

# 6

## WEATHER SYSTEMS

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**W**eather systems can be divided into two main classes: one where temperature advection is significant, such as in the frontal system, and one where it is not, such as in the subtropical high. If a system is driven by temperature advection, it is said to be baroclinic, and if not, it is said to be barotropic (equivalent barotropic).

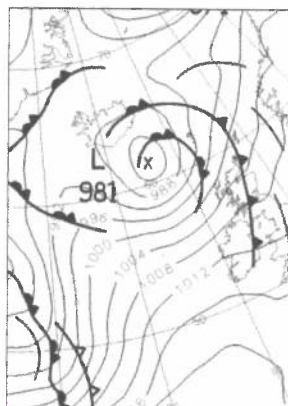
Barotropic weather systems are not driven by thermal advection, so temperature gradients are typically weak. As a result, a jet stream usually does not directly overlie a barotropic system. Since any isotherms are in phase with the isobar field, no thermal advection is indicated in a barotropic system.

The baroclinic weather system is driven by baroclinic instability: horizontal differences in temperature. Such thermal contrast is unstable because the cold air has a tendency to sink and spread out beneath the warm air, and in turn the warm air moves to occupy the region formerly occupied by the cold air. This release of kinetic energy may escalate and produce a major circulation. When enough kinetic energy is depleted, the system dissipates and the thermal gradient has usually been mixed out. So in effect the gradient has been relieved. Naturally, all baroclinic weather systems have temperature advection as their primary feature. The isobars and isotherms also tend to be out of phase, and the system is normally associated with a jet stream over its center.

## 6.1. Baroclinic lows

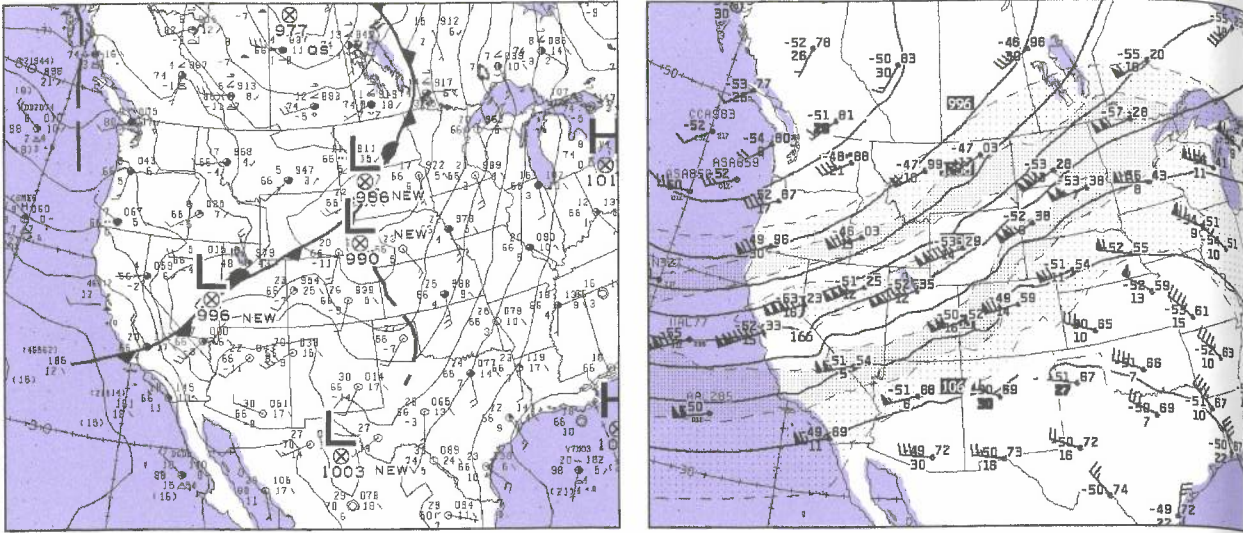
A baroclinic low, also known as an extratropical cyclone or a frontal low, can form along any stagnant polar front boundary. It is responsible for the vast majority of cold season precipitation in the temperate latitudes. The evolution of the baroclinic low was first recognized by Vilhelm Bjerknes in the late 1910s and his conceptual model of evolution, the Norwegian cyclone model, quickly formed the backbone of modern operational forecasting.

**6.1.1. THERMAL GRADIENT.** The ideal state that precedes baroclinic development is a quiescent zone containing a thermal gradient, in other words, an idle stationary front. The isobars and isotherms are in phase, and there is no thermal advection taking place. However, this zone is considered to be baroclinically unstable. If an upper-level disturbance approaches, the surface pressure changes which precede it will distort the isobaric field, causing the isobars to no longer be in phase with the thermal field. The system becomes baroclinic. This begins the stage of baroclinic development.



### Title image

A large occlusion off the northwest coast of Ireland. This was a vertically stacked system with a 981 mb low at the surface. Note the presence of cold core convection, some of this possibly consisting of thunderstorms, due to the steep lapse rates associated with this system. The system appeared as shown above on the UK Met Office surface analysis. (3 April 2011 / 1220 UTC)



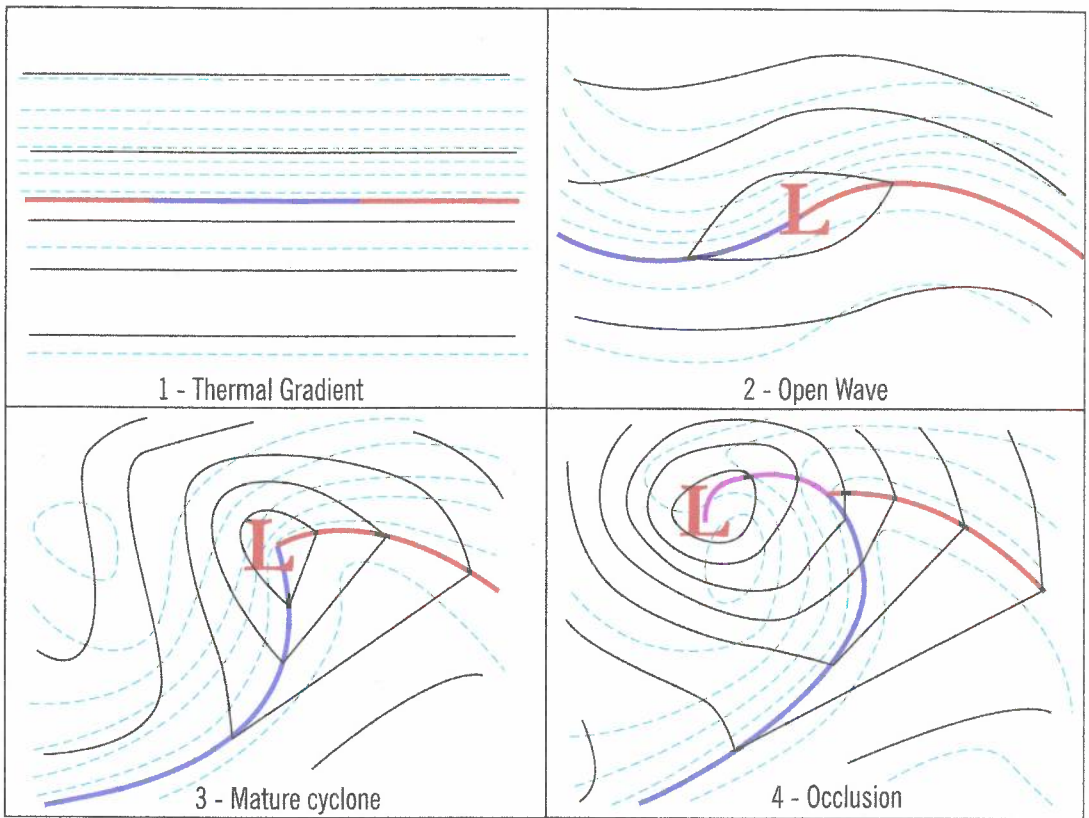
**Figure 6-1. BAROCLINIC LOW.** Baroclinic lows in western South Dakota and in Nevada. Each is directly below or slightly equatorward from a jet streak. (31 March 2010 / 0000 UTC; surface on left; 250 mb on right)

6.1.2. **OPEN WAVE.** Initially a low pressure area forms. This draws the cold and warm air masses closer together, intensifying the thermal contrast. This strengthens the upper-level features, and upper level charts may show intensification of the vorticity patterns and jet strength.

6.1.3. **MATURE STAGE.** Eventually the baroclinic low enters the mature stage. The deepening of the low is at its most intense during this stage. For this deepening to occur, there must be something removing mass from the system. The decrease in mass comes from a combination of upper-level divergence and the widespread release of latent heat as precipitation forms.

6.1.4. **OCCUSION.** Gradually, the warm and cold fronts associated with the surface cyclone are forced to merge. This process cuts off the surface low from the warm sector. We see this on thickness charts as a movement of the surface low from the warm side of the thermal gradient to its middle, and eventually towards the cold pool. The occluded low begins filling, takes on barotropic characteristics, and eventually dissipates or absorbs itself into nearby semipermanent low pressure areas.

6.1.5. **TRIPLE POINT CYCLOGENESIS.** Though the occlusion is no longer a player, temperature contrasts are still very strong along the periphery of a warm sector. The triple point, at the cusp of



the warm sector, is a favored area for new cyclogenesis. This new cyclone matures and eventually follows the same occlusion stage as the original cyclone. A new triple point cyclone can form yet again.

**6.1.6. EXPLOSIVE CYCLOGENESIS.** Explosive cyclogenesis within a baroclinic low is often referred to as a “bomb”. By definition, it occurs when the central pressure falls by more than 1 mb per hour for 24 hours. Exceptionally strong temperature contrasts are usually the catalyst for explosive cyclogenesis; a typical source is the zone where warm Gulf Stream waters meet the cold coastal waters. High lapse rates in the troposphere, strong upper level forcing, and rich low-level moisture are all contributing favors to rapid baroclinic development. The favored location for bombs are along the Atlantic Coast offshore from North Carolina, New England, the Canadian Maritimes, and Iceland. Where such storms graze New England, they are often referred to as Nor’easters.

**6.1.7. CONVEYOR BELTS.** During the 1970s there was a consensus among forecasters that extratropical cyclones were not comprised

**Figure 6-2. The four primary stages of baroclinic cyclogenesis.** Surface isobars are drawn with a solid line, and low-level thickness isopleths are drawn with a dashed line. Frontal boundaries are depicted with a thick line. Note that the baroclinic low retreats on the cold side of the thermal gradient as it dissipates.

**Baroclinic low movement**

Baroclinic low movement can be estimated by steering it with the 500 mb flow and moving it at 50% of the 500 mb wind speed.

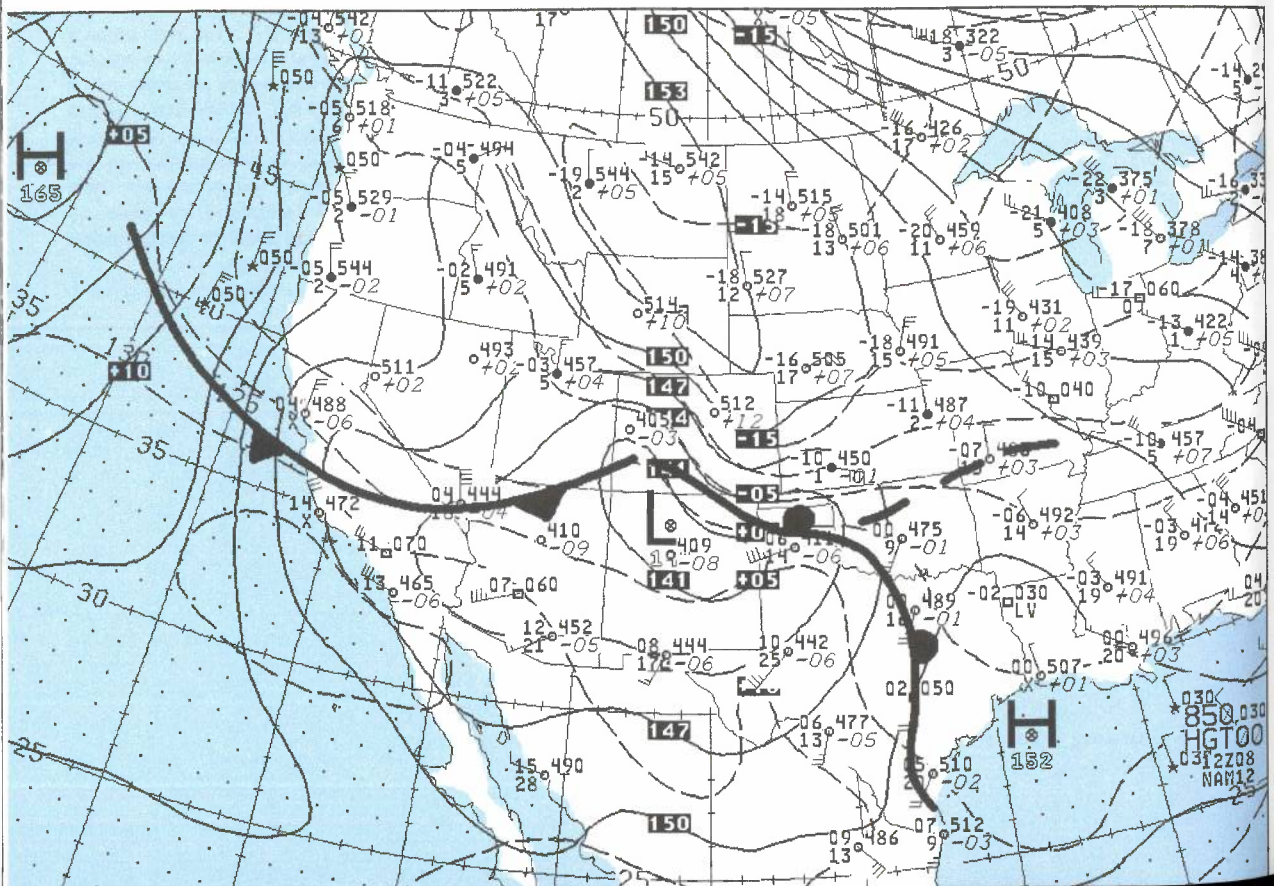
**Figure 6-3. 850 mb analysis showing a baroclinic system about to exit the Rocky Mountain region.** This brought a period of extremely cold weather to the Great Basin and Rocky Mountain region. The 700 mb and 850 mb charts make excellent tools for finding frontal systems in mountainous areas.

of a simple zone of cold air advection behind the cold front and warm advection ahead of the warm front. Cyclones showed evidence of distinctive circulations that extended into the vertical.

The most understandable example is the *warm conveyor belt* (WCB), in which parcels start near the surface in the warm sector, flow upward along the warm front surface, rise into the mid-troposphere, and eventually merge with the upper-level winds where they are swept eastward.

The *cold conveyor belt* (CCB) begins in the cold sector ahead of the warm front. Parcels are initially dry, but as they are swept westward into the cyclone, they receive moisture originating from precipitation falling out of the WCB. The CCB gradually ascends and reaches the area behind the surface low. The isentropic surfaces are sloped more steeply in the colder air feeding into the back of the system, which helps intensify the lift within the CCB. One branch of the CCB turns poleward (anticyclonically) as it rises to join with the upper-level winds, and another turns equatorward (cyclonically). This forms the deformation zone region of the baroclinic cloud system and contributes to precipitation on the rear side of the cyclone.

Finally the *dry conveyor belt* (DCB) begins in the upper troposphere behind the system. It descends in the cyclone's rear and is associated with clear skies, often forming a distinct dry slot.



It should be emphasized that these are simplifications of the flow within the cyclone and may not necessarily fit every system. When appropriate, they describe the generalized airflow regimes within the system.

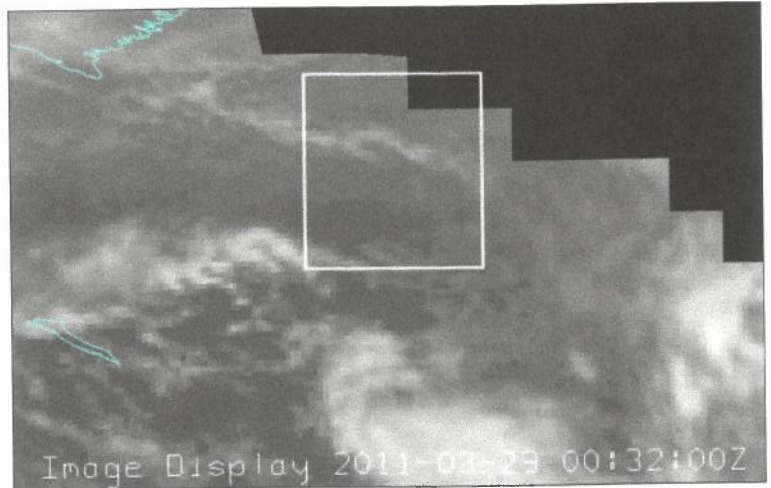
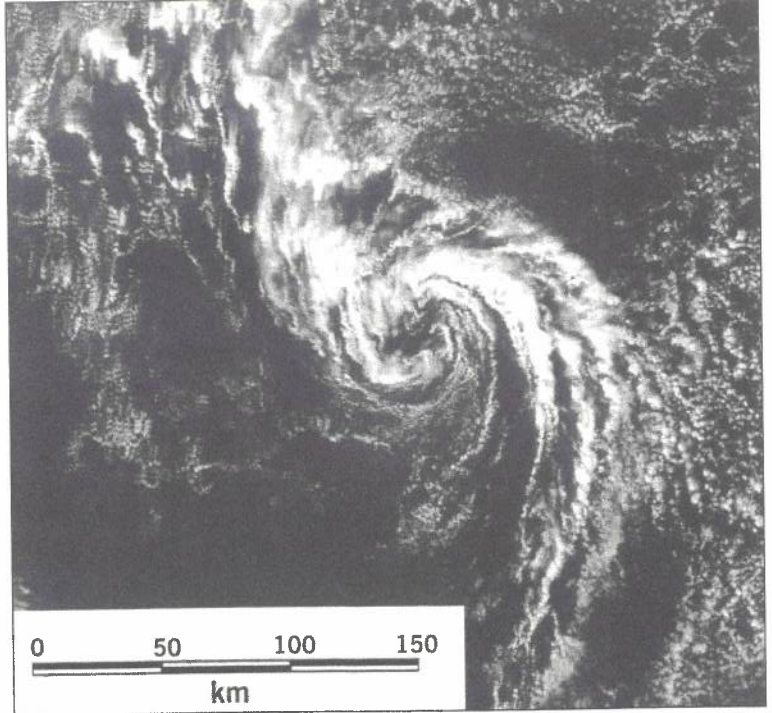
**6.1.8. ELEVATED FRONTS.** Some frontal systems do not adhere to the familiar Norwegian cyclone model, with the commonly expected signs of frontal passage. This usually occurs when upper-level conditions change much more quickly than the low-level portions, owing to terrain blockage, fast flow aloft, or other effects. When this occurs, the mid-level front “splits” from the low-level front, producing a so-called split front. In such a situation, cold front placement is ambiguous, warm fronts are difficult to find, and there is often a disconnect between precipitation fields and apparent frontal positions. The arrival of an elevated cold front and its associated cold advection aloft reduces the stability between low-level and mid-level air, and may result in development or enhancement of clouds and precipitation.

The arrival of an elevated cold front over a warm sector, with the cold front lagging at the surface, is most common in the Rocky Mountain region. The arrival of an elevated cold front over a cold sector tends to be associated with episodes of cold air damming. It is common in the Appalachian region during the winter season.

In either case, pressure tendency may be the best indicator of a frontal passage aloft, since surface pressure is related to density changes aloft.

**6.1.9. POLAR LOWS.** A polar low is an intense mesoscale cyclone that develops in a zone of cold air advection. It always contains deep convection, and stronger examples may develop spiral bands, cirrus outflow, and an eye, with the system appearing as a miniature hurricane on satellite imagery. Although the polar low contains a warm core, it is produced largely from occlusion of the core and subsidence rather than from latent heat release, and the system overall is baroclinic. The polar low forms along a prominent thermal gradient, such as the edge of an ice field or a zone where ice pack changes to open ocean. Some favored locations for polar lows are the far northeast Atlantic near Svalbard, in Hudson Bay, and in the Bering Sea. Generally the term *polar low* is used when the system is known to be producing winds of 35 kt or more. If not, it is referred to as a *polar mesoscale vortex*, not to be confused with the hemispheric *polar vortex*.

**Figure 6-4. A weak polar low or polar mesoscale vortex in the Bering Sea near 59°N 173°E.** This is viewed with 500 m resolution Aqua imagery (top) and best available geostationary satellite image (bottom) using the Japanese Himawari 6. Detection suffers greatly on the geostationary imagery due to foreshortening and the small spatial scale. The system measures no more than 100 miles in size, making the top frame about the size of a traditional radar site image in the United States. (29 March 2011 / 0040 UTC)

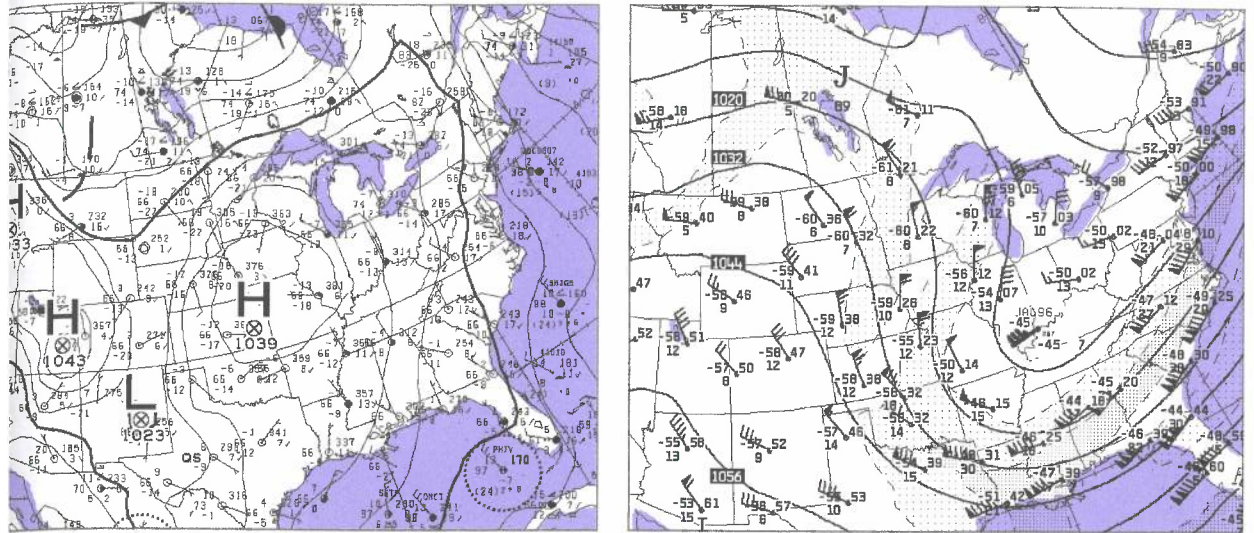


## 6.2. Baroclinic high

A baroclinic high is in effect a “frontal high” that drives the cool air mass within a frontal system. A high pressure area cannot in itself contain a front, because the diverging surface air automatically weakens thermal contrasts. But baroclinic highs represent the source of air masses involved in frontal systems.

A cold air mass is initially barotropic because its temperature is homogenous. As a nearby wave develops, the air mass is drawn towards the baroclinic zone. A high pressure area forms due to the upper-level subsidence behind the wave.

Eventually, the air at the center warms due to subsidence and modification, and the air mass becomes barotropic again, being



**Figure 6-5. BAROCLINIC HIGH.** Baroclinic high centered on Kansas City, Missouri and covering much of the central United States. Directly above it is a 65 kt upper-level jet. For this and subsequent images, the surface chart is on the left; 250 mb chart is on the right.

absorbed into the subtropical ridge, often becoming part of the Bermuda high.

Braking mechanisms slow down and eventually stop the development of baroclinic highs. Although self-development causes baroclinic highs to strengthen, the intensification initiates other processes which slow down and ultimately stop the development. Braking mechanisms are much more efficient for highs than for lows, so highs rarely attain the same intensity as low pressure circulations.

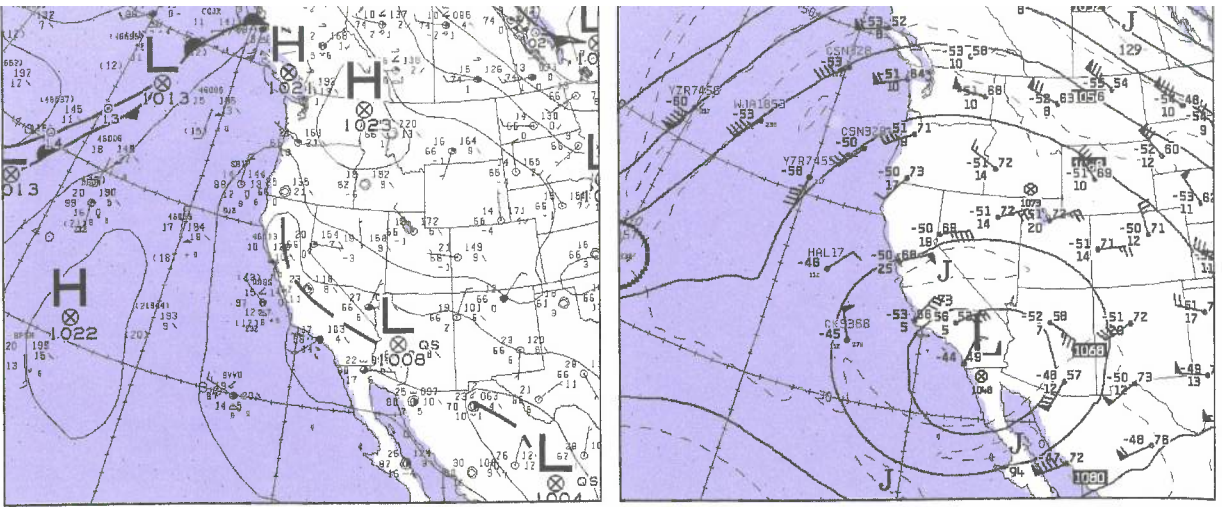
As a baroclinic high builds due to convergence aloft, the low-level anticyclonic circulation increases. Anticyclonically-curved flow in the boundary layer causes low-level divergence, which will partially offset the mass being added by the system aloft. Friction slows down surface air parcels, which reduces the Coriolis effect and causes the pressure gradient force to be dominant; the winds diverge out of the high more strongly.

Subsidence is a warming process. To force this air to sink takes energy out of the high, reducing the energy available for development. It often limits the intensity that highs can attain.

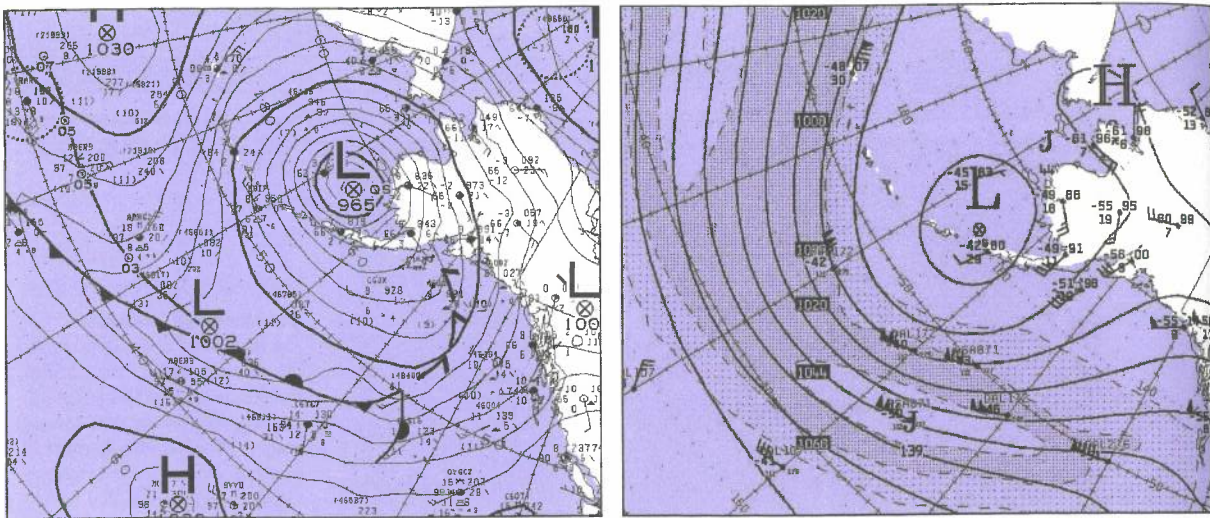
When the 1000-500 mb thickness ribbon spreads apart within the high with time (a weakening thermal gradient), low-level divergence is predominating and the high is weakening. Another indicator of weakening is when the surface high center is located on the south side of the jet and has moved to a higher 1000-500 mb thickness line; adiabatic warming is indicated.

#### Baroclinic high movement

The movement of baroclinic highs can be estimated by taking 50% of the 500 mb flow or 70% of the 700 mb flow in the early development stages. Further development is favored when the short-wave ridge remains within 300 to 450 nm upstream. They may also strengthen under confluent flow in the jet stream pattern. When height rises increase over the surface high, this indicates that self-development is underway. Surface highs north of the jet or north of the tightest 1000-500 mb thickness gradient are favored for further development.



**Figure 6-6. COLD-CORE BAROTROPIC LOW (CUTOFF LOW).** The cutoff low becomes stronger with height. It is sometimes not apparent on the surface except for weak pressure falls and scattered shower activity.



**Figure 6-7. COLD-CORE BAROTROPIC LOW (DECAYING WAVE).** Also known as an occlusion, this is a form of a barotropic cold-core low. The arrow markings east of the low mark a "trowal", the Canadian term for a "trough" of warm air aloft, signifying the axis of deepest tropical air above the occlusion.

Finally, an indicator of weakening is when upper-level height rises are diminishing; upper-level support is decreasing.

### 6.3. Cold-core barotropic low

A cold-core barotropic low is comprised of cold air throughout the atmosphere. It causes low thicknesses within the air, resulting in low upper-level heights. Two examples are the occlusion, which is found poleward of the polar front jet, and the cutoff low, which is found equatorward. Their structures are both quite similar.

**6.3.1. OCCLUSION.** The most common example of a cold-core barotropic low results from the occlusion of a baroclinic system.

The occlusion usually fills due to boundary layer convergence. The cyclonic circulation strengthens with increasing height. The system is vertically stacked, but it may have a small amount of vertical tilt (i.e. an imaginary line drawn between the surface low and the 500 mb low will usually be vertical, but may tilt slightly from vertical). Since the coldest air is in the center of the low, the system is not directly associated with fronts. The occluded low is always the result of a baroclinic system which has occluded (the low has completely wrapped air masses into itself, which mix and

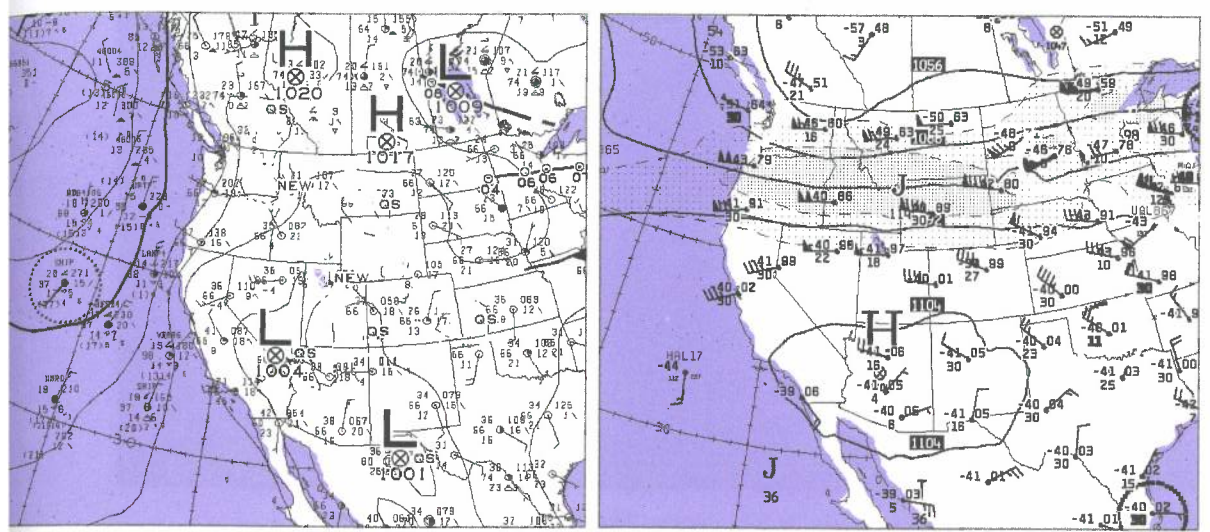


figure 6-8. **WARM-CORE BAROTROPIC LOW (HEAT LOW).** Heat (thermal) low, which is a warm-core barotropic low. It is structurally related to the hurricane but gets its energy from insolation, rather than from the release of latent heat. Surface temperatures are as high as 42°C (108°F) in the region where California, Nevada, and Arizona converge. A heat low is found here at the surface and this translates to a weak co-located high aloft.

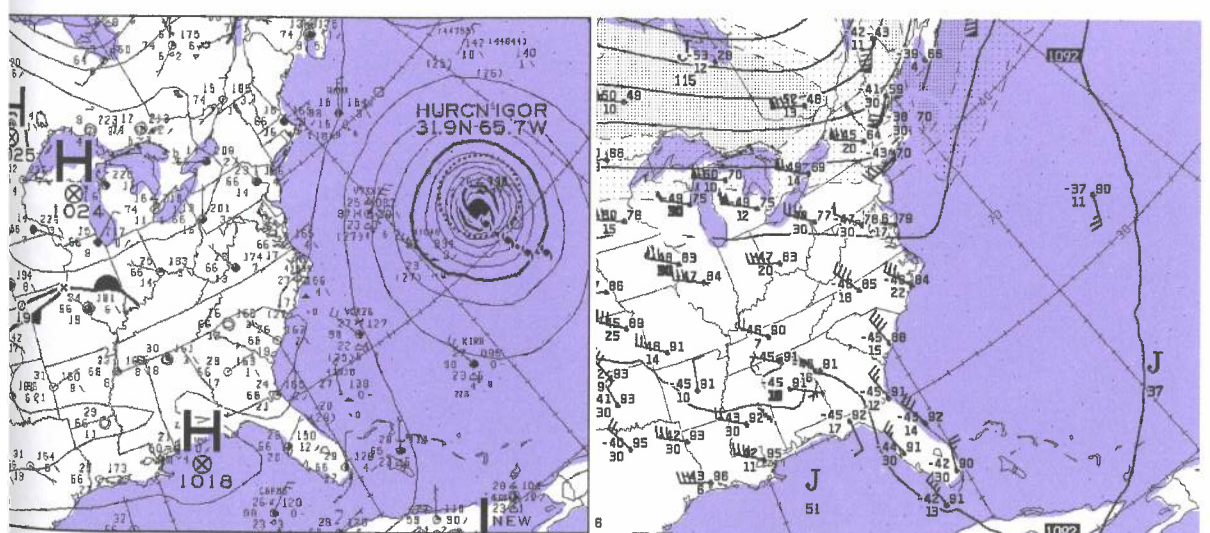
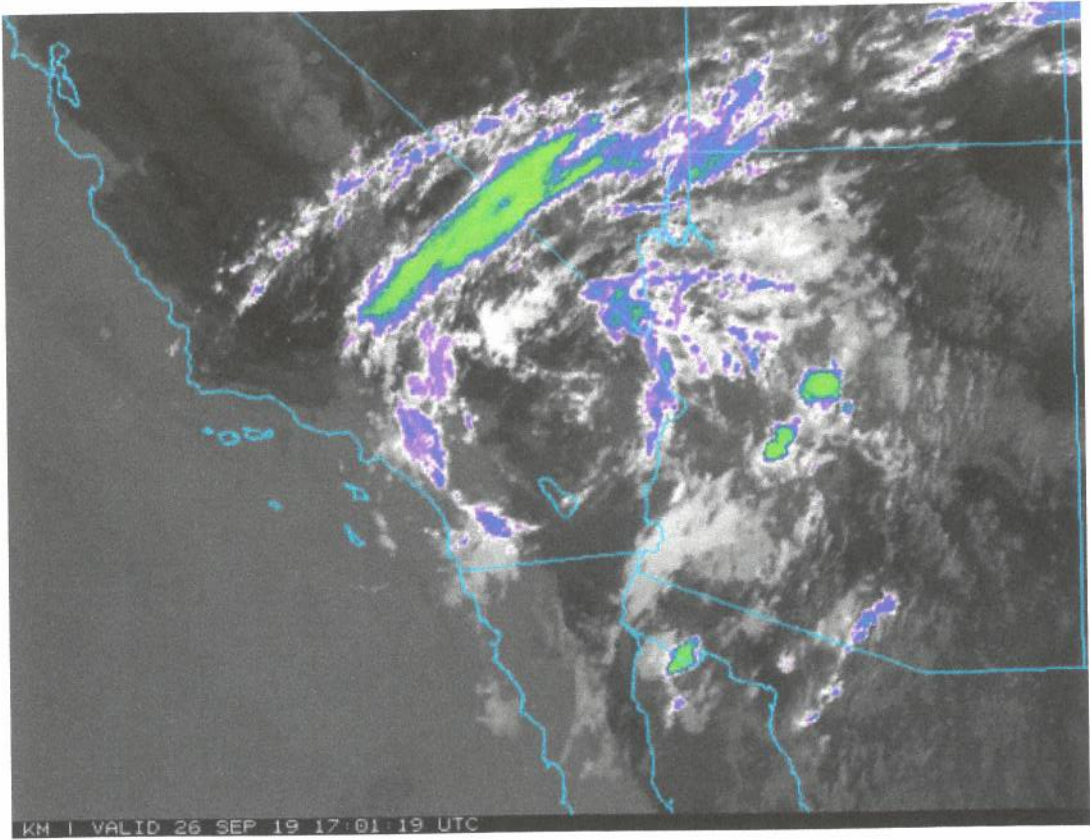
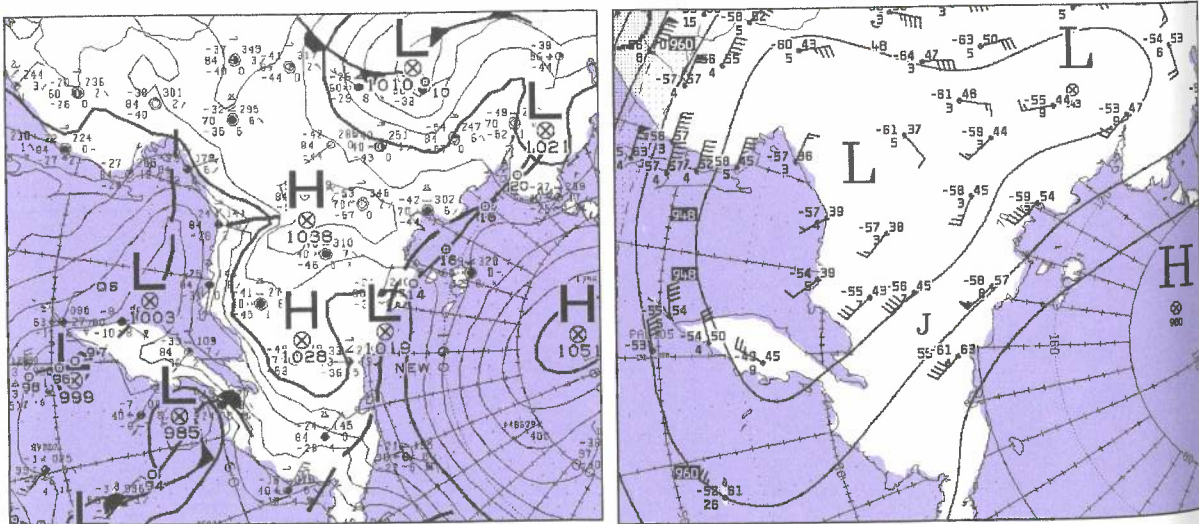


figure 6-9. **WARM-CORE BAROTROPIC LOW (TROPICAL CYCLONE).** This type of feature is a warm-core barotropic low, which implies that high heights should be found aloft. The 500 mb chart, however, shows a low. It is frequently necessary to go to 300 or 00 mb to find the upper-level high over the storm.



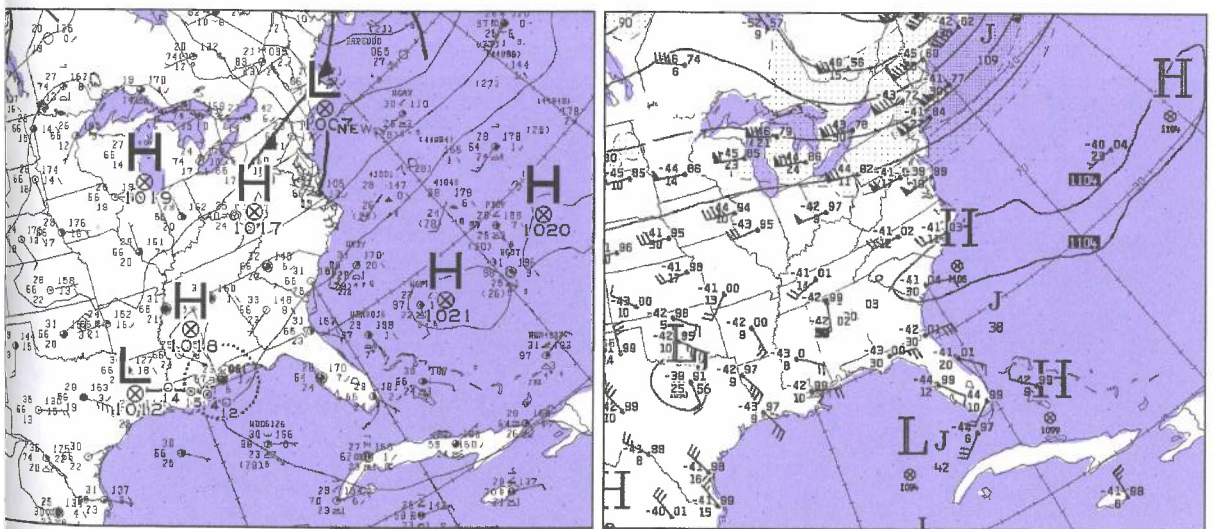
**Figure 6-10. Typical appearance of a cold core low in the southwest United States, as seen on infrared satellite imagery.** Note the extensive middle and high cloud fields, and the suggestion of a closed circulation. There is also a strong marine layer pushing stratus (dull gray) inland from the coast across western Baja California, San Diego, and Los Angeles. (26 September 2019 / 1700 UTC)



**Figure 6-11. COLD-CORE BAROTROPIC HIGH (POLAR AIR MASS SOURCE).** Cold-core barotropic high over northern Saskatchewan. Notice how it sits directly under a sharp trough aloft (low pressure). This high is continental polar air sitting in its source region over snow-covered areas of Canada. Two days later it evolved into a baroclinic high and shifted southward.

become homogenized). It occurs north of the polar front jet. The low usually weakens or absorbs into a larger semipermanent low pressure system, such as those found in the northern Atlantic or northern Pacific. While the occluded low is dissipating, fresh air mass contrasts to its south often lead to the development of new baroclinic system (new waves).

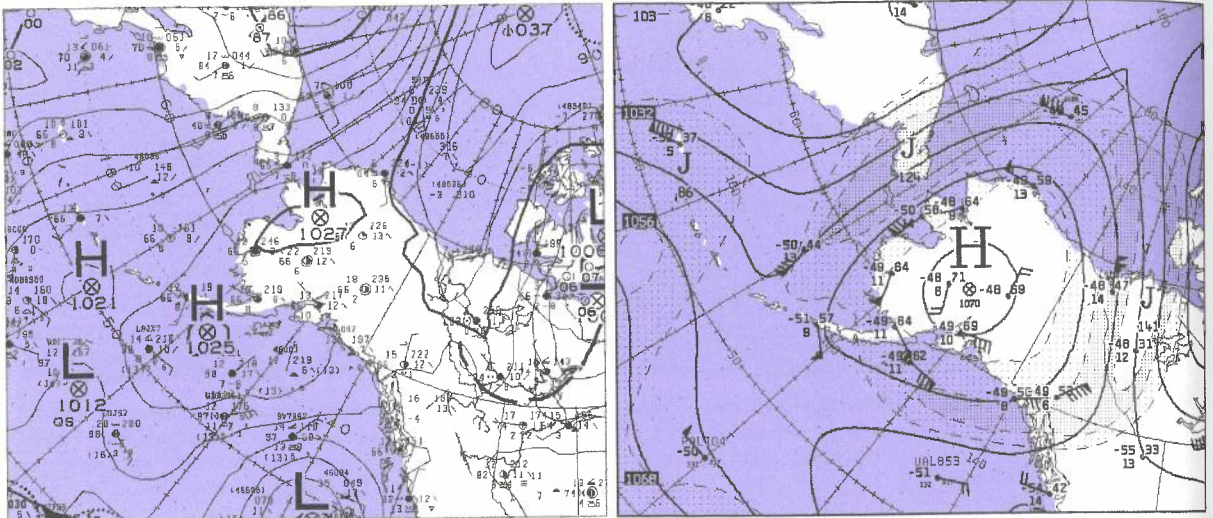
**6.3.2. CUTOFF LOW.** These are isolated upper-level lows that are found south of the polar front jet. They usually develop along the Pacific coast when a strong baroclinic high off of British Columbia transports cold polar air southward off the coast of Washington and California. The polar front jet stays to the north, causing the circulation to isolate itself and close off. The circulation is usually weak and difficult to find at the surface. Cutoff lows typically stay in the northwest Mexico region for days, then wander towards Texas or the Gulf of Mexico, where they may interact with rich moisture and produce thunderstorms. In rare cases a cutoff low may move westward into the Pacific and disappear. Most computer forecast models handle cutoff lows poorly; the most reliable movement indicator is Henry's Rule, which states that a strong short wave along the main polar front jet must come within 1000 miles of the cutoff low; the circulation will then open up.



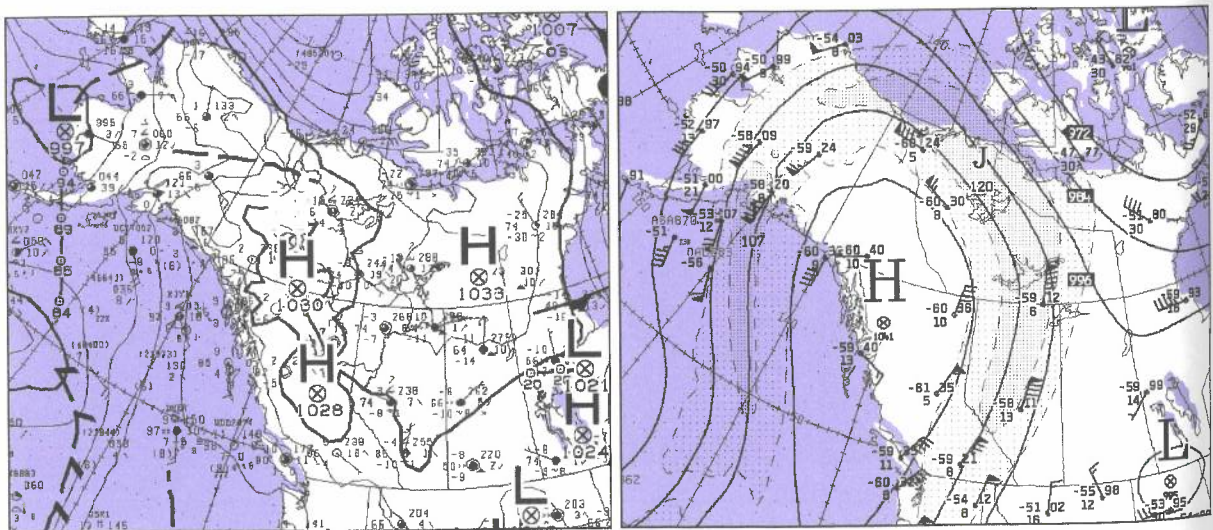
**Figure 6-12. WARM-CORE BAROTROPIC HIGH (SUBTROPICAL HIGH).** Warm-core barotropic high over the southeast United States. It translates to a high directly aloft. This is a classic example of a subtropical high, which usually serves as a source for maritime tropical air.

## 6.4. Warm-core barotropic low

A warm-core barotropic low is comprised of warm air throughout the atmosphere. This warm air causes higher thicknesses within the air, resulting in high upper-level heights. The low density of the warm air also causes low pressure at the surface. The system is barotropic, so it is vertically stacked, though it may have a slight amount of tilt. The cyclonic circulation weakens with increasing height, and may become a high aloft. Since the warmest air is in the center, no fronts are directly associated with the system. The low occurs south of the polar front jet, and is caused by low-level heating of the air mass. Any precipitation is relatively symmetrical around the center.



**Figure 6-13. WARM-CORE BAROTROPIC HIGH (CUTOFF HIGH).** A cutoff high, a form of warm-core barotropic high. It is very similar to a subtropical high. It is sometimes seen in Alaska due when strong insolation or latent heat release occurs north of the polar jet.



**Figure 6-14. WARM-CORE BAROTROPIC HIGH (PLATEAU HIGH).** Plateau high over British Columbia. There is little temperature advection around it, and an upper-level ridge sits above it.

**6.4.1. HEAT (THERMAL) LOW.** The most obvious example of a warm-core barotropic low is the heat low, usually centered over western Arizona during the summer months. A surface trough sometimes extends northwest into the San Joaquin Valley of California, or into southern Nevada. Its energy source is diabatic, originating from strong solar heating on dry desert ground. The surface pressure rarely drops lower than 1000 mb, and the exact center of the surface low is normally ambiguous and difficult to find due to uneven heating. Diurnal thunderstorm activity may develop if there is sufficient moisture.

**6.4.2. TROPICAL CYCLONE.** Another example of a warm-core barotropic low is the tropical cyclone, which is related to the heat low but is more of an adiabatic system. It does receive substantial heat energy from the ocean surface, but the moisture present in the air mass and strong upward vertical motions cause extensive adiabatic warming due to the release of latent heat within the weather system. The circulation in a hurricane weakens only gradually with height, and it is sometimes necessary to go up to 200 mb to find any anticyclonic circulation.

Some very intense extratropical cyclones, particularly bombs, may produce warm-core structures as they occlude. As a result, they may have structures similar to those of hurricanes and may even develop an “eye”.

## **6.5. Cold-core barotropic high**

The cold-core barotropic high contains cold air at the center of the high. The high density causes high surface pressures, while the low thicknesses result in low heights aloft. Since the system is barotropic, the system is vertically stacked, but may have a slight amount of tilt. The circulation weakens with increasing height. Since the coldest air is in the center, it is not directly associated with fronts. The high is usually north of the polar front jet.

The most common example of a cold-core barotropic high is a polar air mass in its source region. It forms due to intense cooling of the air in the low levels. As the air mass moves south, temperature contrasts in the air mass begin developing, causing the high to become a baroclinic high.

## **6.6. Warm-core barotropic high**

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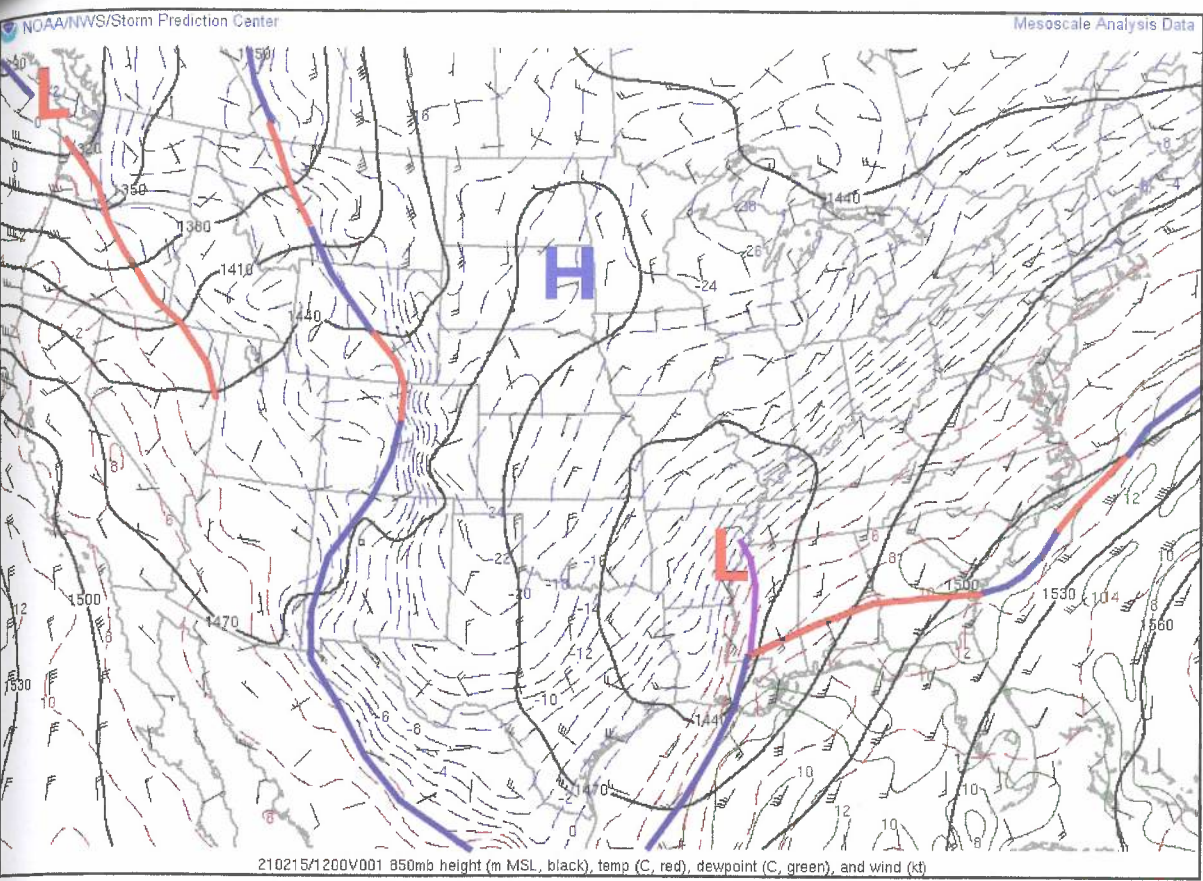
it is vertically stacked (but may have some tilt). The circulation strengthens with height. Since the warmest air is in the center of the system, it is not associated with fronts.

**6.6.1. SUBTROPICAL HIGH.** The subtropical high is a semipermanent feature in the subtropics. It tends to be strong both at the surface and aloft. The high is caused mainly by the upper-level poleward-moving current of air from the tropics, comprising the upper portion of the Hadley cell. The air tends to accumulate at about 30 deg latitude due to eastward deflection by the Coriolis force. This upper-tropospheric convergence causes an increase in mass, and the air sinks (subsides). In turn, it produces a very broad area of light winds and quiescent weather, though where sufficient moisture is available, cumuliform clouds and scattered areas of thunderstorms may be found.

The light winds within the subtropical high comprise a serious hazard to sailing ships, which may be left stranded for days or weeks. One popular legend holds that the region near 30° was named the “horse latitudes” by Spanish ships in subtropical highs which had to throw horses overboard to conserve resources. However, another theory cites the “dead horse ritual”: an effigy of a horse was thrown overboard at the point where the ship’s hands, having spent their advance pay in England and on the voyage, had finally worked off their debts. Either way, these events occurred in the subtropics.

**6.6.2. CUTOFF HIGH.** The cutoff high is a warm barotropic high located north of the polar front jet (either the main one or a southern branch of one). The surface high is typically weak. It forms when a warm air mass aloft is transported to a high latitude by a strong southerly flow. The flow later becomes more zonal, cutting off the upper-level high, leaving a warm pool to the north. Cutoff highs are rare, but are seen more often in the Atlantic regions. When they do develop, they may cause an omega block pattern.

**6.6.3. PLATEAU HIGH.** The plateau high is very similar to the subtropical high, with relatively warm air aloft. However this warm air above the relatively cool ground establishes an inversion. Clouds and fog forms within the valleys, which in turn gradually radiates heat away at cloud top level, promoting cooling of the boundary layer. The increased air mass density within the boundary layer causes high pressure at the surface. This type of pattern sometimes occurs during the winter months in the



210215Z/1200V001 850mb height (m MSL, black), temp (C, red), dewpoint (C, green), and wind (kt)

**Figure 6-15. The severe arctic outbreak of February 2021 as seen on the 850 mb chart, showing the bulk of the cold air moving south into Texas. The strength of this outbreak rivaled the February 1899 and December 1983 outbreaks, and some areas in Texas set all-time minimum temperatures. The independent power grid in Texas nearly collapsed as demand spiked to over 75 GW at a time when only 42 GW of capacity was available. Many parts of Texas, especially in the cities, endured multi-day power outages. The disaster caused \$20 billion in property losses, with economic damage estimated to exceed \$120 billion. (15 February 2021 /15/1200 UTC)**

northeast Great Basin region, leading to days or weeks of below-normal temperatures and fog.

## 6.7. Arctic air outbreaks

A very significant forecast problem in North America, and to a lesser extent, Europe, is caused by severe cold air outbreaks. These outbreaks also become a major player in winter storms. Large amounts of bitterly cold air can only be produced over large areas of snow cover. When more heat is radiated into space than is replaced from underneath by the Earth or overhead by sunlight, cooling occurs.

**6.7.1. ARCTIC AIR MASS PRODUCTION.** Snow cover on the Earth's surface is a key element in strong cold air mass formation. The snow cover insulates the atmosphere from the Earth itself. In the winter the soil tends to be relatively warm and even in the high arctic, it rarely falls very much below -20 to -30°C. Furthermore, snow is highly efficient at radiating heat away to outer space. The air near the surface conducts sensible heat to the snow, which then radiates the energy away.

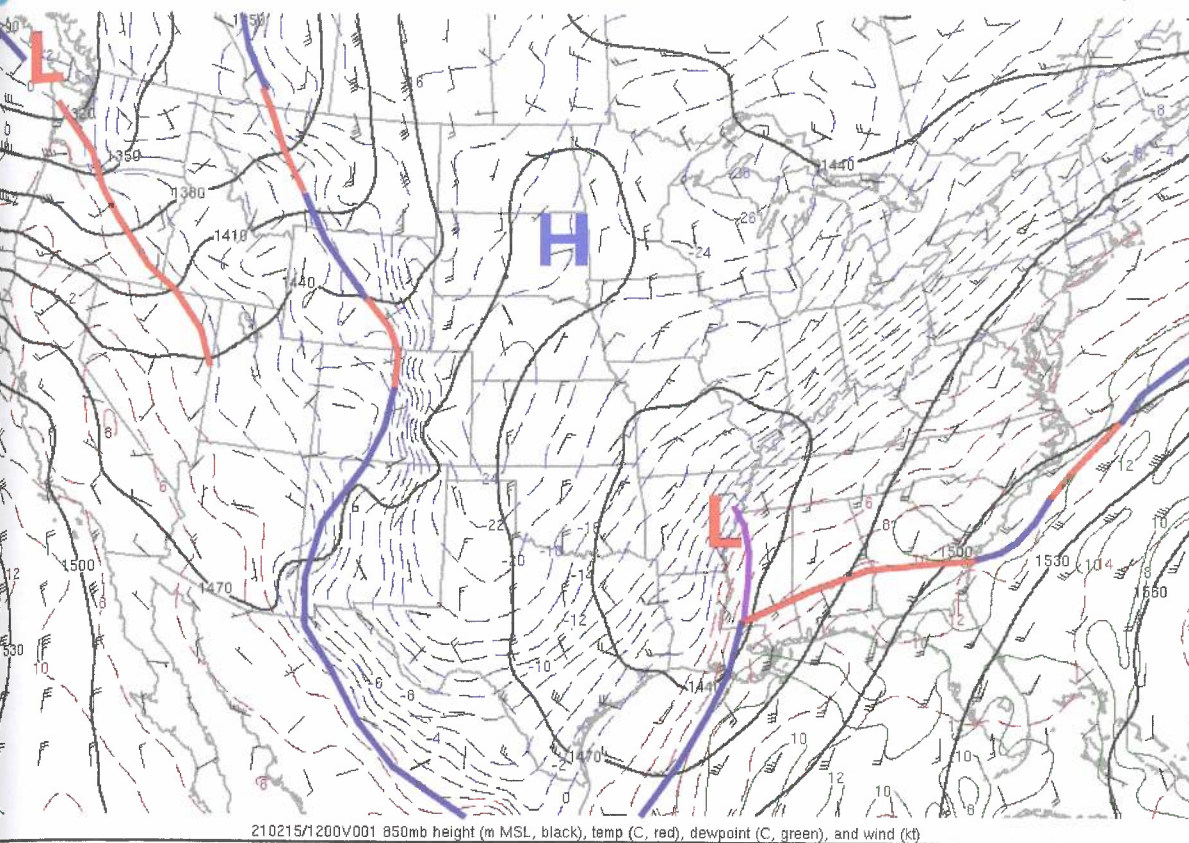
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**6.6.3. PLATEAU HIGH.** The plateau high is very similar to the subtropical high, with relatively warm air aloft. However this warm air above the relatively cool ground establishes an inversion. Clouds and fog forms within the valleys, which in turn gradually radiates heat away at cloud top level, promoting cooling of the boundary layer. The increased air mass density within the boundary layer causes high pressure at the surface. This type of pattern sometimes occurs during the winter months in the



northeast Great Basin region, leading to days or weeks of below-normal temperatures and fog.

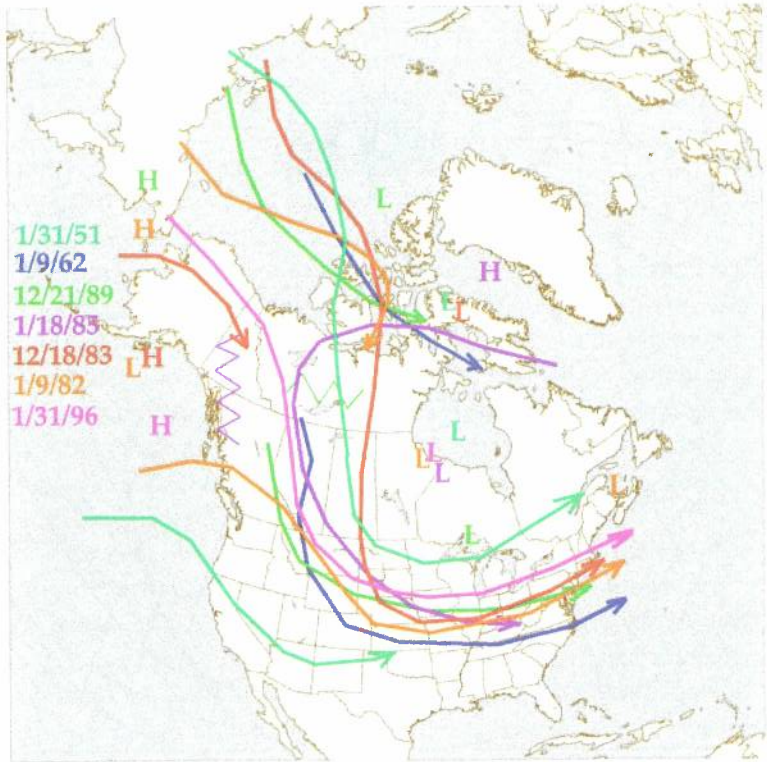
## 6.7. Arctic air outbreaks

A very significant forecast problem in North America, and to a lesser extent, Europe, is caused by severe cold air outbreaks. These outbreaks also become a major player in winter storms. Large amounts of bitterly cold air can only be produced over large areas of snow cover. When more heat is radiated into space than is replaced from underneath by the Earth or overhead by sunlight, cooling occurs.

**6.7.1. ARCTIC AIR MASS PRODUCTION.** Snow cover on the Earth's surface is a key element in strong cold air mass formation. The snow cover insulates the atmosphere from the Earth itself. In the winter the soil tends to be relatively warm and even in the high arctic, it rarely falls very much below  $-20$  to  $-30^{\circ}\text{C}$ . Furthermore, snow is highly efficient at radiating heat away to outer space. The air near the surface conducts sensible heat to the snow, which then radiates the energy away.

**Figure 6-15. The severe arctic outbreak of February 2021** as seen on the 850 mb chart, showing the bulk of the cold air moving south into Texas. The strength of this outbreak rivaled the February 1899 and December 1983 outbreaks, and some areas in Texas set all-time minimum temperatures. The independent power grid in Texas nearly collapsed as demand spiked to over 75 GW at a time when only 42 GW of capacity was available. Many parts of Texas, especially in the cities, endured multi-day power outages. The disaster caused \$20 billion in property losses, with economic damage estimated to exceed \$120 billion. (15 February 2021 /15/1200 UTC)

**Figure 6-16.** Polar jet positions associated with seven of the most significant arctic outbreaks of the 20th century. The outbreaks are associated with a “ridge west, trough east” pattern and a significant north-to-south component from the Northwest Territories into the Northern Plains. (Tim Vasquez)



Not only is snow cover important, but *fresh* snow cover is even more effective. Fresh snow contains substantial amounts of air trapped between the snow crystals, and air is an excellent insulator. But as the snow ages over a period of days and weeks, it settles and loses its composition of air, allowing more and more heat transfer through the snowpack.

All of this radiation results in exceptionally cold temperatures near the ground, with the top of the cooling layer marked by an inversion. This inversion is only centimeters deep when cooling begins but grows to a height of about 0.5 km over a period of days.

**6.7.2. THE ROLE OF CLOUDS AND FOG.** Radiation of heat by snow cover under clear skies is a key method for cooling an air mass. However it fails to explain the low temperatures in exceptionally cold air masses. This is ascribed to heat loss by fog, ice crystals, and cloud layers. Cooling increases relative humidity, and if the humidity is high enough, condensation will occur and these phenomena will develop.

For example, if the air temperature is cold but not severely cold, i.e. above  $-8^{\circ}\text{F}$  ( $-22^{\circ}\text{C}$ ), and sufficient moisture is present, the initial radiational cooling will begin producing supercooled

Freezing drizzle and light freezing rain events can be assessed by evaluating the cloud top temperatures (Huffman and Norman 1988). If the temperature is 0 to  $-10^{\circ}\text{C}$ , this may be an indicator that precipitation layers consist mostly of supercooled water.

water droplets. This will result in either shallow freezing fog or low, thin stratus clouds. These layers of liquid droplets radiate considerable infrared radiation to the ground while blocking outgoing radiation, preventing surface temperatures from falling significantly. The top of the stratus or fog, however, radiates energy away to space and undergoes exceptionally strong cooling. The net result is steady temperatures at the ground with fog and stratus building upward into the lower troposphere as cooling progresses.

High pressure is common and this may be accompanied by tropospheric subsidence. Downward motion will tend to produce adiabatic warming and transport drier air aloft toward the surface. This tends to offset the cooling somewhat and keeps freezing fog and ice crystal layers confined to shallow depths.

If the cooling is allowed to continue below about 0 to  $-10^{\circ}\text{F}$ , this favors condensation directly into ice crystals: diamond dust. These are fine ice crystals that give the air a glittery appearance. Meanwhile the supercooled water gradually falls out. When the low levels contain ice crystals and are free of freezing fog and stratus, cooling then focuses entirely at the Earth's surface.

**6.7.3. ANTICYCLOGENESIS.** As cooling progresses over a large area, surface pressures rise and anticyclogenesis takes place. For large areas of cooling, the pressure rises are proportional to the amount of cooling that takes place. An exceptionally cold and deep air mass is usually required for the air mass to invade lower latitudes, so forecasters watch source regions carefully for signs of unusually strong cooling. The mass divergence at the surface or upper-level riding may result in subsidence, causing drier air to move from the mid-troposphere into the lower troposphere. This may diminish the amount of freezing fog and stratus, reducing the rate of cooling somewhat.

**6.7.4. SOURCE REGIONS.** In North America, the single most important source region for polar air is the Mackenzie River basin, an area centered on the southwest portion of Canada's Northwest Territories. Severe cold outbreaks are favored when the Aleutian Low is weak and when blocking patterns develop around the Alaskan region, a pattern associated with the  $-PNA$  teleconnection. This reduces the southerly wind component in northwest Canada, limiting the effects of downslope warming from the Rockies.

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#### Ice crystal regimes

Type	T (deg C)
Thin plates	0 to -4
Columns, prisms, needles	-4 to -10
Thick plates	-10 to -12
Dendrites	-12 to -16
Sector plates	-16 to -22
Hollow columns, sheaths	< -22

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**Empirical forecast techniques**

Listed here are some popular rules techniques for forecasting winter weather. As thermal structures may be enormously different from one situation to the next, these should all be treated as rules of thumb and should not serve as the primary basis for your forecast.

**Garcia Method:** Use an isentropic chart for the snow production layer (700 to 750 mb is ideal). Assume the mixing ratio field is advecting with the wind shown, and determine which average mixing ratio value will reach the forecast point in 6 hours. Multiply this value in g/kg by 2 to get a 6-hour snow depth in inches.

**Cook Method:** Advect the 200 mb warm pool toward the cold pool, using the wind and estimating 24 hours of movement. Determine the temperature change in deg C along this segment using the isotherms. Multiply by 0.5 to obtain the 24 hour snowfall in inches.

**Magic Chart:** Use model forecasts or FOUS bulletins which depict the 700 mb vertical displacement at a given location in the snow track. Multiply the value in mb by 0.1 to obtain 12 hour snowfall.

**Max sounding temperature:** If the max temperature is below 1 deg C, snow will be the result. If the max temperature is 1-2 deg C, sleet will be the result. Above that value, rain is likely.

**Layer depth method:** If the warm layer is more than 1200 ft deep, it will most likely rain. If it is around 900 ft deep, the chance of it snowing instead of raining is 50%, if it is 700 ft deep, the odds increase to 70%, and at 300 ft deep, the odds are 90%. Liquid that passes through a cold layer of 800 ft depth will usually freeze.

## 6.8. Winter weather systems

Winter weather brings a forecast challenge almost equal in complexity to that of severe thunderstorms. The stakes are high: rather than a few localities being raked by high winds or a tornado, an entire state may be buried in inches of ice or snow. Interestingly some of the techniques for forecasting winter weather have a close kinship with that of severe weather. The underlying processes are mesoscale in nature, and they require close examination of soundings, careful diagnosis of upper-level lift, and hour-by-hour analysis of surface charts.

In discussing winter weather, we will frequently refer to whether a layer or a sector is “warm” or “cold”. This is shorthand for a temperature that is “above freezing” and “below freezing”. The exception is when we discuss falling precipitation: melting and evaporation are a function of wet bulb temperature.

**6.8.1. PRECIPITATION FORMATION.** Winter weather is divided into four main precipitation types: rain, ice pellets (sleet), freezing rain, and snow. Rain is precipitation which is entirely in the liquid state, while freezing rain is perfectly identical to rain but simply freezes upon cold surfaces at ground level. Snow is an aggregation of ice crystals, while ice pellets consist of ice without crystalline shapes. All of the precipitation types can transition from one to the other depending on the layers encountered as they fall, however snow forms only within the ice crystal growth region. Precipitation that refreezes while falling will become sleet.

Rain is the most straightforward precipitation type. It usually forms in a warm layer. However, subfreezing air in the temperature range of 0 to  $-10^{\circ}\text{C}$  may actually be dominated not by ice crystals by *supercooled water*. This means that even with a sounding that is completely cold, light freezing rain might occur. Rain may also be the result when the surface layer is sufficiently warm and deep to melt any type of precipitation that falls into it.

Freezing rain is identical to rain, but has two requirements: exposed surfaces which are below freezing, and a surface-based cold layer that is either fairly close to  $0^{\circ}\text{C}$  throughout its depth or is shallow. The latter prevents the rain drop from freezing, and the former ensures it does freeze upon contact. Because of this, the air temperature is not as important as the temperature of exposed surfaces. Even if air temperatures are  $25^{\circ}\text{F}$ , glaze from freezing rain will be limited to treetops, roofs, and bridges if the weather has been warm and sunny recently. For this reason forecasters should factor in soil temperatures and the character of recent weather.

Ice pellets occur when any type of precipitation changes from a liquid to a solid before reaching the ground. The key ingredient here is a layer of warm air aloft above a cold layer near the surface, consequently this pattern is usually only found in and around frontal systems or in cold areas capped by a low-level inversion.

Snow occurs when the cloud layer is sufficiently cold enough that it consists of ice crystals rather than supercooled droplets. This is likely when the cloud layer is colder than  $-10^{\circ}\text{C}$ . Furthermore, development of snow at temperatures that favors dendrites ( $-12$  to  $-16^{\circ}\text{C}$ ) results in the highest efficiencies of snow production. This is because dendrite crystals are larger and tangle more efficiently with other ice crystals to produce snowflakes. This layer is known as the dendritic growth zone (DGZ) or dendritic growth layer. If strong ascent is forecast within the DGZ, then there is a high likelihood of heavy snow production.

**6.8.2. ICE CRYSTAL GROWTH.** Heterogeneous nucleation is the basic step in ice crystal formation within a snow cloud, particularly in the  $-10$  to  $-20^{\circ}\text{C}$  range. This occurs when droplets of supercooled water freeze directly on any available nuclei, such as dust and pollen. It produces an extremely small ice particle that may then grow further. Ice may also “materialize” directly onto nuclei, a process known as deposition. Both of these methods produce an extremely small ice particle less than 1 mm in size.

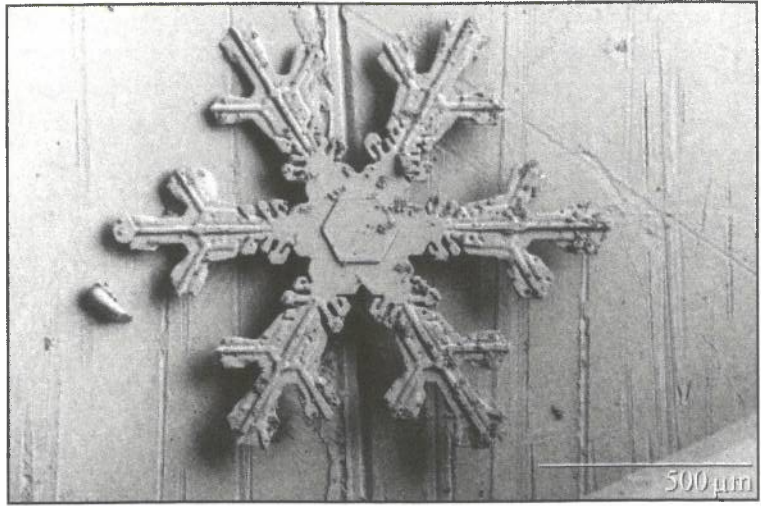
#### Millions of crystals

Renowned cloud physics expert Vincent J. Schaefer estimated that it takes more than half a million ice crystals to cover a one-square-foot area with snow ten inches deep.

**Figure 6-17.** Snow depth is still measured with a ruler. Because of the rise of ASOS, observed snow depth data has become harder to get than in years past. Observer networks like COCORAHS are attempting to supplement this with reports from trained hobbyists. (*Tim Vasquez*)



**Figure 6-18. Hexagonal dendrite snowflake** as seen under an electron microscope. Snowflakes initially start in a growth region, where millions of microscopic ice crystals occupy a single cubic meter. They combine and grow into the familiar shapes seen here. (USDA/BARC)



#### Thickness and winter weather

Studies by Glahn 1975 and others showed that the 540 dam isopach often serves as the discriminator between liquid and solid precipitation near sea level. At higher elevations this changes to 546 dam at 3000 ft MSL, 552 dam at 6000 ft, and 564 dam at 9000 ft MSL. Cantin 1990 studied Canadian winter weather using other thickness levels and found a threshold value of 154 dam for the 850-700 mb thickness chart ("high layer") and a threshold zone of 129-131 dam for 1000-850 mb ("low layer"). Using these values, when the *high layer was cold* (thickness lower than the threshold value), a cold low layer favored snow and a warm low layer favored rain, while a transitional low layer allowed for liquid types if the high layer was marginally cold. When the *high layer was warm*, a warm low layer suggested rain, a cold low layer suggested mixed precipitation, and a transitional low layer suggested freezing rain.

When ice crystals drift into warmer temperature layers,  $-10$  to  $0^{\circ}\text{C}$ , supercooled water droplets freeze directly upon these crystals. This process is known as riming, or accretion. This produces large, fragile crystals. They frequently collide and splinter into pieces, providing new sets of condensation or riming nuclei. This is the ice multiplication process. This splintering greatly speeds ice crystal growth throughout the cloud and is the mechanism by which most snowflakes develop. However if too much riming occurs, graupel and sleet is the result. When all temperatures in a column above a station fall below  $-10$  deg C, the ice multiplication process diminishes and this often results in a decrease in snowfall intensity.

If only one type of ice particle (dendrite, column, etc) is in a cloud, the particles tend to fall at similar speeds, avoiding colliding with one another. However when there are multiple types of ice particles, fall speeds are varied and the chance of ice crystal collision is greatly enhanced. This results in more rapid growth of ice crystals. For this to happen, a broad range of temperatures within the saturated layer (preferably the full range from  $0$  to  $-20$  deg C) is best. Although temperature contrasts are important, if snowflakes fall into a deep, slightly-subfreezing layer with little temperature contrast, this will also cause snowflake growth. This is because snowflakes tend to be "sticky" at these warmer temperatures and this gives them time to aggregate. A 1000 ft depth of  $0$  to  $-5^{\circ}\text{C}$  temperatures seems to be adequate for allowing this to happen.

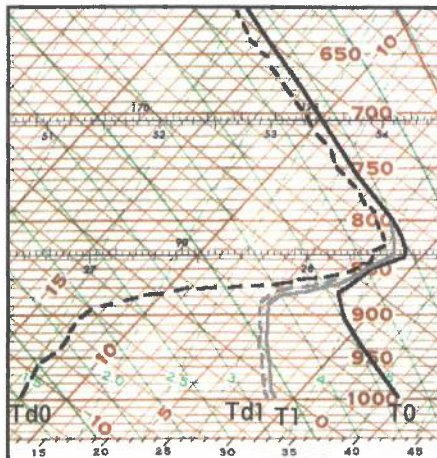
6.8.3. PRECIPITATION TYPE. Some simple rules of thumb exist for differentiating precipitation type. The most well-known rule is

the 540 dam thickness line which establishes the “rain-snow line”. Specific 850 mb isotherms have also been used with some degree of success. However these are based on an ideal winter weather system. Every weather situation is different and may contain very complex thermal structures in the vertical that are not accounted for by rules of thumb. The only reliable way for the forecaster to predict precipitation type is to develop a conceptual model of its life cycle from the growth stage to impact with the ground. This is called the *top-down method*.

First, the forecaster must determine which layer the precipitation will form within. This is bounded by the cloud top height on soundings and infrared satellite. Numerical models can help refine the levels where maximum ascent will occur. The temperature at this level dictates which type of precipitation particle will form. This is checked against actual soundings or forecast soundings to determine temperatures within the precipitation layer. At temperatures of 0 to  $-10^{\circ}\text{C}$ , supercooled droplets and ice crystals will form, while below  $-10^{\circ}\text{C}$  it will consist mostly of ice crystals and any supercooled water will tend to freeze into sleet before leaving the precipitation layer.

From there, the forecaster examines the temperatures that the precipitation will encounter while it falls. The question to ask is, “*Will any liquid precipitation encounter a cold layer, or will any solid precipitation encounter a warm layer?*” If so, this will change the precipitation type if it is sufficiently deep (more than 500-1000 ft, as a rule of thumb). For this purpose, cold or warm layers should be assessed in terms of wet-bulb temperature. In a saturated air mass wet-bulb temperature and air temperature will be equivalent, but they can differ sharply in a dry air mass, making precipitation type forecasting more difficult in dry regions like the western U.S..

**6.8.4. PRECIPITATION LOCATION.** The numerical models, fortunately, excel at predicting the location of synoptic-scale ingredients. There are some well-known rules of thumb in use which help provide the first guess for precipitation location. The heaviest snowfall occurs about 150 nm left



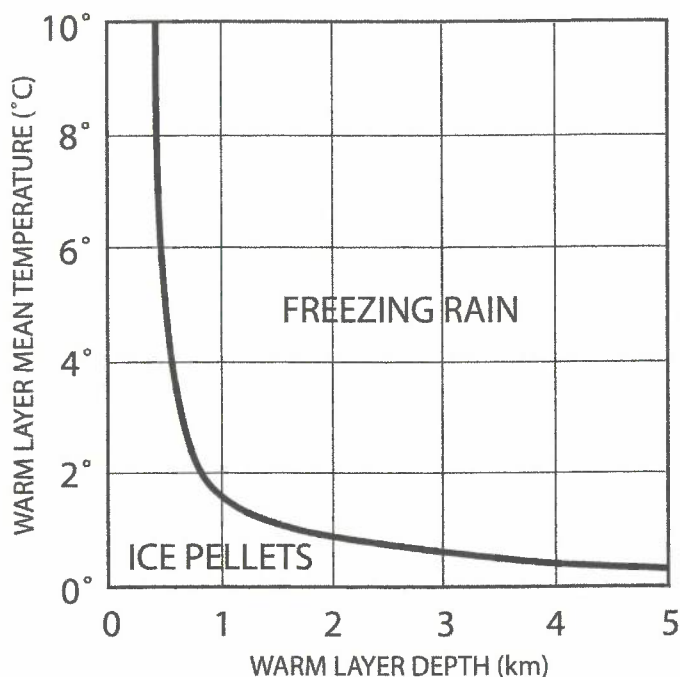
A study of heavy snow in the central and eastern U.S. (Goree and Younkin 1966) examined the track of the surface low and found that heavy snow usually occurred about 150 nm to the left [NH] of the track, about 300 nm in advance of the low, and was most intense when the low was deepening. Likewise a study of 850 mb charts (Browne and Younkin 1970) showed heavy snow was favored 90 nm to the left [NH] of the 850 mb cyclone track, with the  $-5^{\circ}\text{C}$  isotherm bisecting the area of heavy snow.

**Figure 6-19. The effect of evaporative cooling on a sounding.** The initial sounding is represented by the dark T0 and Td0 lines. Note the surface temperature of 4 deg C (39 deg F), the layer of warm air is at least 2000 ft deep (guaranteeing rain), and how the dry air occupies a layer between the surface and 875 mb. As precipitation falls into this dry air, evaporative cooling occurs. Some rain initially reaches the surface. Over the following hour or two, depending on the precipitation rate, the column cools to its wet bulb temperature. When “wet bulbing” is complete, the sounding profile is T1 and Td1. The entire column is subfreezing, snow is the precipitation type, and the surface temperature has cooled to  $-1$  deg C (30 deg F).

[NH] of the surface cyclone track, and is heaviest at the time that the cyclone is undergoing most rapid deepening.

6.8.5. THERMAL ADVECTION. The forecaster should not just think vertically. Thermal advection, the horizontal transport of warm air and cold air around a system, is a strong contributor to changes in precipitation type and is governed by the strength of the tropical and polar air masses and the intensity of the wind field. Due to the complexity of adiabatic and diabatic effects within a weather system, the forecaster should avoid relying on isotherm analysis to assess thermal advection. This is one area where trends on numerical models can help.

6.8.6. DIABATIC PROCESSES. When precipitation falls into a dry layer, it will initially produce virga or light precipitation at the surface. Most of the precipitation evaporates in the dry subcloud layer, where it can produce massive amounts of diabatic cooling. Ultimately an entire column of warm subcloud air can cool to a subfreezing temperature. If precipitation continues, this cooling continues until the air reaches its wet bulb temperature, a process sometimes called *wet bulbing*. It has been shown that only 0.38 inches of liquid equivalent precipitation can cause an air mass to cool by 8 F°! Diabatic cooling can also result from a phase change



**Figure 6-20. The Tau Technique** (Cys et al 1996) is an empirical method that provides some guidance in difficult freezing rain vs. sleet situations. It requires the forecaster to measure the depth of the warm layer using soundings and other available tools and estimate the average temperature of the layer.

from solid to liquid, such as snow falls into an elevated warm layer and melts. This can erode the depth and strength of the warm layer, resulting in a change with time towards solid precipitation types.

6.8.7. SNOW DENSITY. Making things even more complicated is that even if a forecaster correctly forecasts the intensity of the precipitation system, the snow depth forecast can be in error. Snow with a high snow-to-liquid ratio is fluffy, able to produce deep snow cover with a relatively small input of water, and is popularly called “dry snow”. In the northern Plains where dry snow is common, ratios of 1:20 may occur, which means 20 inches of snow melts to 1 inch of water. Likewise, dense snow that produces substantial liquid amounts when melted is known as “wet snow”, which involves ratios of about 1:8. A very cold column and production of unrimed dendrites and plates favors dry snow. Factors that favor wet snow include riming of crystals due to numerous supercooled droplets, snowfall through a marginally warm layer, and proximity to relatively warm ocean bodies.

6.8.8. WINTER WEATHER FORECASTING. Today’s mesoscale models excel in outlining the temporal and spatial distribution of winter weather. They still, however, have considerable problems in anticipating precipitation intensity. Furthermore, winter weather episodes often develop unexpected mesoscale structures with small time and duration scales. Synoptic forecasting techniques like Q vector divergence and vorticity advection do not adequately account for these changes. The forecaster’s job is to find these subsynoptic and mesoscale circulations. Analysis of the frontogenetic fields is one method commonly used to find localized areas of intense upward motion.

Though winter weather is not often associated with instability, steep mid-level lapse rates often occur in winter weather situations. Relatively unstable air within the precipitation layer tends to produce banded precipitation structures, while stable air produces stratiform structures.

It should also be pointed out that there are a vast number of empirical methods for winter weather forecasting, perhaps as many as there are for severe weather forecasting. These should all be used with caution, as rules of thumb are simplifications of elements found within very complex weather systems. If a rule of thumb has been successful with similar winter weather system structures in the past and the parameters it measures are

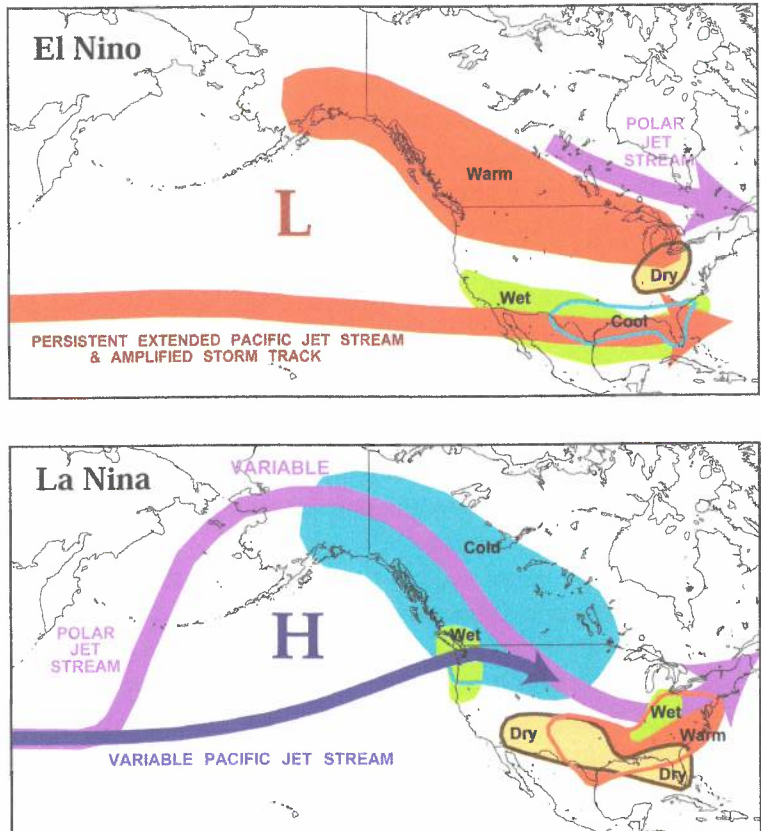
appropriate for the type of pattern at hand, then it may be a good tool to use. Otherwise it should not form the basis for a forecast.

## 6.9. Climate oscillations

Climatological patterns are beyond the scope of this book since they have scales on the order of months or years, and meteorology mostly concerns itself with time scales of hours and days. However a few are directly relevant to weather and medium-range forecasting since they shape the prevailing weather pattern.

6.9.1. EL NIÑO. The so-called El Niño is an episode where the ocean temperatures in the East Pacific are warmer than normal. This is the warm phase of the El Niño Southern Oscillation (ENSO). It is associated with a weaker east-to-west component in the tropical flow across the Pacific, which causes weaker upwelling of cold ocean waters along the coast of the Americas. The episode lasts a few months to a few years, and may occur every few years. El Niño's primary effect on day-to-day meteorology is to impart

Figure 6-21. Summary of El Niño cold and warm episode effects on North America in winter. (Adapted from a NOAA/CPC diagram)





often used in Phoenix as an indicator of the monsoon's presence. When the monsoon is present, storms tend to develop by midday at locations with strong heating and lift such as along mountain ridges, and move out across valley floors as organized multicell complexes during the afternoon and evening. These storms dissipate at night, but if sufficient upper-level shear is present they will sometimes persist overnight and cross great distances. The monsoon pattern weakens by September in response to sharply diminishing solar heating and the increase in the prevailing westerlies which bring storm tracks across the western states, disrupting the moisture fields.

6.9.4. **MADDEN-JULIAN OSCILLATION (MJO).** The Madden-Julian Oscillation is a long-wave phenomenon in the tropics, on the order of 12,000 to 20,000 km, signified by precipitation and pressure anomalies. It moves west to east at about 10 kt, yielding a complete cycle in about 30 to 60 days, and bringing cyclic variations in weather and rainfall to a given location. These oscillations are more easily identified over the Indian and Pacific Ocean basins. MJO-related precipitation enhancement in tropical latitudes tends to couple with the development of atmospheric rivers and tropical air advection. The MJO also couples with subtropical monsoon patterns, though to a lesser extent with the North American southwest monsoon.

6.9.5. **TELECONNECTIONS.** Climatologists monitor the mean pressure difference between two stations in different parts of a continent in order to gauge the potential distribution of energy.

\* *Pacific North American (PNA).* This measures energy across the North Pacific basin. In a positive [negative] phase, the northerly temperate Pacific has unusually low [high] pressure while the southerly subtropical Pacific has unusually high [low] pressure. The result is stronger [weaker] westerlies through the Pacific region. A +PNA favors zonal patterns in the Pacific, while a -PNA pattern favors blocking and often results in severe cold outbreaks into the central United States as cutoff highs build into Alaska.

\* *North Atlantic Oscillation (NAO).* This pattern measures energy across the North Atlantic. It is similar to the PNA pattern in that a +NAO mode favors unusually low pressure over the northerly subarctic region of the Atlantic and high pressure over the southerly temperate latitudes of the Atlantic, producing strong westerlies. Likewise, the -NAO

pattern has an opposite effect, resulting in weak westerlies and blocking.

\* *Arctic Oscillation (AO)*. The AO index looks at pressure patterns between the arctic and temperate latitudes. In a +AO [-AO] phase, the arctic has unusually low [high] pressure, and favors a strong [weak] Icelandic Low while the Aleutian Low is weaker [stronger] than normal. In the United States, a +AO pattern produces warm weather across the Midwest and wetter conditions in the west, while a -AO pattern brings cold weather to much of the country and drier conditions in the Desert Southwest.

## Chapter Six

### REVIEW QUESTIONS

1. Describe the chain reaction of self-development with a baroclinic low.
2. Are coastal regions more favorable for baroclinic development during the summer or during the winter?
3. South of a baroclinic low, a subtropical jet begins producing extensive rain above the warm sector. The warm sector region has been very dry. How will this affect the baroclinic low?
4. How can you use thickness charts to evaluate where baroclinic low development is most likely?
5. What is the final stage in the life cycle of a baroclinic low?
6. Rain falls into a very thick layer of cold air (about 2500 feet deep), then strikes the ground, where the temperature is 25 deg F. What type of precipitation is occurring at the ground?
7. It is 30°F (0°C) and the sounding shows no inversions. What is the most likely precipitation type?
8. A warm front is south of Kansas City, which is currently reporting ice pellets (sleet). As the warm front approaches, what precipitation type transitions can be expected?
9. Why is heavy snow rare when the column of air above a station is below -10 degrees Celsius?
10. Ice pellets have been occurring all day. A television station's engineers need to climb a 1000 ft television tower to perform some urgent maintenance. Will the engineers most likely encounter snow or freezing rain?