Chapter 9

Waves in the Westerlies

Operational meteorologists track middle latitude disturbances in the middle to upper troposphere as part of their analysis of the atmosphere. This chapter describes these waves and highlights the importance of these waves to day-to-day weather changes at the Earth's surface.

The Westerlies

Atmospheric flow above the Earth's surface in the middle latitudes is primarily westerly. That is, the winds have a prevailing westerly component with numerous north and south meanders that impose wave-like undulations upon the basic west-to-east flow. This flow extends from the subtropical high pressure belt poleward to around 65 degrees latitude. A glance at any upper level chart from 700 mb upward to 200 mb shows that the *westerlies* dominate in the middle and upper troposphere. The term *westerlies* will refer to this layer unless otherwise specified.

Upper Level Charts

The westerlies are easily identified on charts of constant pressure in the middle to upper troposphere. That is, charts are prepared from upper level data at specified pressure levels (called standard levels). Traditionally, lines are drawn on these charts to represent the height of the pressure surface above mean sea level, temperature, and, on some charts, wind speed. With modern computer workstations, any observed or derived parameter may be drawn on an upper level chart.

Standard levels include charts for 925, 850, 700, 500, 300, 250, 200, 150 and 100 mb. For our discussion of the westerlies, only levels from 700 mb upward to 200 mb will be considered. The 925 and 850 mb levels represent the transition layer between the upper westerlies and the Earth's surface.

Wave Characteristics

When you look at an upper level chart you see a series of lines that remind you of waves. As a result, when the height above sea level of an upper level pressure surface is described, wave terminology is typically used.

The Theoretical Wave Form: A wave shape can be expressed as a mathematical function. Assuming a Cartesian coordinate system with the wave extending in the x-direction, a general form for a wave can be given by the cosine function:

$$y = A*\cos[kx + \varphi] = A*\cos[(2\pi/\lambda)x + \varphi]$$

where A is the amplitude of the wave; k is the wave number; and φ is the phase of the wave. The wave number, k, is equal to $(2\pi/\lambda)$, where λ is the wavelength.

The point where y attains its maximum value is referred to as a *ridge* while the point where y is at its minimum values is called a *trough*. (See Figure 9-1.)

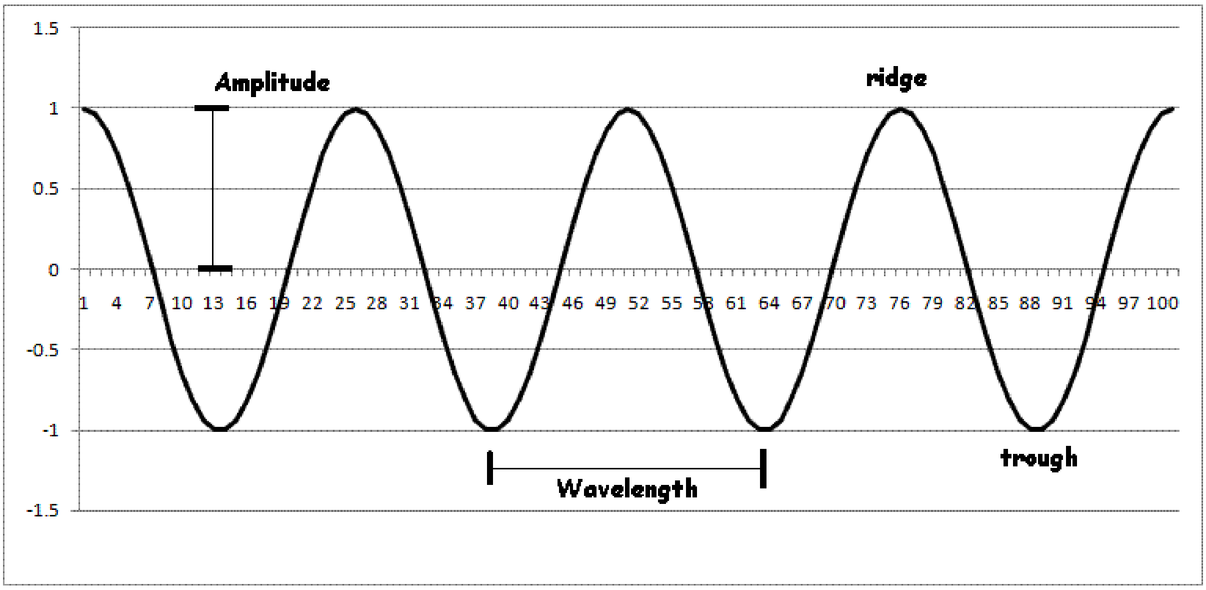


Figure 9-1: Cosine Curve, wavelength=25, amplitude=1

The x-distance from one ridge to the next adjacent ridge, or from one trough to the next adjacent trough, is referred to as *wavelength*, λ. The range in the y-value from the peak of a ridge to the bottom of a trough is twice the wave's *amplitude*, A.

The phase, φ, determines where the peak (or ridge) of the cosine curve occurs. If φ is zero, the peak is at x=0. As φ changes, the peak moves along the x-axis. Can you determine how the peak moves as φ changes from -45^o to 0^o to $+45^o$?

The above equation assumes that the wave does not move. That is, the wave's location does not change with time. If you want to consider a travelling wave where the peak (or ridge) moves in the x-direction, the argument of the cosine function will need to include a phase velocity (v) of the form, $(2\pi/\lambda)vt$ (t=time), in addition to the wave number and phase components.

The equation above represents only one wave of specified wavelength. In real-world situations, things are more complicated. There are waves of various wavelengths occurring at the same time that interact with each other.

Upper Level Charts: As noted above, upper level charts are constructed on surfaces of constant pressure. The height of this surface above sea level is used to depict the main features of the chart. By drawing lines of constant height, called isohypses or contours, you get a picture of the topography of the pressure surface.

Areas of lower height or valleys in the topography correspond to troughs while areas of higher height or ridges in the topography correspond to ridges. Figure 9-2 shows the height of a 500 mb surface along the 50 degree North latitude line as a function of longitude.

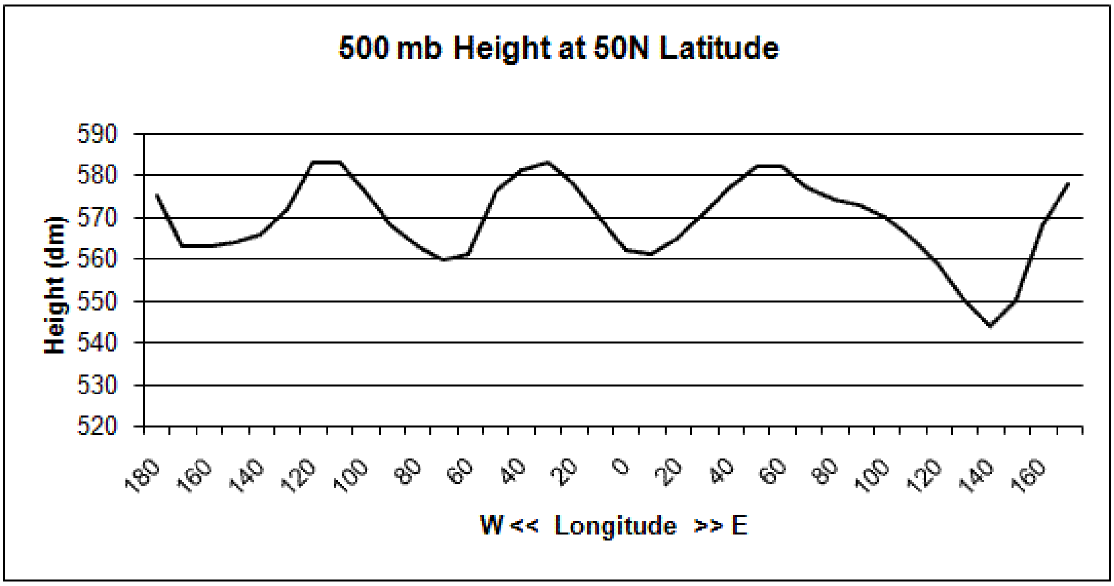


Figure 9-2: 500 mb Height as a Function of Longitude

The first thing to note is that the curve looks somewhat like a cosine wave, although it is not a perfect match. There are troughs or valleys near 160W, 60W, 10E and 145E. There are ridges near 130W, 25W 60W and the international dateline. Thus there are four troughs and four ridges around the hemisphere for this case.

Let’s look at Figure 9-2 from a different perspective. Assume that you want to examine the pressure along a surface of constant height, say 570 dm. Because pressure decreases with increasing height, if the 570 dm level is lower than the height of the 500 mb surface, the pressure is higher than 500 mb; if 570 dm level is higher than the height of the 500 mb surface, the pressure is less than 500 mb. Thus, lower heights correspond to relatively lower pressures, and higher heights correspond to relatively higher pressures.

This brings us to a basic definition for a trough and a ridge on an upper level chart. This is shown schematically in Figure 9-3.

- A *trough* is a broad area of relatively low height. If you move perpendicular to a trough line, or the axis of lowest height, height values increase.

- A *ridge* is a broad area of relatively high height. If you move perpendicular to a ridge line, or the axis of highest height, height values decrease.

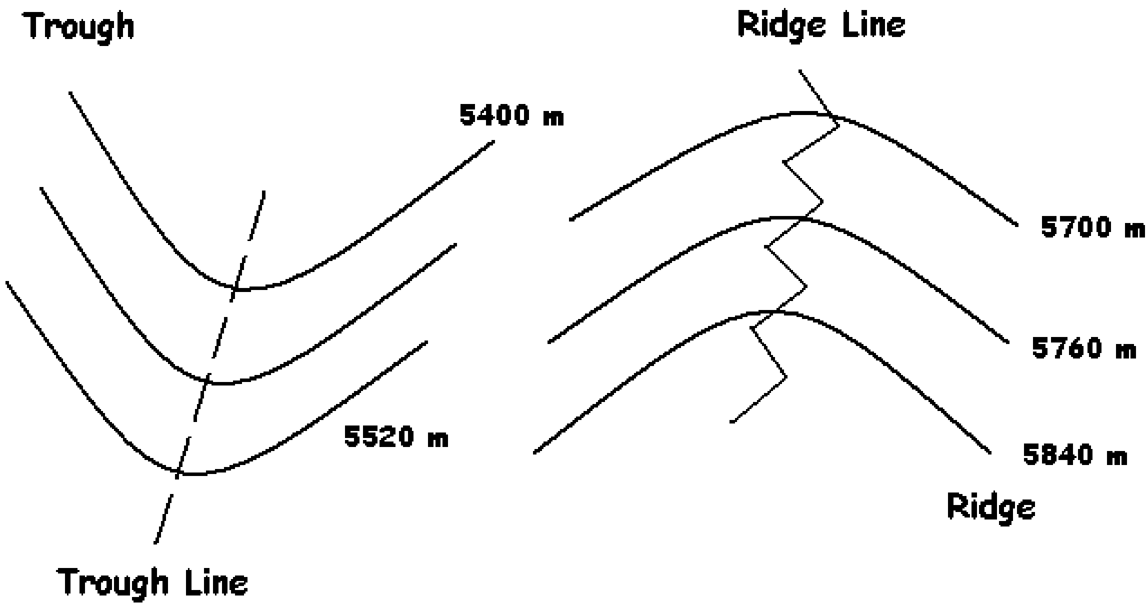
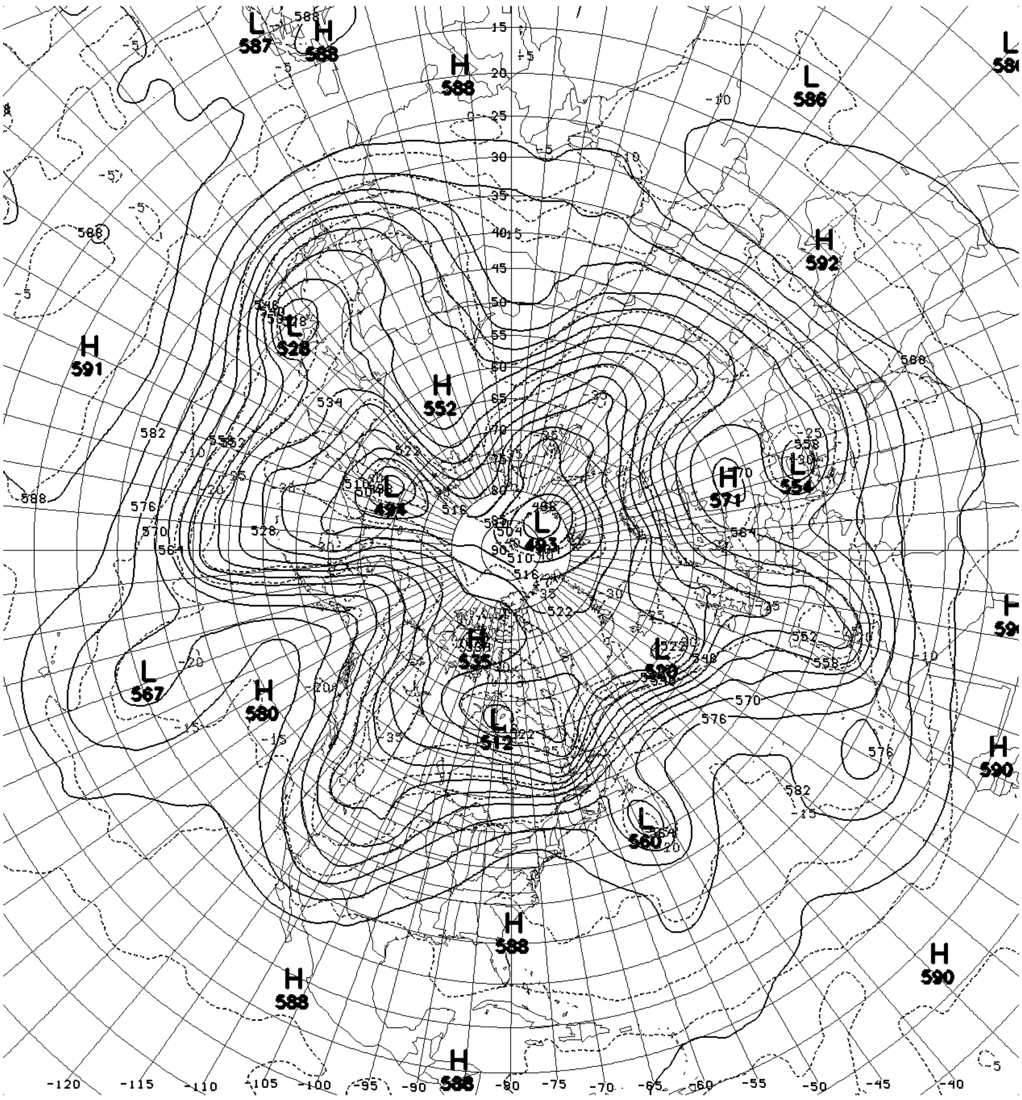


Figure 9-3: Schematic of an Upper Level Trough and Ridge

The trough is the broad area of cyclonically curvature flow while the trough line is located where the cyclonic curvature is maximum. Trough lines are typically shown as dashed lines.

The ridge is the broad area of anticyclonically curvature flow while the ridge line is located where the anticyclonic curvature is maximum. Ridge lines are typically shown as saw-toothed lines. Some ridges do not have a well-defined ridge lines.

500MB ANALYSIS HEIGHTS/TEMPERATURE



04/26/2009 12UTC 000HR FCST VALID SUN 04/26/2009 12UTC NCEP/NWS/NOAA

Figure 9-4: Northern Hemisphere 500 mb Chart

Real World Waves: Figure 9-4 is the hemispheric 500 mb chart for 1200 UTC on 26 April 2009. The contours show a ridge in the eastern Pacific Ocean from the Gulf of Alaska southward and a broad trough across the western third of the contiguous United States. These wave-like features are not a perfect cosine wave but have the general features of the theoretical function. The pattern that you see is a combination of several waves of varying wavelengths and amplitudes. The challenge for the analyst is to identify the more significant waves and their movement over time.

Trough and Ridge Line Identification

Determining the location of troughs and ridge is a significant part of the analysis process. There are three approaches that can be used to place a trough or ridge line on your chart.

Observed Data: If current upper air observations are plotted on a chart, you should be able to place a trough or ridge line based on the wind shift information defined by the observations. In many situations this wind shift is well-defined while in other cases the wind shift may be broad and subtle, making it difficult to precisely place a trough or ridge line.

If you are using computer-generated wind data that is displayed in a gridded format, it is often difficult to delineate a sharp wind shift line. This is due to the nature of objective analysis and numerical processing that tends to smooth discontinuities. This smoothing is particularly true for weak, low amplitude waves.

Contour Curvature: When wind data are not available, you must rely on the contour curvature to place a trough or ridge line. Look for the axis along which the contour curvature is a maximum. In some cases this axis is well-defined, while in other situations it is difficult to identify a trough or ridge line due to the broad, smooth nature of the flow.

Vorticity Pattern: If a field of absolute vorticity is available, it can be useful in placing a trough or ridge line. Vorticity is a measure of rotation in the horizontal plain and can be used to locate the axis of maximum curvature. This may show up as a vorticity maximum or a vorticity lobe (an axis of maximum vorticity across the flow) along a trough line. A minimum in absolute vorticity is not always as well-defined in ridges.

Why Are Upper Waves Important?

When you analyze a series of weather charts, one aim is to explain why the current weather is occurring. Why are there clouds and precipitation here, or clear skies there? Clouds are produced by two main processes: 1) the upward movement of air that is at or near saturation; or 2) vertical mixing that blends and saturates the mixed air.

Upper level troughs are important because they provide the lift needed to produce saturation. Theoretical analysis of a sinusoidal upper level wave shows that the best area for upper tropospheric divergence (and hence, upward vertical motion) extends from the trough downstream to the next ridge with maximum divergence at the point of inflection. Similarly, the best area for upper level convergence (and hence, downward vertical motion), extends from the ridge downstream to the next trough. Upper divergence can also contribute to the development a surface low pressure center below the upper trough. From a practical viewpoint, this general relationship is shown in the satellite identification of troughs described in Chapter 7 where upper troughs are placed at the upstream edge of the cloud feature.

Long Waves and Short Waves

Attempting to identify the wavelength for any particular wave in Figure 9-4 is difficult. Nevertheless, differentiating longer wavelength features from shorter wavelength features can be useful for anticipating future weather conditions. Experience has shown that waves in the middle and upper troposphere can be divided into two main categories: *long waves* and *short waves*.

If wavelength is measured in an east-west direction along a latitude circle, it can referenced in terms of wave number. Wave number describes the number of complete waves that are found around the latitude circle. For example, wave 1 has one trough and one ridge around a latitude circle or a wavelength of 360 degrees of longitude; wave 2 has two troughs and two ridges around a latitude circle or a wavelength of 180 degrees of longitude; wave 3 has three troughs and three ridges around a latitude circle or a wavelength of 120 degrees of longitude; etc.

Long Waves: Long waves have a wave number of 1 through 6. This indicates that the shortest wavelength for a long wave is 60 degrees of longitude or the distance from Honolulu to Kansas City. In other words, a wave with a wave number of 6 would have a ridge around Hawaii and its next ridge around Missouri. Long waves are also known of *major waves* or *planetary waves*.

Long waves are characterized by cold troughs and warm ridges. On most occasions there are from 3 to 6 long waves around the hemisphere. Long waves are slow moving and often stationary with trough and ridge movements from 0 to 15 knots. Sometimes long waves are even retrogressive, that is, they move against the westerly flow toward the west. Trough locations have a preference for the east coasts of continents while ridges prefer the west coasts (during the Northern Hemisphere winter). Figure 9-2 shows a situation with four long waves around the Northern Hemisphere.

Determining the number and location of the long waves is not always straight-forward. In most cases a hemispheric 300 or 500 mb chart is used to indentify long waves. Some studies indicate that a 3 to 5 day mean of the middle tropospheric flow pattern should be used to identify long waves. The National Weather Service has used a composite of the first five wave numbers for a specific time to help determine the long wave number and location. Personal experience has shown that a loop of at least 72 hours of time for a fairly broad area (e.g., from the middle Pacific Ocean to the middle Atlantic Ocean) can be used to observe the amplification of short waves moving through a long wave trough position.

The position of the long wave trough and long wave ridge can help anticipate the level of active weather for an area. Long wave troughs usually have a series of active short wave systems moving through the long wave pattern that create varying degrees of clouds and precipitation. Long wave ridges are usually relatively quiet compared to a long wave trough. A persistent long wave ridge is often accompanied by a period of little to no precipitation downstream from the ridge.

There is one situation which occurs in the long wave pattern that needs to be mentioned: *discontinuous retrogression*. When the wavelength from one long wave trough to the next one downstream becomes excessively large compared to the rest of the hemisphere, the downstream trough is often replaced by a new trough that forms farther west than the position of the original downstream trough. In a loop of this situation it appears as though the downstream trough suddenly shifts westward or upstream in a discontinuous manner. In reality, a new trough forms and the original downstream trough weakens.

Rossby Waves: In the late 1930s Carl Rossby published a paper on the flow patterns in the upper troposphere. Specifically, his work calculates the behavior of the planetary waves in a uniform current in a two-dimensional, non-divergent fluid. The theoretical waves described in this paper are now known as *Rossby Waves* and correlate well with the long waves observed in the middle to upper troposphere. As a result you will often hear the long wave patterns in the real atmosphere referred to as Rossby waves.

Short Waves: Short waves have a wave number between seven and twenty. This indicates that the longest wavelength for a long wave is around 50 degree of longitude or the distance from New York to San Francisco. Short waves are also called *minor waves*.

Short waves move faster than long waves, typically at speeds of 20 to 40 knots. They travel in the direction of the prevailing basic or long wave current. This latter process is sometimes referred to as "steering" by the basic current. These waves are characterized by small amplitudes and isotherm patterns out of phase with the streamlines. When isotherms are out of phase with the streamlines thermal advection can occur which modifies the amplitude of the wave over time. Short waves are strongest at the 700 and 500 mb level and best identified at these levels. They often reflect the high and low pressure systems found in the sea level pressure and 850 mb height patterns.

Long waves and short waves interact with each other and cause changes in the upper flow patterns. For example, when a short wave trough moves into a long wave trough, it often amplifies and contributes to the development of surface low pressure centers. As the short wave trough moves out of the long wave trough, it typically weakens, that is loses amplitude.

Cyclone Waves: In addition to long waves and short waves, the Glossary of Meteorology (2000) defines a *cyclone wave*. This wave is a disturbance with a wavelength of 1000 to 4000 km, or cyclone scale. It corresponds to the migratory low and high pressure systems that dominate middle latitude weather. This wavelength range is the same as that of short waves.

The division into long and short waves is somewhat arbitrary. The real atmosphere has a spectrum of wavelengths. Usually there is one dominant long wavelength with a series of shorter waves travelling through the longer wave pattern. You may only see one trough and one or two corresponding ridges for any particular short wave. Over time, the short waves can often be followed half way around the world as they move into and out of a series of longer waves.

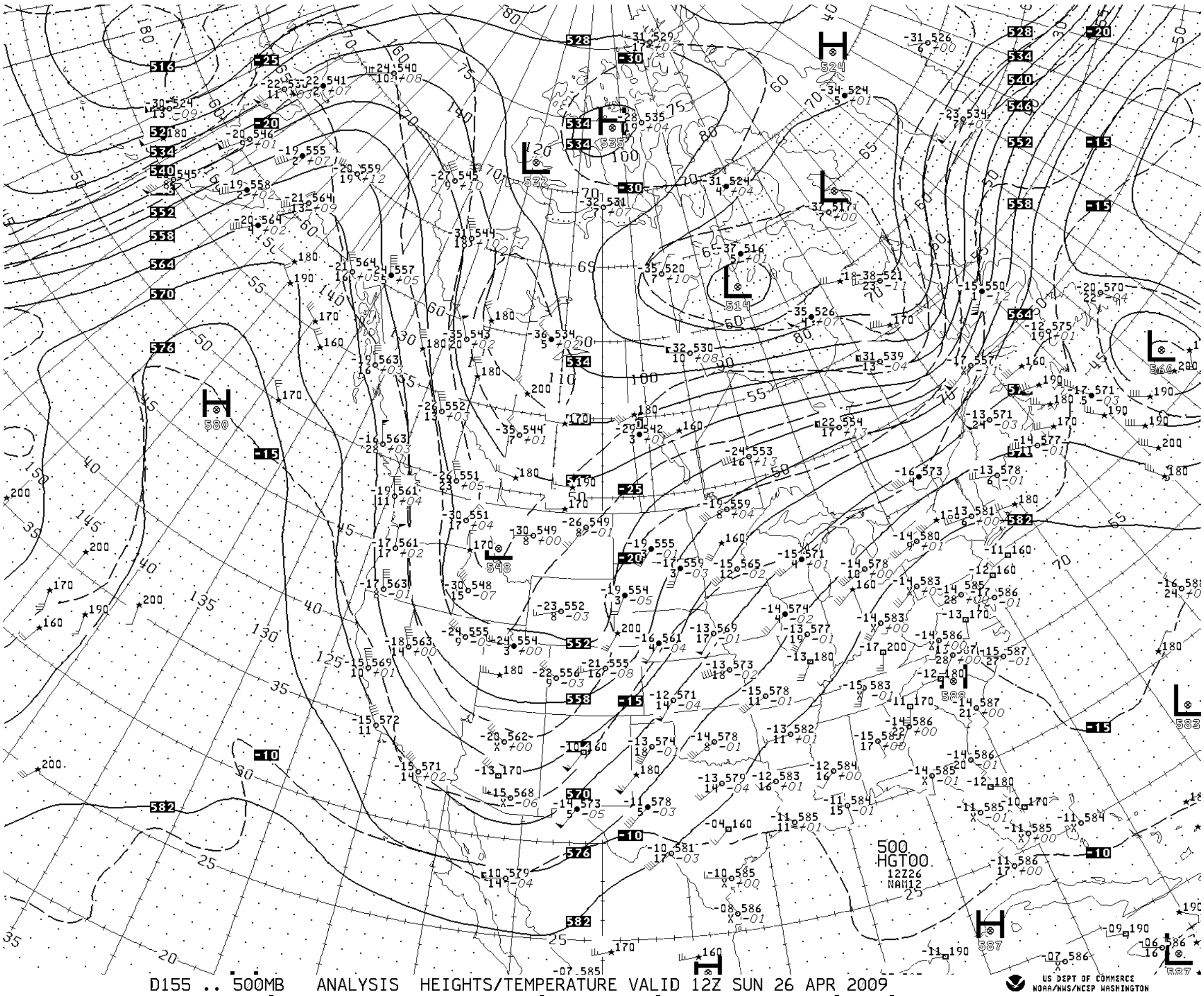


Figure 9-5: North American 500 mb Chart

Long and Short Wave Example

Examination of Figure 9-4 shows five prominent long wave troughs with a weaker amplitude trough south of Newfoundland. This six wave pattern is typically progressive in that the major waves will slowly move toward the east over time.

Figure 9-5 is the North American version of Figure 9-4. This chart shows several short wave troughs superimposed on the long wave trough over the western third of the United States. Specifically, there is a short wave trough moving southward over the Canadian Rockies; another trough extends south from the weak low center over Montana; and a third short wave trough is found from southeast Wyoming into northwest Kansas. These three short wave troughs are moving through, or a steered by, the longer wavelength flow.

Flow Features

There are a variety of terminology used to describe the features found in the middle and upper troposphere. This section defines many of these terms and provides examples. Let’s start with closed circulations.

Closed circulations are often found at 500 mb and show up on 500 mb charts as a closed contour system, that is, there is at least one closed contour around the low center. Two terms are used to describe these types of circulations: closed contour systems; and cut-off systems. A cut-off low is a specific type of closed contour system; not all closed contour lows are cut-off.

Cut-Off Lows: A cut-off low is a closed contour low found equatorward of the main band of the westerlies. A cut-off low is characterized by a cold core and slow movement. Cut-off lows can persist for days before being reabsorbed into the main westerly current. Areas west of the California coast and in the Atlantic Ocean near the Azores are favored regions for the formation of cut-off low centers.

Figure 9-6a is an example of a cut-off low over the Atlantic Ocean. The main westerly flow extends from the east coast of North America, across Newfoundland, to Greenland and Iceland. Figure 9-6b is an example of a cut-off low over the Pacific Ocean. The main band of westerlies flows from the Gulf of Alaska to the California coast and then eastward across the United States.

Closed Contour Lows: A *closed contour low* is a cyclonic circulation that is embedded within or just poleward of the westerly current and moves with the westerly current. The closed contour may open over time or remain closed as the system changes intensity.

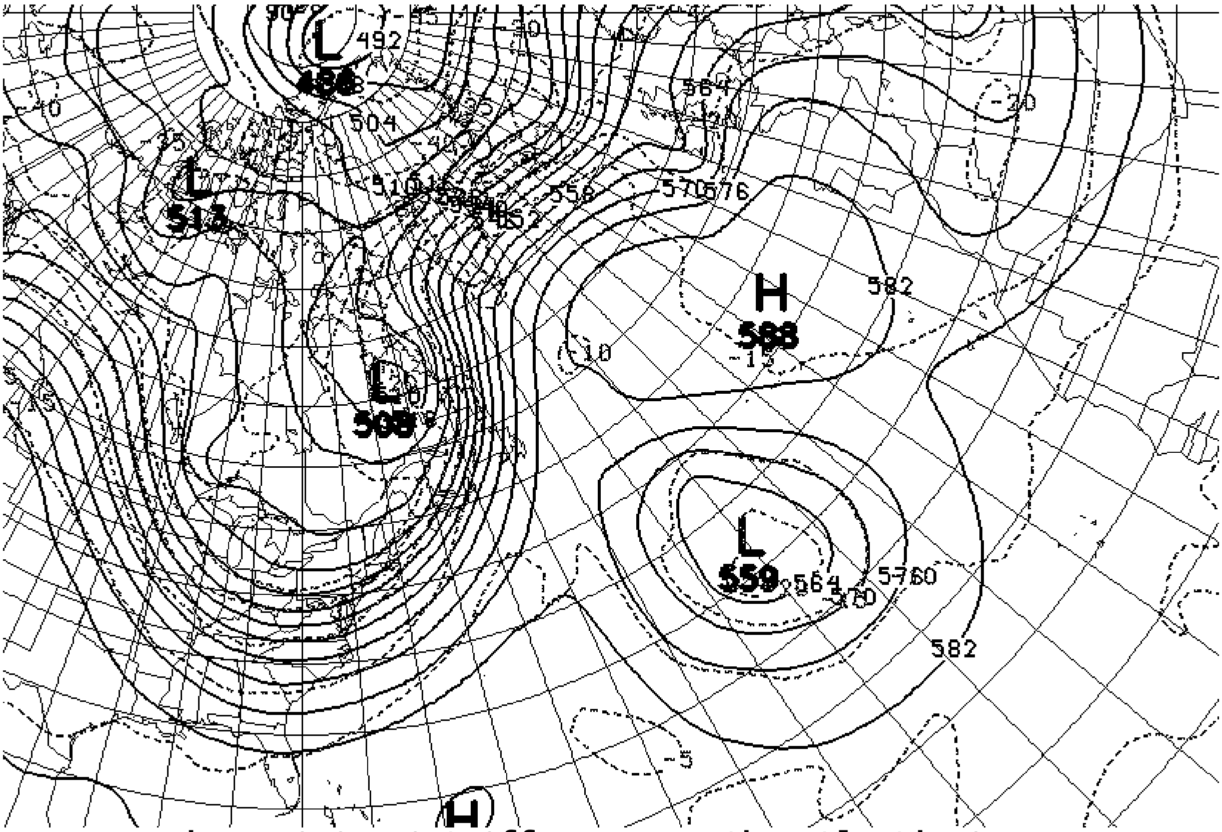


Figure 9-6a: Cut-Off Low over the Atlantic Ocean

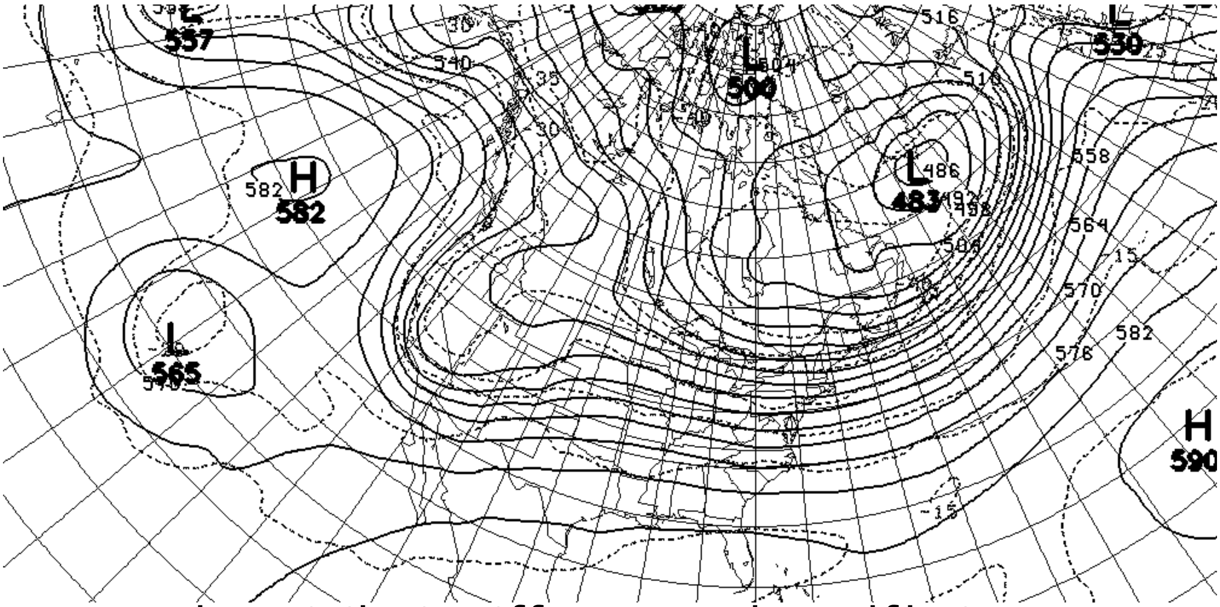


Figure 9-6b: Cut-Off Low over the Pacific Ocean

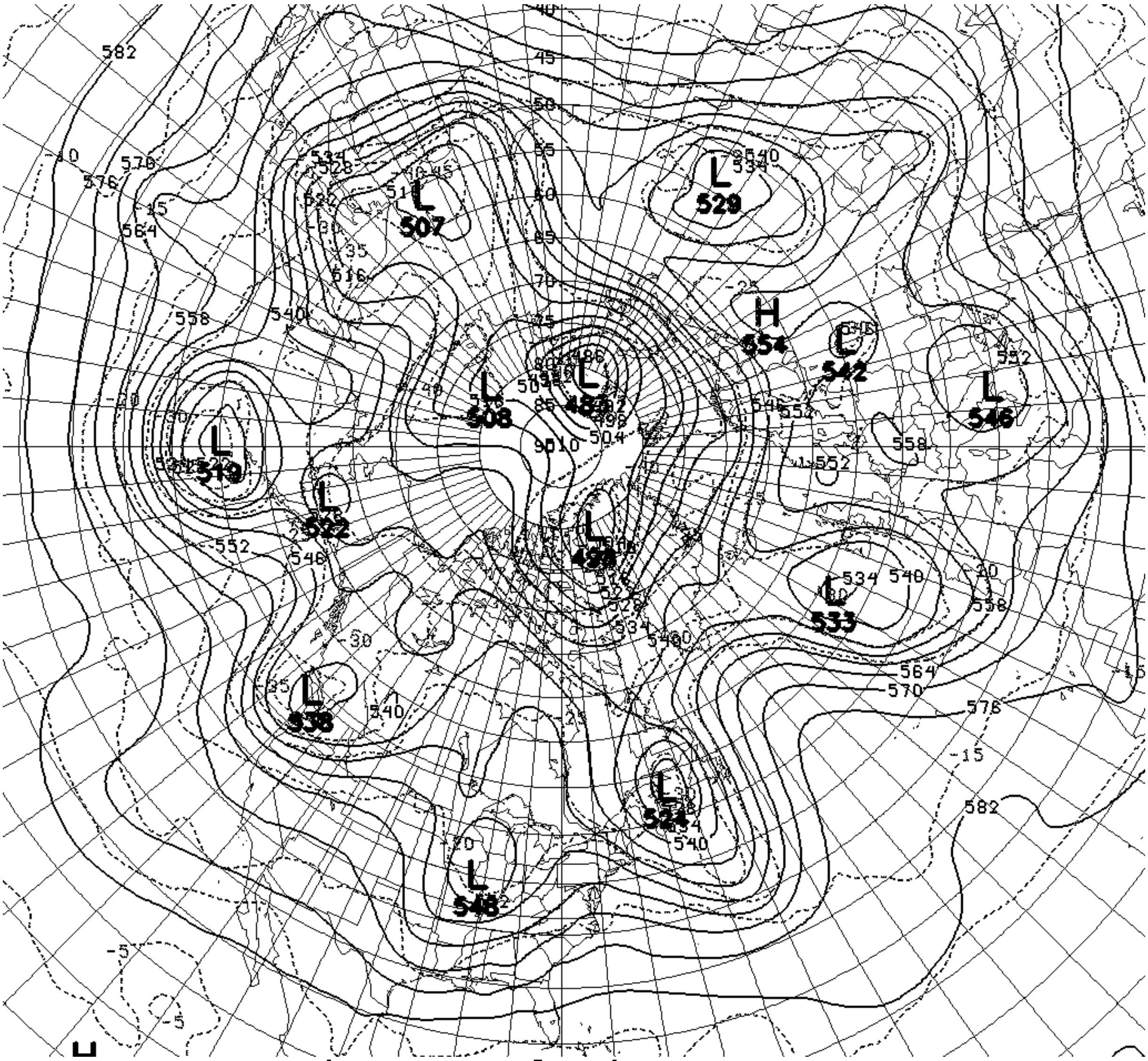


Figure 9-7: Closed Contour Lows

Figure 9-7 shows a series of closed contour lows from the central Pacific Ocean, to the Washington coast, to the Missouri-Illinois border, to the Canadian Maritimes. These lows are on the poleward side of the main westerly current and are moving slowly eastward in the general westerly flow.

Blocking: A special category within the broader class of closed circulations is the blocking high or blocking anticyclone. This high center is warm core, is fairly large in extent, and remains nearly stationary for a week or more. It obstructs the normal west-to-east progression of the middle and upper tropospheric waves. The flow around this high has a significant meridional component and often takes the shape of the Greek letter omega.

As a result blocking highs are often referred to as omega highs or omega blocks.

Prolonged blocking tends to occur during the Spring over the eastern portions of the North Atlantic Ocean or over the eastern North Pacific region. The high is usually centered on the northern edge of the middle latitudes. Closed contour lows are frequently found equatorward of the omega block.

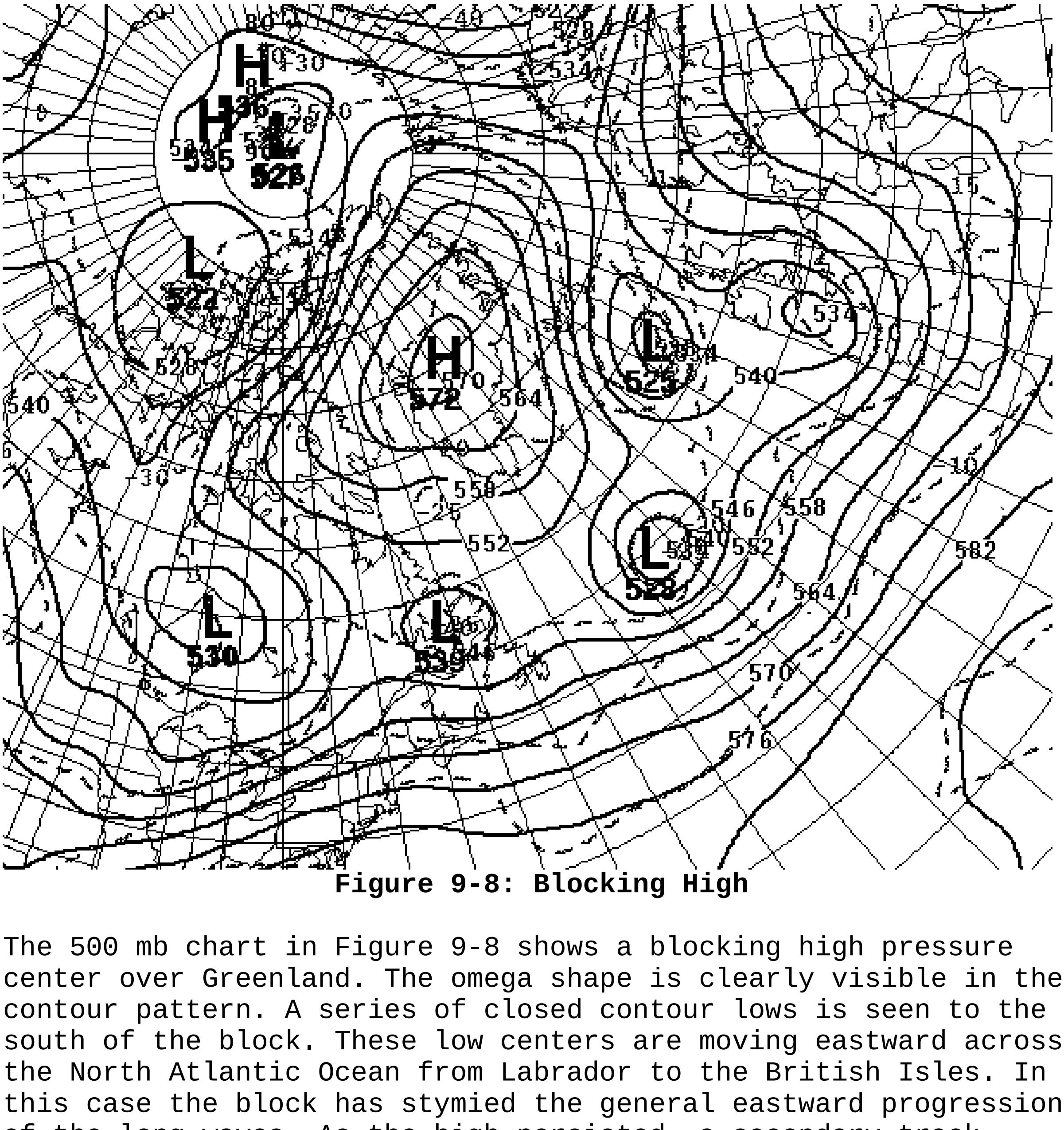


Figure 9-8: Blocking High

The 500 mb chart in Figure 9-8 shows a blocking high pressure center over Greenland. The omega shape is clearly visible in the contour pattern. A series of closed contour lows is seen to the south of the block. These low centers are moving eastward across the North Atlantic Ocean from Labrador to the British Isles. In this case the block has stymied the general eastward progression of the long waves. As the high persisted, a secondary track established itself across the central North Atlantic Ocean.

Split Westerly Currents: Most of the time there is one broad westerly current present in the middle to upper troposphere. This type of pattern is seen in Figure 9-7. There are times, however, when the westerly current splits into two streams. Figure 9-9 shows this type of pattern over the western United States. There is a westerly flow coming off the Pacific Ocean over southern California while a northerly flow extends south from central Canada into the Northern Plains. When the cold northerly flow meets the warmer, more humid flow off the Pacific Ocean, significant winter weather frequently occurs.

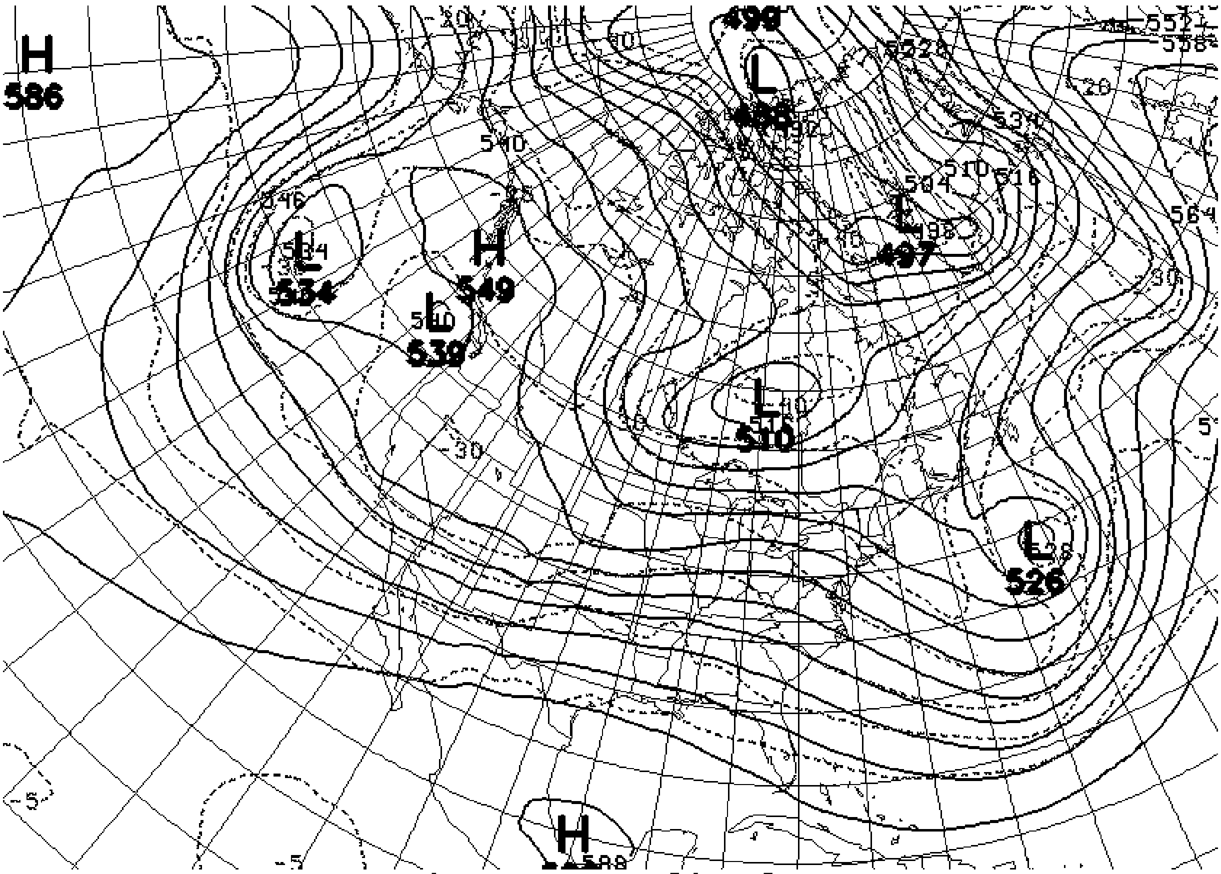


Figure 9-9: Split Flow

Zonal versus Meridional Flow: The terms *zonal* and *meridional flow* are often used to give a general description of the middle latitude westerlies. Zonal flow is middle to upper tropospheric flow that is mainly westerly with a small meridional component. Figure 9-6b shows a broad zonal current from Kansas eastward into the western North Atlantic Ocean. In contrast to zonal flow, meridional flow has unusually pronounced north-south components that move warm air poleward and cold air equatorward. Examples of meridional flow are shown in Figures 9-4 and 9-6a.

These terms should be applied to broad regions on the scale of the 48-contiguous United States or larger, and not to smaller regions.

Concluding Remarks

This chapter has described the main features found in the middle to upper tropospheric westerlies. These features are identified and tracked by operational meteorologists in order to explain and better anticipate local weather. Numerous examples have been used to illustrate the variety of terminology used to describe upper flow features. The jet stream is another feature found in the upper troposphere. It is described in another chapter.

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