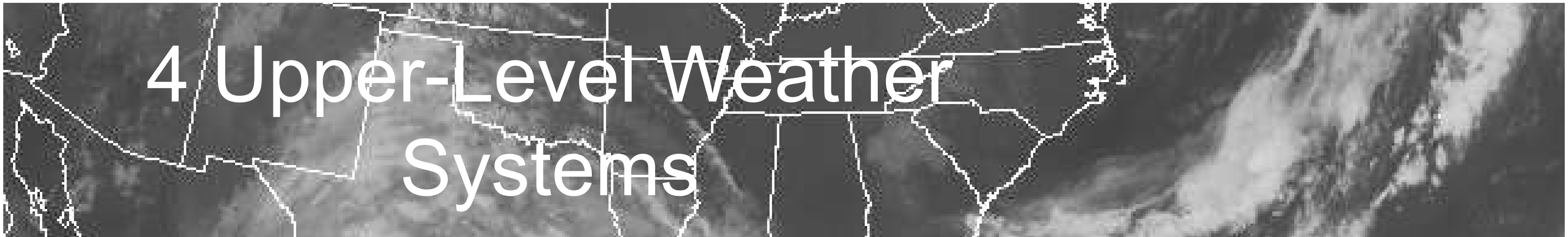
4 Upper-Level Weather Systems



Considerable misunderstanding arises because aviation weather training/material fails to adequately describe and explain non-frontal and upper-level weather systems. Weather occurs at all levels in the troposphere and sometimes into the lower stratosphere. Low-level weather systems and the surface analysis chart often cannot adequately explain the weather—even that occurring at or near the surface. Understanding the flight environment requires a knowledge of the effects of upper-level weather systems.

Upper-level (aloft) refers to phenomena occurring above about 500 mb (~18,000 ft) to the top of the troposphere.

Upper-level weather systems modify and direct surface weather. They may intensify or stabilize conditions at the surface, trigger thunderstorms, and enhance or retard the strength of frontal systems. Upper-level weather systems can cause severe conditions at the surface or dampen or cancel vertical motion required to produce significant weather.

Several years ago during a frustrating period of unsettled weather, a forecaster wrote: "Finally figured out the difference between a ridge and trough in California this month. A trough gives us cold rain; a ridge give us warm rain."

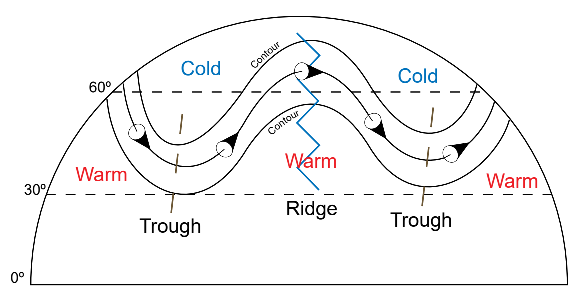
Four to seven major upper waves occur in each hemisphere, with short wave troughs and ridges embedded in the flow. Wind speed and temperature difference determine system strength and movement. Short waves with strong winds and large temperature differences produce violent weather, such as squall lines and severe thunderstorms—typically in the late cool and early warm seasons when temperature differences are greatest.

Case Study

> I attended the FAA's Flight Watch school in 1986. It was a warm day and after lunch I asked the instructor, Hershel Knolls, the difference between a long wave and a short wave. Hershel's eyes lit up! He proceeded to

Enroute Flight Advisory Service (Flight Watch) was implimented in 1972 and combined with routine FSS inflight service in 2015.

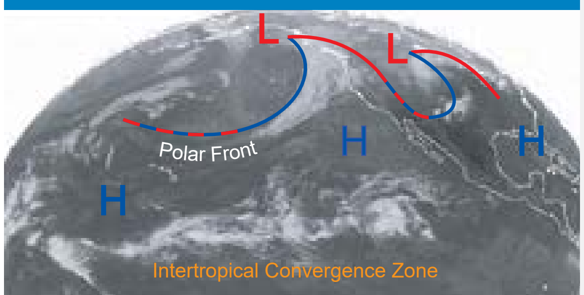
demonstrate with arms extended, “This is a long wave.” Then holding his arm in, “This is a short wave.” He continued, turning at 90° angles: “This is a north wave, ...an east wave, ...a south wave, and ...a west wave.” Well, I felt silly, but that afternoon I learned the difference. Now you’ll have the advantage of my somewhat humiliating experience.



Global or long waves (callout) with their associated ridges and troughs extend for thousands of miles. In the northern hemisphere with flow generally west to east, a typical wave has a wavelength from 50° to 120° of longitude. There is no temperature advection; isotherms (lines of equal temperature) are parallel to the contours. Long waves move generally eastward at up to 15 knots but can remain stationary for days or even retreat. The air within the waves, however, moves at a much greater speed.

Case Study

Several years ago, we had a rather unusual weather event along the west coast. Forecasters commented that rain fell from every cloud. A frustrated prognosticator wrote—in an internal NWS product that they had finally determined the difference between a trough and a ridge. “Cold rain falls from a trough and warm rain from a ridge.” This would seem to prove the proposition that weather forecasting can be as much an art as a science.



Some parts of the polar front produce weather and others do not. Refer to Fig. 1-4 callout. There are upper ridge axes on a north-south line through the western Pacific, along the west coast of United States, and over the eastern United States—associated with high pressure. Upper-level troughs exist on a line through the central Pacific to the Gulf of Alaska and east of the Rockies—associated with low pressure. These is a general absence of clouds in the ridge-to-trough flow over the western Pacific and considerable clouds in the trough-to-ridge flow in the eastern Pacific, western Canada, and Pacific Northwest.

Fact

Forecasters occasionally use the term “flat ridge.” According to Dick Williams, AWC forecaster (retired): “Flat Ridge—sounds sort of contradictory

> doesn't it? We usually use the term when a TROF is crossing over the top of a ridge, reducing the amplitude of the ridge and consequently reducing the 'ridge effects' such as subsidence or downward vertical motion. It's a means of transitioning from high amplitude or meridional flow to zonal flow patterns. A little jargony as terms go, but standard stuff...."

Like surface low and high pressure areas, lows and highs occur aloft. Upper-level cut-off lows are powerful vertical motion producers. They can cause severe surface weather, as well as enhance the development and severity of thunderstorm, and generate severe Clear Air Turbulence (CAT).

Upper lows occur when cold air at the base of the trough is cut off from the cold air to the north. Lifting continues even though the surface front has passed. With sufficient moisture, these systems tend to bring extended periods of poor weather. With unstable air, weather can sometimes be severe.

Upper-level convergence and divergence occurs when air piles up or spreads out over a region. Convergence aloft results in downward vertical motion; divergence aloft upward vertical motion.

Note

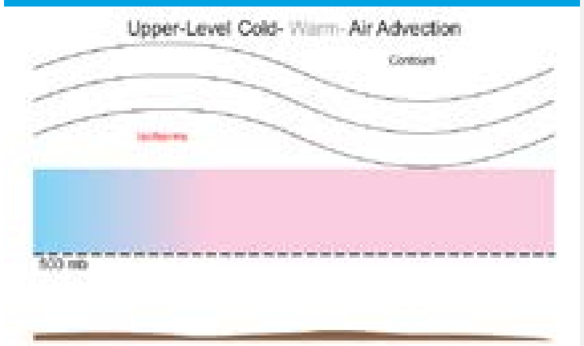
> This is opposite to the effects of surface convergence and divergence—discussed in chapter 3.

Like other atmospheric properties, vorticity—a powerful vertical motion producer—can be advected by the upper winds. Vorticity often explains strengthening and weakening weather systems, the development of low pressure areas, and the existence of clear skies associated with upper-level lows and hurricanes. Air moving through a trough, spinning counterclockwise, gains cyclonic relative vorticity. Air moving through a ridge, spinning clockwise, gains anticyclonic relative vorticity. Therefore, there tends to be upward vertical motion in trough-to-ridge flow and downward vertical motion in ridge-to-trough flow.

The hurricane is probably the best example of a non-frontal weather producing system.

clear air turbulence (CAT) — Turbulence encountered in clear air not associated with cumuliform clouds; usually occurring above 15,000 ft and associated with wind shear.

The Great New England hurricane (category 3) of 1938 resulted in over 600 deaths and massive destruction.



"Click" *Upper-Level Cold- Warm-Air Advection* to view animation.

Thermal advection—The horizontal transport of temperature by the wind.

Hurricanes produce just about every kind of weather hazard, covering thousands of square miles. Although these storms develop in the tropics, their devastation can reach well into midlatitudes. With the exception of the Pacific Northwest and Alaskan coasts, their weather can affect all coastal areas of the United States; and, their remnants affect areas hundreds of miles inland.

Upper-level troughs and ridges transport (advect) temperature aloft. Cold-air advection destabilizes the atmosphere above the 500 mb level. Warm-air advection at this level stabilizes the atmosphere. Why? As cold air aloft is advected into an area, any rising air will be warmer than surrounding air. Therefore, cold-air advection aloft enhances the development of weather—like thunderstorms—by enhancing upward vertical motion. Warm-air advection at this level stabilizes the atmosphere, strengthens high pressure ridges, and diminishes low pressure troughs.

Note

> The effects of upper-level cold- and warm-air advection are opposite to those of low-level cold- and warm-air advection.

How does cold- or warm-air advection occur? (Isotherms are lines of equal temperature.) For cold- or warm-air advection to occur, wind must blow across isotherms. This is the mechanism for the transportation of cold or warm air.

Short Wave Troughs and Ridges

Forecasters L-O-V-E troughs. They must, they have even given them a nickname—TROF. (I don't think that's really true, TROF is the FAA/NWS contraction for trough, but it makes good copy.) Forecasters use this term endlessly to explain all types of weather. They hide behind the term when a forecast goes sour, often blaming a busted forecast on a too strong, too weak, too fast, or too slow trough. Why do they love'em so? Upper troughs are a key to the evolution of weather systems.

Short waves, embedded in the overall flow, tend to pass through the long wave pattern at speeds of 20 to 40 knots. They have wavelengths from 1° to 40° of longitude. Short waves usually produce thermal advection. Typically, low-level cold-air advection occurs to the west of the trough axis and warm-air advection to the east.

Short waves can be strong vertical motion producers. As a short wave trough moves through a long wave trough, upward vertical motion is amplified. Most surface lows and frontal systems are associated with upper-level short wave troughs. Because short wave troughs move faster than their associated surface frontal systems, a front can become stationary and left behind only to become active as the next short wave approaches.

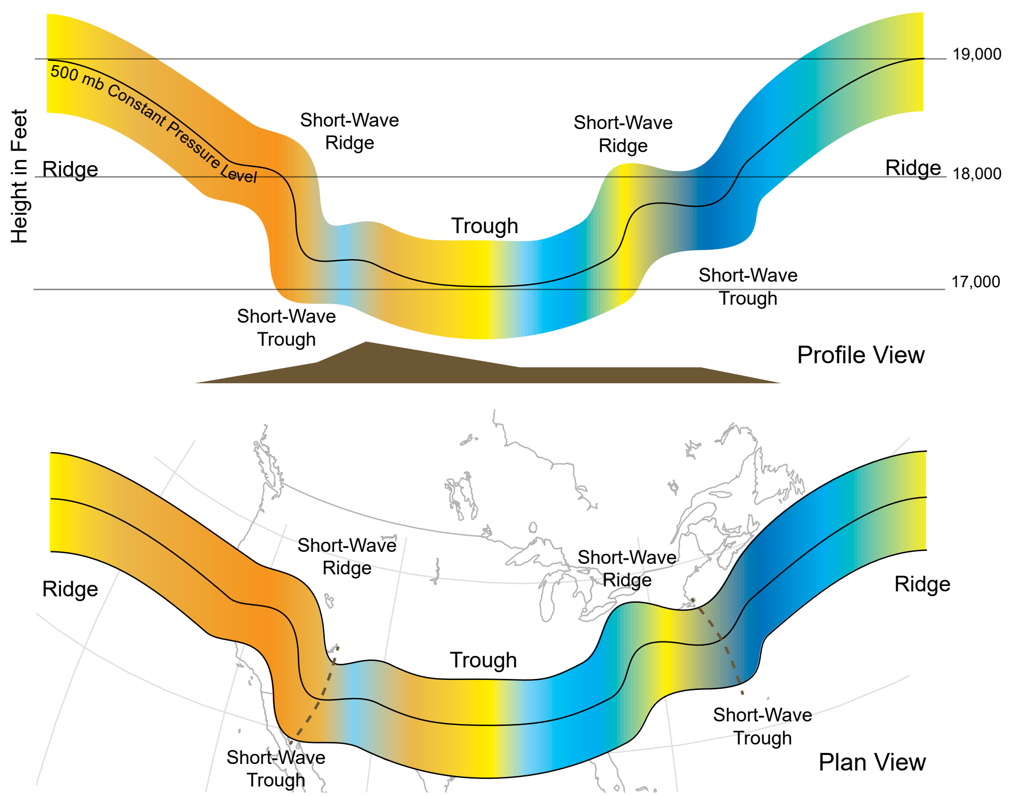
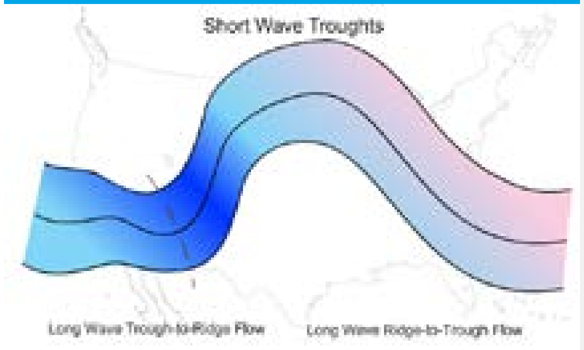


Fig. 4-1. *A short wave trough can even produce upward vertical motion in a long wave ridge-to-trough flow.*

How do short waves develop? Use the following analogy. Air, like water, behaves like a fluid. Think of the "Plan View" (lower portion of Fig. 4-1) as a river. Water, like air, flows swiftly through the large meanders. Similar to a raging river the flow comes against one bank and then the other, and may be disrupted by debris in the river bed. To atmospheric flow major mountain ranges, like debris in the river bed, affects flow. This causes eddies to develop that move downstream at about the same speed as the overall wind flow. These eddies correspond to short waves in the atmosphere.

Moisture and clouds sometimes spill over the top or move through a ridge. When this occurs it's sometimes refer to it as a "dirty ridge". I'm not sure if *dirty* refers to the unsettled character of the weather or the difficulty forecasting associated weather.



"Click" *Short Wave Troughs* to view animation.

Figure 4-1 illustrates short waves embedded in the long wave flow. "Warm" colors represent downward vertical motion—subsidence. "Cool" colors indicate areas of upward vertical motion. The "Profile View" (upper portion) corresponds to the wave "looking side-on." In this view the solid, black lines show the height of 500 mb constant pressure level. The air moves vertically through the wave as indicated by the altitudes. The "Plan View" shows the wave "looking down from the top." The air flows parallel to the contours represented by the solid, black lines.

The left side of Fig. 4-1 shows air descending in the long wave ridge-to-trough flow. Subsidence, downward vertical motion, is strongest associated with the short wave ridge-to-trough flow. Ahead of the short wave trough is an area of upward vertical motion—indicated by the "blue tint." A strong short wave trough may even produce upward vertical motion in the long wave ridge-to-trough flow.

Air ascends in the long wave trough-to-ridge flow shown in the right half of Fig. 4-1. Ahead of the short wave ridge is an area of subsidence, indicated by the "yellow tint." A strong short wave ridge may even cancel out the upward vertical motion in the long wave trough. Upward vertical motion, is strongest associated with the short wave trough—typically the area of the most significant weather.

Upper-Level Lows and Highs

At and above 500 mbs low pressure areas surrounded by a contour are known as *closed lows* or *cut-off lows*. These lows—also referred to as "cold lows aloft" or "upper-level lows"—are an important cool season weather feature. Under their influence they may be reflected from the surface to the tropopause. When an area of low pressure is reflected vertical through the atmosphere storms tend to be powerful and their movement tends to be slow and erratic. These storms produce widespread precipitation, and low ceilings and visibilities. Forecasting the formation and movement of these lows is difficult. Under their influence, weather can remain poor for several days or more. Figure 4-2 illustrates a 500 mb cut-off low.

When the low develops over the Great Basin of Nevada and Utah, it is sometimes called an *Ely Low*. When these lows move over the north-central Rockies and plains, widespread blizzards and heavy snow results. During the warm season, closed lows aloft support the development of thunderstorms, once surface lifting begins.

Upper-level lows tend to form “bands” of weather. The weather deteriorates as a band approaches, then improves, only to deteriorate with the approach of the next band. Pilots must be careful not to get “suckered” by a temporary improvement. These bands typically show up well on satellite imagery—illustrated by the inset in Fig. 4-2.

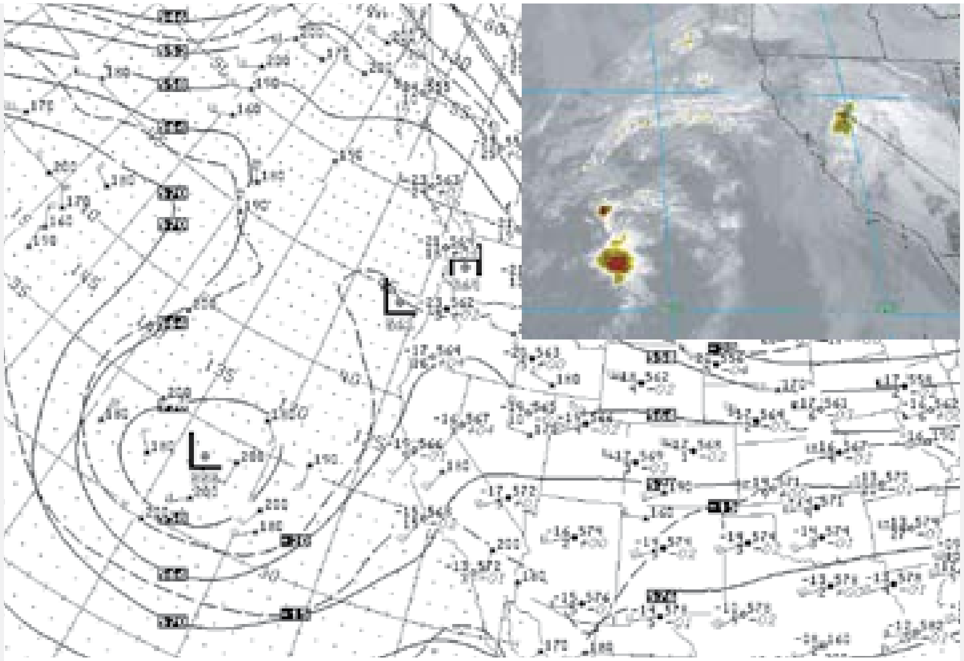


Fig. 4-2. *When an area of low pressure is reflected vertically, storms tend to be powerful and erratic.*

Case Study

> During one episode an upper low drifted in the vicinity of Red Bluff, California and remained there for five days. Pilots would call the FSS day after day wanting to know when the weather would clear. After a while, the common response became, “The low is forecast to move east out of the area tomorrow, but that’s what they said yesterday.”

Upper-level highs typically bring warm, dry weather. They tend to block approaching weather systems in the normal west-to-east flow, and are sometime known as “blocking highs.” Heat waves can develop when subsidence lingers over an area causing droughts and hellish-like heat waves, such as the “Dust Bowl” of the 1930s. Blocking highs form most often over the eastern Pacific in the late cool and warm seasons. Figure 4-3 show

blizzard —A term used to describe a severe weather condition characterized by low temperatures, strong winds, and large amounts of snow fall. The term is thought to have originated in Virginia, but now applied to similar occurrence in other countries. In North America blizzards occur with the northwesterly winds in the rear of low pressure areas in the cool season.

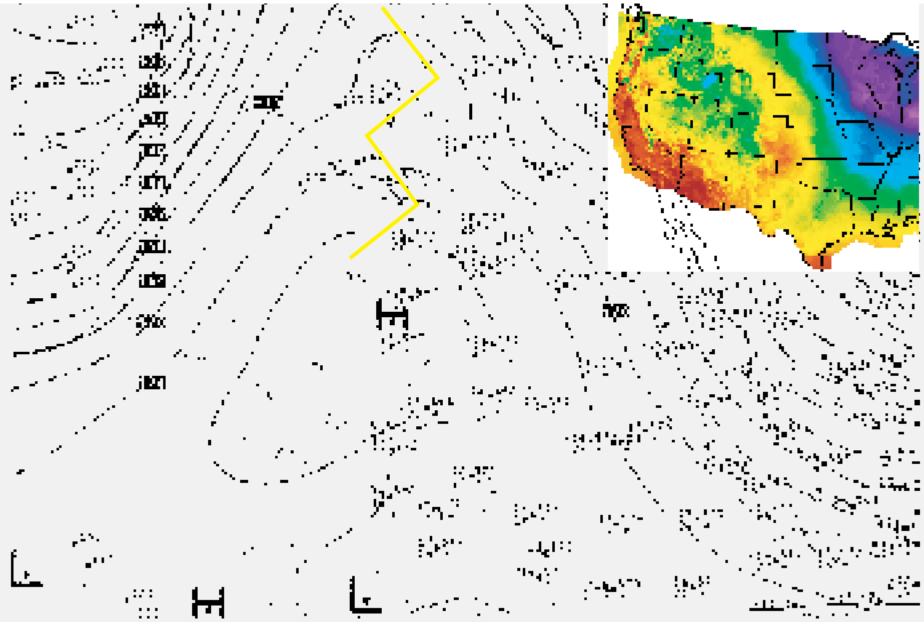


Fig. 4-3. *Upper-level highs block approaching weather systems, resulting in warm, dry weather.*

the 500 mb chart for January 16, 2009. (The upper-level ridge extends well into southeastern Alaska.) The strong upper-level high resulted in record high temperatures (inset temperature forecast chart Fig. 4-3) and mostly clear skies for almost two weeks in the western U.S.

An upper-level high over a surface low splits the flow. One branch moves poleward, the other toward the equator. Storms that approach the block from the west tend to weaken and either go over the ridge to the north or pass through the ridge to the south.

A specific pattern associated with upper-level highs is called an "omega block". Upper-level flow resembles the Greek letter omega (Ω), with an upper-level high in the center of the pattern. This is a strong blocking high that can remain stationary for days or weeks. Short waves, and their associated weather, ride up over the high.

Dry, stable weather occurs in areas dominated by upper-level highs. Typically poor surface visibilities develop in the stagnate air. High temperatures result in high density altitude. Hot, dry conditions are ideal for brush and forest fires producing smoke layers and reduced visibilities. If the wind picks up, pilots may have to contend with widespread areas of blowing dust and sand.

At times upper-level highs develop over surface lows. Thermal lows and hurricanes exhibit warm-core lows. This results in a relatively shallow low. Convergence occurs

warm-core low —An area of low pressure that is warmer at its center than at its periphery. Thermal lows and tropical cyclones are examples.

below the 500 mb level, due to thermal heating in the case of a thermal low and the release of latent heat in the case of hurricanes. Divergence occurs above the 500 mb level.

Upper-Level Convergence and Divergence

Low-level convergence and divergence occurs from the surface to about 10,000 ft. The 500 mb level is a level of non-divergence. The air does not tend to converge or diverge at this level. Upper-level convergence and divergence occurs above the 500 mb level.

Refer to Fig. 4-4. Convergence in the upper atmosphere is the piling up of air over a region; the only place for the air to go is down—a downward vertical motion producer. Divergence, a spreading out of air over a region leaves a void or vacuum. Air is sucked up from below—an upward vertical motion producer.

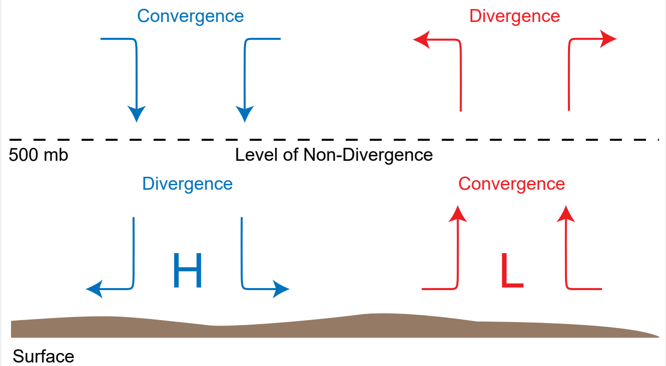


Fig. 4-4. *Upper-level convergence and divergence occur above the 500 mb level.*

Upper-level convergence and divergence explains one reason for intensifying surface high pressure areas and deepening surface lows. An area of upper-level divergence may be all that's needed to trigger thunderstorms and severe weather.

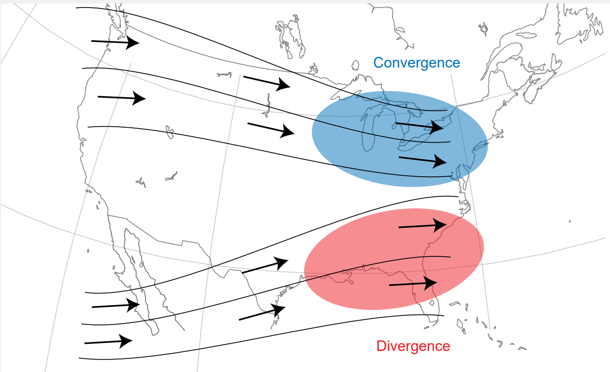


Fig. 4-5. *Convergence and divergence is one mechanism for the formation of surface lows and highs.*

Upper-level convergence and divergence result from changes in wind direction and speed. Refer to Fig. 4-5. Areas of convergence occur where contours move closer together; similar to the funneling effect of terrain. Wind speed increases. This causes surface divergence and increased anticyclonic vorticity. Surface highs develop in this way. Areas of divergence occur in areas where contours move apart. Wind speed decreases. This causes surface convergence and increased cyclonic vorticity. This mechanism results in the formation of surface lows.

Surface high pressure strengthens when upper-level winds converge. If upper-level convergence exceeds surface divergence, high pressure will build and surface pressure increase. When surface winds flow into a surface low, winds diverge in the upper atmosphere. Under these conditions the low strengthens. If upper-level divergence exceeds surface convergence, the storm intensifies and surface pressure decreases.

Case Study

> One afternoon the forecast predicted scattered thunderstorms over northern California, northern Nevada, and eastern Oregon. No weather systems were depicted on either the surface or upper-level charts. However, thunderstorms did develop. This occurred along a line of *difluence*. Difluence caused just enough surface convergence, along with a moist, unstable air mass to trigger thunderstorms.

Jet Streams

The polar jet marks the boundary between polar air and warmer midlatitude air. The subtropical jet separates warm midlatitude air from hot tropical air. At times there may be a third jet stream. The arctic jet, north of the polar jet, occurs between the boundary of extremely cold arctic air and cold polar air.

Small, sudden changes in the jet stream often coincide with the development of surface storms. These changes affect the upper wind pattern both upstream and downstream from the occurrence. This has the effect of strengthening or weakening surface weather systems.

A jet embedded in the long wave flow can remain relatively stationary for weeks; this usually brings long periods of poor weather north of its location and good weather to the south. Low pressure areas tend to move with the jet stream flow. As the wave with the jet passes, a ridge builds aloft usually bringing high pressure and good weather. However, as high pressure builds surface pressure gradients may increase, resulting in strong surface winds and associated turbulence.

When the jet stream parallels a surface front, the front tends to be slow moving and relatively weak. However, a jet perpendicular to a surface front results in a fast moving, strong front.

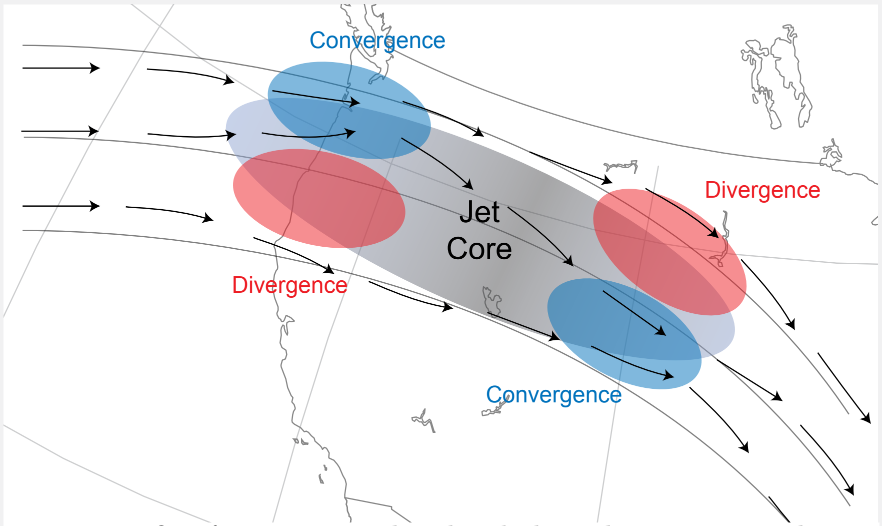


Fig. 4-6. *Surface storms develop below the strongest divergence in the southwest quadrant.*

Areas of convergence and divergence are associated with the jet stream—as illustrated in Fig. 4-6. As air enters the jet maximum its speed increases rapidly over a relatively short distance. Thus the air swings slightly to the north across the contours. As the air leaves the jet max it swings slightly to the south, across contours. This causes convergence—regions of downward moving air from the jet stream level to the surface—in the northwest and southeast quadrants of the jet. Divergence—regions of upward moving air—develop in the northeast and southwest quadrants, with the southwest quadrant usually most active due to greatest temperature differences.

At the surface, deepening storms develop below the strongest divergence in the southwest quadrant. In the late cool and early warm seasons this may be all that's required to trigger severe thunderstorms and tornadoes. Forecasters look for these mechanisms in the development of the Convective Outlook and other severe weather products. Beneath the area of strongest convergence, the northwest quadrant, anticyclones build.

In general, locations north of the jet stream associated with a surface front are likely to be cold and stormy; locations south of the boundary tend to be warm and dry.

Weather folks often have interesting and obtuse terms to describe weather systems. For example, when a jet stream behind a trough increases the trough's strength it is referred to as "digging". Therefore, a trough "digging" southward means a trough increasing in strength as it moves.

Vorticity

Pilots will occasionally come across the term vorticity in forecast products and discussions. Vorticity refers to the tendency of air to spin; the faster it spins, the greater the vorticity. (The spin can occur in any direction; our concern is air spinning within the overall horizontal flow.) A parcel of air that spins counterclockwise (cyclonically) has *positive vorticity*; a parcel that spins clockwise (anticyclonically) has *negative vorticity*.

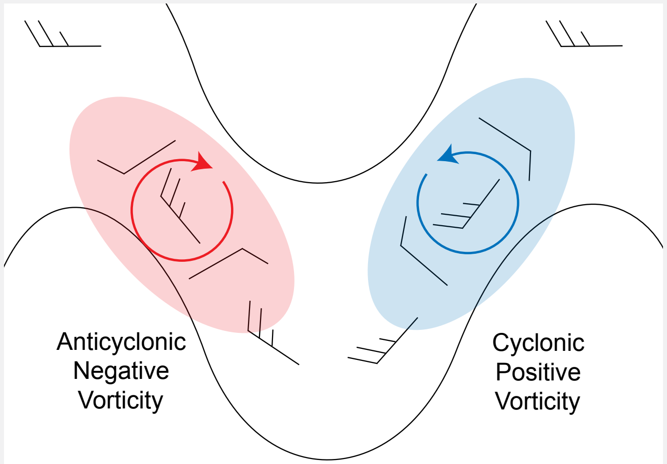


Fig. 4-7. *Divergence and convergence produce vorticity in a column of air.*

Even though air rotates within the overall flow, observations only measure the mean, or average, wind speed and direction—as illustrated in Fig. 4-7. The wind speed before and after the region of vorticity is 25 knots. There is an anticyclonic flow embedded in the ridge-to-trough flow of 10 knots—as indicated by the wind barbs. An area of embedded cyclonic flow of 10 knots has developed in the trough-to-ridge flow. An aircraft flying through the area only experiences the overall wind component of 25 knots.

The Earth produces vorticity as it spins. The Earth's vorticity—also known as Coriolis vorticity—is zero at the equator and increases with wind flow toward the pole. Divergence aloft must be compensated by convergence near the surface. For the total mass of air to remain constant, the column is elongated vertically. Upward vertical motion is independent of other vertical motion producers. As the column stretches, spin—vorticity—increases. Conversely, convergence aloft produces low level divergence. The column flattens and its spin decreases, vorticity decreases—downward vertical motion.

Air moving through a ridge (spinning clockwise) gains anticyclonic vorticity. Air moving through a trough (spinning counterclockwise) gains cyclonic vorticity. This creates downward vertical motion in ridge-to-trough flow, and upward vertical motion in trough-to-ridge flow.

Like other atmospheric properties, vorticity can be advected. As illustrated in Fig. 4-7 areas of vorticity move with the overall flow embedded in the long wave pattern. Regions of positive vorticity advection (PVA) and negative vorticity advection (NVA) describe these phenomena.

Positive Vorticity Advection

- A trough or low moving into an area.
- A ridge or high moving out of an area.
- Upward vertical motion probably occurring.
- Increasing clouds and precipitation.

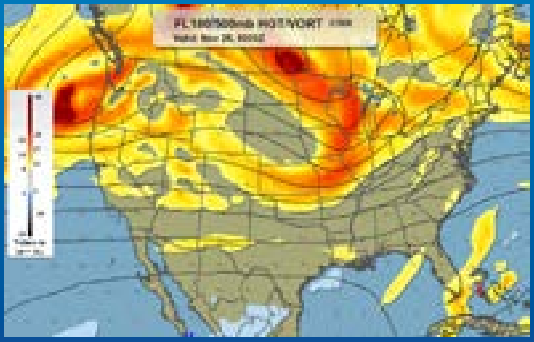
Negative Vorticity Advection

- A ridge or high moving into an area.
- A low or trough moving out of an area.
- Downward vertical motion probably occurring.
- Decreasing clouds.

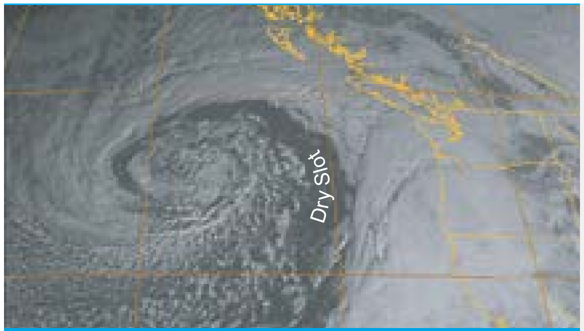
If an area of PVA moves over a stationary front, a wave can form, and a storm develops. An area of PVA might be all that's required (a lifting mechanism), with adequate moisture and instability, to trigger thunderstorms. NVA retards or prevents thunderstorm development.

Vorticity explains the development of low pressure areas east of mountain barriers, particularly in eastern Colorado. These lows are most predominant east of the Rockies because of high mountain elevations, sometimes referred to as "Lee-Side Lows." (Lee: The direction or side away from the prevailing wind.)

How do lee-side lows form? In the typical westerly flow across the Rockies, air is forced up the west slopes and trapped below the tropopause. To compensate for the column's resulting compression, vorticity decreases. This imparts an anticyclonic flow to the southeast. As the air moves downslope, the column of air expands, and vorticity increases. The air now begins a cyclonic track to the northeast. This results in a low pressure area to the lee of the mountain barrier.



500 mb Vorticity chart available from Liedoes Flight Service.



dry slot—A term used to describe a cloud free area associated with upper-level NVA.

"Hurricane" likely comes from the Spanish *huracan*. Although, it was probably derived from the indigenous peoples of the Caribbean and Latin America. The Mayan storm god was "Hunraken." The Quiche of Guatemala referred to their god of thunder and lightning as "Huraken." The Tainos and Caribe tribes' god of evil was "Huracan."

Closed upper-level lows produce bands of weather as illustrated in Fig. 4-2. Vorticity explains this phenomenon. Positive vorticity advection results in the areas of clouds and weather. Between these bands areas of negative vorticity advection account for relatively clear skies and a lack of weather. This area of NVA is referred to as the "Dry Slot."

Hurricanes

It appears the practice of giving hurricanes women's names began with writer George Stewart in his book Storm, published in 1941. A character in the book was a Weather Bureau meteorologist who used this method to track storms. During World War II Army and Navy weather folks tracked storms over the Pacific. Using names to communicate storm information was short, quick, and less confusing than previous methods. The practice continued after the War. In the 1980s the convention of using only women's names changed. Storms are still named alphabetically, with "A" the first storm of the season; however, male and female names are used alternately. Cultural diversity soon followed, as storms were given English, Spanish, and French names.

For sheer strength and areal coverage not much can compare to the weather generated by hurricanes. Figure 4-8 shows a satellite image of hurricane Katrina from August 29, 2005.

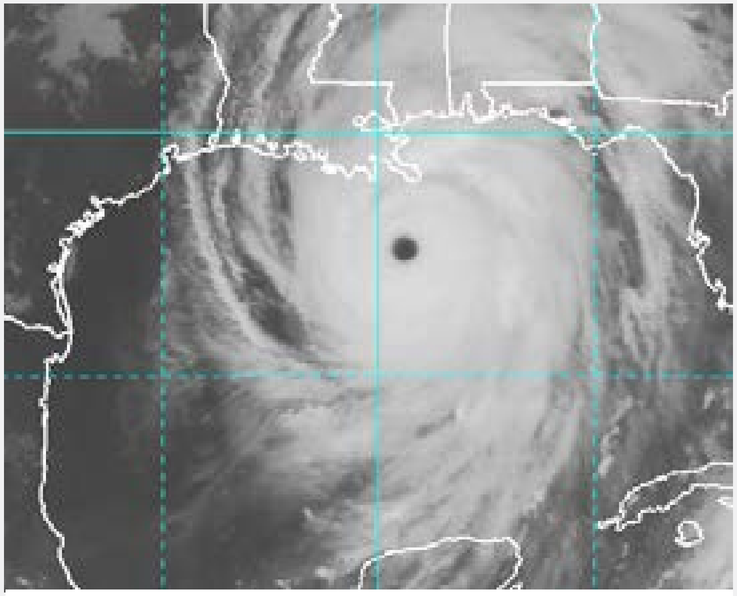


Fig. 4-8. *Hurricane Katrina reached category 5 status as it blasted into the Gulf Coast with a central pressure of 26.81 IN HG.*

Tropical cyclones typically develop during the mid to late warm season. Principle months are August, September, and October; with most occurring in September. However, early season storms can develop during May, June, or July. Storms that affect North America evolve in the warm tropical waters of the

Atlantic, Caribbean, Gulf of Mexico, and off the west coast of Mexico.

Tropical cyclones develop under optimum sea surface temperature and weather systems that produce low-level convergence and cyclonic wind shear. They favor tropical, easterly waves, troughs aloft, and areas of converging northeast and southeast trade winds along the intertropical convergence zone.

Tropical cyclones are classified according to their intensity based on wind speed.

- Tropical Depression—highest sustained winds up to 34 knots.
- Tropical Storm—highest sustained winds 35 to 64 knots.
- Hurricane—highest sustained winds 65 knots or more.

Hurricanes are further classified by intensity using the Saffir-Simpson Scale of hurricane intensities contained in Table 4-1.

Table 4-1. *Hurricane Intensity*

Category	Central Pressure (mb)	Storm Surge (ft)	Mean wind (knots)
1. Weak	>980	4-5	64-82
2. Moderate	965-979	6-8	83-96
3. Strong	945-964	9-12	96-112
4. Very Strong	920-944	13-18	113-13
5. Devastating	<920	>18	≥137

Low-level convergence associated with these systems, by itself, will not support the development of a tropical cyclone. The system must also have horizontal outflow—divergence—at high troposphere levels in an anticyclonic flow. This combination creates a “chimney” which forces air to rise causing clouds and precipitation. Condensation releases large quantities of latent heat which raises the temperature of the system and accelerates upward vertical motion. The increased temperature lowers surface pressure which increase low-level convergence. This draws more moisture-laden air into the system. These chain of events generates a huge vortex which may culminate in hurricane force winds.

Tropical cyclones usually develop between 5° and 20° latitude. They’re unlikely within

tropical cyclone—A generic term for non-frontal cyclones originating over tropical or subtropical waters; these include tropical disturbance, tropical depression, tropical storm, and hurricane or typhoon—based on organization and wind speed.

Hurricanes can produce tornadoes, but most twisters are relatively small. They tend to form on the outer spiral rainbands on the right front quadrant as the hurricane makes landfall.

5° of the equator because Coriolis is so small cyclonic circulation cannot develop. Winds flow directly into an equatorial low and it rapidly fills.

In the northern hemisphere tropical cyclones usually move in a direction between west and northwest while in low latitudes. As storms move toward midlatitudes, they come under the influence of the prevailing westerlies. Thus a storm may move erratically, reverse course, or even circle. As the prevailing westerlies become dominant, storms recurve toward the north, then to the northeast, and finally to the east-northeast.

If a storm tracks along a coast line or over open sea, it dissipates slowly unleashing its devastation far from tropical regions. However, if the storm moves inland, it weakens due to surface friction and loss of its moisture source. Like the process of air mass modification, as storms curve toward the north or east they begin to lose their tropical characteristics and acquire features more like midlatitude low pressure areas. Strength weakens as cooler air flows into the storm.

While developing, tropical cyclone have the characteristics of a circular area of broken to overcast, multilayered clouds. Numerous rain showers and thunderstorms are embedded in these clouds. Coverage ranges from scattered to almost solid. Lightning is relatively scarce due to weak updrafts, compared to those in continental thunderstorms.

As cyclonic flow increases, thunderstorms and rain showers form into broken or solid bands paralleling the wind flow that spirals into the center of the storm. These spiral rain bands frequently appear on satellite and radar images. All the hazards associated with thunderstorm, including tornadoes—although weaker than their continental cousins—are present. Weather between the bands is less severe, but like upper-level lows have the potential to “sucker” an unwary pilot; this is especially true of the eye—which is clearly visible in Fig. 4-8.

Near the top of the thunderstorms the air is relatively dry. Losing its moisture, the air begins to flow outward away from the center, in a diverging anticyclonic flow. This flow extends several hundred miles from the center of the storm. The air begins to sink and warm as it reaches the limit of the storm. This results in clear skies outside the storm.

The "eye" usually forms in the tropical storm stage and continues through the hurricane stage. A wall of clouds surrounds the eye which may extend above 50,000 ft. This "wall cloud" contains torrential rains and the strongest winds in the storm. As a result of eye wall thunderstorms the air warms from the release of latent heat. This initiates downward motion in the eye, which helps account for the absence of weather at the storm's center. In the eye, skies are cloud free, flight conditions smooth, and winds comparatively light. The average diameter of the eye is between 15 and 20 miles—although sometimes smaller or larger.

Figure 4-9 shows two Pacific storms—tropical storm Eugene at 140° W and hurricane Dora at 125° W longitude. Like all tropical cyclones their energy comes from the ocean, they dissipate rapidly over land. Occasionally, eastern Pacific hurricanes reach Hawaii and southern California. The moist, unstable remnants of these storms can be carried north and inland to affect central California and the southern part of the intermountain region.

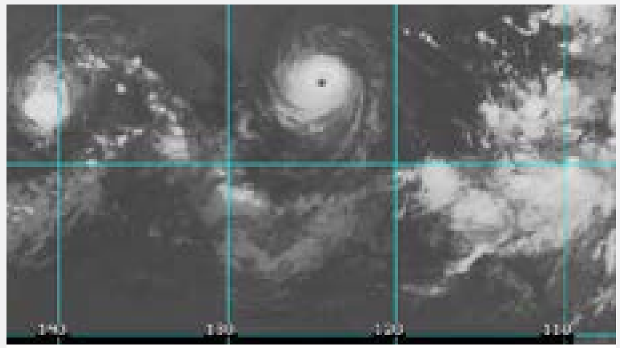


Fig. 4-9. *Eastern Pacific hurricanes can reach Hawaii and southern California.*

Figure 4-10 shows moisture resulting in thunderstorms from Tropical Storm Linda that has moved into southern California and Arizona. Analysis of these southerly disturbances was first studied in the 1930s. Because they sometimes approached from

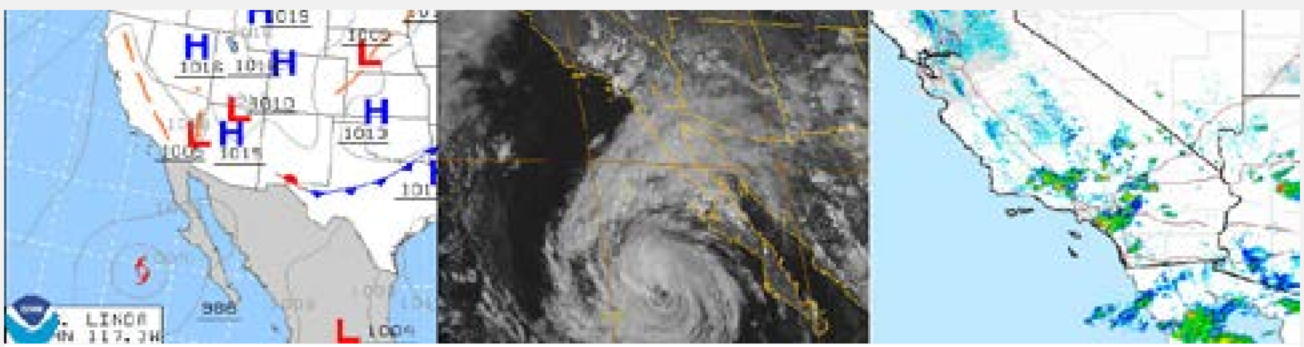


Fig. 4-10. *Extent of Tropical Storm Linda as depicted on the surface analysis chart, and visual satellite and radar images.*

Fact

Like great sports players' jerseys, the World Meteorological Organization retires the names of great hurricanes, including Katrina in 2005—the 78th Western Hemisphere storm name to be so honored (?).

What happens if a tropical storm or hurricane moves from the Atlantic into the eastern Pacific? The storm may be the same, but the name changes. In 1988 hurricane Joan underwent a "sex change" as it moved through Nicaragua, ending up as tropical storm Omar in the Pacific.

the southeast, they were called "Sonoran" storms, after the Mexican state of that name. (The callout shows Tropical Storm Henriette as it moves into the southern portion of the intermountain region.)

More on the operational aspects of tropical weather in chapter 24 Weather Systems.

Effects of Upper-Level Systems

Frontogenesis can result from the interaction of a long wave trough over the stationary portion of the polar front. Refer to Fig. 4-11. Cooler air exist on the polar (north) side and warmer air on the tropical (south) side of the surface stationary front—Fig. 4-11 (a). Strong winds aloft produce dynamic shear between the surface and upper-levels. As a short wave trough moves through, instability develops as cool air sinks and warm air rises enhancing horizontal and vertical cyclonic circulation—Fig. 4-11 (b).

As a result of the short wave trough, the flow aloft develops into an area of converging air behind the short wave. Diverging air forms ahead of the short wave. At the surface, pressures change and wind speed increases. This mechanism can start the "chain of events" that brings air masses of different properties together. Presto, magic, a front is born—Fig. 4-11 (c).

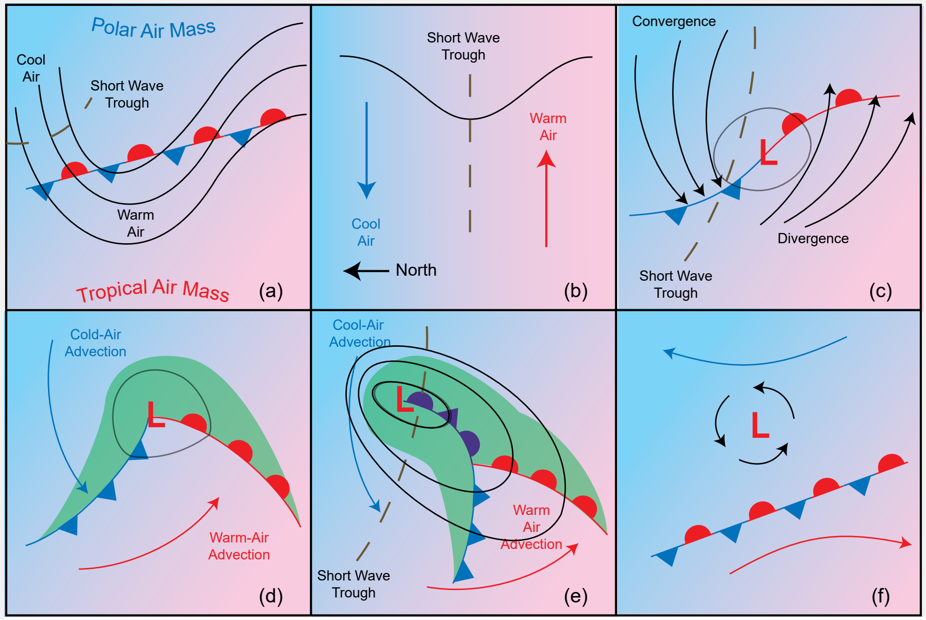


Fig. 4-11. *Frontogenesis can result from the interaction of an upper trough and the polar front.*

As the converging surface air begins to spin, cold air flows southward and warm air northward—cyclonic flow. The stationary front now develops into distinct cold and warm fronts, resulting in warm- and cold-air advection below the 500 mb level—Fig. 4-11 (d).

Above the 500 mb level cold-air advection occurs behind the cold front bringing cold air into the trough. Upper-level cold-air advection increases air density and lowers the height of the column of air between the surface and 500 mbs. Pressure in the trough lowers and the trough deepens. Ahead of the trough upper-level warm-air advection occurs which has the effect of raising the height of the 500 mb surface, increasing pressure and strengthening the ridge. As a result of differential temperature advection cyclone flow increases. Condensation in the ascending air releases latent heat, further intensifying the system—Fig. 4-11 (e).

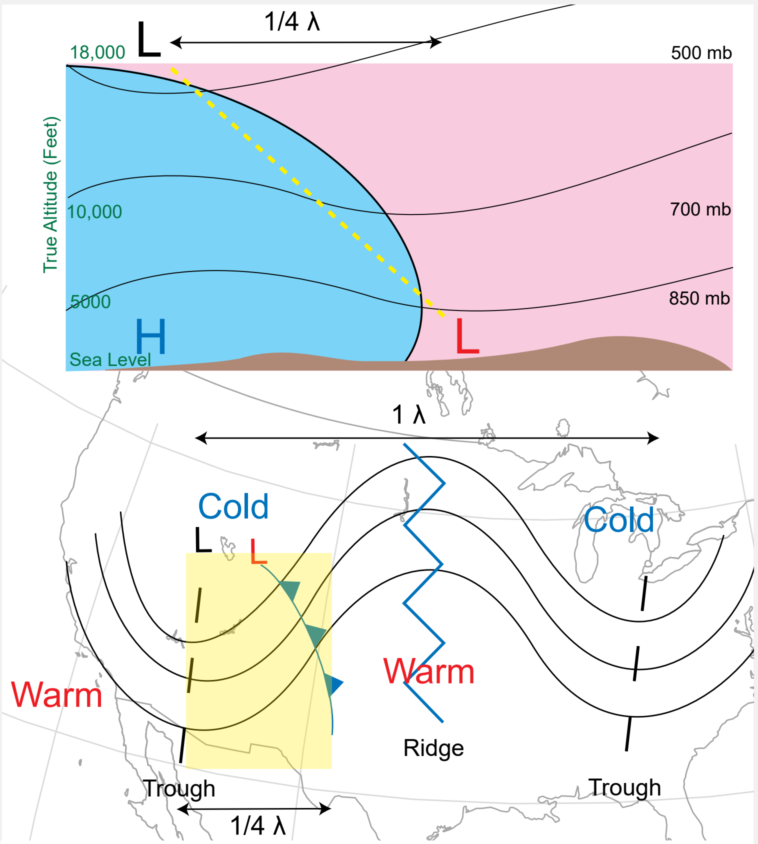


Fig. 4-12. *The relative position of surface and upper-level phenomena determines the strength of surface weather systems.*

Eventually the supply of warm surface air is cut off. A pool of cold air, which has broken off from the main flow, lies directly above the surface low. Temperature advection ceases and the surface system gradually weakens—frontolysis. The upper low itself may persist as a cut-off low—Fig. 4-11 (f).

Just as upper-level weather systems can generate or break up fronts, they affect the strength of surface systems. The lower portion of Fig. 4-12 (plan view) shows the upper-level flow (black contours), with the trough-to-ridge-to-trough distance consisting of 1 wavelength (λ). The profile view shows a vertical cross section of the atmosphere.

The surface front is located one-quarter wavelength ahead of the upper-level trough—represented by the yellow shading in the plan view. This slope—represented by the dashed yellow line in the profile view—produces maximum vertical motion and frontal intensity. (Frontal intensity depends on the moisture available and temperature contrast between the warm and cold sectors; the type of weather—convective or non-convective—by the stability of the atmosphere.)

As shown in Fig. 4-12 the frontal boundary extends vertically as well as horizontally, upward over the colder, denser air and exhibits an abrupt temperature difference throughout its vertical extent. This is known as a *baroclinic* zone. It results in a strong, active front. The opposite is a *barotropic* atmosphere. In a barotropic atmosphere density difference across the front are small, resulting in a weak, inactive front.

With the approach of an upper-level trough, a period of eight to 12 hours of poor weather can be expected. The surface front will precede the trough, usually bringing IFR weather. However, without a front, an upper trough or low may only bring marginal VFR conditions with localized areas of IFR. VFR flight might be possible, except in mountainous areas where higher terrain remains obscured in clouds and precipitation.

The absence of an upper-level trough will tend to weaken and slow a front's progress. A ridge aloft even with a surface front will not tend to produce thunderstorms or severe weather because the ridge prevents the vertical motion required. With weak fronts it's not unusual to have cloud tops below 10,000 ft; with little moisture no clouds at all.

Like previous chapters in Part I, don't become overly concerned with the discussions thus far. It's background information that will help your understanding of aviation weather presented in subsequent parts and chapters.