctic. There is Russian CHAYKA coverage (Russian equivalent to LORAN) in the western part of the NSR, but a CHAYKA receiver must be employed.

3340. Radio Beacons

Other electronic aids exist in parts of the Arctic, particularly along the NSR of Russia. As of 2013, 47 radio beacons were reported along the NSR. Two types are reported to be in use, one with a range of 100 nm and the other with a range of 150 nm. It is also reported at there are radar reflectors along the NSR coast.

3341. Sonar

Sonar is useful primarily for detecting ice, particularly growlers. Since approximately 50%-85% of the ice is under water, its presence can sometimes be detected by sonar when it is overlooked by radar or visual observation.

CELESTIAL NAVIGATION

3342. Celestial Navigation in High Latitudes

Of the various types of navigation, celestial is perhaps

least changed in polar regions. However, certain special considerations are applicable. Because of the limitations of other forms of navigation, as discussed earlier in this chapter, celestial navigation provides the principal means of determining geographical position. However, as indicated in Section 3328, position relative to nearby dangers is usually of more interest to the polar navigator than geographical position. Since ships in high latitudes are seldom far from land, and since celestial navigation is attended by several limitations, discussed in Section 3343, its use in marine navigation is generally confined to the following applications:

1. Navigation while proceeding to and from polar regions;
2. Verifying the accuracy of dead reckoning;
3. Verifying the accuracy of charted positions of landmarks, shoals, etc.; and,
4. Providing a directional reference, either by means of a celestial compass or by providing a means of checking the magnetic or gyrocompass.

Although its applications are limited, celestial navigation is important in high latitudes. Application 3 above, and application 4, even more so, can be of great value to the polar navigator.

3343. Celestial Observations

The best celestial fixes are usually obtained by star observations during twilight. As the latitude increases, these periods become longer, providing additional time for observation. But with this increase comes longer periods when the sun is just below the horizon and the stars have not yet appeared. During this period, which in the extreme condition at the pole lasts for several *days*, no celestial observations may be available. The moon is sometimes above the horizon during this period and bright planets, notably Venus and Jupiter, may be visible. With practice, the brighter stars can be observed when the sun is 20° to 30° below the horizon.

Beyond the polar circles the sun remains above the horizon without setting during part of the summer. The length of this period increases with latitude. At Thule, Greenland, about 10° inside the Arctic Circle, the sun remains above the horizon for four months. During this period of continuous daylight the sun circles the sky, changing azimuth about 15° each hour. A careful observation, or the average of several observations, each two hours provides a series of running fixes. An even better check on position is provided by making hourly observations and establishing the most probable position at each observation. Sometimes the moon is above the horizon, but within several days of the new or full phase it provides lines of position nearly parallel to the sun lines and hence of limited value in establishing fixes.

During the long polar night the sun is not available and the horizon is often indistinct. However, the long twilight, a bright aurora, and other sources of polar light (Section 3305) shorten this period. By adapting their eyes to darkness, some navigators can make reasonably accurate observations throughout the polar night. The full moon in winter remains above the horizon more than half the time and attains higher altitudes than at other seasons.

In addition to the long periods of darkness in high latitudes, other conditions are sometimes present to complicate the problem of locating the horizon. During daylight the horizon is frequently obscured by low fog, frost smoke, or blowing snow, yet the sun may be clearly visible. Hummocked sea ice is sometimes a problem, particularly at low heights of eye. Nearby land or an extensive ice foot can also be troublesome. Extreme conditions of abnormal refraction are not uncommon in high latitudes, sometimes producing false horizons and always affecting the refraction and dip corrections.

Because of these conditions, it is advisable to be provided with an artificial horizon sextant (see Section 1415). This instrument is generally not used aboard ship because of the excessive acceleration error encountered as the ship rolls and pitches. However, in polar regions there is generally little such motion and in the ice there may be virtually none. Some practice is needed to obtain good results with an artificial-horizon sextant, but these results are sometimes superior to those obtainable with a marine sextant, and when some of the conditions mentioned above prevail, the artificial-horizon sextant may provide the only means of making an observation. Better results with this instrument can generally be obtained if the instrument is hung from some support, as it generally is when used in aircraft.

An artificial horizon, even an improvised one, (Section 1414) can sometimes be used effectively as by placing heavy lubricating oil in a bucket.

It is sometimes possible to make better observations by artificial-horizon sextant or artificial horizon from a nearby cake of ice than from the ship. Clouds and high fog are frequent in high latitudes, but it is not uncommon, particularly in the Antarctic, for the fog to lift for brief periods, permitting an alert navigator to obtain observations.

As the latitude increases, an error of time has less effect upon altitude. At the equator an error of 4 seconds in time may result in an error in the location of the position line of as much as 1 mile. At latitude 60° a position error of this magnitude cannot occur unless the timing error is 8 seconds. At 70° nearly 12 seconds are needed, and at 80° about 23 seconds are needed for such a position error.

Polaris is of diminished value in high northern latitudes because of its high altitude. At high latitudes the second correction to observed altitude (al) becomes greater. The almanac makes no provision for applying this beyond latitude 68°. Bodies at high altitudes are not desirable for azimuth determination, but if Polaris is used, the use of the actual azimuth given at the bottom of the Polaris tables of the *Nautical Almanac* is of increased importance because of

its larger variation from 000° in high latitudes. No azimuth is provided beyond latitude 65°.

In applying a sextant altitude correction for dip of the horizon, one should use height of eye *above the ice at the horizon*, instead of height above water. The difference between ice and water levels at the horizon can often be estimated by observing ice near the vessel.

3344. Low-Altitude observations

Because of large and variable refraction at low altitudes, navigators customarily avoid observations below some minimum, usually 5° to 15°, if higher bodies can be observed. In polar regions low-altitude observations are often the only ones available. The sun, moon, and planets remain low in the sky for relatively long periods, their diurnal motion being nearly horizontal. The only lower limit is that imposed by the horizon itself. In fact, good observations can sometimes be made without a sextant by noting the time at which either the upper or lower limb is tangent to the horizon. To such an observation sextant altitude corrections are applied as for a marine sextant without an index correction.

If a bubble or other artificial-horizon sextant is used, corrections are made as for higher altitudes, being careful to use the refraction value corrected for temperature, or to make a separate correction for air temperature. In addition, a correction for atmospheric pressure (Table 24) is applied if of sufficient size to be of importance.

3345. Abnormal Refraction and Dip

Tables of refraction correction are based upon a standard atmosphere. Variations in this atmosphere result in changes in the refraction, and since the atmosphere is seldom exactly standard, the mean refraction is seldom the same as shown in the tables. Variations from standard conditions are usually not great enough to be troublesome.

In polar regions, however, it is normal for the atmosphere to differ considerably from the standard, particularly near the surface. This affects both refraction and dip. Outside polar regions, variations in refraction seldom exceed 2' to 3', although extreme values of more than 30' have been encountered. In polar regions refraction variations of several minutes are not uncommon and an extreme value of about 5° has been reported. This would produce an error of 300 miles in a line of position. The sun has been known to rise as much as ten days before it was expected.

Most celestial observations in polar regions produce satisfactory results, but the high-latitude navigator should be on the alert for abnormal conditions, since they occur more often than elsewhere, and have greater extreme values. A wise precaution is to apply corrections for air temperature (Table 27) and atmospheric pressure (Table

28), particularly for altitudes of less than 5°.

Abnormal dip affects the accuracy of celestial observations equally at any altitude, if the visible horizon is used. Such errors may be avoided by using any one of four methods:

1. The artificial-horizon sextant may be used, as indicated in Section 3343.
2. When stars are available, three stars may be observed at azimuth intervals of approximately 120°, (or four at 90° intervals, five at 72°, etc.). Any error in dip *or refraction* will alter the size of the enclosed figure, but will not change the location of its center unless the dip or refraction error varies in different directions. The stars should preferably be at the same altitude.
3. The altitude of a single body may be observed twice, facing in opposite directions. The sum of the two readings differs from 180° by twice the sum of the index and dip corrections (also personal and instrument corrections, if present). This method assumes that dip is the same in both directions, an assumption that is usually approximately correct. Also, the method requires that the arc of the sextant be sufficiently long and the altitude of the body sufficiently great to permit observation of the back sight in the opposite direction. In making such observations, it is necessary that allowance be made for the change of altitude between readings. This may be done by taking a direct sight, a back sight, and then another direct sight at equal intervals of time, and using the average of the two direct sights.
4. A correction for the difference between air and sea temperatures may be applied to the sextant altitude. This will often provide reasonably good results. However, there is considerable disagreement in the manner in which temperature is to be measured, and in the factor to use for any given difference. Therefore, the validity of this correction is not fully established.

There is still much to be learned regarding refraction and even with all known precautions, results may occasionally be unsatisfactory.

3346. Sight Reduction

Sight reduction in polar regions is virtually the same as elsewhere. Computation can be made by nearly any method, or by use of common computer applications. One special method of considerable interest is applicable only within about 5° of the pole, a higher latitude than is usually attainable by ships. This is the method of using the pole as the assumed position. At this point the zenith and pole coincide and hence the celestial equator and celestial horizon also coincide, and the systems of coordinates based upon

these two great circles of the celestial sphere become identical. The declination is computed altitude, and GHA replaces azimuth. A "toward" altitude intercept is plotted along the upper branch of the meridian over which the body is located, and an "away" intercept is plotted in the opposite direction, along the lower branch. Such a line or its AP is advanced or retired in the usual manner. This method is a special application of the meridian altitude sometimes used in lower latitudes. Beyond the limits of this method the meridian altitude can be used in the usual manner without complications and with time of transit being less critical. However, Table 24, for reduction to the meridian, extends only to latitude 60°.

3347. Manual Plotting of LOPs

Lines of position from celestial observations in polar regions are plotted as elsewhere, using an assumed position, altitude intercept, and azimuth. If a paper Mercator chart is used, the error introduced by using rhumb lines for the azimuth line (a great circle) and line of position (a small circle) is accentuated. This can be overcome by using a chart on a more favorable projection.

If a chart with nonparallel meridians, such as the Lambert conformal, is used, the true azimuth should be plotted by protractor or plotter and measured at the meridian of the assumed position. On a chart having a grid overprint the true azimuth can be converted to grid azimuth, using the longitude of the assumed position, and the direction measured from any grid line. This method involves an additional step, with no real advantage.

Lines of position from high-altitude observations, to be plotted as circles with the geographical position as the center, should not be plotted on a paper Mercator chart because of the rapid change of scale, resulting in distortion of the circle as plotted on the chart.

Lines of position are advanced or retired as in any latitude. However, the movement of the line is no more accurate than the estimate of the direction and distance traveled, and in polar regions this estimate may be of less than usual accuracy. In addition to the problem of estimated direction of travel, the polar navigator may encounter difficulty in accurately plotting the direction determined. If an accurate gyrocompass is used, the ship follows a rhumb line, which is accurately shown only on a Mercator chart. If a magnetic compass is used, the rapid change in variation may be a disturbing factor. If the ship is in ice, the course line may be far from straight.

Because of the various possible sources of error involved, it is good practice to avoid advancing or retiring lines for a period longer than about two hours. When the sun is the only body available, best results can sometimes be obtained by making an observation every hour, retiring the most recent line one hour and advancing for one hour the line obtained two hours previously. The present position is then obtained by dead reckoning from the running fix of an hour before. Another technique is to advance the one or two previous lines to the present time for a running fix. A third method is to drop a perpendicular from the dead reckoning or estimated position to the line of position to obtain a new estimated position, from which a new dead reckoning plot is carried forward to the time of the next observation. A variation of this method is to evaluate the relative accuracy of the new line of position and the dead reckoning or estimated position run up from the previous position and take some point between them, halfway if no information is available on which to evaluate the relative accuracies. None of these techniques is suitable for determining set and drift of the current.

3348. Rising, Setting and Twilight

Rising, setting, and twilight data are tabulated in the almanacs to latitude 72°N and 60°S. Within these limits the times of these phenomena are determined as explained in Chapter 17, The Almanacs.

Beyond the northern limits of these tables the values can be obtained from a series of graphs given near the back of the Air Almanac. For high latitudes, graphs are used instead of tables because graphs give a clearer picture of conditions, which may change radically with relatively little change in position or date. Under these conditions interpolation to practical precision is simpler by graph than by table. In those parts of the graph which are difficult to read, the times of the phenomena's occurrence are themselves uncertain, being altered considerably by a relatively small change in refraction or height of eye. The use of the graphs is explained in Chapter 17, The Almanacs.

SUMMARY

3349. Knowledge of Polar Regions

Operations in polar regions are attended by hazards and problems not encountered elsewhere. Lack of knowledge, sometimes accompanied by fear of the unknown, has prevented navigation in these areas with the same confidence that is pursued in more familiar areas. As experience in high latitudes has increased, much of the mystery surrounding these areas has been dispelled, and operations have become more predictable.

Before entering polar regions, navigators will do well to acquaint themselves with the experience of those who have preceded them into the areas and under the conditions they anticipate. This information can be found in the growing literature composed from the accounts of explorers, reports of previous operations in high latitudes, articles in professional journals, and several books on operations in polar regions. Some of it is published in various volumes of

sailing directions.

The search for knowledge should not be confined to navigation. The wise polar navigator will seek information on living conditions, survival, geography, ice, climate and weather, and operational experience of others who have been to the same area. As elsewhere, knowledge and experience are valuable. The Encyclopedia of the Arctic (3 Volumes), Mark Nuttall Editor is the reference for all things "arctic" from Archaeology to Zagoskin (ie Lavrentii Zagoskin), and includes chapters on weather, wildlife, politics, history, oceanography, environment and indigenous peoples.

3350. Planning

Planning, important in any operation, is vital to the success of polar navigation. The first step to adequate planning is the acquisition of full knowledge, as discussed in Section 3349. No item, however trivial, should escape attention. The ship should be provided with all the needed charts, publications, and special navigational material. All available data and information from previous operations in the area should be studied. Key personnel should be adequately instructed in polar navigation prior to departure or while enroute to the polar regions. Forecasts on anticipated ice and weather conditions should be obtained before getting under way. All equipment should be in top operating condition.

All material should be carefully inspected for completeness and accuracy. The navigator should make certain that all items of equipment are familiar to those who will use them. This is particularly true of items not generally used at sea, such as charts on an unfamiliar projection, or a bubble sextant. Do not assume anything that can be known. Successful polar navigation depends on adequate and thorough advanced planning and preparation.

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