Pearson New International Edition

McKnight's Physical Geography
A Landscape Appreciation
Darrel Hess Dennis Tasa
Eleventh Edition

ALWAYS LEARNING

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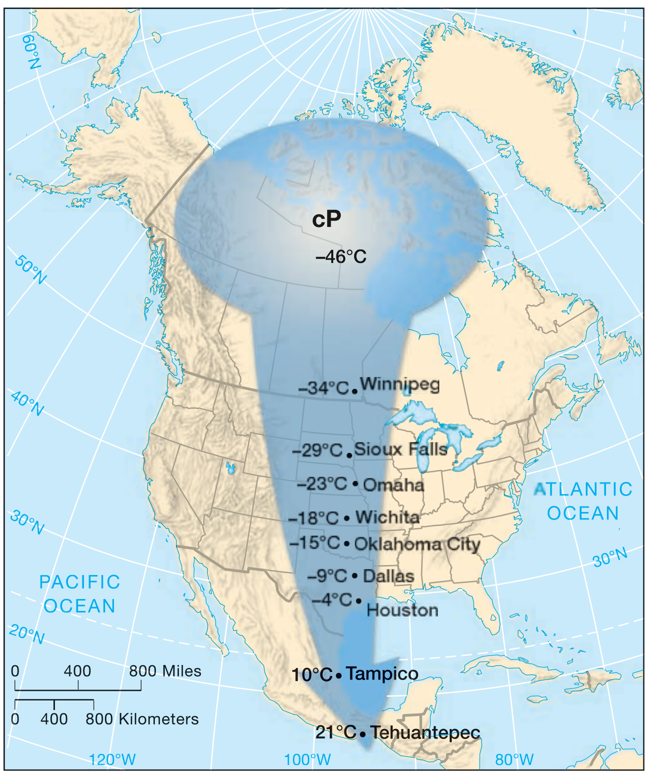
TABLE 1 Simplified Classification of Air Masses

Type	Code	Source Regions	Source Region Properties
Arctic/Antarctic	A	Antarctica, Arctic Ocean and fringes, and Greenland	Very cold, very dry, very stable
Continental polar	cP	High-latitude plains of Eurasia and North America	Cold, dry, very stable
Maritime polar	mP	Oceans in vicinity of 50°–60° N and S latitude	Cold, moist, relatively unstable
Continental tropical	cT	Low-latitude deserts	Hot, very dry, unstable
Maritime tropical	mT	Tropical and subtropical oceans	Warm, moist, of variable stability
Equatorial	E	Oceans near the equator	Warm, very moist, unstable

part to dynamic modification (uplift, subsidence, convergence, turbulence), and perhaps also in part to addition or subtraction of moisture.

Once it leaves its source area, an air mass modifies the weather of the regions into which it moves: it takes source-region characteristics into other regions. A classic example of this modification is displayed in Figure 2, which diagrams a situation that may occur one or more times every winter. A midwinter outburst of continental polar (cP) air from northern Canada sweeps down across the central part of North America. With a source-region temperature of –46°C (–50°F) around Great Slave Lake, the air mass has warmed to –34°C (–30°F) by the time it reaches Winnipeg, Manitoba, and it continues to warm as it moves southward. Throughout its southward course, the air mass becomes warmer, but it also brings some of the coldest weather that each of these places will receive all winter. Thus, the air mass is modified, but it also modifies the weather in all regions it passes through.



▲ **Figure 2** An example of temperatures resulting from a strong midwinter outburst of cP air from Canada. All temperatures are in degrees Celsius.

Temperature, of course, is only one of the characteristics modified by a moving air mass. There are also modifications in humidity and stability.

North American Air Masses

The North American continent is a prominent area of air mass interaction. The lack of mountains trending east to west permits polar air to sweep southward and tropical air to flow northward unhindered by terrain, particularly over the eastern two-thirds of the continent (see Figure 1). In the western part of the continent, though, air masses moving off the Pacific are impeded by the prominent north–south trending mountain ranges.

Continental polar (cP) air masses develop in central and northern Canada, and *Arctic* (A) air masses originate farther north and so are colder and drier than cP air masses—both are dominant features in winter with their cold, dry, stable nature.

Maritime polar (mP) air from the Pacific in winter can bring cloudiness and heavy precipitation to the mountainous west coastal regions. In summer, cool Pacific mP air produces fog and low stratus clouds along the coast. North Atlantic mP air masses are also cool, moist, and unstable, but except for occasional incursions into the mid-Atlantic coastal region, Atlantic mP air does not affect North America because the prevailing circulation of the atmosphere is westerly.

Maritime tropical (mT) air from the Atlantic/Caribbean/Gulf of Mexico is warm, moist, and unstable. It strongly influences weather and climate east of the Rockies in the United States, southern Canada, and much of Mexico, serving as the principal precipitation source in this broad region. It is more prevalent in summer than in winter, bringing periods of uncomfortable humid heat.

Pacific mT air originates over water in areas of anticyclonic subsidence, and so it tends to be cooler, drier, and more stable than Atlantic mT air; it is felt only in the southwestern United States and northwestern Mexico, where it may produce coastal fog and moderate orographic rainfall where forced to ascend mountain slopes. It is also the source of some summer rains in the southwestern interior.

Continental tropical (cT) air is relatively unimportant in North America because its source region is not extensive. In summer, hot, very dry, unstable cT air surges into the southern Great Plains area on occasion, bringing heat waves and dry conditions.

Equatorial (E) air affects North America only in association with hurricanes. It is similar to mT air except that E air provides an even more copious source of rain than does mT air because of high humidity and instability.

Learning Check 2 Describe and explain the temperature and moisture characteristics of a maritime polar (mP) air mass.

FRONTS

When unlike air masses meet, they do not mix readily; instead, a boundary zone called a **front** develops between them. A front is not a simple two-dimensional boundary. A typical front is a narrow three-dimensional transition zone several kilometers or even tens of kilometers wide. Within this zone, the properties of the air change rapidly.

The frontal concept was developed by Norwegian meteorologists during World War I, and the term *front* was coined because these scientists considered the clash between unlike air masses to be analogous to a confrontation between opposing armies along a battle front. As the more "aggressive" air mass advances at the expense of the other, some mixing of the two occurs within the frontal zone, but for the most part the air masses retain their separate identities as one is displaced by the other.

Types of Fronts: The most conspicuous difference between air masses is usually temperature. A **cold front** forms where an advancing cold air mass meets and displaces warmer air (Figure 3), whereas a **warm front** forms where an advancing warm air mass meets colder air (Figure 4). In both cases, there is warm air on one side of the front and cool air on the other, with a fairly abrupt temperature gradient between. Air masses may also have different densities, humidity levels, wind patterns, and stability, and so these factors can have a steep gradient through the front as well.

In some cases, a front may remain stationary for a few hours or even a few days. More commonly, however, a front is in more or less constant motion. Usually one air mass is displacing the other; thus, the front advances in the direction dictated by the movement of the more active air mass.

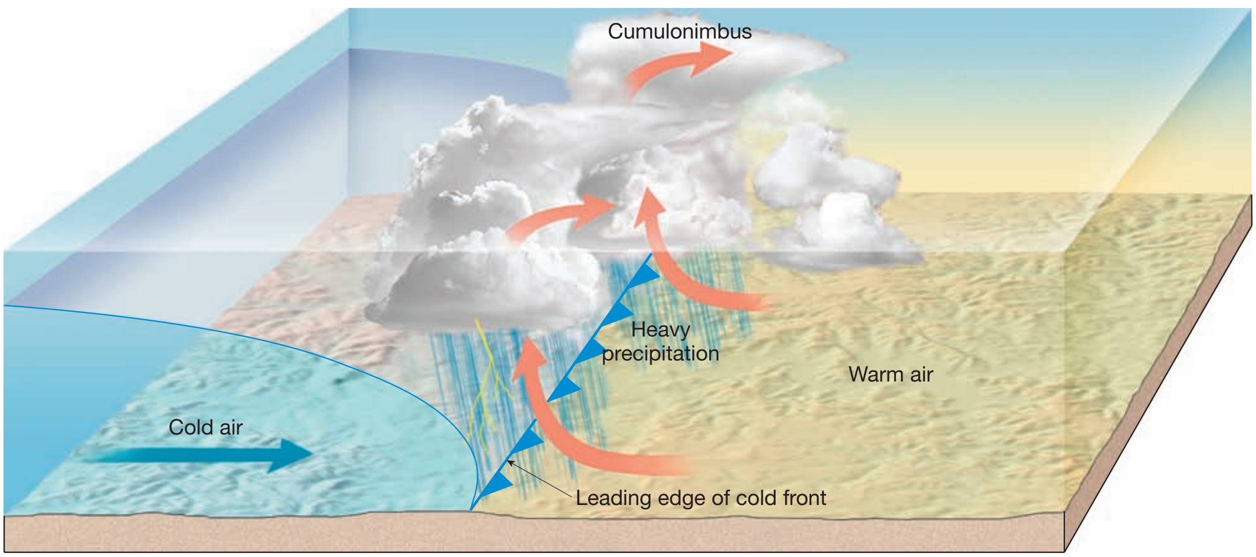
Regardless of which air mass is advancing, it is always the warmer air that rises over the cooler. The warmer, lighter air is inevitably forced aloft, and the cooler, denser air mass functions as a wedge over which the lifting occurs. As you can see in Figures 3 and 4, fronts "lean" or slope upward from the surface, and it is along this slope that the warmer air rises and cools adiabatically to form clouds and often precipitation. Indeed, fronts lean so much that they are much closer to horizontal features than vertical ones. The slope of a typical front averages about 1:150, meaning that 150 kilometers away from the surface position of the front, the height of the front is only 1 kilometer above the ground. Because of this very low angle of slope (less than 1°), the steepness shown in most diagrams of fronts is greatly exaggerated.

Notice that the "leading edge" of a cold front precedes its higher altitude "trailing edge," whereas a warm front leans "forward" so that the higher altitude part of the front is ahead of its lower altitude "trailing edge."

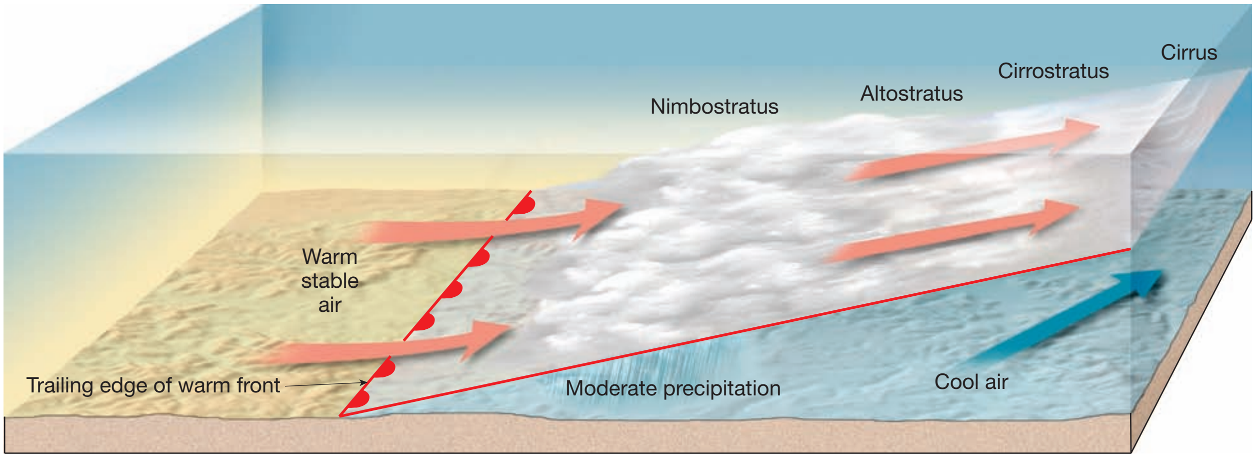
Cold Fronts

Animation
Cold Fronts

Because of friction with the ground, the advance of the lower portion of a cold air mass is slowed relative to the upper portion. As a result, a cold front tends to become steeper as it moves forward and usually develops a



▲ **Figure 3** A cold front forms when a cold air mass is actively underriding a warm air mass. As a cold front advances, the warm air ahead of it is forced upward. This displacement often creates cloudiness and relatively heavy precipitation along and immediately behind the ground-level position of the front. (In this diagram, the vertical scale has been exaggerated.)



▲ **Figure 4** A warm front forms when a warm air mass is actively overriding a cold air mass. As warm air rises above cooler air, widespread cloudiness and precipitation develop along and in advance of the ground-level position of the front. Higher and less dense clouds are often dozens or hundreds of kilometers ahead of the ground-level position of the front. (In this diagram, the vertical scale has been exaggerated.)

protruding "nose" a few hundred meters above the ground (see Figure 3). The average cold front is twice as steep as the average warm front. Moreover, cold fronts normally move faster than warm fronts because the dense, cold air mass easily displaces the lighter, warm air.

This combination of steeper slope and faster advance leads to rapid lifting and adiabatic cooling of the warm air ahead of the cold front. The rapid lifting often makes the warm air very unstable, and the result is blustery and violent weather along the cold front. Vertically developed clouds, such as cumulonimbus clouds, are common, with considerable turbulence and showery precipitation. Both clouds and precipitation tend to be concentrated along and immediately behind the ground-level position of the front. Precipitation is usually of higher intensity but shorter duration than that associated with a warm front.

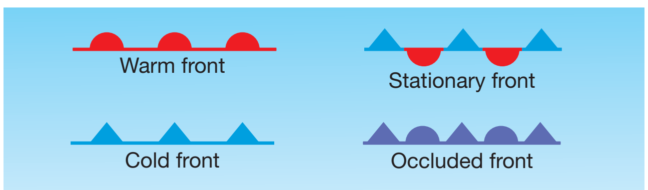
On a weather map, the ground-level position of a cold front is shown either by a blue line or a solid line studded at intervals with solid triangles that extend in the direction toward which the front is moving (Figure 5).

Warm Fronts

The slope of a typical warm front is more gentle than that of a cold front, averaging about 1:200 (see Figure 4). As the warm air pushes against and rises over the retreating cold air, it cools adiabatically, usually resulting in clouds and precipitation. Because the frontal uplift is very gradual, clouds form slowly and turbulence is limited. High-flying cirrus clouds may signal the approaching front many hours before it arrives. As the front comes closer, the clouds become lower, thicker, and more extensive, typically developing into altocumulus or altostratus. Precipitation usually occurs broadly; it is likely to be protracted and gentle, without much convective activity. If the rising air is inherently unstable, however, precipitation can be showery and even violent. Most precipitation falls ahead of the ground-level position of the moving front.

Animation
Warm Fronts

The ground-level position of a warm front is portrayed on a weather map either by a red line or by a solid line along which solid semicircles are located at regular intervals, with the semicircles extending in the direction toward which the front is moving (see Figure 5).



▲ **Figure 5** Weather map symbols for fronts.

Learning Check 3 **What is the difference between a cold front and a warm front?**

Stationary Fronts

When neither air mass displaces the other—or if a cold front or warm front "stalls"—their common boundary is called a **stationary front**. It is difficult to generalize about the weather along such a front, but often gently rising warm air produces limited precipitation similar to that along a warm front. As Figure 5 shows, stationary fronts are portrayed on a weather map by a combination of warm and cold front symbols, alternating on opposite sides of the line—cold air is opposite the triangles, and warm air opposite the half circles.

Occluded Fronts

A fourth type of front, called an *occluded front*, is formed when a cold front overtakes a warm front. Occluded fronts are shown on a weather map by a combination of warm and cold front symbols, alternating on the same side of the line. The development of occluded fronts is discussed later in this chapter.

Air Masses, Fronts, and Major Atmospheric Disturbances

We will now turn our attention to the major kinds of atmospheric disturbances that occur within the general circulation. Most of these disturbances involve unsettled and sometimes violent atmospheric conditions and are referred to as *storms*. Some, however, produce calm, clear, quiet weather that is quite the opposite of stormy. Some of these disturbances involve air mass contrasts or fronts, and many are associated with migrating pressure cells.

The following are common characteristics of atmospheric disturbances in general:

- They are smaller than the components of the general circulation, although they are extremely variable in size.
- They are migratory.
- They have a relatively brief duration, persisting for only a few minutes, a few hours, or a few days.
- They produce characteristic and relatively predictable weather conditions.

Midlatitude Disturbances: The midlatitudes are the principal "battleground" of tropospheric phenomena: where polar and tropical air masses meet, where most fronts occur, and where weather is most dynamic and changeable from season to season and from day to day. Many kinds of atmospheric disturbances are associated with the midlatitudes, but two of these—*midlatitude cyclones* and *midlatitude anticyclones*—are much more important than the others because of their size and prevalence.

Tropical Disturbances: The low latitudes are characterized by monotony—the same weather day after day, week after week, month after month. Almost the only breaks are provided by transient atmospheric disturbances, of which by far the most significant are *tropical cyclones* (locally known as *hurricanes* when they intensify), but also less dramatic disturbances known as *easterly waves*.

Localized Severe Weather: Other localized atmospheric disturbances occur in many parts of the world. Short-lived but sometimes severe atmospheric disturbances such as *thunderstorms* and *tornadoes* often develop in conjunction with other kinds of storms.

MIDLATITUDE CYCLONES

Probably most significant of all atmospheric disturbances are **midlatitude cyclones**. Throughout the midlatitudes, they dominate weather maps, are basically responsible for most day-to-day weather changes, and bring precipitation to much of the populated portions of the planet. Consisting of large, migratory low-pressure cells, they are usually called *depressions* in Europe and *lows* or *low pressure systems*, *wave cyclones*, *extratropical cyclones*, or even simply (although not very precisely) as "storms" in the United States.

Midlatitude cyclones are associated primarily with air-mass convergence in regions between about 30° and 70° of latitude. Thus, they are found almost entirely within the band of westerly winds. Their general path of movement is toward the east, which explains why weather forecasting in the midlatitudes is essentially a west-facing vocation.

Because each midlatitude cyclone differs from all others in greater or lesser detail, any description must be a general one only. The discussions that follow, then, pertain to "typical" or idealized conditions. Moreover, these conditions are presented as Northern Hemisphere phenomena. For the Southern Hemisphere, the patterns of isobars, fronts, and wind flow should be visualized as mirror images of the Northern Hemisphere patterns (see Figure 13).

Characteristics

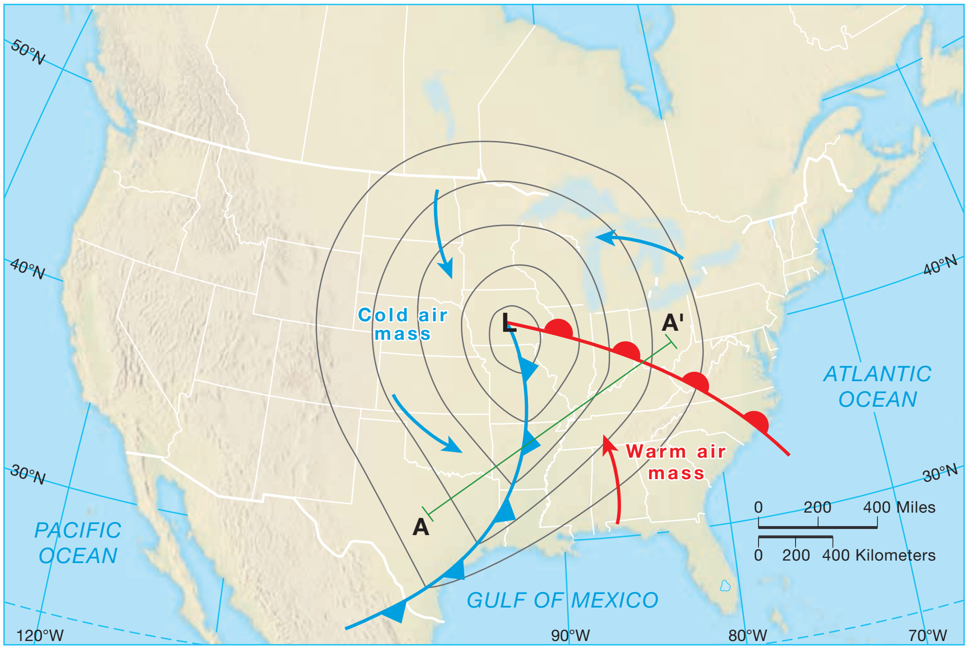
A typical mature midlatitude cyclone has a diameter of 1600 kilometers (1000 miles) or so. It is essentially a vast cell of low-pressure air, with ground-level pressure in the center typically between 990 and 1000 millibars. The system (shown by closed isobars on a weather map, as in Figure 6a) usually tends toward an oval shape, with the long axis trending northeast–southwest. Usually a clear-cut pressure trough extends southwesterly from the center.

Formation of Fronts: Midlatitude cyclones have a converging counterclockwise circulation pattern in the Northern Hemisphere. This wind flow pattern brings together cool air from the north and warm air from the south. The convergence of these unlike air masses characteristically creates two fronts: a cold front that extends to the southwest from the center of the cyclone and runs along the pressure trough extending from the center of the storm, and a warm front extending eastward from the center and running along another, usually weaker, pressure trough.

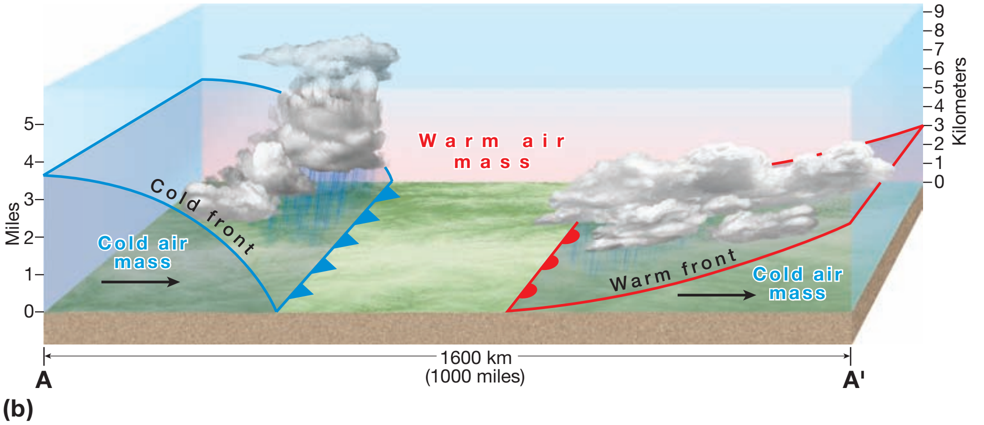
Sectors: The two fronts divide the cyclone into a *cool sector* north and west of the center where the cold air mass is in contact with the ground, and a *warm sector* to the south and east where the warm air mass is in contact with the ground. At the surface, the cool sector is the larger of the two, but aloft the warm sector is more extensive. This size relationship exists because both fronts "lean" over the cool air. Thus, the cold front slopes upward toward the northwest and the warm front slopes upward toward the northeast, as Figure 6b shows.

Learning Check 4 **What causes fronts to develop within a midlatitude cyclone?**

Clouds and Precipitation: Clouds and precipitation develop in the zones within a midlatitude cyclone where air is rising and cooling adiabatically. Because warm air rises along both fronts, the typical result is two zones of cloudiness and precipitation that overlap around the center of the storm (where air is rising in the center of the low pressure cell) and extend outward in the general direction of the fronts.



(a)



(b)

Figure 6 A map (a) and a cross section (b) of a typical mature midlatitude cyclone. In the Northern Hemisphere, there is usually a cold front trailing to the southwest and a warm front extending toward the east. A well-developed trough of low pressure usually accompanies the surface position of the cold front. Arrows in (b) indicate the direction of frontal movement.

Along and immediately behind the ground-level position of the cold front (the steeper of the two fronts), a band of cumuliform clouds usually yields showery precipitation. The air rising more gently along the more gradual slope of the warm front produces a more extensive expanse of horizontally developed clouds, perhaps with widespread, protracted, low-intensity precipitation (Figure 7). In both cases, most of the precipitation originates in the warm air rising above the fronts and falls down through the front to reach the ground in the cool sector.

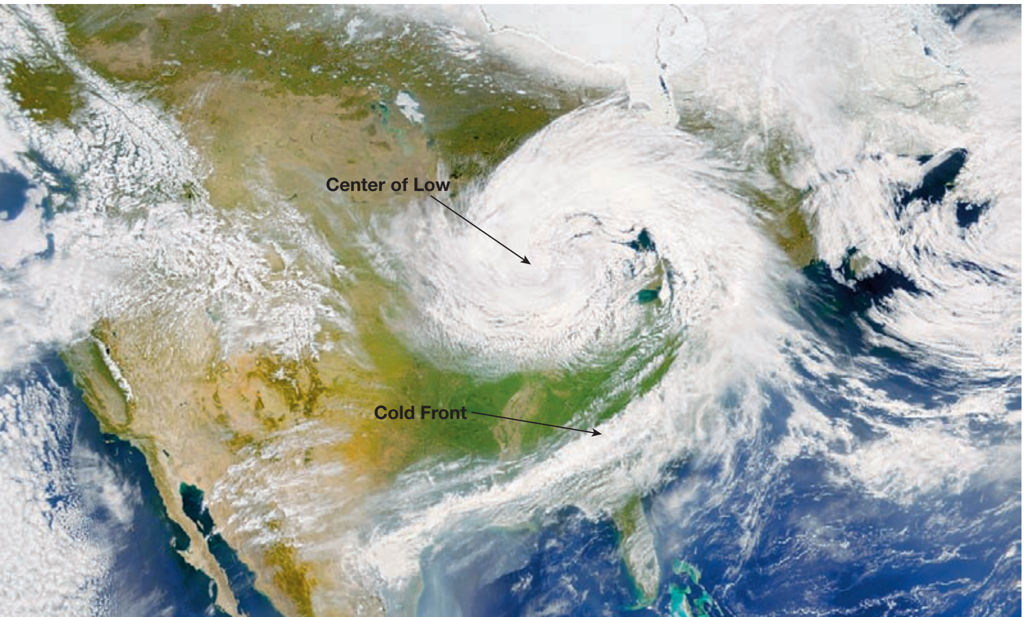


Figure 7 A large midlatitude cyclone centered near Lake Michigan. The band of clouds extending down across the southern states to the west marks the cold front.

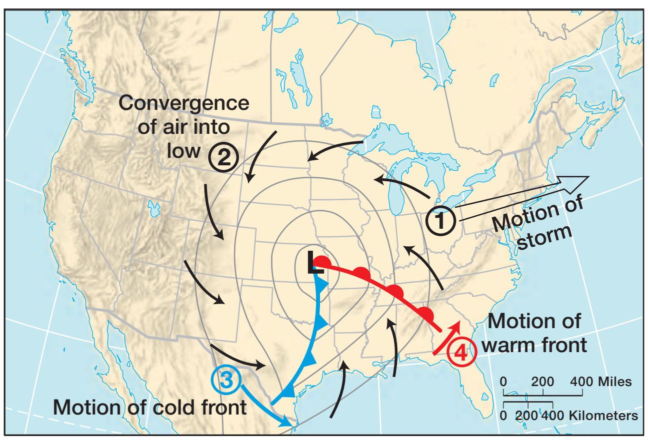
This precipitation pattern does not mean that the entire cool sector has unsettled weather and that the warm sector experiences clear conditions throughout. Although most frontal precipitation falls within the cool sector, the general area to the north, northwest, and west of the center of the cyclone is frequently cloudless as soon as the cold front has moved on. Thus, much of the cool sector is typified by clear, cold, stable air. In contrast, the air of the warm sector is often moist and tending toward instability, and so thermal convection and surface-wind convergence may produce sporadic thunderstorms. Also, sometimes one or more *squall lines* of intense thunderstorms develop in the warm sector in advance of the cold front.

Movements

Animation
Midlatitude Cyclones

Midlatitude cyclones are essentially transient features, on the move throughout their existence. Four kinds of movement are involved (Figure 8):

1. The whole storm moves as a major disturbance in the westerlies, traversing the midlatitudes generally from west to east. The rate of movement averages 30 to 45 kilometers (about 20 to 30 miles) per hour, which means that the storm can cross North America in three to four days (often faster in winter than in summer). The route of a cyclone is likely to be undulating and erratic, although it moves generally from west to east, often in association with the path of the jet stream.
2. The system has a cyclonic wind circulation, with wind generally converging counterclockwise (in the Northern Hemisphere) into the center of the storm from all sides.
3. The cold front usually advances faster than the center of the storm (the advancing dense, cold air easily displaces the lighter, warm air ahead of the front).



▲ **Figure 8** Four components of movement occur in a typical midlatitude cyclone: (1) The entire storm moves west to east in the general flow of the westerlies; (2) airflow is cyclonic converging counterclockwise; (3) the cold front advances; (4) the warm front advances.

4. The warm front usually advances more slowly than the center of the storm, causing it to appear to lag behind. (This is only an apparent motion, however. The warm front is actually moving west to east, just like every other part of the system.)

Learning Check 5 **Explain where and why precipitation develops within a midlatitude cyclone.**

Life Cycle

Cyclogenesis: A typical midlatitude cyclone progresses from origin to maturity, and then to dissipation, in about three to ten days. It is believed that the most common cause of *cyclogenesis* (the birth of cyclones) is upper troposphere conditions in the vicinity of the polar front jet stream. Most midlatitude cyclones begin as "waves" along the polar front. Waves are undulations or curves that develop in the paths taken by upper-level winds such as a jet stream, and that the polar front is the contact zone between the relatively cold polar easterlies and the relatively warm westerlies. The opposing airflows normally have a relatively smooth linear motion on either side of the polar front (Figure 9a). On occasion, however, the smooth frontal surface may be distorted into a wave shape (Figure 9b).

There appears to be a close relationship between upper-level airflow and ground-level disturbances. When the upper airflow is *zonal*—by which we mean relatively straight from west to east—ground-level cyclonic activity is unlikely. When winds aloft begin to meander north to south in a *meridional airflow* (Figure 10), large waves of alternating pressure troughs and ridges are formed and cyclonic activity at ground level is intensified. Most midlatitude cyclones are centered below the polar front jet stream axis and downstream from an upper-level pressure trough.

A cyclone is unlikely to develop at ground level unless there is divergence above it. In other words, the convergence of air near the ground must be supported by divergence aloft. Such divergence can be related to changes in either speed or direction of the wind flow, but it nearly always involves broad north-to-south meanders in the Rossby waves and the jet stream.

Various ground factors—such as topographic irregularities, temperature contrasts between sea and land, or the influence of ocean currents—can apparently initiate a wave along the front. For example, cyclogenesis also occurs on the leeward side of mountains. A low-pressure area drifting with the westerlies becomes weaker when it crosses a mountain range. As it ascends the range, the column of air compresses and spreads, slowing down its counterclockwise spin. When descending the leeward side, the air column stretches vertically and contracts horizontally. This change in shape causes it to spin faster and may initiate cyclonic development even if it were not a full-fledged cyclone before.

This chain of events happens with some frequency in winter on the eastern flanks of the Rocky Mountains,