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### Midlatitude Cyclones

Midlatitude cyclones (also called *extratropical cyclones*, or simply *cyclones* in the rest of this article) are nearly circular regions of reduced surface pressure that generally range in diameter from a few hundred to a few thousand kilometers and occur in association with the jet streams in the middle-latitude regions of the globe (roughly 30°–70° latitude). Cyclones derive their energy from the potential energy in the pole-to-equator temperature gradient. This temperature gradient can become concentrated within zones called *fronts* where the temperature changes rapidly and the wind abruptly shifts direction. Winds around a cyclone blow counterclockwise in the Northern Hemisphere and clockwise in the Southern Hemisphere, transporting warm air poleward and cold air equatorward. Consequently, cyclones are one means by which heat is transported from the tropics to the poles. Because cyclones are the primary source of most winter precipitation in the midlatitudes, understanding the structure and dynamics of cyclones can lead to improved weather forecasts.

**History of Research.** One of the earliest theories of cyclone formation, the *thermal or convectional theory*, was based on James Espy’s work in the 1840s. Espy argued that, as an organized mass of clouds forms, the release of latent heat of condensation in the clouds causes warming, resulting in a decrease in pressure within the air column. This decrease in surface pressure leads to increased inflow of warm, moist air in the lower troposphere and then to further pressure falls upon condensation. Mounting observational evidence indicated that many cyclones were not warm at mid-levels.
as the thermal theory predicts, but cold. By the early 1900s, the stage was set for one of the most profound developments in meteorology—the polar front theory of cyclones (also called the Norwegian cyclone model).

The polar front theory for midlatitude cyclones was developed at the Geophysical Institute in Bergen, Norway, headed by Vilhelm Bjerknes. In a series of landmark papers published just after World War I, Jacob Bjerknes, Halvor Solberg, and Tor Bergeron developed a model for cyclone structure, based on data collected within numerous cyclones. Their results built upon the work of Sir William Napier Shaw, Max Margules, Felix Exner, and other earlier researchers who recognized that cyclones possessed discontinuities in wind and temperature (later called fronts by Bjerknes’s group). Polar front theory was an advance over previous models of cyclones for three reasons. First, polar front theory described for the first time the life cycle of cyclones on the polar front, a globe-encircling boundary between cold polar air and warm tropical air. The Bergen meteorologists argued that cyclones are not unchanging features moving across the Earth; instead, they are born, mature, and die. Second, polar front theory argued that the potential energy in the temperature gradient across the polar front provides the energy for cyclones, not the latent heat release due to condensation. Third, polar front theory represented a simple, elegant, practical, and verifiable representation of midlatitude cyclones, something that had not been developed before.

Polar front theory held that the polar front, initially a straight (linear) feature, may spontaneously produce small perturbations, or waves (Figure 1). As the polar front becomes deformed by one of these waves, a weak cyclonic circulation causes warm tropical air to move poleward and cold polar air to advance equatorward. The cold front rotates around the cyclone more rapidly than the warm front, eventually catching up to the warm front and forming an occluded front. With the formation of an occluded front, the cyclone center becomes surrounded by cold polar air (also known as the occlusion process). As development of the cyclone is contingent upon the conversion of potential energy in the temperature gradient to kinetic energy of the cyclone, the cyclone weakens after occlusion. Therefore, the occlusion process, J. Bjerknes and Solberg argued, represents the beginning of the decay phase of the cyclone. [See Occluded Fronts.]

Although polar-front theory was a monumental advance, several aspects of the theory were not supported by observations of cyclones. First, cyclones, especially those that deepen rapidly, often continue to deepen after the occluded front forms. Thus, the occlusion process is not the end of deepening, as the Bergen meteorologists had described. Instead, an explanation for cyclone development would await further theoretical advances, described below.

![Figure 1](image-url)
Second, the catch up of the cold front by the warm front does not occur in all cyclones, nor does it explain the length of highly spiraled occluded fronts. Instead, the occlusion process is best viewed as the wrap up of the thermal pattern into a spiraled front, a result of the deformation and rotation in the flow around the cyclone center. Third, although the Norwegian cyclone model advocates a close association between clouds/precipitation and surface fronts, clouds and precipitation are often related to processes occurring aloft, not to the surface fronts. New theories to explain these and other discrepancies between polar front theory and observations of cyclones have been proposed and are being evaluated. [See Occluded Fronts.]

The next major advance in understanding midlatitude cyclones occurred after the discovery of the jet stream, a narrow region of high winds in the upper troposphere. In the late 1930s, the global release of instrumented weather balloons, which regularly measure the temperature, humidity, and winds above the surface, made it possible to analyze the structure and motions within the jet stream. Disturbances in the jet stream, called jet streaks and shortwave troughs (Rossby waves), are associated with convergence and divergence. Regions of diverging air at the level of the jet stream are favorable locations for surface cyclones to form owing to evacuation of air in the column. Therefore, for a surface cyclone to deepen, the divergence of air aloft must be greater than the convergence of air into the low-pressure center near the surface. Divergence aloft tends to occur on the east side of a trough, making that region favorable for surface cyclone development. [See Jet Stream.]

As the vertical structure of cyclones and their relationship to the jet stream became better understood, practical means were explored for determining whether a cyclone would intensify or weaken. The most significant contribution during the 1940s and early 1950s came from two European meteorologists, Reginald Sutcliffe and Sverre Petterssen. They found that as a trough in the jet stream (a region of cyclonic vorticity advection aloft) and its associated cyclonic flow move over a low-level thermal gradient (a frontal zone), cyclonic flow is induced at the surface. The weak circulation about the frontal zone causes deformation of the frontal zone, resulting in warm air advection ahead of the surface cyclone and cold air advection behind. The warm advection leads to decreasing surface pressure ahead of the cyclone, and hence the surface cyclone propagates forward. The warming of the air column ahead of the cyclone also builds the downstream ridge and causes the wave to amplify, thereby increasing the amount of cyclonic vorticity advection aloft, leading to further warm advection, and so on. This “bootstrapping” process is referred to as self-development. Eventually, the strength a cyclone can attain through self-development is limited by the opposing influence of vertical motion, which cools the rising air ahead of the system and limits the magnitude of the pressure falls. Sutcliffe and Petterssen also showed that the strength of cyclogenesis depends on the local static stability of the atmosphere.

Yet another approach to understanding cyclogenesis was pioneered by Jule Charney in 1947 and Eric Eady in 1949. This theoretical approach states that cyclones are the result of an instability in the jet stream called baroclinic instability. Baroclinic instability theory links the observational approach to understanding cyclones from polar front theory and the practical approach of Sutcliffe and Petterssen. Baroclinic instability theory states that if the temperature gradient is large enough (or equivalently, if the vertical shear of the horizontal wind is large enough), then the jet stream will spontaneously break down into Rossby waves, resulting in the formation of cyclones. In most observed cases, disturbances in the jet stream appear to be linked with surface cyclogenesis, suggesting the validity of baroclinic instability as an explanation for cyclogenesis in the atmosphere. In addition, baroclinic instability theory is often used for theoretical studies of cyclogenesis, providing further support for its utility in explaining observations of cyclogenesis. [See Baroclinic Instability.]

Another way of viewing the structure of cyclones is to depict the different airstreams that flow
through the cyclone. This view, pioneered by Jerome Namias in the late 1930s, became popular in the mid to late 1960s. Instead of looking at discontinuities in temperature (fronts), a more holistic view examines the different source regions of the air flowing through the cyclone. This airstream model yields three main airflows in midlatitude cyclones: the warm conveyor belt, the cold conveyor belt, and the dry airstream.

The warm conveyor belt originates in the tropical air in the warm sector and rises up over the warm front into the jet stream. The warm conveyor belt is responsible for most of the clouds and precipitation associated with cyclones. The cold conveyor belt originates in the lower troposphere in the cooler air ahead of the cyclone, travels westward underneath the warm conveyor belt, and then turns cyclonically around the low center. The dry airstream originates in the middle and upper troposphere west of the cyclone and then descends behind the cyclone. The dry airstream provides the westward limit to most of the clouds and precipitation in a midlatitude cyclone.

Finally, a recent way of viewing the atmosphere is to examine the structure of the potential vorticity field. Sutcliffe–Petterssen self-development or baroclinic instability theory can be viewed in the framework of potential vorticity as a region of locally high potential vorticity (a depression of the tropopause), which approaches another region of high potential vorticity (a lower tropospheric area of warm air). The induced cyclonic circulation associated with the tropopause depression causes the deformation of the warm pool near the surface, in turn strengthening the tropopause depression. The cyclone therefore develops by mutual amplification of potential vorticity anomalies on the tropopause and near the surface. When moisture is present, a third potential vorticity anomaly may form beneath regions of condensation. The formation of this anomaly and its associated cyclonic flow can enhance the intensity of the surface cyclone. [See Potential Vorticity.]

**Life Cycle.** The current view of the life cycle of a midlatitude cyclone is illustrated in Figure 1. Prerequisites for cyclone development include a lower-tropospheric frontal zone and an upstream upper-tropospheric disturbance, usually a jet streak or a shortwave trough in the jet stream. The upper-level disturbance generally moves faster than the surface frontal zone, so the upper-level disturbance will move over the frontal zone. Cyclonic flow associated with the upper-level disturbance will deform the surface frontal zone, forming a weak surface low-pressure system. The cyclonic flow induced from the upper-level disturbance will cause warm air to the south of the frontal zone to be advected northward, east of the low center. The movement of warm air replacing cold air forms a warm front. Likewise, on the west side of the low center, cold air to the north will be advected southward, replacing the warm air and forming a cold front. [See Fronts.] If the cyclone is strong enough, the movement of air around the cyclone eventually stretches the cold front and warm front, bringing them closer together, just as ribbons of milk lengthen and merge when stirred into coffee. As the air in the cold conveyor belt wraps around the low center and the air in the warm conveyor belt is lifted over the warm front, the amount of warm air near the cyclone center is reduced and the surface cyclone becomes wrapped in cold air. Around this time or shortly after, the upper-level disturbance catches up to the surface cyclone, and the three-dimensional structure of the low-center becomes vertically stacked.

The cloud pattern of a midlatitude cyclone is typically in the shape of a comma. The head of the comma is nearly coincident with the low-pressure center at the surface. Warm rising air in the warm conveyor belt is responsible for most of the clouds and precipitation in the comma head. Steady precipitation, often with embedded regions of heavier precipitation, falls out of the clouds ahead of the warm front. As the warm front approaches, surface temperatures rise. In the warm air, skies may be clear or partly cloudy, or they may have scattered showers and thunderstorms. The tail of the comma is often associated with convection that forms along a line extending equatorward from the low center. This line may sometimes be associated with the passage
of the cold front or occluded front, producing heavy precipitation. Following the cold frontal passage, skies clear and surface temperatures fall as the winds shift from the south to the west and north.

**Geographical Variability.** Midlatitude cyclones occur in many midlatitude locations around the world, but they tend to move along preferential routes called *storm tracks*. In the Northern Hemisphere, two primary storm tracks lie across the North Atlantic Ocean and the North Pacific Ocean. In contrast, cyclones in the Southern Hemisphere most commonly travel within a single storm track around the Southern Ocean, best defined over the southern Indian Ocean and least well defined over the South Pacific Ocean. In the Northern Hemisphere, a large number of cyclones generally intensify at the entrance region (western end) of the storm tracks off the east coasts of North America and Asia, travel across the oceans, and weaken at the end of the storm tracks over the eastern ocean basins. Although most cyclones follow these storm tracks and look like cyclones in the polar front theory, individual cyclones may differ substantially from this conceptual model. A few examples of these differences are discussed next.

Since 1980, the meteorological community has placed particular emphasis on understanding rapidly developing ocean cyclones, which have been named *bombs*, and are often poorly forecast. In the late 1980s, several field projects began discovering unusual frontal structures in these cyclones. Cyclogenesis appears to be initiated much as described above, but instead of the cold front rotating into the warm front to form an occluded front, the cold front breaks (or fractures) from the warm front and begins to move perpendicularly to the warm front, so that it never catches up (Figure 2). The rapid movement of the surface low center also results in the warm front being left behind the cyclone in the form of a *back-bent front*. A region of strong localized surface winds can sometimes occur in association with the back-bent front and is called the *sting jet*. When they occur, sting jets can cause extensive wind damage, especially in the United Kingdom and continental Europe. As the cyclone continues to intensify, the back-bent front encircles the relatively warmer air behind the cold front, resulting in a pool of warm air over the low center, known as the *warm seclusion*. This cyclone evolution is called the *Shapiro–Keyser cyclone model*. [See Cyclones, subentry on Explosive Cyclones.]

Modeling results suggest that the roughness of the Earth’s surface may affect the types of frontal structures that arise. For instance, when surface friction is high, as it is over land, cyclones tend to undergo an evolution more consistent with the polar front cyclone model. When the surface friction is lower, as it is over the ocean, the cyclone tends to develop features more akin to the Shapiro–Keyser cyclone model.

Research suggests that the shape of the jet stream over the surface cyclone also affects the resulting frontal structure. In cases where the jet stream is diffluent, warm fronts are short and weak while cold fronts are long and strong. These cyclones tend to resemble the polar front cyclone model. In confluent flow, the warm fronts are long and strong and the cold fronts are short and weak. These cyclones tend to have structures like the Shapiro–Keyser cyclone model.

Because of the Rocky Mountains, a developing low-pressure center in central North America may be inhibited from developing in the same manner as an ideal cyclone. Such cyclones develop most often in Colorado or Alberta, where the slope of the Rockies is steepest. The cyclones that develop here are likely to exhibit certain structures (Figure 3). South of the low center, a lee trough separates warm, moist, southerly air to the east from warm, dry air that has recently descended off the mountains. A lee trough has a structure very similar to that of a warm front. Depending on the amount of moisture ahead of the lee trough, the lee trough may also resemble a dryline, a type of air-mass boundary in the south-central United States that is often a locus of severe weather. Southwest of the cyclone, a cold front separates the subsided air off the mountains from moist Pacific Ocean air. Northwest of the low center, a cold front occurs at the leading edge of southward-moving arctic air trapped against the Rockies. North of the
low center, an inverted trough separates easterlies over the midwestern states from the northerly arctic air against the Rockies. Often a quasi-stationary or warm front south of the easterlies separates the warm moist southerly air from the Gulf of Mexico. Finally, a squall line in the warm southerly air is often associated with an upper-level frontal zone advancing above; the term cold front aloft has sometimes been applied to this feature. These cyclones differ substantially from the polar front and Shapiro–Keyser cyclone models presented earlier.

In desert areas during the summer, intense solar heating and the lack of moisture available for evaporation can lead to very high surface temperatures (higher than about 35°C). As the air warms, it expands, and compensating circulations arise that remove mass from the column of air. As a result, the pressure falls. These low-pressure centers are not associated with the polar front and jet stream and are usually not migratory. They are called thermal lows or heat lows to indicate their method of formation, and they are distinct from midlatitude cyclones.
As their name suggests, midlatitude cyclones (whose energy is derived from the pole-to-equator temperature gradient) are typically distinct from cyclones in the tropics (whose energy is derived from the release of latent heat of condensation). Sometimes, however, tropical cyclones may transition into midlatitude cyclones as they move poleward. [See Cyclones, subentry on Tropical Cyclones.]

Because of the variety of topography and geography on the Earth, midlatitude cyclones across the world possess a great variety of frontal structure and evolutions. For example, the Gulf Stream and Kuroshio ocean currents are an important source of the low-level temperature gradients and low static stability needed for rapid cyclone development. In another example, off the south coast of Australia and in the center of the Pacific Ocean, cyclones usually develop without strong warm fronts. Much remains to be learned about how midlatitude cyclones vary around the world, and more important, about the causes of these structural and developmental differences.

[See also Storms.]

BIBLIOGRAPHY
**Subtropical Cyclones**

Subtropical cyclones have characteristics similar to those of extratropical and tropical cyclones, but unlike true tropical storms, subtropical storms can occur at any time of the year. Because they are hybrid storms, it is difficult to define consistent physical characteristics for them.

Most subtropical storms have their maximum intensity of rain and wind approximately 420 kilometers (300 miles) from the center. Unlike tropical cyclones, subtropical cyclones often have large centers, as much as 140 kilometers (100 miles) in diameter. Within this zone, precipitation is light and pressure gradients are weak.

While tropical cyclones depend on latent and sensible heat as driving mechanisms, subtropical storms develop from cold upper-level polar troughs (as do extratropical storms). Occasionally the southern portion of an upper-level trough “cuts off” and develops an upper-level cold-core low. If this circulation extends to the surface, the development of a subtropical storm is initiated. Although the original polar trough from which a subtropical storm develops has most of its precipitation east of its axis, subtropical storms themselves are marked by a high degree of symmetry.

Once formed, these storms are noted for their high level of persistence, a result of their being well developed at upper levels (for example, a closed cyclonic circulation at 500 millibars) while becoming progressively weaker toward the surface. Thus, the effect of friction is small; in tropical cyclones, by contrast, friction plays a major role in dissipation over land. Rather than dissipating, subtropical storms are often absorbed into advancing polar troughs.

In some regions, subtropical storms are an integral part of the hydrological cycle. For example, in Hawaii the subtropical storm known locally as the *Kona* storm provides a large portion of the winter rainfall.

Most subtropical storms form from upper-level cold-core lows, but there are also other modes of formation. For example, a hurricane that moves inland can change into a subtropical storm as part of its decay process. This often produces more prolonged and intense rainfall than would a dissipating, purely tropical system. A subtropical storm can also become converted to a tropical system when warm, moist air flows closely around the center. Rainfall, which had been heavy on the storm’s periphery, slackens as a new enhanced area of rainfall develops close to the center. Fluxes of latent heat now increase near the center. The net result is an increase in temperature in the center and conversion to a warm-core tropical system. For this reason, subtropical...