
Basic Characteristics of Mid-Latitude Cyclone Formation

Mid-latitude cyclones form as a result of the release of *baroclinic instability*. While a full treatment of baroclinic instability is beyond the scope of this course, we nevertheless wish to understand the synoptic-scale conditions associated with such instability. We find that baroclinically-unstable westerly flow is associated with a large north-south thermal contrast, or *baroclinic zone*, with warm air toward the Equator and cold air toward the pole. At the outset of the cyclone’s life, this thermal contrast is manifest by a stationary front; as the cyclone intensifies and matures, well-defined cold and warm fronts develop. Consequently, mid-latitude cyclones are often referred to as *frontal cyclones* given their association with frontal boundaries.

From the thermal wind relationship, the presence of a large north-south thermal contrast implies strong vertical wind shear, nominally characterized by westerly flow that increases in speed with increasing altitude. This westerly flow peaks in magnitude near the tropopause, at the level of the jet stream; indeed, vertical wind shear is typically maximized in the presence of an upper tropospheric jet stream or jet streak. Consequently, mid-latitude cyclones typically develop in the presence of a jet stream. They intensify as they extract energy from the vertically-sheared flow and begin to decay once there is no further energy that can be extracted. A full treatment of mid-latitude cyclone energetics is left for coursework in atmospheric dynamics, however.

As a cyclone intensifies, the baroclinically-unstable westerly flow becomes amplified in the north-south direction. This gives rise to waves within the flow, and consequently mid-latitude cyclones are sometimes also referred to as *wave cyclones*. We also sometimes refer to mid-latitude cyclones as *extratropical cyclones* given that they form in what are known as the extratropics (i.e., outside of the tropical latitudes).

Where do Mid-Latitude Cyclones Form?

Climatologies of mid-latitude cyclone occurrence suggest that, globally, mid-latitude cyclones predominantly form in one of two locations:

- Downwind of major mountain ranges (e.g., the Rocky Mountains of North America).
- Near the eastern coastlines of continents.
For North America, this is illustrated graphically in Figure 1.

**Figure 1.** Predominant formation locations and tracks (black arrows) for mid-latitude cyclones in North America in January (left) and July (right), as derived from a climatology of mid-latitude cyclones that occurred between 1950 and 1977. The blue contouring represents the relative variability in cyclone occurrence, with mid-latitude cyclones typically forming in regions of low relative variability. Figure reproduced from *Meteorology: Understanding the Atmosphere* (4th ed.) by S. Ackerman and J. Knox, their Figure 10-6.

One might ask, then, why do mid-latitude cyclones form in such locations? Let us work in reverse, starting with the second bullet above. There exist warm ocean currents that transport relatively warm waters poleward along the western edge of the world’s oceans. This results in relatively warm conditions, particularly in the lower troposphere, along eastern continental coastlines. As relatively cool air encroaches upon these coastlines from the west, a strong baroclinic zone develops. It is along this baroclinic zone that the necessary conditions for cyclone formation are present, thereby fostering mid-latitude cyclone development.

Strong baroclinic zones can also be found downwind, or in the lee, of major mountain regions as well. However, there exists an equally-important process that is an important contributor to mid-latitude cyclone formation in these locations: vorticity stretching. This process is illustrated schematically in Figure 2. Downwind of the mountain range, the surface becomes found at progressively lower altitudes above sea level. As mid-latitude westerly flow in the lower to middle troposphere crosses over a mountain range, sometimes a portion of this flow is forced to descend along the mountain range. Imagine that there is a small amount of vertical vorticity within this westerly flow. In this example, as it crosses over the mountain range, it is stretched in the vertical direction. Like a figure skater bringing in their arms as they stretch out in the vertical while rotating, the rotation rate of the air increases. This can foster cyclone development in the lee of the world’s major mountain ranges.
Figure 2. Idealized schematic of a mountain range (green line) and westerly wind flowing across the mountain range (black arrows). Note how the wind spreads out vertically in the lee, or downwind, of the mountain peak. Such conditions are most commonly observed when a stable layer exists at or near mountain top.

Types of Mid-Latitude Cyclogenesis

There exist two primary types of mid-latitude cyclone formation, or cyclogenesis: Type A and Type B. Note that both modes of cyclogenesis can occur downwind of major mountain ranges and/or along eastern continental coastlines. The primary difference between Type A and Type B cyclogenesis, rather, lies in the nature of the middle to upper tropospheric flow found in association with the cyclogenesis event. In Type A cyclogenesis, there exists no precursor disturbance in the middle to upper tropospheric flow; by contrast, in Type B cyclogenesis, there exists a precursor upstream disturbance, or trough, in the middle to upper troposphere.

Type A cyclogenesis occurs under a nearly-straight polar jet stream and is initially characterized by lower tropospheric warm advection. Upstream, lower tropospheric cold advection is found several hundred kilometers west of the developing mid-latitude cyclone. As we shall soon see, lower tropospheric warm advection promotes the development of the cyclone at the surface while lower tropospheric cold advection promotes the development and amplification of a middle to upper tropospheric trough upstream of the surface cyclone.

Type B cyclogenesis occurs in advance of a pre-existing middle to upper tropospheric trough. As we shall again soon see, cyclonic vorticity advection in the lower to middle troposphere ahead of this trough promotes the development of the cyclone at the surface. Indeed, Type B cyclogenesis most frequently occurs when strong middle to upper tropospheric cyclonic vorticity advection becomes superposed with a strong lower tropospheric baroclinic zone.

The Basic Life Cycle of Mid-Latitude Cyclones

The basic life cycle of mid-latitude cyclones, from birth to decay, is illustrated in Figures 3 and 4. Note that not every cyclone follows this life cycle perfectly. For instance, the peak intensity of
mid-latitude cyclones and length of time that it takes a cyclone to progress from one stage to another varies substantially between cyclones. Furthermore, as well will discuss later, the mature stage of a mid-latitude cyclone need not necessarily be associated with cyclone occlusion. Nevertheless, the basic life cycle depicted in Figures 3 and 4 captures the essence of mid-latitude cyclone formation, maturity, and decay.

**Figure 3.** Idealized view of the birth and developing stages of a mid-latitude cyclone. In the second column, blue lines denote cold fronts, red lines denote warm fronts, and black lines with arrows depict streamlines at the surface. Figure reproduced from *Meteorology: Understanding the Atmosphere* (4th ed.) by S. Ackerman and J. Knox, their Table 10-1.

**Figure 4.** As in Figure 3, except for the mature and decay stages of a mid-latitude cyclone. Figure reproduced from *Meteorology: Understanding the Atmosphere* (4th ed.) by S. Ackerman and J. Knox, their Table 10-1.
Mid-latitude cyclones typically form along pre-existing baroclinic zones, such as an old stationary front, whether or not a notable precursor upstream middle to upper tropospheric disturbance is present. Clouds and precipitation associated with birth stage mid-latitude cyclones are typically oriented in a linear fashion, not acquiring the archetypal comma shape until the development stage.

Well-defined cold and warm fronts develop as the mid-latitude cyclone intensifies. The rotational flow of the cyclone leads to cold air advection to its south and west and warm air advection to its north and east. As a result, the cyclone’s cold front becomes found to the south and west of the cyclone and the cyclone’s warm front becomes found to the east of the cyclone. Concurrently, the magnitudes of the cross-front thermal contrast (or temperature gradient) associated with the cyclone’s cold and warm fronts strengthen, a process known as *frontogenesis*.

At all stages, mid-latitude cyclones are tilted to the west, or against the vertically-sheared westerly flow, with increasing altitude. The separation distance between the surface cyclone and accompanying middle to upper tropospheric trough is largest during the formation and development stages and gradually decreases as the cyclone matures and occludes. This westerly-tilted structure fosters warm air advection, cyclonic vorticity advection, and middle to upper tropospheric diffluence atop the surface cyclone, all processes that are favorable for the cyclone’s intensification. It also fosters cold air advection into the base of the upstream middle to upper troposphere trough, a process that is favorable for the trough’s intensification. The magnitudes of each advection decreases as the cyclone’s tilt decreases, eventually becoming zero once the cyclone reaches its decay stage. We will examine this implied conjoined evolution between the lower and upper troposphere later this semester.

As the mid-latitude cyclone reaches maturity and the cyclone reaches its peak intensity, an occluded front develops. Furthermore, the separation distance between the upstream middle to upper tropospheric trough and lower tropospheric cyclone decreases, manifest by the latter moving more slowly poleward and to the east than the former.

Finally, as the mid-latitude cyclone reaches its decay stage, the cyclone becomes separated from its fronts, thus becoming isolated in relatively homogeneous air. This reflects the notion that the baroclinic energy source fueling the cyclone – the large lower tropospheric horizontal thermal contrast and its accompanying vertical wind shear – has been expended. The lower, middle, and upper tropospheric features become superposed or vertically-stacked and, in most cases, cut-off from the synoptic-scale mid-latitude westerly flow. Due to mass convergence at all altitudes within the troposphere and the effects of friction, the cyclone gradually fills and spins down.
The Structure of Developing and Mature Mid-Latitude Cyclones

The cloud and precipitation structure typically found in association with a developing or mature mid-latitude cyclone system is depicted in Figure 5. In satellite or radar imagery, mid-latitude cyclones typically have a comma-shaped appearance. Precipitation along the mid-latitude cyclone’s cold front (E-D-C in Figure 5) is often convective in nature, whereas precipitation along and poleward of the mid-latitude cyclone’s warm front (A-B-F in Figure 5) is predominantly stratiform (e.g., light to moderate and steady) in nature.

Figure 5. Idealized depiction of the cloud (and precipitation) structure associated with a frontal cyclone. Reproduced from Weather Analysis by D. Djurić, their Figure 10-4.

A conceptual model of a mid-latitude cyclone is depicted in Figure 6. Mid-latitude cyclones are associated with four primary air streams. The first of these is the primary warm conveyor belt, depicted by the thick open arrow labeled W1 in Figure 6. The warm conveyor belt ascends from near the surface in the warm air to the middle and, ultimately, upper troposphere as it ascends over the warm front. Consequently, the warm conveyor belt is the feature responsible for cloud and precipitation development along and poleward of a warm frontal zone, a process that we will examine further in our lecture on isentropic analysis principles. It may turn anticyclonically (i.e., eastward) after ascending over the lower tropospheric warm frontal zone.

The second of these is the secondary warm conveyor belt, depicted by the arrow labeled W2 in Figure 6. Though not explicitly shown, this conveyor belt may turn cyclonically after ascending over the lower tropospheric warm frontal zone. Middle-tropospheric ascent over the lower tropospheric warm frontal zone associated with this conveyor belt is believed to be responsible for the comma head structure found on the northwest side of the mid-latitude cyclone. Post-cold frontal convection may develop in proximity to either W1 or W2 in an environment characterized by potential instability, where equivalent potential temperature decreases with height, as manifest by W1 and/or W2 flowing poleward in the lower troposphere beneath the
descending dry intrusion, to be discussed shortly. Recall: in the context of the layer method for assessing stability, lifting of an initially-stable layer that is moister at its bottom than at its top can potentially result in this layer becoming less stable or even unstable. This can thus enable deep, moist convection to develop if the layer can be lifted sufficiently (whether on the synoptic or mesoscale(s)).

The third air stream is the cold conveyor belt, depicted by the westward-directed arrow labeled CCB in Figure 6. The cold conveyor belt is located poleward of the surface warm frontal zone and moves rearward with respect to the surface cyclone, gradually ascending from the lower to the middle troposphere as it does so. Upon reaching the northwestern quadrant of the frontal cyclone system, it may curve cyclonically around the rear of the translating cyclone.

The last air stream is the dry intrusion, depicted by the multiple dotted arrows in the rear of the surface cold frontal zone in Figure 6. The dry intrusion is a descending air stream located immediately rearward of the surface cyclone. It originates in the middle to upper troposphere and descends to the lower troposphere in the rear of the surface cold front. This descending air stream is responsible for the clear skies and drier conditions that are often found in the rear of cold frontal zones. It is also associated with a tropopause fold, or localized lowering of the tropopause, that is often found immediately upstream of mid-latitude cyclones.

Figure 6. Idealized depiction of the primary air streams of a developing frontal cyclone system.  
Figure reproduced from Browning (2005, Quart. J. Roy. Meteor. Soc.), their Figure 4b.
Mid-Latitude Cyclone Maturity: Occlusion Versus Seclusion

At the outset of the 20th century, Norwegian meteorologists associated with the so-called Bergen School identified the mature stage of a mid-latitude cyclone as being associated with the development of an occluded front, wherein the mid-latitude cyclone’s cold front overtakes its warm front. In such cases, the cyclone itself is said to become occluded and becomes embedded within a cold air mass. The life cycle of a mid-latitude cyclone leading to occlusion is illustrated in Figures 3 and 4 above and Figure 7 below.

Alternatively, as has been observed with real-world mid-latitude cyclones (e.g., the case over the North Atlantic Ocean examined by Nieman and Shapiro 1993 *Mon. Wea. Rev.*), the cyclone may become embedded within a localized pocket of warm air as a consequence of frontal fracture. In an earlier lecture, we termed such a cyclone structure a warm seclusion and briefly examined the structure of a warm seclusion mid-latitude cyclone. The development of a warm seclusion structure is an alternative hallmark of a mid-latitude cyclone reaching maturity, and the life cycle of a mid-latitude cyclone leading to the development of such a structure is illustrated in Figure 8.

**Figure 7.** Life cycle of a synoptic-scale, mid-latitude cyclone from development to occlusion, as viewed from the Norwegian/Bergen School perspective. Figure reproduced from Nieman and Shapiro (1993, *Mon. Wea. Rev.*), their Figure 1.
Figure 8. As in Figure 7, except from the Shapiro-Keyser model for frontal cyclone evolution. An occluded front still develops; however, its orientation (east-west) differs from that in the Bergen School model (north-south). Figure reproduced from Neiman and Shapiro (1993, *Mon. Wea. Rev.*), their Figure 21.