

## Chapter 6

# Atmospheric Analysis Models

There is an abundance of weather data available to meteorologists. These include surface and upper air observations as well as a tremendous amount of computer forecast model output. As a forecaster you need a way to ingest these data, visualize patterns, interpret these patterns, and translate them into a clearly communicated forecast. One approach to this process involves drawing isolines of various parameters and identifying the patterns and weather systems shown. These weather systems tell you what is currently happening as well as how the atmosphere may evolve in the near future. Atmospheric analysis models provide the information needed to interpret data and isoline patterns.

### ***What is an Analysis Model?***

An *atmospheric analysis model* is an idealized representation of a weather system that helps you as a forecaster visualize that system, its associated weather, and its evolution. It provides a distribution in time and space of what the system looks like in three dimensions. It gives you a sense or feel for that system and how it might look in terms of real data or computer forecast model output.

### ***How to Use Analysis Models***

Because an atmospheric analysis model is an idealization, there will be differences between the idealized and real world. You must fit the models to the data and adjust the model to the observations or computer forecast model output. For actual observations, the adjustment typically depends upon the data density. Where data are sparse, an analysis model will have a strong influence on the final analysis; where data are dense, the model will influence the result less and the data will define the final analysis. For computer forecast model output, data density is high and the model helps make sense out of the numbers and isolines, and reduces data saturation.

As you look at a set of data or NWP output fields, you should ask questions like:

- Which analysis model fits the situation?

- How does this situation differ from the idealized model?
- Does the vertical structure fit the idealized model?
- Is there a good thermal gradient to support a front?
- Is there sufficient moisture to produce clouds and/or precipitation?

Asking questions like these and others help you better understand what is happening in atmosphere and how things will evolve in the near term.

### ***Basic Analysis Models***

Let's start our exploration with very basic analysis models. After taking a good introductory meteorology course you should already know what these patterns represent. Nevertheless, it is important to define these basic patterns (or analysis models) so that there is a common basis for discussion.

All descriptions refer to horizontal depictions of weather data. Definitions used below are paraphrased from the *Glossary of Meteorology*. Keywords in descriptions are in italics.

*Low Centers*: A "low center" is a *relative minimum* in a variable field characterized by at least one *closed isoline*. Low centers are found in sea level pressure and upper height fields, and in temperature and moisture patterns. Low centers in the pressure and height fields are often referred to as cyclones due to the cyclonic flow associated with the low center. The term "cold core" is used for cold temperature centers. If an area of lower values cannot be enclosed in a closed isoline, the term "trough" is used to describe that area. (See below.)

*High Centers*: A "high center" is a *relative maximum* in a variable field characterized by at least one *closed isoline*. High centers are found in sea level pressure and upper height fields, and in temperature and moisture patterns. High centers in the pressure and height fields are often referred to as anticyclones due to the anticyclonic flow associated with the high center. The term "warm core" is used for warm temperature centers. If an area of higher values cannot be enclosed in a closed isoline, the term "ridge" is used to describe that area. (See below.)

*Troughs and Trough Lines*: The terms "trough" and "trough line" are often used interchangeably, even though they are distinct features. A trough is a *broad elongated area* of relatively lower

values characterized by *open isolines*. A trough line is a *quasi-linear feature* within the trough where the *curvature* of the isolines is maximum. If you move away from the trough line, values increase, that is, there is relative minimum along the trough line compared to values perpendicular to the trough line. Troughs are identified in the pressure, height, temperature, and moisture fields.

*Ridges and Ridge Lines:* The terms "ridge" and "ridge line" are often used interchangeably, even though they are distinct features. A ridge is a *broad elongated area* of relatively higher values characterized by *open isolines*. A ridge line is a *quasi-linear feature* within the ridge where the *curvature* of the isolines is maximum. If you move away from the ridge line, values decrease, that is, there is relative maximum along the ridge line compared to values perpendicular to the ridge line. Ridges are found in the pressure, height, temperature, and moisture fields. Pressure and height ridge lines are often difficult to identify, compared to the broader ridge itself, due to lack of a maximum in the isoline curvature. Ridges in the surface dew point pattern are often called a "moist tongues."

*Gradients:* The term "gradient" refers to the *rate of change of a variable in space*. Mathematically, the gradient of a scalar quantity is a vector directed from low toward high values of the scalar, perpendicular to isolines of the scalar field (in a horizontal plane). The two dimensional gradient magnitude is expressed as:  $(\partial f/\partial x + \partial f/\partial y)$ . In meteorology, gradient is often used in equations with a minus sign. As a result, meteorological gradient vectors usually are directed from higher toward lower values.

From a practical perspective, isolines are drawn at a constant interval so that the spacing of the isolines can be interpreted as a measure of gradient. For example, the strength of the geostrophic wind (Chapter 5) is proportional to the spacing (or gradient) of the pressure/height field. Where isobars are closer together, winds are stronger, while where isobars are farther apart, winds are weaker. Pressure, height, temperature, and moisture gradients are routinely evaluated by forecasters.

*Flow Curvature and Inflection Points:* Curvature refers to the *change in direction of the flow*. "Cyclonic curvature" is associated with flow that turns counterclockwise in the Northern Hemisphere and clockwise in the Southern Hemisphere. "Anti-cyclonic curvature" is associated with flow that turns clockwise in the Northern Hemisphere and counterclockwise in the Southern

Hemisphere. The point where the flow changes from cyclonic to anticyclonic or from anticyclonic to cyclonic is called the "inflection point." Curvature terminology is often used when discussing both low level and mid-tropospheric flow.

*Cols:* There are situations where a trough line and a ridge line intersect each other. It is point of relative low value between two high centers as well as a point of relative high value between two low centers. This location is called a col, or mathematically, a *saddle point*. There is no flow at the point itself.

*Discontinuities:* The term "discontinuity" refers to an abrupt variation or jump in the value of some variable along a quasi-linear feature. On some scales it looks like field suddenly changes value. In reality, it is a very narrow band of very strong gradient. The two examples of discontinuities are fronts and drylines. Fronts, by definition, should be associated with a strong temperature gradient while drylines have strong gradients of moisture.

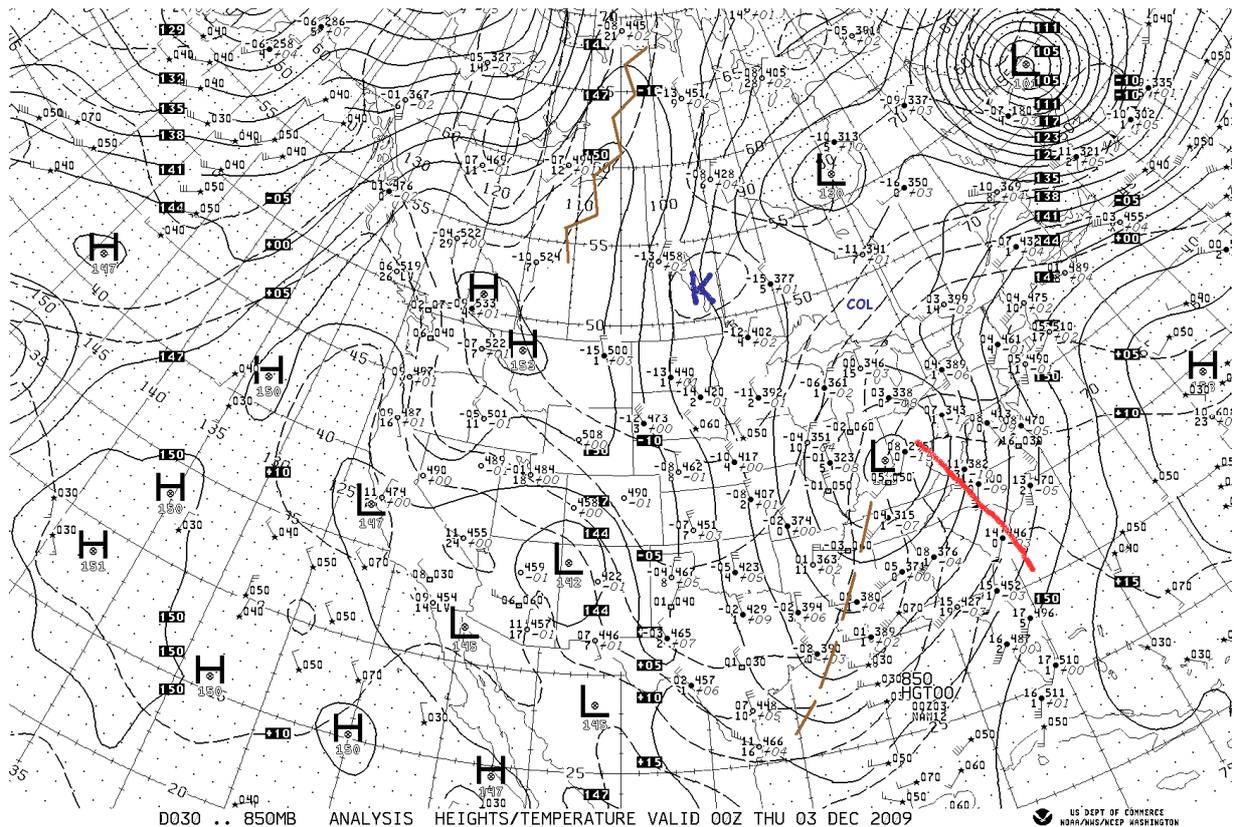
*Wind Shift:* Wind flow across a large area tends to change direction and vary in speed. In some areas, the wind changes direction relatively abruptly. This change in direction typically occurs along what is called a "wind shift line." A wind shift line is a curve along which the wind direction shifts by at least 60 degrees over a short distance. For most surface wind shift lines, the curvature of the flow across the wind shift line is cyclonic.

*Practical Application:* If you are an analyst, you need to know more than just the definition of the above terms. You also need to be able to identify these features on an operational chart.

Figure 6-1 shows an 850 mb chart for 00 UTC, 03 December 2009. Several basic analysis model features are highlighted. There are at least three examples of low height center surrounded by one or more contours. These are located over Indiana, over the southeastern portion of Hudson Bay, and along the Labrador coast. A trough line extends from the Indiana low center toward the south-southwest through Mississippi into the western Gulf of Mexico. This trough line is shown as a dashed brown line.

A high center is found over the Rockies along the United States-Canada border. A ridge line extends toward the north-northeast into the Canadian arctic and is marked by a saw-tooth brown

line. The multiple high centers, marked by several H's over the eastern Pacific Ocean, in the lower left of the figure, show a feature of computer line drawing that a human analyst would replace with less H's. If the computer finds a relative maximum in its grid field, it places an H there, even though it may also place another H a several hundred miles away. A human analyst would tend to combine these H's into one center. A similar feature is often seen for low centers in relatively flat gradient regions.



**Figure 6-1: Example of Basic Analysis Model Features**

Other features seen in Figure 6-1 include a cold core near Lake Winnipeg, marked with a blue K (from the German *kalt* for cold), and thermal ridge from South Carolina into Ohio, marked by a red line. There is also a col over Ontario. It is located between the two low centers noted above and the high centers to the east and west. Areas of stronger height and temperature gradients are also visible over the eastern United States and the Gulf of Mexico. Can you identify areas of WAA and CAA?

### ***Norwegian Cyclone Model/Mid-Latitude Cyclones***

One of the more well-known atmospheric analysis models is the Norwegian Cyclone Model (NMC). This depiction of a surface low pressure center and associated fronts was introduced by meteorologists from Bergen, Norway, around 1920 (Bjerknes, 1919; Bjerknes and Solberg, 1922). The Bergen analysis method was adopted by the U.S. Navy in the mid 1920s, but it was the middle to late 1930s before the U.S. Weather Bureau started using this approach to analysis.

The original NCM was a surface-based analysis model. As upper tropospheric flow patterns were explored and classified over the next 30 years, the NCM was expanded into a three-dimensional model of mid-latitude cyclone evolution and development. All introductory textbooks provide a series of images of the evolution of a low center from an initial wave along a front to the fully developed occlusion. The typical description in these textbooks is not all that different from the description in the 1922 article.

At this point you might expect to see a series of figures showing the three dimensional development of a mid-latitude cyclone. However, rather than adding another set of pictures to those that already exist, you are referred to the depiction provided by Carlson (1991, pp. 226-233). These figures nicely show the three dimensional relationship among the surface low center, surface fronts, the upper level trough, the upper jet streak, the associated cloud pattern, and vertical motion for the various stages in the development of a mid-latitude cyclone. Summarizing these figures:

- During Stage 1, a weak low pressure center forms along a stationary front. There is a mid-tropospheric trough well upstream from the surface low center and a jet streak on the upstream side of upper trough.
- During Stage 2, a weak circulation develops with warm air advection ahead of the low center and cold air advection behind the low. Both the upper trough and jet streak get closer to the surface low. Positive vorticity advection (PVA) found above the surface low center. The precipitation expands as the mid-tropospheric trough amplifies.
- During Stage 3, a well defined wave cyclone is found with warm air advection ahead of the low center and cold air advection behind the low. The mid-tropospheric trough

continues to amplify and the divergent quadrant of the jet streak is found above the surface low.

- During Stage 4, the surface low occludes and precipitation wraps around the low. The surface low moves under the mid-tropospheric trough (or low) and the jet streak moves downwind from the upper trough. Dry air intrudes into the systems from the west.
- During Stage 5, the surface low weakens and eventually dissipates.

Even though all mid-latitude cyclones start as weak low pressure centers, not all cyclones evolve through the entire sequence depicted in the NCM. That is, not all cyclones become occluded. Some cyclones develop into a weak to moderate wave cyclones and stay in that stage throughout their lifetime. Other cyclones go through the entire development process. How much a low center intensifies depends upon the thermal and divergence patterns associated with the three-dimensional structure of the system. A discussion of these factors is beyond the scope of this chapter and is covered in more advanced meteorology courses.

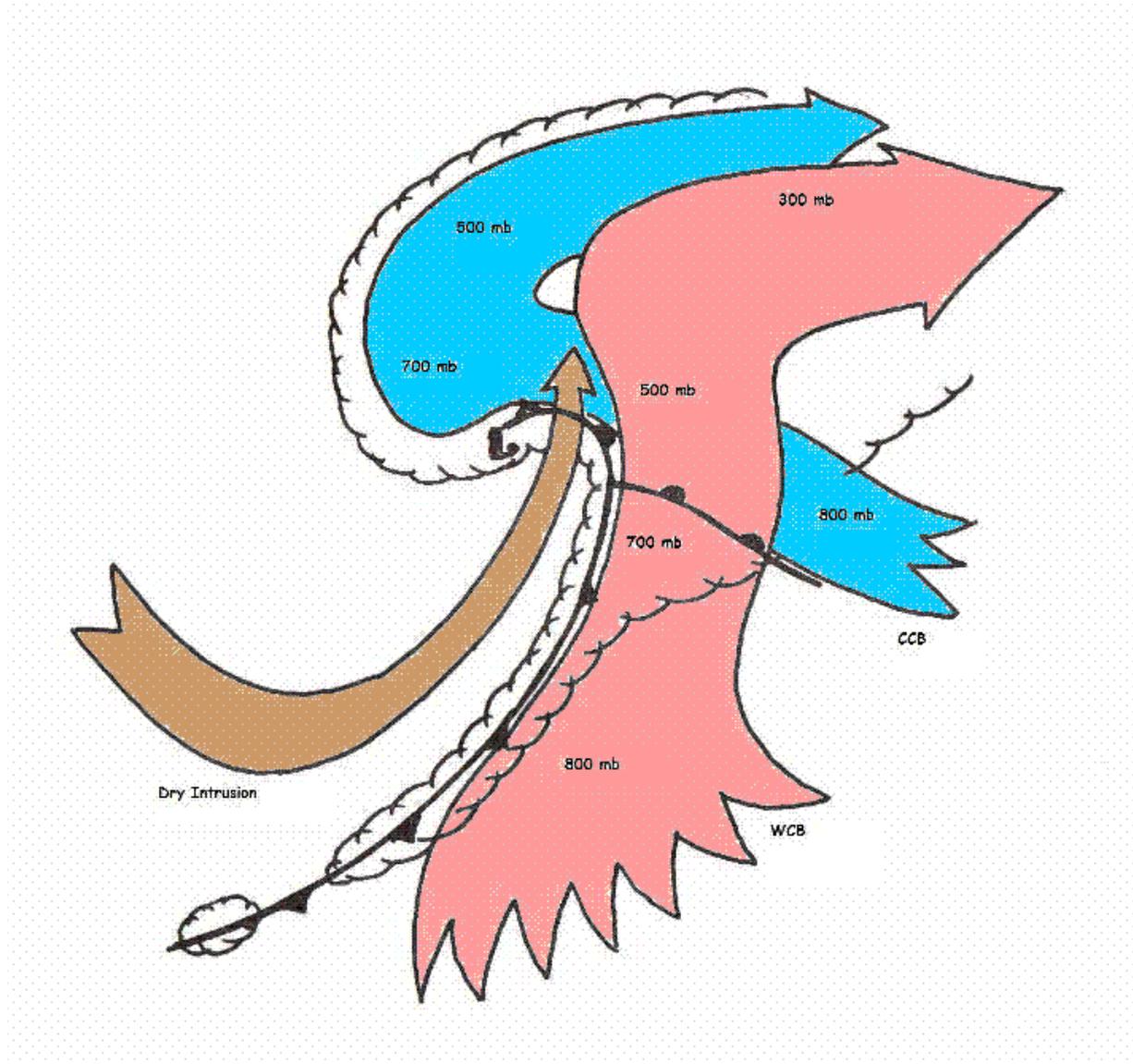
### ***Conveyor Belt Model***

One of the best ways to visualize the three-dimensional flow around a mature frontal cyclone is to use the conveyor belt model. Even though Carlson (1980) first presented the conceptual model in 1980, parts of this concept were developed earlier by Harrold (1973), modified later by Young et al (1987), and summarized by Browning (1999).

This model was intended to describe the storm-relative flow around a mature frontal wave. Carlson assumed a constant movement of the system to determine the relative motion using isentropic analysis. Figure 6-2 shows the conveyor belts at one point in time. Please realize these belts change somewhat during the life cycle of the cyclone.

*Warm Conveyor Belt:* The **warm conveyor belt** (marked WCB in the figure) represents the main source of warm, moist air that feeds the cyclone. It originates in the warm sector of the cyclone and flows poleward parallel to the cold front. This layer can be 200 to 300 mb deep and typically begins in the convective mixing layer well away from the low center. As the flow approaches the warm front, it begins to ascend with its strongest rise over the warm front, in the area of strongest warm air advection. It eventually starts to turn anticyclonically as it joins the jet

level flow in the upper troposphere. The pressure values in the figure represent the approximate pressure level of the flow at that point in space.



**Figure 6-2: Conveyor Belt Model (after Carlson, 1980)**

One representation of the WCB takes a branch of this flow and curves it around the occlusion into the cyclonic circulation. This variation is more likely to occur during the later stages of a cyclone's life cycle. Browning (1999) referred to the main WCB as W1 and this secondary branch as W2.

The amount of precipitation produced by a cyclone depends upon the amount of moisture flowing into the circulation along the WCB. During the winter over the Central United States, well-

organized lows with strong dynamics move out of the High Plains of Colorado. However, if the WCB is not tapping good moisture, the snowfall may be relatively light compared to what the dynamics could support. *Nota bene*: as you develop your precipitation forecast, pay special attention to the amount of moisture that the WCB is feeding into a system.

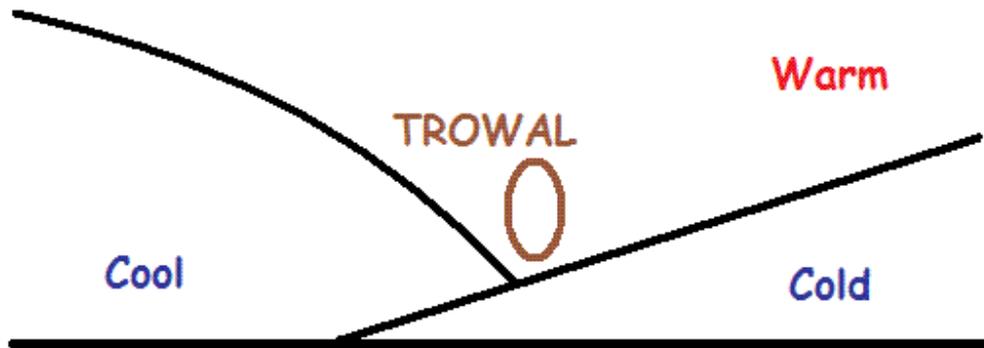
*Cold Conveyor Belt*: The **cold conveyor belt** (marked CCB in the figure) originates poleward and east of the low pressure center, typically in the easterly flow on the backside of a high pressure system to the east. This air flows westward, on the cold side of the warm front, below the WCB, toward the center of the low pressure circulation. The air becomes saturated through a combination of precipitation falling into the CCB from the WCB above and slow ascent from the boundary layer to the mid-troposphere north of the low center. The flow eventually rises and turns anticyclonically into the upper tropospheric ridge ahead of the developing cyclone.

*Dry Intrusion*: As a cyclone develops there is typically an intrusion of dry air equatorward of the low pressure system between the intensifying surface low center and the cold front. This air originates near the tropopause fold or break, descends on the backside of the developing cyclone to mid tropospheric levels, and starts to rise once it is east of the upper trough that is associated with the developing cyclone. This dry air eventually rises over the CCB parallel to the WCB. The penetration of this dry air over the low level moisture creates potential instability that may be released as convective clouds. The dry air intrusion is usually obvious on water vapor imagery.

*Operational Application*: The flow of air through midlatitude cyclones is important to understanding the cloud and precipitation distribution around the cyclone. The **conveyor belt model** helps visualize this flow pattern. It helps you identify the best area for rising air and precipitation. When applying this concept in actual forecast situations, remember that this model displays "storm-relative" flow and that weather maps display actual wind. Nevertheless, by examining the winds at several levels on your analysis or prognostic charts, you can still get a good feeling for the flow pattern and their source regions. Use the conveyor belt concept to help you visualize what is happening and better understand the current weather situation.

### **TROWALS**

TROWAL is an acronym for "trough of warm air aloft." It has been used by Canadian meteorologist for years to describe the area above the intersection of the warm and cold air in a warm occlusion (Figure 6-3).



**Figure 6-3: Location of a TROWAL**

The TROWAL originates at the Earth's surface near the point of occlusion and rises along the upper level intersection of the frontal boundaries. Significant clouds and precipitation is found along the TROWAL where there is rapid cyclonic ascent of air that originates in the warm section. Some studies call this the "TROWAL airstream." The TROWAL is easily seen as a ridge of equivalent potential temperature on a horizontal chart. If you compare this depiction to the conveyor belt model described above, there are some common features between the warm conveyor belt and the TROWAL airstream. [Martin, 1999]

By comparing and correlating the Norwegian Cyclone Model, the Conveyor Belt concept, and the TROWAL with current data or computer model forecast output, you can get an excellent picture of the flow around a mid-latitude cyclone. You can use these images to better understand what is happening in the atmosphere.

### **Identifying a Front on Operational Charts**

Locating a front on a weather chart is sometimes easy and sometimes a challenge. If there are two distinct and strongly contrasting air masses on either side of the front, placing the front is straightforward. On the other hand, if the difference between the two air masses is small, the main question is: Is this boundary a front or just a trough?

The standard features which you look for when placing a front on a surface chart are as follows:

- A thermal gradient is found along the frontal zone with the front itself on the warm side of the gradient.
- The front lies in a pressure trough.
- There is a cyclonic wind shift along the front. This creates a relative maximum in the surface vorticity associated with the cyclonic shear and curvature of the flow.
- There is a band of confluence along the front. This is most easily seen in a streamline analysis of the surface flow.
- There is a band of clouds and possibly precipitation along or on the cold side of the front. This factor varies, depending upon the available moisture.
- There is a moisture gradient across the frontal zone. This factor can also vary and is not always a good indicator of a front.

Most of these factors can be evaluated from surface data. Because a front is three-dimensional system, the thermal gradient should be examined above the surface to ensure that the air mass contrast has depth. The 1000-700 mb thickness is a good way to do this. There should be a thickness gradient on the cold side of the surface front that indicates there is thermal contrast through at least 10,000 feet MSL.

Surface troughs and fronts share several features in common (after Sanders, 2005):

- A cyclonic wind shift.
- A local pressure minimum.
- A change in dew point (moisture).
- A different source region for air on either side.
- A substantial temperature change for a 24-hour period.

Comparing the two lists just presented indicates that there are two main differences between troughs and fronts:

- For a front, the cyclonic wind shift is accompanied by a significant temperature change. That is, the cyclonic wind shift is on the warm side of the thermal gradient. For a trough, the two features do not coincide. The thermal gradient is often found parallel to the trough line.

- Clouds and precipitation tends to be along and to the cold side of the wind shift for a front. For a trough, they tend to occur before the wind shift.

The main point emphasized here is that you should carefully examine all factors identifying a front before you decide to call it a *front* or call it a *trough*.

### **Mesoscale Models**

Identification of mesoscale features is a challenge due to the general lack of mesoscale data. Standard surface observations, except in special networks, have a sub-synoptic spacing. Upper air data have synoptic scale spacing. Satellite imagery and radar data provide qualitative mesoscale information. By combining these data sources and mesoscale models, you can get a good feel for what is happening on the mesoscale.

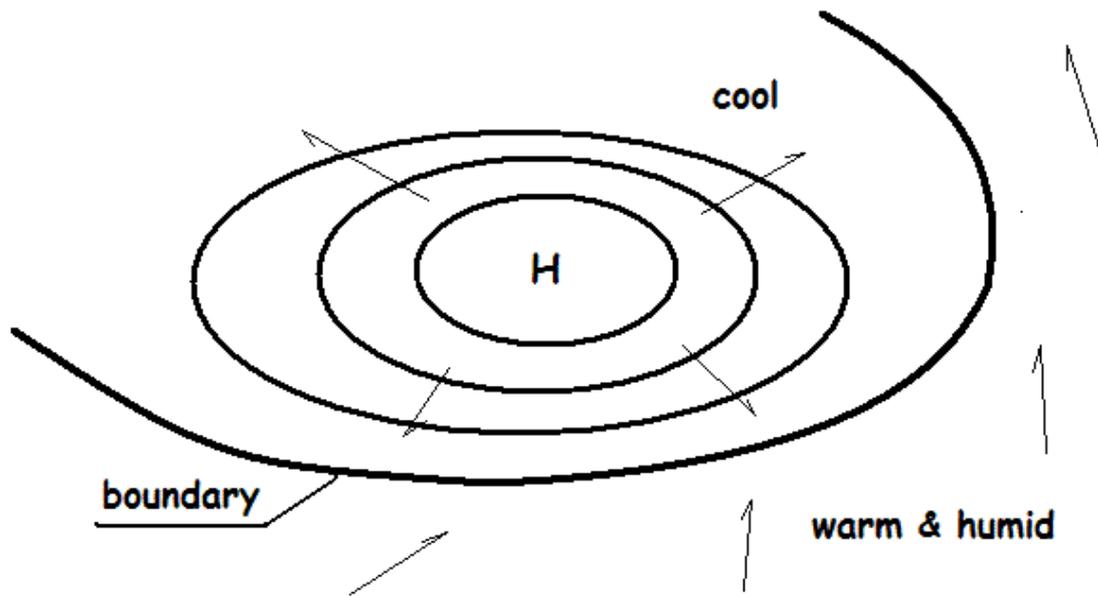
*Boundaries:* A feature that is found on mesoscale as well as synoptic scale charts is the *boundary*. A boundary is a curvilinear-discontinuity characterized by cyclonic shear and convergence. To be significant, a boundary should persist from one chart to the next. Transient boundaries are usually of little importance. This definition fits many features including fronts and troughs.

*Mesohigh:* A cluster of thunderstorms often accumulates a pool of cool air at the Earth's surface under the cluster. This cool air originates from the thunderstorm downdrafts. The air is denser than surrounding air and creates a mesoscale high pressure center, commonly referred to as a *mesohigh* or *bubble high*. The boundary that is created between the cool air and the surrounding warm humid air is called an outflow boundary or convectively induced boundary. Figure 6-4 shows a schematic of these features.

The core of the cooler air is shown by the letter H (high pressure center) surrounded by several isobars. The air flows away from the high center (thin arrows) toward the thick line or boundary. The warm humid air is found to the right and below the boundary with wind flowing into the boundary. This schematic was originally proposed by Fujita in 1955.

The boundary between the cool high and warm humid air is a favored location for the development of new convection. The low level convergence of warm, moist, unstable air along the outflow

boundary produces the low level lift needed for convective initiation. If the cool air covers a sufficient area, it can be identified in a sectional chart.



**Figure 6-4: Schematic of a Mesohigh Center**

Figure 6-5 shows an example of a mesohigh on a surface chart for 1400 UTC, 01 June 2008. Thunderstorms are occurring across north central Oklahoma, with rain extending north into south central and southeast Kansas. Various boundaries are shown on the figure as solid lines from central Kansas into northern Missouri, across the Texas Panhandle, and from Arkansas into east central Oklahoma. The boundary that curves from southeast Kansas, into northeast Oklahoma, to central Oklahoma is the outflow boundary associated with the thunderstorm complex. Note that temperatures within the outflow are 5 to 10 degrees Fahrenheit lower than the air to the east and south. Although pressure values are a little difficult to see on this presentation, there is a mesohigh center between Chanute and Wichita, Kansas, marked as an H. The winds around the mesohigh are flowing outward from the high center toward the outflow boundary. Winds across Texas and Oklahoma are from the south and continue to "feed the mesoscale beast," that is, the thunderstorm complex in northern Oklahoma.

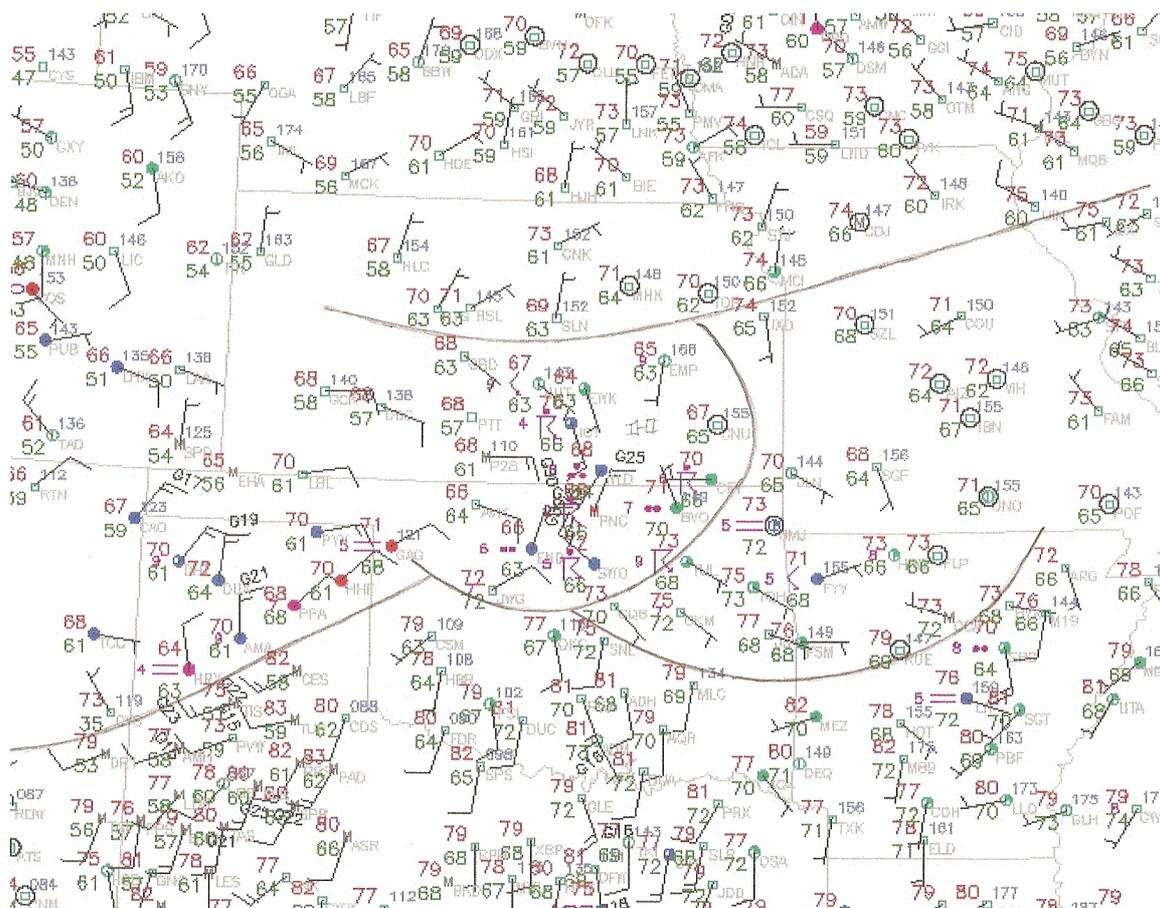


Figure 6-5: Example of a Mesohigh and Outflow Boundary

**Concluding Remarks**

This chapter is not a comprehensive discussion of all possible atmospheric analysis models. It only touches on a few of the more important ones. Other topics covered in other chapters may be considered types of analysis models. For example, the concept of geostrophic wind in Chapter 5 and Chapter 9 on "Waves in the Westerlies" fall into this category.

The idea of an atmospheric model is to be able to use the idealized representation of a weather system to help you as a forecaster visualize the weather system, its associated weather, and its evolution. Models provide a distribution in time and space of what the system looks like in three dimensions. It gives you a sense or feel for the weather system and how it changes over time. These things are important to you as a forecaster.

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