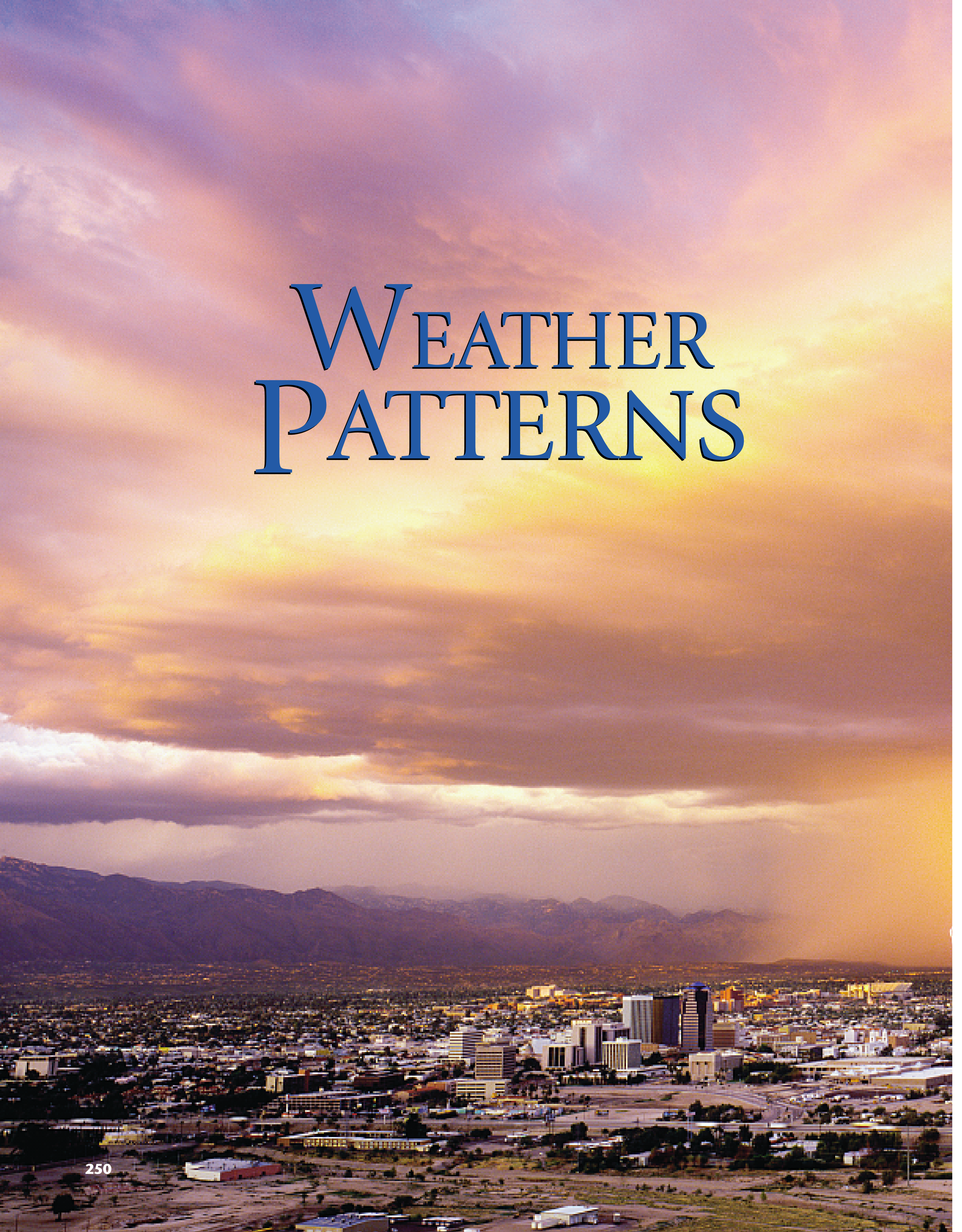


WEATHER PATTERNS

CHAPTER 9

Storm clouds over Tucson, Arizona.
(Photo by A. T. Willett/Alamy)

The winter of 1992–1993 came to a stormy conclusion in eastern North America during a weekend in mid-March. The daffodils were already out across the South, and people were thinking about spring when the Blizzard of '93 struck on March 13 and 14. The huge storm brought record-low temperatures, record-low barometric-pressure readings, and record-high snowfalls to an area that stretched from Alabama to the Maritime Provinces of eastern Canada (Table 9–1). The monster storm, with its driving winds and heavy snow, combined the attributes of both hurricane and blizzard as it moved up the spine of the Appalachians, lashing and burying a huge swatch of territory (Figure 9–1). Although the atmospheric pressure at the storm's center was lower than the pressures at the centers of some hurricanes and the winds were frequently as strong as those in a hurricane, this was definitely not a tropical storm but a classic winter cyclone (Figure 9–2).

The event quickly earned the title Storm of the Century. The name was well deserved. Although many notable storms occurred during the twentieth century, none could match the extreme dimensions of this event. A famous nineteenth-century storm known as the Blizzard of '88 was equally severe but affected a much smaller area.

TABLE 9-1 A look at the Storm of the Century

Snowfall totals

City	(CM)	(IN.)
Mount LeConte, Tenn.	140	56
Mount Mitchell, N.C.	125	50
Syracuse, N.Y.	108	43
Lincoln, N.H.	88	35
Mountain City, Ga.	60	24
Chattanooga, Tenn.	50	20
Asheville, N.C.	48	19

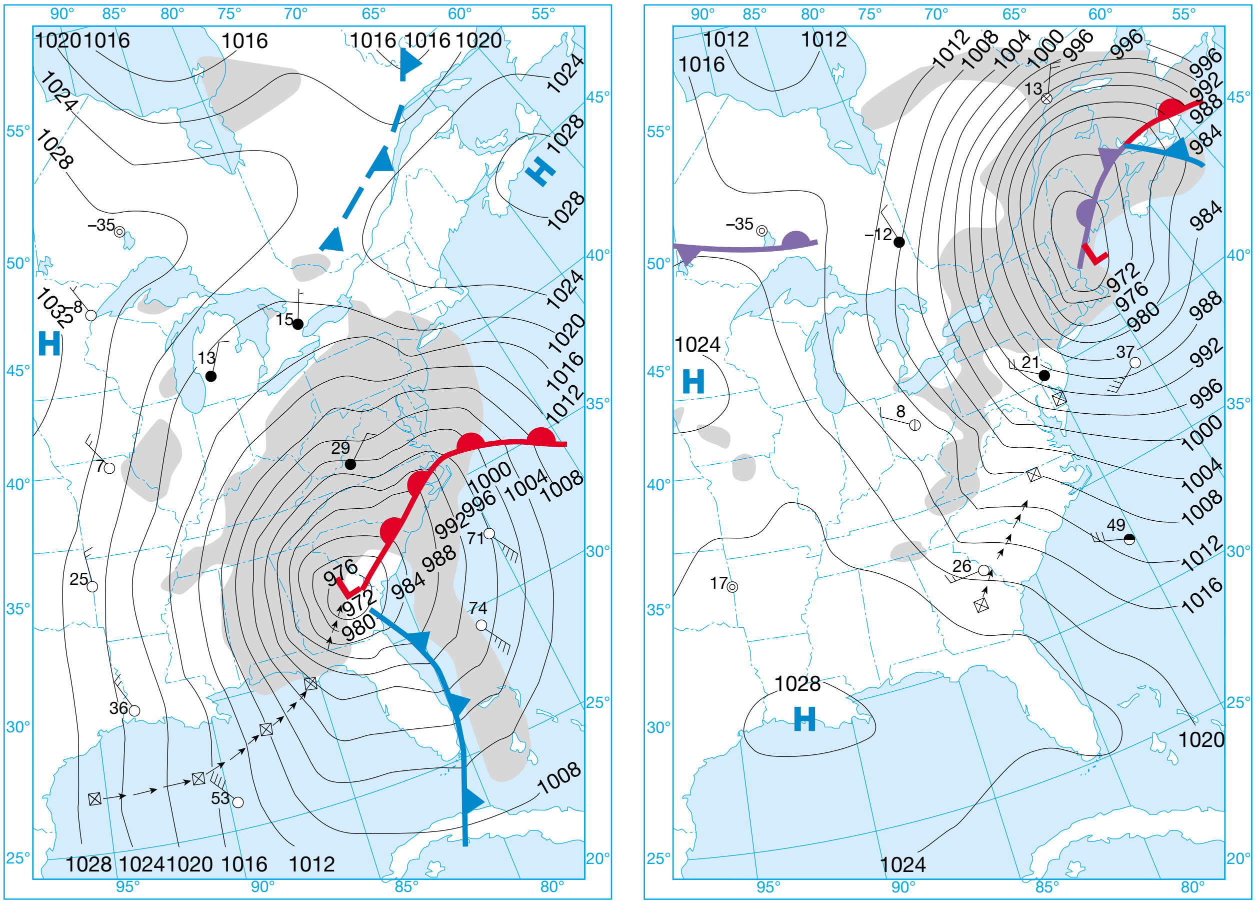
Record-low temperatures in the south

City	(°C)	(°F)
Mount LeConte, Tenn.	−23	−10
Waynesville, N.C.	−20	−4
Birmingham, Ala.	−17	2
Knoxville, Tenn.	−14	6
Atlanta, Ga.	−8	18
Daytona Beach, Fla.	−0.6	31

Strong wind gusts

City	(KPH)	(MPH)
Mount Washington, N.H.	232	144
Flattop Mountain, N.C.	163	101
South Marsh Island, La.	148	92
Myrtle Beach, S.C.	145	90
Fire Island, N.Y.	143	89
Boston, Mass.	130	81

FIGURE 9-1 One of the heaviest snowstorms to hit New York City since the Blizzard of '93, occurred on February 17, 2003. *(Photo by Benjamin Lowy/CORBIS)*



(a) Saturday, March 13, 1993

(b) Sunday, March 14, 1993

FIGURE 9-2 These simplified weather maps show the positions of an enormous cyclonic storm on March 13 and 14, 1993. After the storm formed in the Gulf of Mexico, it moved northeastward, spawning tornadoes in Florida and dumping huge quantities of snow from Alabama to Canada's Maritime Provinces. The closely spaced isobars depict the steep pressure gradient that generated hurricane-force winds in many places. The strong winds caused extreme drifting of snow and created storm waves in the Atlantic that pounded the coast, causing much beach erosion and damage to shoreline homes. The shaded areas indicate regions where precipitation occurred.

Despite excellent forecasts that permitted timely warnings, at least 270 people died as a result of the storm, more than three times the combined death tolls of hurricanes Hugo and Andrew. In Florida severe weather that included 27 tornadoes killed 44 people. At one time or another, every major airport on the U.S. East Coast was closed, as were most highways. Hundreds of hikers were stranded in the mountains by the record snowfalls, and thousands of others were stranded away from home in a variety of settings. At one point, 3 million people were without electricity. As the blizzard buried the region, hundreds of roofs collapsed under the wet, heavy snow. The National Weather Service office in Asheville, North Carolina, reported an extraordinary snow-to-water ratio of 4.2 to 1. A general ratio of 10 units of snow to 1 unit of water is common. Meanwhile, storm-generated waves pounded the coast. About 200 homes along the Outer Banks of North Carolina were damaged, with many left uninhabitable, and on Long Island 18 houses succumbed to the surf.

In the aftermath of the storm, temperatures plunged to record low levels as a frigid continental arctic air mass spilled into the region. On Sunday, March 14, some 70 cities in the East and South experienced record low temperatures. The next day 75 more record-low daily minimums were established. Freezing temperatures that reached as far south as Orlando, Florida, and Birmingham, Alabama, set a new March record of −17°C (2°F). The Storm of the Century was truly an awesome event that inhabitants of eastern North America will not soon forget.

Polar-Front Theory (Norwegian Cyclone Model)

In previous chapters we examined the basic elements of weather as well as the dynamics of atmospheric motions. We are now ready to apply our knowledge of these diverse phenomena to an understanding of day-to-day weather patterns in the middle latitudes. For our purposes, *middle latitudes* refers to the region between southern Florida and Alaska, essentially the area of the westerlies. The primary weather producer here is the **mid-latitude** or **middle-latitude cyclone**[*]. These are the same phenomena that a TV weather reporter calls a *low-pressure system* or simply a *low*.

Mid-latitude cyclones are low-pressure systems with diameters often exceeding 1000 kilometers (600 miles) that travel from west to east across the planet (Figure 9–3). Lasting from a few days to more than a week, these weather systems have a counterclockwise circulation pattern with a flow inward toward their centers. Most mid-latitude cyclones have a cold front and a warm front extending from the central area of low pressure. Surface convergence and upward flow initiate cloud development that frequently produces precipitation.

As early as the 1800s, it was known that cyclones were the bearers of precipitation and severe weather. Thus, the barometer was established as the main tool in "forecasting" day-to-day weather changes. However, this early method of weather prediction largely ignored the role of air-mass interactions in the formation of these weather systems. Consequently, it was not possible to determine the conditions under which cyclone development was favorable.

The first encompassing model to consider the development and intensification of a mid-latitude cyclone was constructed by a group of Norwegian scientists during World War I. The Norwegians were then cut off from weather reports, especially those from the Atlantic. To counter this deficiency, a closely spaced network of weather stations was established throughout the country. Using this network, several Norwegian-trained meteorologists made great advances in broadening our understanding of the weather and in particular our understanding of the middle-latitude cyclone. Included in this group were Vilhelm Bjerknes (pronounced *Bee-YURK-ness*), his son Jacob Bjerknes, Jacob's fellow student Halvor Solberg, and Swedish meteorologist Tor Bergeron (see Box 5–3). In 1921 the work of these scientists resulted in a publication outlining a compelling model of how mid-latitude cyclones progress through stages of birth, growth, and decay. These insights, which marked a turning point in atmospheric science, became known as the **polar-front theory**—also referred to as the **Norwegian cyclone model.** Even without the benefit of upper-air charts, these skilled meteorologists presented a working model that remains remarkably accurate to this day.

In the Norwegian cyclone model, middle-latitude cyclones develop in conjunction with the polar front. Recall that the polar front separates cold polar air from warm subtropical air (Chapter 7). During cool months the polar front is generally well defined and forms a nearly continuous band around Earth that can be recognized on upper-air charts. At the surface, this frontal zone is often broken into distinct segments. These frontal segments are separated by regions of more gradual temperature change. It is along frontal zones where cold, equatorward-moving air collides with warm, poleward-moving air that most middle-latitude cyclones form.

Students Sometimes Ask…

What is an extratropical cyclone?

Extratropical means "outside the tropics," so this is just another name for a mid-latitude cyclone. The term cyclone refers to the circulation around any low-pressure center, regardless of its size or intensity. Hence, hurricanes and mid-latitude cyclones are two types of cyclones. Whereas "extratropical cyclone" is another name for a mid-latitude cyclone, the name "tropical cyclone" is often used to describe a hurricane.

Because mid-latitude cyclones develop in conjunction with fronts, we will first consider the nature of fronts and the weather associated with their movement and then apply what we learn to the model of cyclone development (Figure 9–3).

Fronts

Basic Weather Patterns

▶ Fronts

Fronts are boundary surfaces that separate air masses of different densities. One air mass is usually warmer and often contains more moisture than the other. However, fronts can form between any two contrasting air masses. When the vast sizes of air masses are considered, these 15- to 200-kilometer- (9- to 120-mile-) wide bands of discontinuity are relatively narrow. On the scale of a weather map, they are normally thin enough to represent as a broad line.

Above the ground the frontal surface slopes at a low angle so that warmer air overlies cooler air, as shown in Figure 9–4. In the ideal case the air masses on both sides of the front would move in the same direction and at the same speed. Under this condition the front would act simply as a barrier that travels along with the air masses. Generally, however, the distribution of pressure across a front is such that one air mass moves faster relative to the frontal boundary than does the other. Thus, one air mass actively advances into another and "clashes" with it. The Norwegian meteorologists visualized these zones of airmass interactions as analogous to battle lines and tagged them "fronts," like battlefronts. It is along these zones of conflict that mid-latitude cyclones develop and produce much of the precipitation and severe weather in the belt of the westerlies.

As one air mass moves into another, limited mixing occurs along the frontal surface, but for the most part, the air masses retain their identity as one is displaced upward over the other. No matter which air mass is advancing, it is always the

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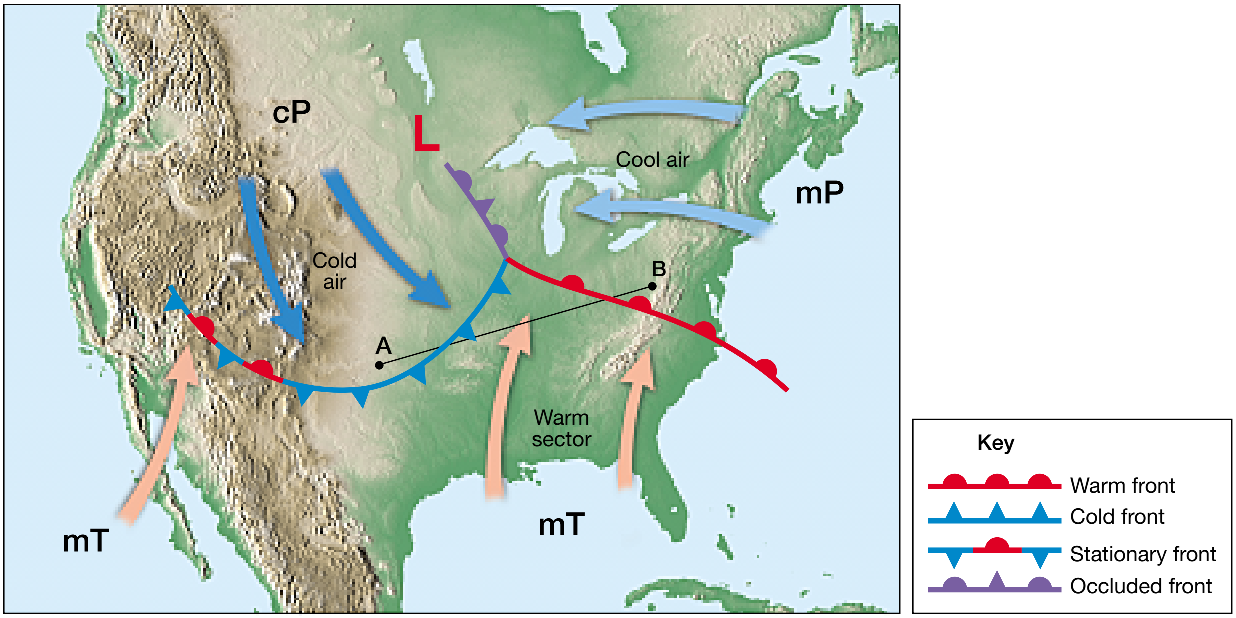
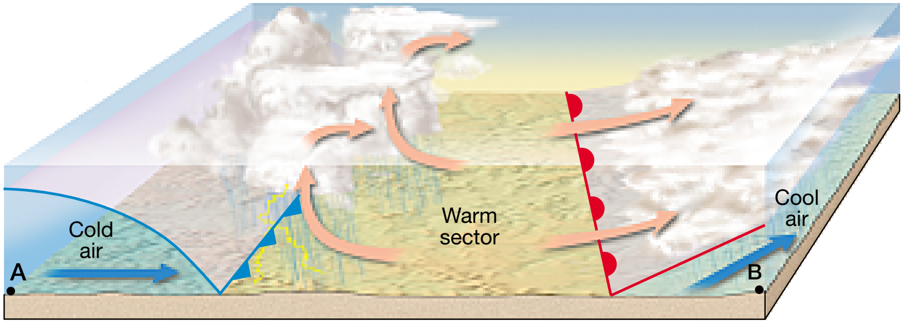
[*] Mid-latitude cyclones go by a number of different names, including wave cyclones, frontal cyclones, extratropical cyclones, low-pressure systems, and, simply, lows.



(a) Map view.



(b) Three-dimentional view from points A to B.

FIGURE 9-3 Idealized structure of a mid-latitude cyclone. (a) Map view showing fronts, air masses, and surface flow. (b) Three-dimensional view of the warm and cold fronts along a line from point A to point B.

warmer, less dense air that is forced aloft, whereas the cooler, denser air acts as a wedge on which lifting takes place. The term **overrunning** is generally applied to warm air gliding up along a cold air mass. We now shall look at five types of fronts—*warm, cold, stationary, occluded*, and *drylines*.

Warm Fronts

When the surface (ground) position of a front moves so that warm air occupies territory formerly covered by cooler air, it is called a **warm front** (Figure 9–4). On a weather map, the surface position of a warm front is shown by a red line with red semicircles protruding into the cooler air. East of the Rockies, maritime tropical (mT) air often enters the United States from the Gulf of Mexico and overruns receding cool air. As the colder air retreats, friction with the ground greatly slows the advance of the surface position of the front compared to its position aloft. Stated another way, less dense, warm air has a hard time displacing heavier, cold air. Consequently, the boundary separating these air masses acquires a very gradual slope. The slope of a warm front (height compared to horizontal distance) averages only about 1:200. This means that if you traveled 200 kilometers (120 miles) ahead of the surface location of a warm front, the frontal surface would be only 1 kilometer (0.6 miles) overhead.

As warm air ascends the retreating wedge of cold air, it expands and cools adiabatically, causing moisture in the ascending air to condense into clouds that often produce precipitation. The cloud sequence in Figure 9–4a typically precedes a warm front. The first sign of the approaching warm front is cirrus clouds. These high clouds form where the overrunning warm air has ascended high up the wedge of cold air, 1000 kilometers (600 miles) or more ahead of the surface front. Another indication of an approaching warm front is provided by aircraft contrails. On a clear day, when these condensation trails persist for several hours, you can be fairly certain that comparatively warm, moist air is ascending overhead.

As the front nears, cirrus clouds grade into cirrostratus that gradually blend into denser sheets of altostratus. About 300 kilometers (180 miles) ahead of the front, thicker stratus and nimbostratus clouds appear and precipitation commences.

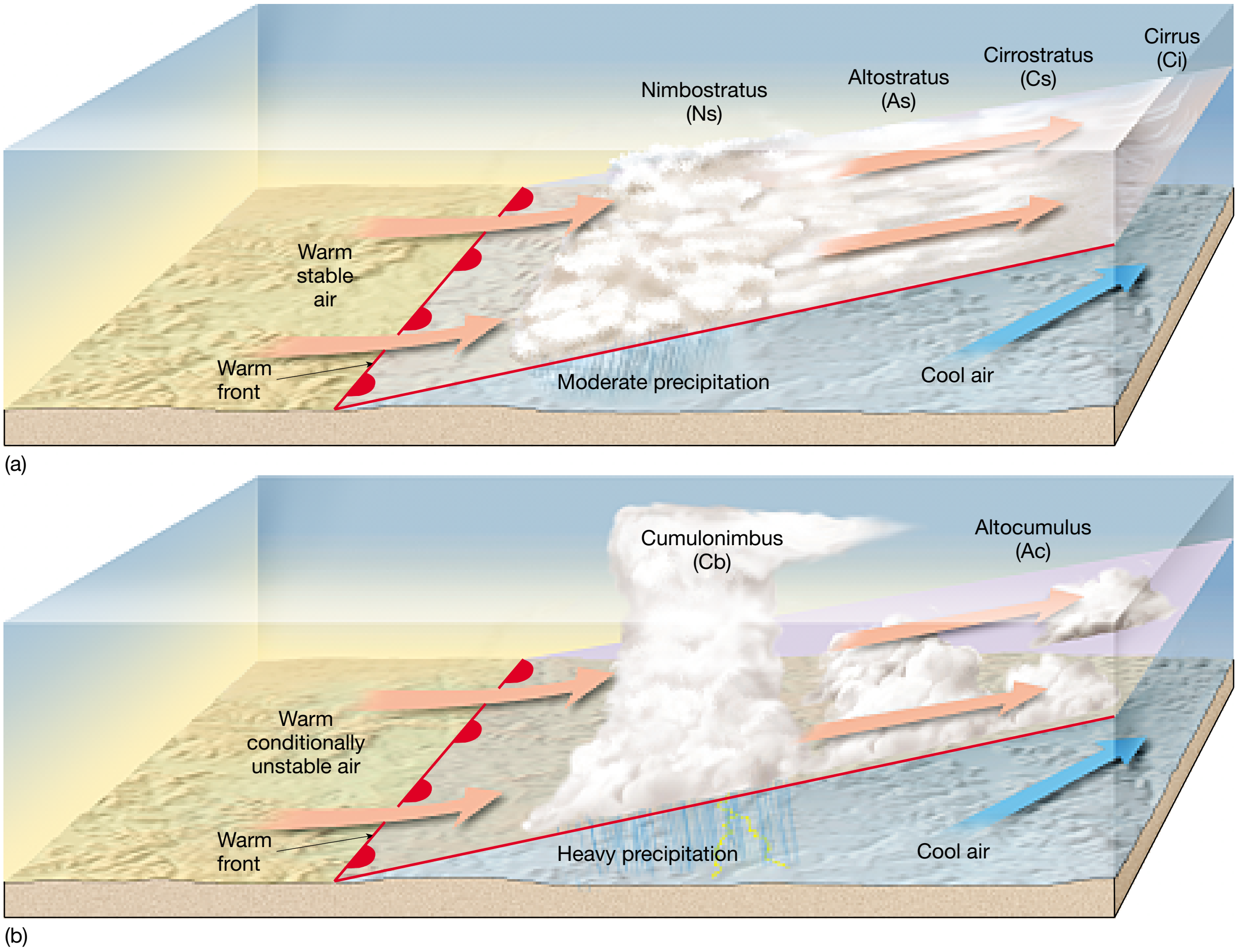


FIGURE 9-4 Warm fronts. (a) Idealized clouds and weather associated with a warm front. During most of the year, warm fronts produce light-to-moderate precipitation over a wide area. (b) During the warm season, when conditionally unstable air is forced aloft, cumulonimbus clouds and thunderstorms often arise.

Because of their slow rate of advance and very gentle slope, lifting associated with warm fronts has a large horizontal component. As a result, warm fronts tend to produce light-to-moderate precipitation over a wide area for an extended period (Figure 9–5). But this is not always the case. If, for example, the overriding air mass is relatively dry (low dew-point temperatures), there will be minimal cloud development, and no precipitation. By contrast, during the hot summer months, very moist air is commonly associated with an approaching warm front. If this conditinally unstable air is lifted sufficiently it will freely rise on its own, producing towering cumulonimbus clouds and thunderstorms (Figure 9–4b).

As you can see from Figure 9–4, the precipitation associated with a warm front occurs ahead of the surface position of the front. Some of the rain that falls through the cool air below the clouds evaporates. As a result, the air directly beneath the cloud base often becomes saturated and a stratus cloud deck develops. These clouds occasionally grow rapidly downward, which can cause problems for pilots of small aircraft that require visual landings. One minute pilots may have adequate visibility and the next be in a cloud mass (frontal fog) that has the landing strip "socked in." Occasionally during the winter, a relatively warm air mass is forced over a body of subfreezing air. When this occurs, it can create hazardous driving conditions. Raindrops become supercooled as they fall through the subfreezing air. Upon colliding with the road surface they flash-freeze to produce the icy layer called *glaze.*

When a warm front passes, temperatures gradually rise. As you would expect, the increase is most apparent when a large contrast exists between adjacent air masses. Moreover, a wind shift from the east to the southwest is generally noticeable. (The reason for this shift will become evident later.) The moisture content and stability of the encroaching warm air mass largely determine the time period required for clear skies to return. During the summer, cumulus and occasionally cumulonimbus clouds are embedded in the warm unstable air mass that follows the front. These clouds may produce precipitation, which can be heavy but is usually scattered and of short duration.

FIGURE 9-5 Light rain associated with a warm front in late fall. *(Photo by Miro Vintoniv/Stock Boston)*

Cold Fronts

When cold, continental polar air actively advances into a region occupied by warmer air, the zone of discontinuity is called a **cold front** (Figure 9–6). As with warm fronts, friction slows the surface position of a cold front compared to its position aloft. Thus, the cold front steepens as it moves. On the average, cold fronts are about twice as steep as warm fronts, having a slope of perhaps 1:100. In addition, cold fronts advance at speeds around 35 to 50 kilometers (20 to 35 miles) per hour compared to 25 to 35 kilometers (15 to 20 miles) per hour for warm fronts. These two differences, steepness of slope and rate of movement, largely account for the more violent nature of cold-front weather, compared to the weather generally accompanying a warm front.

The arrival of a cold front is sometimes preceded by altocumulus clouds. As the front approaches, generally from the west or northwest, towering clouds can often be seen in the distance. Near the front, a dark band of ominous clouds foretells the ensuing weather. The forceful lifting of warm, moist air along a cold front is often so rapid that the released latent heat increases the air's buoyancy. The heavy downpours and vigorous wind gusts associated with mature cumulonimbus clouds frequently result. Because a cold front produces roughly the same amount of lifting as a warm front, but over a shorter distance, the precipitation intensity is greater but of shorter duration (Figure 9–7).

In addition, a marked temperature drop and wind shift from the southwest to the northwest usually accompany frontal passage. The reason for this shift will be explained later in this chapter. The sharp temperature contrast and sometimes violent weather along cold fronts are symbolized on a weather map by a blue line with blue triangular points extending into the warm air mass (Figure 9–6).

FIGURE 9-6 Fast-moving cold front and cumulonimbus clouds. Thunderstorms often occur if the warm air is unstable.

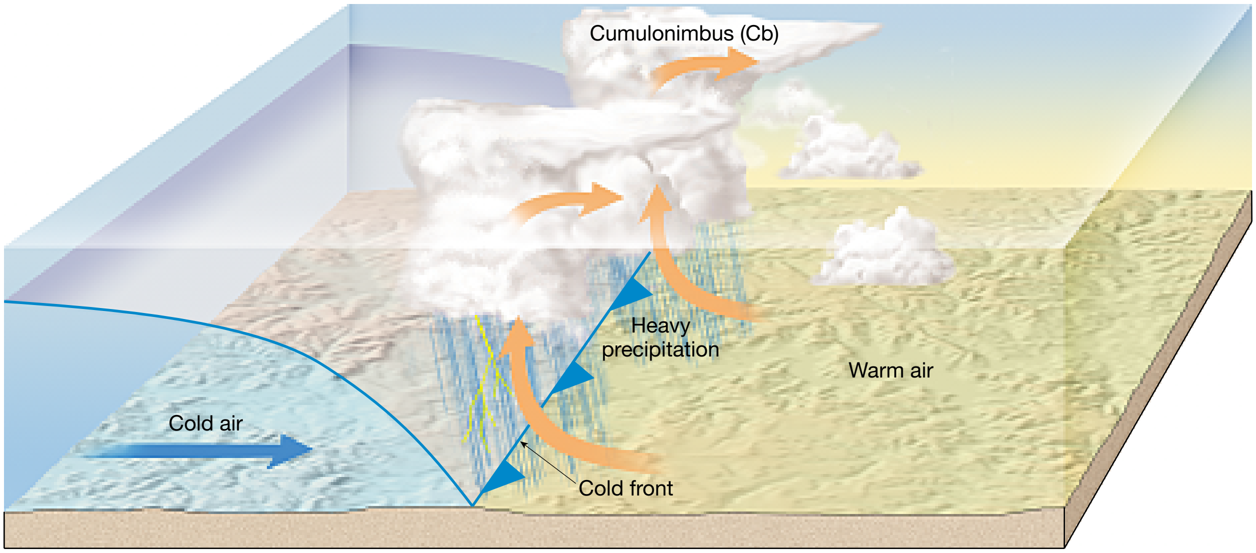


FIGURE 9-7 Thunderstorm development along a cold front over the Great Plains. *(Photo by A. and J. Verkaik/CORBIS)*

Most often the weather behind a cold front is dominated by subsiding air within a continental polar air mass. Thus, the drop in temperature is accompanied by clearing that begins soon after the front passes. Although subsidence causes adiabatic heating aloft, the effect on surface temperatures is minor. In winter the long, cloudless nights that often follow the passage of a cold front allow for abundant radiation cooling that reduces surface temperatures.

When a cold front moves over a relatively warm surface, radiation emitted from Earth can heat the lower atmosphere enough to produce shallow convection. This in turn may generate low cumulus or stratocumulus clouds behind the front. However, subsidence aloft renders these air masses quite stable. Any clouds that form will not develop great vertical thickness and will seldom produce precipitation. One exception is lake-effect snow (discussed in Chapter 8) where the cold air behind the front acquires both heat and moisture when it traverses a comparatively warm body of water.

Stationary Fronts

Occasionally, the airflow on both sides of a front is neither toward the cold air mass nor toward the warm air mass, but almost parallel to the line of the front. Consequently, the surface position of the front does not move, or moves very slowly. This condition is called a **stationary front.** On a weather map, stationary fronts are shown with blue triangular points on one side of the line and red semicircles on the other. Because overrunning usually occurs along stationary fronts, gentle to moderate precipitation is likely. Stationary fronts may remain over an area for several days, in which case flooding is possible.

Occluded Fronts

The fourth type of front is the **occluded front.** Here a rapidly moving cold front overtakes a warm front, as shown in Figure 9–8a. As the cold air wedges the warm front upward, a new front forms between the advancing cold air and the air over which the warm front is gliding (Figure 9–8b). The weather of an occluded front is generally complex. Most precipitation is associated with the warm air being forced aloft (Figure 9–8c). When conditions are suitable, however, the newly formed front is capable of initiating precipitation of its own.

As you might expect, there are cold-type occluded fronts and warm-type occluded fronts. In the occluded front shown in Figure 9–9a, the air behind the cold front is colder than the cool air it is overtaking. This is the most common type of occluded front east of the Rockies and is called a **cold-type occluded front.**

It is also possible for the air behind the advancing cold front to be warmer than the cold air it is overtaking. These **warm-type occluded fronts** (Figure 9–9b) frequently occur along the Pacific Coast, where milder maritime polar

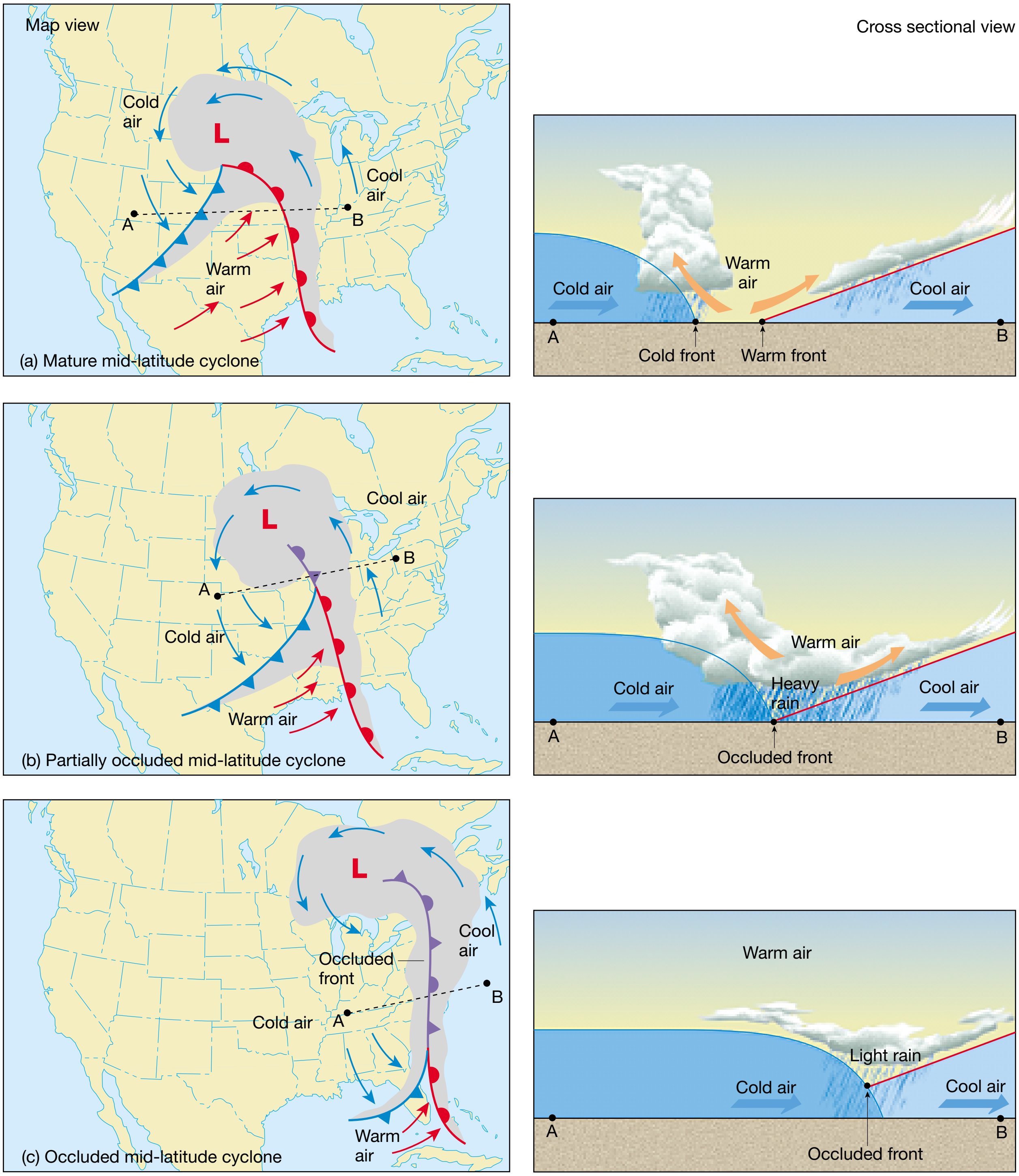
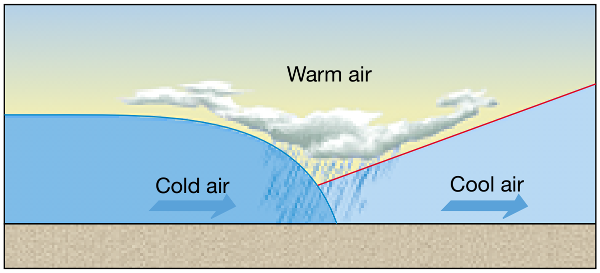


FIGURE 9-8 Stages in the formation of an occluded front and its relationship to a developing mid-latitude cyclone. After the warm air has been forced aloft, the system begins to dissipate. The shaded areas indicate regions where precipitation is most likely to occur.

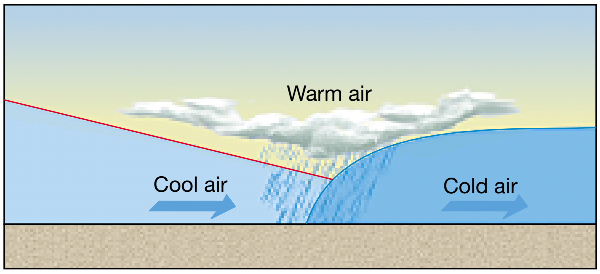
air invades more frigid polar air that had its origin over the continent.

Notice in Figure 9–9 that in the warm-type occluded front, the warm air aloft (and hence the precipitation) often precedes the arrival of the surface front. This situation is reversed for the cold-type occluded front, where the front aloft (and its associated precipitation) lags behind the surface front. Also note that cold-type occluded fronts frequently resemble cold fronts in the type of weather generated.

Because of the complex nature of occluded fronts, they are often drawn on weather maps as either warm or cold fronts, depending on what kind of air is the aggressor. In those cases when they are drawn as an occluded front, a



(a) Cold-type



(b) Warm-type

FIGURE 9-9 Occluded fronts of (a) the cold type and (b) the warm type.

purple line with alternating purple triangles and semicircles pointing in the direction of movement is employed.

Drylines

Classifying fronts based only on the temperature differences across the frontal boundary can be misleading. Humidity also influences the density of air, with humid air being less dense than dry air, all other factors being equal. In the summer it is not unusual for a southeastward moving air mass that originated over the northern Great Plains to displace warm, humid air over the lower Mississippi Valley. The front that develops is usually labeled a cold front, even though the advancing air may not be any colder than the air it displaces. Simply, the drier air is denser and forcefully lifts the moist air in its path, just like a cold front. The passage of this type of frontal boundary is noticed as a sharp drop in humidity, without an appreciable drop in temperature.

A related type of frontal boundary, called a **dryline,** develops over the southern Great Plains. This occurs when dry, continental tropical (cT) air originating over the American Southwest meets moist, maritime tropical (mT) air from the Gulf of Mexico. Basically a spring and summer phenomenon, drylines most often generate a band of severe thunderstorms along a line extending from Texas to Nebraska that moves eastward across the Great Plains. A dryline is easily identified by comparing the dew point temperatures of the cT air west of the front with the dew points of the mT air mass to the east (see Figure 10–12, p. 296).

In summary, because cold fronts are the aggressor, the lifting associated along a cold front tends to be more concentrated and forceful than that along a warm front. Hence, the precipitation associated with a cold front usually occurs along a narrower zone and is heavier than that associated with a warm front. Further, most severe weather occurs along cold fronts or drylines in which dry continental air aggressively lifts warm maritime air.

Life Cycle of a Mid-latitude Cyclone

Basic Weather Patterns

▶ Introducing Middle-Latitude Cyclones

The polar-front theory, which describes the development and intensification of a mid-latitude cyclone, was created primarily from near-surface observations. As more data became available from the middle and upper troposphere, some modifications were necessary. Yet this model is still a useful working tool for interpreting the weather. It helps us to visualize our dynamic atmosphere as it generates our day-to-day weather. If you keep this model in mind as you observe changes in the weather, the changes will no longer come as a surprise. Furthermore, you will begin to see some order in what had appeared to be disorder, and you might even correctly forecast the impending weather!

Formation: The Clash of Two Air Masses

According to the Norwegian model, cyclones form along fronts and proceed through a generally predictable life cycle. This cycle can last a few days to over a week, depending on whether atmospheric conditions are favorable. Figure 9–10 shows six stages in the life of a typical mid-latitude cyclone. In part (a), the stage is set for **cyclogenesis** (cyclone formation). Here two air masses of different densities (temperatures) are moving roughly parallel to the front, but in opposite directions. (In the classic polar-front model, this would be continental polar air associated with the polar easterlies on the north side of the front and maritime tropical air driven by the westerlies on the south side of the front.)

Under suitable conditions the frontal surface that separates these two contrasting air masses will take on a wave shape that is usually several hundred kilometers long (Figure 9–10b). These waves are analogous to the waves produced on water by moving air, except that they are much larger. Some waves tend to dampen, or die out, whereas others grow in amplitude. Those storms that intensify or "deepen" develop waves that change in shape over time, much like a gentle ocean swell does as it moves into shallow water and becomes a tall, breaking wave (see Figure 9–10c).

Development of Cyclonic Flow

As the wave develops, warm air advances poleward invading the area formerly occupied by colder air, while cold air moves equatorward. This change in the direction of the surface flow is accompanied by a readjustment in the pressure pattern that results in nearly circular isobars, with the low pressure centered at the crest of the wave. The resulting flow is a counterclockwise cyclonic circulation that can be seen clearly on the weather map shown in Figure 9–11. Once the

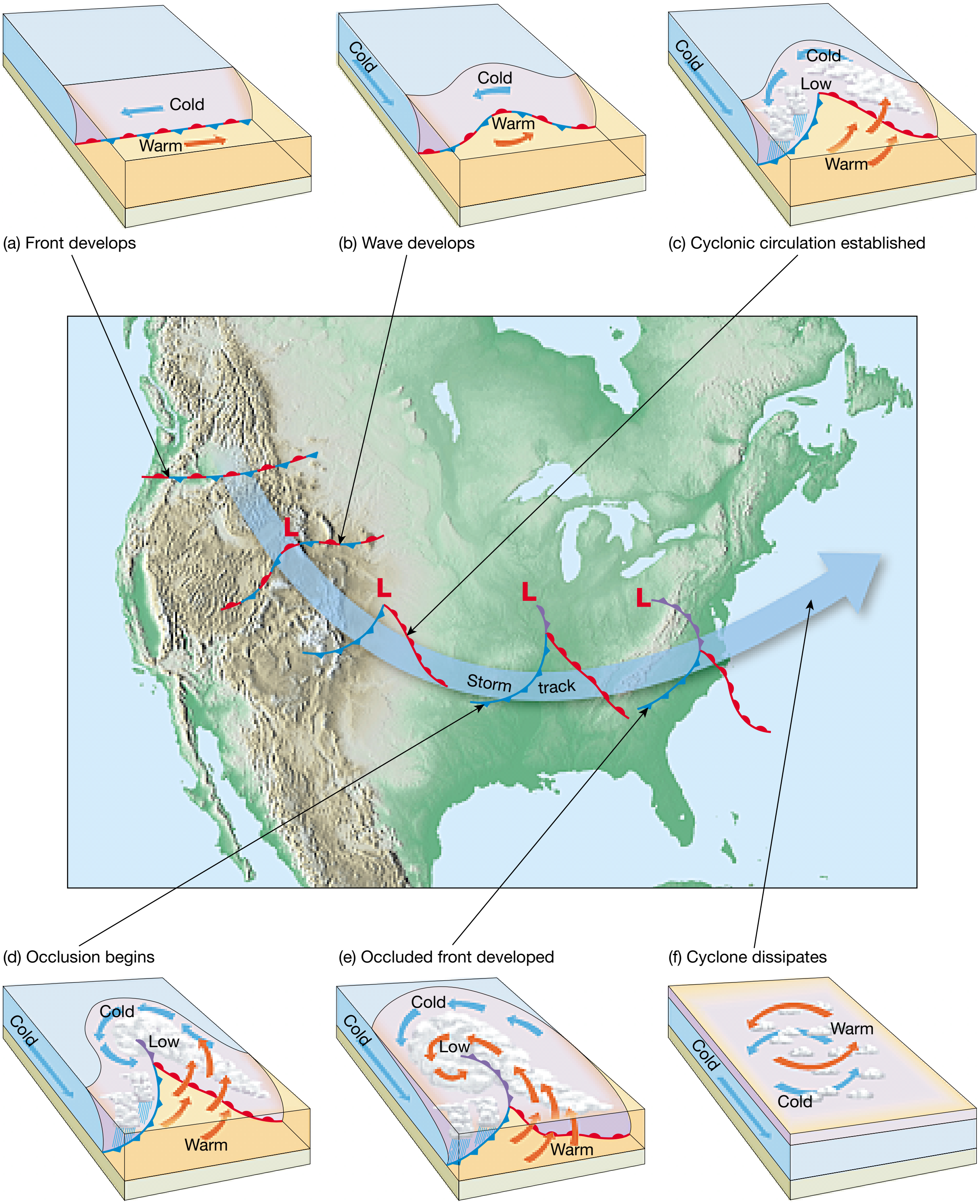


FIGURE 9-10 Stages in the life cycle of a middle-latitude cyclone, as proposed by J. Bjerknes.

cyclonic circulation develops, we would expect general convergence to result in lifting, especially where warm air is overrunning colder air. You can see in Figure 9–11 that the air in the warm sector (over the southern states) is flowing northeastward toward colder air that is moving toward the northwest. Because the warm air is moving in a direction perpendicular to this front, we can conclude that the warm air is invading a region formerly occupied by cold air. Therefore, this must be a warm front. Similar reasoning indicates that to the left (west) of the cyclonic disturbance, cold air from the northwest is displacing the air of the warm sector and generating a cold front.

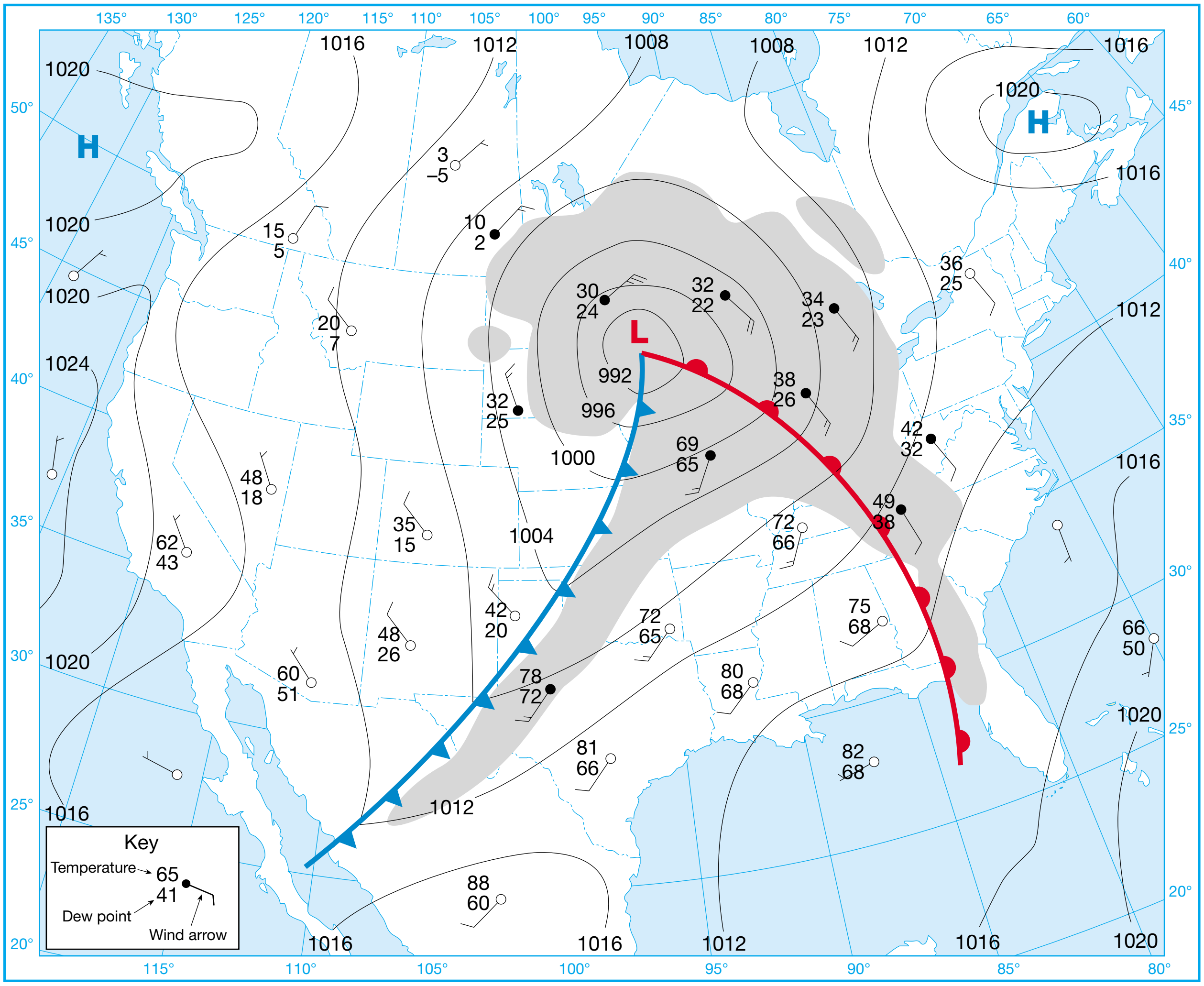


FIGURE 9-11 Simplified weather map showing the circulation of a middle-latitude cyclone. The gray areas indicate regions of probable precipitation.

Occlusion: The Beginning of the End

Usually, the position of the cold front advances faster than the warm front and begins to close (lift) the warm front, as shown in Figure 9–10c,d. This process, known as **occlusion,** forms an *occluded front,* which grows in length as it displaces the warm sector aloft. As occlusion begins, the storm often intensifies. Pressure at the storm's center falls, and wind speeds increase. In the winter, heavy snowfalls and blizzardlike conditions are possible during this phase of the storm's evolution.

As more of the sloping discontinuity (front) is forced aloft, the pressure gradient weakens. In a day or two the entire warm sector is displaced, and cold air surrounds the cyclone at low levels (Figure 9–10f). Thus, the horizontal temperature (density) difference that existed between the two contracting air masses has been eliminated. At this point the cyclone has exhausted its source of energy. Friction slows the surface flow, and the once highly organized counterclockwise flow ceases to exist.

A simple analogy may help you visualize what is happening to the cold and warm air masses in the preceding discussion. Imagine a large water trough that has a vertical divider separating the tank into two equal parts. Half of the tank is filled with hot water containing red dye, and the other half is filled with blue-colored ice water. Now imagine what happens when the divider is removed. The cold, dense water will flow under the less dense warm water, displacing it upward. This rush of water will come to a halt as soon as all of the warm water is displaced toward the top of the container. In a similar manner a middle-latitude cyclone dies once all of the warm air is displaced aloft and the horizontal discontinuity between the air masses no longer exists.

Idealized Weather of a Mid-latitude Cyclone

GEODe ATMOSPHERE **Basic Weather Patterns**

▶ Introducing Middle-Latitude Cyclones

As stated earlier, the Norwegian model is a useful tool for examining weather patterns of the middle latitudes. Figure 9–12 illustrates a mature mid-latitude cyclone; note the

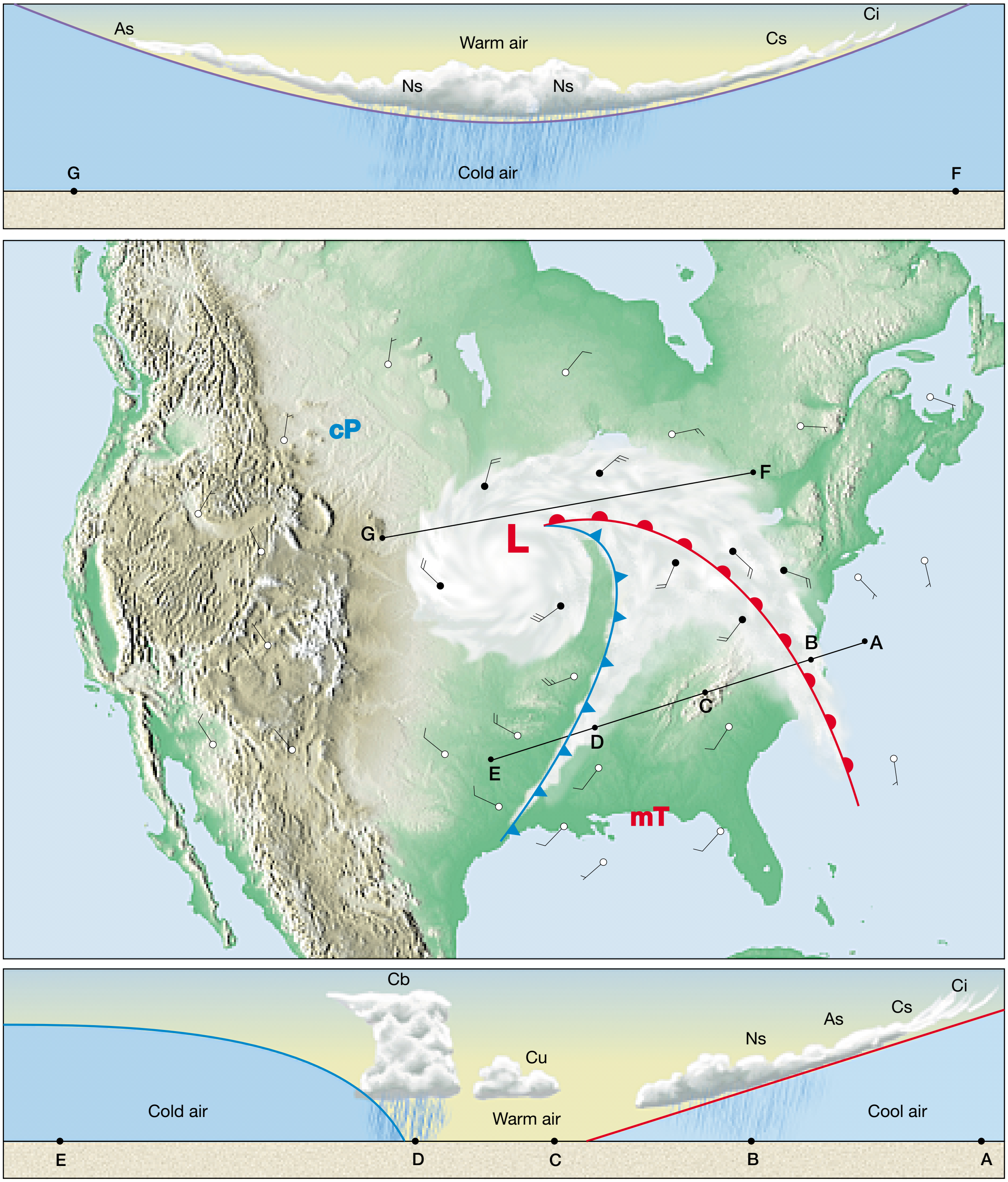


FIGURE 9-12 Cloud patterns typically associated with a mature middle-latitude cyclone. The middle section is a map view. Note the cross-section lines (F–G, A–E). Above the map is a vertical cross section along line F–G. Below the map is a section along A–E. For cloud abbreviations, refer to Figures 9–4 and 9–6.

distribution of clouds and thus the regions of possible precipitation. Compare this map to the satellite image of a cyclone in Figure 9–25 (p. 280). It is easy to see why we often refer to the cloud pattern of a cyclone as having a "comma" shape.

Guided by the westerlies aloft, cyclones generally move eastward across the United States. Therefore, we can expect the first signs of a cyclone's arrival to appear in the western sky. In the region of the Mississippi Valley, however, cyclones often begin a more northeasterly trajectory and occasionally move directly northward. Typically, a mid-latitude cyclone requires two to four days to pass completely over a region. During that period, abrupt changes in atmospheric conditions may occur, particularly in the winter and spring when the greatest temperature contrasts occur across the middle latitudes.

Using Figure 9–12 as a guide, let us examine these weather producers and the changes you could expect if a mid-latitude cyclone passed over your area. To facilitate our discussion, profiles of the storm are provided above and below the map. They correspond to lines A–E and F–G on the map. (Remember, these storms move from west to east; therefore, the right side of the cyclone shown in Figure 9–12 will be the first to pass by.)

First, imagine the change in weather as you move from right to left along profile A–E (bottom of Figure 9–12). At point *A* the sighting of high cirrus clouds is the first sign of the approaching cyclone. These high clouds can precede the surface front by 1000 kilometers (600 miles) or more, and they are normally accompanied by falling pressure. As the warm front advances, a lowering and thickening of the cloud deck is noticed. Within 12 to 24 hours after the first sighting of cirrus clouds, light precipitation usually commences (point *B*). As the front nears, the rate of precipitation increases, a rise in temperature is noticed, and winds begin to change from an easterly to a southerly flow.

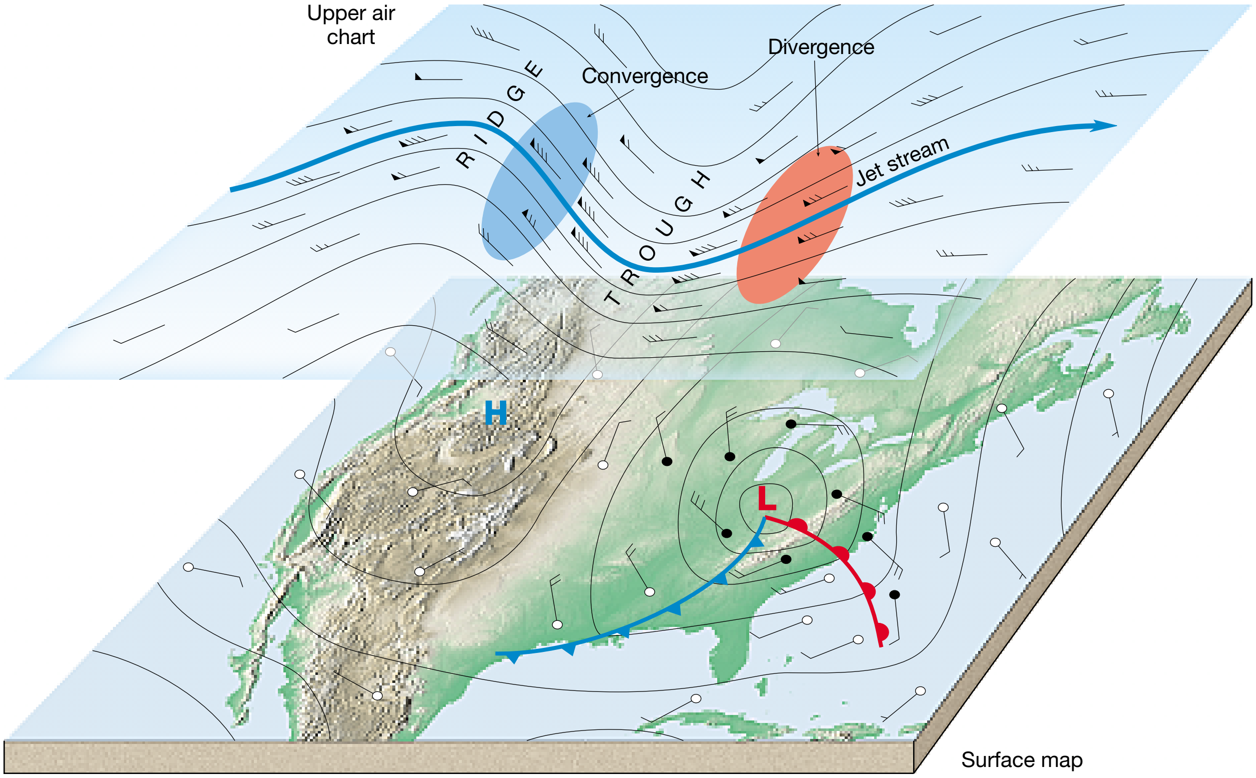
With the passage of the warm front, the area is under the influence of the maritime tropical air mass of the warm sector (point *C*). Generally, the region affected by this part of the cyclone experiences relatively warm temperatures, southerly winds, and clear skies, although fair-weather cumulus or altocumulus clouds are not uncommon.

The rather pleasant weather of the warm sector passes quickly in the spring and is replaced by gusty winds and precipitation generated along the cold front. The approach of a rapidly advancing cold front is marked by a wall of rolling black clouds (point *D*). Severe weather accompanied by heavy precipitation and occasionally hail or a tornado is common at this time of year.

The passage of the cold front is easily detected by a wind shift. The warm flow from the south or southwest is replaced by cold winds from the west to northwest, resulting in a pronounced drop in temperature. Also, rising pressure hints of the subsiding cool, dry air behind the cold front. Once the front passes, the skies clear quickly as cooler air invades the region (point *E*). A day or two of almost cloudless deep blue skies are often experienced, unless another cyclone is edging into the region.

A very different set of weather conditions prevails in the portion of the cyclone that contains the occluded front along profile F–G (top of Figure 9–12). Here temperatures remain cool during the passage of the storm. The first hints of the approaching low-pressure center are a continual drop in air pressure and increasingly overcast conditions. This section of the cyclone most often generates snow or icing storms during the coldest months. Moreover, the occluded front usually moves more slowly than the other fronts. Thus, the entire wishbone-shaped frontal structure shown in Figure 9–12 rotates counterclockwise so that the occluded front appears to "bend over backward." This effect adds to the misery of the region influenced by the occluded front,

FIGURE 9-13 Relationship of the wavy flow pattern aloft to surface cyclones and anticyclones.



for it remains over the area longer than the other fronts (see Box 9–1).

Cyclone Formation

The polar-front model shows that cyclogenesis (cyclone formation) occurs where a frontal surface is distorted into a wave-shaped discontinuity. Several surface factors are thought to produce this wave in a frontal zone. Topographic irregularities (such as mountains), temperature contrasts (as between sea and land), or ocean-current influences can disrupt the general zonal flow sufficiently to produce a wave along a front. In addition, an intensification of the flow aloft frequently precedes the formation of a surface cyclone. This fact strongly suggests that upper-level flow contributes to the formation of these rotating storm systems.

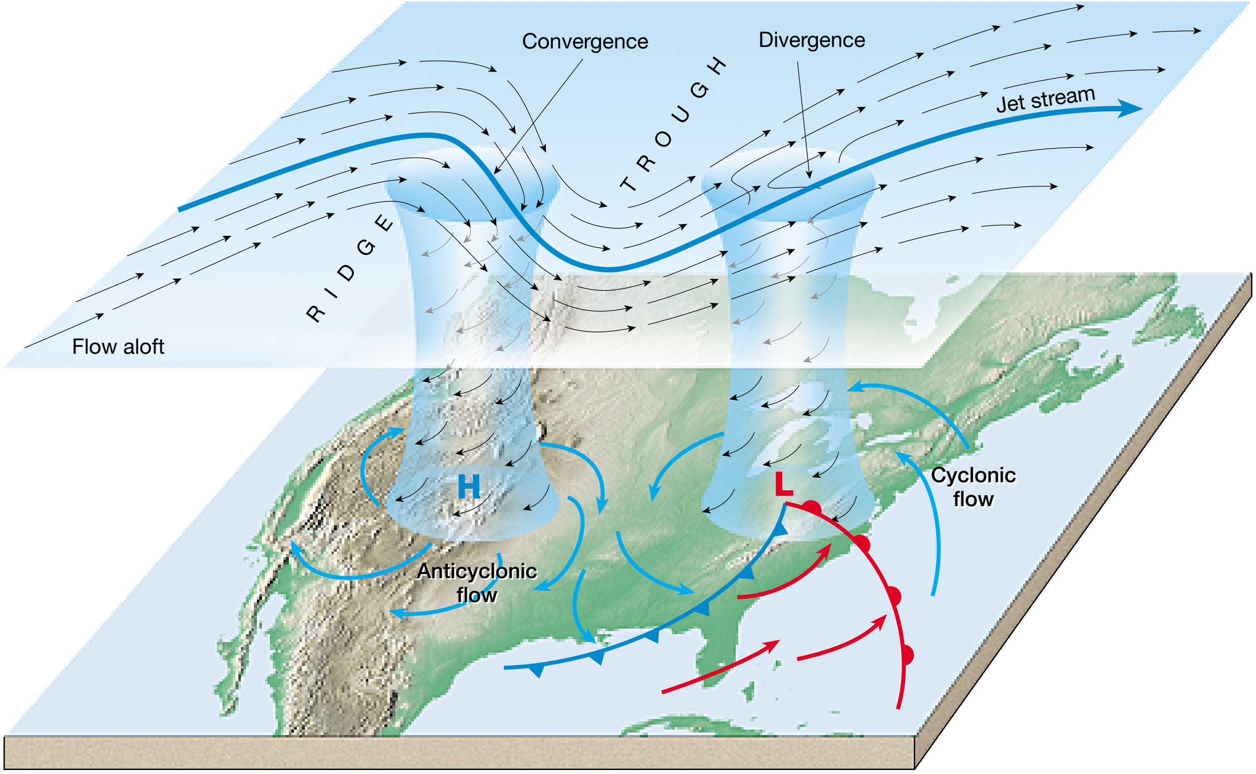
When the earliest studies of cyclones were made, little data were available on airflow in the middle and upper troposphere. Since then, a close relationship has been established between surface disturbances and the flow aloft. Whenever the winds aloft exhibit a relatively straight zonal flow—that is, from west to east—little cyclonic activity occurs at the surface. However, when the upper air begins to meander widely from north-to-south, forming high-amplitude waves of alternating troughs (lows) and ridges (highs), cyclonic activity intensifies (Figure 9–13). Moreover, when surface cyclones form, almost invariably they are centered below the jet-stream axis and downwind from an upper-level trough (Figure 9–13).

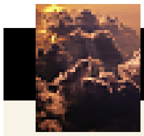
Cyclonic and Anticyclonic Circulation

Before discussing how surface cyclones are generated and supported by the flow aloft, let us review the nature of cyclonic and anticyclonic winds. Recall that airflow about a surface low is inward, a fact that leads to mass convergence (coming together). Because accumulation of air is accompanied by a corresponding increase in surface pressure we might expect a surface low-pressure center to "fill" rapidly and be eliminated, just as the vacuum in a coffee can is quickly equalized when we open it. However, cyclones often exist for a week or longer. For this to happen, surface convergence must be offset by outflow aloft (Figure 9–14). As long as divergence (spreading out) aloft is equal to or greater than the surface inflow, the low pressure can be sustained.

Because cyclones are bearers of stormy weather, they have received far more attention than their counterparts, anticyclones. Yet the close relationship between them makes it difficult to totally separate a discussion of these two pressure systems. The surface air that feeds a cyclone, for example, generally originates as air flowing out of an anticyclone (Figure 9–14). Consequently, cyclones and anticyclones are typically found adjacent to one another. Like the cyclone, an anticyclone depends on the flow aloft to maintain its circulation. In the anticyclone, divergence at the surface is

FIGURE 9-14 Idealized depiction of the support that divergence and convergence aloft provide to cyclonic and anticyclonic circulation at the surface.





BOX 9-1 Winds As a Forecasting Tool

> Every wind has its weather.
>
> *Francis Bacon*

People living in the middle latitudes know well that during the winter, northerly winds can chill you to the bone. Conversely, a sudden change to a southerly flow can bring welcome relief from these frigid conditions. If you are more observant, you might have noticed that when the winds switch from a southerly flow to a more easterly direction, foul weather often follows. By contrast, a change in wind direction from the southwest to the northwest is usually accompanied by clearing conditions. Just how are the winds and the forthcoming weather related?

Modern weather forecasts require the processing capabilities of high-speed computers as well as the expertise of people with considerable professional training. Nevertheless, some reasonable insights into the impending weather can be gained through careful observation. The two most significant elements for this purpose are barometric pressure and wind direction. Recall that anticyclones (high-pressure cells) are associated with clear skies, and that cyclones (low-pressure cells) frequently bring clouds and precipitation. Thus, by noting whether the barometer is rising, falling, or steady, we have some indication of the forthcoming weather. For example, rising pressure indicates the approach of a high-pressure system and generally clearing conditions.

The use of winds in weather forecasting is also quite straightforward. Because cyclones are the "villains" in the weather game, we are most concerned with the circulation around these storm centers. In particular, changes in wind direction that occur with the passage of warm and cold fronts are useful in predicting the impending weather. Notice in Figure 9–12, that with the passage of both the warm and cold fronts, the wind arrows change positions in a clockwise manner. Specifically, with the passage of the cold front, the wind shifts from southwest to northwest. From nautical terminology, the word *veering* is applied to this clockwise wind shift. Because clearing conditions normally occur with the passage of either front, veering winds are indicators that the weather will improve.

In contrast, the area in the northern portion of the cyclone will experience winds that shift in a counterclockwise direction, as can be seen in Figure 9–12. Winds that shift in this manner are said to be *backing.* With the approach of a mid-latitude cyclone, backing winds indicate cool temperatures and continued foul weather.

A summary of the relationship among barometer readings, winds, and the impending weather is provided in Table 9–A. Although this information is applicable in a very general way to much of the United States, local influences must be taken into account. For example, a rising barometer and a change in wind direction, from southwest to northwest, is usually associated with the

balanced by convergence aloft and general subsidence of the air column (Figure 9–14).

Divergence and Convergence Aloft

Because divergence aloft is so important to cyclogenesis, we need a basic understanding of its role. Divergence aloft does not involve the outward flow in all directions as occurs about a surface anticyclone. Instead, the winds aloft flow generally from west to east along sweeping curves. How does zonal flow aloft cause upper-level divergence?

One mechanism responsible for divergence aloft is a phenomenon known as **speed divergence.** It has been known for some time that wind speeds can change dramatically in the vicinity of the jet stream. On entering a zone of high wind speed, air accelerates and stretches out (divergence). In contrast, when air enters a zone of slower wind speed, an air pile-up (convergence) results. Analogous situations occur every day on a toll highway. When exiting a toll booth and entering the zone of maximum speed, we find automobiles diverging (increasing the number of car lengths between them). As automobiles slow to pay the toll, they experience convergence (coming together).

In addition to speed divergence, several other factors contribute to divergence (or convergence) aloft. These include *directional divergence,* which is horizontal spreading of an air stream, and *vorticity,* which is the amount of rotation exhibited by a mass of moving air. Vorticity can either enhance or inhibit divergence aloft.

The combined effect of the phenomena that influence flow aloft is that an area of upper-air divergence and surface cyclonic circulation generally develop downstream from an upper-level trough, as illustrated in Figure 9–14. Consequently, in the United States surface cyclones generally form east of an upper-level trough. As long as divergence aloft exceeds convergence at ground level, surface pressures will fall and the cyclonic storm will intensify.

Conversely, the zone in the jet stream that experiences convergence and anticyclonic rotation is located downstream from a ridge (Figure 9–14). The accumulation of air in this

TABLE 9-A Wind, barometric pressure, and impending weather

Changes in wind direction	Barometric pressure	Pressure tendency	Impending weather
Any direction	1023 mb and above (30.20 in.)	Steady or rising	Continued fair with no temperature change
SW to NW	1013 mb and below (29.92 in.)	Rising rapidly	Clearing within 12 to 24 hours and colder
S to SW	1013 mb and below (29.92 in.)	Rising slowly	Clearing within a few hours and fair for several days
SE to SW	1013 mb and below (29.92 in.)	Steady or slowly falling	Clearing and warmer, followed by possible precipitation
E to NE	1019 mb and above (30.10 in.)	Falling slowly	In summer, with light wind, rain may not fall for several days; in winter, rain within 24 hours
E to NE	1019 mb and above (10.10 in.)	Falling rapidly	In summer, rain probable within 12 to 24 hours; in winter, rain or snow with strong winds likely
SE to NE	1013 mb and below (29.92 in.)	Falling slowly	Rain will continue for 1 to 2 days
SE to NE	1013 mb and below (29.92 in.)	Falling rapidly	Stormy conditions followed within 36 hours by clearing and, in winter, colder temperatures

Source: Adapted from the National Weather Service.

passage of a cold front and indicates that clearing conditions should follow. However, in the winter, residents of the southeast shore of one of the Great Lakes may not be so lucky. As cold, dry northwest winds cross large expanses of open water, they acquire heat and moisture from the relatively warm lake surface. By the time this air reaches the leeward shore, it is often humid and unstable enough to produce heavy lake-effect snow (see Chapter 8).

region of the jet stream leads to subsidence and increased surface pressure. Hence, this is a favorable site for the development of a surface anticyclone.

Because of the significant role that the upper-level flow has on cyclogenesis, it should be evident that any attempt at weather prediction must take into account the airflow aloft. This is why television weather reporters frequently illustrate the flow within the jet stream.

In summary, the flow aloft contributes to the formation and intensification of surface low- and high-pressure systems. Areas of upper-level convergence and divergence are located in the vicinity of jet stream, where dramatic changes in wind speeds cause air either to pile up (converge) or spread out (diverge). Upper-level convergence is favored downstream (east) of a ridge, whereas divergence occurs downstream of an upper-level trough. Below regions of upper-level convergence are areas of high pressure (anticyclones), whereas upper-level divergence supports the formation and development of cyclonic systems (lows).

Traveling Cyclones

Cyclone development does not occur uniformly over Earth but tends to favor certain locations, such as the leeward sides of mountains and coastal regions. In general, cyclones form in areas where large temperature contrasts occur in the lower troposphere. Figure 9–15 shows areas of greatest cyclone development over North America and adjacent oceans. Notice that the main sites for cyclone formation occur along the lee side of the Rocky Mountains and along the Atlantic Coast east of the Appalachian Mountains. Other important sites are in the North Pacific and the North Atlantic.

Patterns of Movement

Once formed, cyclones tend to first travel in an easterly direction across North America and then follow a more northeasterly path into the North Atlantic (Figure 9–16). However, numerous exceptions to this general trend occur.

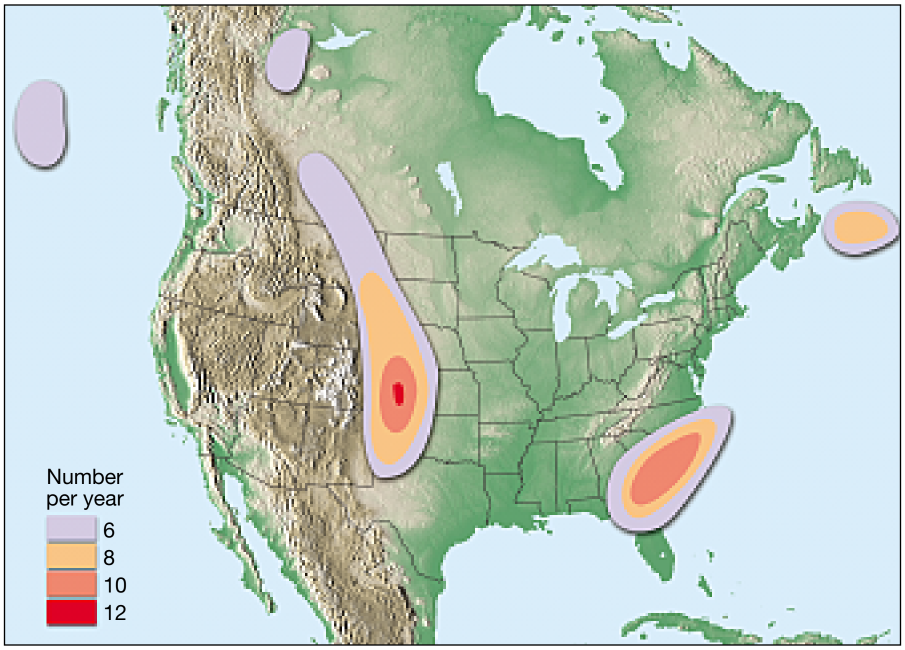


FIGURE 9-15 Major sites of cyclone formation.

One well-known example is a storm that goes by the name of *Panhandle Hook*. The "Hook" describes the curved path these storms follow (Figure 9–16). Developing in southern Colorado near the Texas and Oklahoma panhandles, these cyclones first travel toward the southeast and then bend sharply northward traveling across Wisconsin and into Canada.

Cyclones that influence western North America originate over the North Pacific. Many of these systems move northeastward toward the Gulf of Alaska. However, during the winter months these storms travel farther southward and often reach the coast of the contiguous 48 states, occasionally traveling as far south as southern California. These cyclonic systems provide the winter rainy season that affects much of the West Coast.

Most Pacific storms do not cross the Rockies intact but may redevelop on the lee (eastward) side of these mountains. A favorite site for redevelopment is Colorado, but other common sites of formation exist as far south as Texas and as far north as Alberta. The cyclones that form in Canada tend to move southeastward toward the Great Lakes and then turn northeastward and move out into the Atlantic. Cyclones that redevelop over the Great Plains generally migrate eastward until they reach the central United States, where a northeastward or even northward trajectory is followed. Many of these cyclones traverse the Great Lakes region, making it the most storm-ridden portion of the country. Another area where cyclogenesis occurs is east of the southern Appalachians. These storms tend to move northward with the warm Gulf Stream and bring stormy conditions to the entire East Coast.

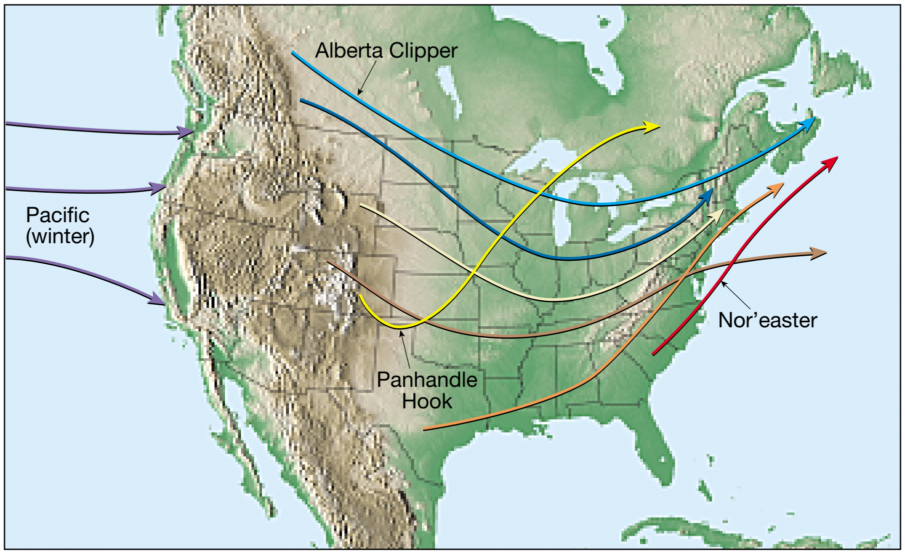


FIGURE 9-16 Typical paths of cyclonic storms that affect the lower 48 states.

Alberta Clipper. An *Alberta Clipper* is a cold, windy cyclonic storm that forms on the eastern side of the Canadian Rockies in the province of Alberta (Figure 9–16). Noted for their speed, they are called "clippers" because in Colonial times the fastest vehicles were small ships by the same name. The average Alberta Clipper dives southeastward into Montana or the Dakotas and than tracks across the Great Lakes where it brings dramatically lower temperatures. Winds associated with Clippers frequently exceed 50 kilometers (30 miles) per hour. Because clippers move rapidly and remain a long way from the mild waters of the Gulf of Mexico they tend to be moisture deprived. As a result they do not drop large amounts of snow. Instead, they may leave a few inches in a narrow band from the Dakotas to New York over a span as short as two days. However, because these winter storms are relatively frequent occurrences, they make a significant contribution to the total winter snowfall in the northern tier of states.

Nor'easter. From the Mid-Atlantic Coast to New England, the classic storm is called a *nor'easter* (Figure 9–16). They are called nor'easters because the winds preceding the passage of these storms in coastal areas are from the northeast. They are most frequent and violent between September and April when cold air pouring south from Canada meets relatively warm humid air from the Atlantic. Once formed, nor'easters follow the coast often bringing rain, sleet, and heavy snowfall to the Northeast. Because the circulation produces strong onshore winds, these storms can cause considerable coastal erosion, flooding, and property damage. The popular book and movie *The Perfect Storm* was based on a true story of a fishing boat that was caught in an intense nor'easter in October 1991.

Flow Aloft and Cyclone Migration

Recall that the wavy flow aloft is important to the development and evolution of a surface cyclonic storm. In addition, the flow in the middle and upper troposphere appears to strongly influence the rate at which these pressure systems advance and the direction they follow. As a general rule of thumb, surface cyclones move in the same direction as the 500-millibar wind, but at about half the speed. Normally these systems travel at 25 to 50 kilometers (15 to 30 miles) per hour so that distances of roughly 600 to 1200 kilometers (400 to 800 miles) are traversed each day. The faster speeds occur during the coldest months when temperature gradients are greatest.

One of the most exacting tasks in weather forecasting is predicting the paths of cyclonic storms. We have already seen that the flow aloft tends to steer developing pressure systems. Let us examine an example of this steering effect by seeing how changes in the upper-level flow correspond to changes in the path taken by a cyclone.

Figure 9–17a illustrates the changing position of a middle-latitude cyclone over a four-day period. Notice in Figure 9–17b that on March 21, the 500-millibar contours are relatively flat. Also notice that for the following two days, the cyclone moves in a rather straight southeasterly direction. By March 23 the 500-millibar contours make a sharp bend northward on the eastern side of a trough situated over Wyoming (Figure 9–17c). Likewise, the next day the path of the cyclone makes a similar northward migration.

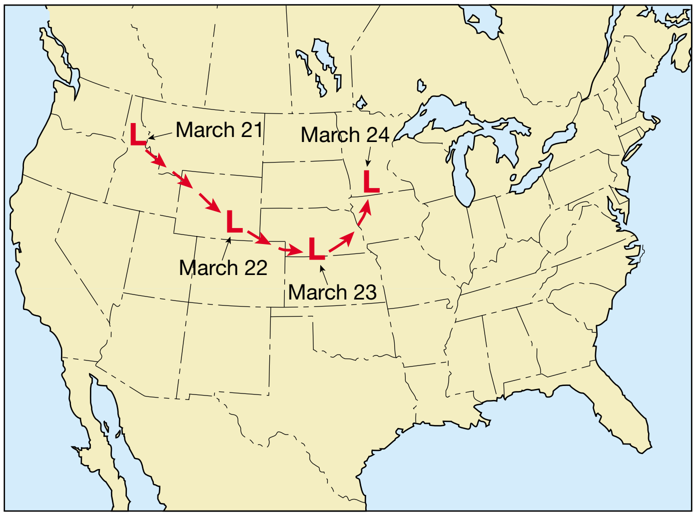
Although this is an oversimplified example, it illustrates the "steering" effect of upper-level flow. Here we have examined the influence of upper airflow on cyclonic movement after the fact. To make useful predictions of future positions of cyclones, accurate appraisals of changes in the westerly flow aloft are required. For this reason, predicting the behavior of the wavy flow in the middle and upper troposphere is an important part of modern weather forecasting.

Anticyclonic Weather and Blocking Highs

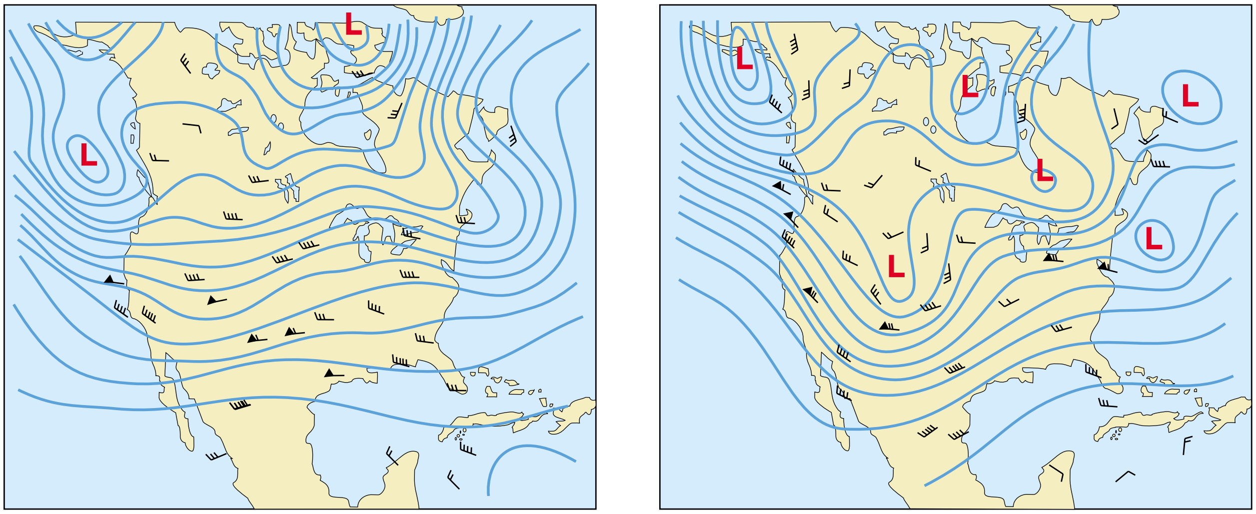
Owing to the gradual subsidence within them, anticyclones generally produce clear skies and calm conditions. Because these high-pressure systems are not associated with stormy weather, both their development and movement have not been studied as extensively as that of mid-latitude cyclones. This does not imply, however, that anticyclones always bring desirable weather. Large anticyclones often develop over the Arctic during the winter. These cold high-pressure centers are known to migrate as far south as the Gulf Coast where they can impact the weather over as much as two-thirds of the United States (Figure 9–18). This dense frigid air often brings record-breaking cold temperatures (Figure 9–19).

Approximately one to three times each winter, and occasionally during other seasons, large anticyclones form and persist over the middle latitudes for nearly two weeks and sometimes longer than a month. These large highs deflect the nearly zonal west-to-east flow and send it poleward. Thus, they are sometimes called *blocking highs.* Once in place, these stagnant anticyclones block the eastward migration of cyclones. As a result, one section of the nation is kept dry for a week or more while another region remains continually under the influence of cyclonic storms. Such a situation prevailed during the summer of 1993 when a strong high-pressure system became anchored over the southeastern United States and caused migrating storms to stall over the Midwest. The result was the most devastating flooding on record for the central and upper Mississippi Valley (see Box 9–2). At the same time, the Southeast experienced severe drought.

Large stagnant anticyclones can also contribute to air-pollution episodes. The subsidence within an anticyclone can produce a temperature inversion that acts like a lid to trap pollutants. (For more on this, see Chapter 13.) Further, the light winds associated with the center of an anticyclone do little to disperse polluted air. Both Los Angeles and Mexico City experience air pollution episodes when



(a) Movement of cyclone from March 21-24



(b) 500-mb chart for March 21

(c) 500-mb chart for March 23

FIGURE 9-17 Steering of mid-latitude cyclones. (a) Notice that the cyclone (low) moved almost in a straight southeastward direction on March 21 and March 22. On the morning of March 23, it abruptly turned northward. This change in direction corresponds to the change from (b) rather straight contours on the upper-air chart for March 21 to (c) curved contours on the chart for March 23.

strong, stagnant high-pressure systems dominate their circulation for extended periods.

Case Study of a Mid-latitude Cyclone

GEODe ATMOSPHERE **Basic Weather Patterns**

▶ In the Lab: Examining a Mature Middle-Latitude Cyclone

To give you a picture of the weather one might expect from a strong late-winter cyclonic storm we are going to look at an actual event. Our sample storm was one of three cyclones to migrate across the United States during the latter half of March. This cyclone reached the U.S. West Coast on March 21 a few hundred kilometers northwest of Seattle, Washington. Like many Pacific storms, this one rejuvenated over the western United States and moved eastward into the Plains states. By the morning of March 23, it was centered over the Kansas–Nebraska border (Figure 9–20). At this time, the central pressure had reached 985 millibars, and its well-developed cyclonic circulation exhibited a warm front and a cold front.

During the next 24 hours, the forward motion of the storm's center became sluggish. It curved slowly northward through Iowa, and the pressure deepened to 982 millibars (Figure 9–21). Although the storm center advanced slowly, the associated fronts moved vigorously toward the east and somewhat northward. The northern sector of the cold front overtook the warm front and generated an occluded front, which by the morning of March 24 was oriented nearly east-west (Figure 9–21).

This period in the storm's history marked one of the worst blizzards ever to hit the north-central states. While

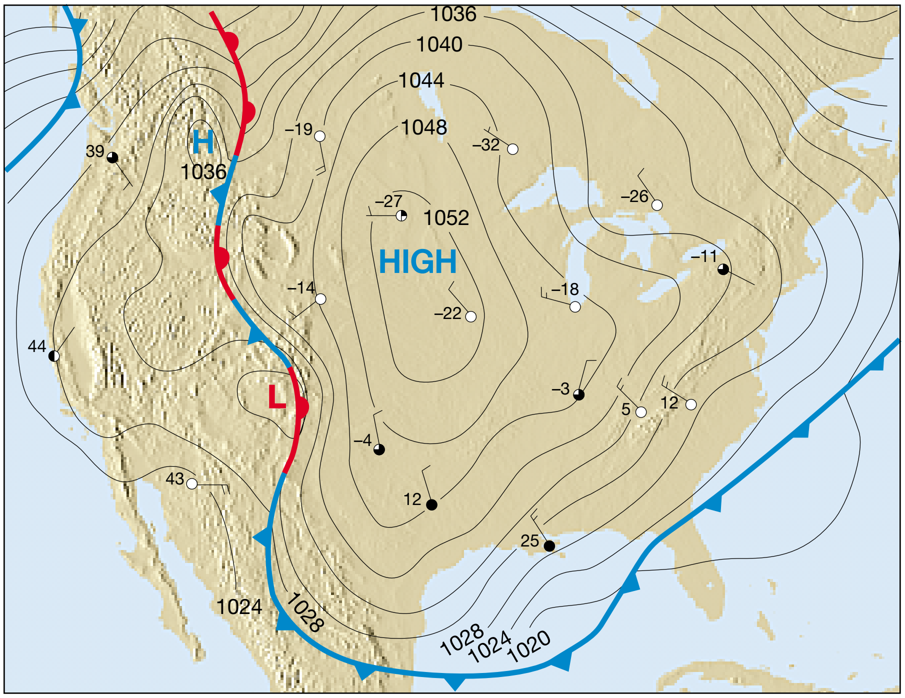


FIGURE 9-18 A cold anticyclone associated with an outbreak of frigid arctic air impacts the eastern two-thirds of North America. Temperatures are shown in degrees Fahrenheit.

FIGURE 9-19 Cold outbreak of arctic air invades New England, bringing subzero temperatures and mostly clear skies. *(Photo by Karen Thomas/PictureQuest)*

BOX 9-2 Atmospheric Hazard: The Great Flood of 1993

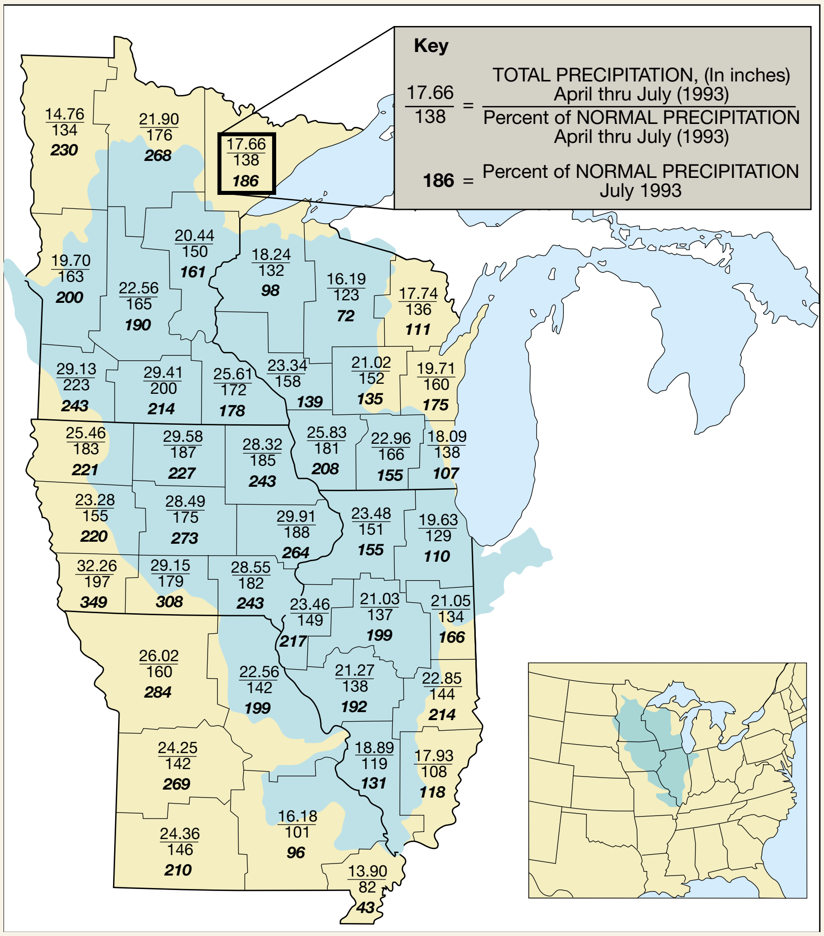
by Steven Hilberg*

Unprecedented rainfall produced the wettest spring and early summer of the twentieth century for the Upper Mississippi River basin (upstream of Quincy, Illinois), according to rainfall data gathered by the Midwestern Regional Climate Center at the Illinois State Water Survey. Portions of the basin received over twice the normal rainfall (Figure 9–A).

The magnitude of rainfall over such a vast area of the Upper Midwest resulted in flooding of extraordinary and catastrophic proportions on the Mississippi and many of its tributaries, affecting large portions of Illinois, Iowa, Kansas, Minnesota, Missouri, Nebraska, South Dakota, and Wisconsin (Figure 9–B).

Soils throughout the Midwest were already saturated from ample rainfall in summer and fall 1992, and

FIGURE 9-A Precipitation data for the upper Mississippi River basin between April 1 and July 31, 1993. *(Data from the Illinois State Water Survey)*



the winter storm was brewing in the north, the cold front marched from northwestern Texas (on March 23) to the Atlantic Ocean (March 25). During its two-day trek to the ocean, this violent cold front generated numerous severe thunderstorms and 19 tornadoes.

By March 25 the low pressure had diminished in intensity (1000 millibars) and had split into two centers (Figure 9–22). Although the remnant low from this system, which was situated over the Great Lakes, generated some snow for the remainder of March 25, by the following day it had completely dissipated.

Violent Spring Weather

Now that you have read an overview of this storm, let us revisit this cyclone's passage in detail using the weather charts for March 23 through March 25 (Figures 9–20 to 9–22). The weather map for March 23 depicts a classic developing cyclone. The warm sector of this system, as exemplified by Fort Worth, Texas, is under the influence of a warm, humid air mass having a temperature of 70°F and a dew-point temperature of 64°F. Notice in the warm sector that winds are from the south and are overrunning cooler

FIGURE 9-B Water rushes through a break in an artificial levee in Monroe County, Illinois. During the record-breaking 1993 Midwest floods, many artificial levees could not withstand the force of the floodwaters. Sections of many weakened structures were overtopped or simply collapsed. *(Photo by James A. Finley/AP/Wide World Photos)*

soils remained moist as winter began. This pattern continued into spring and summer 1993.

Compared to the long-term average, rainfall in the Upper Mississippi River basin during April and May was 40 percent higher than average, and June rainfall was double the average. As the deluge continued through July, much of the basin received rainfall between two and three times the norm.

A stationary weather pattern over the United States was responsible for the Midwest's persistent, drenching rains. Most of the showers and thunderstorms developed in the boundary area between cooler air over the Northern Plains and warm, very humid air over the South. This front oscillated north and south over the Midwest during much of June and July. Meanwhile, a strong high-pressure system (the "Bermuda High") became anchored over the southeastern United States, blocking the progression of weather systems through the eastern half of the nation.

Some of the individual station reports were nothing short of astounding. In northwestern Missouri, Skidmore reported 25.35 inches of rain in July, and Worth County reported 30.30 inches through July 25. Normal July rainfall for this area is about 4 inches, while the average annual rainfall is 35 inches. Alton (northwestern Iowa) had a July rainfall total of 20.41 inches, and Leon (southcentral Iowa) reported 20.68 inches.

July rainfall in Illinois was also much above normal in most areas, but maximum amounts were in the 10- to 15-inch range: 10.65 inches at the Quincy Memorial Bridge, 11.45 inches at Monmouth, 11.83 inches at Galesburg, and 13.88 inches at Flora. Rainfall totals such as these leave no doubt that the record-breaking flooding on the Mississippi and other rivers in the Midwest was directly related to the exceptional rainfall during the spring and early summer.

*Steven Hilberg is Meteorologist and Director, Office of Extension Services and Operations, Illinois State Water Survey.

air situated north of the warm front. In contrast, the air behind the cold front is 20° to 40°F cooler than the air of the warm sector and is flowing from the northwest, as depicted by the data for Roswell, New Mexico.

Prior to March 23, this system had generated some precipitation in the Northwest and as far south as California. On the morning of March 23, little activity was occurring along the fronts. As the day progressed, however, the storm intensified and changed dramatically. The map for March 24 illustrates the highly developed cyclone that evolved during the next 24 hours. The extent and spacing of the isobars indicate a strong system that affected the circulation of the entire eastern two-thirds of the United States. A glance at the winds reveals a robust counterclockwise flow converging on the low.

The activity in the cold sector of the storm just north of the occluded front produced one of the worst March blizzards ever to affect the northcentral United States. In the Duluth–Superior area of Minnesota and Wisconsin, winds of up to 81 miles per hour were measured. Unofficial estimates

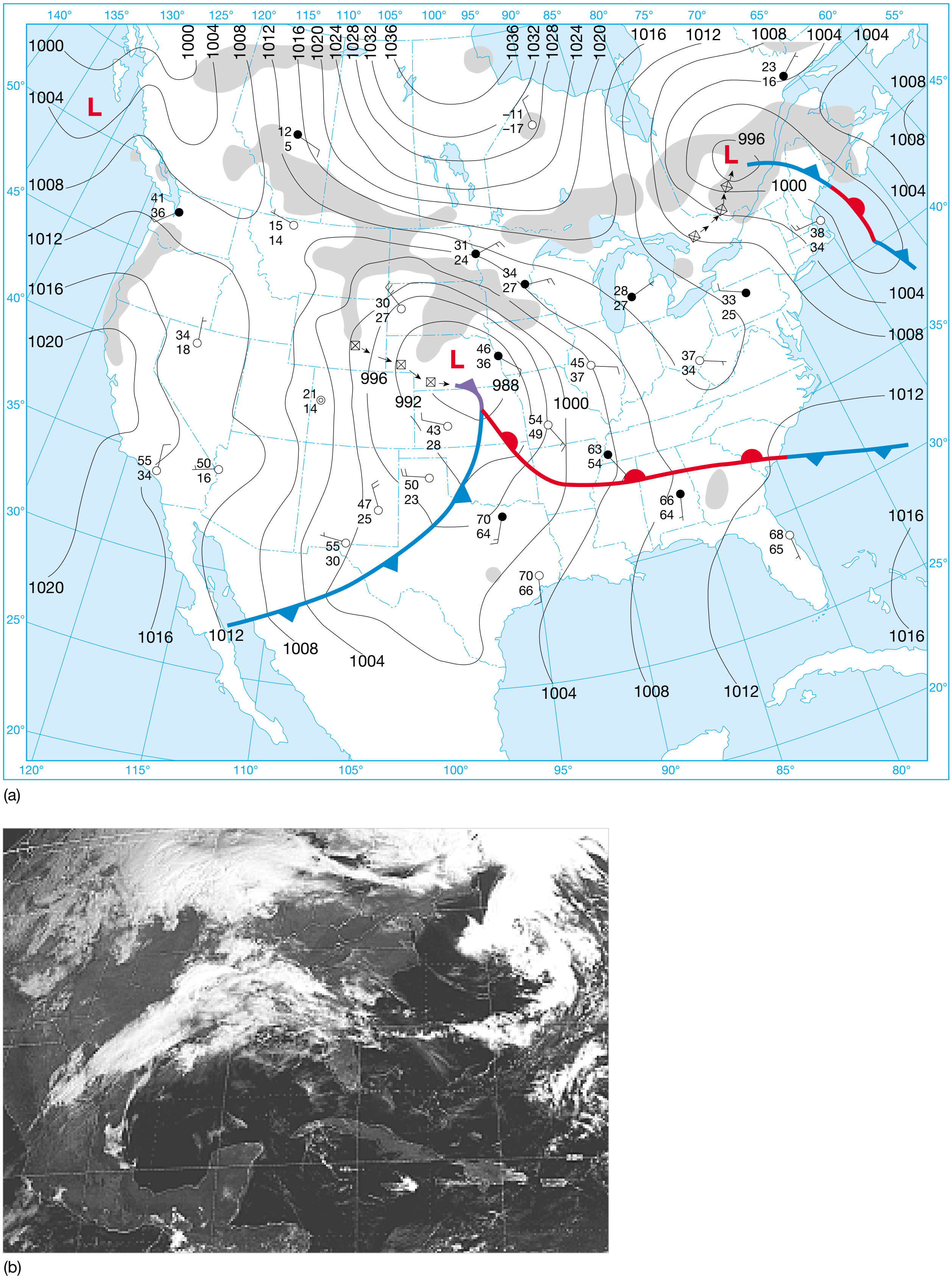


FIGURE 9-20 (a) Surface weather map for March 23. (b) Satellite image showing the cloud patterns for March 23. *(Courtesy of NOAA/Seattle)*

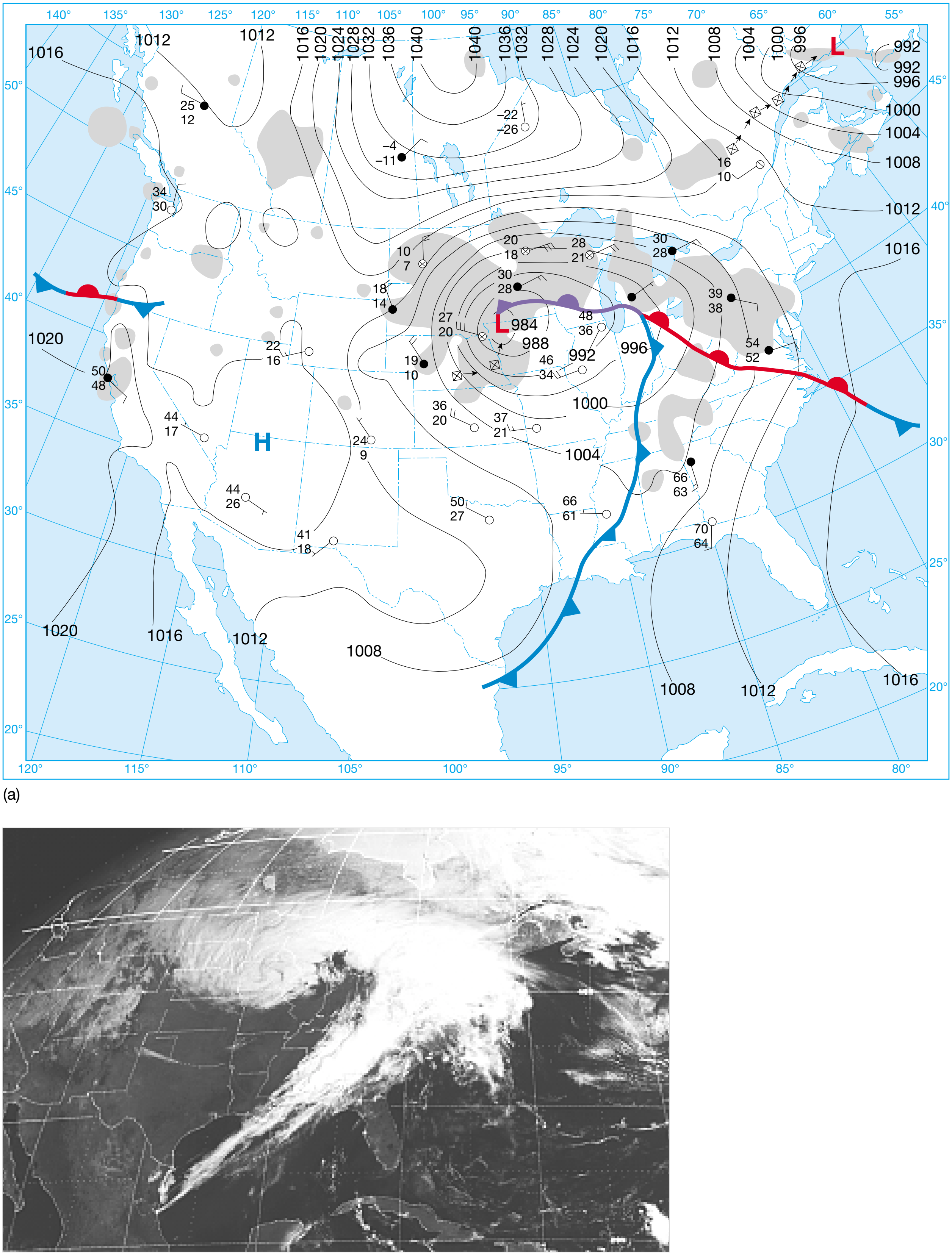


FIGURE 9-21 (a) Surface weather map for March 24. (b) Satellite image showing the cloud patterns on that day. *(Courtesy of NOAA/Seattle)*

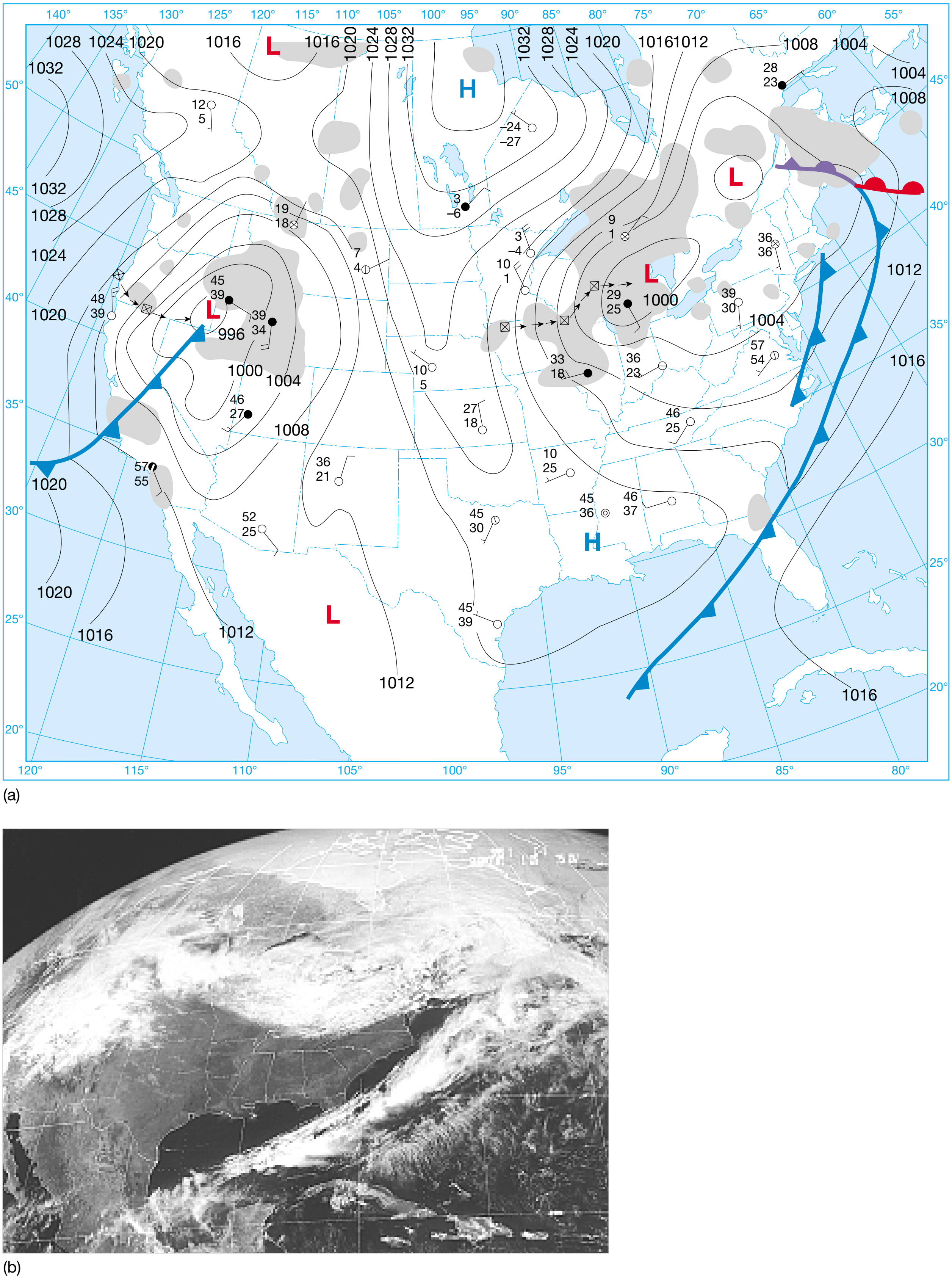


FIGURE 9-22 (a) Surface weather map for March 25. (b) Satellite image showing the cloud patterns on that day. *(Courtesy of NOAA/Seattle)*

of wind speeds in excess of 100 miles per hour were made on the aerial bridge connecting these cities. Winds blew 12 inches of snow into 10- to 15-foot drifts, and some roads were closed for three days (Figure 9–23). One large supper club in Superior was destroyed by fire because drifts prevented fire-fighting equipment from reaching the blaze.

At the other extreme was the weather produced by the cold front as it closed in on the warm, humid air flowing into the warm sector. By the late afternoon of March 23, the cold front had generated a hailstorm in parts of eastern Texas. As the cold front moved eastward, it affected all of the southeastern United States except southern Florida. Throughout this region, numerous thunderstorms were spawned. Although high winds, hail, and lightning triggered extensive damage, the 19 tornadoes generated by the storm caused even greater death and destruction.

The path of the front can be easily traced from the reports of storm damage. By the evening of March 23, hail and wind damage were reported as far east as Mississippi and Tennessee. Early on the morning of March 24, golf ball size hail was reported in downtown Selma, Alabama. About 6:30 A.M. that day the "Governor's Tornado" struck Atlanta, Georgia. Here the storm displayed its worst temper. Damage was estimated at over $50 million, three lives were lost, and 152 people were injured. The 12-mile path of the "Governor's Tornado" cut through an affluent residential area of Atlanta that included the governor's mansion (hence the name). (The official report on this tornado notes than no mobile homes lay in the tornado's path. Why was this fact worth noting?) The final damage along the cold front was reported at 4:00 A.M. on March 25 in northeastern Florida. Here hail and a small tornado caused minor damage. Thus, a day and a half and some 1200 kilometers (about 750 miles) after the cold front became active in Texas, it left the United States to vent its energy harmlessly over the Atlantic Ocean.

By the morning of March 24, you can see that cold polar air had penetrated deep into the United States behind the cold front (Figure 9–21). Fort Worth, Texas, which just the day before was in the warm sector, now experienced cool northwest winds. Subfreezing temperatures had moved as far south as northern Oklahoma. Notice, however, that by March 25, Fort Worth was again experiencing a southerly flow. We can conclude that this was a result of the decaying cyclone that no longer dominated the circulation in the region. We can also safely assume that a warming trend was experienced in Fort Worth over the next day or so. Also notice on the map for March 25 that a high was situated over southwestern Mississippi. The clear skies and weak surface winds associated with the center of a subsiding air mass are well illustrated here.

You may have already noticed another cyclone moving in from the Pacific on March 25 as our storm exited to the east. This storm developed in a similar manner, but was centered somewhat farther north. As you might guess, another blizzard hammered the northern Plains states and a few tornadoes spun through Texas, Arkansas, and Kentucky, while precipitation dominated the weather in the central and eastern United States.

FIGURE 9-23 Paralyzing blizzard strikes the north-central United States. *(Photo by Mike McCleary/Bismarck Tribune)*

Weather in Peoria

Having examined the general weather associated with the passage of this cyclone from March 23 through March 25, let us now look at the weather experienced at a single location during this time. We have selected Peoria, a city in central Illinois located just north of the Springfield station shown on the weather charts.

Before you read the description of Peoria's weather, try to answer the following questions by using Table 9–2, which provides weather observations at three-hour intervals during this time period. Also use the three weather charts (Figures 9–20 through 9–22) and recall the general wind and temperature changes expected with the passage of fronts.

1. What type of clouds were probably present in Peoria during the early morning hours of March 23?
2. At approximately what time did the warm front pass through Peoria?
3. List two lines of evidence indicating that a warm front did pass through Peoria.
4. How did the wind and temperature changes during the early morning hours of March 23 indicate the approach of a warm front?
5. Explain the slight temperature increases experienced between 6:00 P.M. and 9:00 P.M. on March 23.
6. By what time had the cold front passed through Peoria?
7. List some changes that indicate the passage of the cold front.
8. The cold front had already gone through Peoria by noon on March 24, so how do you account for the snow shower that occurred during the next 24 hours?
9. Did the thunderstorms in Peoria occur with the passage of the warm front, the cold front, or the occluded front?

TABLE 9-2 Weather data for Peoria, Illinois, March 23 to 25

	Temperature (°F)	Wind direction	Cloud coverage (tenths)	Visibility (miles)	Weather and precipitation
March 23					
00:00	43	ENE	5	15	
3:00 A.M.	43	ENE	8	15	
6:00 A.M.	42	E	5	12	
9:00 A.M.	50	ESE	10	10	
12:00 P.M.	61	SE	10	12	
3:00 P.M.	64	SE	10	10	Thunderstorm with rain showers
6:00 P.M.	64	SE	10	6	Haze
9:00 P.M.	65	S	10	10	Thunderstorm with rain
March 24					
00:00	57	WSW	10	15	
3:00 A.M.	47	SW	2	15	
6:00 A.M.	42	SW	6	15	
9:00 A.M.	39	SW	8	15	
12:00 P.M.	37	SSW	10	15	Snow showers
3:00 P.M.	33	SW	10	10	Snow showers
6:00 P.M.	30	WSW	10	10	Snow showers
9:00 P.M.	26	WSW	10	6	Snow showers
March 25					
00:00	26	WSW	10	15	
3:00 A.M.	25	WSW	10	8	Snow shower
6:00 A.M.	24	WSW	10	1	Snow
9:00 A.M.	26	W	10	3	Snow
12:00 P.M.	25	W	10	12	Snow
3:00 P.M.	27	WNW	10	12	Snow
6:00 P.M.	25	NW	9	12	
9:00 P.M.	24	NW	4	15	

10. Basing your answer on the apparent clearing skies late on March 25, would you expect the low temperature on March 26 to be lower or higher than on March 25? Explain.

Now read the following discussion to obtain a more complete description of the weather you just reviewed.

We begin our weather observations in Peoria just after midnight on March 23 (Table 9–2). The sky contains cirrus and cirrocumulus clouds, and cool winds from the ENE dominate. As the early morning hours pass, we observe a slight wind shift toward the southeast and a very small drop in temperature. Three hours after sunrise, altocumulus clouds are replaced by stratus and nimbostratus clouds that darken the sky, yet the warm front passes without incident. The 20°F increase in temperature and the wind shift from an easterly to a southeasterly flow mark the passage of the warm front as the warm sector moves over Peoria. The pleasant 60°F temperatures are welcome in Peoria, which enjoys a day 14°F above normal.

But the mild weather is short-lived because the part of the cyclone that passed Peoria was near the apex of the storm, where the cold front is generally close behind the warm front. By afternoon the cold front generates numerous thunderstorms from cumulonimbus clouds embedded in the warm sector just ahead of the cold front. Strong winds, half-inch hail, and a tornado cause local damage. The temperature remains unseasonably warm during the thunderstorm activity.

Early on the morning of March 24 the passage of the cold front is marked by a wind shift, rapidly clearing skies, and a temperature drop of nearly 20°F, all in less than four hours. Throughout March 24 southwesterly winds bring cold air around the back (west) side of the intensifying storm (see Figure 9–22). Although the surface fronts have passed, this intense cyclone, with its occluded front aloft, is generating snowfall over a wide area. This is not unusual behavior. Occluding cyclones often slow their movement as this one did. For about 24 hours, snow flurries dominate Peoria's weather picture.

By noon on March 25 the storm has lost its punch and the pressure begins to climb. The skies start clearing and the winds become northwesterly as the once tightly wound storm weakens. The mean temperature on March 25 is 16°F below normal, and the ground is covered with snow.

This example demonstrates the effect of a spring cyclone on the weather of a mid-latitude location. Within just three days, Peoria's temperatures changed from unseasonably warm to unseasonably cold. Thunderstorms with hail were followed by snow showers. You can see how the north–south temperature gradient, which is most pronounced in the spring, generates these intense storms. Recall that it is the role of these storms to transfer heat from the tropics poleward. Because of Earth's rotation, however, this latitudinal heat exchange is complex, for the Coriolis force gives the winds a zonal (west-to-east) orientation. If Earth rotated more slowly or not at all, a more leisurely north-south flow would exist that might reduce the temperature gradient. Thus, the tropics would be cooler and the poles warmer, and the mid-latitudes would not be as stormy.

A Modern View: The Conveyor Belt Model

The Norwegian cyclone model has proven to be a valuable tool for describing the formation and development of mid-latitude cyclones. Although modern ideas have not replaced this model, a great deal more has been learned about the structure and evolution of these storm systems as a result of upper-air and satellite data. Armed with this additional information, meteorologists have developed another model to describe the circulation of a mid-latitude cyclone.

Along with this new way of describing the flow within a cyclone comes a new analogy. Recall that the Norwegian model describes cyclone development in terms of the interactions of air masses along frontal boundaries, similar to armies clashing along battlefronts. By contrast, the new model employs an example from industry—conveyor belts. Just as conveyor belts transport goods (or at airports, people) from one location to another, these atmospheric conveyor belts transport air with distinct characteristics from one location to another.

The modern view of cyclogenesis, called the **conveyor belt model,** provides a good picture of the airflow within a cyclonic system. It consists of three interacting airstreams: two that originate near the surface and ascend, and a third that originates in the uppermost troposphere. A schematic representation of these airstreams is shown in Figure 9–24.

The *warm conveyor belt* (shown in red) carries warm, moist air from the Gulf of Mexico into the warm sector of the mid-latitude cyclone (Figure 9–24). As this airstream flows northward, convergence causes it to slowly ascend. When it reaches the sloping boundary of the warm front, it rises even more rapidly over the cold air that lies beyond (north of) the front. During its ascent, the warm, humid air cools adiabatically and produces a wide band of clouds and precipitation. Depending on atmospheric conditions, drizzle, rain, freezing rain (glaze), and snow are possible. When this airstream reaches the middle troposphere, it begins to turn right (eastward) and eventually joins the general west-to-east flow aloft. The warm conveyor belt is the main precipitation producing air stream in a mid-latitude cyclone.

The *cold conveyor belt* (blue arrow) is airflow that starts at the surface ahead (north of) of the warm front and flows westward toward the center of the cyclone (Figure 9–24). Flowing beneath the warm conveyor belt, this air is moistened by the evaporation of raindrops falling through it. (Near the Atlantic Ocean this conveyor belt has a marine origin and feeds significant moisture into the storm.) Convergence causes this air stream to rise as it nears the center

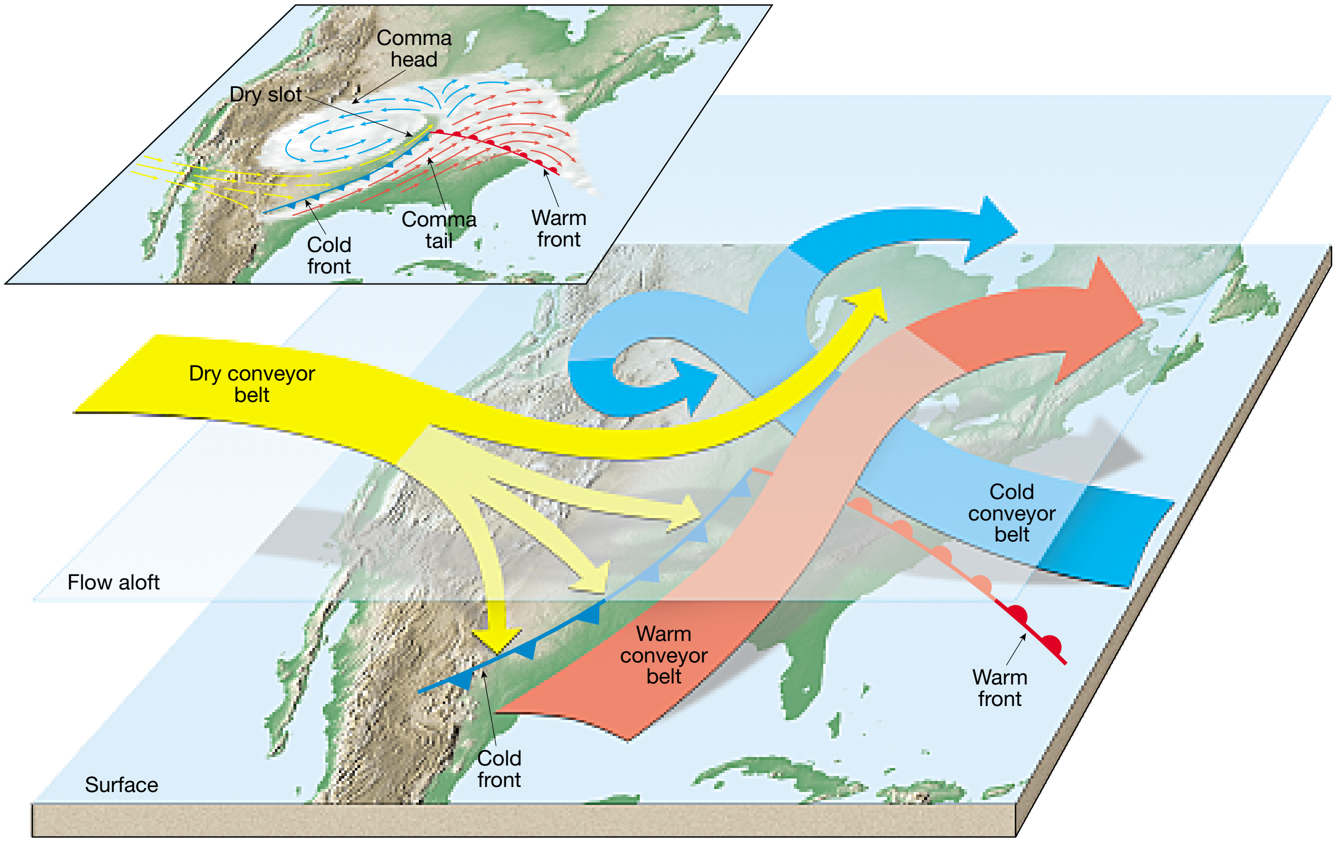
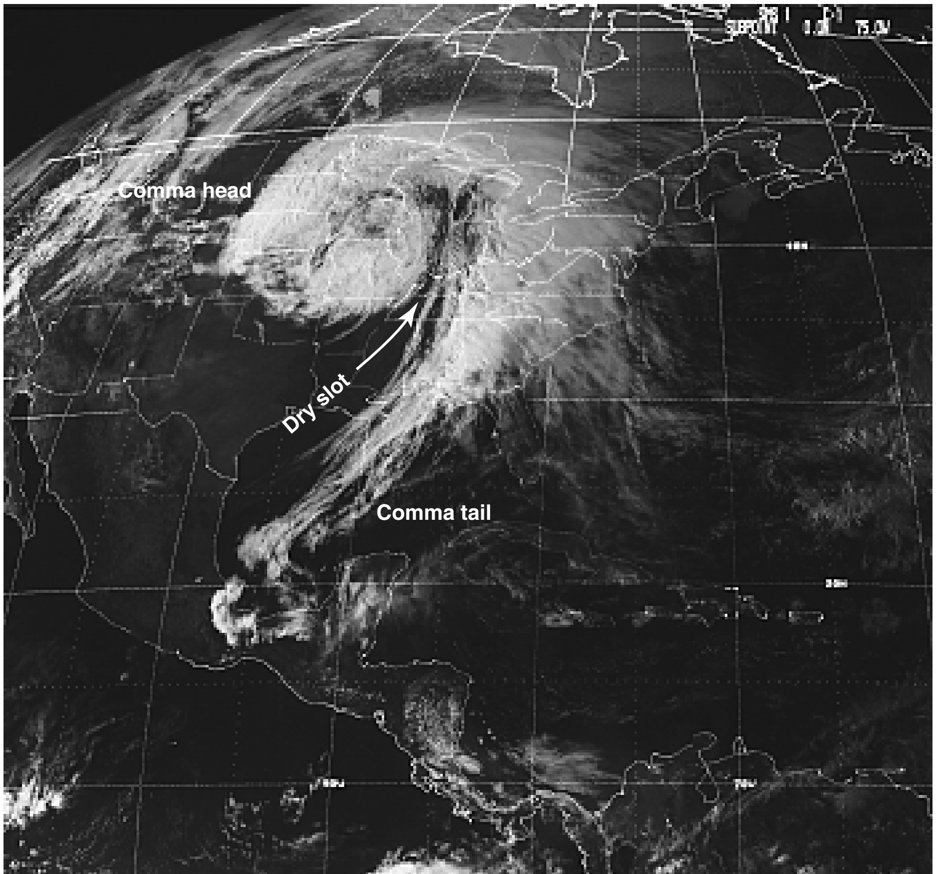


FIGURE 9-24 Schematic drawing of the circulation of a mature mid-latitude cyclone, showing the warm conveyor belt (red), cold conveyor belt (blue), and dry conveyor belt (yellow). The inset shows the cloud cover produced by the warm and cold conveyor belts and the dry slot produced by the dry conveyor belt.

FIGURE 9-25 Satellite view of a mature mid-latitude cyclone over the eastern half of the United States. It is easy to see why we often refer to the cloud pattern of a cyclone as having a "comma" shape. *(Courtesy of John Jensenius/National Weather Service)*



of the cyclone. During its ascent, this air becomes saturated and contributes to the cyclone's precipitation. Upon reaching the middle troposphere, some of the flow rotates cyclonically around the low to produce the distinctive "comma head" of the mature storm system (Figure 9–25). The remaining flow turns right (clockwise) and becomes incorporated into the general westerly flow. Here it parallels the flow of the warm conveyor belt and may generate precipitation.

The third airstream, called the *dry conveyor belt*, is shown as a yellow arrow in Figure 9–24. Whereas the warm and cold conveyor belts begin at the surface, the dry airstream originates in the uppermost troposphere. Being part of the upper-level westerly flow, the dry conveyor belt is relatively cold and dry. As this air stream enters the cyclone, it splits. One branch descends behind the cold front. The result is the clear, cool conditions normally associated with the passage of a cold front. In addition, this flow maintains the strong temperature contrast observed across the cold front. The other branch of the dry conveyor belt maintains its westerly flow and forms the *dry slot* (cloudless area) that separates the head and tail of a comma cloud pattern (Figure 9-25).

In summary, the conveyor belt model of the mid-latitude cyclone provides a three dimensional picture of the major circulation of these storm systems. It also accounts for distribution of precipitation and the comma-shaped cloud pattern characteristic of mature cyclonic storms.

Chapter Summary

- The primary weather producer in the middle latitudes (for our purposes, the region between southern Florida and Alaska, essentially the area of the westerlies) is the *middle-latitude* or *mid-latitude cyclone.* Mid-latitude cyclones are large low pressure systems with diameters often exceeding 1000 kilometers (600 miles) that generally travel from west to east. They last a few days to more than a week, have a counterclockwise circulation pattern with a flow inward toward their centers, and have a cold front and frequently a warm front extending from the central area of low pressure. In the *polar front theory* (also called the *Norwegian cyclone model*), mid-latitude cyclones develop in conjunction with the *polar front.*
- *Fronts* are boundary surfaces that separate air masses of different densities, one usually warmer and more moist than the other. As one air mass moves into another, the warmer, less dense air mass is forced aloft in a process called *overrunning*. The five types of fronts are (1) *warm front,* which occurs when the surface (ground) position of a front moves so that warm air occupies territory formerly covered by cooler air, (2) *cold front,* where cold continental polar air actively advances into a region occupied by warmer air, (3) *stationary front,* which occurs when the airflow on both sides of a front is neither toward the cold air mass nor toward the warm air mass, (4) *occluded front,* which develops when an active cold front overtakes a warm front and wedges the warm front upward, and (5) a *dryline,* a boundary between denser dry, air and less dense humid air often associated with severe thunderstorms during the spring and summer. The two types of occluded fronts are the *cold-type occluded front,* where the air behind the cold front is colder than the cool air it is overtaking, and the *warm-type occluded front,* where the air behind the advancing cold front is warmer than the cold air it overtakes.
- According to the polar front model, mid-latitude cyclones form along fronts and proceed through a generally predictable life cycle. Along the polar front, where two air masses of different densities are moving parallel to the front and in opposite directions, *cyclogenesis* (cyclone formation) occurs and the frontal surface takes on a wave shape that is usually several hundred kilometers long. Once a wave forms, warm air advances poleward invading the area formerly occupied by colder air. This change in the direction of the surface flow causes a readjustment in the pressure pattern that results in almost circular isobars, with the low pressure centered at the apex of the wave. Usually, the position of the cold front advances faster than the warm front and gradually closes the warm sector and lifts the warm front. This process, known as *occlusion,* creates an occluded front. Eventually all the warm sector is forced aloft and cold air surrounds the cyclone at low levels. At this point, the cyclone has exhausted its source of energy and the once highly organized counterclockwise flow ceases to exist.
- Guided by the westerlies aloft, cyclones generally move eastward across the United States. As an idealized mid-latitude cyclone moves over a region, the passage of a warm front places the area under the influence of a maritime tropical air mass and its generally warm temperatures, southerly winds, and clear skies. The passage of a cold front is easily detected by a wind shift, the replacement of south or southwesterly winds with winds from the west or northwest. There is also a pronounced drop in temperature. A passing occluded front is often associated with cool, overcast conditions, and snow or glaze during the cool months.
- Airflow aloft (divergence and convergence) plays an important role in maintaining cyclonic and anticyclonic circulation. In a cyclone, divergence aloft does not involve the outward flow of air in all directions. Instead, the winds flow generally from west to east, along sweeping curves. Also, at high altitudes, speed variations within the jet stream cause air to converge in areas where the velocity slows, and to diverge where air is accelerating. In addition to *speed divergence, directional divergence* (the horizontal spreading of an air stream) and *vorticity* (the amount of rotation exhibited by a mass of moving air) also contribute to divergence (or convergence) aloft.

- During the colder months, when temperature gradients are steepest, cyclonic storms advance at their fastest rate. Furthermore, the westerly airflow aloft tends to steer these developing pressure systems in a general west-to-east direction. Cyclones that influence western North America originate over the Pacific Ocean. Although most Pacific storms do not cross the Rockies intact, many redevelop on the lee (eastern) side of these mountains. Some cyclones that affect the United States form over the Great Plains and are associated with an influx of maritime tropical air from the Gulf of Mexico. Another area where cyclogenesis occurs is east of the southern Appalachians. These cyclones tend to migrate toward the northeast, impacting the Eastern Seaboard.
- Due to the gradual subsidence within them, anticyclones generally produce clear skies and calm conditions. One to three times each winter, large highs, called *blocking highs*, persist over the middle latitudes and deflect the nearly zonal west-to-east flow poleward. These stagnant anticyclones block the eastward migration of cyclones, keeping one section of the nation dry for a week or more while another region experiences one cyclonic storm after another. Also due to subsidence, large stagnant anticyclones can produce a temperature inversion that contributes to air pollution episodes.
- In the spring, Earth's pronounced north–south temperature gradient can generate intense cyclonic storms. At a mid-latitude location, as a spring cyclone with its associated fronts passes, temperatures can change quickly from unseasonably warm to unseasonably cold, and thunderstorms with hail can be followed by snow showers.

Vocabulary Review

cold front (p. 257)
cold-type occluded front (p. 258)
conveyor belt model (p. 279)
cyclogenesis (p. 260)
dryline (p. 260)
front (p. 254)
middle-latitude (mid-latitude) cyclone (p. 252)
Norwegian cyclone model (p. 253)
occluded front (p. 258)
occlusion (p. 262)
overrunning (p. 255)
polar-front theory (p. 253)
speed divergence (p. 266)
stationary front (p. 258)
warm front (p.256)
warm-type occluded front (p. 258)

Review Questions

1. How did the early Norwegian meteorologists describe fronts?

2. If you were located 400 kilometers ahead of the surface position of a typical warm front, how high would the frontal surface be above you?

3. Compare the weather of a warm front with that of a cold front.

4. Why is cold-front weather usually more severe than warm-front weather?

5. Explain the basis for the following weather proverb:

Rain long foretold, long last;

Short notice, soon past.

6. How does a stationary front produce precipitation when its position does not change, or changes very slowly?

7. Distinguish between cold-type and warm-type occluded fronts.

8. Describe the initial stage in the formation of a mid-latitude cyclone.

9. Mid-latitude cyclones are sometimes called *wave cyclones*. Why do you think this is so?

10. Although the formation of an occluded front often represents a period of increased intensity for a mid-latitude cyclone, it also marks the beginning of the end of the system. Explain why such is the case.

11. For each of the weather elements listed here, describe the changes that an individual experiences when a middle-latitude cyclone passes with its center *north* of the observer. (*Hint:* See Figures 9–11 and 9–12)
   a. wind direction
   b. pressure tendency
   c. cloud type
   d. cloud cover
   e. precipitation
   f. temperature

12. Describe the weather conditions that an observer would experience if the center of a mid-latitude cyclone passed to the south.

13. Distinguish between veering and backing winds (see Box 9–1).

14. Briefly explain how the flow aloft maintains cyclones at the surface.

15. What is speed divergence? Speed convergence?

16. Given an upper air chart, where do forecasters usually look to find favorable sites for cyclogenesis? Where do anticyclones usually form in relation to the upper-level flow?

17. What are two possible ways a blocking high might influence the weather?

18. Briefly describe the various weather phenomena that could be associated with a strong springtime cyclonic storm traveling across the United States.

Atmospheric Science Online

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