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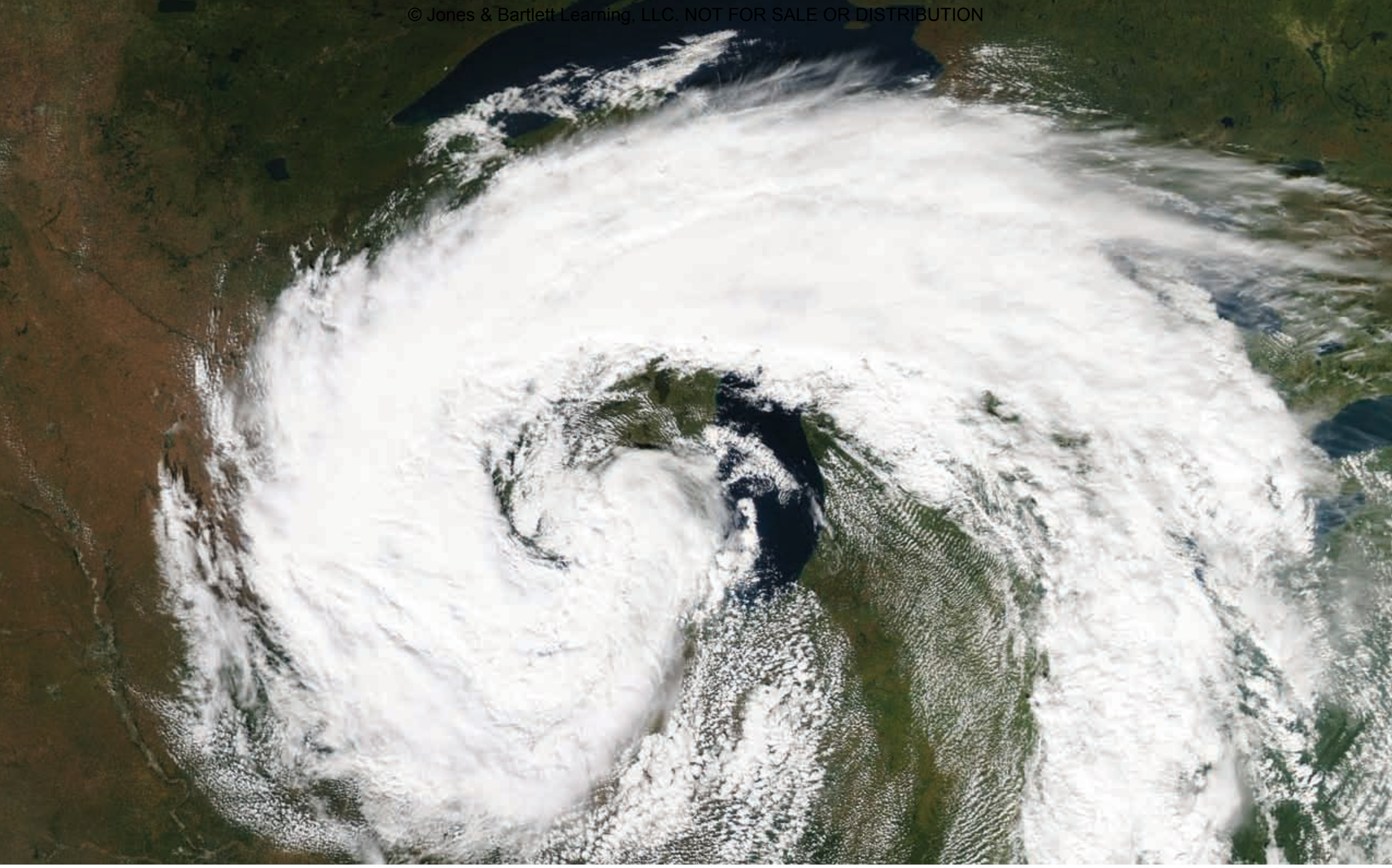

Courtesy of Jeff Schmaltz, the MODIS Rapid Response Team at NASA GSFC/NASA

10 Extratropical Cyclones and Anticyclones

CHAPTER OUTLINE

INTRODUCTION

A TIME AND PLACE OF TRAGEDY

A LIFE CYCLE OF GROWTH AND DEATH

DAY 1: BIRTH OF AN EXTRATROPICAL CYCLONE

- Typical Extratropical Cyclone Paths

DAY 2: WITH THE *FITZ*

- Portrait of the Cyclone as a Young Adult
- Cyclones and Fronts: On the Ground
- Cyclones and Fronts: In the Sky
- Back with the *Fitz:* A Fateful Course Correction
- Cyclones and Jet Streams

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DAY 3: THE MATURE CYCLONE
- Bittersweet Badge of Adulthood: The Occlusion Process
- Hurricane West Wind
- One of the Worst . . .
- "Nosedive"

DAY 4 (AND BEYOND): DEATH
- The Cyclone
- The *Fitzgerald*
- The Sailors

THE EXTRATROPICAL ANTICYCLONE

HIGH PRESSURE, HIGH HEAT: THE DEADLY EUROPEAN HEAT WAVE OF 2003

PUTTING IT ALL TOGETHER
- Summary
- Key Terms
- Review Questions
- Observation Activities

AFTER COMPLETING THIS CHAPTER, YOU SHOULD BE ABLE TO:

- Describe the different life-cycle stages in the Norwegian model of the extratropical cyclone, identifying the stages when the cyclone possesses cold, warm, and occluded fronts and life-threatening conditions
- Explain the relationship between a surface cyclone and winds at the jet-stream level and how the two interact to intensify the cyclone
- Differentiate between extratropical cyclones and anticyclones in terms of their birthplaces, life cycles, relationships to air masses and jet-stream winds, threats to life and property, and their appearance on satellite images

INTRODUCTION

What do you see in the diagram to the right: a vase or two faces? This classic psychology experiment exploits our amazing ability to recognize visual patterns. Meteorologists look for patterns in weather observations. Instead of pondering "is that a nose, or the narrow part of a vase?" the meteorologist asks, "Is this a line of rain showers? Could that be a wind shift? Should I be focusing on the areas of warm and cold air or the regions in between?" Finding the "face" in the weather is a lot more confusing than in a textbook diagram!

Early 20th-century weather forecasting reflected this confusion. Some meteorologists focused on the location and shape of low-pressure areas. Others scrutinized temperature patterns; still others looked at cloud types. No one yet saw the overall "face," only these individual weather features.

In 1918, 20-year-old meteorologist Jacob "Jack" Bjerknes (see photo; pronounced BYURK-nizz) discovered the "face in the clouds" of his native Norway: the extratropical cyclone or low-pressure system. His conceptual model of this type of cyclone emphasized the importance of the fronts that extend like a moustache from the center of midlatitude lows on a weather map.

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(Courtesy of Geophysical Institute, University of Bergen.)

Jack and his father Vilhelm's "Bergen School" of meteorology fleshed out this face using their intuition and observations of the sky. They realized that the extratropical cyclone, like a face, has a distinctive three-dimensional shape. Furthermore, like a person, the cyclone matures from youth to old age in a recognizable and predictable way. At last, meteorology knew what face to look for! Weather maps and forecasts have never been the same since.

In this chapter, we learn how to recognize the face of the extratropical cyclone. To make this face come alive for you, we look at weather data leading up to a tragic day in American history: November 10, 1975. On that day, a cyclone fitting Bjerknes's description ravaged the midwestern United States and contributed to the wreck of the Great Lakes iron ore freighter *Edmund Fitzgerald.* Twenty-nine sailors perished on the *Fitzgerald* without a single "mayday." More than 35 years later, this tragedy lives on through television documentaries, books, and folk songs. We learn here what the face of a classic cyclone looks like from a variety of angles and why it looks that way.

Some faces and people are not so memorable, but the impacts they make are. This is also the case with the cyclone's counterpart, the anticyclone or high-pressure system. Highs look like bland and boring blobs on the weather map, but they can also harbor potentially tragic weather conditions. This chapter ends with an examination of a heat wave in 2003 that quietly killed 70,000 people in western Europe in the space of just a few days.

A TIME AND PLACE OF TRAGEDY[1]

The year is 1975—the Vietnam War ends, and a gallon of gasoline costs 44 cents in the United States. A small upstart computer software company named Microsoft is founded in Albuquerque, New Mexico. Meanwhile, teenagers are starting to buy platform shoes and boogie to the newest pop music fad, "disco."

On the Great Lakes (**FIGURE 10-1**) in 1975, large boats deliver iron ore from Minnesota to the steel mills and car factories of Indiana, Michigan, and Ohio. Lake Superior, Earth's broadest lake, serves as a highway for these boats. The pride of the American ore freighters is the 222 meter (729 foot)-long *Edmund Fitzgerald* (**FIGURE 10-2**). Her respected captain, Ernest McSorley, has weathered 44 years on the lakes. His crew of 29 includes six sailors younger than age 30 years, including 22-year-old Bruce Hudson and 21-year-old Mark Thomas (**FIGURE 10-3**).

In November 1975, "Big Fitz" is completing just its 17th full shipping season on Lake Superior. It's a young boat by Great Lakes standards. The end of the shipping season comes when the "gales of November" howl across the Lake and winter's icy cold freezes some of the lake surface solid. One trip too many, during a fierce extratropical cyclone, will sink the *Fitzgerald* and its crew in 160 meters (530 feet) of churning Lake Superior water on November 10, 1975.

A LIFE CYCLE OF GROWTH AND DEATH

In the 1920s, Jack Bjerknes helped discover that cyclones such as the one that would sink the *Fitzgerald* often follow a stepwise evolution of development. The left-hand side of **TABLE 10-1** shows how Bjerknes himself depicted the **Norwegian Cyclone Model** life cycle. The cyclone arises as a **frontal wave** along a stationary front separating cold, dry cP air from warm, moist mT air. It is called a "wave" because the **warm sector** region between the cold and warm fronts resembles

[1]Details of the *Edmund Fitzgerald*'s last voyage used in this chapter are primarily derived from the following books: *The Wreck of the Edmund Fitzgerald* by Frederick Stonehouse (Avery Color Studios, Marquette, Michigan, reprinted 1997), *Gales of November* by Robert J. Hemming (Thunder Bay Press, Holt, Michigan, 1981), and the words of Captain Bernie Cooper in *The Night the Fitz Went Down* by Hugh E. Bishop (Lake Superior, Port Cities, Inc., 2000).

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FIGURE 10-1 Map of the Great Lakes region, showing the path of the *Edmund Fitzgerald's* final voyage and locations referred to in this chapter.

FIGURE 10-2 The ore freighter *Edmund Fitzgerald*, in a photograph provided by Ruth Hudson, mother of *Fitzgerald* sailor Bruce Hudson (Figure 10-3). (Courtesy of Ruth Hudson.)

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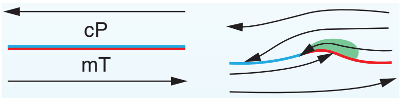
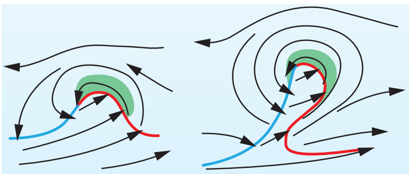
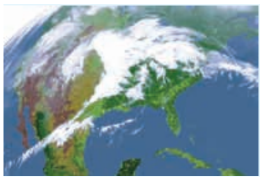
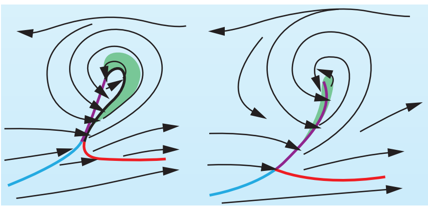
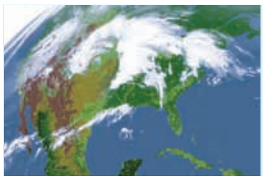
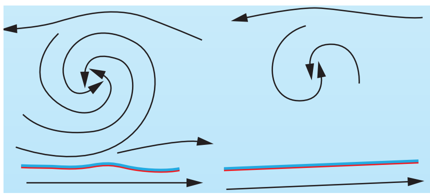
FIGURE 10-3 *Edmund Fitzgerald* sailors Bruce Hudson (left) and Mark Thomas on the main deck of the *Fitz*. (Courtesy of Ruth Hudson.)

a gradually steepening ocean wave. In adolescence, the **open wave** develops strong cold and warm fronts with obvious wind shifts as the entire system moves to the east or northeast. Precipitation (in green shading) falls in a broad area ahead of the warm front and in a narrow line in the vicinity of the cold front.

At full maturity, the **occluded cyclone** sprouts an occluded front, which Bjerknes conceived of as the result of the cold front outrunning the warm front. Usually, the barometric pressure at the center of the cyclone reaches its minimum during this stage, sometimes plummeting to 960 mb or below in a few intense cyclones—as low as in the eye of a Category 3 hurricane! Because of the strong gradient of pressure near its center, the cyclone's winds are usually strongest during this stage. The accompanying satellite images in Table 10-1 reveal how the cloudiness associated with the fronts progressively wraps poleward and around the back side of the cyclone. In the final stage, the **cut-off cyclone** slowly dies a frontless death, as clouds and precipitation around the low's center dissipate.

The life cycle shown in Table 10-1 is an idealized conceptual model. Some real-life cyclones do not follow this life cycle in every detail. For example, cyclones do not necessarily form on stationary fronts; some cyclones occlude soon after birth, and many others never reach the cut-off stage. The cyclone that hits the *Edmund Fitzgerald* is an actual storm brought about by a unique combination of circumstances. Nevertheless, the conceptual model provides a remarkably accurate guide to the overall life cycle of the *Fitzgerald* cyclone from its birth on November 8, 1975, until its death several days later, as we see in the following sections.

TABLE 10-1 The Life Cycle of the Extratropical Cyclone, Based on the Norwegian "Bergen School" Model

Stage	Weather Map Depiction of Norwegian Cyclone Model	Typical Satellite Image of Life-Cycle Stage	Typical Sea-Level Pressure at Cyclone Center	Corresponding Dates of *Edmund Fitzgerald* Cyclone
Birth (frontal wave)			1000–1010 mb	November 8, 1975
Young adult (open wave)			990–1000 mb	November 9, 1975
Mature (occluded cyclone)			960–990 mb	November 10–11, 1975
Death (cut-off cyclone)			Slowly rising from 960–990 mb up to 1010 mb	November 11–15, 1975

(Photos courtesy of SSEC and CIMSS, University of Wisconsin-Madison.)

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DAY 1: BIRTH OF AN EXTRATROPICAL CYCLONE

Saturday, November 8, 1975, is a gorgeous day across much of the United States. Calm and almost summer-like conditions predominate. High temperatures of above 26° C (80° F) bathe the South and Southwest, with 70s as far north as Indianapolis and Burlington, Vermont. The *Edmund Fitzgerald* glides on smooth Lake Superior waters toward its next load of iron ore at the Duluth (Minnesota)/Superior (Wisconsin) harbor.

Weather maps and satellite pictures (**FIGURE 10-4**) show some cloudiness associated with weak fronts extending from Iowa to Colorado and from Ontario, Canada, to Kentucky. Very little precipitation is falling, however. The fronts will soon stall and will combine into a stationary front lying southwest to northeast from New Mexico to New England. Along this stalling front a very weak (1006 millibar, or mb) low is forming just northwest of Amarillo, Texas, in the northern Texas Panhandle. The low is so weak and the air is so dry (note the low dew point of 30° F [-1° C] at Amarillo) that there is not a cloud in the sky associated with it (Figure 10-4c).

The presence of a low just east, or "downstream," of the Rocky Mountains is a natural consequence of upper-level winds blowing across high mountain ranges. Figure 10-4b shows the observed winds and altitudes (in feet) at the 500-mb level, about midway between the ground and the tropopause. The strong west-to-east winds over the Rocky Mountains are occurring where the solid lines of equal height are closest together.

During Saturday the 8th, the counterclockwise circulation around this weak low drags colder, drier air southward through the Rockies and draws warmer, moister air northward from the Gulf of Mexico. As a result, temperature and moisture gradients near the low become stronger throughout the day. The occluded front will turn into a "leading" warm front just northeast of the low and a "trailing" cold front that will extend to the southwest of the low.

At the same time, winds above the low intensify for two reasons. First, strong upper-troposphere jet-stream winds are moving into this region. Second, strong winds are usually located above strong surface temperature gradients, and the region around the low is becoming an area of strong temperature gradients. As we'll see shortly, this upper-level wind pattern helps the low grow, which in turn helps the fronts intensify, which intensifies the upper-level winds even more and makes the low grow even faster. . . . It's a cycle of growth!

Meteorologists give this cycle of cyclone birth and growth a special name: **cyclogenesis**. Why cyclogenesis happens at one place and time, but not another, is almost as complicated as explaining how human babies are born. Key ingredients for cyclogenesis include surface temperature gradients, a strong jet stream, and the presence of mountains or other surface boundaries (e.g., a coastline near a warm ocean current). Wherever winds blow across temperature gradients, warm air can glide upward, and cold air can dive and sink, leading to clouds and precipitation; we see this with both cold and warm fronts. This tilted pattern of rising and sinking air liberates energy for a cyclone and is called **baroclinic instability**.

The Norwegian Cyclone Model emphasized the importance of fronts and mountains in cyclogenesis. More recently, meteorologists who, unlike the Bjerkneses, have access to upper-level data from radiosondes have identified short waves in the jet stream as a main triggering mechanism. On November 8, 1975, all three of these ingredients—fronts, a strong jet stream, and mountains—give birth to a memorable extratropical cyclone, a low-pressure system structured completely differently than a hurricane but with the same ability to cause harm.

Typical Extratropical Cyclone Paths

For residents of the Great Lakes region, a strengthening cyclone in the Texas Panhandle in November is cause for concern—although the two locations are a thousand miles apart! This is because extratropical cyclones grow and move quickly away from their places of birth, often to the east or northeast.

FIGURE 10-5 shows the typical regions of cyclogenesis (shaded) and typical cyclone paths (arrows) for storms that hit the state of Wisconsin in each season of the year. The figure reveals

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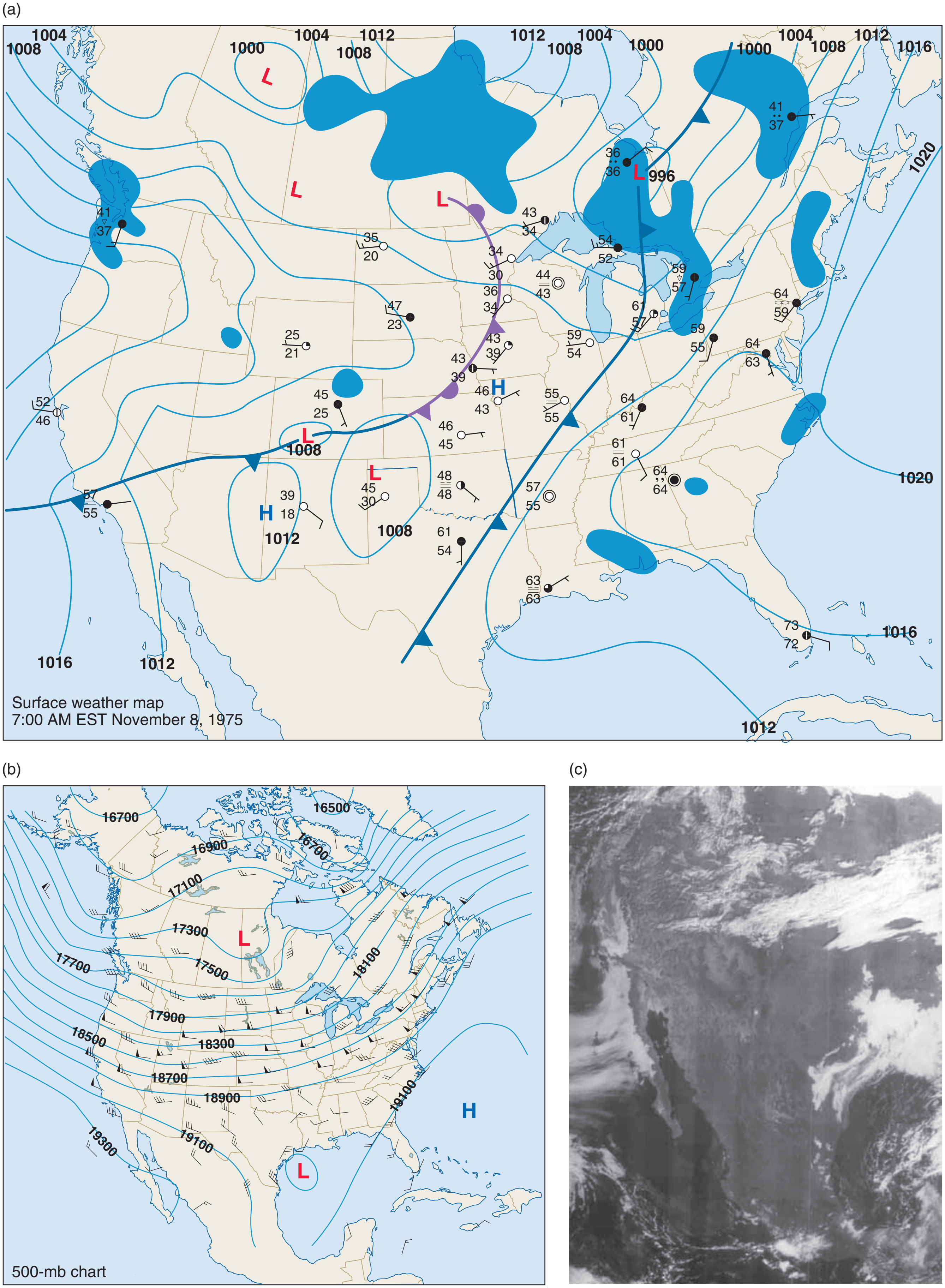

FIGURE 10-4 Surface weather (a) and 500-mb conditions (b) for 7:00 AM (EST), Saturday, November 8, 1975. The heights in B are in feet, but the rules relating wind to height patterns are unaffected. The Defense Meteorological Satellite Program visible satellite picture from 10:30 AM (EST) is at the lower right (c). The satellite picture is centered over extreme western Texas; clouds are visible along the west coast of Baja California at the left of the image. (Parts a and b data from NOAA. Part c courtesy of National Snow and Ice Data Center.)

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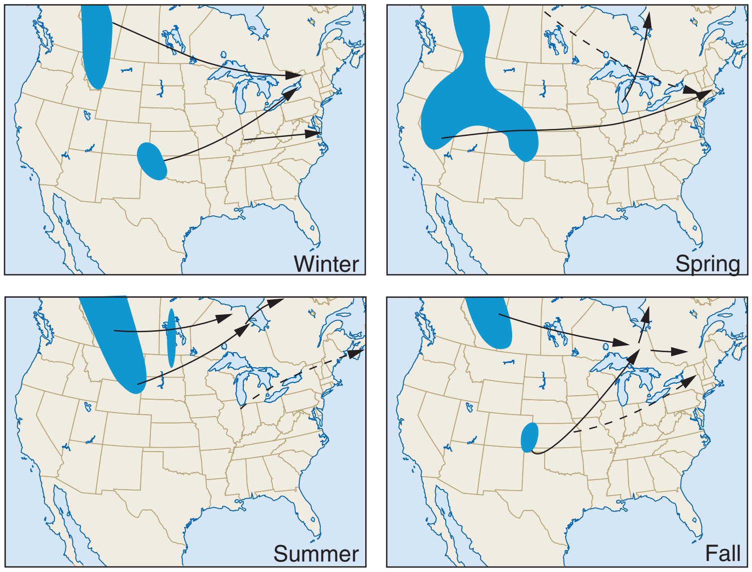

FIGURE 10-5 Typical regions of cyclogenesis (shaded) and paths of cyclones (arrows; likeliest paths in solid lines, other possible paths in dashed lines) that affect the state of Wisconsin on a seasonal basis. (Modified from an illustration by Pam Naber Knox, former Wisconsin State Climatologist.)

that the birthplaces of cyclones vary from season to season, moving north in the summer. Why? Because temperature gradients and jet streams, key ingredients for cyclogenesis, move north with the Sun during the summer.

Figure 10-5 indicates that during the fall and winter months the region from southern Colorado to the Oklahoma and Texas Panhandles is a prime breeding ground for Wisconsin-bound cyclones. In fact, this path is so common that these cyclones have a generic name attached to them: **Panhandle Hooks**. The "hook" describes the curved path that these cyclones often take, first bending to the southeast and then curving northeast toward the Great Lakes (**BOX 10-1** explains this bending and curving).

Other parts of the United States are hit by extratropical cyclones that form in regions far away from the Rockies (**FIGURE 10-6**). For example, the Northeast is pummeled by winter cyclones called **nor'easters** that develop along the East Coast over the Gulf Stream near Cape Hatteras, North Carolina. Also, as seen in Figure 10-6a, the Great Lakes region is visited by cyclones born in western Canada that move southeastward. These storms are called **Alberta Clippers** because of their birthplace and their fast forward speed. The Pacific Northwest is often soaked and windblown by cyclones that spin themselves out in the Gulf of Alaska. More rarely (but especially during El Niño and positive Pacific Decadal Oscillation years), the West Coast is drenched by extratropical cyclones riding the **Pineapple Express** jet stream blowing northeast from Hawaii. The cyclone paths generally shift northward in summer (Figure 10-6b) along with the regions of strongest temperature gradients.

The Panhandle Hook of November 1975 will also race toward the Great Lakes at a high rate of speed, gathering more energy with every passing hour. The next 2 days will make history, and tragedy, on Lake Superior.

DAY 2: WITH THE *FITZ*

Early on Sunday morning November 9th, 1975, workers at the Duluth/Superior docks begin the task of loading the *Edmund Fitzgerald.* On this trip, the *Fitz* will carry enough iron ore to make 7500 automobiles. The iron ore pellets slide down huge chutes like large marbles into the 21 hatches in the middle of the boat. The crew then anchors each of the 6,350-kilogram (7-ton)

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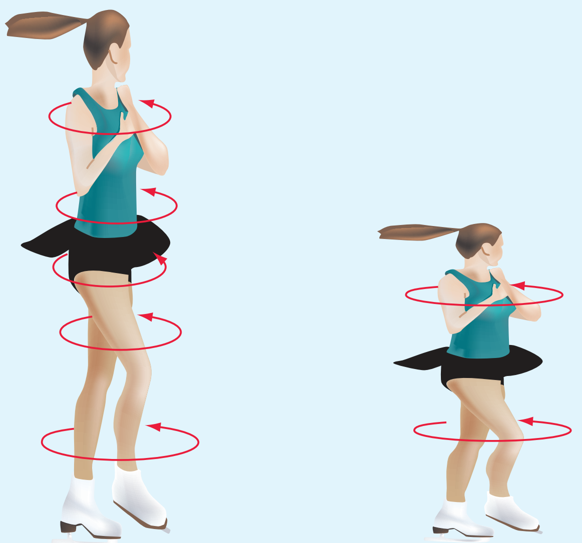
Box 10-1 Making Cyclones and Waves

Extratropical cyclones, mountain ranges, and upper-level wave patterns in the wind—what's the connection? It's simple if you know a little about the atmosphere and ice skating.

The closer a skater's body is "tucked in" to the axis of rotation, the faster he or she spins. This is why skaters bring their arms and legs in tight against their bodies during fast spins.

What if we could alter the shape, but not the mass, of our skater? Imagine stretching and squashing the skater like a lump of clay. Stretching the skater (see left) has the same effect as pulling the arms and legs in, and so the skater spins faster.



Conservation of angular momentum and skaters.

The same principle, with a twist, works for a spinning cyclone. The tropopause acts as a "ceiling" on cyclones and most other weather. The tropopause is, to a first approximation, at about the same altitude throughout the middle latitudes, so a cyclone can be stretched or squashed depending on the altitude of the surface that is beneath it. High mountains squash cyclones; lower oceans and plains help stretch them.

What does this imply about the spin of our cyclones? Just like our skater, a squashed cyclone spins more slowly and a stretched cyclone spins more rapidly. The rate of spin increases as the height of the cyclone increases; spin decreases as cyclone height decreases. Therefore, a meteorological form of the Conservation of Angular Momentum is this: Spin divided by the cyclone height must be a constant. (This works for anticyclones too.)

Now, the twist. A skater spins for a minute or so. This is far too short a time for the Earth's spin to affect the skater via the Coriolis force. However, a cyclone spins for days and is strongly affected by the Coriolis force. Because of this, the cyclone, but not the skater, feels the effect of the Earth's spin. So the cyclone has a double dose of spinning. Therefore, the meteorological form of Conservation of Angular Momentum is as follows:

$$\text{total spin} \div \text{cyclone height} = \text{constant}$$

In meteorological terminology, spin around a vertical axis is called "vertical vorticity," or just "vorticity" for short. The spin of winds in a weather system, such as a cyclone, is called "relative vorticity" because it is measured relative to the ground, but the air and ground are all spinning because of the Earth's rotation too. The Earth's spin is called "planetary vorticity." Vorticity is defined as positive if the direction of rotation is in the same direction as the Earth's spin. Looking down from above the North Pole, the Earth appears to rotate

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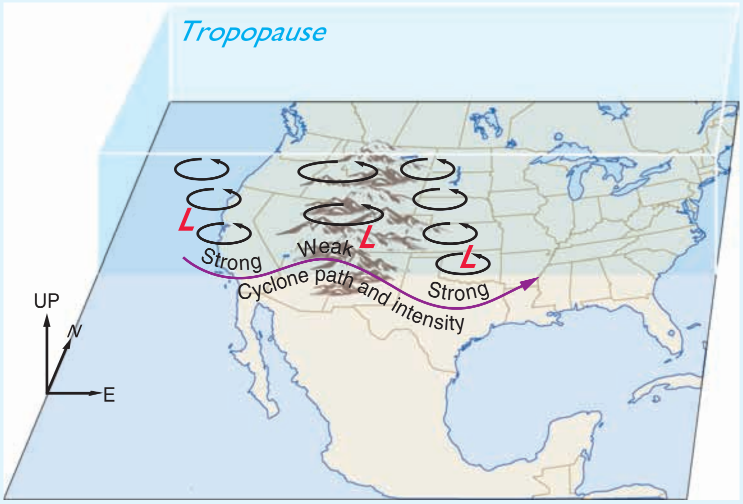
counterclockwise, and so do cyclones; therefore, the relative vorticity of a cyclone in the Northern Hemisphere is positive.

With these definitions, we can put everything together and write a special version of the Conservation of Angular Momentum used in meteorology, known as the Conservation of Potential Vorticity:

$$(\text{planetary vorticity} + \text{relative vorticity}) \div \text{cyclone height} = \text{constant}$$

in which the left-hand side of the equation is a special quantity known as "potential vorticity." Because in this equation potential vorticity is always constant, it is being conserved.

Conservation of potential vorticity lets us link up cyclones, mountains, and upper-level waves in the wind. Imagine a cyclone moving more or less eastward from the Pacific Coast to the Great Plains as depicted in the illustration. Over the Pacific, the cyclone is strong. Lows are associated with upper-level troughs. The trough's winds steer the cyclone southeast and then northeast in a cyclonically curved path.



Cyclone strength and path changes as a result of conservation of potential vorticity over the Rocky Mountains.

As the cyclone moves over the high Rockies, however, it gets squashed. Conservation of potential vorticity says that in this circumstance the total spin of the cyclone must decrease, too. The once-strong Pacific low appears to decrease in intensity as it moves over the Rockies, and its path curves anticyclonically over the mountains, heading southeast as the weather system crosses the Rockies.

Then suddenly the bottom drops out of the cyclone as it crosses the high Rockies and moves over the lower Great Plains. Over the Plains, the cyclone is stretched. By conservation of potential vorticity, this means the sum of the vorticities needs to increase, too. The cyclone does this in two ways: by "spinning up" (intensifying rapidly), which increases its relative vorticity, and by heading toward the northeast, which increases its planetary vorticity. The northeast path is consistent with the steering winds in the upper-level trough that develops in tandem with the strengthening cyclone.

Because the cyclone seemed to disappear over the Rockies, its reappearance and strengthening just east of the Rockies seem to come out of nowhere. However, they are natural results of potential vorticity conservation, as is the characteristic hook-shaped path of the cyclone (southeast over the front range of the Rockies, northeast over the Plains).

Obviously, the cyclone is closely related to the upper-level winds. The wavy path of the cyclone is mirrored in the waviness of the jet-stream winds that guide the storm. These large-scale waves of wind are Rossby waves, which move horizontally, like ocean waves. We can be more precise about how quickly they move. Using the concept of potential

(continued)

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Box 10-1 Making Cyclones and Waves, continued

vorticity conservation, famed 20th-century meteorologist C.-G. Rossby found that these waves' west-to-east (W–E) speed is dependent on how fast the jet stream is and how big the wave is (in other words, size matters). Rossby's formula for his waves' speed can be simplified to

$$\text{Rossby wave W–E speed} = \text{500-mb W–E wind speed} - (\text{Rossby wave W–E wavelength})^2 \times \text{a constant}$$

Because the two terms on the right-hand side of the equation are subtracted from each other, this means that the speed of a Rossby wave is a push–pull of wind speed versus size. Short waves (the size of the Great Lakes region) move eastward almost as fast as the 500-mb wind because the wind speed factor dominates. However, long waves (the size of a continent) travel very slowly eastward, stop, or even move backwards toward the west. This is because the wavelength term is almost as big, or bigger than, the wind speed term.

As you read this chapter, compare the forward speed of the *Fitzgerald* cyclone with Rossby's simple formula: Does the storm move fastest when it is young and small? Does it slow as it matures and grows bigger? Try it and see.

hatch covers using 68 special clamps. Shortly before 2:00 PM, the *Fitzgerald* departs into the open waters of Lake Superior.

Less than 2 hours later, the *Arthur M. Anderson,* sister ship to the *Fitzgerald,* leaves Two Harbors, Minnesota, with a load of iron ore for the Gary, Indiana, steel mills near Chicago. The *Anderson*'s captain, "Bernie" Cooper, recalled years later that this Sunday "was one of the special days on Lake Superior—just ripples on the water, sunny and warm for November. As we departed we could see the *Edmund Fitzgerald*. . . ." The two ships will sail together for the rest of the *Fitzgerald*'s last journey.

Portrait of the Cyclone as a Young Adult

The baby cyclone of November 8 has matured overnight—literally (**FIGURE 10-7**). The surface weather map for Sunday morning on the 9th (Figure 10-7a) shows a 999-mb low over

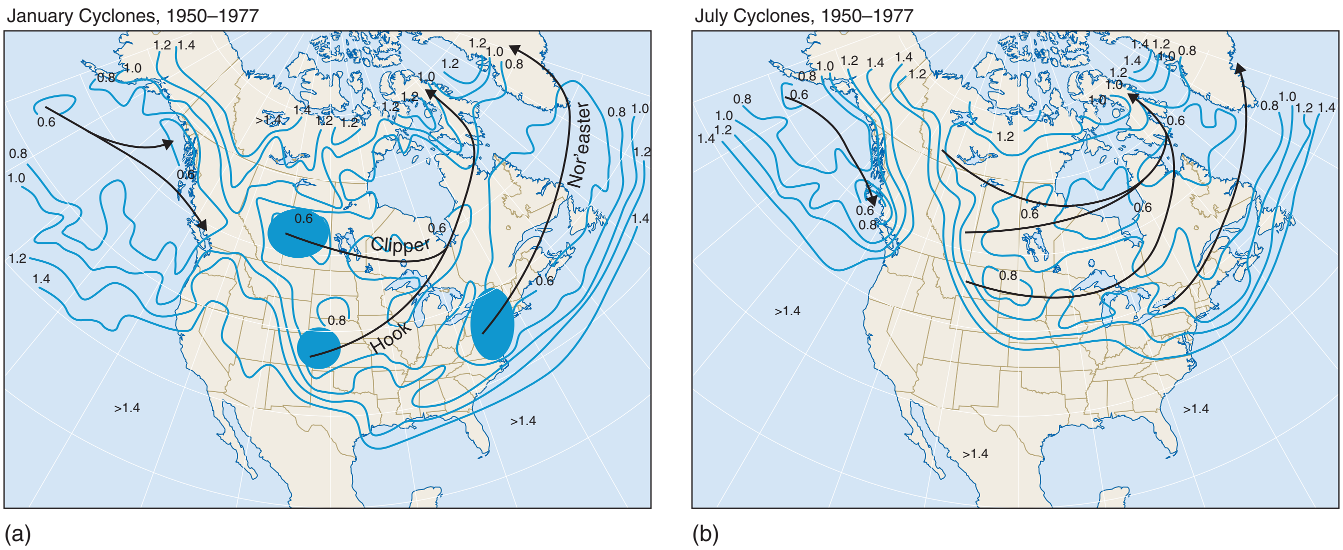

FIGURE 10-6 Typical regions of cyclogenesis (shaded) and paths of cyclones (arrows; likeliest paths in solid lines, other possible paths in dashed lines) that affect North America in January and July. (Adapted from Zishka, K. M., and P. J. Smith, *Monthly Weather Review*, April 1980: 391–392.)

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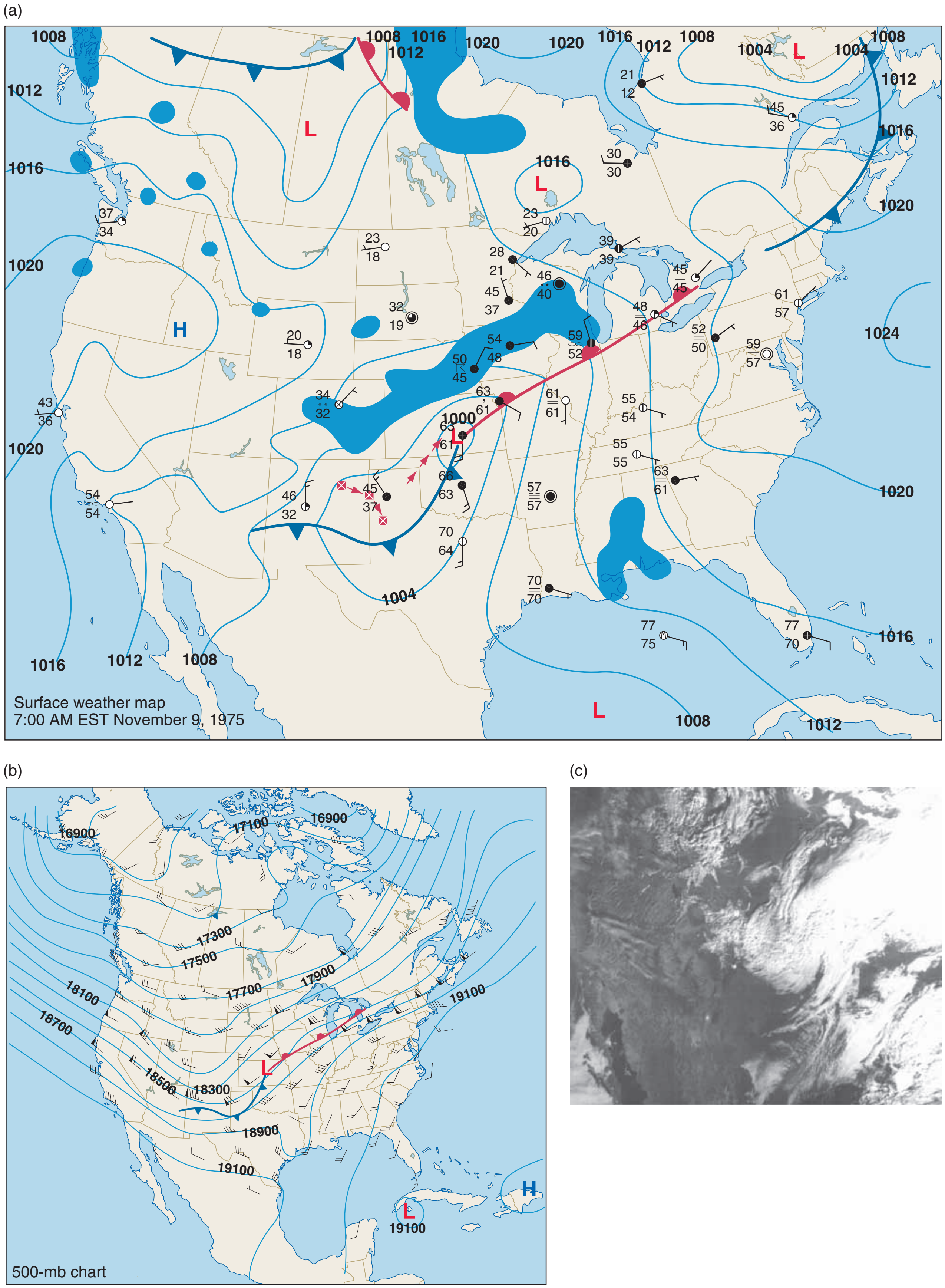

FIGURE 10-7 Surface weather (a) and 500-mb conditions (b) for 7:00 AM (EST), Sunday, November 9, 1975. The small boxes in (a) denote the location of the surface low 6, 12, and 18 hours earlier. The surface low and fronts are superimposed in (b) for reference. The Defense Meteorological Satellite Program visible satellite picture at the lower right (c) is from 10:12 AM (EST) that same morning. (Parts a and b data from NOAA. Part c courtesy of National Snow and Ice Data Center.)

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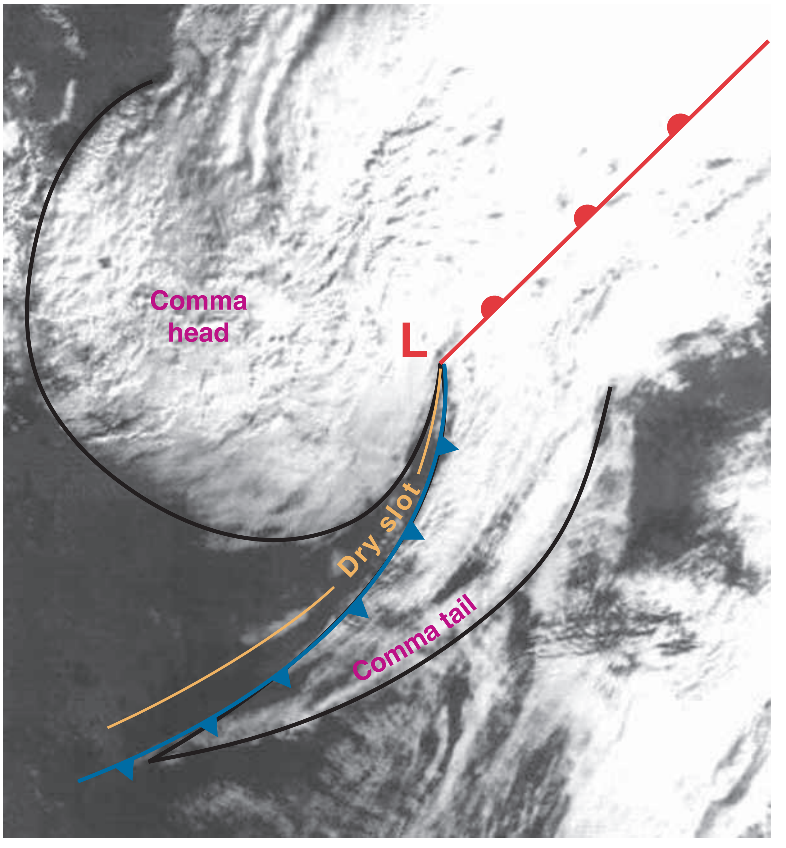

FIGURE 10-8 A close-up of Figure 10-7c. The center of the cyclone, which is underneath the "comma head" clouds, is just northwest of Wichita, Kansas, at this time. (Courtesy of National Snow and Ice Data Center.)

Wichita, Kansas, a pronounced cold front digging southward into Texas, and a warm front pushing north toward Iowa. Temperature contrasts across the cold front are now 11° C (20° F), and 5.5 C (10° F) across the warm front. The 500-mb map (Figure 10-7b) shows a deepening short wave trough to the west of the surface low, part of the cycle of growth of the storm. The baby is now a young adult, teeming with energy.

A high-resolution satellite picture taken just 3 hours later (Figure 10-7c, and enlarged in FIGURE 10-8) reveals that this cyclone has taken on a classic form at an early age. Seen from space, it has the shape of a **comma cloud**, which is characteristic of mature extratropical cyclones and is quite different from the circular tropical cyclone. The tail of the comma is clouds along the trailing cold front, which a tropical cyclone lacks. The comma head consists of clouds and light precipitation circling counterclockwise around the low's center. The cloudless region between the comma head and tail is the **dry slot**, a feature more often seen in more mature extratropical cyclones and not in hurricanes—we discuss it in more detail shortly. The lumpy areas in and just to the east of the comma head are taller convective clouds casting shadows on the lower clouds around them (Omaha, Nebraska, just north of the warm front, reports a thunderstorm at 6:00 AM). All in all, this picture tells a simple story: This cyclone is mature beyond its tender age. The weather map provides an even more ominous fact: The cyclone is now racing northeastward toward the Great Lakes at up to 64 kilometers per hour (40 mph).

Cyclones and Fronts: On the Ground

Madison, Wisconsin, lies just to the east of the cyclone's path on November 9. The changes in temperature, dew point, winds, pressure, and clouds at Madison on this day illustrate that an extratropical cyclone is a frontal cyclone. In other words, much of the exciting weather happens along the fronts connected to the low, just as Jack Bjerknes envisioned it.

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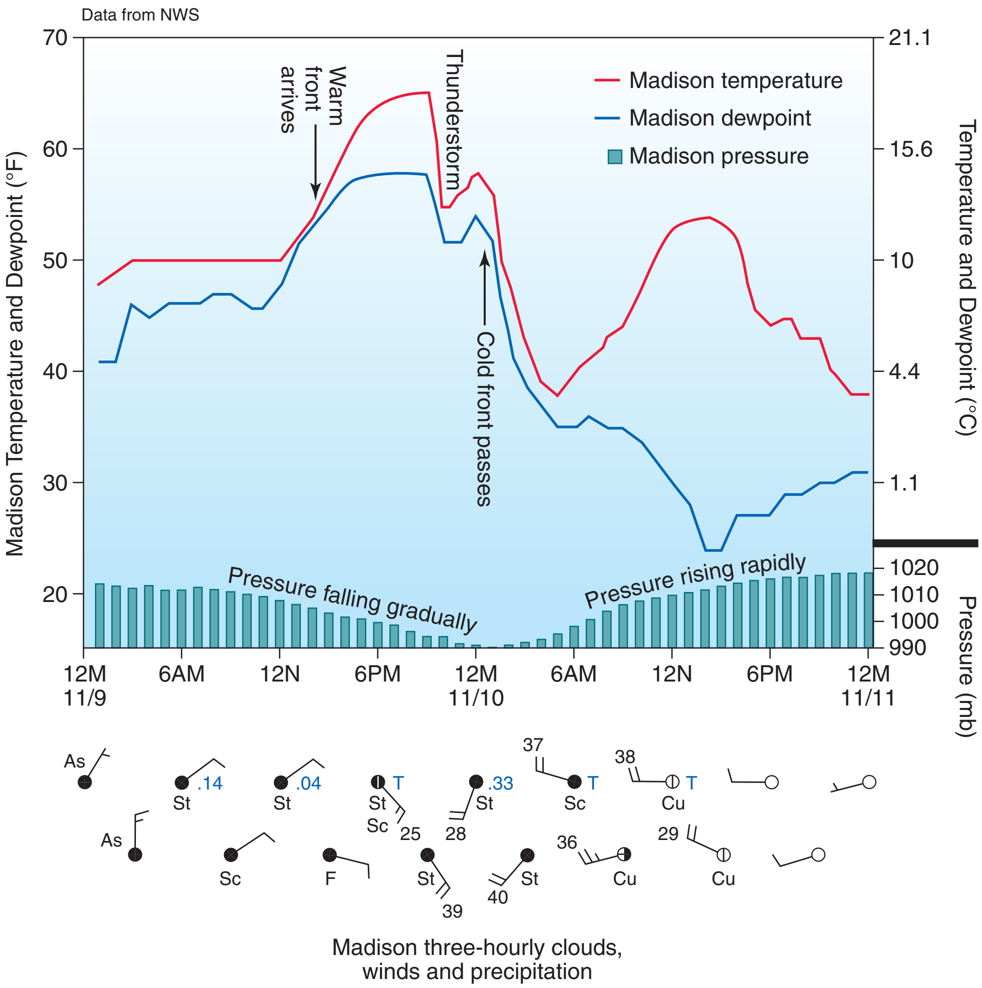

FIGURE 10-9 Madison, Wisconsin, weather during the passage of the *Edmund Fitzgerald* cyclone. Cloud types, wind gusts (in knots), and precipitation (in inches) are shown at the bottom, along with cloud cover and wind speed and direction. (Data from NWS.)

FIGURE 10-9 tells the story as a timeline of weather at Madison. Before dawn on the 9th, Madison reports altostratus clouds and east winds. Temperatures hover around 10° C (50° F), and dew points are slowly rising into the 40s. The warm front is approaching. Altostratus (As) clouds give way to stratus (St) clouds as the front nears, and light rain falls on Wisconsin's capital. The pressure falls slowly but steadily. In the afternoon, the warm front passes, and winds shift to southeasterly. Despite fog (F) and the lack of sunshine, Madison temperatures soar into the 60s by nightfall. At 9:00 PM, Madison reports a temperature of 18° C (65° F) with a dew point of 14° C (58° F)—unusually balmy November nighttime weather in Wisconsin. The wind circulation around the strengthening low has advected warm, moist maritime tropical (mT) air from the Gulf of Mexico all the way to the Great Lakes region.

Because Madison is close to the path of the cyclone, the warm sector is narrow, and the cold front arrives soon after the warm front. Between 9:00 and 11:00 PM on the 9th, a thunderstorm ahead of the cold front hits the city, dropping about 0.85 cm (0.33 inch) of rain in a short time. The temperature drops 5.5° C (10° F) as a result of evaporational cooling, but the warm Gulf air pushes the thermometer back up to 14° C (58 F) by midnight. Then the cold front rushes through. The winds veer to a more westerly direction and strengthen, peaking at 46 knots (53 mph). The temperature and dew point drop into the 30s by sunrise on the 10th. Stratus clouds break up and are replaced by a few puffy cumulus clouds in the drier air, and the pressure rises rapidly. By nightfall on the 10th, the pressure is high. Winds are slackening. The clouds have dissipated, and the cyclone is past—at Madison.

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Cyclones and Fronts: In the Sky

Cyclones and fronts are three dimensional. Jack Bjerknes and the Bergen School used observations from the surface, including cloud types, to determine indirectly the upper-level patterns. We can do the same with the *Fitzgerald* cyclone.

One technique for visualizing a cyclone is shown in **FIGURE 10-10**: take a vertical slice through it, as if the cyclone were a cherry pie. Let's make a cut across the center of the U.S. so that we can slice through both the fronts and the center of the *Fitzgerald* cyclone itself. Figure 10-10a depicts this cut, and in Figure 10-10b, the clouds and weather along this line from Amarillo, Texas, to the Great Lakes is shown graphically for 6:00 AM Central time on the 9th. The transitions in clouds, precipitation, temperatures, moisture, and winds across the fronts are almost exactly what you would expect from the Norwegian Cyclone Model. The cold front is less textbook case, but part of the reason is that clouds ahead of a cold front often need a boost from the Sun to grow. At 6:00 AM in November, the eastern sky is just beginning to glow over the Great Plains, so only stratocumulus clouds hover over Tulsa, Oklahoma.

By 3:00 PM on the 9th (Figure 10-10c) the strengthening low and the Sun have combined to create severe weather. The Tulsa weather observer can see towering cumulonimbus clouds as the cold front pushes past—so can the observer at Des Moines, Iowa, in the immediate vicinity of the center of the cyclone. Severe thunderstorms are breaking out all over Iowa; winds shred the inflatable stadium dome at the University of Northern Iowa. Meanwhile, the lowering clouds and rising winds on Lake Superior concern the captain of the *Edmund Fitzgerald*.

Back with the *Fitz*: A Fateful Course Correction

Captains McSorley and Cooper pay careful attention to the National Weather Service (NWS) forecasts on the 9th. Cooper recalls, "When the meteorologists become nervous we then start our own weather plots. It did show a low pressure to the south . . . normal November low pressure."

Unfortunately, the rapid growth of the cyclone tests the ability of the NWS and the boat captains to keep up with it. At first the severe weather experts in Kansas City call it a "typical November storm" headed south of Lake Superior. Because of the counterclockwise circulation around a low, this means strong east and northeast winds and waves of 1 to 2.5 meters (3–8 feet) on Lake Superior on Monday. By mid afternoon on Sunday the forecast is revised. Gale warnings are issued for winds up to 38 knots (44 mph)—not too unusual, but no longer typical.

The deteriorating weather forecasts prompt Cooper and McSorley to discuss over the radio the first of several weather-related course changes. The "fall north route" the two captains eventually choose to take (Figure 10-1) will add many miles to the usual shipping path. However, by staying close to land and minimizing fetch, this route protects boats from high seas caused by north and northeast winds.

By 10:39 PM, the cyclone compels the NWS to revise its forecast again. Now, the winds are supposed to howl at more than 40 knots (46 mph) across Lake Superior on Monday. More significantly, these winds will be coming from the west and southwest, generating waves of 2.5 to 5 meters (8–15 feet). The forecast of a storm near the Great Lakes has been consistent, but in just 12 hours the wave heights forecast for Monday have doubled and the forecast wind direction has turned 180°.

At midnight, the *Fitzgerald* is 37 kilometers (23 miles) south of Isle Royale and reports 52-knot (60 mph) north-northeast winds, heavy rain, and 3.5-meter (10-foot) waves. Shortly the NWS will upgrade the gale warning to a storm warning. The cyclone is strengthening rapidly and aiming northward across Lake Superior. The strongest winds over the lake will soon be coming out of the west, not the northeast. This and later course corrections, based on the best available weather information at the time, will leave the freighter exposed to hurricane-force west winds and high seas on the 10th.

Cyclones and Jet Streams

Why is the cyclone strengthening? Why is it moving so quickly and changing direction? Why is the forecast changing every few hours? To understand this better, we need to look closely at what is happening above the surface low.

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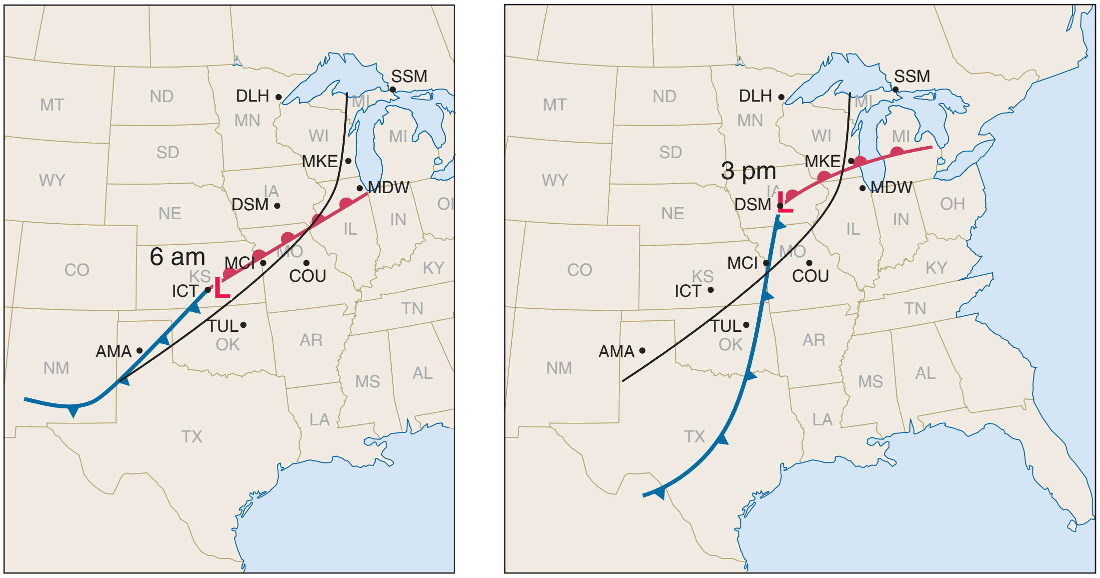
(a)

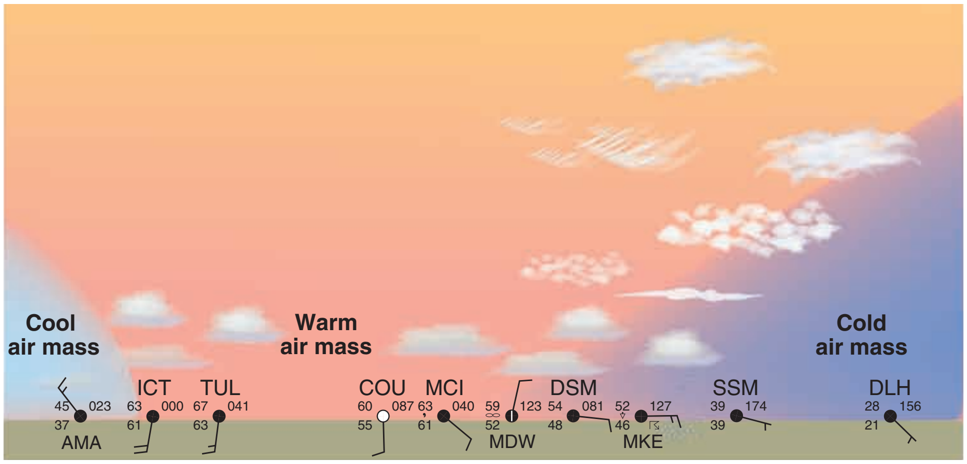
Airport city codes

SSM (Sault Ste. Marie, MI)
DLH (Duluth, MN)
MKE (Milwaukee, WI)
MDW (Chicago, IL)
DSM (Des Moines, IA)

COU (Columbia, MO)
MCI (Kansas City, MO)
ICT (Wichita, KS)
TUL (Tulsa, OK)
AMA (Amarillo, TX)

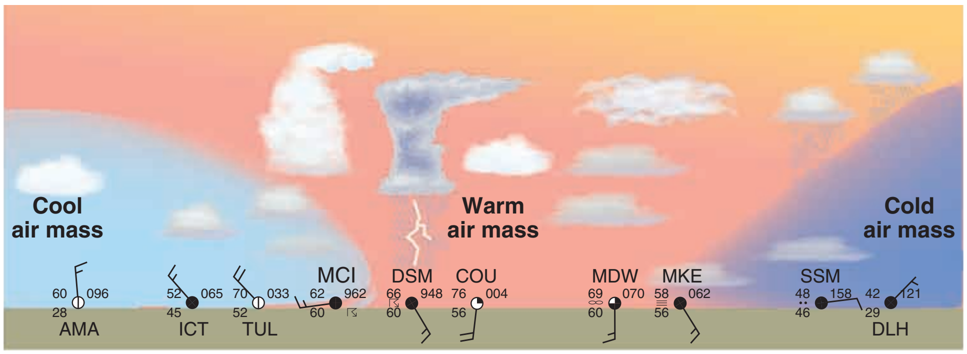


(b)



November 9, 1975 6AM CST

(c)



November 9, 1975 3PM CST

FIGURE 10-10 (a) The approximate positions of the *Fitzgerald* cyclone and its fronts at 6:00 AM and 3:00 PM Central Standard Time, November 9, 1975. The line from Texas to the Great Lakes is used in constructing b and c, which are cross-sections through the cyclone of surface weather observations at 6:00 AM (b) and 3:00 PM (c), respectively. (Part a data from NWS.)

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During the 9th, the upper-troposphere wind pattern has been affected by two factors: the jet-stream winds moving east across the Rockies (see Box 10-1) and also the increasing temperature gradients along the surface fronts. Cold air moving southward near the surface helps the upper-level trough "dig" or extend southward. Similarly, warm air moving northward leads to a "building" upper-level ridge (i.e., extending north and northwestward). These upper-level changes, in turn, affect three characteristics of the surface low: its speed, direction, and intensity.

Surface lows tend to move at about half the speed of the 500-mb winds above them. During the 9th, 85-knot (98 mph) winds over New Mexico increased and moved east toward the Great Lakes. This helps explain the rapid movement of this storm.

Surface lows and fronts also generally move in the same direction as the "steering winds" at the 500-mb level. During the 9th (Figure 10-7), the combination of the digging trough and the building ridge bends the wind pattern, causing the direction of these steering winds to shift from northeastward to a more northerly direction, across Lake Superior. In other words, the storm's steering wheel keeps turning on the 9th, and this is why the storm's future path is hard to forecast precisely.

A better understanding of cyclone–jet-stream relationship requires us to delve more deeply into concepts of atmospheric forces and winds and the Norwegian Cyclone Model. Most important is the relationship between the surface low's strength and the jet-stream winds. A simple law of meteorology explains the connection: Surface pressure drops when there is **divergence** of the wind in the column of air above the low. Ordinarily, winds converge into a low near the surface. Therefore, strong upper-level divergence must exist so that the net effect is divergence above the low. If this happens, then the low will intensify because there is less air over it to exert pressure on the surface (FIGURE 10-11).

Upper-level divergence can occur in two different ways. Either the winds can accelerate in a straight line, or they can spread out rapidly in a variety of directions. The straight-line acceleration is called **speed divergence**, and the spreading out is called **diffluence**, as illustrated in Figure 10-11. (The opposite of diffluence is confluence, which turns out to be an important distinguishing characteristic for extratropical cyclones.)

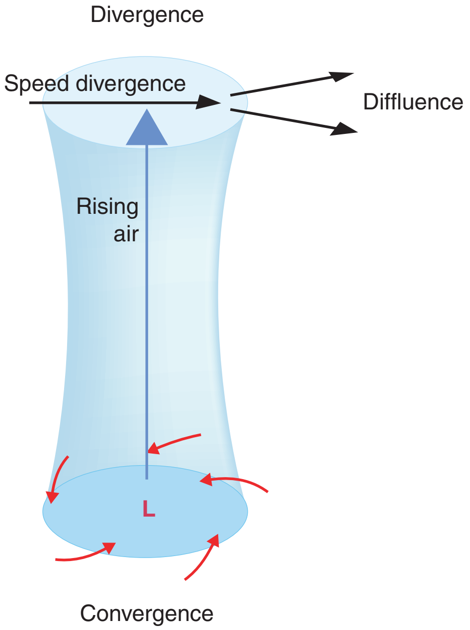

FIGURE 10-11 The relationship between the two types of divergence (speed divergence and diffluence) at upper levels and the development of a surface cyclone. The length of arrows at top is proportional to wind speed.

The intertwined connections between the surface cyclone and the jet-stream pattern are summarized for the first three stages of the idealized Norwegian model in FIGURE 10-12. Upper-level divergence exists above and ahead of the low. (Remember that for equal spacing of height lines, the winds in a trough are slower than winds in a ridge. Therefore, divergence commonly occurs east of a trough. Figure 10-12 also shows some speed divergence and diffluence, especially for the mature cyclone.) This divergence helps the cyclone deepen and propagate northeastward because the surface pressure drops along and ahead of the low. Upward motion brought about by this divergence helps in the formation of clouds and precipitation. The upper-level convergence behind the cyclone causes sinking air, which suppresses clouds. This sinking air also drags down warm air from the stratosphere above and behind the cyclone (as discussed in BOX 10-2). These interrelationships between surface and jet-stream patterns make it clear that the extratropical cyclone is a complex three-dimensional phenomenon, as illustrated in Box 10-2. This explains why observations of upper-level winds are so crucial to weather analysis and forecasting in the middle latitudes.

Figure 10-12 is an idealized model, however. FIGURE 10-13 shows the actual winds measured by radiosondes at 300 mb at 6:00 PM Central time on November 9, 1975. Following the lines of constant height from Nebraska to Minnesota, the winds double in speed going from the trough to the ridge. As a result, on the 9th speed divergence exists over Iowa and Minnesota. The winds over Minnesota are southerly, whereas the winds over Michigan are southwesterly. This spreading out of the wind is an example of diffluence.

The combination of these two types of divergence leads to sudden pressure drops over the upper Midwest. Therefore, this cyclone accelerates to the northeast

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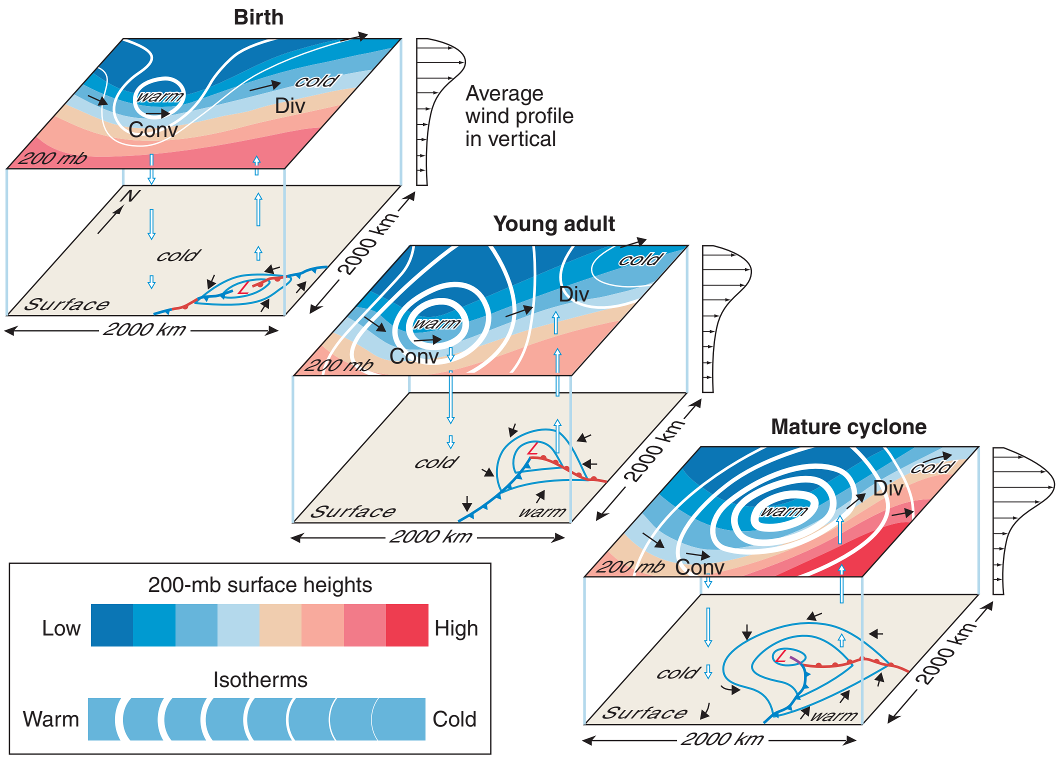

FIGURE 10-12 The relationship between upper-level (200 mb) and surface conditions during the first three stages of the Norwegian Cyclone Model. (Adapted from Carlson, T. N. *Mid-Latitude Weather Systems*. American Meteorological Society, 1998.)

Box 10-2 Cyclone Winds in 3D: Belts and Slots

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The Bergen School saw the cyclone as a face in the clouds and used military metaphors (e.g., fronts) to describe it. Today, meteorologists visualize the cyclone the way a cartoonist would, using just a few deft pen strokes to capture the essence of that face. Along with this new way of seeing the cyclone comes a new metaphor borrowed from industry, not war: "conveyor belts" of air that carry air parcels through an ever-moving, ever-evolving cyclone.

The figure above illustrates the approximate locations of these conveyor belts, superimposed on a rare weather satellite picture of the *Fitzgerald* cyclone at 5:00 PM Eastern time on November 10, 1975. The "warm conveyor belt" (WCB) is essentially the warm air that rises up and over the warm front. It then peels off toward the east as it is pushed by the strong jet stream above the surface cyclone. The WCB is the main cloud- and precipitation-making air flow in the cyclone.

The "cold conveyor belt" (CCB) is a flow of air ahead of the warm front that is wrapped into the center of the cyclone, causing clouds. These clouds are the distinctive "comma head" of the extratropical cyclone.

The "dry conveyor belt" or "dry slot" is the key to understanding at least some cyclone-related windstorms. It is a tongue of air dragged down by the jet stream from high aloft, even as high as the lowest part of the stratosphere. This air is very dry; as a result, it appears as a cloudless region in a visible satellite picture—helping to form the "dry slot," as seen in Figure 10-8. The strong westerly and southwesterly winds above the cyclone descend in the dry slot and make the surface beneath it a blustery place.

To positively identify a dry slot, meteorologists can try at least two different approaches. One is to look for narrow bands of dark (i.e., dry) air leading into a cyclone on water vapor satellite images. Another way is to look for signs of upper-tropospheric and lower-stratospheric air being dragged down into the troposphere.

(continued)

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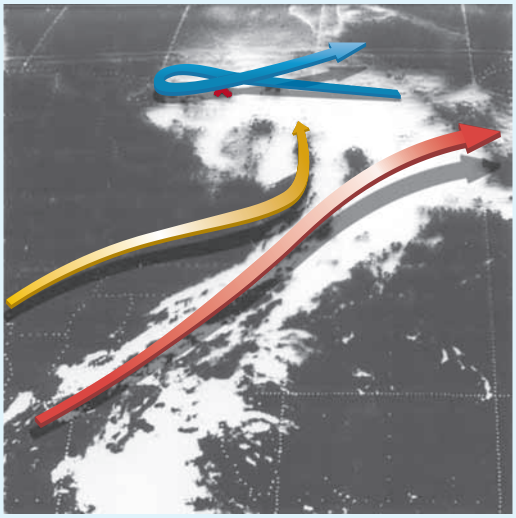
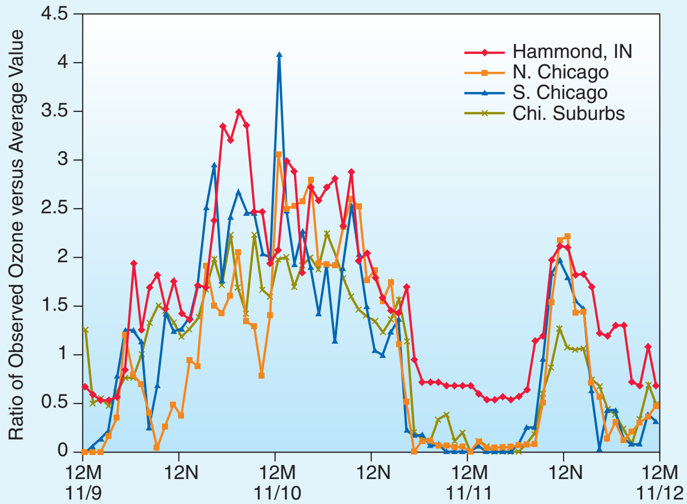


The conveyor belts of an extratropical cyclone, overlaid on top of the weather satellite image for 5:00 PM Eastern time November 10, 1975. The red arrow indicates the WCB, the blue arrow the CCB, and the yellow arrow the DCB. The red X underneath the blue arrow indicates the position of the *Edmund Fitzgerald* at the time the satellite picture was taken. (Modified from Wilson, E. E., "Great Lakes Navigation Season." *Mariners Weather Log* 20 [1975]: 139–149.)

Water vapor imagery didn't exist in 1975, but surface ozone concentrations were being measured in large metropolitan regions, such as Chicago, in order to keep track of daytime ozone pollution. These observations can also be used to look for signs of stratospheric air descending in the dry slot of the cyclone.

On the night before the *Fitzgerald* sank, surface ozone values were rising all over the Midwest, particularly in a band stretching through Chicago. The figure below, using data gleaned from several Chicago high schools by student researcher Stino Iacopelli, tells the story. The ozone values peaked around midnight, right around the time that thunderstorms hit the area (compare with the Madison, Wisconsin, observations in Figure 10-9). Meanwhile, ozone values were also above normal back in Iowa, behind the low. At this same time, winds gusted to 61 knots (70 mph) in the Chicago area, and a man was killed in northeast Iowa when winds behind the cyclone overturned his airplane. It is possible the *Fitzgerald* cyclone had a well-developed dry slot, and high-speed, high-ozone air plunged toward the surface.

Is this why the *Fitzgerald* and the *Anderson* were ravaged by high winds on Lake Superior the next day? No surface ozone data exist in the vicinity of the wreck, but we do know that the *Fitzgerald's* last hours were spent behind the low in heavy lake-effect snow squalls. The convective snow squalls, like the Chicago thunderstorms the night before, would help convey any high-speed air above them down to the surface. This question won't be settled until the evidence is presented as a formal journal article and the article's results are discussed and debated by today's leading extratropical cyclone experts.



Surface ozone levels in and near Chicago on November 9–11, 1975. The values are ratios of the observed ozone concentration vs. the November 1975 average for that time and site. Values greater than 1 indicate greater-than-usual ozone concentrations. Notice the unusually high ozone values around midnight on the 10th as the extratropical cyclone passed by Chicago.

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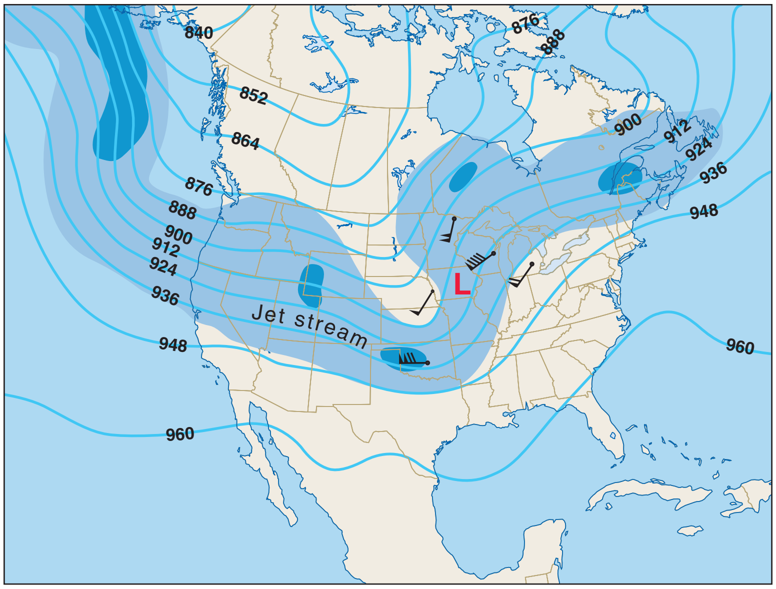

FIGURE 10-13 Winds and heights (in tens of meters) at the 300-mb level for 6:00 PM (CST) on November 9, 1975. The pattern of winds shown here helps the surface cyclone (the L over Iowa) strengthen rapidly. (Data from NWS.)

and deepens rather rapidly, from a central minimum pressure of 999 mb at 6:00 AM (CST) to 993 mb 12 hours later. The lowest pressure of the cyclone is dropping 0.5 mb per hour. This cyclone is on its way to becoming the "Storm of the Year" on the Great Lakes.

DAY 3: THE MATURE CYCLONE

Early on November 10, the *Fitzgerald* sails into the Eastern time zone and heads for an unexpected rendezvous with a dangerous, mature, extratropical cyclone. The 7:00 AM (EST) surface weather map (**FIGURE 10-14**) reveals that this cyclone (and its associated fronts) now dominates the eastern half of the United States! Just 48 hours ago, it was a cloudless swirl over Texas.

The cyclone's power and scope of influence indicate that it has reached full maturity. The low itself is centered directly over Marquette, Michigan, in that state's Upper Peninsula. Its lowest pressure has plummeted overnight to 982 mb, a drop of nearly 1 mb per hour. To the west of the low, cold air spiraling in toward the storm across tightly packed isobars is causing blizzard conditions—heavy wet snow blown by 60-knot (69 mph) winds is tearing down power lines and piling up as much as 36 centimeters (14 inches) of snow in parts of northern Wisconsin. Meanwhile, the cyclone's warm front has crossed over into Canada, and its cold front has barreled south to the Gulf of Mexico. From Iowa to Tennessee, residents are combing through debris and tending to casualties after 15 tornadoes spawned ahead of the cold front injured 25 people. In the life cycle of this extratropical cyclone, Saturday's baby and Sunday's adolescent is Monday's ferocious adult.

Bittersweet Badge of Adulthood: The Occlusion Process

If you look closely at Monday's weather map in Figure 10-14, you will notice that the cold and warm fronts no longer join like halves of a moustache at the center of the cyclone. Instead, an occluded front joins the low and the cold and warm fronts.

What is an occluded front? The Bergen School envisioned it as the cold front "catching up" with the warm front to form an occluded front. The modern understanding of occluded fronts is more complicated. Cyclone researchers David Schultz and Geraint Vaughan describe the process of **occlusion** in this way: If the cyclone becomes strong enough, its structure may begin to change, both at the surface and aloft. As the warm and cold fronts wrap around the cyclone, they lengthen, just as ribbons of milk lengthen when stirred into coffee. Cold air ahead of the warm front travels

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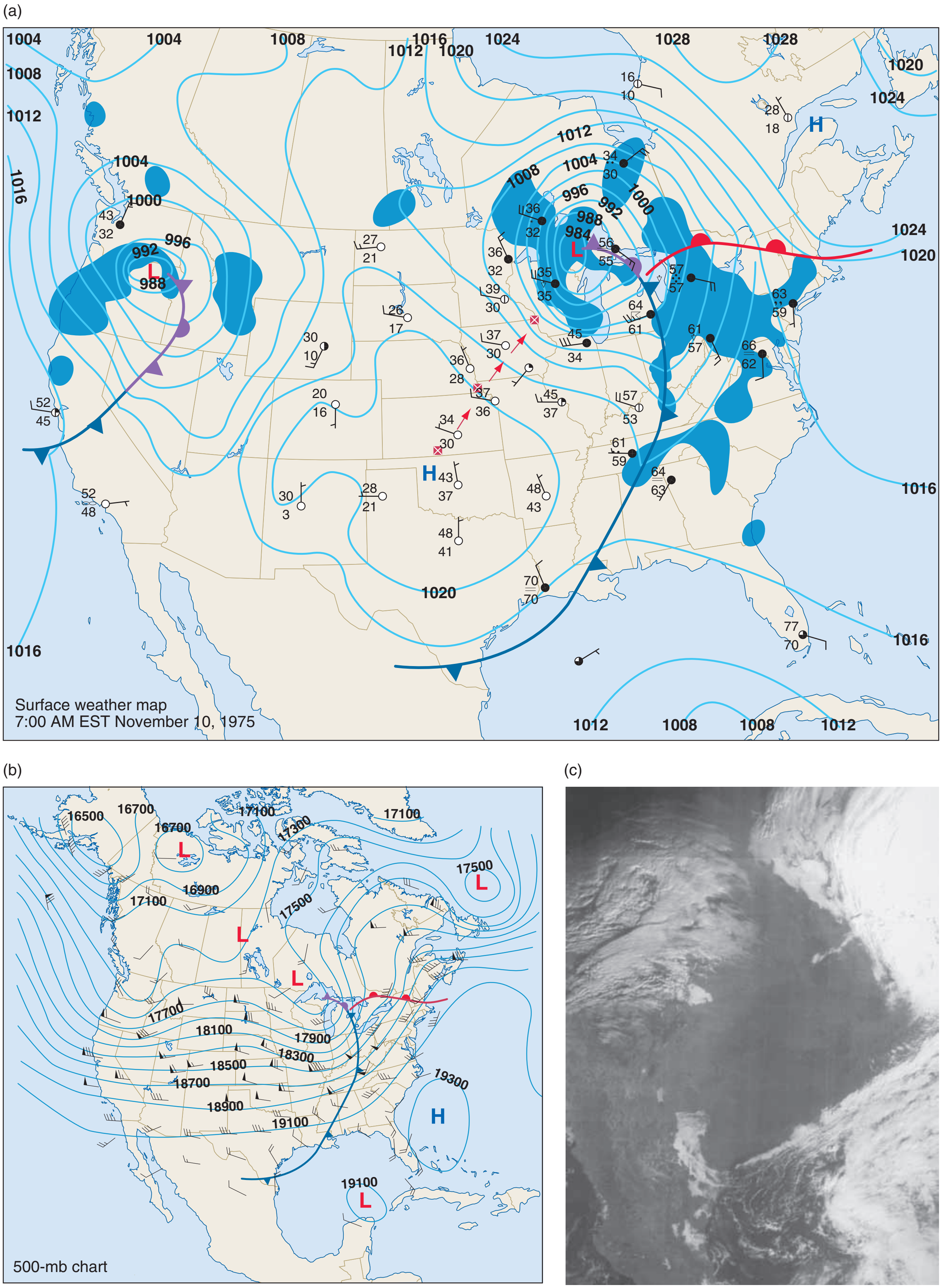

FIGURE 10-14 Surface weather (a) and 500-mb conditions (b) for 7:00 AM (EST) on Monday, November 10, 1975. The Defense Meteorological Satellite Program visible satellite image in the lower right (c) is from 9:55 AM that morning and is centered over Kansas. (Part a data from NOAA. Part c courtesy of National Snow and Ice Data Center.)

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around the low center, and the warm air ascends over the warm front (Box 10-2), which removes warm air from the surface. Eventually, the narrowing region of warm air is completely lifted from the surface near the low center, leaving a boundary between two cold air masses called the occluded front.

During occlusion, the surface low gradually retreats from the zone of sharp temperature contrasts and isolates itself in the cold air to the north and west of the intersection of the cold and warm fronts. The surface low ultimately ends up directly underneath the upper-level low—far removed from the tilted "baroclinic" situation of its youth. In an extratropical cyclone in confluent jet-stream flow over a large body of water, the Shapiro-Keyser model can be more accurate than the Norwegian model, and the storm can wind up with warm air at its center. Even over the Great Lakes, extratropical lows can develop eyes, just like hurricanes (**BOX 10-3**).

Box 10-3 Cyclones and Water: Bomb and Bust

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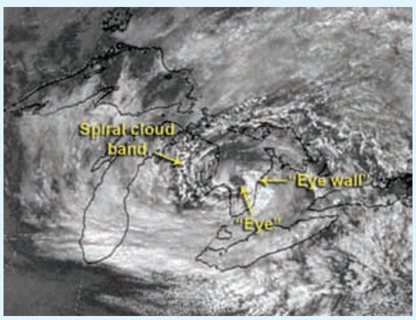
Is an extratropical cyclone the same thing as a hurricane? No. Extratropical cyclones thrive on ingredients such as fronts and strong jet streams, which could weaken a hurricane by cutting off its fuel sources and disrupting its circulation.

Even so, it's true that the same fuel sources that feed the engines of hurricanes—warm surface waters and lots of water vapor—can also stoke the fires of their extratropical cousins. As a result, extratropical cyclones that are over oceans or that have access to lots of warm, moist air often become more intense than "drier" cyclones. This rapid intensification even has a meteorological nickname—"bomb"—that is reserved for midlatitude cyclones whose central pressure drops approximately 1 mb per hour every hour for 24 hours. It's not typical to see the pressure drop a whole millibar in just 1 hour, let alone keep up that pace for an entire day! Such explosive growth sounds more like a hurricane than an extratropical cyclone, and there are some similarities.

An extreme example is the maritime "polar low" that develops over the seas north of Europe. The water there is cold, but the air is even colder. The water transfers warmth and energy to the air at the surface; this is called sensible heat. Latent heat is also released into the air when the seawater evaporates and then later condenses into cloud droplets. These two water-based energy sources give the polar low its energy, just as in a hurricane. In fact, the polar low is called an "arctic hurricane" by some meteorologists because of its hurricane-like appearance in satellite pictures.

In the middle latitudes, cyclones live and die with fronts and jets. But even here, water plays a key role and makes forecasting very difficult. Midlatitude cyclones born over water are a little like hurricanes and are especially responsive to water-borne energy. One study of a February 1979 nor'easter that became a "bomb" off the U.S. East Coast revealed that the presence of water helped drop the cyclone's pressure by 32 mb (nearly 1 full inch of mercury). That's the difference between a weak cyclone and a record setter! The forecasters were taken completely by surprise, which is called a "bust," short for a "busted" or broken forecast.

The Great Lakes are also big enough to affect the strength of extratropical cyclones that pass over them. Below is a satellite picture of the September 14, 1996, "Hurricane Huron." Notice how it seems to have an "eye" and spiral rainbands, a little like a hurricane. It's not a hurricane, but the presence of warm water underneath the cyclone fueled its fires. This extratropical cyclone stalled over Lakes Michigan and Huron for 4 days and deepened 19 mb over that time—not a "bomb," but impressive nonetheless.



"Hurricane Huron," a mid-latitude cyclone influenced by the waters of the Great Lakes. (Modified from Steenburgh et al., *Bull. Amer. Meteor. Soc.*, 81, [2000]: 224.)

Did the Great Lakes play a role in the cyclone that helped sink the *Edmund Fitzgerald*? Yes, most likely on the back side of the storm where cold air passed over warmer water. There, just as in a polar low, sensible and latent heat would be released into the air. This energy release helped cause the lake-effect snow squalls that enshrouded the *Fitzgerald* in its final minutes.

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The irony is that the occlusion process eventually removes the mature extratropical cyclone from its fuel source, strong temperature gradients, and (once the surface cyclone is underneath the upper-level low) the deepening effects of the jet stream. The mature cyclone's growth eventually cuts it off from its ability to grow further. (Cyclones can keep on growing for a time, primarily because of latent heat energy from the condensation of water vapor.) The cyclone gradually turns into a frontless cut-off low and slowly dies. The occlusion process is, therefore, not only a badge of adulthood—it is also a sign that an extratropical cyclone is approaching the end of its life cycle.

An occluding cyclone is still at the peak of its powers initially and may even initially intensify further, as the crew of the *Fitzgerald* learns on the 10th. As the cyclone races toward Lake Superior before dawn on the 10th, captains Cooper and McSorley adjust course again, "hauling up" near the eastern Canadian shore of the lake. There the boats will be less vulnerable to northeast winds because the winds will be blowing over only a short distance or "fetch" of water.

Unfortunately, the cyclone outmaneuvers the ore freighters. The cyclone is now moving northeast at 30 mph; even the powerful "Big Fitz" cannot match this speed. The low and the boats cross paths in Canadian waters in northern Lake Superior.

"The low had reached Lake Superior and was intensifying dramatically," Cooper recalls. "Shortly after noon, we were in the eye of the storm. The Sun was out . . . light winds, no sea." The *Anderson's* barometer, adjusted for sea level, bottoms out at 28.84 inches of mercury or 976.6 mb, as low a pressure as will be recorded for this cyclone.

The good weather cannot last because of the raging contrasts near the heart of an extratropical cyclone. As the low and its occluded front race past, strong winds from the west will soon lash at the *Anderson* and *Fitzgerald.* At 1:40 PM, Cooper and McSorley agree to yet another weather-related course correction, cutting between woody Michipicoten Island and Caribou Island on a southeastward heading toward safe haven in Whitefish Bay and Sault Ste. Marie, Michigan. But it's too late.

By 2:45 PM, the *Anderson* reports snow with northwest winds at a steady 42 knots (48 mph), a 180° reversal of direction and a doubling of speed in less than 2 hours. Instead of being sheltered from northeast winds, they are now fleeing rising winds and waves that are rushing at them from behind across the vast expanse of Lake Superior.

Hurricane West Wind

Meanwhile, a severe, localized windstorm is developing directly in front of the *Fitzgerald.* **FIGURE 10-15** shows the hourly barometric pressure readings for four weather stations in or near the path of the cyclone. At most of these locations, the pressure rises rapidly after the storm passes. Mariners recognize this as an ominous sign. According to a saying at least as old as 19th-century British meteorologist Admiral FitzRoy (the captain of the *HMS Beagle*):

> "Fast rise after low
> Foretells stronger blow."

This folklore forecast is based partly on force-balance ideas. Rapid pressure changes behind a low imply that there is a strong horizontal pressure gradient in the area. Geostrophic and gradient wind balances both require strong horizontal winds in such cases.

FIGURE 10-16 proves the wisdom of FitzRoy's rhyme. In the figure, hourly wind observations at Marquette and Sault Ste. Marie, Michigan, tell a tale of increasing, and increasingly gusty, winds after the passage of the cyclone. Marquette is hit first, shortly after noon on the 10th; **FIGURE 10-17** is a rare photograph showing the tempest at Marquette that very afternoon. The pressure rises move east, and Sault Ste. Marie is hammered with gusts of 62 knots (71 mph) after nightfall, knocking out electricity over much of the region.

By the time high winds blow through Marquette and Sault Ste. Marie, the cyclone is well into Canada. These damaging west and northwest winds are far removed from any thunderstorms or tornadoes, nor are they concentrated in an eye wall around the lowest pressure as in a hurricane. These winds stand in the path of the *Fitzgerald*, which is now in a race to safe harbor before the winds and waves sink it.

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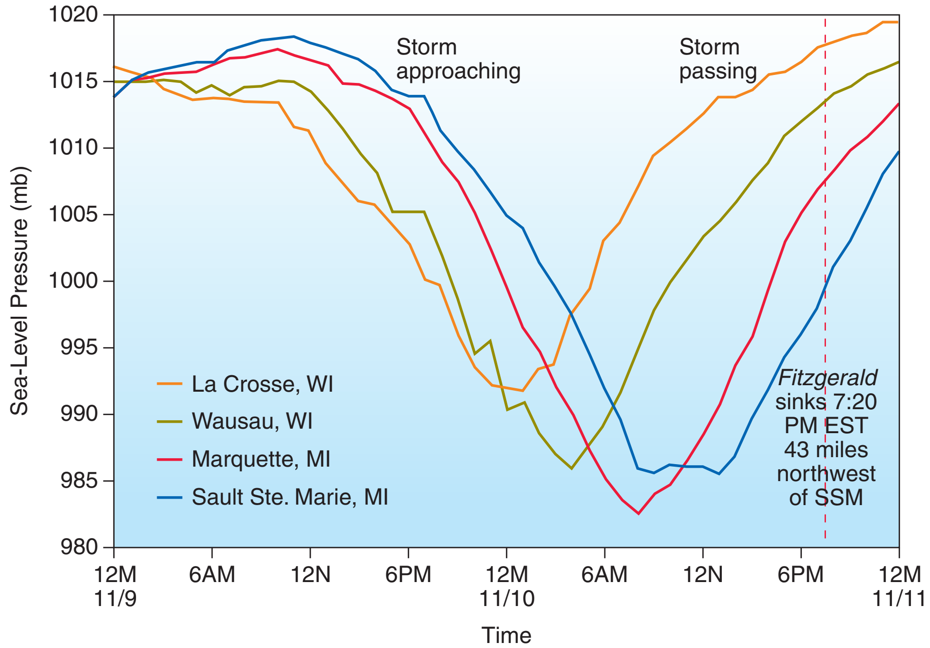

FIGURE 10-15 Hourly sea-level pressures at four stations in the general path of the *Fitzgerald* cyclone. Notice the pattern of falling and then rapidly rising pressure at each city as the storm first approaches and then passes. The *Edmund Fitzgerald* sank during rising pressure northwest of Sault Ste. Marie, Michigan. (Data from NWS.)

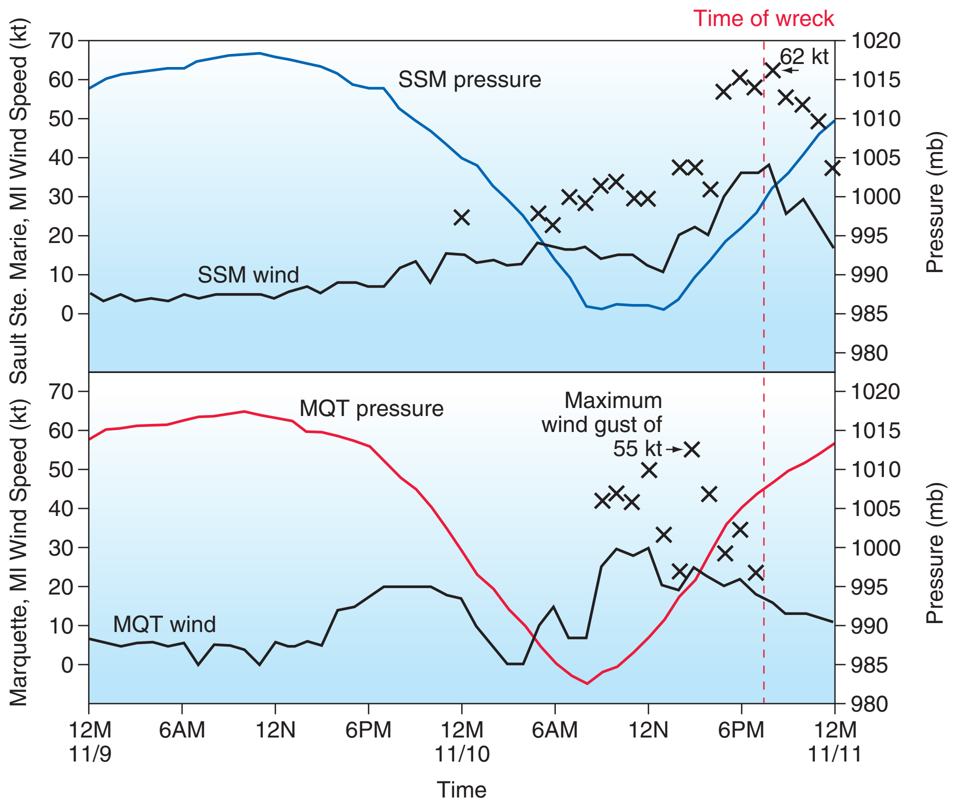

FIGURE 10-16 Hourly wind speeds (average and gusts, in knots) at Sault Ste. Marie and Marquette, Michigan, during the approach and passage of the *Fitzgerald* cyclone. Hourly barometric pressure readings are also depicted. (Data from NWS.)

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FIGURE 10-17 *The Wreck of the Edmund Fitzgerald* author Frederick Stonehouse's photograph of heavy surf at Marquette, Michigan on November 10, 1975. (Courtesy of Frederick Stonehouse.)

One of the Worst . . .

As daylight dims on the 10th, the *Anderson* and *Fitzgerald* are laboring to make headway in worsening weather. All around the Anderson, the winds and seas rise in fury: 43 knots (49 mph) and 3.7- to 4.9-meter (12- to 16-foot) waves at 3:20 PM, 58 knots (67 mph) and 3.7- to 5.5-meter (12- to 18-foot) waves at 4:52 PM. It is profoundly bad timing. At this point in the voyage, treacherous shoals near Caribou Island demand precise navigation as the boats thread the needle between Michipicoten and Caribou (Figure 10-1).

In the middle of the howling winds, snow, sea, and spray, something goes wrong. Around 3:20 PM, McSorley calls Cooper on the radio:

> "*Anderson*, this is the *Fitzgerald.* I have sustained some topside damage. I have a fence rail laid down, two vents lost or damaged, and a list. I'm checking [slowing] down . . . Will you stay by me 'til I get to Whitefish [Bay]?"
> "Charlie on that *Fitzgerald.* Do you have your pumps going?"
> "Yes, both of them."

Something has damaged the *Fitzgerald*, inflicting wounds worse than anything that has happened to the boat in 17 full years on the Great Lakes. It is tilting to one side, or "listing," presumably as a result of a leak that is letting lake water pour into the boat. The leak is bad enough that even the *Fitzgerald's* large pumps, capable of removing thousands of gallons of water every minute, apparently do not correct the list for the remainder of its journey. Perhaps the water is filling the spaces between the taconite pellets, much as sand holds water. The captain is concerned enough to ask his companion boat to stay nearby. But what happened, exactly, is a mystery forever.

The windstorm intensifies. Around 4:10 PM, gusts blow away the *Fitzgerald's* radar antenna. Then winds knock out power to the remote navigation station at the entrance to Whitefish Bay, making it that much more difficult for storm-tossed ships to gain their bearings. At 4:39 PM, the National Weather Service in Chicago fine tunes its forecast for eastern Lake Superior, calling for northwest winds 38 to 52 knots (44 to 60 mph) with gusts to 60 knots (69 mph) early Monday night. Waves are still expected to be 2.4 to 4.9 meters (8 to 16 feet).

Once again the storm exceeds expectations, however (see Box 10-2 for reasons why this might be so). At 5:00 PM, the lighthouse at Stannard Rock north of Marquette, the closest observing station to the *Fitzgerald* at that moment, records a gust of 66 knots (77 mph). Cooper, on board the *Anderson*, estimated wind gusts of more than 100 mph. Before 6:00 PM, McSorley tells another ship captain via radio the following:

> "I have a bad list, lost both radars. And am taking heavy seas over the deck. One of the worst seas I've ever been in."

Blind and ruptured, the *Fitzgerald* steams into the teeth of raging wind and snow, the *Anderson* 10 miles behind her.

"Nosedive"

> "Sometime before 7 PM . . . we took two of the largest seas of the trip. . . . The second large sea put water on our bridge deck! This is about 35 feet above the waterline!"
>
> —Bernie Cooper, captain of the *Anderson*

At 7:00 PM, 50-knot (58-mph) winds and 4.9-meter (16-foot) waves are still buffeting the *Anderson's* crew. They are in touch with the *Fitzgerald* by radio and by following the *Fitz's* blip on the radar. The *Fitzgerald* has struggled to within 24 kilometers (15 miles) of shore and about 32 kilometers (20 miles) of Whitefish Bay.

But even the bay is not safe harbor. Six Native American commercial fishermen are tending their nets in the western part of Whitefish Bay when, in the words of one of the fishermen, "all of a sudden, the lake began to boil and churn enormously. It was like nothing I'd seen before." Another

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fisherman barely survives his boat's capsizing from "a giant wall of water coming at us." There is little shelter from this storm.

At 7:10 PM, the *Anderson* gives navigation instructions to the radarless *Fitzgerald* up ahead of it. As an afterthought, the *Anderson's* first mate asks, "Oh, and by the way, how are you making out with your problems?" The *Fitzgerald* replies, "We are holding our own." Immediately after this conversation, another severe snow squall enshrouds the two boats. The *Fitzgerald* is hidden from the radar beam of the *Anderson*, lost in a chaos of snow and sea. Just as suddenly, around 7:30 PM, the snow ends. For the first time in many hours, visibility is excellent. Lights from ships coming north from Sault Ste. Marie shine through clearly on the horizon. A TV/radio tower blinks across the water in Ontario. But the *Fitzgerald* is nowhere to be found: no lights, no radar blip, and no radio contact.

Captain Cooper searches for the *Fitzgerald*. Did the *Fitz* duck into a harbor during the snow squall? How can you lose a 222-meter (729-foot) ore freighter in the middle of a lake? Cooper calls the U.S. Coast Guard in Sault Ste. Marie with his worst fears:

> "This is the *Anderson*. I am very concerned with the welfare of the steamer *Edmund Fitzgerald*. . . . I can see no lights as before, and I don't have him on radar. I just hope he didn't take a nosedive."

The *Fitzgerald* is gone, without a mayday, an eyewitness, or a survivor.

DAY 4 (AND BEYOND): DEATH

The Cyclone

The surface weather map for 7:00 AM Eastern time on Tuesday, November 11, 1975 (**FIGURE 10-18a**), betrays little hint of the maelstrom of the past 24 hours. On Monday, cyclone winds blew Lake Michigan waters over a pier drowning two people in Grand Haven, Michigan. That same day the cyclone's southwest winds blew across the entire length of Lake Erie from Toledo, Ohio, to Buffalo, New York, piling up Erie's waters a full 9 feet above normal in Buffalo and killing a Buffalo woman by blowing her off a second-story porch. Showers and thunderstorms spawned by the storm brought rain to every state east of the Mississippi (Figure 10-18c). But on Tuesday, light and variable winds are now firmly in place over the entire Great Lakes.

Bergen School member Sverre Petterssen once said, "Extratropical cyclones are born in a variety of ways, but their appearance at death is remarkably similar." So it is for the storm that helped wreck the *Edmund Fitzgerald*. Figure 10-18a shows an occluded cyclone skirting the eastern shore of Hudson Bay—it is the *Fitzgerald* storm. The surface low is underneath the 500-mb low, and the nearest strong temperature gradients are now hundreds of miles away over the Atlantic. The storm will die a slow death in the coming days as it crosses northern Canada, its fronts dissolving, the face becoming unrecognizable.

Another low, a youngster, is speeding across the Great Plains toward the Great Lakes. Like its predecessor, it has a potent upper-level trough associated with it (Figure 10-18b), but unlike the *Fitzgerald* storm, it has no warm, moist air to feed on; dew points ahead of it hover around the freezing mark. It has also reached the occluded stage early in its lifetime (see also Figure 10-14a). Lacking the energy sources of temperature gradients and moisture, it will not grow into a killer.

Yet in death the *Fitzgerald* storm, like all extratropical cyclones, accomplishes tasks needed to keep weather and climate in balance. For example, on this day at 7:00 AM, Great Whale, Quebec, reports drizzle with a temperature of 2.7° C (37° F), up from –8.8° C (16° F) the previous morning. Meanwhile, cooler and drier air has invaded the Gulf Coast of the United States. This poleward transport of heat and moisture is vital to Earth's overall energy balance. Viewed from this perspective, the cyclone is not a meaningless killer—instead, it is part of Nature's broader design for a stable, habitable world.

The tale of this storm and other similar storms (**BOX 10-4**) should illustrate how useful the Norwegian model of the frontal cyclone is for explaining the wide variety of weather associated with it. Vilhelm Bjerknes summed up the Bergen School's contribution in this way:

> During 50 years meteorologists all over the world looked at weather maps without discovering their most important feature. I only gave the right kind of maps to the right young men, and soon they discovered the wrinkles in the face of the Weather.

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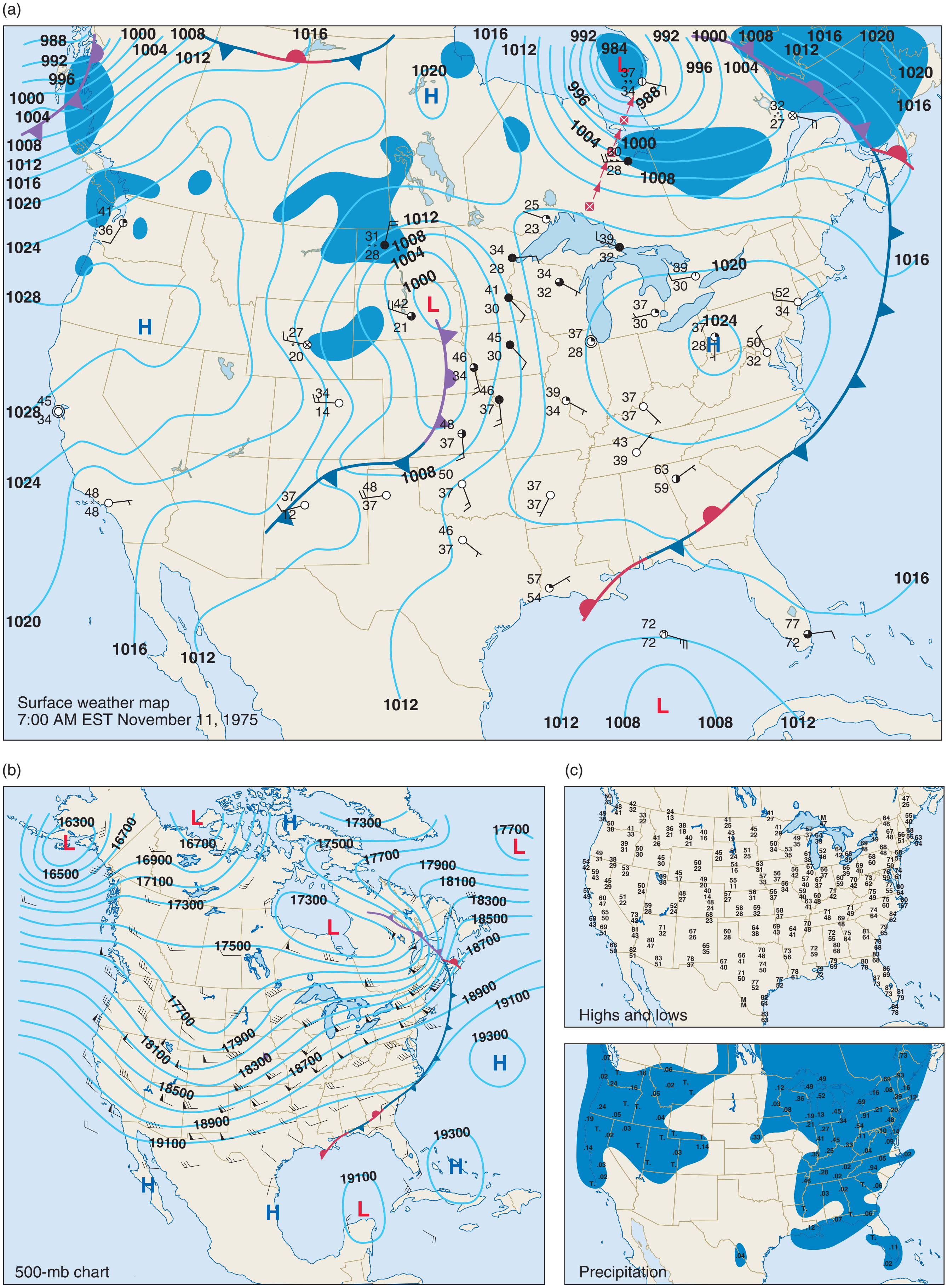

FIGURE 10-18 Surface weather (a) and 500-mb conditions (b) at 7:00 AM (EST) on Tuesday, November 11, 1975. The past day's high and low temperatures are shown in the lower right (c). (Data from NOAA.)

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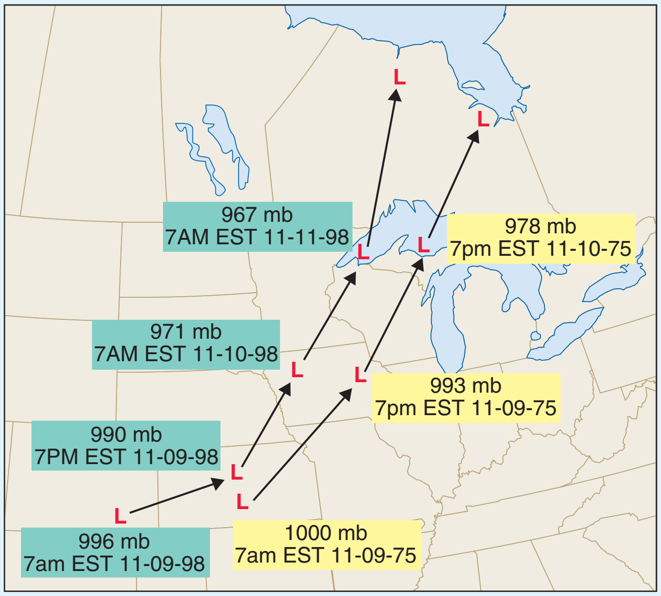
Box 10-4 Weather History Repeats Itself (Almost)

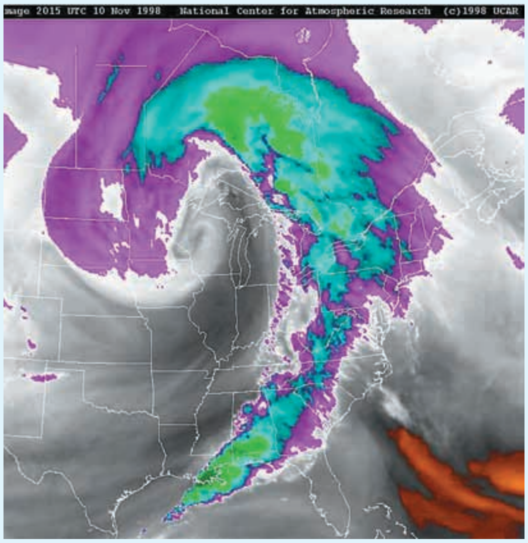
Does history repeat itself? Sometimes it seems to be the case, even in weather history.

Nature provided a near-perfect twin of the *Fitzgerald* cyclone exactly 23 years later, on November 10, 1998. Following a slightly more westerly track than the 1975 storm (see figure below), this 1998 "Witch of November" storm was even more intense, setting low pressure records of 963 to 966 mb in Iowa and Minnesota (see the text's website). Ten deaths, 34 injuries, and at least $40 million in property and crop damage were caused by this storm.

From a scientific perspective, one big difference in the two storms was the advance of remote sensing techniques from 1975 to 1998. In the water vapor image (left) from the 1998 cyclone, the hook-shaped dark region near the center of the cyclone is a spiral arm of the dry slot that has wrapped around the center of the low. Underneath the dry slot, southwesterly winds gusted to 81 knots (93 mph) at La Crosse, Wisconsin, with 8 gusts over 61 knots (70 mph). The dry-slot winds also caused stunning lighthouse-topping waves at South Haven, Michigan, on Lake Michigan (photo on next page).



Paths of the Nov. 1998 (left) and Nov. 1975 (right) extra-tropical cyclones that hit the upper Midwest. (Data from Don Rolfson, National Weather Service Marquette/NOAA.)



Colorized water vapor image of an intense cyclone over western Wisconsin at 3:15 PM Eastern time on November 10, 1998 (the 23rd anniversary of the sinking of the *Edmund Fitzgerald*). The colors indicate the temperature of the clouds (dark green = cold thunderstorm clouds). The dry conveyor belt is denoted by the dark region across Illinois and Michigan and the hook-shaped area over extreme southeastern Minnesota and western Wisconsin. (Copyright, University Corporation for Atmospheric Research, NCAR RAP.)

(continued)

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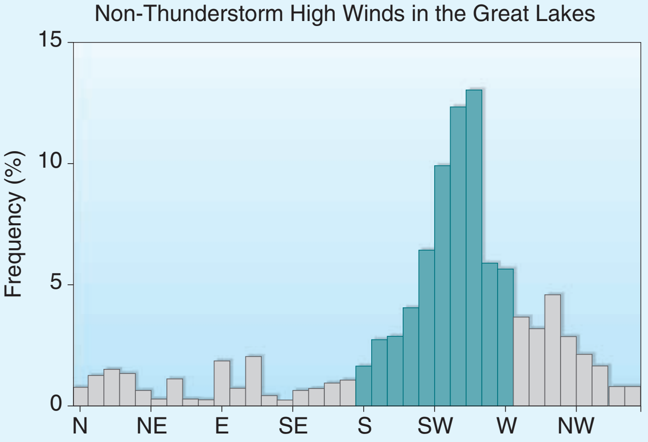
Box 10-4 Weather History Repeats Itself (Almost), continued

(© Kalamazoo Gazette, Taya Kashuba/AP Photos.)

Despite many similarities, however, weather history did not repeat itself on November 10, 1998. No large boats sank on the Great Lakes during the 1998 storm. More generally, weather does not repeat itself, which has big implications for how to forecast the weather.

Nevertheless, by examining many different cases of high winds due to extratropical cyclones, we can learn more about their common characteristics. According to climatological research by University of Georgia students and faculty, these non-thunderstorm winds in the Great Lakes region are almost always from the south-through-west direction (see figure below)—confirming Gordon Lightfoot's "hurricane west wind" description. The predictable direction of the high winds may be due to the orientation of the dry slot. And so while weather history does not quite repeat itself, sometimes it's close enough for scientists to be able to "connect the dots" and advance our understanding.



Distribution of nonconvective high (sustained) wind observations as a function of direction, as observed in the U.S. Great Lakes region during the period 1967–1995. Winds from the south-through-west direction are highlighted in red. (Modified from Lacke et al., *Journal of Climate*, 20 [2007]: 6012–6022. © American Meteorological Society. Reprinted with permission.)

The *Fitzgerald*

Early on the 11th, the crew of the Anderson sights the first debris from the wreck of the *Edmund Fitzgerald*: part of an unused life jacket. Other "flotsam" washes up near shore: more life jackets, a severely damaged lifeboat (FIGURE 10-19), a stool, a plastic spray bottle. The *Fitzgerald* itself is not officially located at the bottom of Lake Superior until the next spring, with the help of underwater camera equipment. The end of the *Fitzgerald* was swift and violent, probably a nosedive straight to the bottom. The freighter was torn into two main pieces as it plummeted, the front half landing right side up, the back half upside down. It lies in 162 meters (530 feet) of water just 27 kilometers (17 miles) from the entrance to Whitefish Bay (FIGURE 10-20).

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Why did the *Fitzgerald* sink? There is no one simple answer. U.S. government investigators blame non–water-tight hatch closures where the iron ore was loaded into the belly of the boat. A dissenting opinion by one of the government's own investigation board members suggests the possibility that the *Fitzgerald* ran aground on the shoals near Caribou Island. Others implicate the unusually high waves that pounded the *Anderson* and others early on the evening of the 10th. Meteorologists are not to blame; the NWS forecasts are deemed "excellent." The storm was anticipated more than a day in advance, even if its exact intensity and path were not forecast precisely. Theories and controversy abound; probably no one factor is solely to blame. Sadly, the wreck of the *Edmund Fitzgerald* has become the maritime equivalent of the assassination of President John F. Kennedy, complete with disbelieved government explanations and endless intrigue among its latter-day investigators.

FIGURE 10-19 One of the *Fitzgerald's* two mangled lifeboats, now on display in the Museum Ship Valley Camp in Sault Ste. Marie, Michigan. (Courtesy of Le Sault de Sainte Marie Historical Sites, Inc.)

What is rarely, if ever, pointed out is that regardless of the proposed cause—leaky hatch covers, shallow shoals, high waves—the *Edmund Fitzgerald* never would have sunk on a calm, sunny day. An overriding reason for this shipwreck is actually quite simple: a powerful extratropical cyclone and a vulnerable boat crossing paths at the worst of all possible times. Over 30 years after the storm, NWS meteorologists proved this point by simulating this storm using high-resolution computer models. The highest winds and waves converged on the location of the *Fitzgerald* in the model simulations at the very hour of the shipwreck.

The Sailors

The bodies of the 29 sailors on board the *Edmund Fitzgerald* (**BOX 10-5**) have never been recovered or buried. Bruce Hudson's grieving parents preserve his room—books, photos, musical instruments—exactly as Bruce left them in November 1975. He never met his daughter, Heather, born 7 months after the *Fitzgerald* was lost.

The next June, singer/songwriter Gordon Lightfoot's haunting and meteorologically accurate account of the shipwreck (**BOX 10-6**) was released, spreading the story of the *Fitzgerald* and its sailors to an international audience.

FIGURE 10-20 *The Wreck Site II*, a painting by David Conklin of the *Edmund Fitzgerald* in its final resting place at the bottom of Lake Superior. (Courtesy Great Lakes Shipwreck Historical Society.)

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Box 10-5 *Fitzgerald* Sailors Lost at Sea

Ernest M. McSorley, 63, Captain, Toledo, Ohio
John H. McCarthy, 62, first mate, Bay Village, Ohio
James A. Pratt, 44, second mate, Lakewood, Ohio
Michael E. Armagost, 37, third mate, Iron River, Wisconsin
George J. Holl, 60, chief engineer, Cabot, Pennsylvania
Edward F. Bindon, 47, first assistant engineer, Fairport Harbor, Ohio
Thomas E. Edwards, 50, second assistant engineer, Oregon, Ohio
Russell G. Haskell, 40, second assistant engineer, Millbury, Ohio
Oliver J. Champeau, 41, third assistant engineer, Milwaukee, Wisconsin
Frederick J. Beetcher, 56, porter, Superior, Wisconsin
Thomas Bentsen, 23, oiler, St. Joseph, Michigan
Thomas D. Borgeson, 41, able-bodied maintenance man, Duluth, Minnesota
Nolan F. Church, 55, porter, Silver Bay, Minnesota
Ransom E. Cundy, 53, watchman, Superior, Wisconsin
Bruce L. Hudson, 22, deckhand, North Olmsted, Ohio
Allen G. Kalmon, 43, second cook, Washburn, Wisconsin
Gordon F. MacLellan, 30, wiper, Clearwater, Florida
Joseph W. Mazes, 59, special maintenance man, Ashland, Wisconsin
Eugene W. O'Brien, 50, wheelsman, Perrysburg Township, Ohio
Karl A. Peckol, 20, watchman, Ashtabula, Ohio
John J. Poviach, 59, wheelsman, Bradenton, Florida
Robert C. Rafferty, 62, temporary steward (first cook), Toledo, Ohio
Paul M. Riippa, 22, deckhand, Ashtabula, Ohio
John D. Simmons, 60, wheelsman, Ashland, Wisconsin
William J. Spengler, 59, watchman, Toledo, Ohio
Mark A. Thomas, 21, deckhand, Richmond Heights, Ohio
Ralph G. Walton, 58, oiler, Fremont, Ohio
David E. Weiss, 22, cadet (deck), Agoura, California
Blaine H. Wilhelm, 52, oiler, Moquah, Wisconsin

There will always be another extratropical cyclone. The Sun and the tilt of the Earth see to this by the endless re-creation of temperature gradients, and as long as there is cargo to be hauled, there will be Great Lakes freighters. But, people are unique and irreplaceable, and their loss is felt forever. Honor the memory of the *Fitzgerald* and her crew[2] by never losing your life to the many weapons—wind, rain, snow, and wave—of an extratropical cyclone.

THE EXTRATROPICAL ANTICYCLONE

Did you notice the large weather system that moved in immediately behind the *Fitzgerald* cyclone? It was an **anticyclone**, or high-pressure system. To complete our understanding of large-scale extratropical weather, we need to learn how to recognize the seemingly boring "face" of the anticyclone.

The anticyclone is the natural complement to the cyclone, the yang to the cyclone's yin:

- Lows form and grow near fronts, the boundaries of air masses where contrasts of temperature and moisture are strongest. Highs are air masses, with temperature and moisture varying little across hundreds of miles.
- Lows are usually cloudy, wet, and stormy. Highs are often clear, relatively dry, and calm.

[2]To honor the *Fitzgerald's* crew and thank their families for the use of the story of their loved ones, a portion of the proceeds from this textbook project has been donated to the Great Lakes Mariners Memorial Project of the Great Lakes Shipwreck Historical Society, located at Whitefish Point, Michigan.

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Box 10-6 Gordon Lightfoot, Songwriter—and Amateur Meteorologist

Gordon Lightfoot is a Canadian songwriter whose many hits in the 1960s and 1970s are part of the rich musical legacy of that era. He is also a Great Lakes sailor. Shortly after the *Edmund Fitzgerald* shipwreck, Lightfoot spent two months researching the story behind the disaster. In three days he wrote the eight verses and 430 words, plus music, of his song "The Wreck of the *Edmund Fitzgerald*." The song became one of the top hits of 1976 in North America and has never left the airwaves; it is part of our culture and history. Author Joseph MacInnis writes, "as the years passed, the song and the shipwreck and the men and the lake became one."

Lightfoot's song tells many stories, not the least of which is the meteorology behind the *Fitzgerald* shipwreck. Below are the lyrics to the first five verses of "The Wreck of the *Edmund Fitzgerald*." At the sides are commentaries on the factual accuracy of the lyrics, especially with regard to the weather. May you become as good an amateur meteorologist as Gordon Lightfoot!

The Wreck of the Edmund Fitzgerald
Words and music by Gordon Lightfoot
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The first European shipwreck on the Great Lakes occurred in 1680.

The legend lives on from the Chippewa on down
of the big lake they call Gitche Gumee.
The lake, it is said, never gives up her dead
when the skies of November turn gloomy.

235 sailors died and 10 boats sank in a November 9, 1913 cyclone on the Lakes.

Were the gales early? Several famous Great Lakes storms hit on Nov. 9-10.

With a load of iron ore twenty-six thousand tons
more than the *Edmund Fitzgerald* weighed empty,
The good ship and true was a bone to be chewed
when the "Gales of November" came early

The boat was named for the president of Northwestern Mutual Life Insurance Company, whose grandfather and all five of his grandfather's brothers were Great Lakes captains.

The Fitz was the flagship of the shipping division of Oglebay Norton Company, headquartered in Cleveland.

The ship was the pride of the American side
coming back from some mill in Wisconsin.
As the big freighters go it was bigger than most
with a crew and good captain well seasoned,

Concluding some terms with a couple of steel firms
when they left fully loaded for Cleveland
And later that night when the ship's bell rang,
could it be the north wind they'd been feelin'?

Its destination is actually Detroit. Oglebay Norton's location caused the confusion.

Correct: Fitz reports 60 mph NNE winds at 1 AM EST with 10-foot seas; individual waves higher, enough to break over the railing.

The wind in the wire made a tattletale sound
and a wave broke over the railing.
And every man knew as the captain did too
'twas the witch of November come stealin'.

Correct on two counts: cyclone clouds obscure the sunrise; Fitz records a gale at 7 am EST.

The dawn came late and the breakfast had to wait
when the gale of November came slashin'.
When afternoon came it was freezing rain
in the face of a hurricane west wind.

No proof of freezing rain, but not inconsistent with observations: air temperatures drop to near freezing in the afternoon with lake-effect squalls.

Correct: Strongest winds are westerly, behind the cyclone. Even experts miss this key meteorological fact.

When supper-time came the old cook came on
deck sayin' "Fellas, it's too rough t' feed ya"
At seven p.m., it was dark, it was then he said,
"Fellas, it's bin good t'know ya!"

Theories of the wreck vary. Lightfoot has changed this stanza over time in light of new research.

Captain's reports were from the mid-afternoon.

The captain wired in he had water comin' in
and the good ship and crew was in peril.
And later that night when 'is lights went out of sight
came the wreck of the *Edmund Fitzgerald* . . .

Correct: Fitz vanishes in zero-visibility snow squalls at night.

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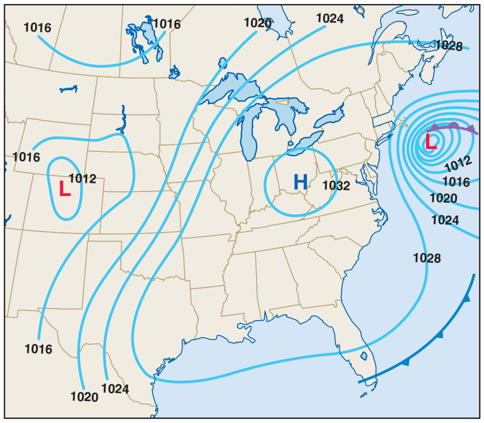

FIGURE 10-21 Surface weather map for 7:00 PM Eastern Standard Time on February 20, 1979. Notice the stark difference in appearance of anticyclones versus cyclones. The bull's-eye–like low off the U.S. East Coast has fronts and a tight pressure gradient near its center. The blobby high over Ohio covers the entire eastern half of the United States, yet pressures over this vast region differ by only 4 millibars. (Read Box 10-3.) (Adapted from Kocin, P. and Uccellini, L., *Snowstorms Along the Northeastern Coast of the United States: 1955 to 1985*. American Meteorological Society, 1990.)

- The pressure pattern of a low looks like a bull's-eye on a weather map, with tightly packed, concentric isobars. A high looks like a large blob with weak pressure gradients near its center (**FIGURE 10-21**).
- Lows live for a few tumultuous days. Highs can loiter, sometimes for several languorous weeks in summer.

We can explain these features of an anticyclone the same way we did for the cyclone. For example, air in a high diverges at the surface. Diverging air weakens temperature and humidity gradients by spreading out the lines of constant temperature and moisture. Weak gradients mean no fronts in a high; fronts exist instead at the periphery of highs.

Diverging air at the surface in a high requires air to sink toward the surface from above. Sinking air warms adiabatically and dries out in a relative sense. A temperature inversion forms above the ground as a result of the compressional warming of this sinking air. This makes highs stable and often cloudless.

Lows can develop strong pressure gradients near their centers because the pressure gradient force in a low can be counterbalanced by both the Coriolis and centrifugal forces. In a high, the pressure gradient force teams up with the centrifugal force, and the Coriolis force must counterbalance both of them. The stronger the pressure gradient, the harder it is for the Coriolis force to do this. The end result is that nature prefers highs with weak pressure gradients, which implies a spreading out of isobars over large distances. Therefore, highs are large and blobby compared with lows; by the geostrophic wind approximation, this makes the winds almost calm near a high's center.

Highs, being air masses, form where air can sit around for a period of time before being steered elsewhere by jet-stream winds. **FIGURE 10-22** shows these regions of **anticyclogenesis**. Many wintertime highs in the United States originate in northern Canada—they are continental polar (cP) air masses. Cold air outbreaks occur when strong anticyclogenesis over Canada is combined with jet-stream winds from the northwest that guide the high into the U.S. If a strong, cold high surrounds even a typical low in wintertime, the resulting tight pressure gradient and high winds can lead to blizzards (**BOX 10-7**).

Summertime highs deserve special attention. They share something in common with wintertime lows—both can become cut off from the main jet-stream winds and the surface

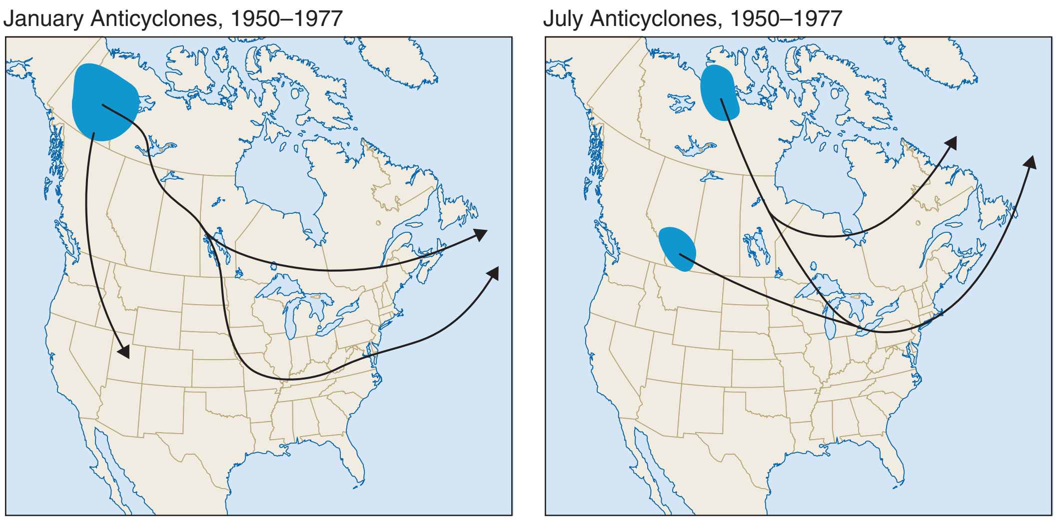

FIGURE 10-22 Typical regions of anticyclogenesis (shaded) and anticyclone paths (arrows) that affect North America in the months of January and July. Compare this figure with the corresponding data for cyclones in Figure 10-7. (Adapted from Zishka, K. M., and P. J. Smith, *Monthly Weather Review*, April 1980: 394–395.)

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Box 10-7 The Groundhog Day Blizzard of 2011

In early February 2011, the central and eastern United States experienced one of the epic blizzards of the past several decades. Dubbed the "Groundhog Day Blizzard," it was caused by a fairly average (996 mb) but sopping-wet extra-tropical cyclone moving northeast from Texas. However, this low was surrounded by an intense (up to 1054 mb) and bitter-cold anticyclone to its north and west. The resulting very tight pressure gradient caused high winds gusting over 60 knots (69 mph) across parts of the upper Midwest.

The exceptional amount of Gulf of Mexico moisture in the system rode up and over the cold air, leading to heavy snow accompanied at times by thunder and lightning. Record or near-record snow amounts occurred from Tulsa, Oklahoma (35.5 cm, or 14″, its biggest snowstorm ever) to the Chicago-Milwaukee area (for example, 51.3 cm or 20.2″ at Chicago's O'Hare International Airport, the third-largest snowstorm there).

(© Kiichiro Sato/AP Photos.)

The snow, combined with the high winds, created blizzard conditions with near-zero visibility and snow drifts up to 1.5 meters (5 feet). Interstates, airports, and businesses were shut down from New Mexico and Texas to the Northeast, and the blizzard turned Chicago's famed Lake Shore Drive into a parking lot of abandoned cars (see photo).

Computer forecast models anticipated this major snowstorm about a week in advance. Meteorologists knew 3 to 4 days ahead of time that there would be a wide swath of heavy snow, ice, and wind across the southern Plains extending to the Great Lakes region and even into New England. Nevertheless, at least 20 people died in the Groundhog Day Blizzard, and damages were estimated initially in the billions of dollars. However, the storm had an impact on over 100 million Americans in over 30 states; in this context, the losses were far less than they would have been without the ample warning provided by meteorologists. No groundhog could have foreseen this monster storm!

temperature gradients beneath the jet. Because an extratropical cyclone thrives on temperature contrasts, a cut-off cyclone weakens and dies. A summer anticyclone, however, which is an air mass without significant horizontal temperature gradients, can thrive and intensify in this situation. A cut-off high is a form of "blocking." A blocking high over land in summer can trap and recirculate hot air around and around its center for weeks. This may lead to a heat wave, a drought, or an episode of air pollution.

We've recognized and explained the identifying features of the anticyclone. Underneath its calm exterior, however, lurks a potential killer. Did you sense any danger? Neither did the residents of western Europe in the summer 2003. Now we turn to their story.

HIGH PRESSURE, HIGH HEAT: THE DEADLY EUROPEAN HEAT WAVE OF 2003

It began innocuously enough, as a high-pressure system settled over western Europe in June. Residents of London and Paris noticed the heat, which was at first a welcome respite from the cooler temperatures of a European spring. But then the heat became oppressive; England and

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Wales experienced their hottest June since 1976. The peak of summer had not yet arrived, however, so even record heat for June was not necessarily deadly heat.

Then, in July, the heat abated a little near London as the focus of the high pressure and heat shifted southeast toward Italy and the Mediterranean. In Switzerland, ice melting on the Matterhorn in the sweltering heat led to rockslides, requiring rescues of dozens of trapped mountain climbers. In Croatia and Serbia, the dry heat drained rivers to their lowest levels in a century or more. So much French wheat wilted in the hot sun that flour prices in Britain rose dramatically. A crisis was in the making.

Then on August 3rd, the high pressure and high heat returned with a vengeance to western Europe. An intense blocking high formed above the English Channel (**FIGURE 10-23**), baking much of western Europe in temperatures as much as 10° C (18° F) warmer than typical clear-sky late-summer conditions (**FIGURE 10-24**). Daytime temperatures exceeded 38° C (100° F) for the first time on record in the United Kingdom. In parts of France, Belgium, and Switzerland, temperatures also reached historic peaks. Nighttime temperatures remained unusually warm, preventing people and animals from cooling down adequately overnight before the next day's heat. Pollution trapped in the stagnant high made it difficult for residents with asthma or other respiratory conditions to breathe. Forest fires raged in Spain and Portugal, causing $1 billion in damage and adding still more smoke and pollution to the toxic air.

A cold front finally ended the heat wave on August 17th, but by then the damage had already been done. When it was over, the summer of 2003 ranked as by far the hottest in at least a century across much of Europe (**FIGURE 10-25**), causing over $12 billion in crop losses. Statistically speaking, the summer's heat was as far off the chart as the IQ of an Einstein or da Vinci.

The death toll slowly mounted across Europe; heat waves, unlike tornadoes and hurricanes, are silent killers. Ultimately, researchers determined that over 70,000 Europeans had died because of the heat—an astonishing death toll even compared to that of the deadliest hurricanes. In towns and cities all across western Europe, the elderly and those with heart and lung conditions died in large numbers during the peak of the heat wave during August (**FIGURE 10-26**).

The 2003 European heat wave was the deadliest weather-related disaster of the first decade of the 2000s, probably 30 to 40 times deadlier than Hurricane Katrina, and all because of a very persistent high-pressure area.

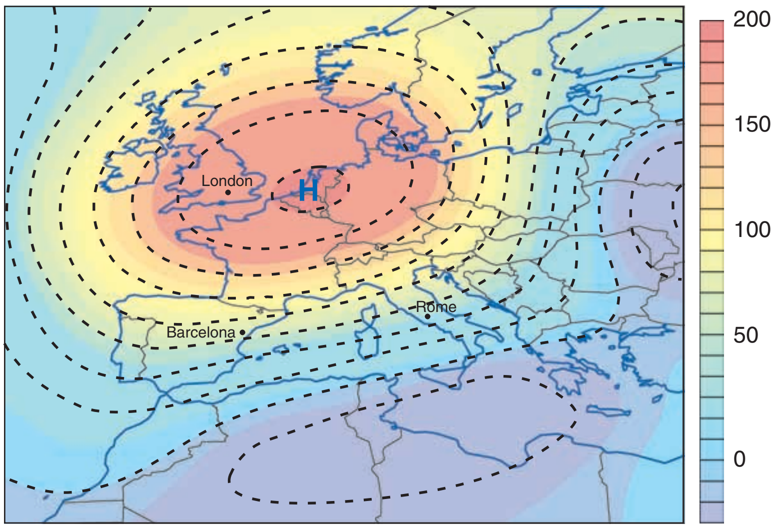

FIGURE 10-23 Anomalies in 500-mb geopotential height over western Europe during August 1 to 13, 2003, versus an average August. Red regions over Great Britain and France indicate much higher than normal heights, where high pressure was concentrated. (From G. A. Meehl et al., *Science* 305, 994–997 [2004]. Reprinted with permission from AAAS.)

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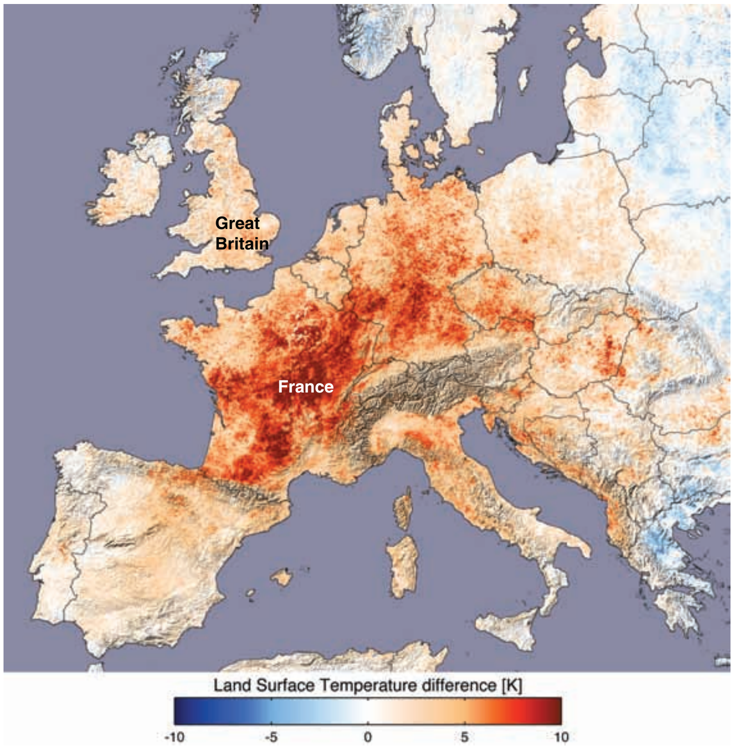

FIGURE 10-24 High-resolution (1 km) MODIS satellite image of western European land surface temperature differences during July 20 to August 20, 2003, versus clear-sky conditions in July and August of 2001, 2002, and 2004. The dark red regions over France were 10° C (18° F) warmer than in comparable clear-sky conditions in other years. (Image by Reto Stöckli, Robert Simmon and David Herring, NASA Earth Observatory, based on data from the MODIS land team.)

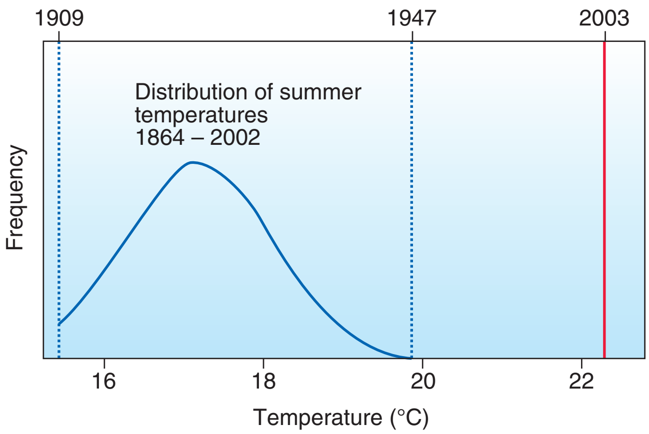

FIGURE 10-25 Average summer temperatures in Switzerland for the years 1864 to 2003. Each vertical line represents the average temperature of one summer. The summer of 2003 was more than 2° C warmer than any previous summer. (Adapted from C. Schär et al., *Nature* 427, 332–336.)

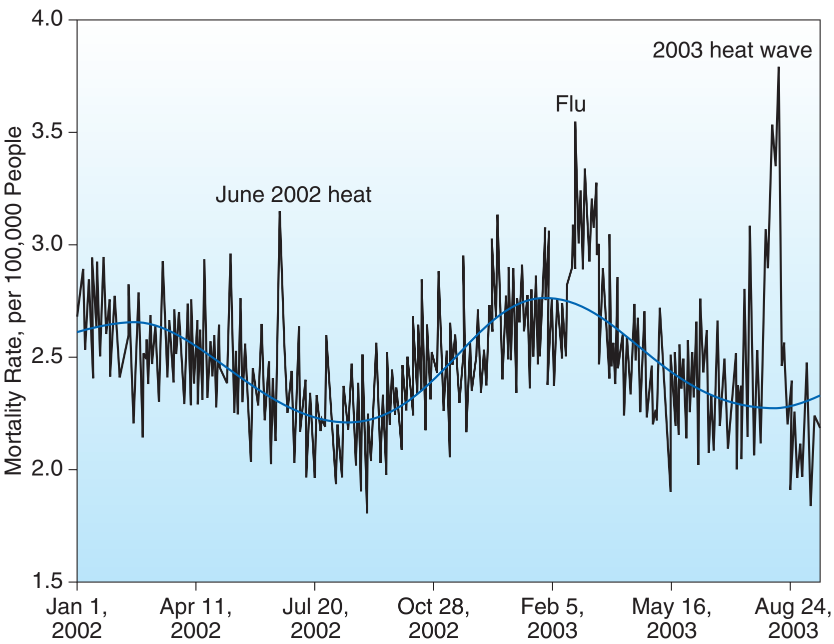

FIGURE 10-26 Daily mortality rate in the state of Baden-Württemberg, Germany, from January 2002 through August 2003. Notice the huge spike in deaths in August 2003, associated with the deadly European heat wave. (Lesser spikes in June 2002 and February 2003 were due to a heat wave and a flu outbreak, respectively. On average, mortality is greater in winter.) The August 2003 heat wave caused about 1,000 more deaths than usual in Baden-Württemberg, which with a population of 10.7 million is slightly larger than the Chicago metropolitan area. (Adapted from Koppe, C. and Jendritzky, G. *Gesundheitliche Auswirkungen der Hitzewelle*. Socialministerium Baden-Wurttemberg, Stüttgart, 2004.)

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PUTTING IT ALL TOGETHER

Summary

Extratropical cyclones are low-pressure systems that cause wet and often windy weather, but they are very different than tropical cyclones. Norwegian meteorologists discovered that extratropical cyclones are associated with fronts and that they have a definite life cycle, growing from birth as a frontal wave to maturity as an occluded cyclone to death as a cut-off cyclone over the course of several days.

Extratropical cyclones are born on the downwind side of tall mountain ranges, near warm ocean currents, and beneath strong jet-stream winds. Further growth of these storms may occur if the upper-tropospheric air is diverging above the cyclone. The age and strength of extratropical cyclones can be estimated by looking at satellite pictures and weather maps. Strong cyclones often have comma-cloud shapes with dry slots and well-defined cold and warm fronts; the presence of an occluded front indicates a mature, but soon-dying, cyclone.

We learned these facts in the context of the storm that helped wreck the *Edmund Fitzgerald* on Lake Superior in 1975. This storm demonstrates that the Norwegian Cyclone Model, although simplified, can help explain most of the characteristics of a real-life, deadly extratropical cyclone. The Shapiro-Keyser Cyclone Model is more appropriate for extratropical cyclones that occur in confluent jet-stream flow over oceans.

The extratropical anticyclone is in many ways the complement to the cyclone. An extratropical cyclone lives at the clashes of different air masses. In contrast, an anticyclone is one big, often slow, fairly calm, and stable air mass. Even so, a high can become deadly, for example during the European heat wave in summer 2003 that killed over 70,000 residents.

Key Terms

You should understand all of the following terms. Use the glossary and this chapter to improve your understanding of these terms.

Alberta Clippers
Anticyclogenesis
Anticyclone
Baroclinic instability
Comma cloud
Cut-off cyclone
Cyclogenesis
Diffluence
Dry slot
Frontal wave
Nor'easters
Norwegian Cyclone Model
Occluded cyclone
Occlusion
Open wave
Panhandle Hooks
Pineapple Express
Speed divergence
Warm sector

Review Questions

1. What are the four stages in an extratropical cyclone's life cycle, according to the Bergen School conceptual model used in this chapter? During which stage(s) would you expect to see an occluded front? Strong warm and cold fronts? A cut-off low? Make a sketch of the low and the fronts at each stage of the life cycle.
2. Why do the birthplaces of cyclones vary in location throughout the year? Would this be true if the Earth was not tilted on its axis?
3. Can a cyclone develop out of a clear blue sky? If so, how?
4. Intense cyclones are more common east of the Appalachian Mountains than east of the much higher Rocky Mountains. Why (see Boxes 10-1 and 10-3)?
5. Which one of the cyclone types discussed in this chapter is not named for the region in which it is "born"? It didn't get its name from the region it affects either. So how did it get its name? (Hint: Think about how wind flows around a cyclone.)
6. In Figure 10-9, you can see that Madison, Wisconsin's, temperature rose but its dew point fell on the day after the cold front passed. Using air mass and radiation concepts from this textbook, explain why this happened.

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7. Using the real-life cross-sections in Figure 10-10 as a guide, explain how temperature, dew point, pressure, cloud altitude and type, and wind direction change as a warm front approaches and passes a location. Do the same for the cold front. Compare your result to idealized models of warm and cold fronts.
8. It is 8:00 AM on Monday, your first day of work at the National Weather Service office in Chicago, Illinois. You notice a developing low-pressure system centered over Wichita, Kansas, about 1,000 kilometers (600 miles) to the southwest. The winds at 500 mb above the cyclone are blowing toward the northeast at 100 kilometers per hour (60 mph). If the storm maintains its current intensity, when do you forecast that the center of the cyclone will pass near the Chicago area? If the cyclone and the upper-level trough strengthen, do you think the low will pass to the north or the south of Chicago?
9. What are two causes of upper-level divergence? Why does upper-level divergence help intensify a cyclone?
10. According to Box 10-3, was the *Fitzgerald* cyclone a "bomb"? What key fuel source did this cyclone have in limited supply compared to a cyclone just east of Cape Hatteras, North Carolina?
11. Name five different ways that weather associated with an extratropical cyclone can injure or kill people.
12. Assume that you have the power to remove extratropical cyclones from the Earth's weather. How might this affect the wintertime weather in eastern Canada? Could this cause a long-term trend in temperatures in the tropics?
13. Why is it that wintertime Canadian high-pressure systems are colder when they are in Canada than when they reach the Gulf of Mexico several days later?
14. Based on the wind circulation around a high, describe the changes in temperature, dew point, and wind direction as an anticyclone moves across the central United States from west to east.

Observation Activities

1. Keep track of the development and movements of fronts across the continents. Make a cross-section through a front (see Figure 10-10 for an example) and discuss how these observations match and don't match our simple conceptual model of frontal weather.
2. Memorable weather events can shape the lives of communities, and people recall these events via stories and song. What weather stories do people in your town tell? Why do you think these stories endure? Can you explain the cause of this weather to your neighbors?

This rain cloud icon is your clue to go to the *Meteorology* website at http://physicalscience.jbpub.com/ackerman/meteorology/4e. Through animations, quizzes, Web exercises, and more, you can explore in further detail many fascinating topics in meteorology.