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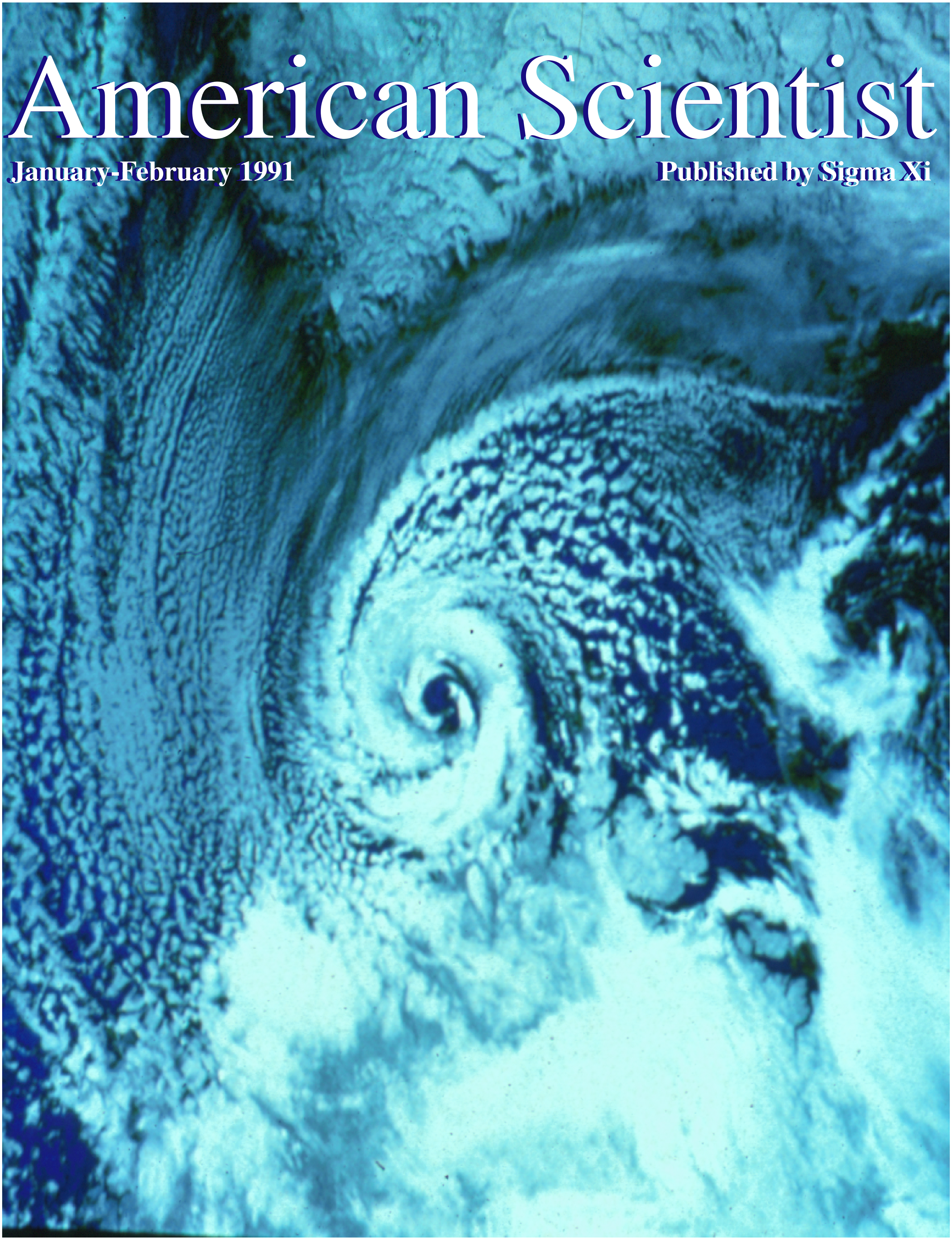

Arctic Hurricanes

The closest cousin to the leviathans of the tropics may be a ferocious storm that stalks the arctic winter

Steven Businger

Figure 1. Sea and sky become one off the coast of Kodiak Island, Alaska, as a polar low, or arctic cyclone, approaches. Arctic maritime storms, moving along at speeds greater than 30 knots, can quickly spoil a clear day. A dark band of low clouds precedes gale-force winds, lightning, blinding snow and high, confused seas. (Photograph courtesy of the author.)

On March 7, 1977, a Soviet icebreaker plied the western Bering Sea near the edge of the arctic winter ice. The day dawned clear and cold; the first rays of a feeble arctic sun failed to offset the sting of a gusty northeast wind.

Suddenly, with the approach of midday, a dark band of clouds obscured the horizon. The winds, at first light and northerly, veered to southwest and rapidly increased to gale force, gusting to hurricane strength of over 64 knots and engulfing the ship in a confused onslaught of 30-foot waves. Snow and sea spray swirled thickly; frequent lightning illuminated a deck thickly encrusted with ice. The barometric pressure, already low, plunged further as evening temperatures rose to their warmest in a month.

That night, the sky unexpectedly cleared to reveal a cathedral of cloud, illuminated by the moon and a fresco of stars. But there was barely time to think of breaking the rime off the rigging when the storm set in again with even greater fury, the winds now bearing down from the north. Finally, around midnight, the turmoil abated as the snow squalls became less frequent and less violent. By dawn the sky had cleared and the seas gradually smoothed in response to a light, though bitterly cold, northwest wind. The ship's crew returned to port grateful to have survived a fierce—and utterly unforeseen - arctic storm.

What kind of storm was this? At the time it occurred, scientists had just begun to investigate the diverse storms of the Arctic. As yet, little was understood about the structure and evolution of the fast-forming, quick-striking, destructive storms of the far north, storms that for centuries had sunk fishing boats under heavy burdens of rime—a tough, grainy accumulation of frozen mist and sea spray. In 1977 data on these arctic disturbances consisted largely of scattered reports from ships and aircraft; the storms' dynamics remained nearly as mysterious to meteorologists as they were to the ancient.

Viking poets, called skalds, whose adventures in the Norwegian Sea inspired verses such as this:

> *The steed of the sea-peak, wind-ridden,*
> *tears his breast spread with red stain*
> *from out the mouth of the white*
> *sea-goddess.*

In the 1970s scientists began taking a close look at the cloud shapes revealed by satellites that looked down on the winter Arctic from polar orbits. The shapes were intriguing, varied and often surprising. Photographs of some intense storms, such as the one experienced by the Soviet icebreaker, raised a fascinating question: Is it possible for a storm with a structure analogous to a hurricane to form over open water in the Arctic? These storms shared many of the observed characteristics of tropical hurricanes: highly symmetric, spiral cloud signatures, vigorous cumulonimbus clouds surrounding a clear "eye" and a band of strong winds reaching maximum strength at low altitudes close to the core.

One sees such a distinctive signature in satellite images of the Bering Sea from March 7 and 8, 1977. The pictures show an unusually symmetric spiral cloud shield less than 300 kilometers in diameter, with a clear eye. Hourly observations at the National Weather Service station at St. Paul Island in the Pribilof Islands yield other clues: The surface-pressure trace exhibits a sharp V, marking the passage of a center of low pressure. In contrast, traces of temperature and dew-point temperature show pronounced maxima as this low-pressure center passes—indicative of a warm core, also observed in tropical cyclones and distinctly unlike the cold core of most midlatitude cyclones.

It is only rarely that entirely unknown phenomena are discovered in the earth's atmosphere, which is under almost constant instrument surveillance and has been watched by polar-orbiting and geostationary satellites for a number of years now. The atmosphere of the Arctic, however, still holds many secrets. Over the open water of the remote arctic seas, where meteorological data are sparse, no one expected the variety and profusion of storms that satellite imagery has revealed. These disturbances form rapidly, and, because of their small size, often escape detection as they traverse the coastal waters off Norway and Alaska, with catastrophic consequences for fishing and offshore oil interests. We are just beginning to gain scientific insight into theses storms to complement a wealth of anecdotal lore, from the ancient Norse legends to the tales still passed among fishermen in coastal villages. Spurred by support from the petroleum industry and affected governments, especially those of Norway and the United States, scientists have made a concerted effort in recent years to understand the complex atmospheric environment of the Arctic, and the numerous storms fostered in the cold air there.

The generic term "polar lows" has been applied to the severe disturbances of the arctic atmosphere. The use of this term is evolving; as used in this article, it refers to small-scale cyclones whose main cloud mass is largely of convective origin and that (in the Northern Hemisphere) form in cold air masses north of the polar front, the zone in the middle latitudes where contrasting polar and tropical air masses meet and mix. Investigations of these storms are proceeding along several avenues (see, for example, Twitchell et al. 1989). Here the discussion will be confined to a small group of particularly intense systems that stand out as peculiar, especially in the parallels that can be drawn to tropical cyclones. These storms will be called arctic hurricanes. Using the Bering Sea storm as a case study, this article will examine the observed characteristics of arctic hurricanes and discuss the application of a numerical hurricane model to further investigate the similarities and differences between arctic hurricanes and their tropical counterparts.

It is important to note that hurricanes are, by definition, tropical storms. A combination of conditions unique to the tropical oceanic atmosphere is considered necessary to their development. The notion that these tropical cyclones might have analogues outside the tropics, however, is not new; in 1954 Tor Bergeron used the term "extra-tropical hurricane" when describing the small-scale storms that are generated in the cores of dissipating midlatitude cyclones as they pass over relatively warm waters.

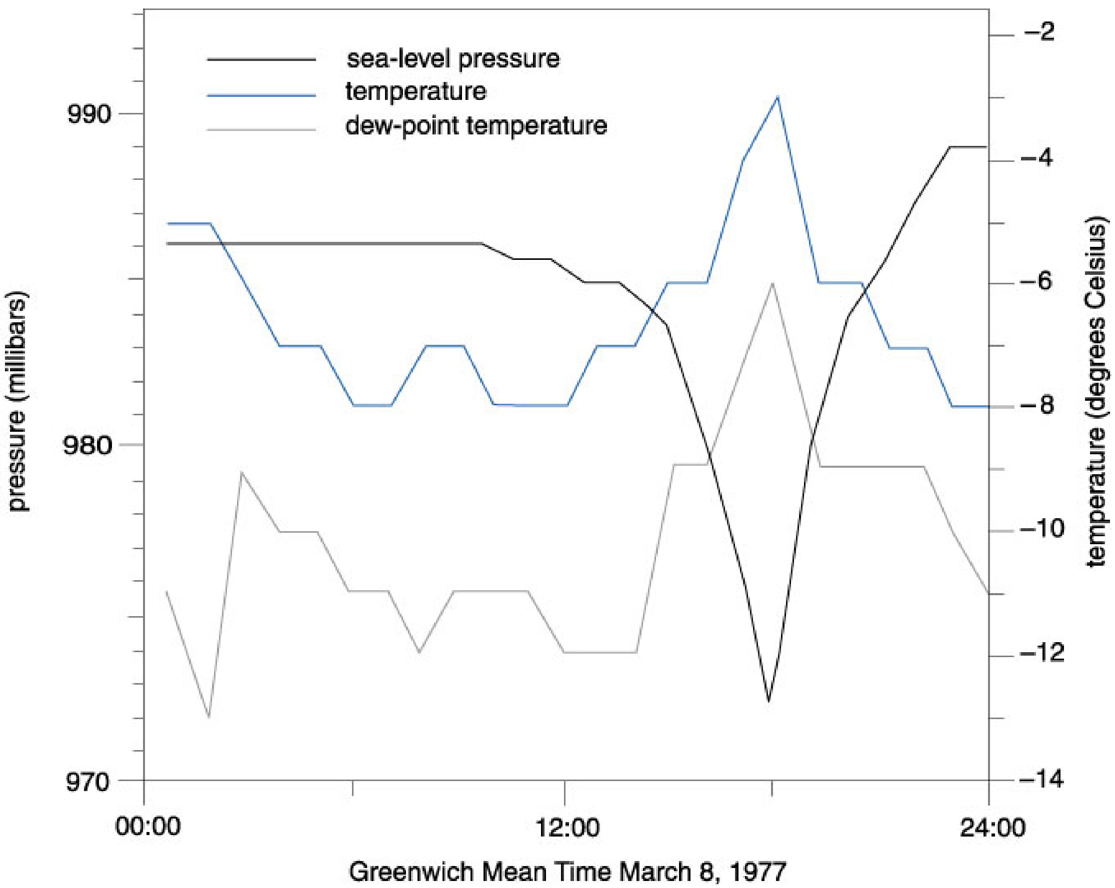

Figure 2. Warm, low-pressure core of an arctic hurricane left its signature in the record books as it passed St. Paul Island in the Bering Sea on March 8, 1977. Hourly National Weather Service data show a clear V in the sea-level pressure trace, accompanied by sharp spikes in temperature and dew-point temperature, as the storm center passes by at about 18:00 Greenwich Mean Time (7:00 a.m. local time).

In this article the term "arctic hurricane" will be used to refer to a polar low with a symmetric cloud signature and winds of at least 30 meters per second (or 58 knots; the traditional threshold for hurricane-force winds, 64 knots, also is regularly exceeded by these storms), in which fluxes of heat at the sea surface play the dominant role in the structure and sustenance of the mature storm. This definition, as will be explained below, places these storms within the context of an emerging general theory of hurricanes, reviewed by Kerry Emanuel in *American Scientist* in 1988. This theory is based on the premise that the primary source of energy for hurricanes lies in the disequilibrium between the atmosphere and the underlying ocean.

The Genesis of Polar Lows

It is perhaps ironic that tropical and arctic hurricanes arise under conditions that are at opposite extremes. Tropical hurricanes are creatures of warm-season conditions in warm climates, whereas arctic hurricanes inhabit the polar winter, most commonly occurring in the months of November through March. To understand how a hurricane-like storm might form in the frigid atmosphere of the arctic winter, one must first explore the sources of energy important to the development of cyclones in cold air streams over relatively warm oceans.

During the long arctic winter night, outgoing longwave radiation allows air temperatures over the pack ice covering the Arctic Ocean to fall well below zero degrees Celsius; surface readings as low as –40 degrees Celsius (which happens to be equivalent to –40 degrees Fahrenheit) are not uncommon. Strong low-level inversions—stable layers of air in which temperature increases with height—form over the ice sheet in winter because of the cooling of surface air. When cold arctic air is blown over open water, however, its thermodynamic state is rapidly modified by fluxes of heat and moisture from the sea surface, where warm ocean currents

Figure 3. Rime, the thick crust of frozen mist and sea spray that engulfs boats caught in arctic winter storms, is a major hazard to commercial vessels, making them vulnerable to capsizing. This U.S. Coast Guard cutter was caught in a gale in the North Atlantic in the early 1970s. Arctic cyclones give their victims little opportunity to beat ice off decks and rigging. (U.S. Coast Guard photograph.)

keep temperatures several degrees above freezing. Recent observations by research aircraft have shown that the modification of arctic boundary-layer air (the lowest kilometer or so of the atmosphere that directly feels the influence of the ocean surface directly). by surface fluxes can produce zones of contrast called arctic fronts (Shapiro and Fedor 1989). An arctic front is, in essence, the boundary between air that has been warmed on a long path over the sea and air that has just left the ice pack.

Weather disturbances are known to develop along arctic fronts by a process called baroclinic instability, in which warm air is lifted over colder descending air. The warm air expands and cools as it rises, resulting in the formation of clouds and precipitation. As this happens, gravitational potential energy stored in the air is transformed into the kinetic energy of the winds. This transformation is analogous to a situation in which two fluids of differing densities in a tub are separated by a partition. When the partition is removed, the denser fluid will flow underneath the lighter one, resulting in horizontal motions—the equivalent of wind—until all the fluid is redistributed, with the denser fluid coming to rest at the bottom of the tub.

Baroclinic instability is the same mechanism that provides the primary energy source for the midlatitude cyclones that form along the circum-hemispheric polar front. These systems, also called frontal cyclones, are seen most commonly in the latitudes between 30 degrees and 60 degrees north. They are large-scale disturbances, typically 1,500 kilometers across. The driving force for the temperature contrast across the polar front is the unequal distribution of solar radiation across the earth's surface from the equator to the pole. Frontal cyclones mix warm air northward and cold air southward, reducing this contrast.

It is unlikely that, by itself, the baroclinic instability associated with a shallow arctic front can explain the combination of features exhibited by arctic hurricanes, such as their warm cores and the symmetric spiral bands of deep, convective clouds seen in satellite imagery. In search of a more complete understanding of such

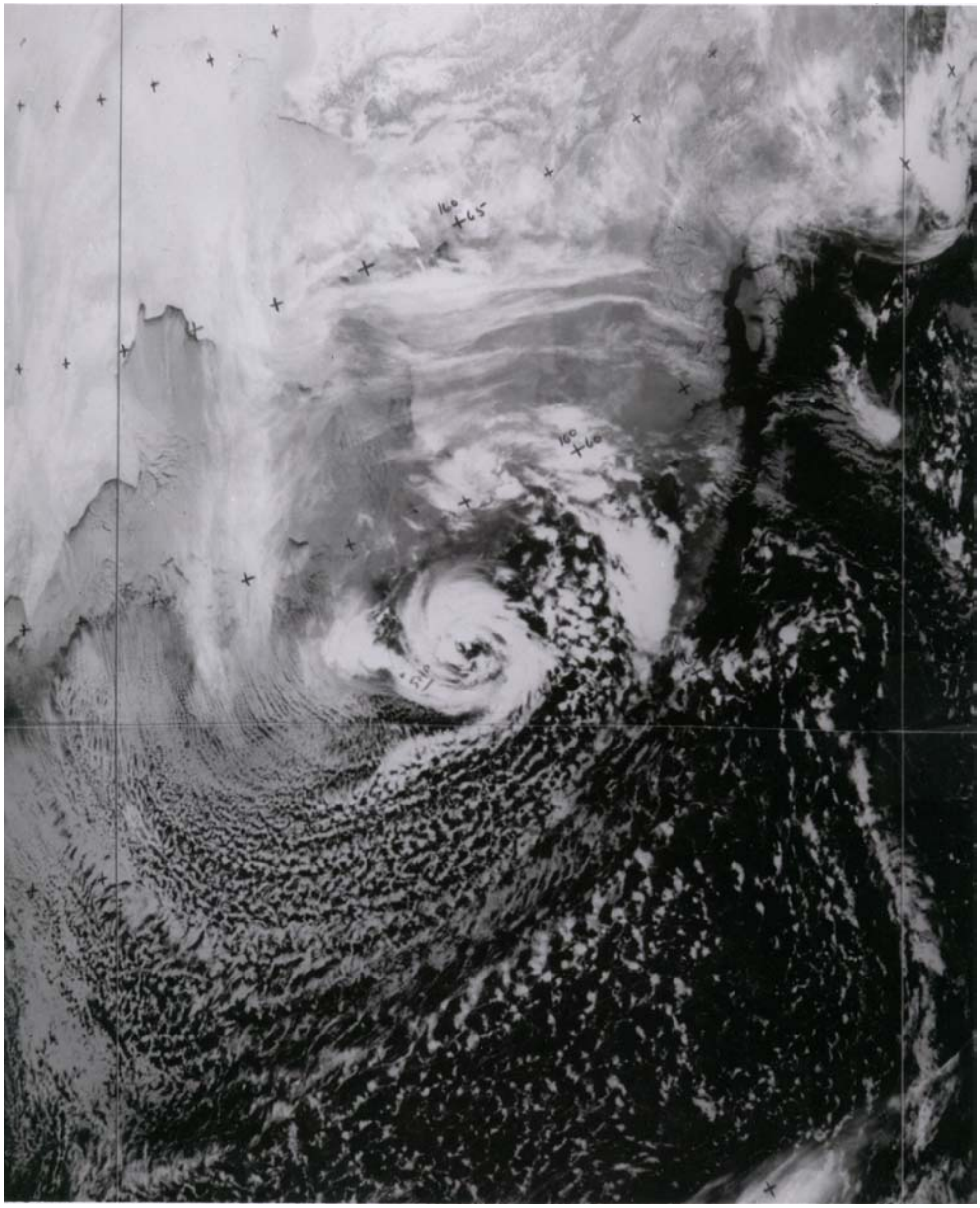

Figure 4. Arctic hurricane, seen from space, bears striking similarities to images of tropical hurricanes. An infrared image of clouds in the Bering Sea, taken by the *NOAA-5* satellite at 21:00 Greenwich Mean Time on March 8, 1977, shows a mature cyclone tightly organized around a cloud-free "eye." The storm is about six kilometers in height and some 300 kilometers in diameter; arctic storms are compact compared to tropical hurricanes, which are as tall as 16 kilometers and as much as 1,500 kilometers in diameter. A feature not seen in tropical hurricanes is the cloud streets, parallel streaks of cumulus clouds, indicative of arctic air streaming off the winter ice to the north. Red crosses indicate intersections of latitude and longitude lines every five degrees. The eye is just east of St. Paul Island and south of the arctic ice edge.

hurricane-like storms, a number of studies have examined the processes whereby heat is transferred within these storms—in particular, the release of latent heat in clouds and the fluxes of heat from the underlying ocean surface.

Clouds that form over the ocean serve as the agents of a convective process in the atmosphere that can greatly intensify during a storm. Since heat in the atmosphere comes primarily from the earth's surface, cumulus convection plays an important role in redistributing this energy upward through the troposphere. Water vapor rising from the sea surface carries with it latent heat, heat that had to be invested to evaporate the water. When air rises in updrafts, it cools as it expands, and some of the water vapor condenses into clouds. In forming clouds the vapor gives up the latent heat, warming the upper-level air—just as water condensing on a cold bottle of beer quickly warms the contents.

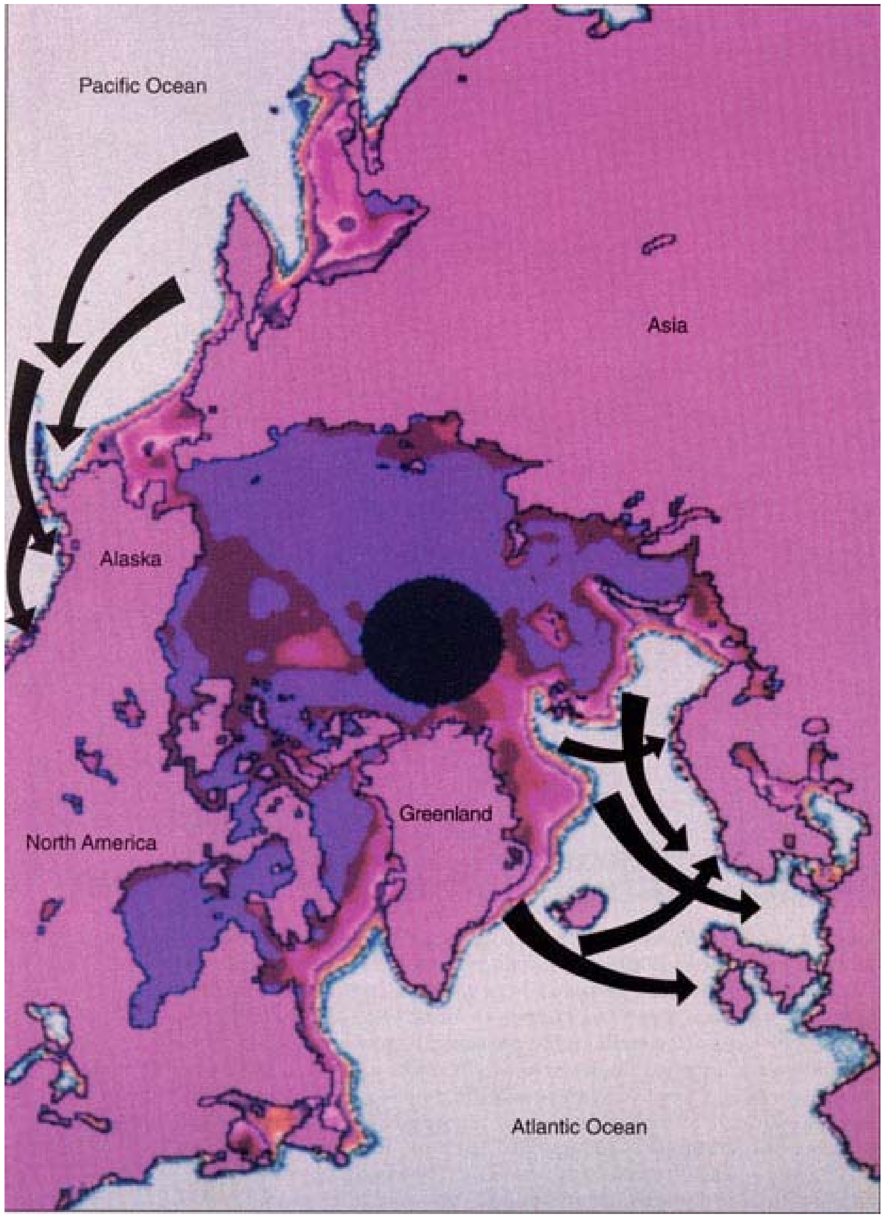

Figure 5. Arctic sea areas where relatively warm open water meets winter pack ice are the spawning grounds of hurricane-like storms. This *Nimbus-7* satellite image shows the average concentration of winter ice in northern seas during February 1987, when the storm shown on the cover of this issue of *American Scientist* developed over the Norwegian Sea. The edge of the sea ice is shown in blue-green, which represents partial coverage, whereas deep purple indicates ice concentrations of 96 to 100 percent. Areas without data are shown in black. Arrows show the general areas of origin and the common paths of polar lows, which dissipate after reaching the coasts of Alaska or Norway. (Image courtesy of Per Gloersen, Laboratory of Hydrospherics, NASA Goddard Space Flight Center.)

In some situations where there are large air-sea temperature differences—common in the arctic winter—there are also large fluxes of sensible heat from the ocean. Sensible heat is heat that is not transported upward by evaporation but is absorbed directly into the air at the ocean surface, producing a measurable (sensible) change in air temperature. This change can encourage the development of an area of low pressure at the sea surface because of the relationship between air temperature and pressure. Since warm air is less dense than cold air, the surface pressure—the summed weight of all the air in a column extending upward from the earth's surface—is less in a region where the air is warmer than in its surroundings. The release of latent heat in convective clouds and the input of sensible heat at the surface, therefore, can result in locally warm regions, characterized by low sea-level pressure.

Much debate about the combined effects of latent-heat release in clouds and heat fluxes from

Figure 6. Fluxes of heat from a warm ocean surface into a cold atmosphere can produce a visible interaction between air and sea. In this photograph taken during the Genesis of Atlantic Lows Experiment, steam plumes, representing strong fluxes of moisture and latent heat, rise from the warm Atlantic as cold, dry arctic air passes over the water. Sensible-heat fluxes, the direct transport of heat from water to air, cannot be seen but are a significant source of energy to arctic storms. (Photograph courtesy of Allen Riordan, North Carolina State University.)

the ocean surface has focused on a concept called conditional instability of the second kind, or CISK, a term introduced by Jule Charney and Arndt Eliassen in 1964 to explain the growth of tropical depressions into hurricanes. CISK theory explains hurricane formation as the result of a cooperative interaction between the circulation within cumulus clouds and large-scale storm circulation associated with the region of low pressure at the center. (In the Northern Hemisphere strong low-pressure centers create cyclonic, or counterclockwise, wind patterns that result from the tendency of air to move from areas of high pressure to areas of lower pressure. The rotation of the earth under the air produces a circular wind flow around the low-pressure center; however, friction at the surface causes the low-level air to spiral into the low.) The process called CISK occurs if the cumulus convection becomes sufficiently organized that a positive feedback develops, in which the storm-scale wind circulation generated by low pressure provides a convergence of moisture for the cumulus clouds, which in turn provide latent heating that intensifies the storm through a further lowering of the surface pressure.

An alternative and perhaps more compelling hypothesis for explaining the energy source of hurricane-like storms was first developed by Herbert Riehl in 1954. Riehl recognized that disequilibrium between the atmosphere and the underlying ocean—reflected in the fact that the air immediately above the tropical ocean is subsaturated—could serve as an energy source and provide the potential for transfer of entropy (in the form of latent heat) from the ocean to the air.

This line of thought has been reinforced in recent years by Kerry Emanuel, a meteorologist at the Massachusetts Institute of Technology, who notes that the original CISK theory assumes that there is a reservoir of buoyant energy in the tropical atmosphere. Buoyant energy is proportional to the temperature difference between a cloud parcel and the cloud’s environment; warm clouds, like hot-air balloons, rise in cooler air. Emanuel has noted, however, that the buoyancy of cloud parcels is reduced by drag from cloud water and by evaporational cooling that results from the entrainment of drier environmental air into a cloud. He argues that when these factors are taken into account, there

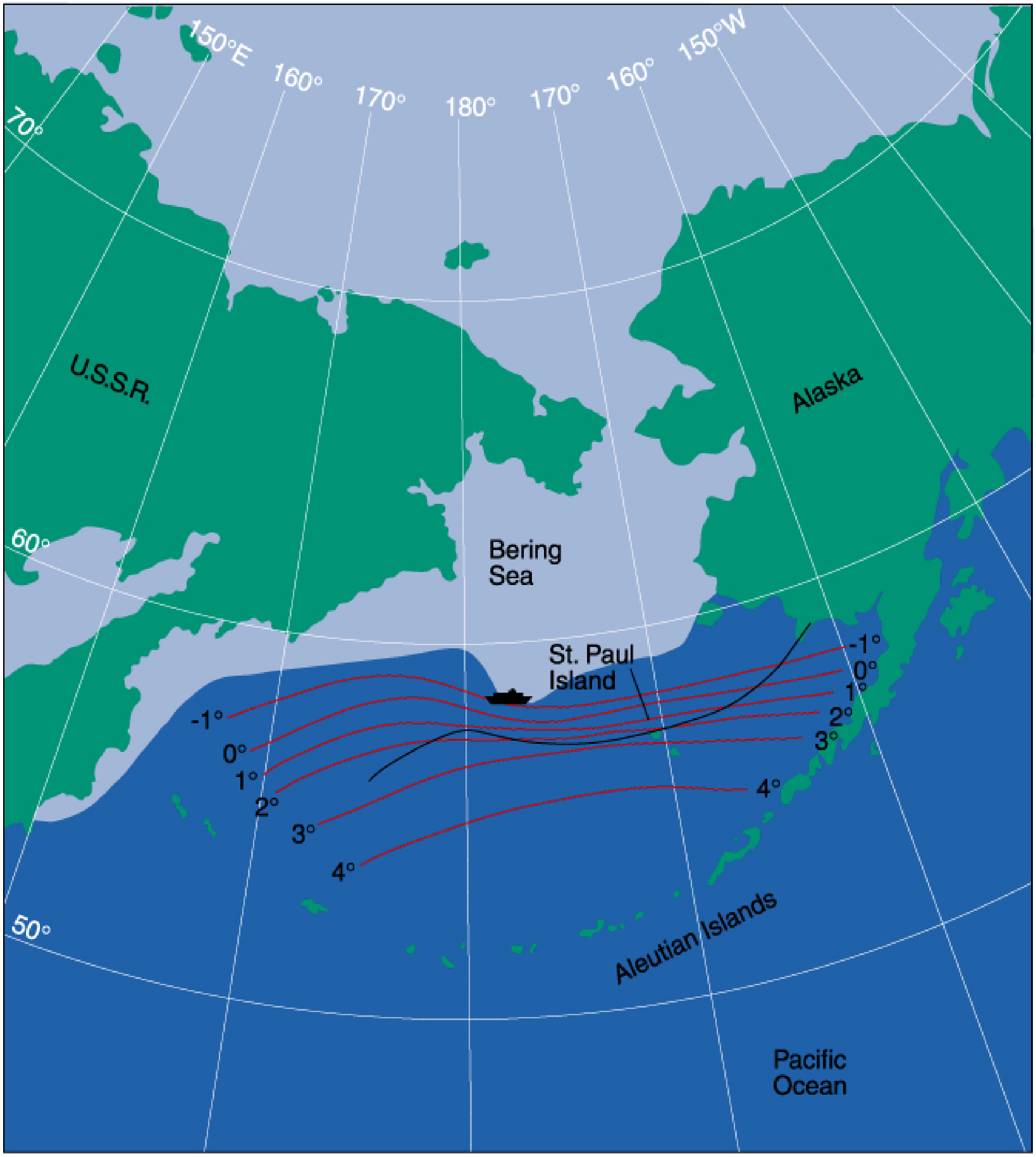

Figure 7. Arctic hurricane's track across the Bering Sea in March 1977 paralleled the edge of the sea ice before reaching the Alaskan coast. The pale-blue area is the ice sheet; deep blue represents open ocean. The solid lines show the monthly mean sea-surface temperature, and circles indicate the position of the storm's surface low-pressure center over a 48-hour period. Noted on the map are the positions of the Soviet ship that weathered the storm and of the National Weather Service Station at St. Paul Island in the Pribilof Islands.

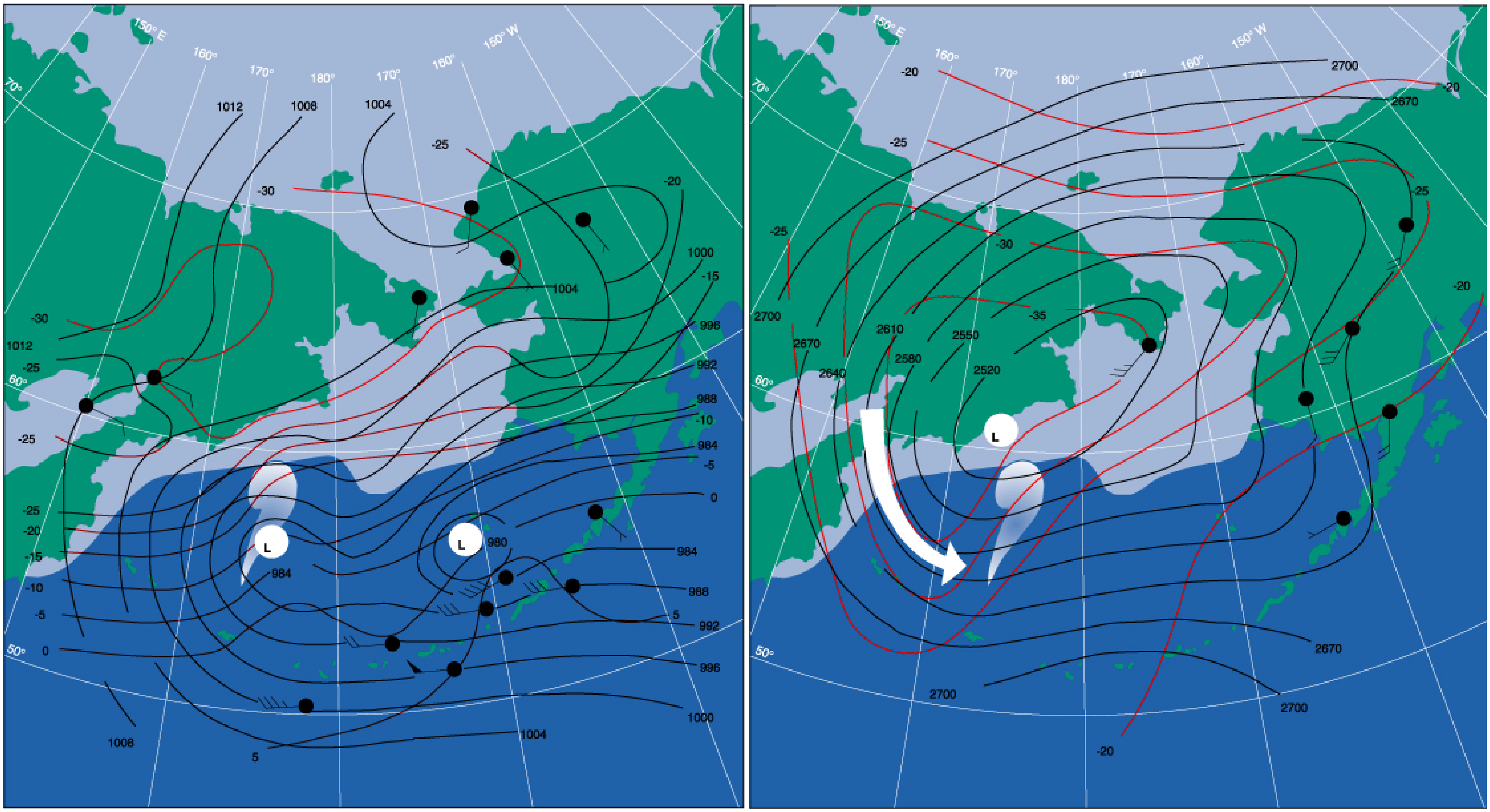

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Figure 8. Birth of an arctic hurricane is documented in charts mapping atmospheric conditions at the surface and at the middle-troposphere level at 00:00 Greenwich Mean Time on March 7, 1977. An *L* marks the position of a center of low pressure at each level. On the surface chart at left, isobars (*black*) represent pressure expressed in millibars; on the right is a chart where the black bars show the height, in meters, of the 700-millibar pressure surface. The red lines indicate temperature every five degrees Celsius. The comma-shaped cloud revealed by satellite imagery over the western Bering Sea at about this time (see Figure 9) is asssociated with the incipient arctic hurricane. A packing of isobars to the west of the developing low-pressure center encourages advection of cold air over the western Bering Sea. Further to the east, a second low is the core of a dissipating frontal cyclone. In the middle troposphere, a region of enhanced flow, or jet streak, is located on the west side of a single cold low-pressure center, providing conditions conducive to vertical air motion. Wind direction and speed are indicated (*barbed symbols)* at locations where balloon soundings or surface observations were made; the orientation of the staff attached to each circle indicates the wind direction, and the barbs indicate wind speed (each barb being equivalent to roughly 10 knots, triangles indicating 50 knots and half-barbs five knots).

is not enough buoyant energy remaining in convective clouds to account for the vast energy released in a hurricane.

The notion of disequilibrium between atmosphere and ocean as an alternative energy source for hurricanes is further buttressed by investigations utilizing numerical models. Katasyuki Ooyama (1969) was the first to successfully simulate a hurricane; his results clearly showed the critical importance of latent-heat fluxes through the sea surface as a source of energy.

As an alternative to CISK, Emanuel has proposed that tropical cyclones result from an instability of the air-sea interaction in which anomalous sea-surface fluxes of sensible and latent heat, induced by strong surface winds and low pressure, lead to increased temperature anomalies and thereby to further drops in pressure. At the heart of this feedback process is the fact that sea-surface heat fluxes increase as wind speed increases. Emanuel shows, using a simple nonlinear analytical model, that this hypothesis is consistent with observations of tropical cyclones.

As the notion of air-sea disequilibrium as an energy source for hurricanesgained recognition, meteorologists studying arctic cyclones wondered whether the same mechanism could fuel storms in polar air masses. Evidence to support this idea came from the Arctic Cyclone Experiment, a joint U.S.-Norwegian field experiment held off the coast of Norway in 1984. Large flows of sensible and latent heat into the boundary layer of incipient polar lows were measured by Melvin Shapiro and Len Fedor during this project. Combined fluxes of sensible and latent heat may have been as high as 1,000 watts per square meter over the Norwegian Sea during the development of a particularly intense arctic low (Shapiro et al. 1987). This value is comparable to the surface-heat fluxes observed in tropical hurricanes.

Arctic hurricanes, however, tend to produce much larger surface fluxes of sensible heat than do tropical hurricanes, which are limited in this respect by the small air-sea temperature difference in the tropics. The large sensible-heat flux in the arctic hurricane helps offset the fact that, because cold air is able to hold little water vapor, the latent-heat flux is relatively small. Erik Rasmussen, a Danish meteorologist active in polar-low research, and Magne Lystad, a Norwegian colleague, have pointed out that in the cold-air outbreaks within which polar lows develop, sensible-heat fluxes, by warming the surface air, produce large amounts of buoyant air and convective instability (Rasmussen and Lystad 1987). Therefore, arguments about a lack of buoyant energy to drive the CISK process may not apply to the arctic systems.

Emanuel and Richard Rotunno (1988) tested whether Emanuel's air-sea interaction mechanism might be at work in polar lows by using conditions observed in the atmosphere over the Norwegian Sea in advance of a complex polar low development documented by Rasmussen (1985). This case was chosen in part because of the warming seen at the core of the polar low—warming that did not appear to come from the horizontal movement of warm air by winds. Numerical simulations by Emanuel and Rotunno show that the air-sea interaction hypothesis is consistent with the observed development of arctic lows, but requires a pre-existing disturbance to act as a triggering mechanism before the air-sea interaction instability can operate. It is known that a pre-existing disturbance is also needed to trigger the development of tropical hurricanes. A two-stage concept of storm development is consistent with evidence for two stages in the deepening of the Norwegian disturbance. However, the rate of deepening calculated numerically on the basis of air-sea interaction is less than that observed, a discrepancy that points to the likely importance of an additional energy source, such as baroclinic instability, especially in the early stages of the storm's life cycle.

Other unusual features of the arctic environment have been noticed by meteorologists studying severe arctic storms; these supply pieces of a puzzle whose overall shape is just beginning to emerge. For instance, Hans Økland (1989) has pointed out that low-level inversions (discussed above) are a ubiquitous feature of the environment in which arctic hurricanes form. Økland argues that surface-heat fluxes confined to the shallow arctic boundary layer by such inversions are transported toward the low-pressure center by frictionally induced convergence. At the center, heat and moisture then feed the deep convection. Økland also cites the absence of such low-level inversions in maritime polar air masses in the middle latitudes as a possible reason that storms analogous to arctic hurricanes are not observed in these regions.

The success of any theory or numerical model that attempts to explain the evolution of arctic storms hinges on its ability to predict the features actually observed. A good way to compare theory and reality is to examine a set of observations from a representative storm.

An Arctic Hurricane

Hurricanes, the most destructive storms on earth, have become familiar to residents of the

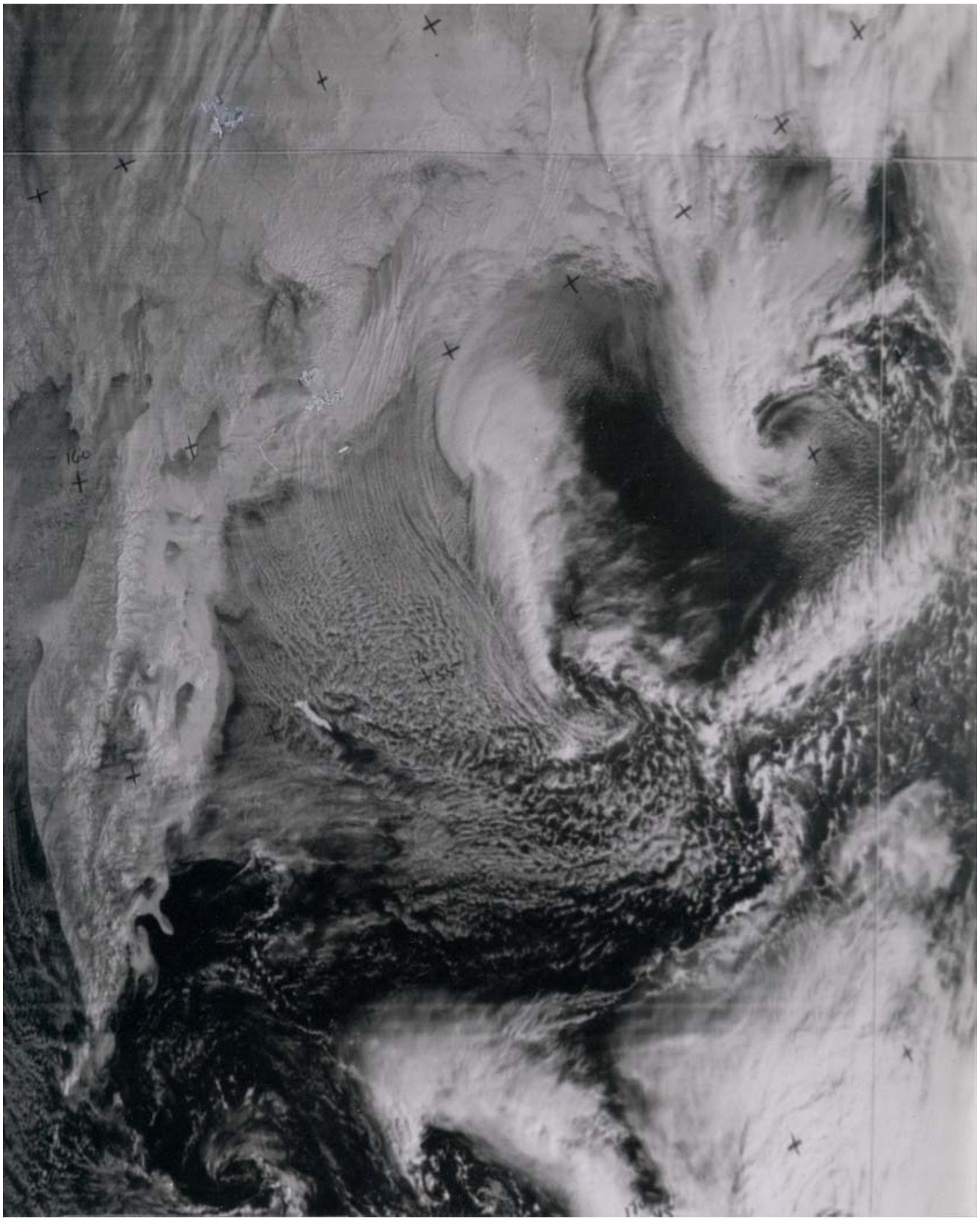


Figure 9. Cloud formations over the Bering Sea, seen by satellite at 22:30 Greenwich Mean Time on March 6, 1977, indicate several kinds of activity in the atmosphere prior to the formation of a major storm. Cloud streets, which are rolls of convective cumulus clouds, are seen as curving streaks over a large region of the western Bering Sea near the Kamchatka Peninsula; these indicate that the arctic surface air is being modified by heat fluxes from the open ocean as pressure gradients promote the sweeping of cold air southward off the ice. A comma-shaped cloud has formed where the arctic air meets warmer air from the south, showing the probable location of an arctic front, a zone of temperature contrast. Near the Alaskan coastline is the dissipating frontal cyclone. (*NOAA-5* infrared image.)

southern and eastern coasts of the United States. Awed by their vast size and strength, we watch them march ponderously across the Atlantic and grow, stage by stage. Arctic hurricanes have life stories as well, though shorter: They grow to full force in 12 to 24 hours, whereas a tropical hurricane may take three to seven days to develop. Since arctic hurricanes often travel at speeds upwards of 30 knots—about twice the average rate of tropical storms—and since the seas in which they occur are relatively narrow bodies of water, they tend to make landfall quickly.

The remarkable storm that developed over the Bering Sea on March 7, 1977, had a life story worth close examination. Some details of this complex tale are missing, but observations gathered during the storm provide an unusually good data set for documenting the environment in which the storm formed, its mature stage, and its dissipation over the Alaskan subcontinent. These observations also provide the basis for comparing an arctic hurricane with observations of tropical hurricanes.

At the National Weather Service station at St. Paul Island (57.3 degrees N, 170.2 degrees W), measurements are made by balloon-borne instrument packages called radiosondes; the data returned by these packages, augmented by the Soviet ship's log and satellite images, provide important glimpses into the mature stage of the storm. Available information includes measurements of temperature, wind speed and atmospheric pressure as well as humidity profiles, which together reveal atmospheric motions and the distributions of moisture and heat energy within the storm and its environment. The geographic setting, the location of the ice edge and the mean sea-surface temperatures in the Bering Sea for March are shown in Figure 8, which also shows how the storm tracked parallel to the ice edge along an axis of enhanced gradient in sea-surface temperature. This temperature gradient can be seen in the close spacing of isotherms, contours of constant sea-surface temperature.

The storm's genesis can be traced to about 00:00 Greenwich Mean Time (GMT) on March 7. Since large-scale atmospheric circulations cross multiple time zones, meteorologists find it convenient to use Greenwich time, rather than local time, when referring to radiosonde measurements. This arctic hurricane crossed the International Date Line early in its evolution; local time, therefore, is approximately 12 hours before GMT for most of the storm.

An analysis of atmospheric pressure at the sea surface at the start of the storm shows a trough of low pressure extending east to west across the Bering Sea south of the ice edge (Figure 9a). The exact location of the low center and details of the stage of development of the storm cannot be resolved at this time because of a void in the data distribution in the vicinity of the incipient low. However, the larger environment, including the likely general location of a low south of the ice edge, can be inferred from the surrounding surface data, from satellite imagery and from the progression of events over time.

The surface map shows that isobars (contours of equal atmospheric pressure) are packed to the west of the incipient surface-low center (where the pressure is approximately 984 millibars) over the western Bering Sea. Moderate to strong winds that bring unmodified arctic air southward over open water are observed in association with this enhanced pressure gradient. A sharp temperature gradient of more than 10 degrees Celsius over a distance of about 200 kilometers is also seen over the western Bering Sea at this time. Satellite imagery for 22:30 GMT March 6 (Figure 10) shows cloud streets, rolls of convective clouds that indicate that the boundary layer is being modified by surface fluxes of latent and sensible heat. Since cloud streets form nearly parallel to surface winds, these pictures allow one to infer the mean wind direction in the boundary layer to within about 10 degrees. It can be seen that arctic air is sweeping toward the low in a broad, counterclockwise curve.

Examination of the cloud streets also reveals that the length of the path taken by arctic air over the open water is varied, setting up the conditions conducive to the formation of an arctic front. A comma-shaped cloud band seen in the northeasterly flow north of the incipient 984-millibar low is probably the reflection of a disturbance that is forming along a zone of enhanced temperature contrast.

The spiral-shaped cloud signature visible to the east of the comma cloud is associated with a weakening low-pressure center (980 millibars) at the heart of a dissipating parent midlatitude cyclone. Frontal cyclones generally migrate into northern oceans as they mature and dissipate, leaving a large cold vortex aloft. Small vortices in the middle and upper troposphere that dance around such larger cold-core circulations often trigger polar lows (Businger 1985).

Conditions at higher altitudes in the atmosphere can be examined by drawing isobaric charts, in which the contours represent the height above sea level at which a certain pressure was measured by a radiosonde, just as a topographic map shows height contours on land. Since pressure decreases with altitude, lower height readings on such a chart indicate areas of generally lower pressure.

An isobaric chart for the 700-millibar level—in the middle troposphere—shows a trough just to the west of the incipient low. The wind flow over the incipient storm is westerly, a direction nearly parallel to the storm's track (Figure 9b). Radiosonde temperatures are unusually cold at this level, especially just to the north and west of the incipient storm. In the vicinity of the trough winds are locally strong, a phenomenon called a jet streak.

The significance of the jet streak lies in the vertical motions that are associated with such features. In the absence of friction, winds in the middle and upper troposphere are constrained toward geostrophic balance: a balance between the force associated with the horizontal pressure

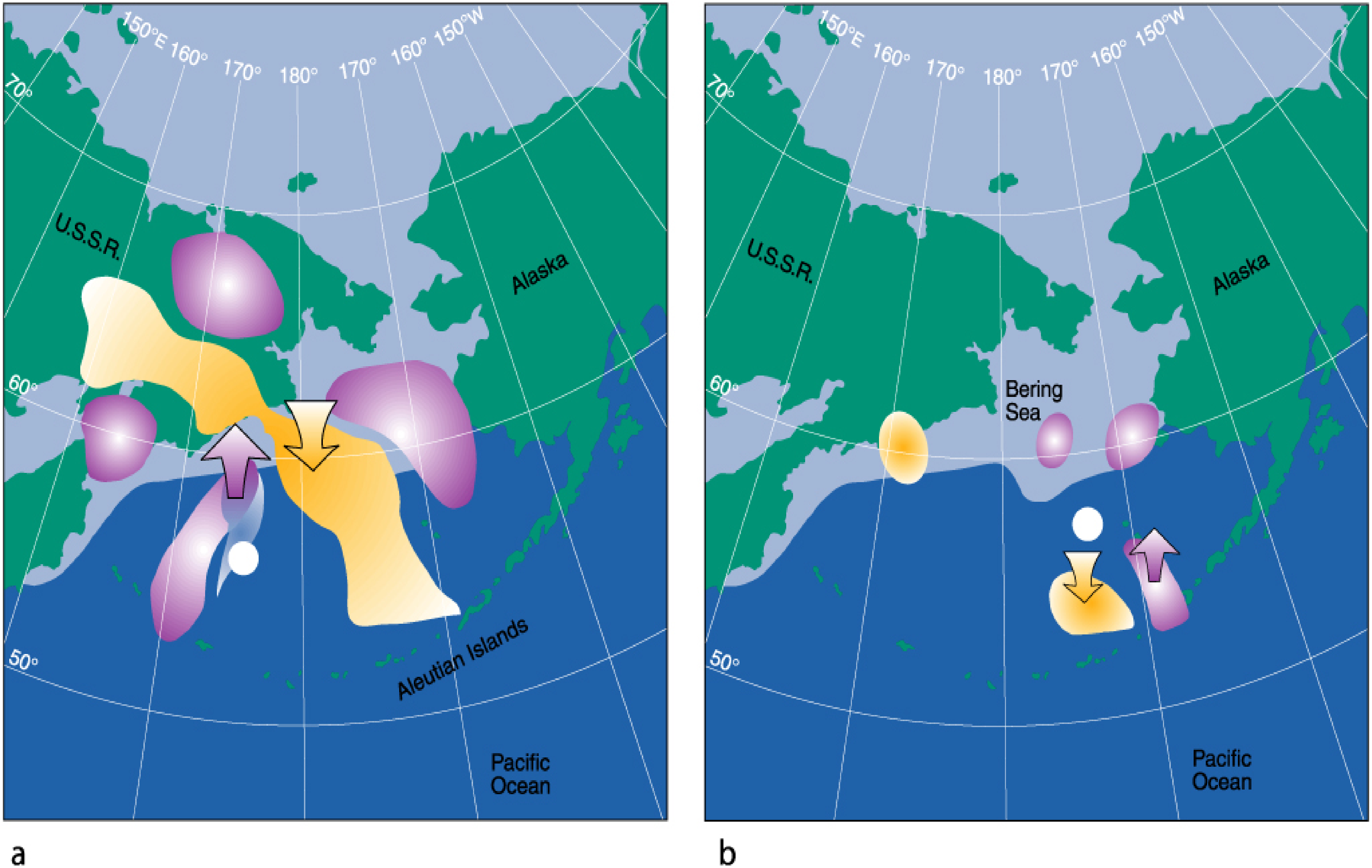


Figure 10. Vertical forcing of air movement occurs when there is an upset in the geostrophic wind balance in the middle troposphere (the balance between horizontal pressure gradients and the Coriolis force, the apparent wind deflection associated with the rotation of the earth). Upward forcing promotes the intensification of cyclones. In the early stages of the 1977 Bering Sea hurricane (analysis for 00:00 Greenwich Mean Time on March 7, *left*), such upward forcing is seen in the vicinity of the comma cloud and in three other areas. In contrast, little forcing is seen over the mature storm (analysis for 12:00 March 8, *right*). Arrow points are placed at the locations of maximum upward (*gold*) or downward (*purple*) forcing; an *L* marks the position of the surface low at each time.

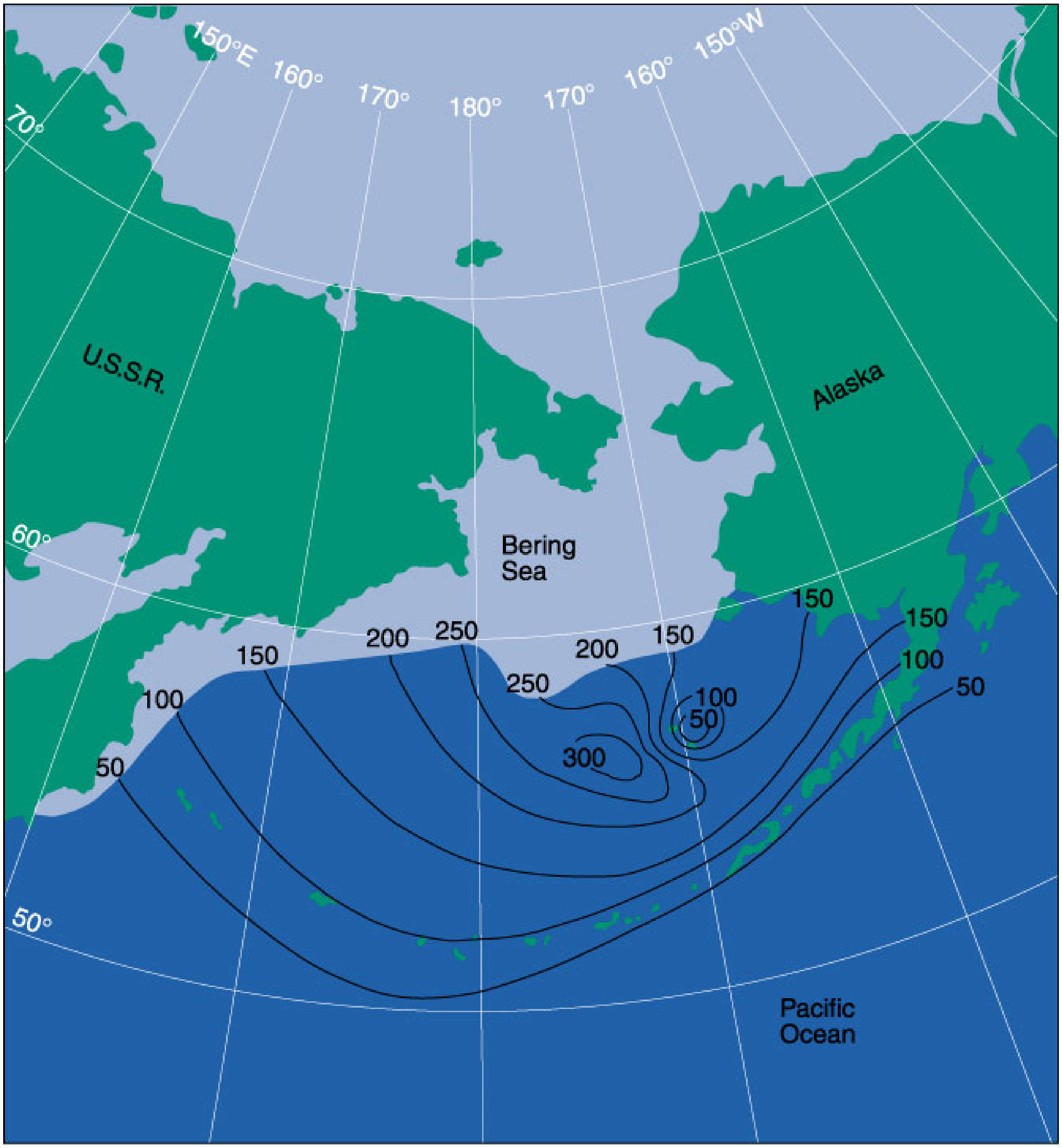


Figure 11. Sensible-heat fluxes—flows of heat from the ocean surface directly into the atmosphere—cause a perceptible warming at the core of an arctic hurricane. This warming, a result of the difference in temperature between air and sea, distinguishes these storms from both tropical hurricanes and midlatitude cyclones. As the mature arctic hurricane in the Bering Sea in 1977 passed over St. Paul Island (at 18:00 Greenwich Mean Time on March 8), these fluxes were greater than 300 watts per square meter in a tongue of arctic air just to the west of the surface low-pressure center. In the center itself, where the winds were light and the air had been warmed by previous surface heat transfer, the fluxes were small.

gradient (represented on the isobaric chart by the spacing between the height contours) and the Coriolis force, the apparent deflection of winds that results from the rotation of the earth under the moving air. As a consequence of this balance of forces, the winds at these levels blow nearly parallel to the height contours.

In the vicinity of jet streaks, where there is horizontal transport of higher momentum by the winds, the forces are no longer in geostrophic balance, resulting in vertical motions that act to restore the balance. A quasi-geostrophic analysis can be used to investigate the implied vertical-motion pattern, or forcing, associated with the 700-millibar pressure trough and jet streak at the time of initial storm formation (Businger and Baik in press).

This analysis shows that, during the incipient phase of the storm, the approach of the jet streak to the surface low results in forcing that induces upward movement of air (Figure 11a) over the comma cloud associated with the incipient low. It is likely that the initial development of the disturbance is enhanced by this forcing, since sustained upward motion has been shown to lead to condensation, precipitation and the intensification of cyclones.

A later satellite image, taken at 21:45 GMT March 7, shows a fully developed and well-organized arctic hurricane. Cold convective clouds and an asymmetric distribution of cirrus clouds surround a cloud-free eye (Figure 14). The diameter of the cirrus clouds, which represent a high-level outflow of air from the storm, is greater than 600 kilometers at this time. Wind speeds have reached a steady 40 knots, with gusts of 60 knots. The Soviet icebreaker, located at 58 degrees N, 177 degrees W near the ice edge, provides critical confirmation of the intensity of the surface circulation. The pattern of isotherms in the surface analysis shows that there is a region of enhanced temperature gradient in the vicinity of the mature low center, with cold air flowing south and warm air flowing north around the low (Figure 13a).

At the 700-millibar level the low is located just to the north of the surface-low center, placing the surface low near the region of coldest temperatures aloft. The large-scale wind flow over the Bering Sea has become more circular (Figure 13b), with westerly winds over the center of the low, apparently steering the storm eastward. In Figure 11 it can be seen that little or no quasi-geostrophic forcing is evident in the middle troposphere over the storm during its mature phase.

By 18:00 GMT March 8 the surface low has just passed St. Paul Island, with an estimated central pressure of about 970 millibars, similar to that of a moderate-strength tropical hurricane. The remarkable spiral cloud pattern in a satellite image taken three hours later (Figure 2) bears witness to the unusual symmetric organization and continued potency of the arctic hurricane. Cloud streets are observed on the northwest side of the low, indicating enhanced outflow of arctic air in the wake of the storm.

Sea-surface fluxes of sensible heat calculated over the Bering Sea for this period show a maximum flux of more than 300 watts per square meter in a tongue of arctic air just to the west of the surface low center, and a minimum of less than 50 watts per square meter at the core of the low (Figure 12). The flux is smaller in the eye, which is located at St. Paul Island, because conditions there are characterized by relatively warm surface air temperatures and light winds.

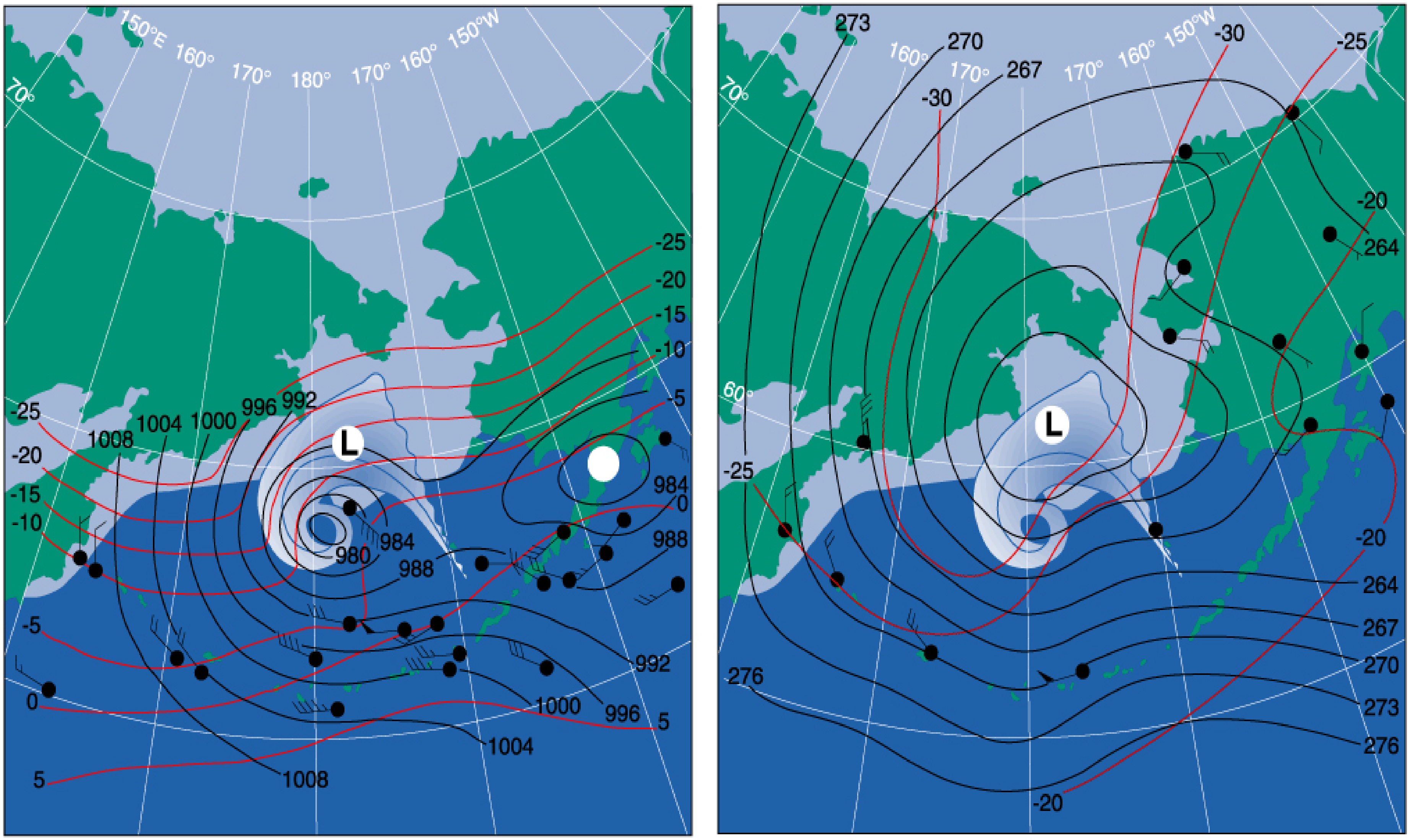
After making landfall at Cape Newenham at about 08:00 GMT on March 9, the arctic hurricane rapidly dissipated over the Alaskan subcontinent. This is illustrated in Figure 15, which shows the minimum sea-level pressure at six-hour intervals from March 7 through March 9. The values of the storm's central pressure on March 7 and those for 06:00 and 12:00 GMT on March 8 are, of necessity, only rough estimates based on the surface analyses, and tend to underestimate the actual intensity of the storm. The proximity of surface observations to the storm center lends greater confidence to the central-pressure estimates for 00:00 GMT on March 8 and for those after 12:00 on the same day. The most rapid pressure rise seen in Figure 15 occurs just after the low crosses the Alaskan coast. The storm is weakened by the removal of its surface heat source—the sea—and the additional dissipative impact of western Alaska's mountainous topography.

Balloon soundings taken at 12:00 GMT March 7 and at 12:00 March 8 (Figures 10a and 10b), just prior to the passage of the arctic hurricane, show that marked cooling has taken place in the middle troposphere (between about 880 and 500 millibars), while warming has occurred below about the 880-millibar level during the intervening 24 hours. Warmer dew-point temperatures are found below about 720 millibars in the later sounding. The soundings also reveal that the tropopause (the boundary between the active troposphere and the stable stratosphere) is very low, about six kilometers above the surface—an observation that highlights the contrast between the heights reached by arctic hurricanes and by tropical hurricanes, which can be as much as 16 kilometers tall. The magnitude of the cooling seen aloft above St. Paul Island in advance of the storm's passage is evidence of the strong large-scale cold-air flow with which the arctic hurricane was associated.

The base of a pronounced inversion—a stable layer of air in which the temperature increases with height—at about the 900-millibar level in the March 7 sounding marks the top of the arctic boundary layer (Figure 11a). This low-level inversion, as pointed out by Økland, may provide a mechanism for confining surface heat fluxes to a shallow layer, enhancing the transport of energy toward the warm storm center.

Modeling the Arctic Hurricane

Analysis of the observations taken during the Bering Sea storm gives us several clues to the sequence of events that can spin up a storm with



a b

Figure 12. Mature arctic hurricane is characterized by a strong wind circulation at the surface (*left*); winds are steady at 40 knots, gusting to 60 knots. Observations shown here were taken at 00:00 Greenwich Mean Time on March 8, 1977, just before the storm's eye passed over the Soviet icebreaker. Surface-temperature contours (*red*) show the warming effect of the storm. Isobars (*black*) are packed tightly around the surface low center, where the pressure has dropped to about 970 millibars. At the 700-millibar level in the middle troposphere (*right*), the low-pressure center is just to the north of the surface low. The white area shows the approximate extent of the storm's cloud cover, seen in the satellite imagery in Figure 13.

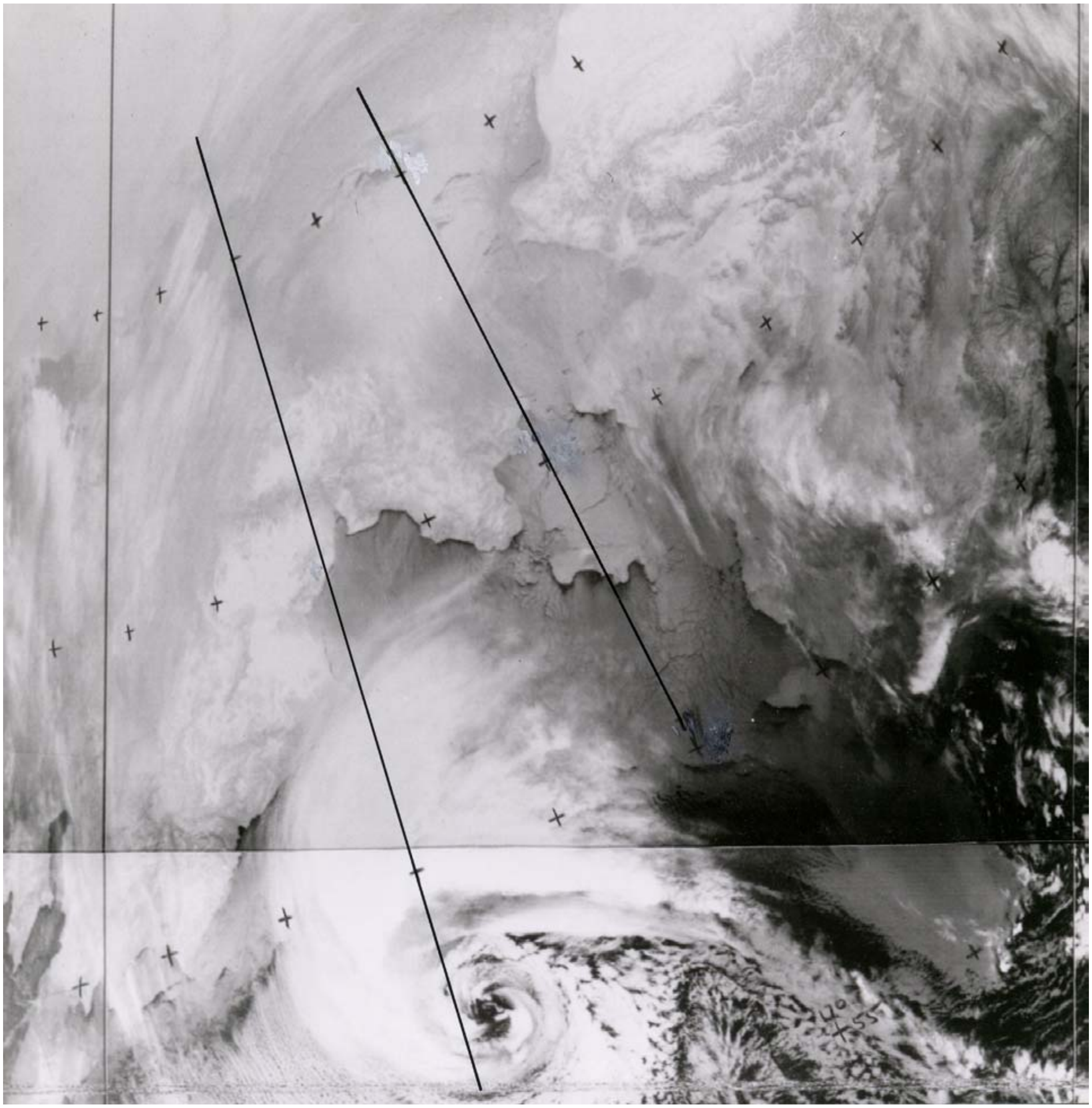


Figure 13. Cloud signature of the mature arctic hurricane is seen in an infrared photograph taken by the *NOAA-5* satellite at 21:45 Greenwich Mean Time on March 7.

many earmarks of a hurricane in the Arctic. The complexity of this chronology may help explain the relatively rare occurrence of arctic hurricanes.

First, a deep pool of cold air over the pack ice began to flow over the open water of the western Bering Sea. At low levels, surface heat fluxes from the sea led to the formation of an arctic front, a narrow zone separating modified air from unmodified air. Baroclinic instability along the arctic front then produced an incipient surface low. Next a jet streak in the middle troposphere crossed the Siberian coast, forcing vertical motions that caused the incipient low to spin up. This series of events triggered the air-sea instability that further intensified the surface low into an arctic hurricane.

It is clear from the pattern of isotherms in the surface analyses and from the data recorded at St. Paul Island that a region of enhanced

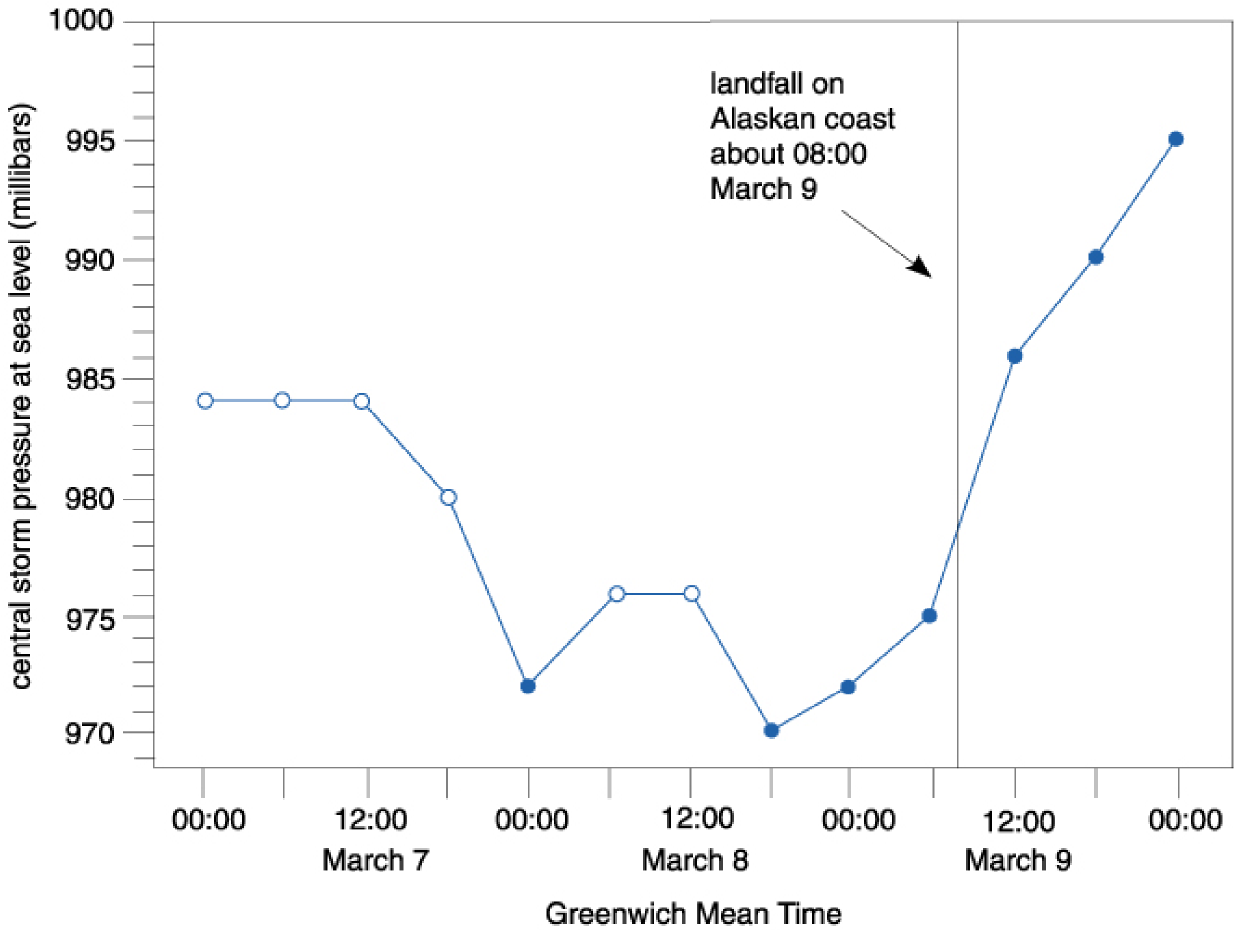


Figure 14. Formation and dissipation of the 1977 Bering Sea storm over its two-day life cycle is documented by changes in the minimum sea-level pressure at the storm center. A dramatic drop in pressure begins at 12:00 Greenwich Mean Time March 7. The storm reaches its greatest measured intensity, with a reading of 970 millibars at St. Paul Island, shortly after 18:00 on March 8. Landfall at about 08:00 on March 9 is accompanied by a rapid rise in the central pressure as the storm is cut off from its energy source, the sea. Filled circles represent actual surface-pressure measurements near the center; open circles are estimates and probably underestimate the depth of the pressure.

temperature gradient was present in the vicinity of the mature low center. However, it is not clear what role this potential for shallow baroclinic instability played in the final structure and energetics of the arctic hurricane.

A partial answer to this question—and an interesting test of the relationship of arctic hurricanes to the evolving general theory of hurricanes—may lie in numerical simulations of the Bering Sea storm. Jong-Jin Baik and I have employed a mathematical hurricane model to analyze, in particular, the role of surface fluxes in the Bering Sea storm (Businger and Baik in press). The model produces numerical simulations by integrating the basic equations governing momentum, mass, heat and water in its various phases.

A shortcoming of current numerical models, it should be noted, is that they cannot resolve the full range of scales important to the evolution of an arctic hurricane. To accurately resolve scales ranging from cumulus convection to the scale of the entire storm, some 100 million grid points would be needed. The burden of making all the calculations necessary for these points over time is far too great for available computers. Furthermore, important processes take place on still smaller scales; these include turbulent fluxes of heat and momentum at the ocean surface, in addition to the microphysics of cloud and snow formation. These small-scale processes cannot be modeled directly; instead they are parametrically related to the fields resolved by the model.

We asked the hurricane model to show whether an arctic hurricane could develop in an environment similar to that documented during the Bering Sea storm. More specifically, we asked the model: If there were a triggering disturbance of sufficient amplitude, could such a storm develop as the result of an interaction between the storm circulation and the ocean that taps a large reservoir of energy at the ocean surface?

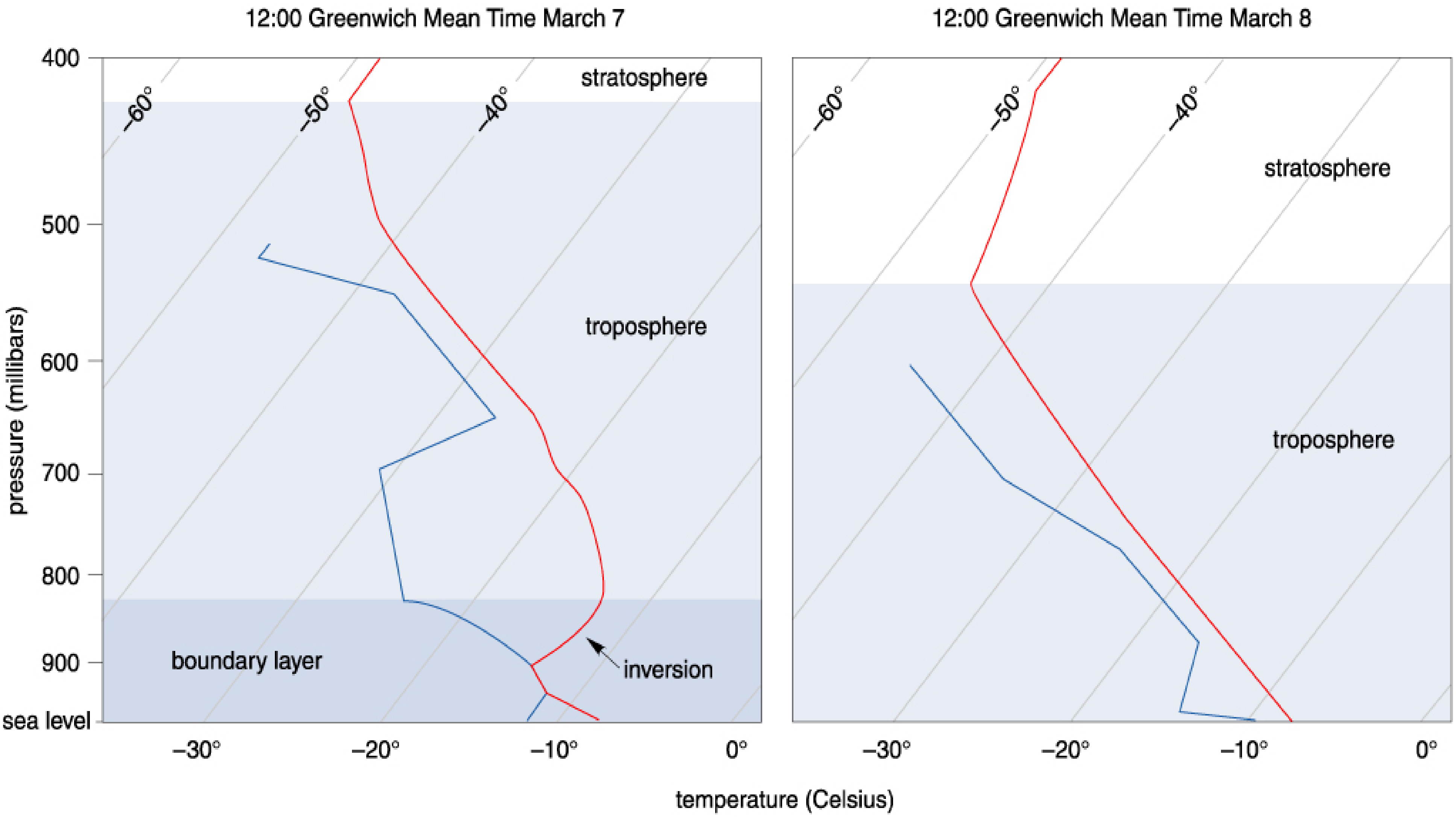


Figure 15. Unusual vertical temperature profiles are seen in the results of balloon soundings of the atmosphere taken at St. Paul Island at 12:00 Greenwich Mean Time on March 7, 1977 (*left*), and 12:00 on March 8, before and during passage of the arctic hurricane. Measurements of temperature (*red)* and dew-point temperature (*blue*) plotted against height (represented by atmospheric pressure) show that cooling takes place in the middle troposphere, between about 880 and 500 millibars, during the intervening 24 hours, greatly diminishing the static stability of this layer of the atmosphere. This cooling is simultaneous with an increase in dew-point temperature, which indicates the amount of moisture in the air, at altitudes below about 720 millibars. A temperature inversion marks the top of the atmospheric boundary layer in the environment of the storm; the boundary layer is not well defined during the mature storm (*right*).

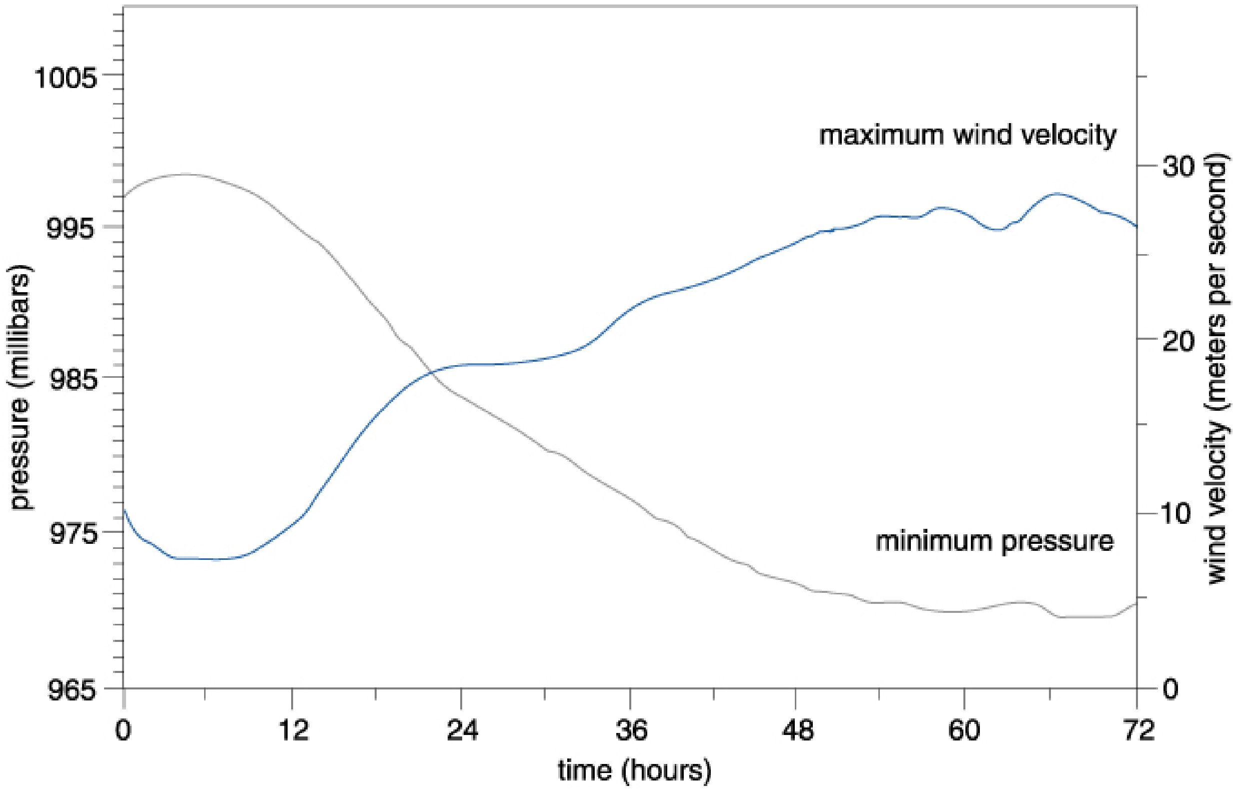


Figure 16. Simulation of the 1977 Bering Sea arctic hurricane with a mathematical model originally devised for tropical hurricanes predicts correctly the pressure and wind velocity achieved by the storm. This success reinforces the notion that sea-surface fluxes of heat play a major role in intensifying and maintaining the mature storm. In the simulation, the storm evolves more slowly than in reality, suggesting that there are additional physical mechanisms at work, such as baroclinic instability, that are not incorporated in the model (Businger and Baik in press).

The hurricane model used is axially symmetric; it does not allow variations of the explicitly calculated fields around circles centered at the storm center. The use of this geometry takes advantage of the symmetry in cloud signature of the arctic hurricane, and it eliminates baroclinic instability (an inherently asymmetric condition, since it involves a confrontation between two air masses) as a mechanism to sustain the arctic hurricane. Thus one can test the model's ability to generate an arctic hurricane from sea-surface fluxes alone.

The initial conditions in the model atmosphere and ocean were set to the environmental values observed over the Bering Sea on March 7. A sea-surface temperature of 2 degrees Celsius was chosen, and an average between the two atmospheric temperature profiles shown in Figure 16 was used as the initial temperature state for the model atmosphere. In the model, cumulus convective processes are parameterized using a scheme developed by H. L. Kuo (1974), in which deep cumulus convective processes are activated when the rate of moisture convergence exceeds a critical value. At the start of the model run, a weak vortex of 20 knots that decays upward from the surface was introduced into the initial conditions.

Figure 17 shows the time evolution of the minimum surface pressure and maximum tangential wind speed for the resulting simulation. We see a gradual deepening of the central pressure over 12 to 36 hours. After about 54 hours, the storm is in a quasi-steady state (mature stage) with a minimum surface pressure of about 970 millibars and maximum tangential wind speeds of nearly 30 meters per second (58 knots). Although the storm develops much more slowly in the simulation than in reality—indicating that additional physical mechanisms not accounted for in the model are at work—these predicted values are in very good agreement with the observations. This suggests that sea-surface fluxes did indeed play a major role in the evolution and maintenance of the arctic hurricane that passed over St. Paul Island. The sensible-heat flux predicted by the model at about 100 kilometers from the center, close to the location of maximum winds, during the mature stage is approximately 314 watts per square meter, close to the value of just over 300 watts per square meter calculated from observations. The predicted latent-heat flux is 250 watts per square meter.

To examine the sensitivity of model storm evolution to sea-surface temperature,

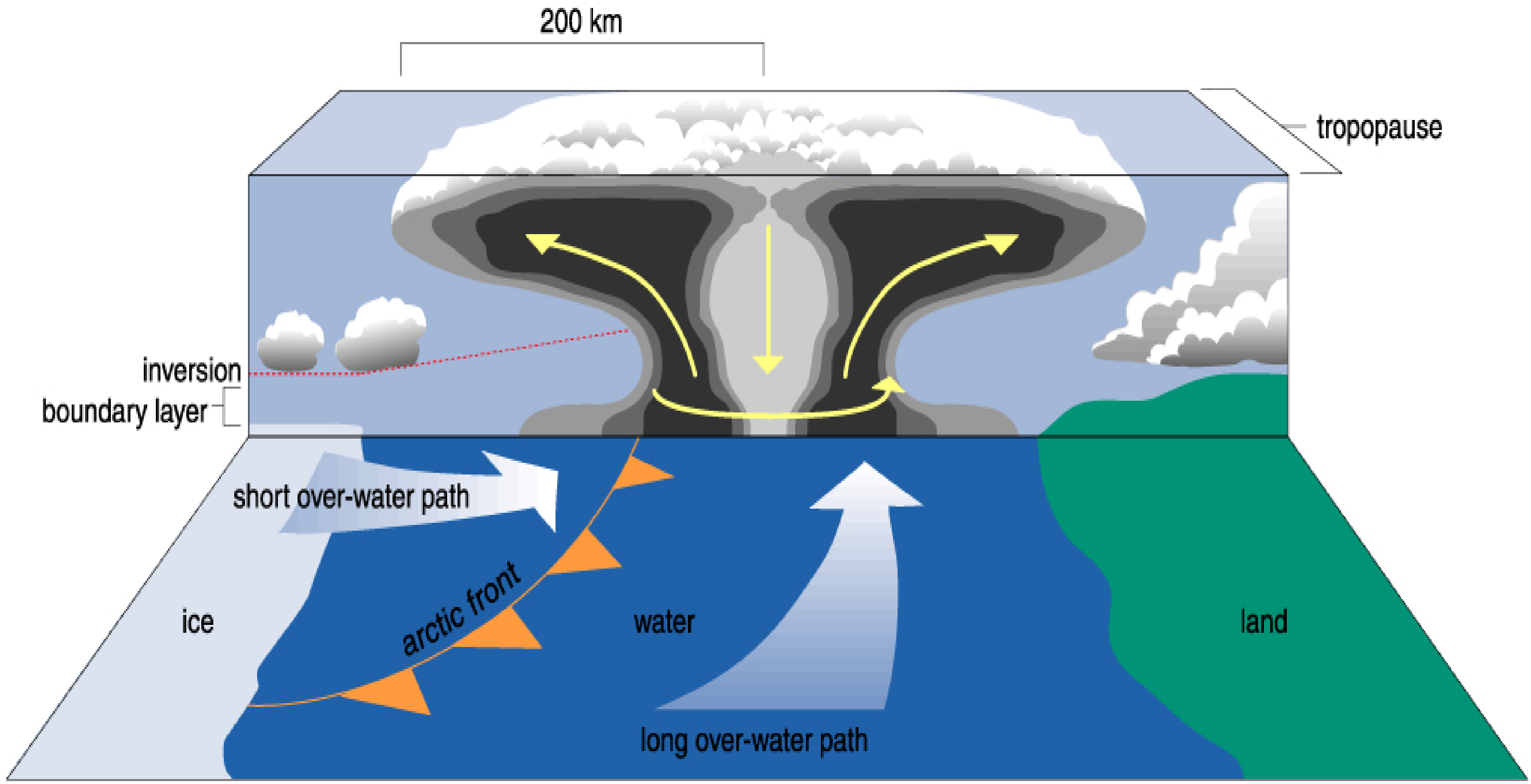


Figure 17. Thermodynamic structure of a simulated arctic hurricane is seen in cross-sectional profiles produced by the hurricane model. The temperature-deviation field maps how temperature in the storm deviates from a temperature chosen as the environmental condition at the lateral boundary of the model. The analysis shows warm regions in the middle altitudes, associated with latent heating, and another warm region near the surface, an indication of sensible-heat fluxes from the ocean. A humidity simulation shows the anvil-shaped outline of cumulus clouds, represented by the 70-percent humidity contour (Businger and Baik in press). These profiles resemble that of a tropical hurricane.

experiments with sea-surface temperatures of 0, 2 (the control simulation) and 4 degrees Celsius were performed. As one might expect, the simulated storm develops more rapidly and attains a more intense final stage as the sea-surface temperature increases—yet another demonstration of the impact of sea-surface heat fluxes.

Figure 18 shows the thermodynamic structure of the simulated arctic hurricane at 72 hours, in its mature stage. For increased resolution, only the radius-height cross sections of the inner 500-kilometer domain are shown. The temperature-deviation field (Figure 18a) exhibits a warm region at middle levels near the center. Another warm region is seen near the surface, representing the strong upward sensible-heat flux from the sea surface. In the simulated relative-humidity field, we see a moist region related to a strong eye-wall updraft and anvil-shaped outflow of air (typically seen in tall cumulus formations as they meet the very stable conditions found in the lower stratosphere) and a dry region near the storm center (Figure 18b). A dry region also exists below the outflow. These structures are very similar to those of tropical cyclones, except that the circulation of the arctic hurricane is shallower and a warm region exists near the surface. Detailed observations above the surface are not available for the Bering Sea case, limiting the comparison with the simulated structure. The diameter of the cirrus outflow in the model is about 600 kilometers, larger than that suggested by the satellite imagery of the storm just prior to landfall, but not inconsistent with earlier observations (see Figure 14).

When the simulation is repeated with an initial vortex of five knots, no storm develops . This implies that a pre-existing disturbance of sufficient amplitude is needed to initiate an arctic hurricane, which is also known to be the case in tropical hurricane formation. The jet-streak forcing diagnosed in the incipient stage of the Bering Sea storm may have provided just such a kick.

Surprises in the Arctic Night

Robert Frost once wrote:

We dance round in a ring and suppose,
But the Secret sits in the middle and knows.

Hazardous storms that spin up suddenly during the arctic winter will always present special challenges to forecasters. Because of their small size and the lack of sufficiently dense observations in the regions where they arise, arctic hurricanes are beyond the capabilities of present-day numerical prediction. The best hope for warning the fishermen, coastal communities and industrial concerns affected by these destructive cyclones lies in the hands of experienced forecasters who have an understanding of the conditions that make polar lows more probable, and who can interpret satellite imagery and ship data quickly to identify potentially dangerous storms.

It is clear that there is much yet to be learned about the arctic atmosphere and its interaction with the sea. Considerable research has focused on the development of midlatitude cyclones and the hurricanes of the tropics, but the investigation of polar lows is just beginning. The possibility that progress in our general understanding of tropical cyclones can be applied to a particularly destructive subgroup of these storms offers a new—and surprising—tool for looking at arctic phenomena.

The St. Paul Island experience suggests that storms with characteristics commonly associated with tropical cyclones—symmetric cloud signatures, vigorous cumulonimbus clouds surrounding a clear eye, and a band of strong winds reaching maximum strength at low altitudes close to a warm core—can form in the arctic, relying largely upon the heat from a relatively warm sea surface for energy. The air immediately above the tropical ocean is subsaturated, and therefore the sea surface can serve as an energy source in the form of latent-heat transfer from the ocean to the air. Similarly, in the case of the arctic hurricane the air is not only subsaturated, but is much colder than the underlying sea, and a combination of sensible and latent heat is available to the storm from the sea. These observations are reinforced by the results from a hurricane model that is able to simulate important characteristics of the hurricane-like arctic storm. From the simulations we can see that, as is the case in the tropics, a significant pre-existing disturbance is needed to trigger the formation of an arctic hurricane. Observations indicate that a jet streak aloft may have provided just such a catalyst for the Bering Sea storm.

Although there are similarities between arctic hurricanes and those of the tropics, important differences remain. The circulation of the arctic hurricane is shallower, and unlike its tropical counterpart it exhibits a warm region near the surface as a result of the strong upward flux of sensible heat from the sea surface.

Current research holds out much promise for resolving some of the questions that remain. A model such as the one used to simulate this storm provides only a rough approximation of the actual three-dimensional environment in which the arctic hurricane formed. There is a clear need for further simulation experiments utilizing a fully three-dimensional model, if a

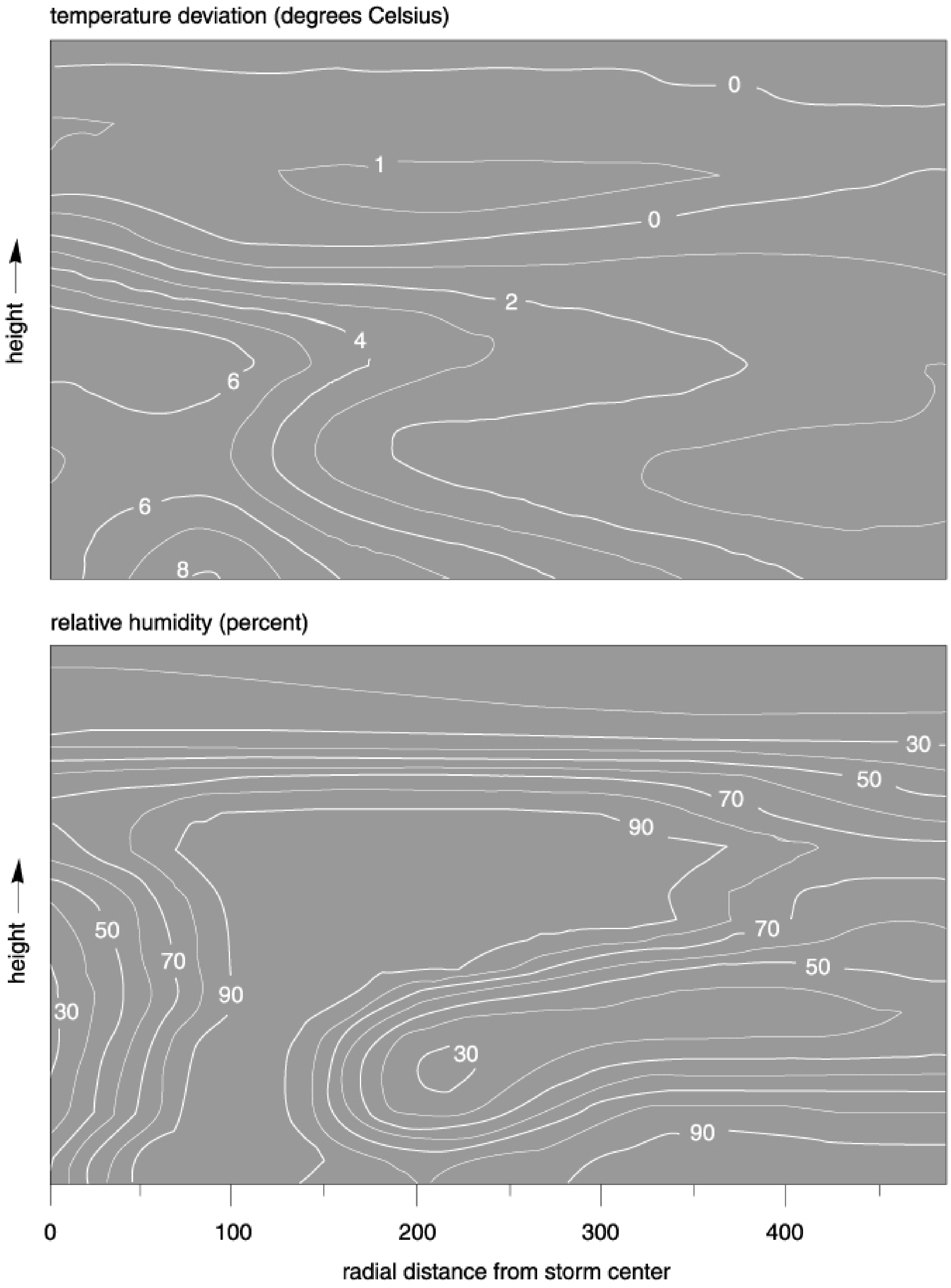


Figure 18. Confrontation of cold air sweeping off the arctic ice with air warmed by a long passage over open water creates a zone of temperature contrast called an arctic front, setting the stage for the formation of a severe arctic storm, or polar low. The shape of the storm shown here is taken from the model results in Figure 17. A cloud-free, warm "eye," in which air is sinking, is surrounded by a symmetric wall of convective cumulus clouds. Fueling the convection is a counterclockwise (cyclonic), converging flow of high winds at the surface that transports heat from the relatively warm ocean surface into the storm center. A key feature of the storm environment is an inversion (a layer in which air temperature is increasing with height) about one kilometer above the surface, a condition that enhances the low-level convergence of heat to the storm by suppressing vertical mixing. At the tropopause—the top of the storm, where the active troposphere meets the stable stratosphere—the outflow of air and heat from the storm creates an anvil-shaped formation of cirrus clouds.

more complete understanding of the complex dynamics of arctic hurricanes is to be attained. Such a model must include realistic parameterizations of the surface transfers of heat, momentum and moisture between the ocean and the atmospheric boundary layer, in addition to a realistic convection prescription—two notably difficult challenges in numerical modeling.

Finally, our ability to test the success of our numerical simulations is limited by the absence of detailed observations—a hurdle not easily overcome when dealing with rapid-forming and small-scale dangerous storms. Much of what is known about tropical hurricanes has come from vital information gathered by instrumented aircraft that deliberately fly through the storms. No similar research program has been established for arctic storms, although some airborne measurements of the atmosphere inside such storms have been made. During the 1940s the German Luftwaffe and the Royal Air Force of Great Britain, on reconnaissance flights over the Norwegian and Barents seas, made the first *in situ* meteorological observations of polar storms; these data have yet to be analyzed closely, but perhaps it will be discovered that one of these planes unknowingly penetrated an arctic hurricane and survived. (Several aircraft were, in fact, lost in storms.) More recently, detailed observations were made by a scientific crew that penetrated an intense polar low over the Norwegian Sea during the Arctic Cyclone Expedition in February, 1984 (venturing out after the hurricane-force winds of a January polar low trapped American scientists for six hours in a damaged plane on an airstrip in Keflavik, Iceland) (Shapiro, Fedor and Hampel 1987). The complex, asymmetric storm documented over the Norwegian Sea bore some of the markings of a hurricane, but the data collected provide only a snapshot of a moment in the storm's evolution. The full life story of the arctic hurricane, therefore, remains to be written by future bold and lucky crews.

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