Synoptic Meteorology I: Midlatitude Cyclone Lifecycle and Structure

For Further Reading

Much of the material contained within these notes is drawn from Chapter 10 of *Weather Analysis* by D. Djurić or Chapter 10 of *Meteorology: Understanding the Atmosphere* (4^{th} ed.) by S. Ackerman and J. Knox. Neiman and Shapiro (1993, *Mon. Wea. Rev.*) describes the life cycle of an intense midlatitude cyclone and, in so doing, compares cyclone occlusion and seclusion.

Basic Characteristics of Midlatitude Cyclone Formation

Midlatitude cyclones form due to *baroclinic instability* being released. 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. 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. As a cyclone initially forms, this thermal contrast is manifest by a stationary front; as the cyclone intensifies and matures, well-defined cold and warm fronts develop. Consequently, midlatitude 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, often characterized by westerly flow increasing 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. As a result, midlatitude cyclones typically develop in proximity to a jet. Midlatitude cyclones intensify as they extract energy from the vertically sheared flow and begin to decay once there is no further energy that can be extracted.

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 midlatitude cyclones are sometimes also referred to as *wave cyclones*. We also sometimes refer to midlatitude cyclones as *extratropical cyclones* given that they form in what are known as the extratropics (i.e., outside of the tropical latitudes).

Where do Midlatitude Cyclones Form?

Midlatitude cyclone climatologies suggest that, globally, midlatitude 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.

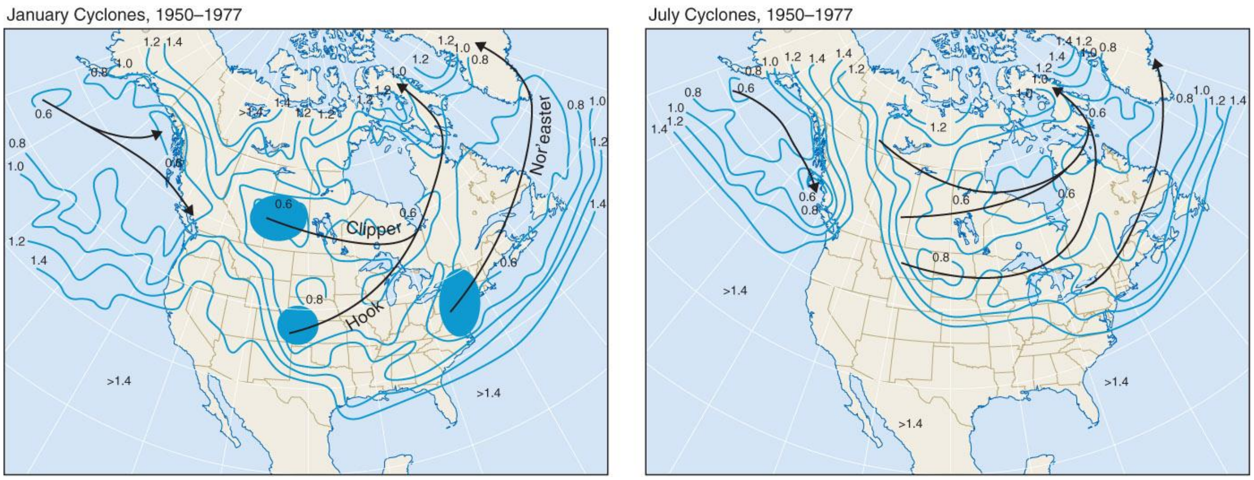

Figure 1. Predominant formation locations and tracks (black arrows) for midlatitude cyclones in North America in January (left) and July (right), as derived from a climatology of midlatitude cyclones that occurred between 1950 and 1977. The blue contouring represents the relative variability in cyclone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

One might ask, then, *why* do midlatitude cyclones form in such locations? Let us work in reverse, starting with the second bullet above. There are warm ocean currents that transport relatively warm waters poleward along the western edge of the world's oceans, resulting in a relatively warm lower troposphere along eastern coastlines. As cold air encroaches upon the coast 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 midlatitude cyclone development.

Strong baroclinic zones can also be found downwind, or in the lee, of major mountain regions as well. However, there exists an important process that is an important contributor to midlatitude 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 midlatitude 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 extend vertically while rotating, the air's rotation rate increases. This can foster cyclone development in the lee of the world's major mountain ranges.

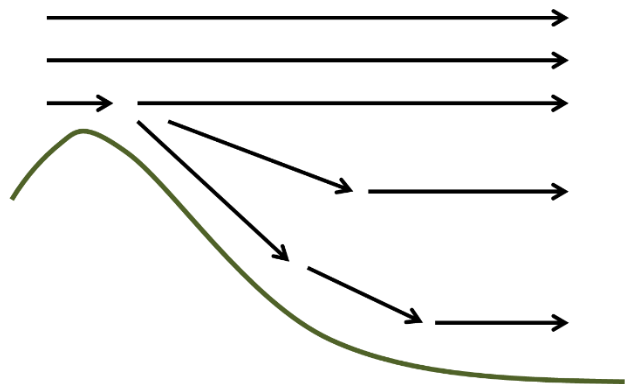

Figure 2. Idealized schematic of a mountain range (green line) and westerly wind flowing across the mountain range (black arrows). Note how the wind spreads out vertically in the lee, or downwind, of the mountain peak. Such conditions are most commonly observed when a stable layer exists at or near mountain top.

Types of Midlatitude Cyclogenesis

There exist two primary types of midlatitude cyclone formation, or *cyclogenesis*: Type A and Type B. The primary difference between Type A and Type B cyclogenesis lies in the middle-to-upper tropospheric flow found in association with the cyclogenesis event. In Type A cyclogenesis, there exists no precursor trough in the middle-to-upper tropospheric flow; in Type B cyclogenesis, there is a precursor upstream trough in the middle-to-upper troposphere.

Type A cyclogenesis occurs under a nearly straight polar jet and is initially characterized by lower-tropospheric warm advection, with lower-tropospheric cold advection upstream several hundred kilometers west of the developing cyclone. As we will examine in detail next semester, lower-tropospheric warm advection promotes cyclone development at the surface and lower-tropospheric cold advection promotes middle-to-upper tropospheric trough development upstream.

Type B cyclogenesis occurs in advance of a pre-existing middle to upper tropospheric trough. As we will examine in detail next semester, large cyclonic vorticity advection in the lower-to-middle troposphere ahead of this trough promotes cyclone development 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 Midlatitude Cyclones

The basic life cycle of midlatitude cyclones, from birth to decay, is illustrated in Figures 3 and 4. Note that not every cyclone follows this life cycle perfectly. For instance, cyclone peak intensity and length of time that it takes a cyclone to progress from one stage to another vary substantially between cyclones. Furthermore, the mature stage of a midlatitude cyclone need not necessarily be associated with occlusion.

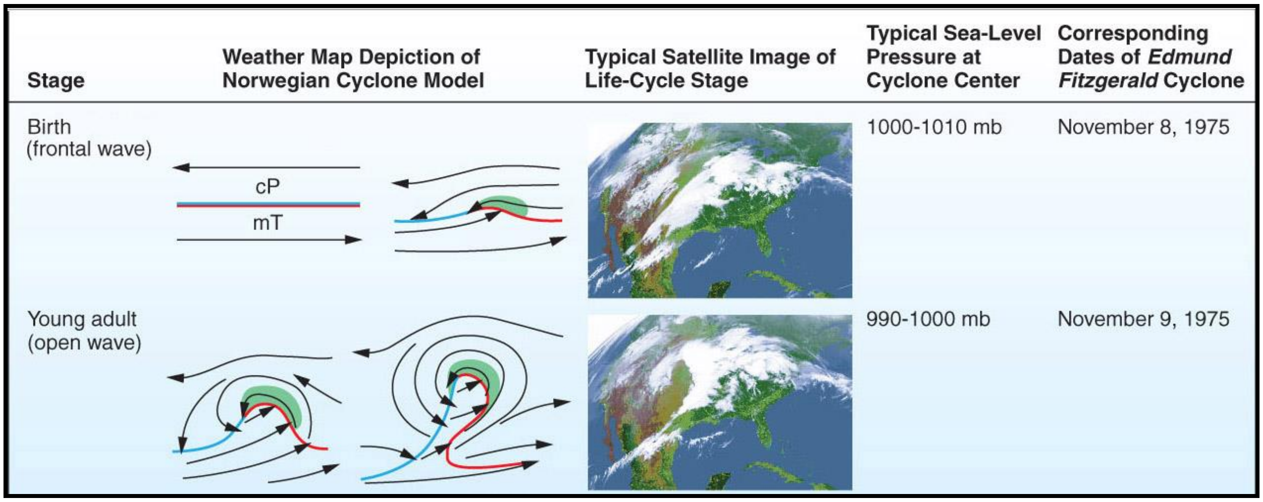

Figure 3. Idealized view of the birth and developing stages of a midlatitude cyclone. In the second column, blue lines denote cold fronts, red lines denote warm fronts, and black lines with arrows depict streamlines at the surface. Figure reproduced from *Meteorology: Understanding the Atmosphere* (4th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

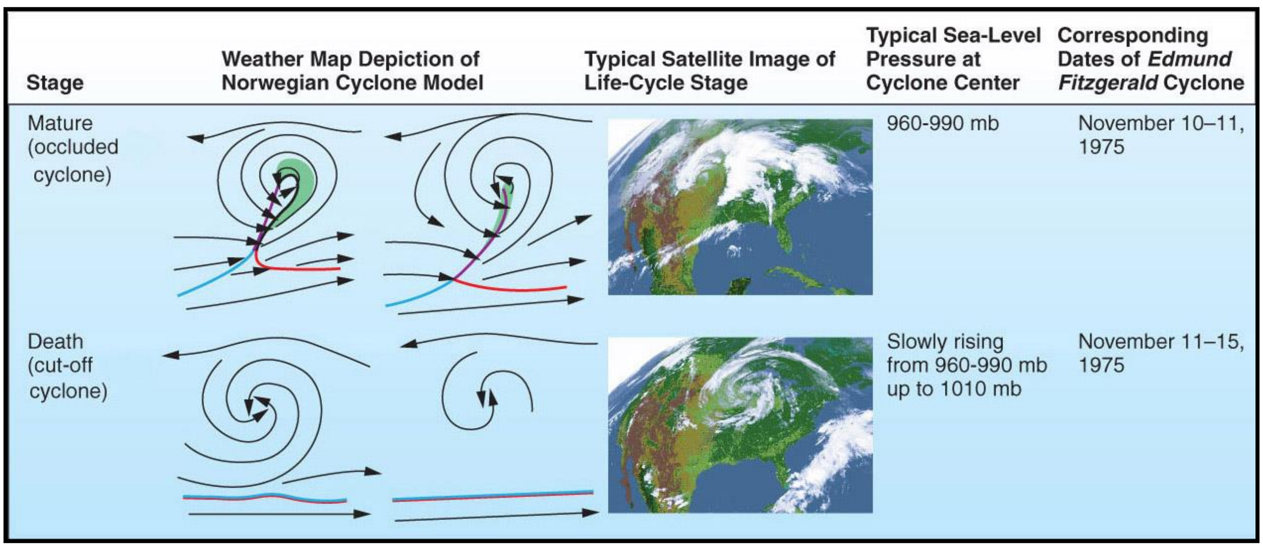

Figure 4. As in Figure 3, except for the mature and decay stages of a midlatitude cyclone. Figure reproduced from *Meteorology: Understanding the Atmosphere* (4th ed.) by S. Ackerman and J. Knox, their Table 10-1.

Midlatitude cyclones typically form along pre-existing baroclinic zones, such as an old stationary front, whether a notable precursor upstream middle-to-upper tropospheric disturbance is present. Clouds and precipitation associated with developing midlatitude 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 midlatitude cyclone intensifies. The rotational flow of the cyclone leads to cold air advection equatorward and to the west and warm air advection poleward and to the east. As a result, the cold front becomes found to the south and west and the warm front becomes found to the east. Concurrently, the magnitudes of the cross-front thermal contrast (or temperature gradient) associated with the cyclone's cold and warm fronts become larger, a process known as *frontogenesis*.

At all stages, midlatitude cyclones are tilted to the west, or against the vertically sheared westerly flow, with increasing height. The separation distance between the surface cyclone and middle-to-upper tropospheric trough is largest during the formation and development stages and gradually decreases as the cyclone matures and occludes. This 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 cyclone intensification. It also fosters cold air advection into the upstream trough's base, which is favorable for the trough's intensification. The magnitudes of each advection decrease as the cyclone's tilt decreases, eventually becoming zero once the cyclone reaches its decay stage.

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

Finally, as the midlatitude cyclone reaches its decay stage, the cyclone becomes separated from its fronts and becomes isolated in relatively homogeneous (with respect to temperature) air. The large lower-tropospheric horizontal thermal contrast and its associated vertical wind shear are gone, and thus the baroclinic energy source fueling the cyclone 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 midlatitude westerly flow. Due to convergence at all altitudes and the effects of friction, the cyclone gradually fills (or increases in mass) and spins down.

The Structure of Developing and Mature Midlatitude Cyclones

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

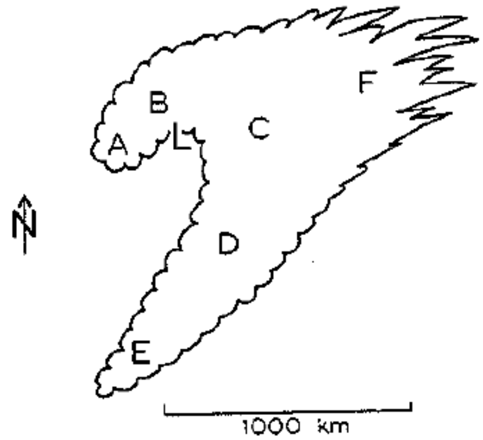

FIGURE 10-4. A comma cloud. A comma proper is ABCDE. Anticyclonically curved outflow occurs at F.

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.

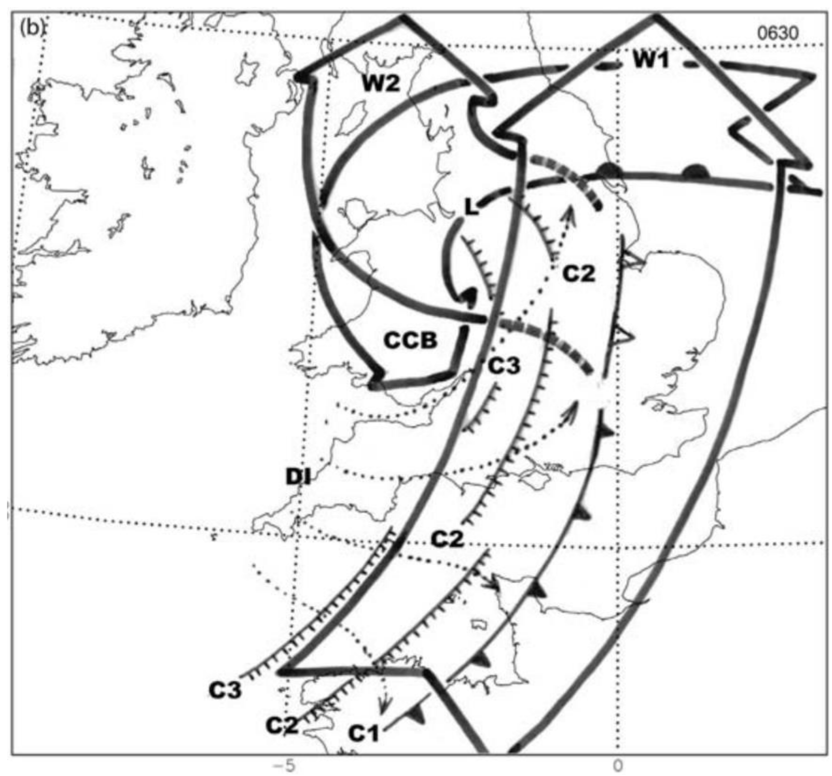

Figure 6. Idealized depiction of the primary air streams of a developing frontal cyclone system. Figure reproduced from Browning (2005, *Quart. J. Roy. Meteor. Soc.*), their Fig. 4b.

A conceptual model of a midlatitude cyclone is depicted in Figure 6. Mid-latitude cyclones are characterized by four primary air streams: *primary (W1) and secondary (W2) warm conveyor belts*, a *cold conveyor belt (CCB)*, and a *dry intrusion* (*DI*).

The primary 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. It may turn anticyclonically after ascending over the warm frontal zone. Recall that warm fronts slope forward over a cold air mass; i.e., isentropes slope upward over the cold air mass. Thus, assuming that an air parcel is unsaturated and that it conserves potential temperature as it moves, air parcels that approach warm fronts must ascend over the warm frontal zone. The primary warm conveyor belt is thus responsible for cloud and precipitation development along and poleward of a warm frontal zone. Stratiform precipitation is favored poleward of warm frontal zones, although the release of elevated CAPE that may exist locally can result in embedded deep, moist convection in some cases.

The secondary warm conveyor belt also ascends from near the surface in the warm air to the middle troposphere as it ascends over the warm front. It may turn cyclonically after ascending over the warm frontal zone. Middle-tropospheric ascent over the warm front associated with this conveyor belt is responsible for the comma head structure on the northwest side of midlatitude cyclones; this is also a favored region for mesoscale banded precipitation resulting from strong frontogenesis or the release of elevated CAPE.

The cold conveyor belt ascends gradually from the lower to the middle troposphere poleward of the surface warm frontal zone. It moves rearward with respect to the surface cyclone. As it reaches the cyclone's northwestern quadrant, it may curve cyclonically around the rear of the cyclone.

Finally, the dry intrusion is a descending air stream located immediately rearward of the cyclone. It originates in the middle to upper troposphere and descends to the lower troposphere in the rear of the surface cold front. Recall that cold fronts slope rearward over a cold air mass; i.e., isentropes slope downward approaching the cold front from the rear. Assuming that potential temperature is conserved following an air parcel's motion, air must descend as it approaches a cold front from the rear. Thus, the dry intrusion is responsible for the absence of middle to high clouds in the rear of cold fronts; in the case where descent reaches to the lower troposphere, it is responsible for clear skies and drier conditions found behind cold fronts.

The secondary warm conveyor belt typically ascends beneath the descending dry intrusion. This can result in potential instability, with equivalent potential temperature decreasing with height. As demonstrated in our earlier stability lecture materials, the forced lifting of such a layer results in its destabilization. Such forcing for ascent is often found in advance of an approaching trough. If the layer can be sufficiently lifted, narrow convective bands may form. This is most common over water for post-frontal convection, although it can also result in pre-frontal convection over land.

Together, the four conveyor belts help us deduce typical mid-latitude cyclone appearance on radar and satellite imagery (as in Figure 5):

- A fan or delta-shaped area of primarily low- to middle-tropospheric cloud cover poleward of a surface warm frontal zone.
- A comma-shaped cloud region, extending equatorward primarily along the cyclone's cold front. If sufficient instability – whether surface-based ahead of the cold front or elevated in proximity to the secondary warm conveyor belt – exists and can be released, deep, moist convection may be found within one or both regions.
- Clear skies or primarily stratiform low clouds behind a surface cold front. Stratiform clouds are favored when sufficiently high lower-tropospheric moisture is trapped beneath the cold frontal inversion.
- In cases where potential instability is realized, narrow convective bands aligned with the middle-to-upper tropospheric flow may be found.

Midlatitude 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 midlatitude cyclone that associated with the development of an occluded front, wherein the midlatitude 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 midlatitude cyclone leading to occlusion is illustrated in Figures 3 and 4 above and Figure 7 below.

Alternatively, as has been observed with real-world midlatitude 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 due to frontal fracture (i.e., when the cold and warm fronts briefly become separated from each other over a finite distance). In an earlier lecture, we termed such a cyclone structure a warm seclusion and briefly examined the structure of a warm-seclusion midlatitude cyclone. The development of warm-seclusion structure is an alternative hallmark of a midlatitude cyclone reaching maturity, and the life cycle of a midlatitude cyclone leading to the development of such a structure is illustrated in Figure 8.

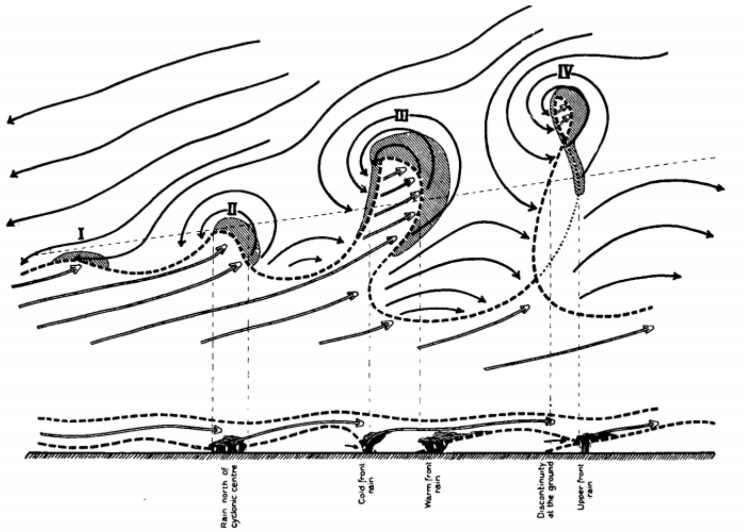

FIG. 1. The Norwegian frontal-cyclone model (Bjerknes 1921; Bjerknes and Solberg 1922) describing the amplification of a frontal wave from initiation (I), through cyclogenesis (II, III), to frontal occlusion (IV).

Figure 7. Life cycle of a synoptic-scale, midlatitude 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.

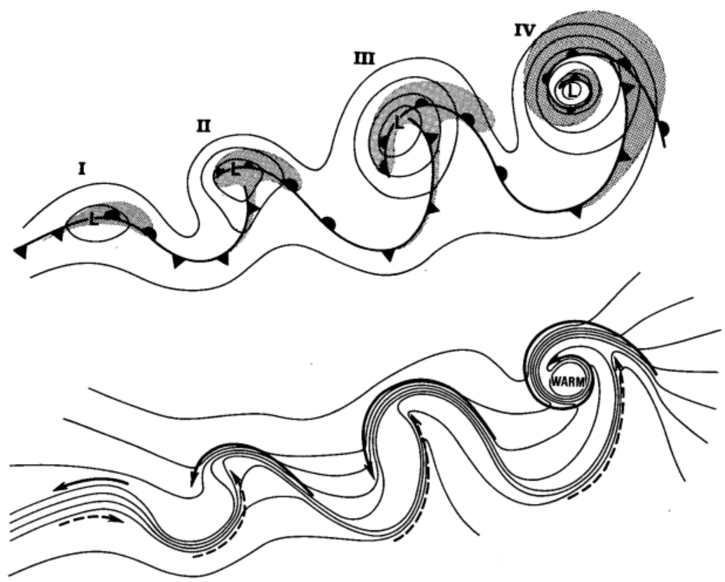

FIG. 21. An alternative model of frontal-cyclone evolution (Shapiro and Keyser 1990): incipient broad-baroclinic phase (I), frontal fracture (II), bent-back front and frontal T-bone (III), and warm-core frontal seclusion (IV). Upper: sea level pressure (solid), fronts (bold), and cloud signature (shaded). Lower: temperature (solid), and cold and warm air currents (solid and dashed arrows, respectively).

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.