Synoptic Meteorology II: Midlatitude Cyclone Lifecycle and Structure

For Further Reading

The material contained in these notes is partially drawn from Chapter 10 of *Weather Analysis* by D. Djurić and Chapter 10 of *Meteorology: Understanding the Atmosphere* (4^{th} ed.) by S. Ackerman and J. Knox. Information related to cyclone occlusion and warm-seclusion development is largely derived from published journal articles. Schultz and Vaughan (2011, *Bull. Amer. Meteor. Soc.*) is a contemporary review on cyclone occlusion. Neiman and Shapiro (1993, *Mon. Wea. Rev.*) discuss warm-seclusion cyclones, and Schultz et al. (1998, *Mon. Wea. Rev.*) discuss the synoptic-scale flow configurations that favor warm-seclusion versus occluded cyclone structural development.

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.

Baroclinic instability is most commonly associated with a large north-south thermal contrast, or *baroclinic zone*, with warm, moist (low density) air toward the Equator and cold, dry (high density) air toward the poles. The magnitude of the thermal contrast across the baroclinic zone is a measure of *baroclinicity*. From the thermal wind relationship, the baroclinic zone is in thermal wind balance with the vertical wind shear. The magnitude of the baroclinicity is directly proportional to that of the vertical wind shear, and for a north-south baroclinic zone associated with warm air to the south (i.e., a temperature gradient vector pointing to the south), the associated thermal wind is westerly. Consequently, midlatitude cyclones often develop in close proximity to an upper-tropospheric jet. Midlatitude cyclones intensify as potential energy (which is associated with the vertically sheared flow) is converted to kinetic energy and begin to decay once the potential energy has been depleted.

As a cyclone forms, the baroclinic zone is manifest as a stationary front. As the cyclone intensifies and matures, the baroclinically unstable westerly flow becomes amplified meridionally. This gives rise to well-defined cold and warm fronts and attendant waves in the large-scale flow. Midlatitude cyclones are thus often called *frontal cyclones* (given their association with frontal boundaries) or *wave cyclones* (given their association with synoptic-scale Rossby waves). We also sometimes refer to midlatitude cyclones as *extratropical cyclones* since they form outside of the tropics.

Where do Midlatitude Cyclones Form?

Climatologies suggest that, globally, midlatitude cyclones typically 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 Fig. 1.

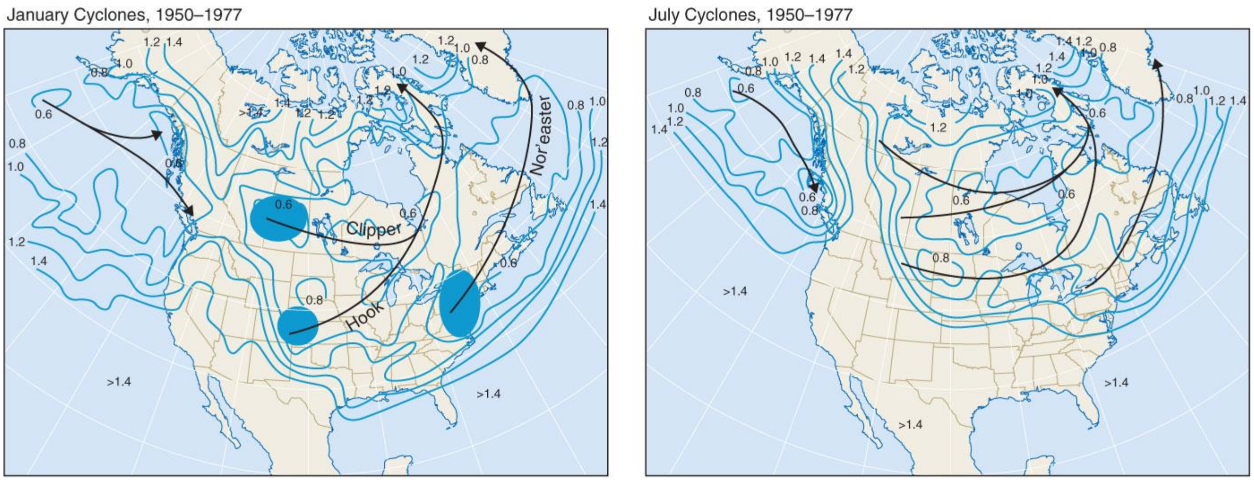

Figure 1. Predominant formation locations and tracks (black arrows) for midlatitude cyclones in North America in January (left) and July (right), as derived from a climatology of midlatitude cyclones that occurred between 1950 and 1977. The blue contouring represents the relative variability in cyclone occurrence, with midlatitude cyclones typically forming in regions of low relative variability. Figure reproduced from *Meteorology: Understanding the Atmosphere* (4th ed.) by S. Ackerman and J. Knox, their Fig. 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 (from land), a strong baroclinic zone develops. Along this baroclinic zone is where the needed 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 Fig. 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.

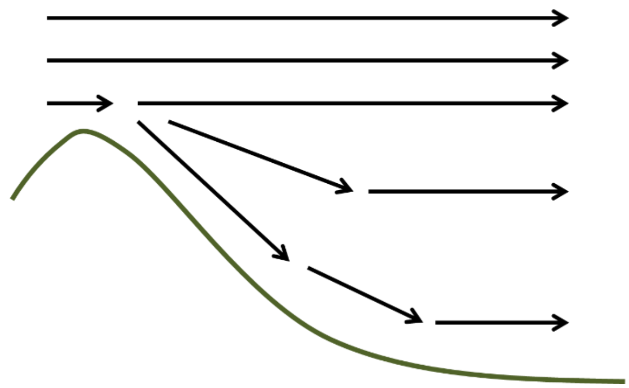

Figure 2. Idealized schematic of a mountain range (green line) and westerly wind flowing across the mountain range (black arrows). Note how the wind spreads out vertically downwind (or in the lee) of the mountain peak. Such conditions are most commonly observed when a stable layer exists at or near mountain 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, with a lower-tropospheric anticyclone of polar origin to the west and lower-tropospheric anticyclone of maritime origin to the east. This gives rise to a dipole of lower-tropospheric temperature advection: cold air advection to the west, warm air advection to the east. As we will examine in detail later this semester, lower-tropospheric warm air advection promotes surface cyclone development.

Type B cyclogenesis occurs in advance of a pre-existing middle-to-upper tropospheric trough, if not also in advance of a pre-existing midlatitude cyclone. As we will examine in detail later this semester, large lower-to-middle tropospheric cyclonic vorticity advection ahead of the upstream trough promotes surface cyclone development. Type B cyclogenesis occurs most frequently when strong middle-tropospheric cyclonic vorticity advection becomes superposed with a strong lower-tropospheric baroclinic zone, such as those near eastern continental coastlines.

Representative surface charts associated with Type A and Type B cyclogenesis events are depicted in Figs. 3 and 4, respectively.

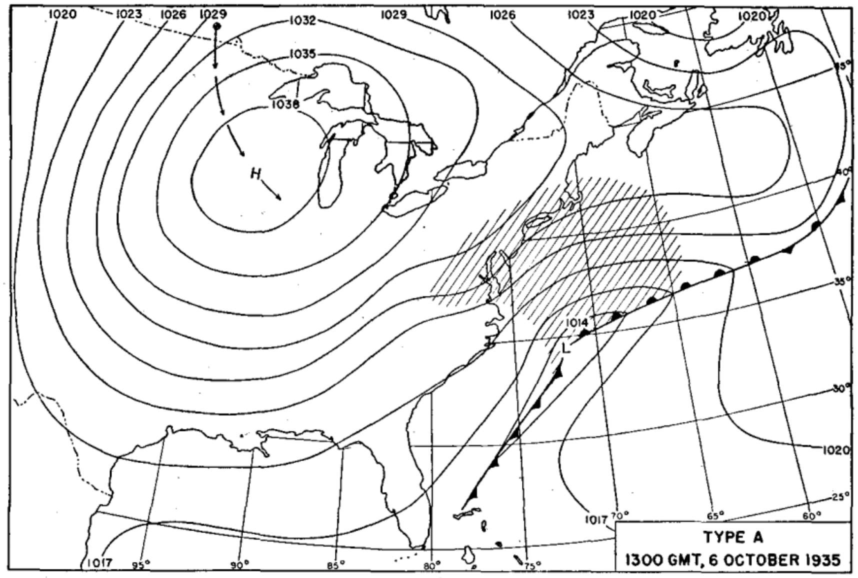

Figure 3. Sea-level pressure (black contours every 3 hPa) and precipitation regions (hatching) at 1300 UTC 6 October 1935, near the genesis time of a Type-A cyclone (here, located near 34.5°N, 72°W). Note the strong anticyclone over the central United States, with implied cold air advection over the eastern United States, and a weaker subtropical anticyclone off the map to the southeast, with implied warm air advection over the western North Atlantic. Figure reproduced from Miller (1946, *J. Meteor.*), their Fig. 1.

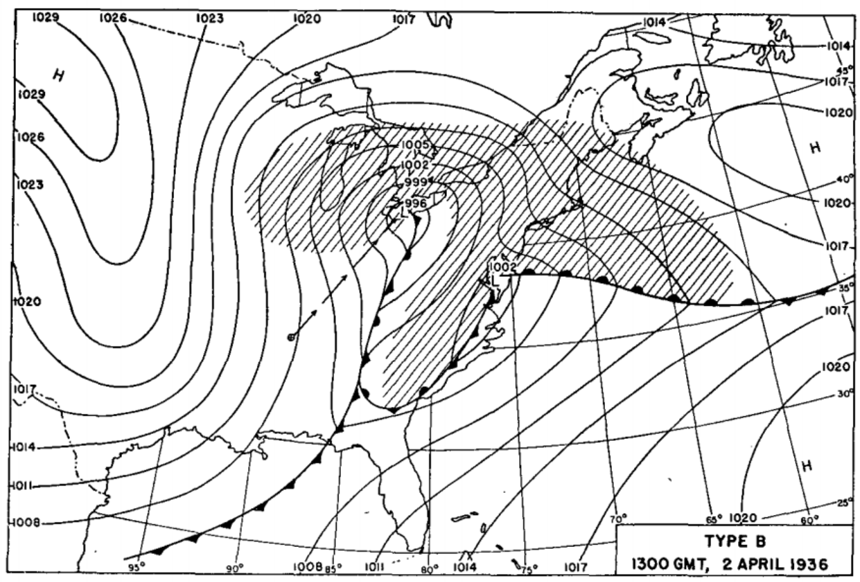

Figure 4. As in Fig. 3, except valid at 1300 UTC 2 April 1936 near the genesis time of a Type-B cyclone (here, located near 38.5°N, 76°W, or near the Delmarva Peninsula). Note the upstream mature midlatitude cyclone near Lake Erie and Type-B cyclogenesis near the Gulf Stream. Figure reproduced from Miller (1946, *J. Meteor.*), their Fig. 3.

The Life Cycle of Midlatitude Cyclones

The general life cycle of a midlatitude cyclone, from birth to decay, is illustrated in Figs. 5 and 6. Not every cyclone precisely follows this life cycle. For instance, cyclones' peak intensities and the time it takes a cyclone to progress from one stage to another vary substantially between cyclones. Furthermore, as we will discuss at the end of this lecture, the mature stage of a midlatitude cyclone need not necessarily be associated with cyclone occlusion.

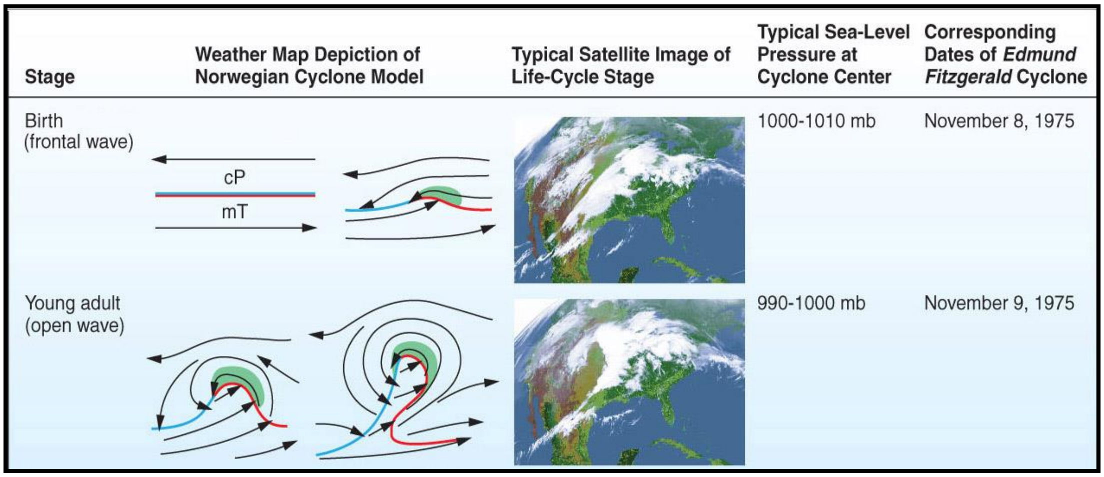

Figure 5. Idealized view of the birth and developing stages of a midlatitude cyclone. In the second column, blue lines denote cold fronts, red lines denote warm fronts, and black lines with arrows depict streamlines at the surface. Figure reproduced from *Meteorology: Understanding the Atmosphere* (4th ed.) by S. Ackerman and J. Knox, their Table 10-1.

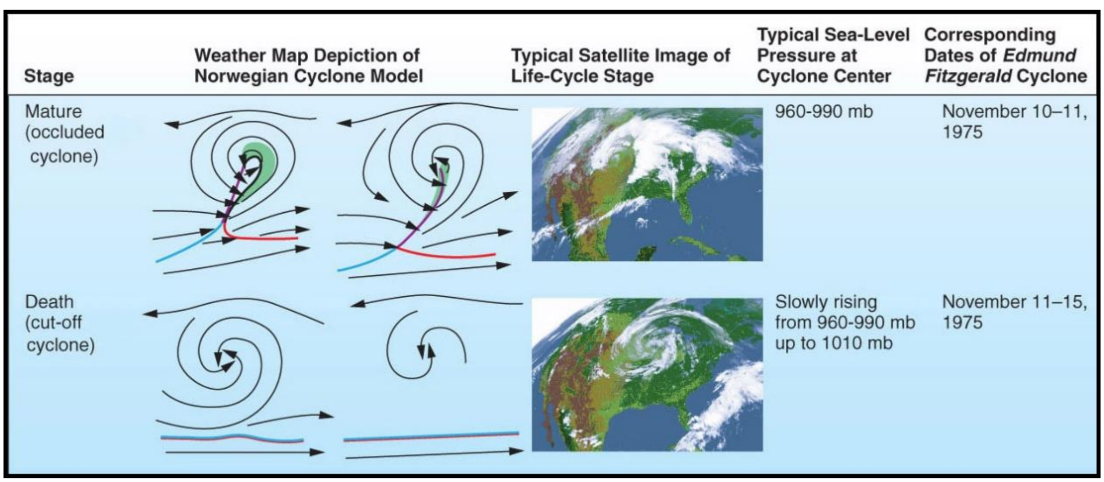

Figure 6. As in Fig. 5, except for the mature and decay stages of a midlatitude cyclone. Figure reproduced from *Meteorology: Understanding the Atmosphere* (4th ed.) by S. Ackerman and J. Knox, their Table 10-1.

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 or not. Clouds and precipitation found 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. The advection of cold air toward where it is warm and warm air toward where it is cold increases the magnitude of the cross-front thermal contrast (temperature gradient), 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.

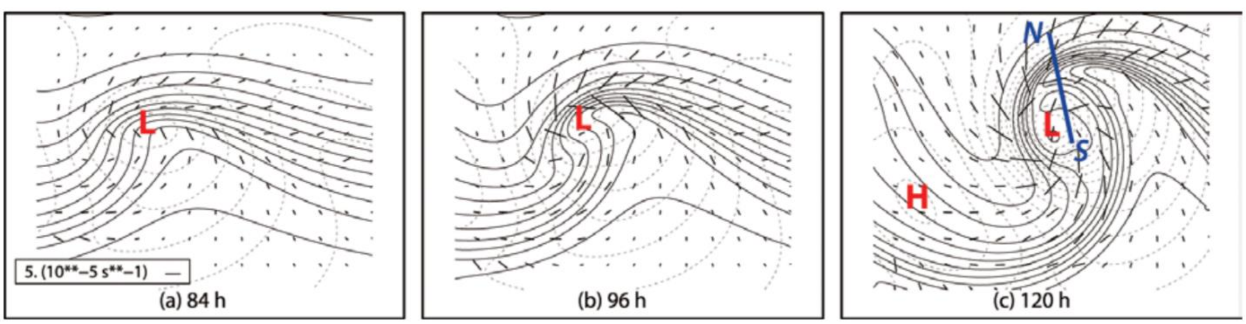

Figure 7. 850 hPa height (dashed grey contours every 60 m; low/high centers labeled in red), 850 hPa potential temperature (solid black contours every 4 K), and 850 hPa horizontal wind (vectors) at three milestones (a, b, c = 84, 96, 120 h) during the mature stage of a midlatitude cyclone. Note the narrowing of the warm air mass around the eastern and northern sides of the cyclone while the cold air mass wraps around from the south and west. Figure reproduced from Schultz and Vaughan (2011, *Bull. Amer. Meteor. Soc.*), their Fig. 6.

As the midlatitude cyclone reaches maturity and the cyclone reaches its peak intensity, an occluded front develops. The occluded front develops as the system's air masses wrap and become deformed around the cyclone. Cold air wraps around the cyclone both from the front (easterly and rearward flow poleward of the warm front) and the back (westerly and forward flow behind the cold front), eventually enveloping the cyclone in cold air, both associated with what is known as the cyclone's cold conveyor belt. Concurrently, warm air wraps around the cyclone from the south and east, gradually becoming deformed into a narrow band that extends rearward toward the cyclone's center. Further, the separation distance between the upstream trough and cyclone decreases during the maturation process, manifest by the latter moving more slowly poleward and to the east than the former. A representative schematic of cyclone occlusion is depicted in Fig. 7.

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 Fig. 8. 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 Fig. 8) is often convective in nature, whereas precipitation along and poleward of the midlatitude cyclone's warm front (A-B-F in Fig. 8) is predominantly stratiform (e.g., light to moderate and steady) in nature.

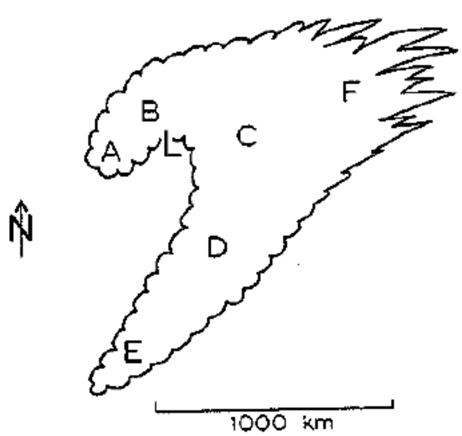

Figure 8. Idealized depiction of the cloud (and precipitation) structure associated with a frontal cyclone. Reproduced from *Weather Analysis* by D. Djurić, their Fig. 10-4.

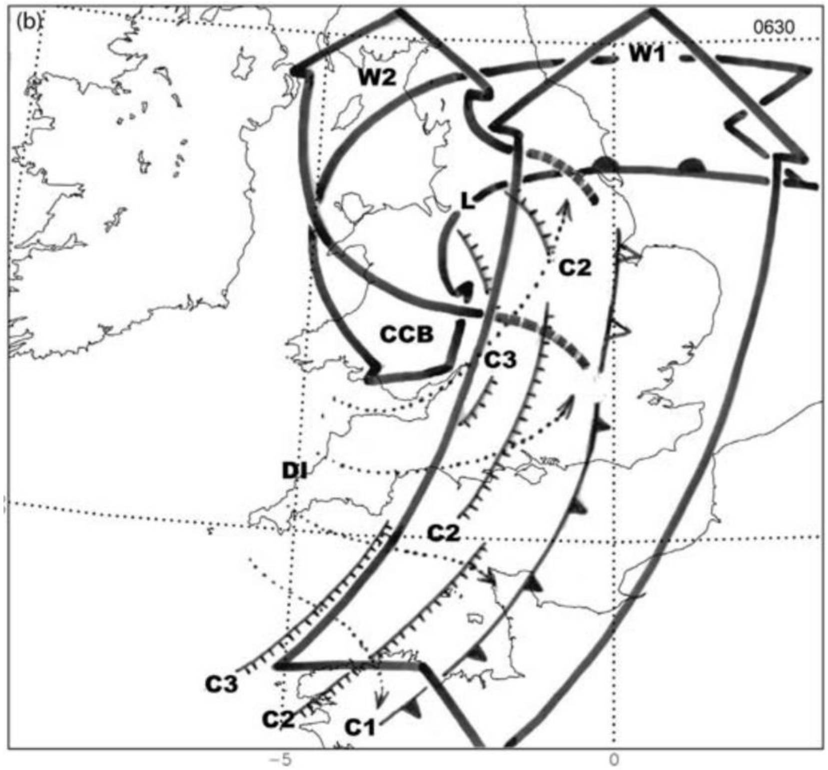

Figure 9. Idealized depiction of the primary air streams of a developing frontal cyclone system. Figure reproduced from Browning (2005, *Quart. J. Roy. Meteor. Soc.*), their Fig. 4b.

A conceptual model of a midlatitude cyclone is depicted in Fig. 9. Midlatitude 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 midlatitude cyclone appearance on radar and satellite imagery (as in Fig. 8):

- 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, which they argued occurs when the midlatitude cyclone's cold front overtakes its warm front. (We now know this to not occur; occluded fronts form as the cyclone's air masses wrap around the cyclone, rather than one air mass catching up to another, as described above.)

In such cases, the cyclone itself is said to become occluded and becomes embedded within a cold air mass (or, more generally, away from the warm air mass). The life cycle of a midlatitude cyclone leading to occlusion is illustrated in Figs. 5 and 6 above and Fig. 10 below.

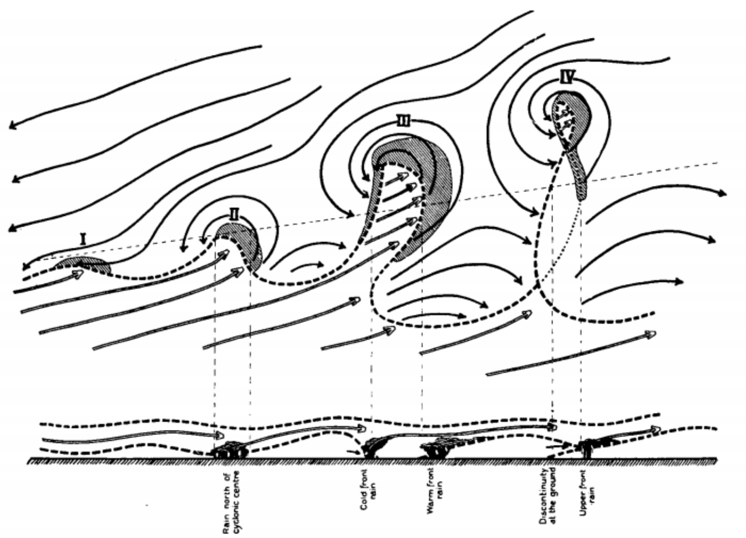

Figure 10. Life cycle of a synoptic-scale, midlatitude cyclone from development to occlusion, as viewed from the Norwegian/Bergen School perspective. Figure reproduced from Nieman and Shapiro (1993, *Mon. Wea. Rev.*), their Fig. 1.

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.*), frontal dissipation along the poleward-most extent of the cyclone's cold front may facilitate *frontal fracture*, wherein the cold and warm fronts become separated from each other over a finite distance. This allows for a pocket of lower-tropospheric warm air (originating ahead of the cyclone's cold front) to become deformed as it is advected rearward along the cyclone's warm and bent-back occluded fronts. This warm air ultimately surrounds the cyclone's center, with cold air surrounding the warm pocket and separating the cyclone from the synoptic-scale warmer air to its south and east. This represents a *warm seclusion*, with warm-seclusion development representing an alternative yet complementary hallmark of a mature midlatitude cyclone. These cyclones are often among the most intense of all midlatitude cyclones. The life cycle of a warm-seclusion cyclone is illustrated in Fig. 11, and the lower-tropospheric thermodynamic structure of a warm-seclusion cyclone is illustrated in Fig. 12.

While a full discussion of the differences between warm-seclusion and classical occluded cyclone development is beyond the scope of this course, it is nevertheless fruitful to briefly consider some of their differences before ending this discussion. Warm-seclusion structure typically but does not always form when a cyclone moves into a strongly confluent lower- to midtropospheric synoptic-scale environment. Warm-seclusion development primarily takes place over water, where surface friction is relatively low and surface sensible and latent heat fluxes can be relatively large and directed upward. It is often characterized by cyclonic Rossby wave breaking, wherein the cyclone and its upstream midtropospheric trough roll up cyclonically like a rearward-crashing wave.

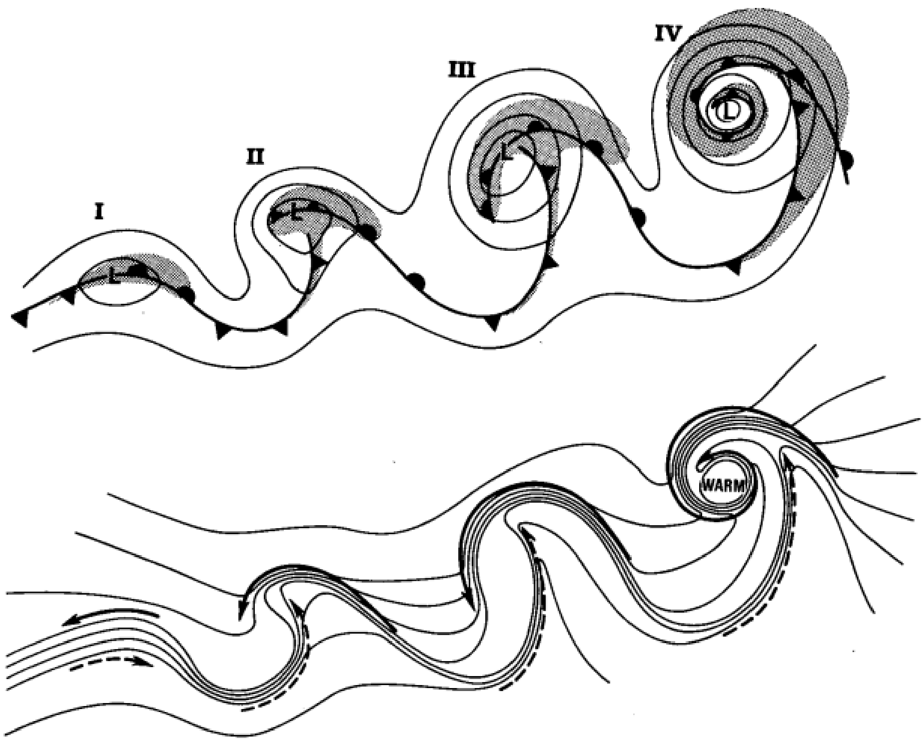

FIG. 21. An alternative model of frontal-cyclone evolution (Shapiro and Keyser 1990): incipient broad-baroclinic phase (I), frontal fracture (II), bent-back front and frontal T-bone (III), and warm-core frontal seclusion (IV). Upper: sea level pressure (solid), fronts (bold), and cloud signature (shaded).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

Figure 11. As in Fig. 10, 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 Fig. 21.

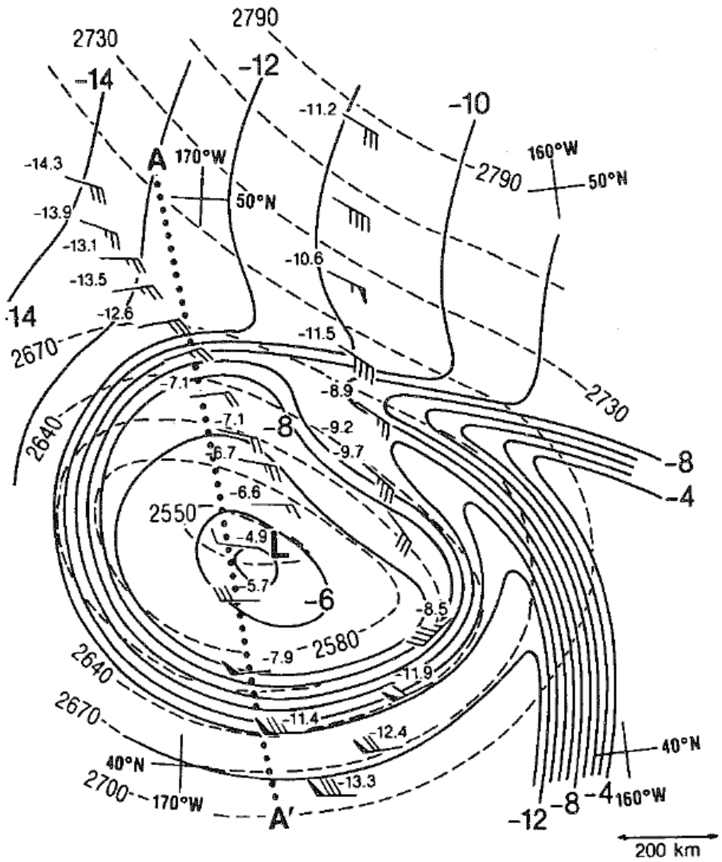

Figure 12. Analysis of surface isotherms (°C; solid lines), 700 hPa height (m; dashed lines), and aircraft-obtained winds (barbs; half: 5 kt, full: 10 kt, pennant: 50 kt) depicting a warm seclusion extratropical cyclone. Reproduced from *Synoptic-Dynamic Meteorology in Midlatitudes (Vol. II)* by H. Bluestein, their Fig. 2.33.