1. Introduction

Countless tales of mariners whose ships have been trapped, lost, crippled, or sunk while navigating in winter or in the frigid passages of the North are a stark reminder of the challenges and hazards of operating a vessel in ice-covered waters.

It is easy to underestimate the strength and thickness of ice—which, at times, can be as solid as rock. Depending on the speed and structure of a ship, a collision between the two could be disastrous. Adding to the danger is the fact that localized fog often forms in the area where the ice edge and open water meet.

Changes in the consistency of the water due to the formation of ice crystals can also increase fuel consumption, and could lead to a vessel becoming stranded in extremely cold conditions.

While ice floes can provide shelter from rough seas and reduce vessel icing caused by freezing spray, mariners operating in or near ice-covered waters must factor extra precautions into their planning. They must also have the knowledge, equipment, and crew needed to navigate safely in such conditions.

This chapter provides basic information on the properties of different types of ice, how the local environment and weather influence ice conditions, and how to read and interpret ice and iceberg charts. Additional information is available in Chapter 4 of the Canadian Coast Guard publication Ice Navigation in Canadian Waters. Current and expected ice conditions can be found here.
2. Types of Ice

Three types of ice affect marine navigation: freshwater ice (found in lakes and rivers), sea ice (found in oceans), and icebergs (found in oceans, but created from freshwater glaciers).

Not all are the same. The strength and thickness of ice and the way it forms, moves, melts, and breaks up depends on a variety of different factors. Ice formation, for example, is affected primarily by the salinity (or salt content) of the water.

2.1 Freshwater Ice

Fresh water—that is, water that has a salinity of less than 1 gram per kilogram—starts to freeze at approximately 0°C. Freshwater ice forms on inland lakes and rivers at times of the year when the temperature is below freezing for an extended period of time.

2.1.1 Formation

As fresh water cools, it becomes increasingly dense until it reaches what is known as “maximum-density temperature”, which is approximately 4°C. As it drops below this temperature, the opposite occurs, and its density decreases—causing the cooler water to float to the surface. Once it reaches the freezing point, it forms a layer of ice. Ice forms in a different way on lakes than it does on rivers, where it is affected by fast-moving currents and other physical features, such as bends and narrows.

2.1.1.1 Lake Ice

The depth of the water and the strength of the currents in a lake determine where ice will form and how thick it will be.

When the temperature of the air drops below the temperature of the lake, the layer of water at the surface begins losing its heat to the atmosphere. As it cools and becomes more dense, this water sinks and is replaced by warmer water from below.
This “mixing” continues until all of the water in the lake has reached maximum-density temperature, at which point it stops. As the top layer of water continues to cool, it drops below maximum-density temperature, becoming less dense—and, therefore, lighter—than the water below it. As a result, it remains at the surface.

The cooling process in this top layer of water is accelerated because mixing has ceased. It happens even faster if there is a brisk wind, which cools the surface the same way it does exposed skin. Once the water at the surface reaches the freezing point, ice crystals (or “frazil” ice) begin to form and thicken. These soupy conditions can make it difficult for small boats to navigate and can cause watercraft of all sizes to burn more fuel than usual.

As the crystals freeze together, they create a layer of ice on the surface of the lake, which thickens slowly as the water beneath it cools to freezing through conduction, or contact with the ice. By acting as an insulator, the surface ice allows water near the bottom of larger lakes to remain well above freezing throughout the winter.

2.1.1.2 River Ice

Bends and narrows, the depth of the water, and the strength of the currents in rivers determine where ice will form and how thick it will be.

Ice forms first where the currents are weakest and the water is shallowest—often, near the banks of the river. As the air temperature drops further, clumps of frazil ice begin to form. These eventually float to the surface, where they freeze together to create “ice pans”.

These ice pans, which are rough-edged from colliding with one another as they move with the current, can impede boats and cause damage to hulls and engines. They become an even more severe hazard when they freeze together to create larger “ice rafts”. Ice pans and rafts
often get caught and freeze together at bends, narrows, and bridges, causing ice to accumulate upstream of these areas as well.

The ice cover on a river grows thicker in two ways. One is through the same conduction process that occurs on lakes; the other is when the weight of the snow on the surface of the ice is heavy enough to push it down into the water, causing the water below to rise up onto the surface and freeze.

Although ice cover on a river can be significant, there are parts that may never fully freeze due to rapid currents and fluctuations in water level. As a result, sections of ice that appear to be as thick as others may, in fact, be much thinner.

2.1.2 Decay
Ice decays—in other words, it melts and breaks up—at different times and at different rates depending on a variety of local factors and the characteristics of the ice itself. In the same way that ice forms differently on lakes and rivers, it also decays differently.

2.1.2.1 Lake Ice
Lake ice decays mainly through two methods: melting caused by the sun’s radiation and pools of meltwater on the surface of the ice; and heat conduction from the surrounding land and warmer water flowing under the ice from streams or runoff.

As air temperatures increase and meltwater ponds form on the ice’s surface, the ice begins to lose strength.
Eventually, the thinnest parts and those in contact with the land reach 0°C and begin to melt. As portions of the lake become ice-free, and the water is heated directly by the sun, this process speeds up.

2.1.2.2 River Ice
Ice cover on rivers also decays by melting in place, as it does on a lake. As it breaks up, the pieces are then carried downstream on the current. River ice can also break up as a result of an increase in water levels resulting from rainfall, snow melt, or ice jams.

Rising water levels cause cracks to occur in the ice cover, where the thinnest areas have usually already been weakened by melting. The current breaks the fractured ice into sheets and carries it downstream. If the ice catches on islands or in narrow parts of the river, it can create a jam—blocking the flow of the water and causing water levels to rise even higher. Ice jams are extremely dangerous because they can cause flash floods and may suddenly break, sending massive waves of ice and water rushing downstream.
2.2 Sea Ice

Sea water—which has a salinity of approximately 34 grams per kilogram—freezes at about -1.8°C (nearly two degrees lower than fresh water) because of its higher salt content. In Canada, sea ice is found in the waters of the Arctic, Hudson Bay, the Atlantic Coast, and the Gulf of St. Lawrence in consolidated sheets, moving packs, or separate floes.

2.2.1 Formation

Sea water not only has a lower freezing point but also reaches its maximum density at a lower temperature than fresh water. In fact, it reaches its freezing point before it starts to become less dense. If salinity levels at the surface are sufficiently high, and if similar salinity levels extend deep enough, the cooler water at the surface will sink and be replaced by warmer water from below. It is this property that makes it possible for open water to persist in parts of eastern Canada throughout the cold season.

Sea ice forms differently in the open water than it does near shore (where it is also known as “land-fast” sea ice).

2.2.1.1 Open-Water Sea Ice

Sea ice forms in a similar way to river ice, except it freezes at a lower temperature.

When the air temperature drops below the temperature of the sea water, the surface of the water begins to cool—a process enhanced by the presence of brisk winds, which create a wind-chill effect. As the water cools and becomes denser, it sinks and is replaced by warmer water from below.

When the water at the surface has reached -1.8°C, ice crystals begin to form, giving the water an oily appearance. This process continues until the surface is thick and slushy—a stage at which navigation is particularly difficult for smaller boats, and fuel consumption increases.

Eventually, the “New Ice” at the surface consolidates into a sheet and gradually thickens into “Young Ice”, which has two categories of thickness: Grey Ice (10-15 cm) and Grey-White Ice (15-30 cm). Young Ice is less elastic than New Ice and often cracks in swells. It

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**Figure 5f** – A) Ice crystals form as the top layer of water cools below -1.8°C; B) As more surface water cools to freezing, a thick slush forms; C) An ice sheet forms, thickening through conduction with the water below until it is 10-30 cm thick, when it becomes known as Young Ice; D) Thickening continues through the same process until the ice exceeds 30 cm, at which point it is considered First-Year Ice.
thickens as the warmer water below it loses its heat through the surface ice to the colder air above—cooling to the point where it freezes to the underside of the sheet. The greater the temperature difference between the air and water, the faster the ice thickens.

Once ice reaches 30 cm in thickness, it is known as “First-Year Ice” and classified as thin (30-70 cm), medium (70-120 cm) or thick (over 120cm). On October 1 of each year, all remaining First-Year Ice celebrates “ice birthday” and is henceforth known as “Second-Year Ice” or “Old Ice” (see the Local Effects chapter on the Arctic for more information). This date was chosen because it is the point in the season when the oceans in the northern hemisphere start losing more energy than they receive, and ice formation becomes more widespread than ice melt.

2.2.1.2 Land-Fast Sea Ice
Land-fast or near-shore sea ice forms in two ways: in situ, and through the accretion of floe ice.

In Situ
Ice grows easily in a sheltered bay or fiord, as water near the shore is much shallower than water out at sea, so it takes less time for its surface layer to cool to freezing. As with open-water sea ice, once the water has cooled to this point, ice crystals begin to form and thicken, eventually creating a sheet of land-fast ice—so called because it is attached to the shore.

Accretion of Floe Ice
Ice floes are sometimes pushed by winds or currents toward land or land-fast ice, where they freeze in place: a process known as “accretion”. This ice may be a different thickness than the ice that is already there. Where rivers flow into the ocean, the sea water often freezes up first because ice pans that have already formed in the fresh water help lower the water temperature to freezing and salinity levels are lower due to the mixing of fresh and salt water.
2.2.2 Decay
Solar radiation and heat conduction from land and water cause sea ice to decay; however, the higher salt content of sea ice also causes some unique effects.

Pockets of brine (very salty water) and impurities such as dirt and dust that are trapped inside the sea ice have what is known as a lower “albedo” than ice, meaning they are less reflective and absorb more energy from the sun. As a result, they warm up faster, forming puddles in the ice that cause the surrounding ice to melt more quickly. This creates thaw or melt holes that travel all the way down through the ice floe, where the brine and impurities are flushed out in the meltwater. As these holes weaken the ice, it breaks into smaller pieces and eventually melts completely. The time it takes for this process depends on air temperature, but tends to be three to four weeks.

In some coastal areas, the upwelling of warm water from deep below the surface of the ocean can cause sea ice to melt through conduction, even in the middle of winter. In other conditions, melting can occur on top of the ice floe, while it continues to thicken from below. The ongoing process of flushing and growth helps to create Multi-Year Ice (covered in more detail in the Local Effects chapter on the Arctic), which is much stronger than younger ice because its salt content decreases as it ages.

Generally speaking, sea ice melts first
• where rivers drain into the ocean, because their warmer water speeds melting,
• along the edge of floes, where the ice is thinner and breaks off and melts faster,
• near open-water polynyas, because the sun-warmed water and the winds and currents that created the polynya helps melt the surrounding ice, and
• in areas where strong currents or large tidal variations wear the ice away from underneath.

2.2.3 Movement
Sea ice moves two ways, depending on the winds, tides, and currents affecting it: in an outward or divergent direction, or in an inward, convergent one. The direction in which the ice moves affects its distribution, thickness, and other physical characteristics.
2.2.3.1 Divergent Ice Floes
When ice floes diverge or disperse, they spread out to cover a larger area. As a result, they often create leads and cracks in the ice. While some openings may enable vessels to navigate through ice floes, mariners must be very careful not to become trapped if they suddenly freeze up or the ice shifts and the opening closes.

Polynyas are non-linear openings in the ice that regularly occur in areas where strong, warm currents and prevailing wind directions cause any ice that forms to quickly move away. More prevalent in the Arctic, they are critical to marine life in the winter.

A crack is a fracture in fast ice, consolidated ice, or a single ice floe. Cracks occur when an ice sheet breaks and reforms, and vary in width from a few centimetres to a metre. When ice is only a few inches thick, stress cracks are common—most of them associated with thermal stress caused by the temperature difference between the colder air above the ice and the warmer water below it. Larger cracks can also be caused by water level changes, heavy snow loads, or strong winds.

Leads are linear cracks in the ice that are wide enough to be navigable. When they form between the shore and an ice floe, they are called coastal or shore leads; between land-fast ice and an ice floe, “flaw” leads. Covered with thick, slushy waters as a new ice sheet begins to form, they can freeze suddenly and close up quickly if conditions switch from divergent to convergent.
2.2.3.2 Convergent Ice Floes

When ice floes converge, they are driven together into a smaller area, where they collide and often pile up. Floes pushed against the shoreline or land-fast ice by onshore tides and currents may be under particularly high pressure.

Ice floe convergence is associated with three unique phenomena—rafting, ridging, and hummocks—all of which result in stronger, thicker areas of ice. Convergent ice floes can be very hazardous to mariners, because vessels may become trapped between floes as they are forced together.

When younger, thinner ice floes collide under convergent conditions, the pressure often forces one to slide onto the other—a process known as “rafting”. When these layers freeze together, they create stronger, thicker ice.

When older, thicker ice floes collide, their weight and density makes it more likely for the ice on their front edges to break into fragments along their seams, rather than pile up. This process is called “ridging” because these smaller pieces of ice are pushed together and freeze solid, creating a ridge of thicker ice between the two floes.

Small hills of broken ice—known as “hummocks”—that are caused by ridging can indicate the age of an ice floe. More weathered hummocks are associated with older, thicker floes (e.g., Multi-Year Ice), while fresher hummocks are characteristic...
of younger, thinner ones (e.g., First-Year Ice). Hummocks are much stronger than pressure ridges, as they are made of older sea ice that has lost much of its brine through the ongoing process of flushing and growth. As a result, they melt at the same temperature as freshwater ice (0°C), while sea ice floes melt at lower temperatures.

2.3 Icebergs

Icebergs are massive chunks of freshwater ice that have broken off a glacier or an ice shelf that extends over the ocean. Icebergs have a height-to-draft ratio of roughly 1:7, meaning that for every metre visible above the waterline, there are seven below it.

The result of centuries of snowfall, roughly 90 percent of the icebergs encountered in Canadian waters are from glaciers in western Greenland; however, some also come from Ellesmere Island. In Canada, they are found in the eastern Arctic and off the East Coast.

Icebergs are a serious collision hazard for mariners because they are as hard as rock, are difficult to see in high waves, and most of their mass is hidden below water level. They can also shear off, break apart, or roll unexpectedly, creating large waves that could affect vessels in their vicinity.

2.3.1 Formation

Icebergs form as a result of waves and tidal action, which create stress fractures in the part of the glacier or ice shelf that extends over the ocean. Eventually, the weakened ice breaks along its fractures and is released into the ocean: a process known as “calving”.

2.3.2 Decay

Wind-driven waves, collisions with sea ice and land, and frequent freeze-thaw cycles (both daily and seasonal) create crevasses in icebergs, enabling water to seep in and warm them to melting temperature. Before they dissolve completely, icebergs often break apart violently, creating large waves in the surrounding waters. Smaller pieces of iceberg are known as “bergy bits” or “growlers”. Icebergs typically last three to six years, although those trapped in certain winds and currents can survive much longer.

2.3.3. Movement

Icebergs move with the wind and currents. In Canada, most icebergs drift from Greenland to Baffin Bay, through the Hudson Strait, and south to Newfoundland and Labrador, where they eventually melt.
3. Properties of Ice

3.1 Strength

The strength of ice is determined mainly by the temperature of the ice and the number of brine pockets it contains. Ice is much stronger at colder temperatures. As it approaches the freezing point, it loses up to 90 percent of its strength.

The strength of sea ice is lessened by the presence of brine pockets, which makes it less dense—and therefore weaker—than freshwater ice. As it gets warmer, these pockets expand, reducing the strength of the ice even further.

3.2 Thickness

The thickness of ice is affected by the same factors that affect its growth and decay. On lakes and rivers, for example, these factors include fluctuations in water levels, currents, ambient air temperature, prevailing wind direction and speed, and snow cover.

As melting occurs on the surface of the ice as a result of warmer air temperatures, the meltwater evaporates, leaving an ever-thinner layer of ice. Changes in water levels also speed the process by which ice decays. When the water level rises, it exerts an upward force on the ice above, causing it to crack and break, and flooding the surface with water. When the water level drops, it removes support from the layer of surface ice, causing it to eventually collapse under its own weight.
Currents within a river can break up ice cover and wear away ice thickness from below. If air temperatures increase to above freezing, the first effect of melting is a reduction in ice strength, the second a decrease in thickness.

If winds blow from the same direction for a long time, ice in the area where it piles up will be much thicker, while ice in the direction it came from, much thinner. This happens even faster when the winds are strong.

If there is a blanket of snow cover on the surface of ice when it is forming, it will slow its growth by insulating the water below the ice from the colder temperatures above it. This results in thinner ice than expected.

It is possible to estimate the thickness of ice from its appearance, using the following table:

<table>
<thead>
<tr>
<th>Trait</th>
<th>Thin Ice</th>
<th>Thick Ice</th>
</tr>
</thead>
<tbody>
<tr>
<td>Colour</td>
<td>Dark</td>
<td>White</td>
</tr>
<tr>
<td>Fractures</td>
<td>Appear like jagged tears</td>
<td>Occur in straight lines</td>
</tr>
<tr>
<td>Rafting/Ridging</td>
<td>Rafting</td>
<td>Ridges</td>
</tr>
<tr>
<td>Ice Structure</td>
<td>Not readily distinct floes; jagged edges</td>
<td>Distinct floes; rounded edges</td>
</tr>
</tbody>
</table>

4. Ice Forecasting

A variety of forecast products are produced on a daily and weekly basis to provide mariners with the information they need to navigate as safely as possible in ice-covered waters. In order to understand ice charts properly, mariners must be familiar with the “egg code”: the coded symbol developed by the World Meteorological Organization to describe the qualities of both freshwater and sea ice.

4.1 Egg Codes

Egg codes are oval symbols that are divided into four sections, each of which provides different information on the ice present in a given area. From top to bottom, these sections indicate the following:

- **Total Concentration of Ice**: Given in tenths of total coverage.
- **Concentrations of Predominant Ice Types**: The concentration of the thickest types of ice in the area (up to three types). Also given in tenths of coverage.
- **Stage of Development**: The stage of development or thickness of each of the predominant ice types identified.
- **Floe Size**: The floe size of each of the predominant ice types identified.

For more details on the coding used to identify the stage of development and floe size of ice, or other information on egg codes, visit the Canadian Ice Service website.
4.2 Ice and Iceberg Charts

Ice and iceberg charts are used for both tactical (day-to-day) and strategic (longer-term) planning and operational purposes. Different types of charts provide different information, as indicated in the list below.

**Daily ice charts** provide daily estimates of ice conditions in areas of marine activity.

**Regional ice charts** provide weekly estimates of ice conditions and make up the official climate records.

**Departure-from-normal-concentration charts** indicate the difference in ice concentration between the current regional ice chart and the 30-year median.

**Image analysis charts** interpret ice conditions from satellite imagery.

**Aircraft ice charts** provide information on ice conditions observed from an aircraft survey.

**Iceberg charts** provide daily estimates of iceberg conditions.