ICEBERGS

D. Diemand, Coriolis, Shoreham, VT, USA

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Introduction

Icebergs are large blocks of freshwater ice that break away from marine glaciers and floating ice shelves of glacial origin. Although they originate on land, they are often included in discussions of sea ice because they are commonly found surrounded by it. However, unlike sea ice, they are composed of fresh water; therefore their origin, crystal structure, and chemical composition, as well as the hazards they pose, are different.

They are found in both polar regions, their sizes and numbers generally being greater at higher latitudes. They pose a hazard both to shipping and to seabed structures.

Origins and Spatial Distribution

The great ice sheets of Greenland and Antarctica, which produce by far the greatest number of the world's icebergs, flow off the land and into the sea through numerous outlet glaciers. In many cases, especially in Antarctica, the ice spreads out on the sea surface, staying connected to land and forming a floating ice shelf of greater or lesser extent.

There are two major differences between the calving fronts in Greenland and those in Antarctica. First, most of the Greenland icebergs are calved directly from the parent glaciers into the sea, while Antarctic icebergs are mostly calved from the edges of the huge ice shelves that fringe much of the continent. The result is that southern icebergs at the time of calving tend to be very large and tabular, while the northern ones are not so large and have a more compact configuration.

Second, the equilibrium line of the Greenland ice sheet is above 1000 m. Therefore, the entire volume of a Greenland iceberg is composed of ice. In Antarctica, on the other hand, the equilibrium line is at or near the edge of the ice shelves, so that icebergs are commonly calved with an upper layer of permeable firn (see Ice Properties below) of varying thickness that influences later deterioration rates and complicates estimates of draft and mass.

The drift of icebergs is largely governed by ocean currents, although wind may exert some influence. Since ocean currents at depth may differ in speed and direction from surface currents, a large iceberg may move in a direction different from that of the surrounding sea ice, creating a patch of open water behind it. Since its speed and direction are heavily dependent on the depth and shape of the keel, which is usually unknown, trajectory predictions are seldom reliable, even when local current profiles are known.

Because the Antarctic continent is surrounded by oceans while the Arctic is an ocean surrounded by continents, the drift patterns of the icebergs from these areas are very different.

Baffin Bay to North Atlantic region

About 95% of icebergs in northern latitudes originate on Greenland. Most of these are from western Greenland where they calve directly into Baffin Bay, but a few are produced in eastern Greenland. Many of these remain trapped in the fiords where they originated, deteriorating to a great degree before they reach the sea. Those from eastern Greenland that do reach the sea drift south in the East Greenland Current, a small number continuing south into the North Atlantic where they rapidly dwindle, others being carried around the southern tip of Greenland and then north in the warm West Greenland Current, where the few that survive the long trip join the great numbers of bergs originating from Disko Bay north. **Figure 1** shows some of the most active glaciers on Greenland and the drift paths generally followed by icebergs.

Icebergs may remain in Baffin Bay for several years, circulating north along the Greenland coast and then south along the Canadian arctic islands. Since the water temperature in Baffin Bay remains consistently low throughout the year, little deterioration takes place. However, many do escape southward through the Davis Strait and drift down the Labrador coast in the cold Labrador Current until they break free of the annual pack ice and reach the Grand Banks off Newfoundland.

Icebergs have been sighted as far south as Bermuda and the Azores.

Arctic Ocean

The remaining 5% of northern icebergs are calved from numerous glaciers on Ellesmere Island in the Canadian Arctic, the many islands in or bordering the Barents, Kara, and Laptev Seas, and Alaska (see **Figure 2**). Many of these, especially those calved

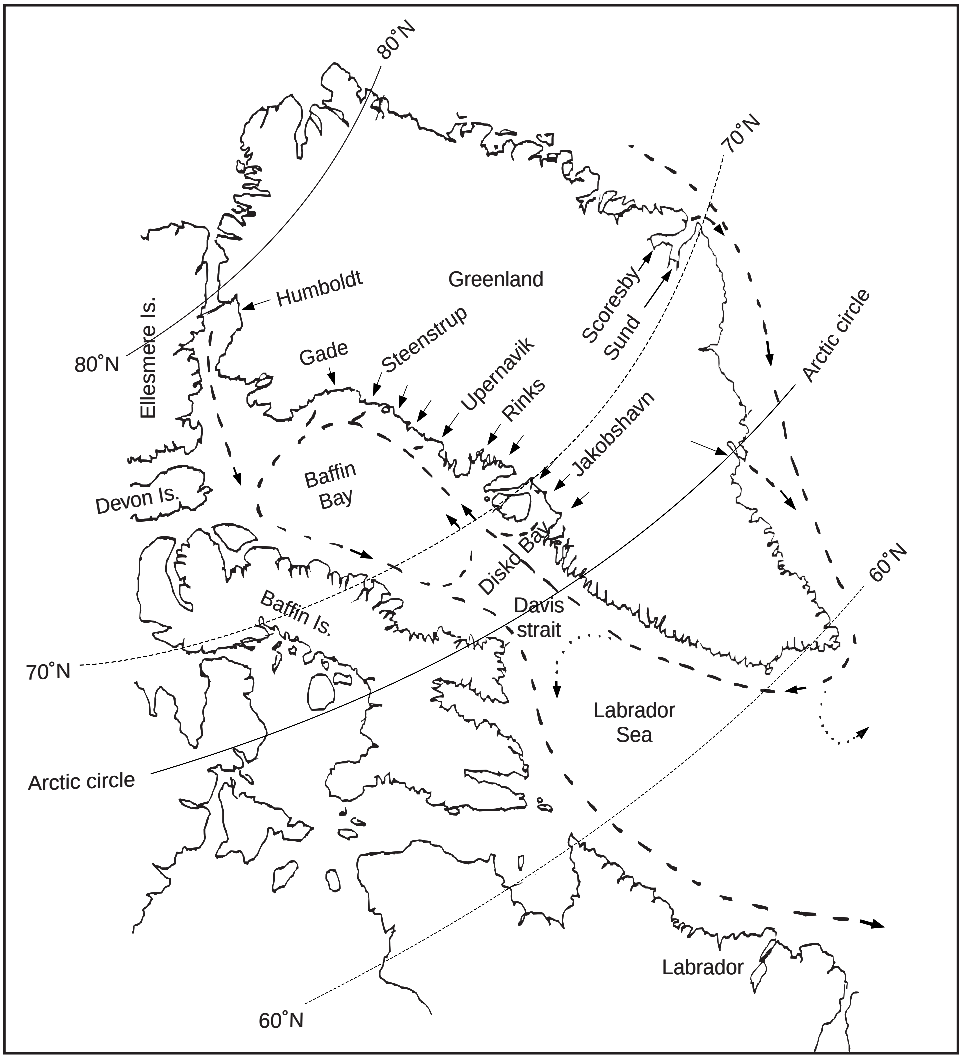


Figure 1 Sources and drift paths of North Atlantic icebergs.

from ice shelves on Ellesmere Island, are tabular in form. When they were first discovered drifting among the Arctic pack, they were referred to as 'ice islands', and the name stays with them. Once they have become incorporated into the pack, they tend to stay there indefinitely, although occasionally one may escape and join the southbound flux through Davis Strait or the east coast of Greenland. The sources and trajectories of these icebergs and ice islands are shown in **Figure 2**.

Southern Regions

Since there is no significant runoff from Antarctica, iceberg production accounts for most mass loss from the continent. Most of these icebergs are calved from the massive ice shelves, such as the Ross, Filchner, Ronne, Larsen, and Amery. About 60–80% by volume are calved from the ice shelves, the remainder from outlet glaciers that empty directly into the sea or from active ice tongues. Once free of the ice front, they drift with the prevailing current along the coast, in some places westward, in others eastward as shown in **Figure 3**. They may remain close to the coast, where their concentration is the greatest, for periods up to 4 years, protected by the sea ice and the cold water. There are several localized places around the coast where icebergs turn north away from the continent. Once they drift beyond the northern limit of the pack ice, about 60°S, they are carried east and north into ever warmer waters until they deteriorate.

The most northerly reported sighting was at 26°S near the Tropic of Capricorn. Few pass 55°S.

Numbers and Size Distribution

Our knowledge of the numbers and size distribution of icebergs is based on visual observations from

Figure 2 Sources and drift paths of icebergs in the Arctic Ocean.

ships and aircraft; from radar data from ships, shore, and aircraft; and from satellite imagery. Each method has its advantages and shortcomings. For example, satellite imagery covers very large areas and all times of the year, but will not detect small bergs; ship's radar will pick up most icebergs within its range but may miss rounded bergs or small bergs in heavy seas; visual observation will catch all sizes of bergs, but only within a limited area in good weather when someone is looking. Thus, any iceberg census will be slanted toward the size and shape categories favored by the observation method used.

The most detailed records of iceberg numbers and sizes in a single location have been kept by the US Coast Guard's International Ice Patrol (IIP) which was formed in the aftermath of the sinking of the *Titanic*. The IIP began patrolling the Grand Banks in 1914 and reporting iceberg locations to ships in the area. Since that time the IIP has kept a detailed record of all icebergs crossing 48°N. These numbers are highly variable from year to year as is apparent

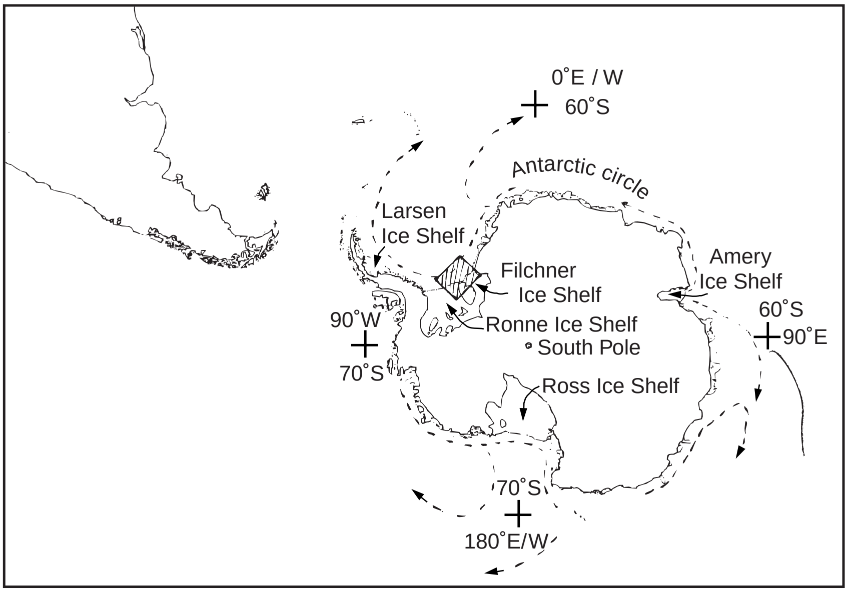


Figure 3 Sources and drift paths of Antarctic icebergs. The shaded box shows the area covered by the satellite image in **Figure 5**.

from **Figure 4**. The reason for this variability is not clear. Both the numbers and sizes are greater at higher latitudes, since the bergs gradually disintegrate as they drift south into warmer waters.

No such long-standing record exists for the southern oceans, so estimates of numbers here may be less reliable. However, the National Ice Center, using satellite imagery, does identify and track icebergs whose longest dimension is greater than 10 nautical miles (18.5 km) when first sighted. They also continue to track fragments smaller than this that may break away but are still detectable by satellite radar. At the same time, Norway's Norsk Polarinstitutt has kept a record of all icebergs sighted in Antarctic waters by 'ships of opportunity', which is most ships in the area, since 1981. This data set includes icebergs of all sizes, but the coverage is restricted to those times and areas where ships are present.

Northern Regions

The total estimated volume of ice calved annually from Greenland is about 225 ± 65 km^3. Estimated numbers of icebergs calved from Greenland's glaciers range from about 10 000 to 30 000 per year. The greatest numbers in northern oceans are found in Baffin Bay. Icebergs may also be seasonally very numerous along the coast of eastern Canada, especially before the pack ice melts. Of those that drift south into the North Atlantic, the annual numbers crossing 48°N, just north of the Grand Banks of

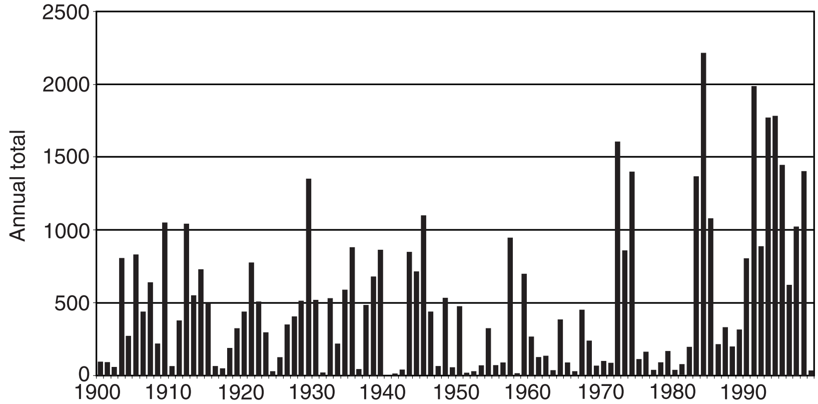


Figure 4 Total numbers of icebergs crossing 48°N each year from 1900 through 1999. Note: The figures for the years of World War I and II are incomplete. (Data courtesy of the US Coast Guard International Ice Patrol.)

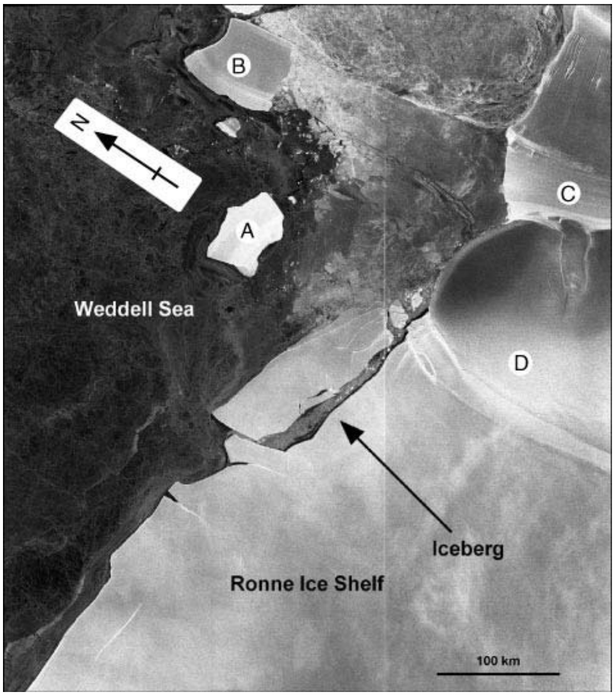


Figure 5 Satellite image showing an extremely large iceberg breaking away from the Ronne Ice Shelf in 1998. The area covered by this image is indicated in **Figure 3**. A and B are the remnants of two other very large icebergs, both of which broke free in 1986 and were grounded at the time of this image. C is a rapidly moving stream of ice moving off the continent through the Filchner Ice Shelf and past Berkner Island (D) into the Weddell Sea. (Radarsat data © 1998 Canadian Space Agency/Agence spatiale canadienne. Received by the Canada Centre for Remote Sensing (CCRS). Processed by Radarsat International (RSI) and the Alaska SAR facility (ASF). Image enhancement and interpretation by CCRS. Provided courtesy of RSI, CCRS, ASF, and the National Ice Center.)

Newfoundland, according to the IIP are shown in **Figure 4**. Once they encounter the warm Gulf Stream waters, they rapidly deteriorate.

Southern Regions

The total estimated volume of ice calved annually from Antarctica ranges from 750 to 3000 km^3 per year. The occasional release of extremely large icebergs has a major impact on annual estimates of Antarctic mass loss. The iceberg shown in **Figure 5** represents as much ice as the total annual mass loss from a 'normal' year. The shaded box shown in **Figure 3** is the area covered by this image. Estimated numbers of icebergs calved range from 5000 to 10 000 each year.

Shapes and Sizes

The range of sizes of icebergs is enormous, spanning about eight orders of magnitude, from small fragments with a mass around 1000 tonnes to the immense Antarctic tabular begs with masses in excess of 10^{10} t. **Table 1** shows the normal range of iceberg sizes in the Labrador Sea.

Table 1 Iceberg size categories

Designation	*Height* (m)	*Length* (m)	*Approximate mass* (Mt)
Growler	<1	<5	0.001
Bergy Bit	1–5	5–15	0.01
Small	5–15	15–60	0.1
Medium	16–45	61–120	2
Large	46–75	121–200	10
Very Large	>75	>200	>10

In terms of shape, no two icebergs are the same. However, as bergs deteriorate they do tend to assume characteristic forms (**Figures 6–10**).

The shape classification in common use is given in **Table 2**. Specialized terms used in classification and description are defined in the Glossary. It should be borne in mind that the shape or extent of the 'sail' does not necessarily reflect the shape of the entire iceberg. **Figures 11A** and **B** show a photograph of an iceberg and a computer-generated image of its underwater configuration. The nearly spherical shape of this medium-sized berg suggests that it had rolled, probably recently and probably several times. Any horizontal tongues of ice, or 'rams', would have broken away during this energetic process. **Figures 12A** and **B** show a larger iceberg that had only tilted from its original in the water. Extensive rams are visible extending outward underwater far beyond the extent of the sail, remnants of a far greater mass that has been lost since the berg moved into relatively warm waters. While these two icebergs have roughly similar shapes above water, their underwater configurations are very different.

Because of this uncertainty in the underwater shape, it is impossible to calculate iceberg draft and

Figure 6 Tabular iceberg. (Photograph by Deborah Diemand.)

Figure 7 Wedge iceberg. (Photograph by Deborah Diemand.)

Figure 9 Drydock iceberg. (Photograph by Deborah Diemand.)

mass accurately using the sail dimensions. However, certain rules of thumb have emerged from empirical studies. To approximate the draft in meters, the relationship of eqn [1] can be used.

$$\text{Draft} = 49.4 \times (\text{height}^{0.2}) \qquad [1]$$

To approximate the mass in tonnes, that of eqn [2] can be used.

$$\text{Mass} = 3.01 \times [(\text{longest sail dimension (m)}) \times (\text{orthogonal width (m)}) \times (\text{maximum height (m)})] \qquad [2]$$

These calculations apply only to icebergs composed entirely of ice, with no firn layer.

Northern Regions

In general, the mean size of icebergs in Baffin Bay is about 60 m height, 100 m width and 100 m draft. Mean mass is about 5–10 Mt. The sizes of icebergs in this area are constrained by the water depth near the calving fronts, which is less than 200 m. Icebergs with a mass greater than 20 Mt are extremely rare, and for those found south of 60°N, a mass greater than 10 Mt is seldom found. The maximum sail height on record for an iceberg in the North Atlantic is 168 m.

The ice islands in the Arctic Ocean extend about 5 m above sea level. They have a thickness of 30–50 m and an area from a few thousand square metres to 500 km^2 or more.

Southern Regions

In general, the thickness of the ice shelves at the calving fronts is about 200–250 m, increasing away from the front. Since the ice edge is very long, and often seaward of seabed obstructions, Antarctic icebergs may be extremely large.

The iceberg shown in **Figure 5** is more than 5800 km^2, larger than the US state of Rhode Island. The largest iceberg ever reported was about 180 km long, with an estimated volume of 1000 km^3.

Figure 8 Pinnacle iceberg. (Photograph by Deborah Diemand.)

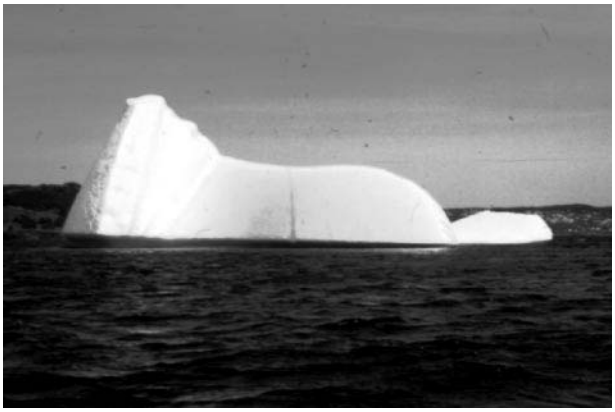


Figure 10 Domed iceberg. (Photograph by Deborah Diemand.)

Table 2 Iceberg shape categories

Designation	*Description*
Tabular types	
Tabular	Steep sides with a flat top; length to height ratio > 5:1 (**Figure 6**)
Blocky	Similar to tabular, but length to height ratio < 5:1
Nontabular types	
Wedge	One flat side sloping gradually to the water; the opposite side sloping steeply, the two meeting at the peak as a spine (**Figure 7**)
Pinnacle	With one or more sharp peaks (**Figure 8**)
Drydock	With two or more peaks separated by a water-filled channel (**Figure 9**)
Dome	Small with rounded top (**Figure 10**)

Deterioration

Deterioration begins as soon as an iceberg calves from its parent glacier. Even icebergs locked into sea ice over the winter show signs of mass loss. However, significant deterioration does not usually begin until after the berg breaks free from the pack ice and is exposed to warmer surface water and wave action. The major causes of ice loss are melting, calving, and splitting and ram loss.

Melting

Ice loss due to melting alone is hard to quantify, but is thought to fall within the shaded region shown in **Figure 13**. It is highly dependent on water temperature, but is also influenced by wave action, water currents, and bubble release. Melting rate at the water line is far greater than that over the rest of the ice surface. This causes a groove to form, undercutting the ice cliffs and creating sometimes extensive underwater rams.

The importance of melting in the overall mass loss depends on the surface/volume ratio, being more significant for small bergs and growlers than for large ones.

One of the side effects of the rapid side melting of icebergs is the vertical mixing of the surrounding seawater. Driven mostly by the release of air from the bubbles in the ice and partly by the lower density of the fresh water of the melted ice, water flows upward near the berg, drawing deep water to the surface. The combination of nutrients brought up from depth by this process and the decreased salinity of the meltwater surrounding the berg results in a specialized community of plankton and fish in the vicinity of icebergs.

Calving of Cliff Faces

Small pieces of ice are constantly breaking off the sides of icebergs, mostly owing to waterline undercutting. Such calving events may produce only a few small pieces, or a great number, especially in warm water. Usually the individual pieces are quite small and are quickly melted, but the total mass loss can be considerable and the resulting imbalance can cause the berg to roll, causing further ice loss. Once the berg has rolled and stabilized, waterline erosion begins anew. This is probably the major cause of mass loss in medium-sized bergs.

Splitting and Ram Loss

Splitting occurs when a large iceberg breaks into two or more pieces, each of which is an iceberg in its own right. This is a common occurrence for very

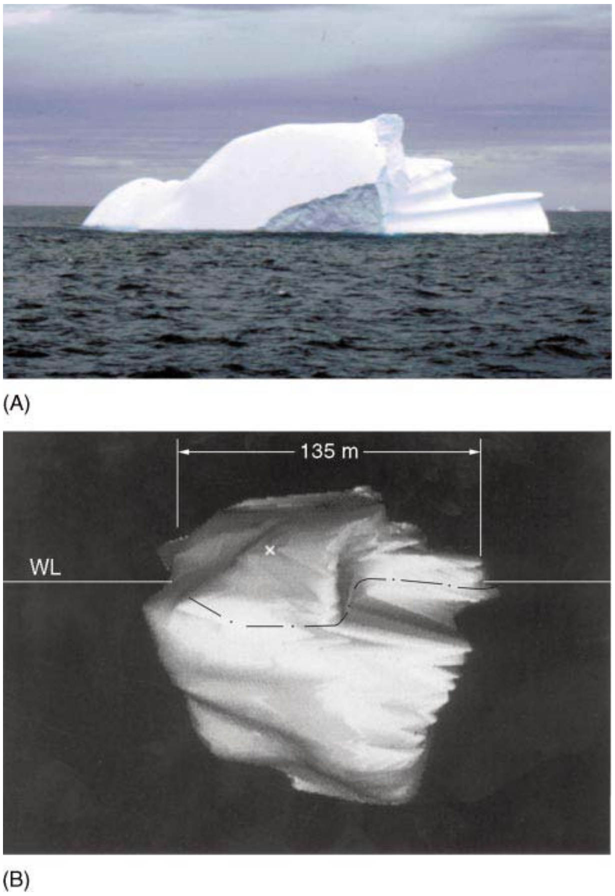
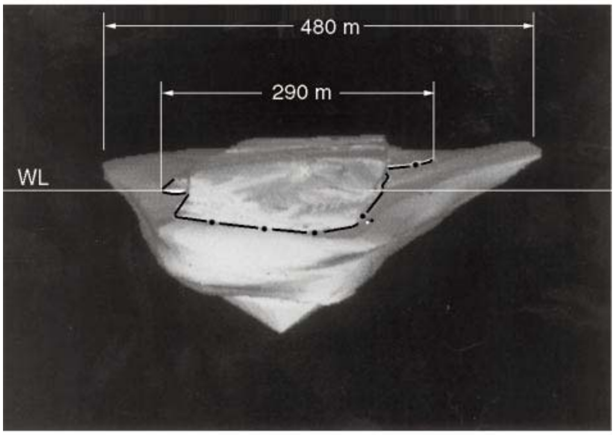


Figure 11 (A) Medium-sized iceberg grounded in 107 m of water. (B) Computer-generated image showing the underwater profile of this berg. The shape and size of the sail were established through stereophotography; those of the keel were determined using acoustic profiling techniques. These two datasets were joined electronically to create this image as well as **Figure 12B**. WL, water line. ((A) Photograph by Deborah Diemand; (B) courtesy of Dr. James H. Lever.)

(A)



(B)

Figure 12 (A) Large iceberg grounded in 134 m of water. (B) Computer-generated image showing the underwater profile of this berg. WL, water line. ((A) Photograph by Deborah Diemand; (B) courtesy of Dr. James H. Lever.)

large Antarctic tabular bergs, and the resulting fragments can still be extremely large. In this case, probably the main cause of breakup is flexure due to ocean waves, although grounding or collision, or both, may contribute. It is likely that grounding is the main cause of splitting for bergs smaller than 1 km^2.

While undercut cliffs on the sides of icebergs tend to shed many small fragments, the corresponding underwater rams remain intact until they are sufficiently large that buoyancy forces alone cause them to break away, or the berg grounds. These rounded fragments, which may be of considerable size, probably represent a large proportion of the domed icebergs common in warmer waters. For example, the calving of the ram extending to the right in **Figure 12B** would create a new iceberg weighing roughly 100 000 tonnes.

Splitting and ram loss are the major cause of size reduction in extremely large bergs.

Ice Properties

Glacial ice is formed by the gradual accumulation of snow over many centuries. As the snow compacts and recrystallizes, it forms firn, a granular, permeable material. The firn layer may reach as deep as 100 m in very cold places, but is seldom deeper than 50 m. This firn layer is not present on the calving fronts of Greenland, but is present on Antarctica's ice shelves, and in the icebergs calved from them. When the firn reaches a density of 830 kg m^{-3} the pores close off, trapping any air that remains. At this point the ice contains about 10% air by volume. Further densification is a result of compression of the air in the bubbles. The bubbles become smaller and may become incorporated into the crystals through recrystallization. The pressure inside them may be as high as 2 MPa (20 bars).

Acoustics

Melting icebergs in the open ocean make a characteristic sound sometimes referred to as 'bergy seltzer'. This is probably created by the explosion or implosion of bubbles as the ice melts. The frequency range of audible sound produced is quite wide, and is largely masked by ambient ocean noise at frequencies below 6 kHz. The sound seems to vary from berg to berg and is undoubtedly influenced by environmental conditions. Estimated detection distances at frequencies above 6 kHz range from 2 to 150 km.

Ice Temperature

Since ice is a good insulator, the original temperature of a large berg at the time of calving will be retained in its central core, and may be as low as $-22°C$. After a year or more in cold water, where little or no ablation takes place, the surface ice will

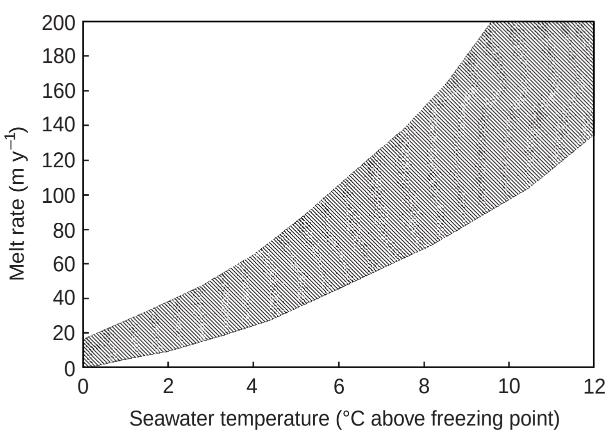


Figure 13 Dependence of the melt rate of icebergs on the temperature above the freezing point of sea water.

warm to about 0°C. In relatively warm waters, however, these outer layers of ice are removed more rapidly than the inner cold core warms up, leaving much colder ice near the iceberg's surface. Since the strength of ice is greater at lower temperatures, the result of a collision with such a berg could be more severe than with one that had not undergone significant melting.

Color

In small quantities, ice appears both colorless and transparent. However, because ice selectively transmits light in the blue portion of the visible spectrum while it absorbs light of other frequencies, sufficiently large pieces of clear, bubble-free ice can appear blue. However, this color is frequently masked in glacial ice by the scattering of light of all wavelengths by the bubbles included in the ice, causing the ice to appear white. Blue bands, commonly present within the greater white mass, are caused when cracks form on the parent glacier or later on the iceberg itself and are filled with meltwater that then freezes relatively bubble free. These blue bands range in size from hairline cracks to a meter or more in width.

Green icebergs are fairly common in certain regions. This has variously been attributed to copper or iron compounds, the incorporation of dissolved organic compounds, or to an optical trick caused by red light of the sun near the horizon causing the apparent green color. It is likely that there is no single cause and that all of these factors may make the ice appear green. In some cases the trace substances may originate on land, as in the blue cracks mentioned above. In others they may result from sea water freezing to the underside of an ice shelf. Unlike in ice formed at the water surface, most salts and bubbles are rejected, but certain compounds may be trapped in trace amounts, causing the green appearance of otherwise clear ice.

Icebergs may also have bands of brown or black; these are caused by morainal or volcanic material deposited while the ice was still part of the parent glacier.

Economic Importance

Hazard to Shipping

A large iceberg poses little threat to shipping on the whole. It will not normally exceed a speed of $1\ \mathrm{m\ s^{-1}}$ (2 knots) and it can be detected with normal marine radar at a considerable distance, allowing the ship to alter course. Ironically, a greater danger is posed by much smaller bergs. These 'small' bergs may weigh in excess of 100 000 t, but owing to their small above-water size and frequently rounded shape they may not be detected by radar until they are dangerously close to the ship, especially in storm conditions when the radar return from the rough sea surface (sea clutter) will tend to mask the weak radar return from the iceberg. In such conditions the peril is further increased because these relatively small ice masses, tossed by the heavy seas, may reach maximum instantaneous velocities 4–5 times larger than hourly drift speeds. A 4000 t bergy bit moving at the maximum fluid particle velocity of $4.5\ \mathrm{m\ s^{-1}}$ in typical Grand Banks storm waves could have about a third of the kinetic energy of a 1 Mt iceberg drifting at $0.5\ \mathrm{m\ s^{-1}}$ ($\sim$ 1 knot). While the influence of waves on ice movement decreases for larger bergs, icebergs as massive as 1 Mt may still exhibit significantly higher maximum instantaneous velocities than their hourly drift values.

Seabed Damage

While small icebergs pose a serious threat to structures at the sea surface, seabed structures such as well-heads, pipelines, cables, and mooring systems are endangered by large icebergs, which may possess a deep enough draft to collide with the seafloor.

Marine navigators have long known that the keels of icebergs drifting south over the relatively shallow banks of Canada's eastern continental shelf may touch the seabed and become grounded.

Modern iceberg scours appear in the form of linear to curvilinear scour marks and as pits, and occur from the Baffin Bay/Davis Strait region to the Grand Banks of Newfoundland. They are present at water depths up to about 200 m. Seabed scouring has also been documented in Antarctica, but to date has generated little interest because of the absence of seabed structures.

A single scour may be as wide as 30 m, as deep as 10 m, and longer than 100 km. An iceberg may also produce pitting when its draft is suddenly increased through splitting or rolling. It may then remain anchored to the seafloor, rocking and twisting, and may produce a pit deeper than the maximum scour depth.

Usage of Icebergs

In the past there has been considerable interest in the possibility of transporting icebergs, representing as they do an essentially unlimited supply of fresh water, to arid areas such as Saudi Arabia, Western Australia, and South America. The two seemingly insurmountable problems that need to be solved are propulsion and prevention of in-transit breakup in warm seas. Proposed means of moving a sufficiently large ice mass over such long distances have ranged from conventional towing to use of a nuclear submarine to wind power. None has proven feasible.

Destruction of Icebergs

Attempts at destroying icebergs have been numerous and varied. Perhaps the most-studied technique has involved the use of explosives, which have been extensively tested on glacial ice in the form of glaciers and ice islands. Both crater blasting and bench blasting have been attempted. The results of this testing suggest that ice is as difficult to blast as typical hard rock, and that therefore the use of explosives for its destruction is impractical.

Other methods tested include spreading carbon black on the berg's surface to accelerate melting, and introducing various gases into the ice to create holes or cavities that can then be filled with explosives of choice. Attempts have also been made to cut through the ice using various means. There is little evidence that any great success was achieved with any of these methods.

The only report of a successful attempt to break up an iceberg involved the use of thermit, a welding compound that reacts at very high temperatures ($\sim 3000°C$). The explanation was that the very high heat produced by the thermit caused massive thermal shock within the mass of ice that ultimately resulted in its disintegration, much as glass can be fragmented by extreme temperature changes.

Conclusions

There is a great deal of uncertainty surrounding iceberg properties, behavior, drift, and other aspects relating to individual icebergs as opposed to laboratory samples or intact glaciers. This is mostly because of the high cost of expeditions to the remote areas where icebergs are most numerous, and the inherent dangers of hands-on measurement and sampling.

Glossary

Calving The breaking away of an iceberg from its parent glacier or ice shelf. Also the subsequent loss of ice from the iceberg itself.

Equilibrium line On a glacier, the line above which there is a net gain due to snow accumulation and below which there is a net loss due to melt.

Firn Permeable, partially consolidated snow with density between 400 kg m^{-3} and 830 kg m^{-3}.

Growler A small fragment of glacial ice extending less than a meter above the sea surface and having a horizontal area of about 20 m^2.

Keel The underwater portion of an iceberg.

Ram Lobe of the underwater portion of an iceberg that extends outward, horizontally, beyond the sail.

Sail The above-water portion of an iceberg.

See also

Antarctic Circumpolar Current. Arctic Basin Circulation. Current Systems in the Southern Ocean. Florida Current, Gulf Stream and Labrador Current. Ice-induced Gouging of the Seafloor. Sea Ice: Overview; Variations in Extent and Thickness. Sonar Systems. Sub Ice-shelf Circulation and Processes. Weddell Sea Circulation. Wind Driven Circulation.

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ICE-INDUCED GOUGING OF THE SEAFLOOR

W. F. Weeks, Portland, OR, USA

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Introduction

Inuit hunters have long known that both sea ice and icebergs could interact with the underlying sea floor, in that sea floor sediments could occasionally be