10. ICING

Inability to forecast vessel icing is one of the most important marine meteorological problems in high latitude waters because rapid accretion on decks and superstructures creates an extreme hazard for vessels due to lack of stability. In the case of smaller ships, the added weight of the ice reduces freeboard and therefore reduces the range of stability of the vessel. Ice formed high on masts, rigging, and superstructure produces a large heeling lever, and the vessel may become topheavy and capsize.

In the case of larger vessels, including warships, accumulation of ice on deck, superstructure, and on deck equipment impairs the ships overall efficiency and maneuverability. In addition, the accumulation of ice on aerials may render the radio and radar systems inoperative.

The regions historically known for producing significant icing conditions are located in the North Atlantic and North Pacific Oceans, as outlined in Fig. 10-1. Icing, however, can occur in other cold weather areas.

10.1 Physical Processes of Icing

The rate of icing depends on (1) precipitation type, (2) wind speed, (3) air temperature, (4) sea surface temperature, and (5) characteristics of the vessel (including size, shape, speed, and heading). Much of the information in this section is taken from Kotsch (1983).

10.1.1 Precipitation Types

Types of precipitation in the Arctic that affect ship icing include freezing rain, Arctic frost smoke, and freezing spray. Snow is not considered a threat due to the inherent lack of adhesion.

Freezing rain will cover a ship or small craft with fresh-water glaze (clear) ice, but the accumulated weights of ice are unlikely to be sufficient to endanger the vessel directly. Because rates of ice accretion depend on the rainfall rates, and the Arctic rainfall rate is not large, the potential hazard is normally not a major one.

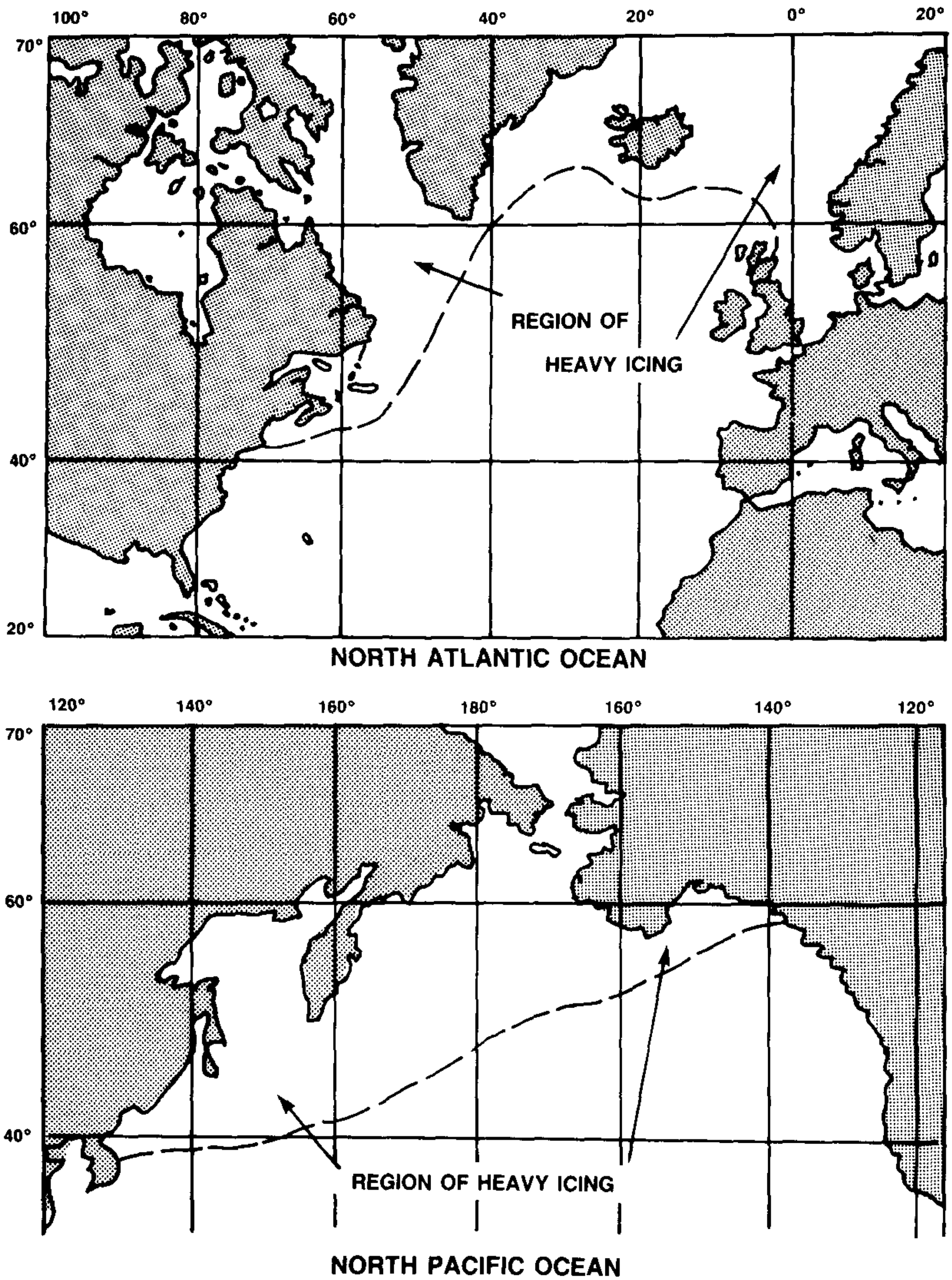


Figure 10-1. Regions of Heavy Icing (U.S. Navy, 1988).

Arctic sea smoke occurs when the air temperature is at least 16 °F (9 °C) colder than the sea. If the air temperature is below 32 °F (0 °C), then the Arctic sea smoke is called Arctic frost smoke. This frost smoke is often confined to a layer only a few feet thick, and trawlermen in northern waters refer to it as "white frost" when the top of the layer is below the observer's eye level. It is referred to as "black frost" when it extends above the observer.

The small water droplets in frost smoke are supercooled. On contact with exposed surfaces on a vessel, part of the droplet freezes immediately while the remainder stays liquid for a short time before it too freezes. The result of the instantaneous freezing of the supercooled droplets is an accretion of opaque, white rime ice with imprisoned air. This rime ice is easier to remove than the clear ice, or glaze (which forms in other circumstances), because rime ice is porous. In one case, a ship (near Bear Island) caught in air temperatures colder than 14 °F (−10 °C), with dense frost smoke, accumulated 4 in (≈ 10 cm) of rime ice on deck in 12 hours. Twelve inches (≈ 30 cm) collected on the ship's side at rail level during the same time. This ice accumulation is equivalent to nearly 2½ tons per hour. Accumulation on isolated structures, such as cranes, can be more than twice as heavy as that on flat surfaces.

Freezing spray is the most dangerous form of icing. It occurs when the air temperature is below the freezing temperature of the sea water, about 28 °F (−2 °C). The spray freezes on the exposed surfaces of the vessel to produce clear ice or glaze. At lower air temperatures, the ice may be opaque, which may be due to the spray being supercooled so that it partially freezes on impact and entraps air. At extremely low temperatures such as 1°F (−17 °C) and below, as might be encountered in anchorages or close inshore, wind-induced spray may be frozen before it strikes the vessel, so that it does not adhere to the vessel but may form drifts on deck.

With air temperatures below 28 °F (−2 °C), freezing spray is observed in winds of 18 kt (9 m/s) or higher. The lower the air temperature and the stronger the wind, the more rapid is the accumulation of ice. A low sea temperature also increases the rate of accumulation of ice.

Once a spray cloud is produced, the vertical distribution of the cloud is significant as it determines the size of the droplets. In turn, droplet size determines the rate of cooling of the droplet on its trajectory toward the ship. Once the spray reaches vessel surfaces, continued cooling of the ocean water from its sea temperature to the freezing point is determined by the heat flux away from the surface, a function of local wind speed and air temperature.

The freezing process itself is complicated because of the influence of ocean salinity, which affects the freezing temperature. The salinity contributes to forming low density "spongy" ice with air and brine pockets.

10.1.2 Wind

Sea spray generation depends on the wave height and period of waves. Waves, in turn, depend on the duration of the wind and fetch. Generally, the higher the wind speed for the critical temperature ranges (discussed in the following subsections), the greater the ice accumulation.

One factor that can reduce the effect of high wind speeds on icing is the concentration of the ice pack. Obviously, if the ice pack concentration exceeds about 50 percent, wave formation is sharply reduced and freezing spray is minimized.

10.1.3 Air Temperature

The critical range for icing is from 0 °F to 32 °F (−18 °C to 0 °C). At temperatures below 0 °F (−18 °C), the spray striking the structure will usually be in the form of nonadhering small, dry ice crystals. A handy rule of thumb was proposed in a Japanese study: During offshore flow of Arctic air, ship icing is likely when the 850-mb temperature is −4 °F (−18 °C) or colder (Taiyo Fishing Company, Limited, 1972).

10.1.4 Sea Temperature

The critical range of sea surface temperatures are 28 °F to 48 °F (−2.2 °C to 8.9 °C). Seawater of normal salinities is generally frozen below 28 °F. The upper value of 48 °F is not an impediment to freezing since sea spray can be cooled rapidly when air temperatures are below 28 °F.

10.1.5 Vessel Design

To the spray blown from the wave caps is added the spray generated by the vessel herself, so that the total rate of ice accretion will also depend on the design and loading of the vessel, on her heading and speed relative to the waves, and also on the relative wind that determines which part of the vessel is most exposed.

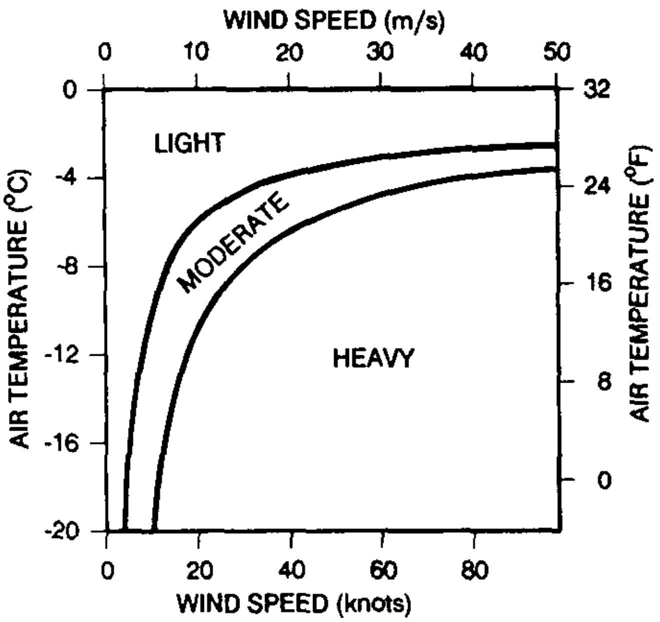
As the dominant wavelength approaches the vessel length, vertical motion is generated between the vessel and the sea, and wave-generated spray is produced. The amount of spray generated by a vessel depends on the ocean wave field, the vessel length, its seakeeping ability, stability, freeboard, hull shape, and vessel heading and speed relative to the wave field.

Finally, note that an accumulation of ice will, in itself, increase the rate of accumulation. The ice already formed increases the effective cross section of rigging, mast, rails, and antennae, exposed to the spray.

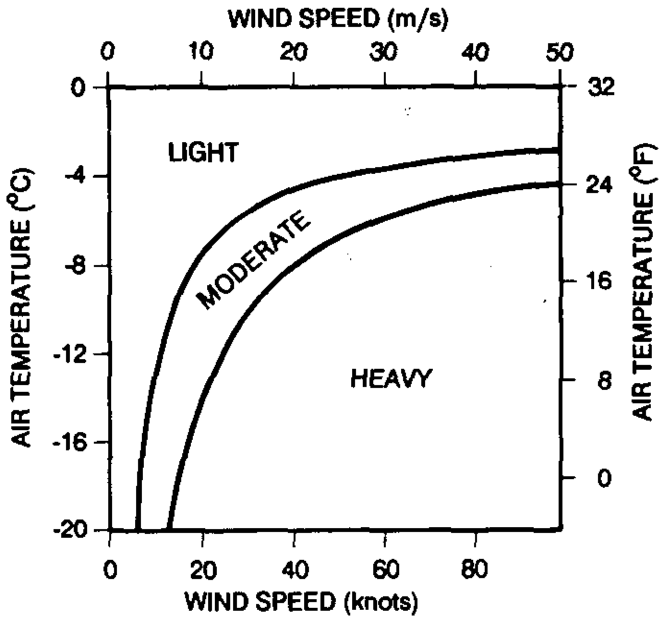
10.2 Estimating Rates of Icing

Considering the variety and number of variables to be studied in forecasting icing conditions, no simple or precise rules can be formulated. Over the past two decades, however, research and observations by scientists and mariners have led to some fairly reliable indicators that can be plotted graphically. The results of the most recent studies are summarized in the nomograms of Fig. 10-2.

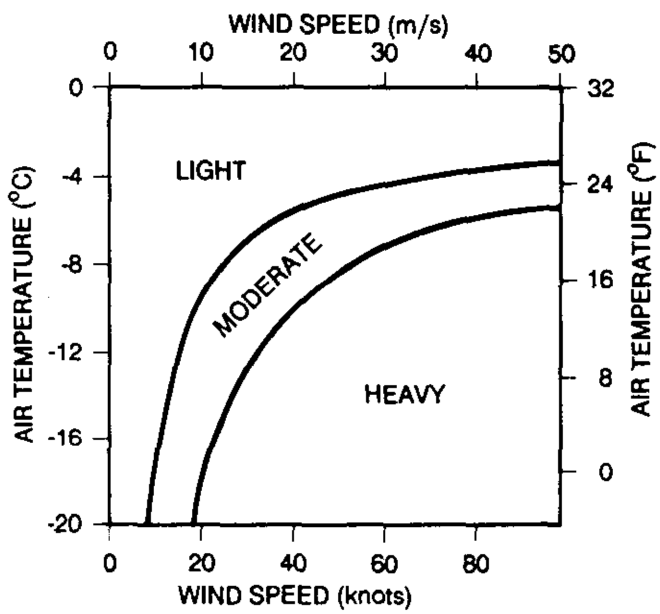
The nomograms of Fig. 10-2 are based on studies of small ships and are provided as baseline data. As the size of the ship increases, a proportional decrease in the amount of accretion can be expected. These nomograms show potential icing on the ship's superstructure for four water temperature ranges and a ship heading into or abeam of the wind. Ships running downwind will not likely incur accretion rates as high.



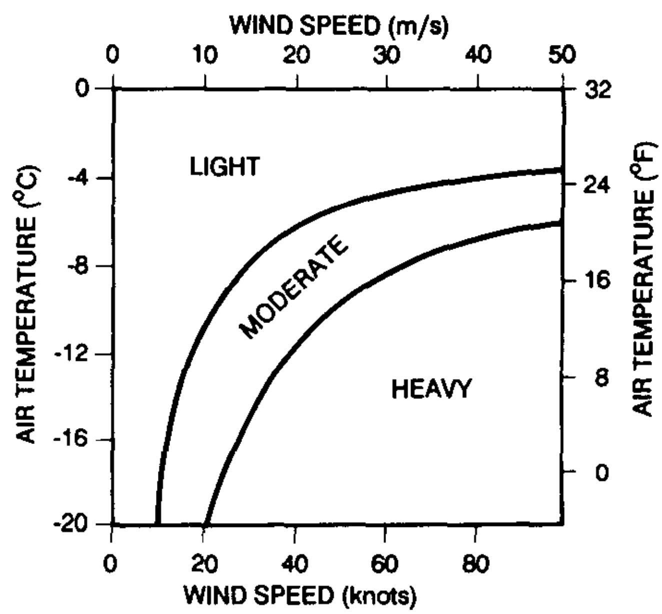
Icing conditions for vessels heading into or abeam of the wind for water temperatures of +1°C (34°F)



Icing conditions for vessels heading into or abeam of the wind for water temperatures of +3°C (37°F)



Icing conditions for vessels heading into or abeam of the wind for water temperatures of +5°C (41°F)



Icing conditions for vessels heading into or abeam of the wind for water temperatures of +7°C (45°F)

Light Icing - Less than 0.7 cm/hr (0.3 in/hr)
Moderate Icing - 0.7 cm/hr (0.3 in/hr) to 2.0 cm/hr (0.8 in/hr)
Heavy Icing - Greater than 2.0 cm/hr (0.8 in/hr)

Figure 10-2. Icing Nomograms (Overland et al., 1986).

These nomograms offer the best prediction method for icing available to the fleet. Laboratory experiments conducted at the Naval Applied Science Laboratory provide some further indication as to the potential weight increase that a ship may experience. A wind speed of 10 kt (5 m/s) and an air temperature of 0 °F (−18 °C) will yield an accretion rate of 8 lb per sq ft (≈ 37 kg per sq m). An Oliver Hazard Perry class frigate has over 7,000 sq ft (650 sq m) of exposed area on the forward one-third of the ship. Therefore, ice accretion could amount to 25 long tons per hour of extra weight. Figure 10-3 is presented to show ice accretion versus wind velocity for six air temperatures. An important note, however, is that icing rates vary with the geometry of structure and orientation, whether horizontal or vertical.

Sea surface temperature has a direct influence on the rate of ice accretion. In addition, warmer sea temperatures frequently mean warmer air temperatures. Since the air temperature also has a strong influence on the rate of ice accretion, the benefit of warmer water may be twofold.

Vessels that seek shelter in the lee of land may still experience low air temperatures, but some reduction of wind speeds and spray blown from the wave caps should be observed. Ship-generated spray in the calmer water will be greatly reduced. Furthermore, attempts to remove the ice will not be thwarted by the vessel's motion and seas sweeping the deck, as would be the case in the open sea.

In very high latitudes, however, ships should not seek shelter in the lee of the ice edge. The ice provides negligible shelter from the wind, and here the coldest air and sea temperatures are found and provide the most severe conditions for icing. If the wind backs

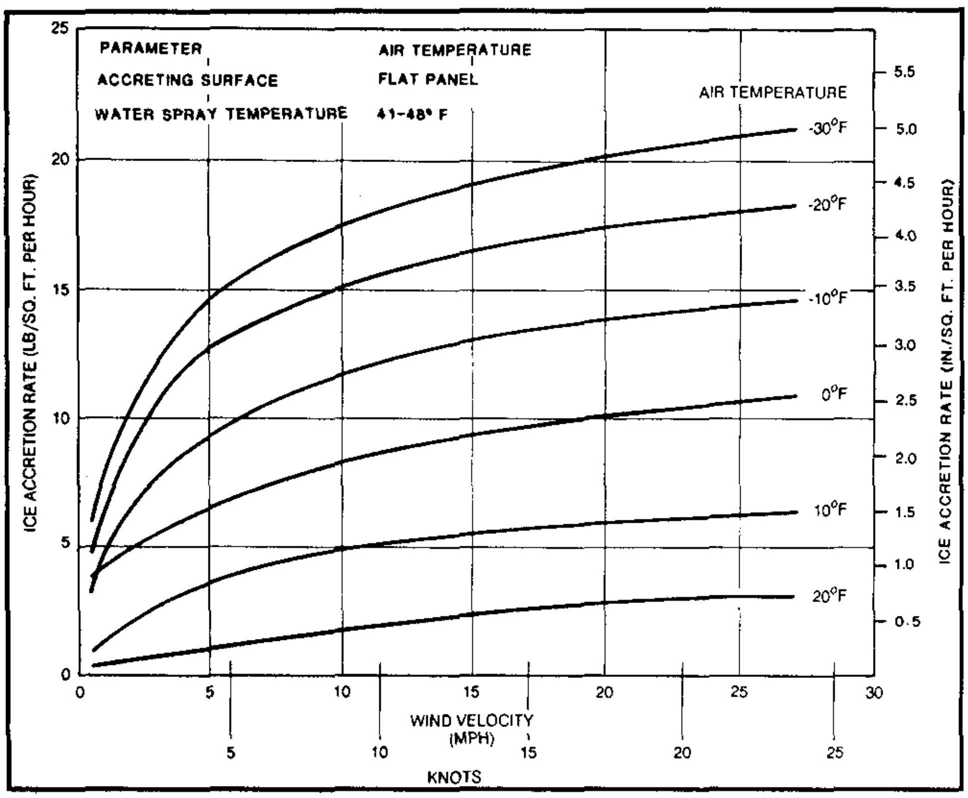


Figure 10-3. Ice Accretion Versus Wind Velocity (U.S. Navy, 1988).

or veers parallel to the ice edge, the air temperature remains very low and heavy seas are soon generated. When ice accumulation reaches 3.9 in (10 cm), dangerous conditions prevail. If this accumulation occurs within 4.5 hours, the condition is one of *extreme icing.* *Heavy icing* would produce this thickness in eight hours, and *light icing* would produce this thickness in one day.

10.3 An Example of Extreme Icing

During the week of 22 to 29 January 1989, the crabbing ship Vestfjord was making its way across the Gulf of Alaska from Cape Spencer, Alaska to the ice edge near Dutch Harbor in the Aleutians (see the locator map Fig. 10-4). As the ship passed south of Kodiak on 28 January the strong westerly winds it had encountered on the previous day intensified significantly and impeded its forward progress. The ship's superstructure began icing up from the supercooled sea spray as the vessel encountered strong cold advection and 50 kt winds.

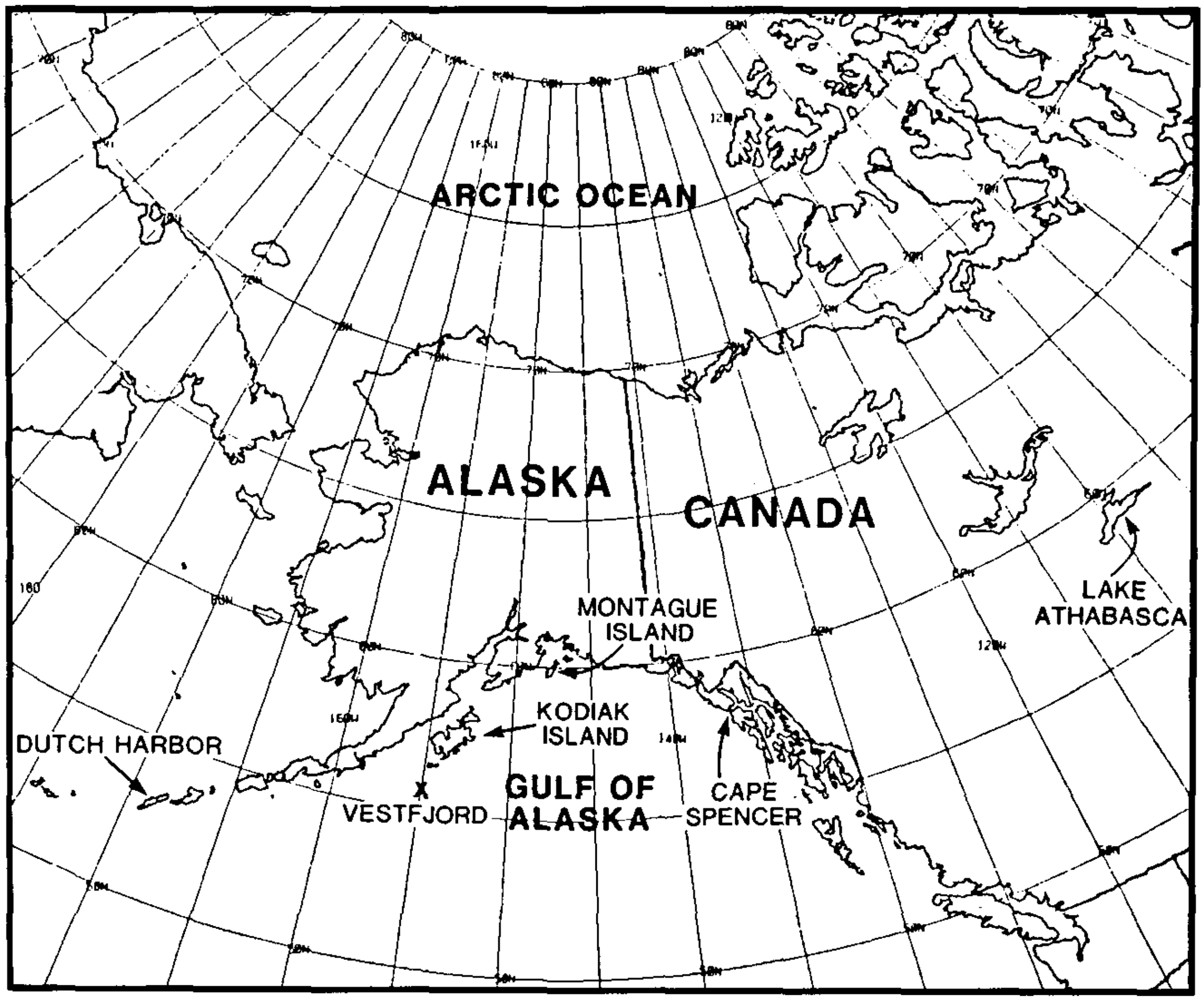


Figure 10-4. Locator Map.

The severity of the situation increased on the 29th, as can be gleaned from the 0600 GMT surface weather map for that date (Fig. 10-5). This surface chart shows a sharp, elongated low-pressure trough oriented nearly east-west and extending from the vicinity of Lake Athabasca, Canada to the central Aleutians. The trough terminated just east of an intense high pressure area centered over the western tip of the Aleutians. Between these two systems was an intense pressure gradient that resulted in northwest winds in excess of 50 kt (26 m/s) with 27 ft (8 m) seas. The air temperature, meanwhile, was about 7 °F (−14 °C) and the sea surface temperature near 39 °F (4 °C).

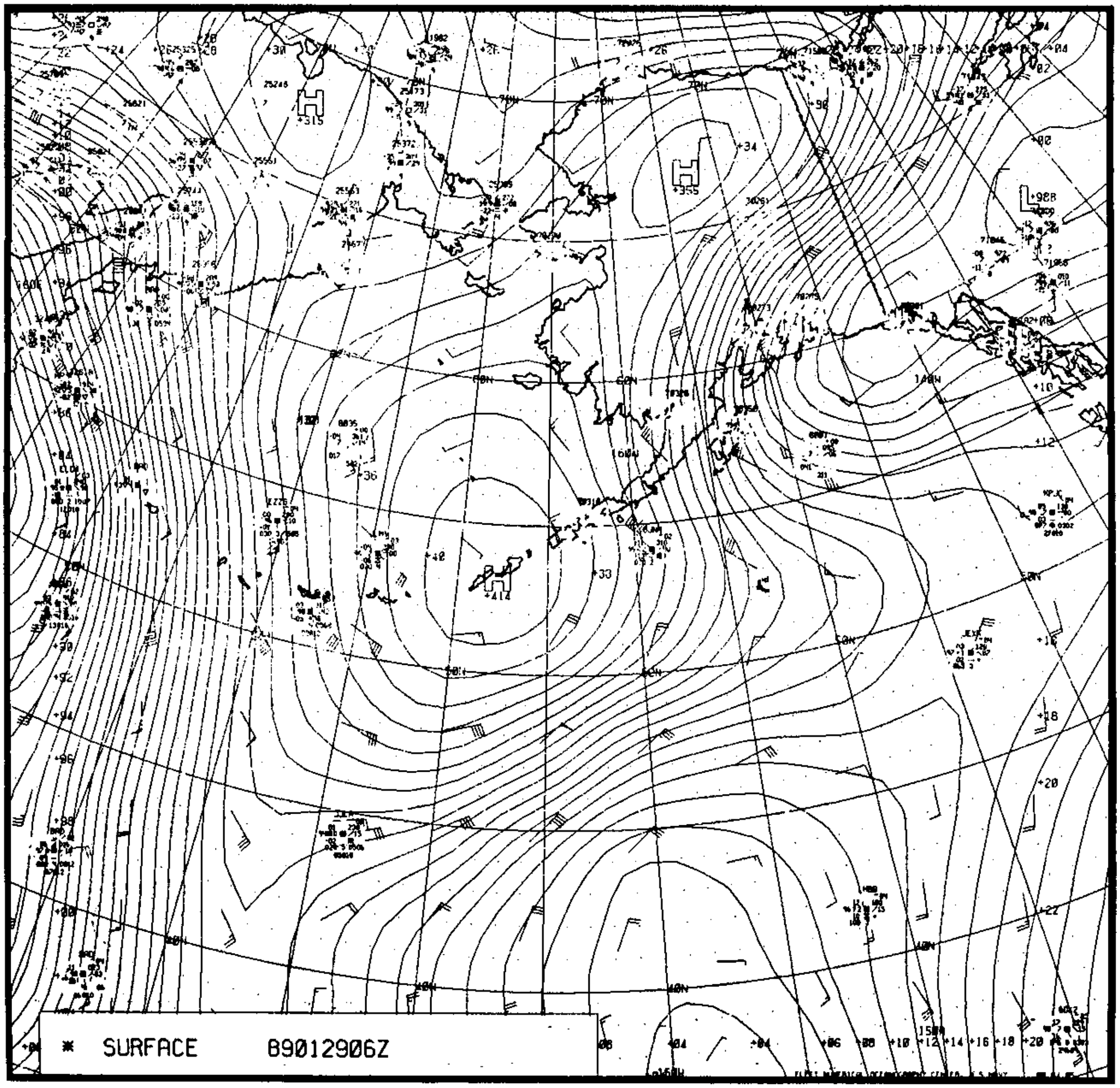


Figure 10-5. The Surface Chart, 0600 GMT 29 January 1989.

The intensity of the cold air advection occurring at the time of heaviest icing is best depicted on the 850-mb chart for 0000 GMT 29 January 1989, as seen in Fig. 10-6. The strongest cold advection on this chart occurs southwest of the low centered near Montague Island on the south-central coast of Alaska. This region is precisely where the ship overturned and sank with all six hands at 1010 GMT on the 29th (last position of Vestfjord shown as an "X" in Fig. 10-4).

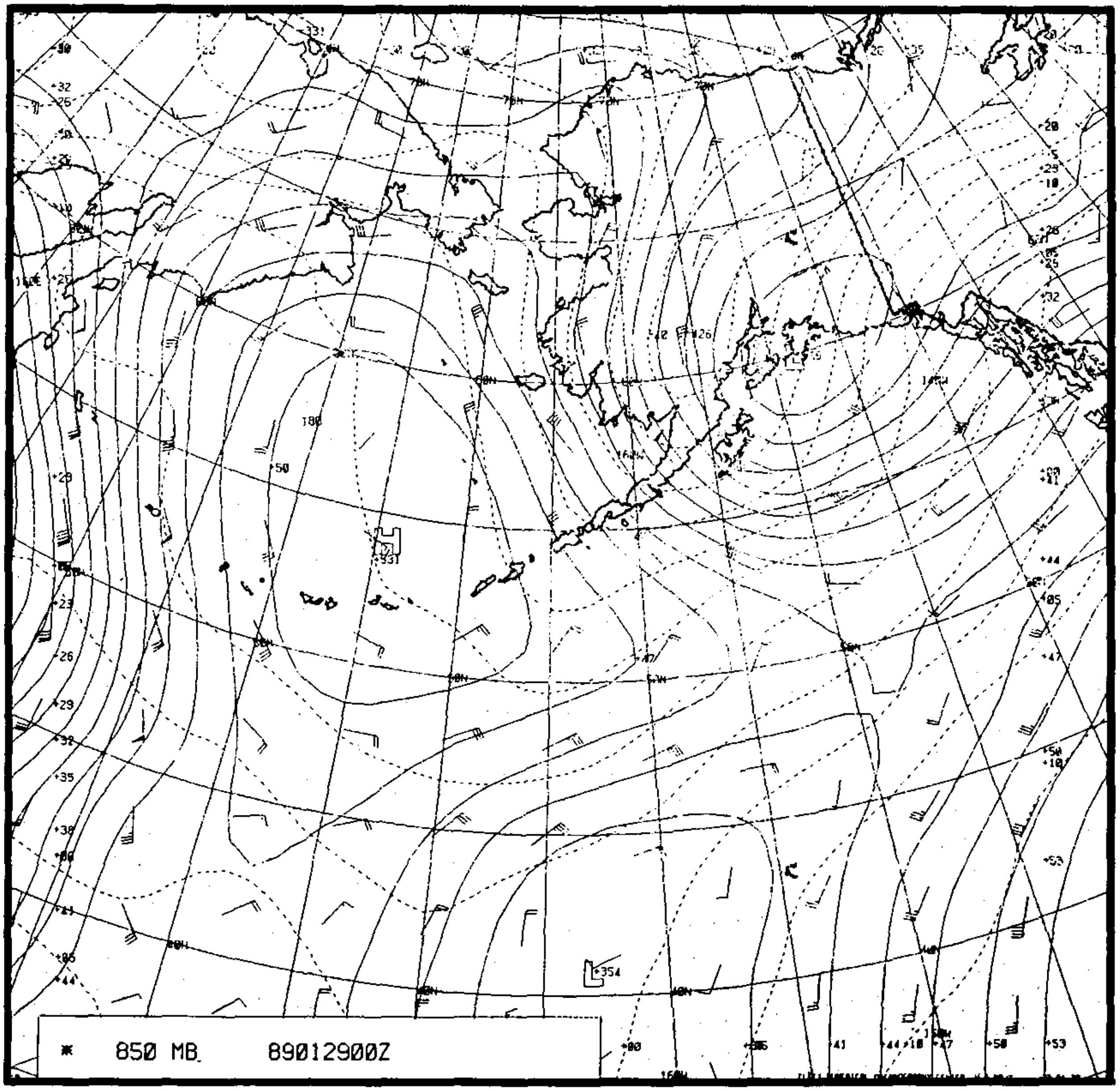


Figure 10-6. The 850-mb Chart, 0000 GMT 29 January 1989.

Figure 10-7 is a satellite imagery from the DMSP satellite for 0552 GMT on the 29th of January 1989. An X marks the approximate location of the ship at that time. The effect of the cold surge on the cloud lines is apparent in the imagery, showing not only strong northwest flow but likely precipitation as well.

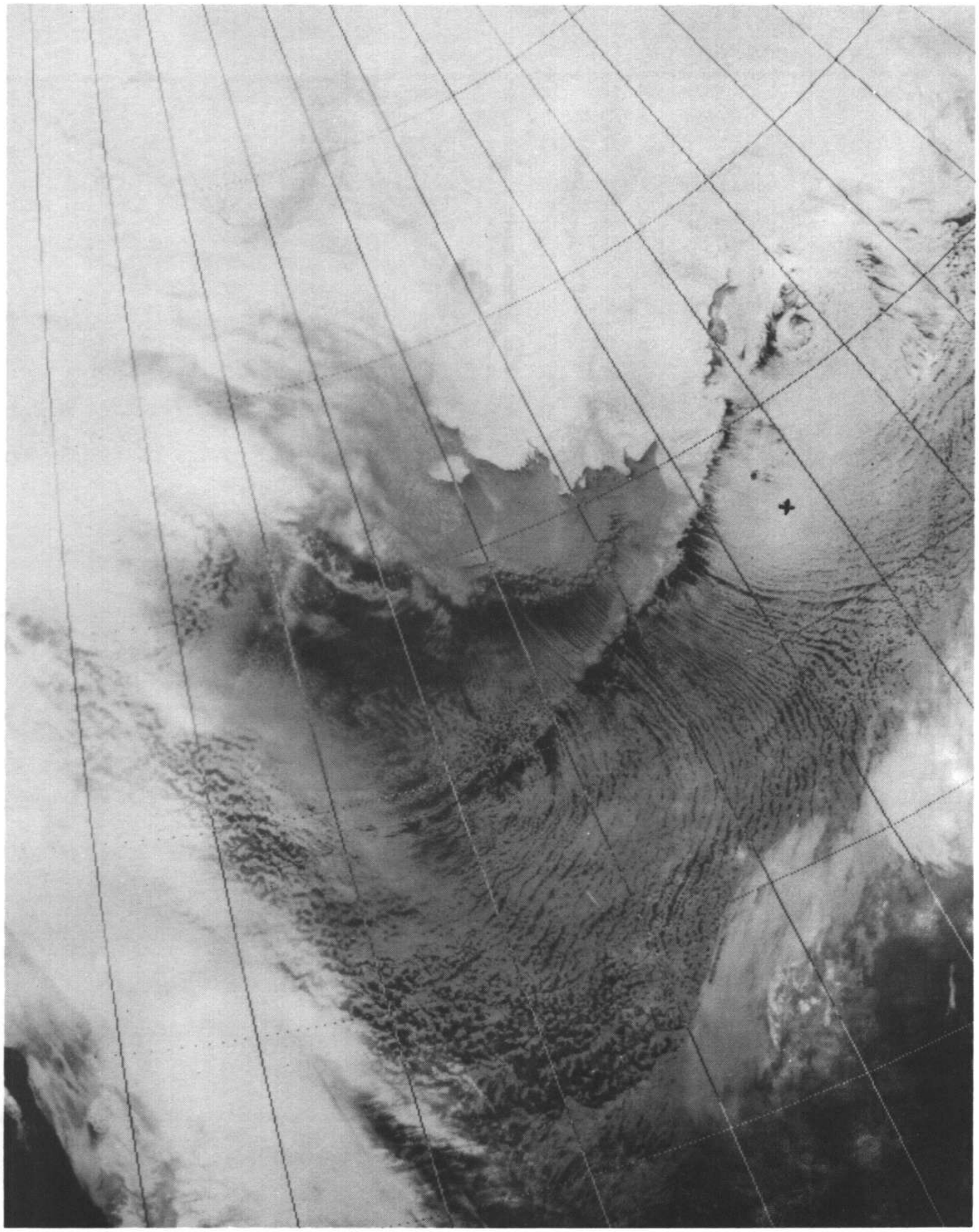


Figure 10-7. IR Satellite Imagery, 0552 GMT 29 January 1989.

As Fett (1989) noted in his study of this case, icing can be heavy even with water temperatures as high as 45 °F (7 °C) if the air temperature is cold enough and wind speeds are high enough. He also noted that icing conditions are especially favored in the region in advance of an approaching 500-mb trough. Figure 10-8 is the 500-mb chart for 0000 GMT 29 January 1989 and shows the trough line just east of and parallel to the Aleutians about 10 hours before the ship went under.

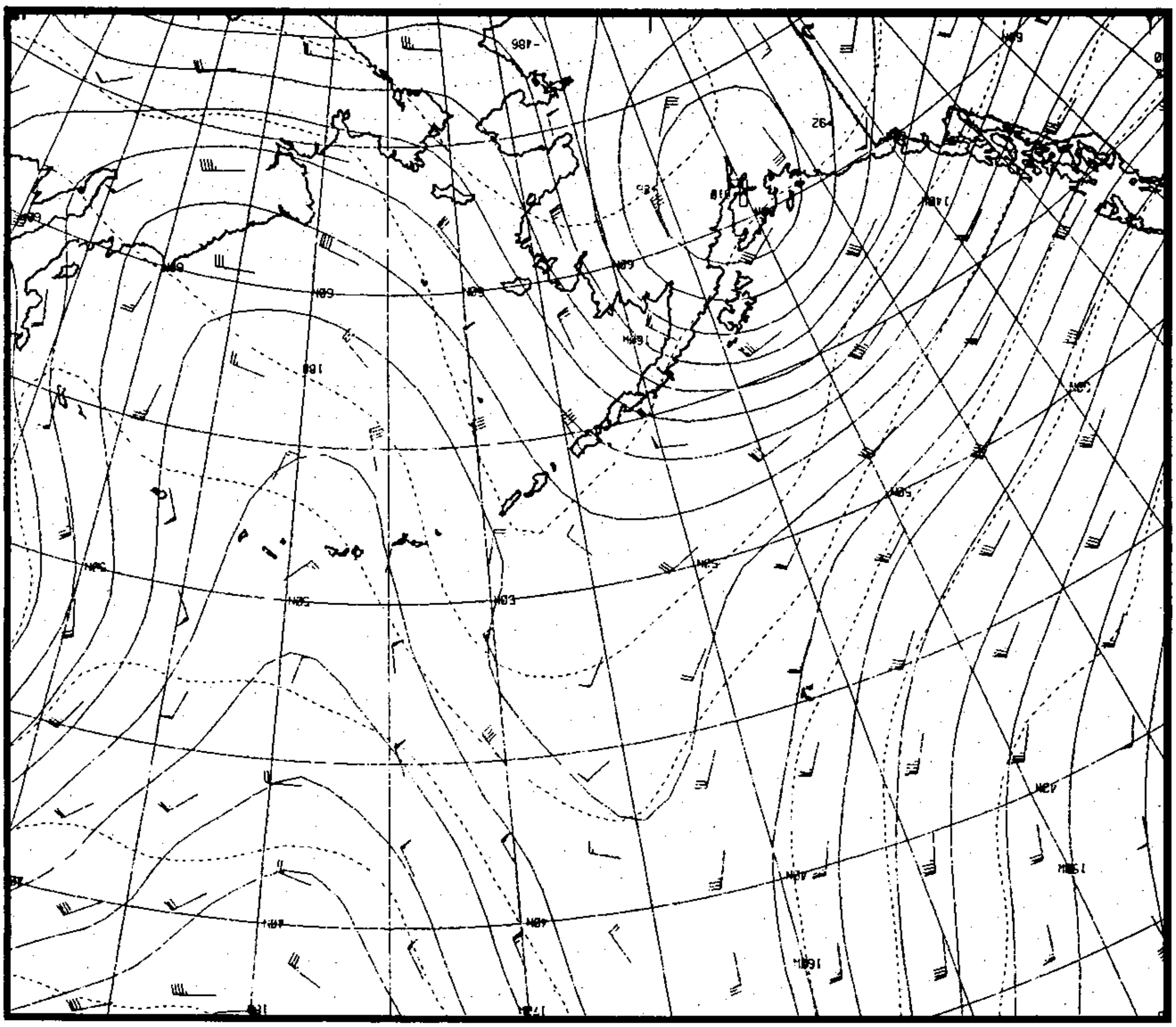


Figure 10-8. The 500-mb Chart, 0000 GMT 29 January 1989.

10.4 Aircraft Icing

Aircraft icing is one of the major weather hazards to aviation. Ice on the airframe decreases lift and increases weight, drag, and stalling speed. In addition, the accumulation of ice on exterior movable surfaces affects the control of the aircraft. Finally, airframe icing greatly increases fuel consumption and decreases range.

The subject of aircraft icing is complex. The following discussion outlines the basic elements of aircraft icing but makes no attempt to encompass all available knowledge on the subject.

10.4.1 The Formation of Ice on Aircraft

Two basic conditions must be met for ice to form on an airframe in significant amounts. First, the aircraft surface temperature must be colder than 32° (0 °C). Second, supercooled water droplets, i.e., liquid water droplets at subfreezing temperatures, must be present. Water droplets in the free air, unlike bulk water, do not freeze at 32 °F (0 °C). Instead, their freezing temperature varies from an upper limit near −23 °F (−31 °C) to a lower limit near −40 °F (−40 °C). The smaller and purer the droplets, the lower is their freezing point. When a supercooled droplet strikes an object, such as the surface of an aircraft, the impact destroys the internal stability of the droplet and raises its freezing temperature. Therefore, the possibility of icing must be anticipated in any flight through supercooled clouds or liquid precipitation at temperatures below freezing. In addition, frost sometimes forms on an aircraft in clear humid air if both aircraft and air are at subfreezing temperatures.

10.4.2 Icing Factors

Temperature of the cloud droplets and aircraft surface temperature are only two of the physical factors involved in aircraft icing. Also to be considered are (1) liquid water content, (2) droplet size, (3) collection efficiency, and (4) aerodynamic heating.

Under icing conditions, the *liquid water content* of the cloud is probably the most important parameter in determining the ice accumulation rate. In general, the lower and warmer the base of the cloud, the higher is its water content. Within the cloud, the average liquid water content increases with altitude to a maximum value and then decreases. The maximum concentration usually occurs at a lower level in stratiform than in cumuliform clouds, and the average liquid water content of a stratiform cloud is usually less than that of a cumuliform cloud.

The *size distribution* and median size of the droplets in a cloud are related to the type, depth, and age of the cloud, the strength of the updrafts, the humidity of the air mass, and to other factors. Since both the liquid water content and droplet size are generally greater in cumuliform clouds than other cloud types, at first glance cumuliform clouds would appear to be particularly conducive to icing. The effect exerted by other variables (such as the speed, shape, and size of the aircraft components), however, may be sufficiently great for meteorological conditions leading to trace icing for one type of aircraft to result in light or moderate icing for another.

The icing rate depends to a large extent upon the *collection efficiency* of the aircraft component involved. Collection efficiency, or the fraction of the liquid water collected by the aircraft, varies directly with droplet size and aircraft speed, and inversely with the size or geometry of the collecting surface. The size of an aircraft component is described in terms of the radius of curvature of its leading edge. Those components that have large radii of curvature (canopies, thick wings, etc.) collect but a small percentage of the cloud droplets, especially of the smallest droplets. Components having small radii of curvature (antenna masts, thin wings, etc.) deform the airflow less, permitting a higher proportion of droplets of all sizes to be caught. Once ice begins to form, the shape of the collecting surface is modified, with the radius of curvature nearly always becoming smaller and the collection efficiency increasing. In general, fighter-type aircraft, because of their greater speed and thinner wings, have higher collection efficiencies than do cargo aircraft.

Aerodynamic heating is the temperature rise resulting from adiabatic compression and friction as the aircraft penetrates the air. (The saturation-adiabatic laws, including the effects of fusion and evaporation, apply to flight through clouds.) The amount of heating varies primarily with the speed of the aircraft and the altitude (air density) ranging from about one centigrade degree for very slow aircraft at low altitudes to more than 50 degrees for supersonic jets at low altitudes. Thus, although an aircraft flying through any supercooled liquid water cloud must anticipate icing (as stated in the previous subsection), in actuality, the amount of supercooling must exceed the amount of aerodynamic heating (U.S. Navy, 1985).

10.4.3 Atmospheric Distribution of Icing

The atmospheric distribution of potential aircraft icing zones is mainly a function of temperature and cloud structure. These factors, in turn, vary with altitude, synoptic situation, orography, location, and season.

Altitude and Temperature

In general, the frequency of icing decreases rapidly with decreasing temperature, becoming rather rare at temperatures below −22 °F (−30 °C). The normal vertical temperature distribution in the atmosphere is such that icing is usually restricted to the lower 30,000 feet (9,140 m) of the troposphere.

The type of icing, also, is highly dependent on temperature. Clear ice usually occurs at temperatures just below freezing, whereas rime ice predominates at lower temperatures. The relative frequency of icing by types is as follows: clear, 10 percent; clear-rime mixture, 17 percent; rime, 72 percent; and frost (in flight), 1 percent.

Clouds

Icing in middle and low level stratiform clouds is confined, on the average, to a layer between 3,000 and 4,000 ft (≈ 900–1,200 m) thick. The intensity of the icing generally ranges from a trace to light, with maximum values occurring in the upper portions of the cloud. Both rime and mixed icing are observed in stratiform clouds. The main hazard lies in the great horizontal extent of some of these cloud decks. High level stratiform clouds are composed mostly of ice crystals and produce little icing.

The zone of probable icing in cumuliform clouds is smaller horizontally but greater vertically than in stratiform clouds. Furthermore, icing is more variable in cumuliform clouds because many of the factors conducive to icing depend to a large degree on the stage of development of the particular cloud. Icing intensities may range from generally a trace in small, supercooled cumulus to often light or moderate in cumulonimbus. Although icing occurs at all levels above the freezing level in a building cumulus, it is most intense in the upper regions in a mature cumulonimbus, and to a shallow layer near the freezing level in a dissipating thunderstorm. Icing in cumuliform clouds is usually clear or mixed.

Frontal Systems

Warm frontal icing may occur both above and below the frontal surface. Moderate or severe clear icing usually occurs where freezing rain or freezing drizzle falls through the cold air beneath the front. This condition is most often found when the temperature above the frontal inversion is warmer than 32 °F (0 °C) and the temperature below is colder than freezing. Icing above the warm frontal surface, in regions where the cloud temperatures are colder than freezing, is usually confined to a layer less than 3,000 ft (914 m) thick. For active, warm, fast-moving fronts, moderate icing, usually clear or mixed, can be found 100 to 200 mi (≈ 160–320 km) ahead of the front.

Whereas warm frontal icing is generally widespread, icing associated with cold fronts is usually spotty. Its horizontal extent is less and the areas of moderate icing are localized. Clear icing is more prevalent than rime icing in the unstable clouds usually associated with cold fronts. Moderate clear icing is usually limited to supercooled cumuliform clouds within 100 miles (160 km) to the rear of the cold front surface position and is usually most intense immediately above the frontal zone. Light icing is often encountered in the extensive layers of supercooled stratocumulus clouds that frequently exist behind cold fronts.

Orographic Influences

High or steep terrain, particularly mountains, causes icing to be more intense than is usual under identical conditions over flat terrain. Icing is greater over the ridges than over the valleys and greater on the windward side than on the lee side. Moderate icing, usually clear, is experienced in convective clouds over mountainous terrain. Windward, mountainous coasts in winter are especially subject to extensive aircraft icing zones.

Geographic Distribution

A wide variation of aircraft icing potential exists between geographic areas because of area-to-area variations in temperature and available moisture. For example, icing during the winter season is very frequent over the warm water areas off the east coast of continents, to the lee of large inland water bodies, and over those western portions of continents where winds transport ample moisture inland from the oceans.

Because of the comparatively small amount of moisture in winter Arctic air and the small liquid water content of clouds, icing is seldom regarded as a serious problem in the Arctic in winter. Not surprising, therefore, icing was reported by weather reconnaissance aircraft only 2 percent of the time over the Arctic Ocean at 10,000 ft ($\approx$ 3,050 m). On the other hand, at the same altitude over the northern portion of the North Atlantic Ocean, icing was reported 19 percent of the time. Weather reconnaissance data at 700 and 500 mb over the oceans suggest that the greatest winter icing frequency was found over the northern and western parts of the North Pacific and North Atlantic, and the least over the Arctic Ocean. These data do not imply that icing is never a hazard in the Arctic. In those instances when moisture-laden air from the North Atlantic and the North Pacific invades the Arctic, conditions conducive to copious icing are established.

Normally, winter is the season of maximum icing. The exception is over the Arctic Ocean, where maximum icing occurs in summer because the temperatures and moisture amounts are much too low in winter.