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APPLICATION OF THE ZERO RELATIVE VORTICITY LINE IN SYNOPTIC FORECASTING

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Introduction

In an earlier paper (Rosendal, 1976) the author discussed the well-known connection between the upper tropospheric jet stream and surface cold fronts. The zero relative vorticity line (ZRVL) at mid tropospheric levels was shown to be a convenient indicator of maximum divergence aloft near the jet and of the accompanying surface convergence along the cold front below. This Technical Memorandum will further examine the concept of relating, via the 500 mb ZRVL, surface convergence, as expressed in active weather and fronts, to a narrow zone of divergence aloft associated with the upper jet. Applying this technique should help the forecaster better understand the cyclone model and hopefully thereby improve his forecasting ability. Many of the statements made in this paper lack conclusive evidence and documentation but are in general based on common meteorological knowledge and on the author's many years of practical experience in synoptic forecasting and climatology in various parts of the world. The validity of the ideas expounded is readily verifiable in areas with good 500 mb vorticity analysis and progs together with satellite and radar data. The author feels that there is enough practical value inherent in the ideas expressed in this Tech Memo to suggest that forecasters give this method of using the ZRVL a cautious attempt. This discussion is tailored for United States forecasters. It would be a simple matter to extend application to other parts of the world.

The Jet Stream

The creation of the circumpolar jet stream from meridionally variable heating is well developed in many texts. The jet is strongest near the tropopause over mid latitudes. Above the tropopause, in the lower stratosphere, temperatures are warmer near the poles than near the equator and thus the westerly jet weakens with height. The jet stream is maintained by the north-south temperature gradient near the surface. Any surface features which cause a sharpening of this north-south temperature gradient will thus tend to strengthen the jet. Such features include boundaries between the warm ocean currents of the middle latitudes and the cold subarctic waters. The ocean-continent distribution also have strong seasonable influences as do the boundaries between large scale snow and ice fields. Large scale albedo and soil moisture difference also affect the strength of the upper jet through the variability in low level sensible heating. The jet stream usually circles the globe within the mid latitude belt in fairly continuous fashion. At times the jet may be rather zonal over a large portion of its path around the hemisphere, while at other times the flow breaks down into large eddies and high amplitude meanders. The flow is confined to some extent along Rossby's constant absolute vorticity trajectories (CAVT). This model flow tends to keep the westerly jet from departing too far from a given equilibrium latitude circle as it oscillates north and south with a total of perhaps 3 to 8 large Rossby waves around the hemisphere with the lesser numbers within this range prevalent during the strong wintertime circulation. Mountain ranges, especially those oriented north-south such as the Rockies and Andes, will tend to induce the formation of so-called dynamic troughs downstream of the mountains. Amplifications of Rossby waves may also occur as ageostrophic wind maxima travel through the flow at times of baroclinic instability. These amplifications are important in the meridional redistribution of heat and moisture.

Zonal vs Meridional Flow - Shear vs Curvature Vorticity

As the upper jet changes from a mostly zonal jet stream into a more meridional mode, contributions to the vorticity of the flow will undergo a similar oscillation: that is, the contribution to vorticity from horizontal wind shear will diminish at the expense of greater contributions due to curvature of the flow. A mostly zonal jet stream (Fig. 1) will have large associated values of horizontal wind shear - cyclonic shear to the north and anticyclonic to the south. The zero relative vorticity line (ZRVL) is found to closely coincide with the jet axis. As the flow becomes more sinusoidal, the 500 mb ZRVL will become displaced away from the speed maximum at 500 mb in such a way that where the flow is cyclonically curved, as in the troughs, the ZRVL will be displaced to the anticyclonic shear side. The opposite applies to the ridge locations. Vorticity analysis is routinely available only at the 500 mb level. The flow at jet stream level, which may be near 150 mb at low latitudes and 250 mb at high latitudes, is however quite similar to the flow near 500 mb except the strength of the flow at upper level is of course considerably greater. There is however some vertical tilt to systems. This tilt is in such a way that if the ZRVL is drawn in one the 500 mb flow level, the jet stream near the tropopause, or at least the divergent part of the jet, will coincide with the 500 mb ZRVL. This divergent part of the jet is found in the anticyclonic environment very close to the upper jet axis during the portion of the flow from trough to ridge (Fig. 2).

Relative and Absolute Vorticity

The ZRVL marks the zero values of <u>relative</u> vorticity. When unspecified the term "vorticity" usually refers to the vorticity of the wind, or the relative vorticity. However, when considering large scale atmospheric fluid dynamics, it is often understood to mean <u>absolute</u> vorticity. The reason is the conservative properties of "constant absolute vorticity" flow operating on this scale. The absolute vorticity is defined as the sum of the vorticity of the wind, ζ , and the spin of the earth's surface, the Coriolis parameter f, or

$$\zeta_a = \zeta + f.$$

The relative vorticity in turn is the sum of contributions due to shear and curvature, or expressed in natural coordinates

$$\zeta = \frac{\partial V}{\partial n} + \frac{V}{r}.$$

Here $\frac{\partial V}{\partial n}$ is the horizontal change in wind speed perpendicular to the flow, while $\frac{V}{r}$ is the wind speed divided by the radius of curvature of the flow. A positive sign is chosen where cyclonic shear or curvature is present. Thus, in zonal flow the relative vorticity is due mainly to shear ($\zeta = \frac{\partial V}{\partial n}$ as $r \to \infty$) while in other cases of highly curved flow there may be little in the way of horizontal shear. Here the vorticity will be due mainly to curvature. In rare cases both shear and curvature may approach zero over some limited area. But, in general, the relative vorticity equals zero at locations where shear and curvature contributions are of equal magnitude but of opposite sign. The locus of these points defines the zero relative vorticity line (ZRVL). Along this line the absolute vorticity equals the Coriolis parameter, or

$$\zeta_a = f.$$

The ZRVL is thus the boundary line encircling an area of cyclonic vorticity of the wind. In this discussion we shall restrict ourselves to the positive vorticity advection (PVA) side of the cyclone (or trough) at 500 mb due to the strong cyclogenetic response of the surface flow to divergence aloft under this side of the ZRVL. An example of the ZRVL encircling a mid-tropospheric circular cyclone is shown in Figure 3. Other significantly broad areas of zero relative vorticity flow at midlevels are probably restricted to the weak wind areas of the deep tropics near the ITCZ. ZRV flow is also thought to exist at midlevels in certain special vortices, such as in tropical cyclones outside the wall cloud area surrounding the calm eye, where contributions due to shear and curvature may cancel out in the strongly sheared and curved flow. Some mid-tropospheric high pressure cells may also possess such shear-curvature combinations as to cause an area of ZRV near the center on the equatorward side. In this paper the author attempts to show that deep, moist convection tends to develop in areas of ZRV, and specifically along the ZRVL on the PVA side of the cyclone. Said difficulty, at a given location, assuming ample moisture is available, convection tends to occur when midlevel relative vorticity changes from anticyclonic to cyclonic.

The Coriolis Parameter

The Coriolis parameter, f, varies with latitude by the relation

$$f = 2\Omega \sin\phi$$

where Ω is the spin of the earth (7.29×10^{-5} sec^{-1}) and ϕ is the latitude. f ranges from zero at the equator to a maximum of 2Ω or 14.58×10^{-5} sec^{-1} at the North Pole. Variation of f with latitude is referred to as $\beta = \frac{\partial f}{\partial y} = 2\Omega\cos\phi / a$ where a is the radius of the earth. For the purpose of this paper, a more convenient way to evaluate the change in f with latitude is to plot these changes on a graph as in Figure 4 or look at this variation in tabular form as in Table I. We then see that f changes in a rather linear fashion from f = 0 at the equator to 1×10^{-5} sec^{-1} at 4°N, and 2×10^{-5} sec^{-1} at 8°N, and 3×10^{-5} sec^{-1} at 12°N, etc. As we move north of 30°N this relationship gradually becomes less linear.

The Vorticity Equation

The vorticity equation is derived from the basic hydrodynamic equations of motion. In constant pressure coordinates the complete vorticity equation reads as follows:

$$\frac{d\zeta_a}{dt} = -\zeta_a \, div_p \mathbb{V} + \left(\frac{\partial \omega}{\partial y}\frac{\partial u}{\partial p} - \frac{\partial \omega}{\partial x}\frac{\partial v}{\partial p} \right) + \left(\frac{\partial F_y}{\partial x} - \frac{\partial F_x}{\partial y} \right).$$

Solving for $div_p \mathbb{V}$ and expanding the total derivative:

$$div_p \mathbb{V} = -\frac{1}{\zeta + f}\left[\left(\frac{\partial \zeta}{\partial t}\right)_p + \mathbb{V}\cdot\nabla_p \zeta + \omega\frac{\partial \zeta}{\partial p} + v\frac{\partial f}{\partial y} + \left(\frac{\partial \omega}{\partial x}\frac{\partial v}{\partial p} - \frac{\partial \omega}{\partial y}\frac{\partial u}{\partial p} \right) + \left(\frac{\partial F_x}{\partial y} - \frac{\partial F_y}{\partial x} \right)\right].$$

The terms within the brackets are usually referred to as the local change or tendency of vorticity, $\left(\frac{\partial \zeta}{\partial t}\right)_p$; the horizontal advection of vorticity (PVA or NVA term) $\mathbb{V}\cdot\nabla_p \zeta$; the vertical advection of vorticity, $\omega\frac{\partial \zeta}{\partial p}$; the latitude term $v\frac{\partial f}{\partial y}$, also written $v\beta$. The remaining terms in the parenthesis are the tipping terms and friction terms.

Divergence Caused by the Various Terms of the Vorticity Equation

The reason for introducing the vorticity equation, and later the continuity equation, into our discussion is to investigate the terms which cause divergence aloft and convergence near the surface and thus support the rising motion and active weather found along the ZRVL. The PVA term makes the largest contribution to divergence in the upper troposphere. This term has been successfully used by meteorologists for many years to help delineate areas with rising motion and precipitation. On the National Meteorological Center's (NMC) charts absolute vorticity isopleths are routinely available at the 500 mb level. Ideally we would like to evaluate PVA at upper levels near 250 mb rather than at the mid-trospheric level of "non-divergence" near 500 mb. The 500 mb level, however, integrates many important aspects of the flow both above and below, and experience has shown that using only one level near the level of non-divergence, such as in the old barotropic numerical model, will usually give good results. The central theme of this discussion of using the 500 mb ZRVL to link upper tropospheric divergence to surface frontal zones certainly confirms this postulation.

Using only the PVA term of the vorticity equation to explain divergence is of course rather crude, since the remaining terms, although normally very small as compared to the PVA term, do become relatively important in the narrow zone near and below the jet stream where the ZRVL and surface front are located. The tipping terms, containing both $\frac{\partial \omega}{\partial x}$ and $\frac{\partial \omega}{\partial y}$, will be large in this zone where large horizontal differences in vertical motion occur. Likewise, the variation of the winds with height from these terms containing $\frac{\partial v}{\partial p}$ and $\frac{\partial u}{\partial p}$ will also be large. The friction terms will also be important near steep speed gradients within the boundary layer as well as in the vicinity of the jet stream with its strong viscous shear. We are also familiar with the effects of terrain roughness differences in inducing divergence such as in the case of winds flowing parallel to a coast line.

The latitude term, $v\beta$, becomes important during strong meridional flow, as in the case of southerly flow ahead of a trough or cyclone. It is normally small, but its order of magnitude can approach the PVA term in cases of strong southerly flow over lower and middle latitudes where β is largest. In the case of strong southerly low level flow, it will cause convergence even up above the 500 mb level during ZRV flow, thus enhancing the contributions toward instability through introduction of low level moisture and heat. This term encourages the low level jet near the ZRVL to feed a deep, moist, convergent flow northward with minimum entrainment to sustain cumulonimbus convection which then is allowed to flare out into large anvils in the strongly divergent flow, caused by the PVA term, near the tropopause.

The vertical advection term, $\omega \frac{\partial \zeta}{\partial p}$, must also be large within the frontal zone, especially in the middle portion of the troposphere where ω is large. The vertical gradient of vorticity above the surface frontal zone is very large throughout the troposphere as the character of the flow varies from strongly cyclonic near the surface through neutral (zero) along the 500 mb ZRVL to anticyclonic near the tropopause. The importance of the remaining term of the vorticity equation, the local change in vorticity $\left(\frac{\partial \zeta}{\partial t}\right)_p$,

is not entirely clear, but it is likely to also be important at various times and levels in the life cycle, from development through decay, of the cyclone.

The foregoing notwithstanding, the largest contribution to divergence in the upper troposphere is generally agreed to be the PVA term. Its effects cover the entire area between the trough line and the downstream ridge line. These effects, however, are usually focused strongly into an often crescent-shaped upper divergence pattern along the jet stream. This crescent-shaped upper divergence maximum is produced from the interaction of the advecting wind with the vorticity field via the dot product $\mathbf{V} \cdot \nabla_p \zeta$. The

vorticity centers, as a rule, are of circular or oval shape and in their intensity depend somewhat on the strength of the advecting wind. The maximum divergence occurs where the advecting wind blows strongest along the steepest vorticity gradient. This is the case near the inflection points along the ZRVL. This strongly focused upper divergence pattern caused by the PVA term in turn, through the continuity equation, induces rising motion at mid levels and pressure falls and convergence in the boundary layer, and if low level instability and air mass contrast have been sufficiently modified, a strong, line-shaped shear zone or cold front of the classical Margules-Bjerknes type will be produced. The initial upper divergence can thus be thought of as a triggering mechanism which in turn increases the divergence (or convergence) caused by the remaining terms of the vorticity and continuity equation as the cyclone evolves through its life cycle.

The Continuity Equation

The effects of the continuity equation were briefly mentioned above. This equation states the principle of conservation of mass. The continuity equation plays an important role in explaining divergence within the atmosphere, especially in the region near the jet. The continuity equation takes the following simple form in pressure coordinates:

$$div_p \mathbb{V} = -\frac{\partial \omega}{\partial p}$$

According to this relationship we can expect divergence to occur where the vertical velocity increases or decreases rapidly with height, such as near the earth's surface and near the tropopause. The well-known phenomenon of convergence within the boundary layer in surface cyclones and troughs must therefore, besides showing the effects of friction, also be a manisfestation of the continuity equation at work.

Importance of Stability and Moisture

Stability and moisture considerations are important in the development of weather associated with a given upper divergence pattern above the 500 mb ZRVL. Strong systems that are also slow moving will decrease stability by imparting heat and moisture into the lower convergent flow and through stretching and rising motion will promote mid and upper level cooling. Through deformation low level convergence will also cause increased baroclinicity and strengthening of the upper jet. This strengthening will continue until the occlusion process has run its course and the lessened baroclinicity of the more vertically stacked, occluded cyclone will usually produce weakening. Weakening may also occur as the cyclone moves into regions of habitually stable, dry air. Using the ZRVL at 500 mb as a tool for tracking fronts and judging their intensity will thus be most effective where instability allows for better coupling of the surface layers with the divergence aloft. Such would be the case where heating and moistening from below would favor instability as over the mid and high latitude oceans in winter and over the continents having suitable moisture in summer. In some parts of the world the stability of the lower troposphere is so overpowering that it requires a very intense upper divergence pattern to produce much of reflection in the surface pressure field and attendant weather. Thus, where instability and moisture supply are high, the ZRVL and surface fronts usually coincide and move across the map together, whereas in a stable environment with fast flow aloft the 500 mb ZRVL will often outrun the surface cold front. Then the cold front will usually weaken as the upper support has been removed. This support, however, may reappear as a new band of strong winds aloft cause the redevelopment of the ZRVL back near the old front. Examples of fast moving ZRVL's travelling out ahead of surface cold fronts in a stable environment would be springtime squall lines across the southern and central United States and wintertime systems moving into areas dominated by the subtropical high pressure cells.

Use of the ZRVL in Forecasting

The relationship of the ZRVL to specific weather patterns will now be discussed. Systems ranging in size from large-scale, wintertime frontal systems with the well-developed Rossby waves down to the smaller-scale, weaker-flow feature of mid latitude summer or of the tropics will be considered. This relationship involves the use of the 500 mb ZRVL during PVA as a marker of the divergent zone aloft accompanying the upper jet and of the associated reflection in the surface cold fronts, squall lines and other signs of low level convergence.

Since the NMC 500 mb height and vorticity charts contain only absolute vorticity isopleths, one must first subtract the local value of the Coriolis parameter to reveal the relative vorticity field. To find the ZRVL on the PVA side of the cyclone (or trough), follow the steps given below:

1) Outline PVA areas to find the "semicircle" of the cyclone where the flow is from trough to ridge. Note that many troughs have considerable tilt away from the usual north-south axis. A negative tilt trough has its axis tilted from southeast to northwest. Negatively tilted troughs usually have a very strong PVA pattern together with favorable low level moisture inflow. The intensity of a system can be judged from the packing of the vorticity isopleths and the strength of the advecting wind. As a rule of thumb, an analyzed absolute vorticity value greater than twice the local Coriolis parameter value indicates a strong system. An advecting wind of 50 knots or greater at 500 mb would likewise be considered strong during summertime or over low latitudes. A higher threshold should be used in winter. The angle that the advecting wind makes with the vorticity gradient, as discussed earlier, also is important. Some uncertainty is present in analysis and forecast charts, so an indication of neutral PVA, where upper flow and vorticity isopleths are in phase, should not necessarily rule out precipitation. When encountering neutral PVA, remember that the depicted vorticity isopleths or the NMC charts are <u>absolute</u> vorticity and the change in pattern resulting from construction of <u>relative</u> vorticity isopleths may be significant. Drawing in the ZRVL on the wind field (contours), as described in step 2, will then tell whether there is PVA of relative vorticity, which is after all what the vorticity equation demands. Caution is also advised in judging these often intense, stationary and mature cyclones with near neutral PVA, since they are often important producers of heavy precipitation and severe weather, as some minor undetected pocket of PVA rotates around its fringes.

2) After the PVA areas have been outlined on the absolute vorticity chart, enter the ZRVL by connecting points where the Coriolis parameter equals the absolute vorticity values using the values found in Table I. It will be useful to commit these f- values and their corresponding latitude circles to memory. South of the United States recall that f increases one number for each four degrees of latitude. Thus 20°N would have an f- value of 5 ($\times 10^{-5}$ sec^{-1}). Across the

United States it may be easier to associate an f-value with a given city or geographical landmark such as for example 6 for Key West, 7 for Cape Canaveral, 8 for Phoenix, 9 for San Francisco, 10 for central Lake Ontario, 11 for the U.S.-Canadian border west of Lake Superior, 12 for southern Alaska Panhandle, 13 for St. Lawrence Island in the Bering Strait and 14 for the area just north of Point Barrow.

The two simple steps outlined above thus gives us the line we are interested in, namely, the line along which points will experience both PVA in the upper troposphere and zero relative vorticity flow at mid levels.

The Limited Fine Mesh (LFM) and the 7-layer Primitive Equation (PE) "baroclinic" models both forecast the vorticity field quite well to 48 hours whereas the quality of the "barotropic" model usually degenerates rapidly after the first 12-hour forecast. All models depict the absolute vorticity field with isopleths given in even numbers.

Some Typical Cyclone Configurations

The following figures show the ZRVL superimposed on typical absolute vorticity patterns. A sample case of an eastward moving cyclone is shown in Figure 5. A southeastward moving system is depicted in Figure 6. A negative tilt northeastward or northward moving cyclone may appear like the one in Figure 7. Referring back to the circular pattern of Figure 3, one can use this example as a general case of a circular vorticity pattern and draw in the ZRVL on the PVA semicircle, which can be determined from the flow direction in the large scale wind field and the direction in which the cyclone is propagating. Once the ZRVL is located on the NMC 500 mb analysis and prog charts, the meteorologist can both hindcast and forecast. Note that the ZRVL usually coincides with the upwind edge of the large cirrus cloud bands on the satellite pictures and with the strong surface fronts or squall lines as determined from synoptic surface maps. The vorticity charts can thus be used to check the initial analysis and to predict the future positions and intensity of frontal systems.

The ZRVL and the Jet Stream

The 500 mb ZRVL also reveals much about the upper tropospheric jet stream and the various phenomena associated with the jet. The ZRVL will help locate the jet on both the initial analysis chart and on the prog charts, since the ZRVL is located underneath the jet stream and above the surface front. The strength of the jet and the horizontal shear near it can be judged by the associated vorticity field and the curvature of the ZRVL. Information about certain tropopause characteristics can be deduced from the patterns. A strong jet with strong cyclonic curvature will have a high and cold tropopause along the jet and to the right of it within the ridge. To the left of the jet, strong subsidence at upper levels is causing the tropopause to slope down steeply toward the center of the cyclone. Here the tropopause is relatively low and warm and free of cirrus. The ZRVL will locate this jet stream and some of the aviation hazards associated with it.

The ZRVL and CAT

The ZRVL will mark areas of strong upper divergence, which induce cumulonimbus growth when moisture is available. If no moisture is available or coupling with the lower moist layers is poor due to high stability, the ZRVL position may still be of value. Areas of clear air turbulence (CAT) are known to be located in strongly sheared flow in the vertical as well as horizontal. These areas often coincide with the zone above the 500 mb ZRVL, particularly in regions with strong curvature and shear. There are also reports of CAT from areas with strong negative vorticity advection (NVA) and anticyclonic curvature, and many reports come in from areas where it is altogether difficult to find any particular synoptic reason for the occurrence of CAT. Many cases, however, occur in cyclogenetic areas with rapid surface development as pointed out by strong cyclonic curvature of the ZRVL. To the left of a strongly cyclonically curved ZRVL, subsidence at upper levels is very large and strong vertical currents extend down from the lower stratosphere. These currents may bring ozone in strong enough concentrations to affect passengers and crew in aircraft flying above 40,000 feet. In some very intense cases this subsidence has penetrated the entire troposphere resulting in high surface ozone concentrations and concomittant vegetation damage. Such stratospheric intrusions typically occur just behind the ZRVL during tornado and severe thunderstorm occurrences in the clear wedge of an occluding cyclone.

Downslope Winds

The same conditions which cause the turbulent upper flow discussed in the previous paragraph will cause downslope winds which at times reach damaging proportions in mountainous areas. There are two main types of these katabatic winds and both occur during strong differential vorticity advection at upper levels. The NVA type is often of the warm Chinook or Santa Ana variety with very stable, anticyclonic flow throughout the majority of the troposphere. The strongest winds occur close to the surface. In contrast to the PVA cases, these winds usually are strongest at night and during early morning since daytime heating causes an upward transfer of momentum. The second or PVA class of katabatic winds is the most violent. These winds are cyclonic at low levels with a surface frontal zone involved. The frontal zone may not be easily recognized initially due to terrain effects. The ZRVL can often flag these cases well ahead of time and thus help the meteorologist forecast a zone of violent winds. Intensity can again be judged from the PVA pattern though there are cases of strong downslopewinds with near neutral PVA along a west to east oriented ZRVL to the south of a stationary cyclone. The eastern slopes of the Rockies are particularly susceptible to these downslope winds. Downslope winds occur in most mountainous areas of the world outside the deep tropics. Even a minor downward slope in the terrain underneath the ZRVL will cause some acceleration of the winds. The large cold season dust and sand storms of the desert southwest and the high plains states are such examples. Even over flat land or over the oceans do we experience strong winds near a frontal passage as the ZRVL moves across the area. Increased instability during the vertical stretching of the air mass and a downward transfer of momentum from the band of the cyclone's strongest winds aloft are involved in these cases. As can readily be seen from the output of the LFM model, along the ZRVL during PVA is the only place where the entire deep troposphere experiences strong upward motion.

Fire Weather Dangers near the ZRVL

Due to terrain effects the weak fronts of summer are often hard to track or locate in mountain regions. The ZRVL will locate these indistinct fronts and predict their future movement and intensity changes. Fire weather meteorologists must thus be especially aware of these unseen fronts since they may cause rapid blow-ups of fires due to the gusty, dry winds and thereby endanger personnel on the fire lines.

The Intensity of Fronts

In evaluating the intensity of numerous fronts, the author has come to the conclusion that it is possible to label a front, or segment of fronts, solely by computing the divergence aloft contributed by the PVA term across a 5 degree wide interval centered on the ZRVL. Computers can do these computations and assign an intensity number to a given segment of a front. Using the 500 mb wind and vorticity data will give very acceptable values. Ignoring the other terms of the vorticity equation does not appear to be too serious an omission as these terms are somewhat proportional to the PVA term. Again, relative vorticity values should be used rather than absolute ones. As an example, a frontal segment near 43N ($f = 10 \times 10^{-5}$ sec^{-1}) could be assigned an intensity number proportional to the divergence caused by a 30m sec^{-1} wind blowing at 135 degrees to the vorticity gradient vector measured in finite difference form at 3.5×10^{-5} sec^{-1} over 5.55×10^{5}m. This product has to be divided by $f + \zeta$ where $\zeta = 0$ at the ZRVL.

In computing the dot product, $\cos 135^{\circ} = -0.707$. This sample calculation is shown below.

$$div_p \mathbb{V} = -\frac{1}{f}\left(\mathbb{V}\cdot\nabla_p\zeta\right) = \left(-\frac{1}{10\times10^{-5}\,sec^{-1}}\right)\left(30m\ sec^{-1}\right)\cdot\left(\frac{3.5\times10^{-5}\,sec^{-1}}{5.55\times10^{5}\,m}\right)\left(-0.707\right) =$$

$$= 1.35\times10^{-5}\ sec^{-1}.$$

The ZRVL and Precipitation

Perhaps the greatest value of the ZRVL is in predicting cloudiness and precipitation. Precipitation depends mainly on the amount of precipitable water present and the rate of PVA acting on this moisture. For precipitation to occur when there is a moderate to strong PVA pattern, 10mm (0.4 inch) of precipitable water is generally necessary. If there is less available moisture, the only sign will be some cloudiness, usually of the cirrus and altocumulus varieties, oriented along the ZRVL as it passes. It is not uncommon to see profuse virga, falling out of only minor cloud elements along the ZRVL at times when moisture is marginal. Such anomalous coalescence is thought to be induced by atmospheric electricity.

Vertical Structure of Moisture and Winds

The vertical structure of the moisture and wind distribution within the atmosphere near the ZRVL has an important effect on the nature of weather. Along the front, shallow moist layers in an otherwise dry atmosphere will cause the precipitation to sublimate or evaporate, and the cooled air will cause vertical currents, which, upon hitting the earth's surface, spread out horizontally generating gusty winds stronger than the mid tropospheric winds would suggest. Where the winds aloft are very strong and the lapse rate steep, a moist lower atmosphere with dry middle and upper layers may result in severe thunderstorms along the ZRVL. In this case both downward momentum transfer and evaporative cooling may combine to cause damaging winds.

High Precipitable Water Values

If the entire troposphere has been moistened through the effects of rising motion and evaporation from the underlying surface or precipitation, any weak disturbance moving into this high moisture environment may cause very heavy rain. Such precipitation is usually not accompanied by excess windiness. Soundings in this nearly saturated warm air mass may indicate 35 to 50 mm (1.50 to 2.00 inches) of precipitable water during a summertime sounding over the continental United States or over tropical areas. Somewhat less moisture would be present in saturated soundings within air masses coming off the high latitude oceans in fall and winter when vertical mixing and instability are high. Moisture build-up in a summertime continental air mass can be accomplished under largely anticyclonic conditions. When maritime tropical air moves in over the continent, solar radiation supplies energy to allow evaporation from soils and vegetation. As much as 8 to 10 mm (.3 to .4 inches) of precipitable water can be added daily from mid-summer solar radiation on warm, moist soils. This additional moisture is then pumped into a deep layer during the diurnal heating cycle. Very intense rainfall of flash flood proportions may then occur as the ZRVL ahead of the next cyclonic disturbance moves into this reservoir of excess moisture. Flash floods often occur under weak flow conditions and a similarly weak 500 mb PVA pattern. The forecaster should therefore be on the alert when the ZRVL moves into a dormant, moist air mass with 35 mm (1.50 inches) or more of precipitable water. Stronger systems can cause flash floods with less available moisture.

Curvature and Orientation of ZRVL

The curvature and orientation of the ZRVL are important in explaining many aspects of the weather associated with the ZRVL. Cyclonic curvature of the ZRVL, as determined by the direction of the upper jet (or the surface flow in the warm sector of the cyclone) suggests an active front with a cold mid tropospheric cyclone and strong low level anticyclogenesis coupled with a developing surface low in the general area near the center of curvature of the ZRVL. Anticyclonic curvature of the ZRVL, in turn, denotes slow subsidence and warming as tropical air pushes poleward as a warm front. Warm fronts are most active when they closely coincide with the ZRVL, such as in an open wave cyclone.

There are times, however, when due to stability over the cold continents, the warm front remains far south of the ZRVL especially when occlusion has occurred at more northern latitudes. This warm front without upper air support can nevertheless still act as a low-level convergence zone for focusing heavy convective activity. The heaviest convection will occur where the warm front intersects the north-south oriented ZRVL.

The Occluding Cyclone

The occlusion process is a phenomenon which the numerical models, when used with the ZRVL, can predict with good accuracy. The occlusion process occurs very rapidly as a more vertical system develops. The ZRVL and the jet change curvature from anticyclonic to cyclonic and swing westward to the north of the cyclone during this period of very rapid development. Heavy, steady precipitation, often in the form of snow, suddenly breaks out to the north of the cyclone center along the ZRVL. Underneath this roughly east-west oriented curved segment of the ZRVL is a favored location for heavy snow. Affected ground stations may spend considerable time underneath this zone as the now-mature system's motion slows. How far north of the center the heavy snow zone will be found, depends on the intensity of the system (Fig. 8). The fact that the low level convergence takes place well north of a deep system suggests that the habit of placing the end of an occluded front into the center of the sea level cyclone is likely erroneous.

Squall Lines

The ZRVL is also helpful with squall lines. With fast upper flow in an expanding, intensifying cyclone, a squall line may propagate well out ahead of the surface front. Frequently this will be suggested by the ZRVL pushing past the surface frontal position. Then the precipitation will occur in the moist air well out ahead of the front. In other cases the ZRVL will remain stationary, such as when associated with a deep mature system, and the surface front will march on southeastward away from the ZRVL. This surface front or shear line is likely to weaken. If moisture is still sufficient, showers may then redevelop near the old "left-behind" ZRVL. In most cases when stability is favorable, the surface front and the ZRVL move together. The ZRVL is least trustworthy along the east to west extent of a cold front or stationary front which has nearly completed its southward push. This may suggest that the latitude term, $v\beta$, of the vorticity equation is one of the more important terms in determining divergence and support for surface fronts.

Tornado outbreaks often occur with the squall lines of occluded cyclones. Strong winds are present throughout the troposphere and moisture is abundant in the low level southerly flow. At middle and upper levels the ZRVL is expanding outward in a big arch over the lower moist flow. Aided by downslope motion off the Rockies and heating over the Plains, a wedge of clear air subsides to the surface from upper tropospheric levels behind the ZRVL. Severe thunderstorms with huge anvils blossom rapidly along the ZRVL as the dry, subsiding air in the clear wedge flows into the moisture. In these cases the LFM vorticity analysis and progs will usually predict the movement of the ZRVL with good accuracy. Timing the future progress of these intense squall lines using the ZRVL will thus help the forecaster to delineate important watch/warning areas.

The ZRVL with Southwesterly Flow Aloft

The most common orientation of the ZRVL is the one found with predominantly southwesterly flow aloft from trough to ridge. This configuration is particularly frequent in winter when the Rossby wave numbers are low. The tendency for continents and mountain ranges to anchor these troughs causes precipitation to fall in rather narrow zones underneath the upper jet. This anchoring phenomenon, together with moisture availability, explains much of the climatic variation in cloudiness and precipitation around the world as cyclone families associated with a wavy ZRVL travel northeastward. The poleward transport of heat and moisture is very extensive in this type of flow.

The ZRVL with Northwesterly Flow Aloft

During summer, the Rossby waves become weak and their numbers increase. The anticyclonic cells aloft become stronger and move northward of their wintertime positions. Smaller cyclonic disturbances travel along the fringes of these highs. Where moisture is abundant, heavy showers will occur along the ZRVL out ahead of these disturbances. During the mid summer months, a climatological upper anticyclone is anchored over the heated Rockies and Plains while an upper cyclone often persists over the cold Hudson Bay and Eastern Canada. This pressure configuration establishes a fairly strong northwesterly flow from southcentral Canada down across the northern Mississippi Valley and Great Lakes Region into the Ohio Valley and the middle Atlantic states. The plentiful Gulf moisture usually available, combines with this northwesterly jet to give frequent showers to the corn and dairy producing areas during the peak growing season. At times the upper jet may sharpen up and the winds at 500 mb reach speeds of 50 to 60 kt. In this flow a strong shear vorticity maximum will develop on the north side of the jet axis. Severe thunderstorms with strong downdrafts and resulting wind damage tend to occur along the ZRVL in these situations as the upper momentum mixes downward in this unstable environment. Flash floods are also possible especially as the ZRVL progresses southeastward into deeper moisture and weaker flow and the shear vorticity gradually evolves into the curvature variety.

The ZRVL with Easterly Flow Aloft

To the south of the upper anticyclone centered over the Rockies in summer, the flow over Texas may be out of the northeast at mid levels and, perhaps, from the southeast over Arizona. The ZRVL accompanying these weaker summertime disturbances can often be seen in satellite movie loops propagating through the moist, unstable low level flow in a fashion sometimes referred to as "thunderstorm outflow boundaries" (Hoxit et al 1978). This term suggests a random and unpredictable movement of these boundaries. However, the position of these boundaries can often be accurately forseen as much as 24 hours in advance by using the ZRVL and the LFM prog charts. The more intense systems duplicate the stronger synoptic scale disturbances in that a cyclonically curved ZRVL segment may produce couplets of meso highs and lows. This may happen even when soundings indicate saturated air through a very deep layer. Evaporative cooling cannot then explain the formation of the meso highs. Rather, a dynamic origin induced by the accumulation of mass in these areas of strong subsidence and low hydrostatic equilibrium is likely. The shape and orientation of the ZRVL in cases of northeasterly, easterly, and southeasterly upper flow are a little more difficult to visualize since meteorologists do not expect "fronts" out to the southwest, west or northwest of a disturbance. Such is the case also for easterly waves to the south of the large subtropical highs where the flow is from the east throughout the major portion of the atmosphere. Shallow easterly waves, where the flow rapidly turns westerly with height, would however have the convection to the east of the upper cyclone center.

The ZRVL During Summer Monsoon

Rainfall during the so-called "summer monsoon season" to the south of the continental upper anticyclones is usually difficult to predict since the weak disturbances causing these showers are difficult to track. The showers typically occur well out ahead and to the west of these disturbances. On a typical monsoon afternoon in Arizona, for instance, showers develop over the mountains in response to very intense surface heating in the moderately moist air mass. Satellite pictures and radar composites usually show more activity than the next morning's 24-hour rainfall totals indicate. In these cases a synoptic triggering mechanism is lacking. The following afternoon, this trigger, in the form of the ZRVL, may be present. Thus in spite of similar appearing satellite, radar, and stability data, rainfall totals will be substantially higher with rains lasting into the night in the valleys. A much more efficient recycling of atmospheric moisture thus seems to occur along the ZRVL. With strong PVA across the ZRVL and with high precipitable water values, flash flooding becomes likely in the deserts. Some typical ZRVL orientations during monsoon rains in Arizona are shown in Fig. 9.

Orientation of ZRVL with Respect to Moisture Sources

Since the low level convergence will tend to gather in moisture and concentrate it ahead of and beneath the ZRVL along the surface front, the orientation of the ZRVL with respect to moisture sources becomes important. When the ZRVL is oriented southeast, from the Gulf of Mexico or Atlantic, to northwest, heavy rain may occur in the Rocky Mountain foothills of Montana, Wyoming, Colorado and South Dakota. Many East Coast and Appalachian heavy precipitation events have similarly oriented ZRVL's bringing in low level moisture from the warm Gulf Stream waters offshore. Some examples of various ZRVL curvature and orientation types are shown in Fig. 10.

The ZRVL and Meso Scale Features

The length of the ZRVL changes seasonally from the long bands several thousand miles long accompanying the strong Rossby waves of winter to the shorter segments of meso scale length with the weaker summertime flow. These shorter segments can, however, produce significant rainfall when precipitable water is high and moderate PVA is present. In most parts of the country, the LFM model resolves these smaller scale vorticity patterns quite well out to 24 hours and beyond. The LFM vorticity progs together with precipitable water data from the NMC charts or the actual soundings are therefore very valuable tools in predicting such phenomena as flash floods. The relatively poor performance of the LFM QPF output with some convective systems may be partially caused by the way the model diffuses the moisture field horizontally among the grid points during the smoothing process. Flash floods often occur at night when the low level flow is quite laminar and favorable for advecting very highly concentrated moisture often from local sources. This moisture is then channeled and set off by terrain influences into developing convection along a slow moving portion of the ZRVL.

Cloud Types and Vorticity Field

The mid tropospheric vorticity field and associated vertical motion and stability exert a strong influence on cloud patterns and types. In summer, mid level anticyclonic conditions over the continents usually are accompanied by enough surface heating and mixing to weaken or wipe out subsidence inversions and to diffuse shallow moisture with resulting clear skies or scattered fair weather cumulus cloudiness during daytime hours. Over the oceans in summer and over the continents in winter, when there is little heating from below, stratiform clouds, fog and drizzle may result. Cirrus cloudiness is also usually associated with mid level anticyclonic flow. It must be remembered that even though we refer to anticyclonic conditions, we may actually have cyclonically curved flow as long as the anticyclonic shear is overpowering. This would be the case along and to the right of a cyclonically curved ZRVL where cirrus may be very profuse. The greatest amount of cirrus occurs during PVA in the region from the ridge line to the approaching ZRVL when rising motion and moistening of upper layers are increasing. Middle cloudiness usually develops along the ZRVL during PVA, and large cumulonimbus towers spring up right on the ZRVL when there are adequate PVA and moisture and good coupling with the surface layers. Behind the ZRVL, upper level subsidence begins as the tropopause rapidly lowers and the cirrus disappears. In the large mid tropospheric cyclonic area behind the ZRVL, skies will often be clear. However, where air mass modification is intense, such as over open water in winter, steam fog and open cellular convection will develop. Low level convergence and instability may also cause heavy showers in the central core of deep, especially moist cyclones. Instability showers with small hail often occur in this environment. The large area under NVA is usually characterized by mostly clear skies.

Temperatures and the Vorticity Field

Not surprisingly, it is possible also to use the ZRVL in temperature forecasting. Since the ZRVL at 500 mb usually coincides with the surface cold front, it will delineate the leading edge of a somewhat cooler air mass. A quick inspection will verify the high correlation between vorticity and thickness isopleths. Vertical motion is linked very strongly to the vorticity field and changes in same. Vertical motion in turn is very quickly reflected in temperature changes in the free atmosphere, where motions are largely adiabatic, and hence in the thickness field. Radiative transfers and mechanical mixing of winds and vertical air currents will help decide how much of this warming due to subsidence--or cooling due to rising motion--will show up as surface temperature changes. These are complicated processes involving many variables such as ground albedo and low cloudiness, soil moisture, heat conductivity and storage in soils, low level atmospheric stability, pressure gradient, slope of terrain, to mention a few. Horizontal advection of colder and warmer air is of course also involved. These are all processes with which forecasters are familiar, so they will not be discussed in any detail here. The main point the author wants to bring across is that the ZRVL can be helpful in temperature forecasting, especially when the analysis of fronts is uncertain, such as in mountain regions, or with the summertime indistinct fronts. As a rule, the best correlation between 1000/500 mb thickness and surface temperatures is found with well mixed continental air masses. Especially good correlation exists at high altitude mountain stations. Stations located at lower elevations, especially in moist valley locations with fog or snow cover in winter, may experience extended periods of chilly weather during anticyclonic conditions with warm air aloft and thus show very poor correlation with the high thickness values over the area. In contrast, at the same time nearby mountain areas may enjoy more typical warm and dry conditions associated with mid level subsidence.

Numerical Guidance Over the North Pacific

The preceding discussion of the ZRVL has been aimed mainly at forecasters who have access to good upper air data and numerical guidance. The use of the ZRVL concept in data-sparse areas requires more careful use of satellite and conventional data. Based on daily evaluations by the author over the last year, the quality of the output of the 7-layer PE model across the north Pacific appear to be of surprisingly good quality and thus is an excellent tool to use in conjunction with the ZRVL technique. The generally good quality of the progs over the Pacific can probably be traced to the relatively high density data upstream over Asia and the NMC procedure of using the previous 12-hour forecast as a "first guess" of the initial analysis. As a rule, very little flow originates over the data-poor areas to the south. In addition, there is an abundance of aircraft wind and temperature data (Aireps) available near the 250 mb level along the major air lanes to the Far East and Australia. Satellite wind estimates from cloud displacements have also added much to the quality of the analysis over the Pacific in recent years. The new TIROS N vertical sounding data also appear to be improving the upper air analysis.

Usefulness of the ZRVL near Hawaii

The usefulness of the ZRVL technique to the forecasters at the Honolulu National Weather Service Forecast Office would be somewhat limited and mainly in the form of aiding in tracking cold fronts moving southeastward toward the Islands in winter. The vigor of these fronts can be deduced from the intensity of the vorticity center behind the ZRVL and the rate of PVA as judged by the strength of the advecting wind and the packing of the vorticity isopleths. Moisture availability, which often is a limiting factor over the continents, is normally not a problem near Hawaii. The low level heat and moisture drawn into a system as well as the stability and moisture modification taking place inside the cyclone itself are proportional to the strength of the system.

The often erratic movement by fronts approaching the Hawaiian Islands is fairly well predicted by the ZRVL of the PE model. In addition, the intensity of shear lines or fronts can also be judged by whether the ZRVL is forecast to coincide with the shear line. There are many cases when the surface shear line will tend to continue moving southeastward while the ZRVL stalls or redevelops farther northwest. Such a shear line will normally weaken with respect to accompanying winds and weather. The ZRVL is even more useful with Kona type storms and cut-off lows. Here the ZRVL helps delineate the area relative to the cyclone center where heavy rain and thunderstorms will occur.

Some limited use of the relationship between the ZRVL and the jet stream may be possible near Hawaii. Good correlation between strong mountain top winds and the ZRVL has been noted. When the ZRVL foretells an unusually intense PVA episode, strong downslope winds will usually follow. The knowledge that a high incidence of CAT occurs along a strong cyclonically curved ZRVL may likewise prove useful in SIGMET issuances. In addition, the preponderance of cirrus to the right of the ZRVL, and the lack of it to the left of this line, may prove helpful when forecasting cirrus for the astronomers working at the observatories on the Big Island and Maui. Of course, the proximity of the Hawaiian region to the 15°N boundary of the PE model introduces uncertainties which are difficult to recognize on the prog charts.

The ZRVL technique is also helpful in analyzing the Pacific surface chart. An analyst's confidence in his frontal analysis can be aided when the ZRVL indicates the front has upper support. The ZRVL can also confirm trends of frontogenesis or frontolysis. Satellite pictures may be difficult to interpret in these cases as old cloud bands slowly fade while the new fronts take over. The progged position and intensity changes of the ZRVL will usually forecast such developments.

Conclusion

The author does not suggest that the ZRVL is a panacea for all Pacific Region forecasting ills. Many difficulties persist. In Hawaii the low level easterlies are frequently overlain by upper westerlies with the change in direction near 500 mb. This situation creates obvious problems because using the ZRVL assumes that the 500 mb flow is representative of a major portion of the troposphere. The ZRVL, however, manages to be useful in most such cases. With a weak flow pattern and near zero relative vorticity over the Hawaiian Islands there will continue to be many cases when trade wind cumulus will suddenly destabilize producing showers which were not foreseen by the ZRVL technique. The state of the art has not yet reached the point where the numerical models can resolve these weak disturbances particularly when they approach from the data-sparse areas to the east and southeast.

Over the continental United States applying the ZRVL concept to the relatively dense grid of the LFM model will supply answers to many of the forecast questions briefly touched upon in this paper. The computer will in seconds integrate the terms of the continuity and the vorticity equations. These terms, as we have seen, simultaneously cause divergence and convergence at the various levels of the atmosphere in a very non-linear fashion so as to affect the life cycle of the cyclone from development to decay. The computer also generates very useful QPF values. The ZRVL concept is only meant to supplement these computer models and to help the forecaster extract that "little bit additional" from the numerical products. Surface cold fronts are very unique and dynamic features of our atmosphere. The ZRVL at 500 mb will mark these fronts with greater accuracy than any other conventional method. For timing precipitation and wind events, forecasting floods and storms of many types and scales, even during the weak patterns of summer, the ZRVL will provide the field forecaster a powerful tool, enabling him to get the best out of his numerical guidance.

This report has attempted to provide the field meteorologist a basic introduction to the use of the ZRVL in synoptic forecasting. Nearly ten years of gradual learning and application of this technique convinced the author that the ZRVL concept, when used cautiously, will improve one's knowledge and understanding of the cyclone model, and thereby lead to better analyses and forecasts.

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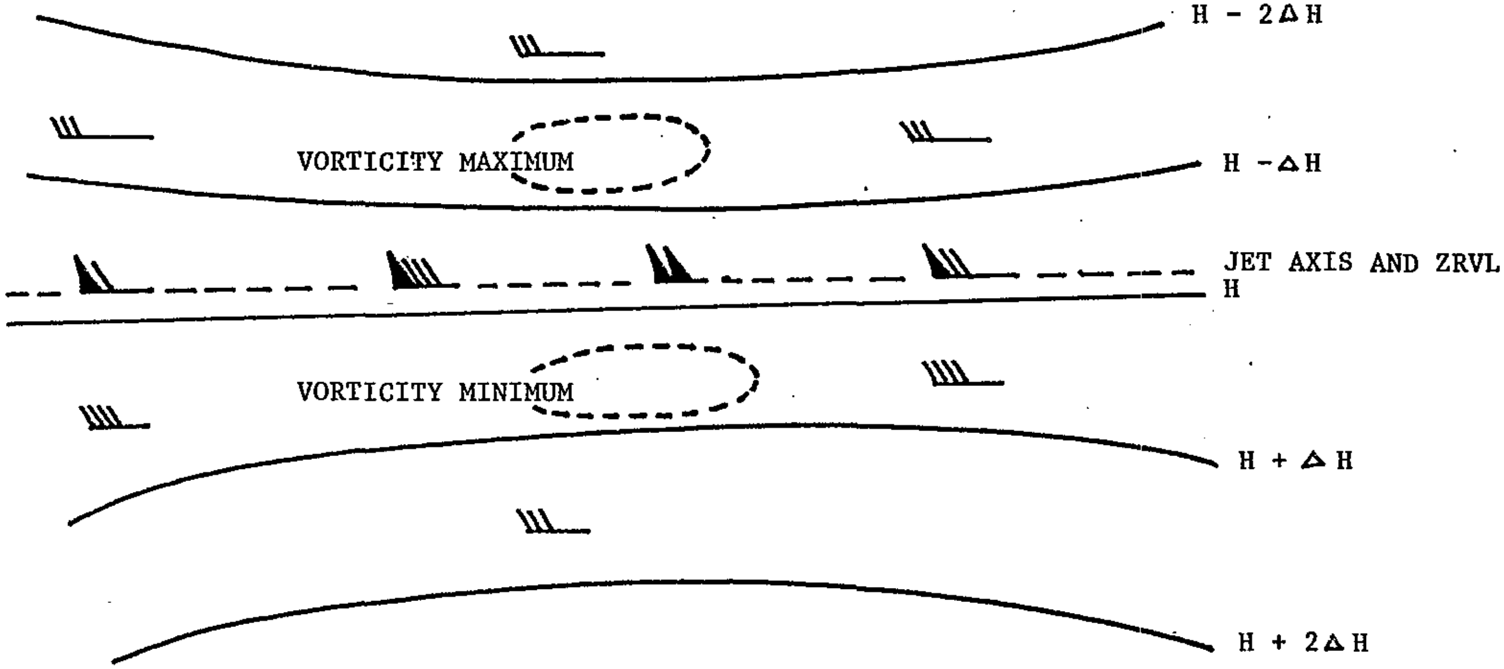
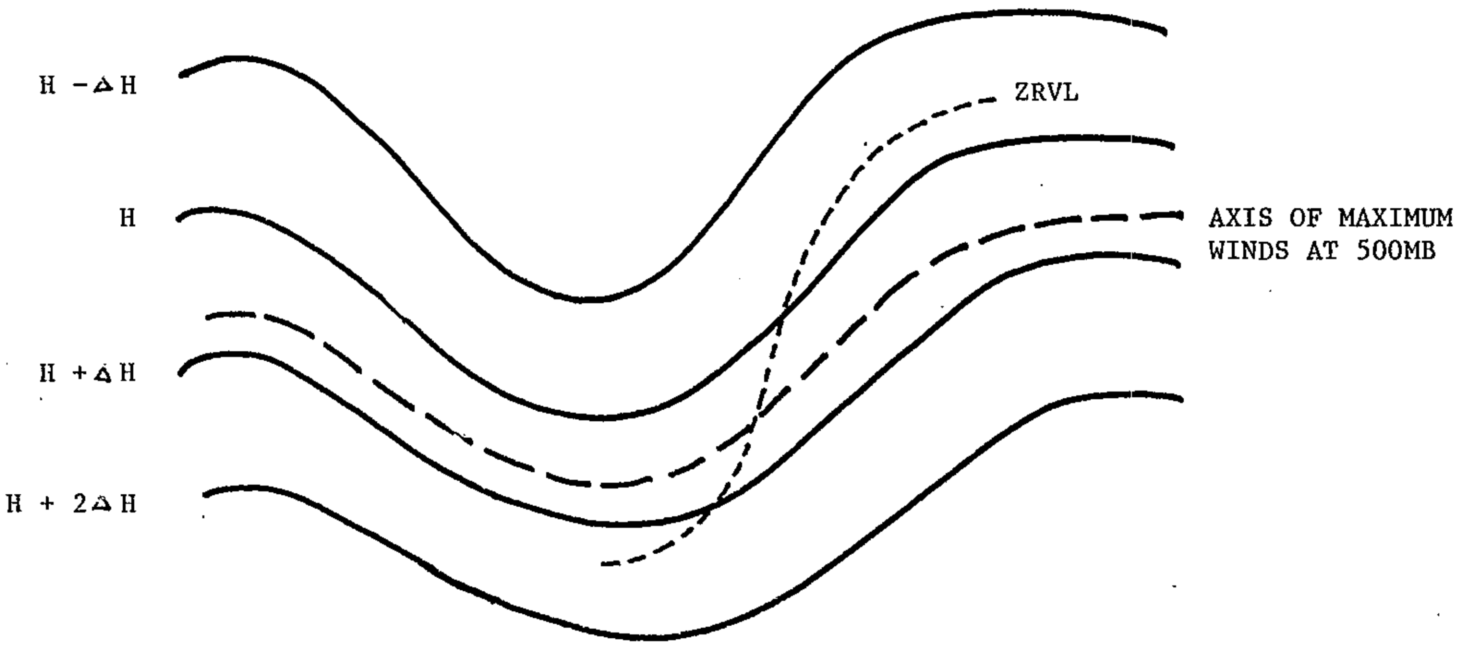
Figure 1



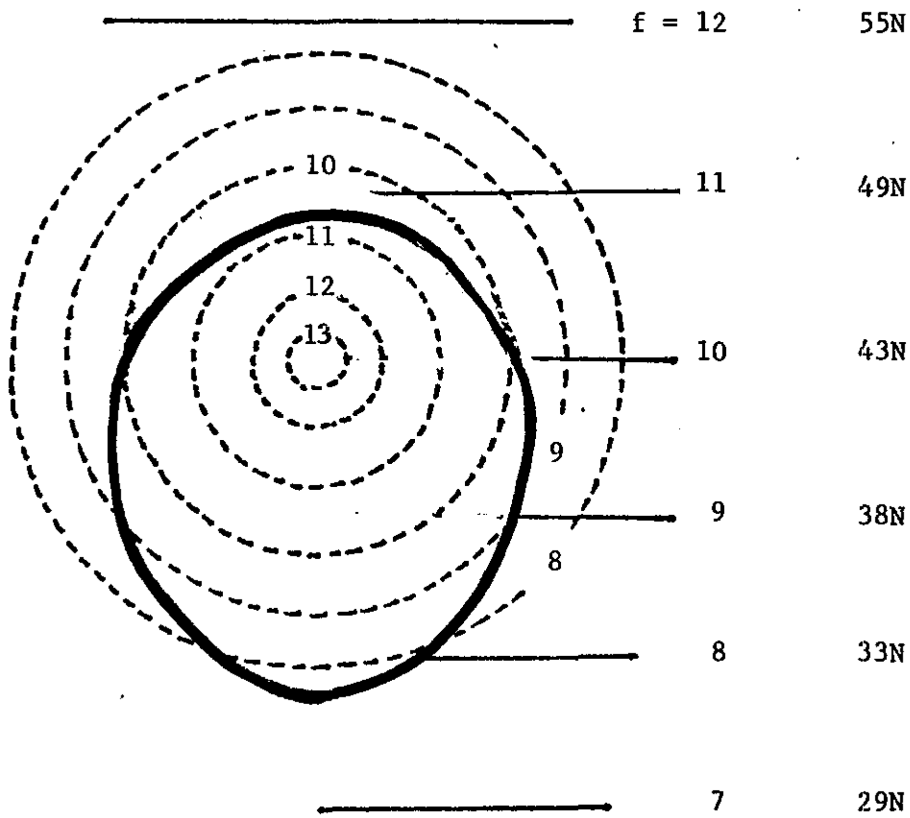
The approximate location of the vorticity maximum and the minimum and the ZRVL associated with an upper zonal jet stream possessing strong horizontal shear and negligible curvature.

Figure 2



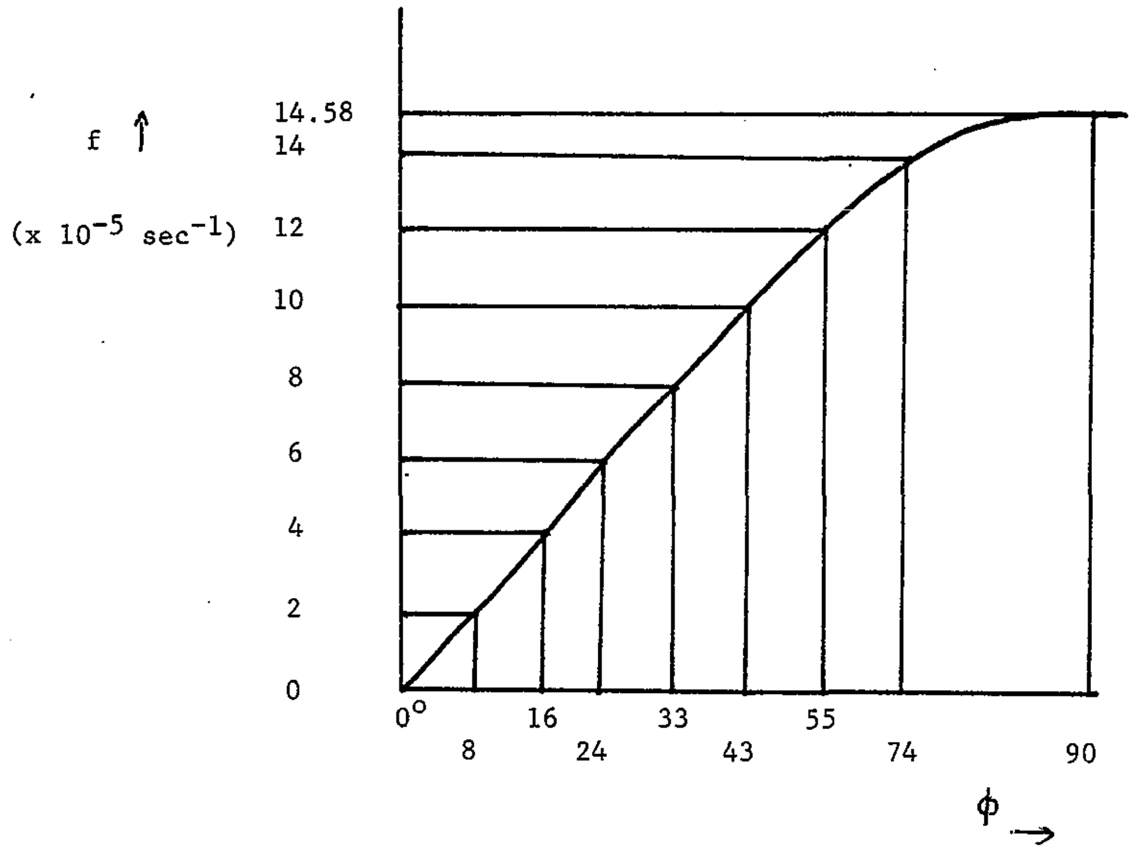
A typical sinusoidal 500 mb flow pattern. The ZRVL has been drawn in along the portion of the flow from trough to ridge. This ZRVL configuration is of the type usually found with an "open wave" cyclone where the ZRVL delineates the strongly divergent flow with the upper jet and the convergence induced near the surface.

Figure 3



A circular-shaped absolute vorticity pattern with the egg-shaped ZRVL drawn in. The ZRVL is the boundary line enclosing an area of cyclonic vorticity. The "PVA semicircle" of the ZRVL, which would usually coincide with the active surface front, thus would depend on the direction of the large scale flow in which this pattern is embedded. Latitude lines and corresponding Coriolis parameter values (x 10^{-5} sec^{-1}) have been included in this and the following figures.

Figure 4



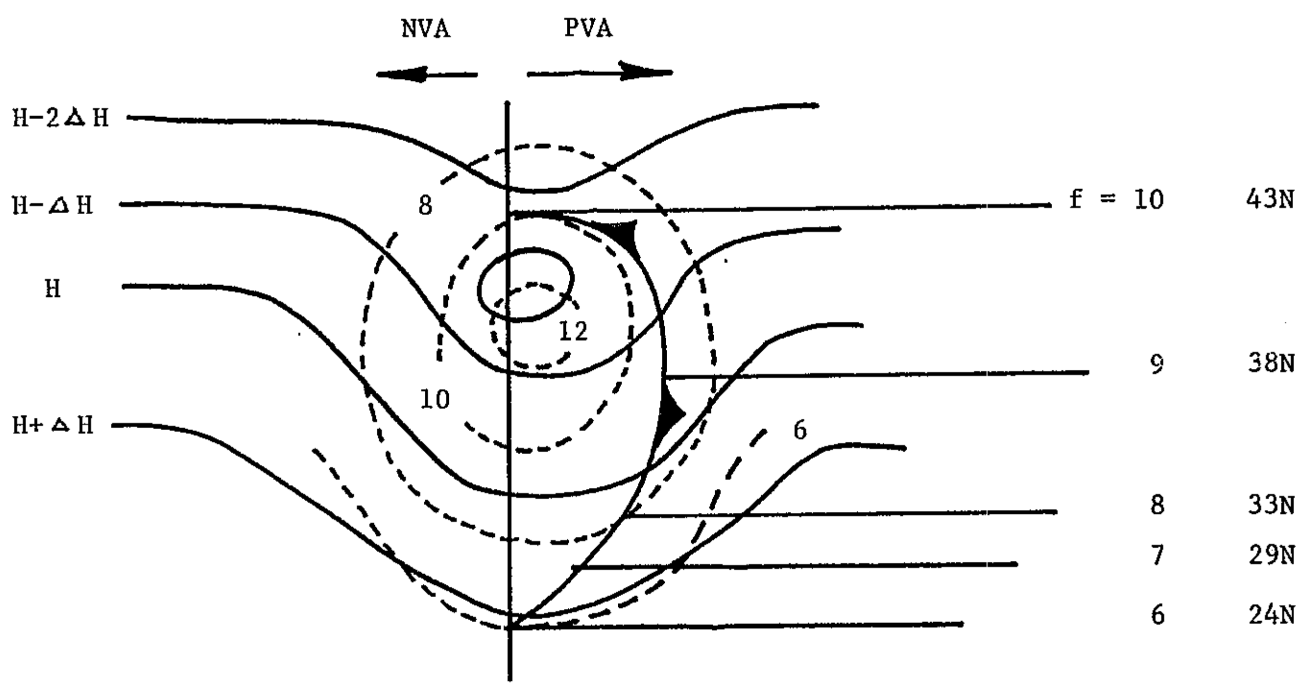
Graph showing latitudinal variation in the Coriolis Parameter, $f = 2\Omega \sin \phi$, in the northern hemisphere.

Table 1

Same information concerning latitudional variation in Coriolis Parameter, $f = 2\Omega \sin \phi$, as shown in Figure 4. For each f-value ($\times 10^{-5}$ sec^{-1}) is given the corresponding latitude circle, .

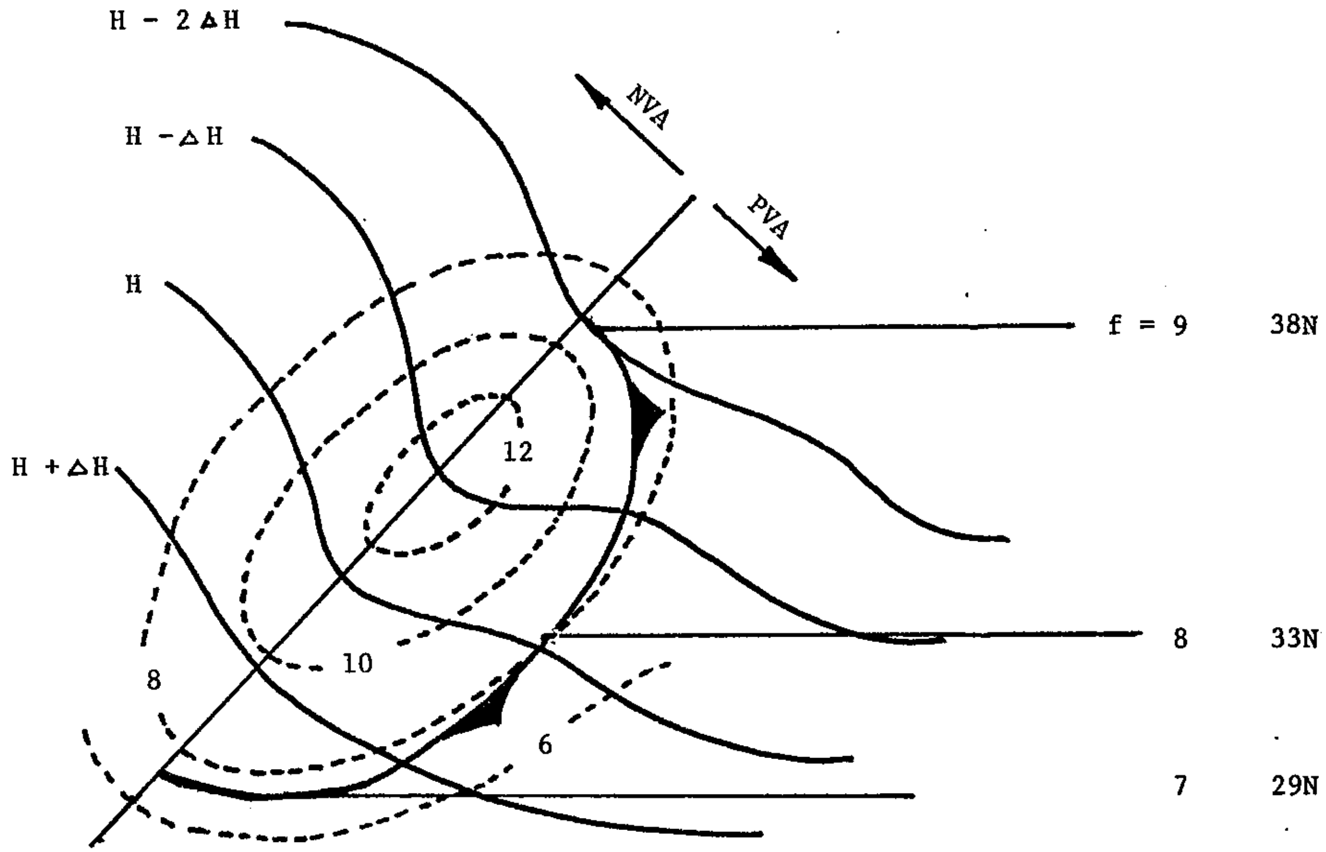
f	ϕ	f	ϕ
0	0	8	33.3
1	3.9	9	38.1
2	7.9	10	43.3
3	11.9	11	49.0
4	15.9	12	55.4
5	20.1	13	63.4
6	24.3	14	73.7
7	28.7	14.58	90.0

Figure 5



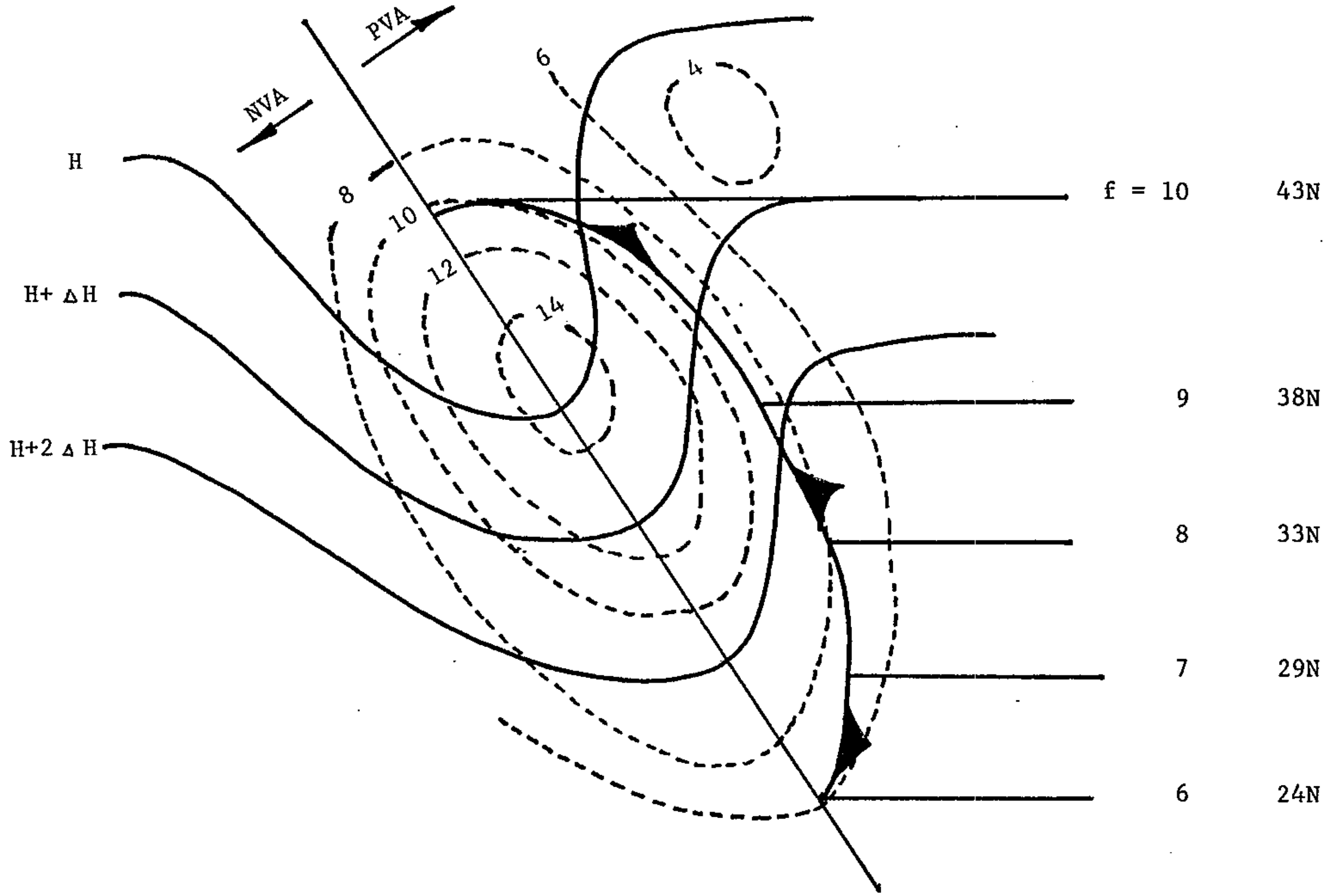
Typical absolute vorticity field and ZRVL (drawn in as a cold front symbol) on the PVA side of a 500mb trough in westerly flow.

Figure 6



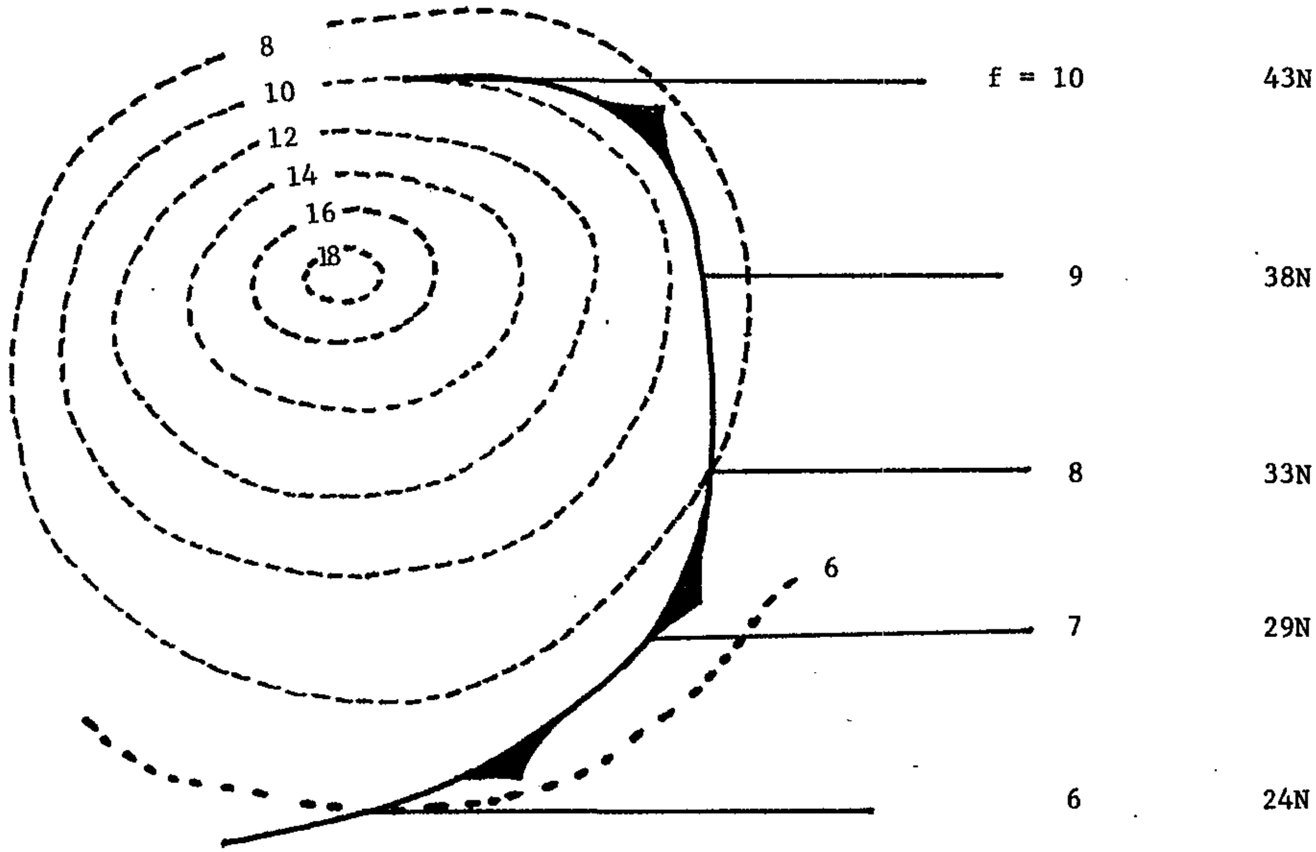
Same as Figure 5 in northwesterly flow.

Figure 7



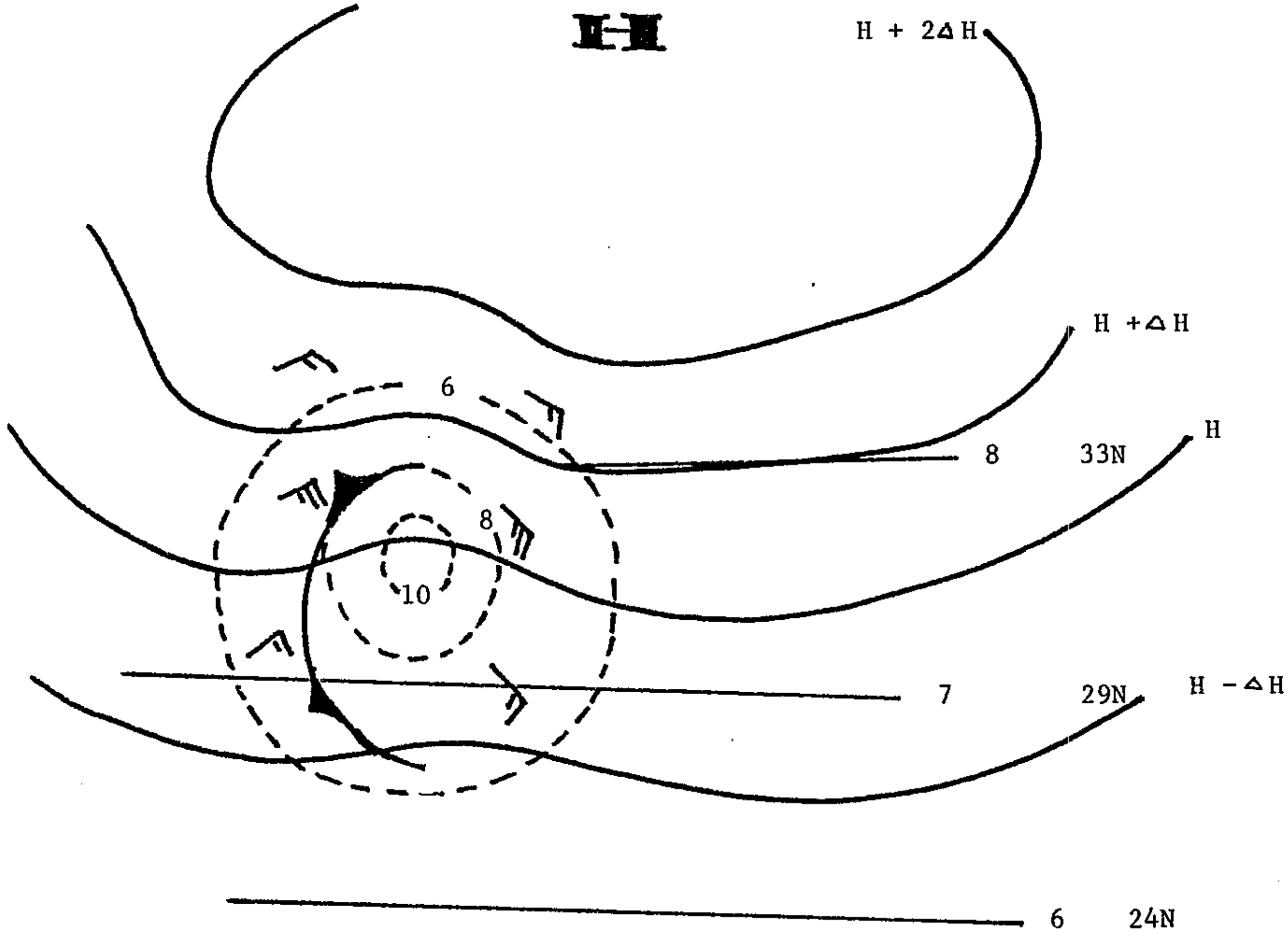
Same as Figure 5 with a negative tilt cyclone.

Figure 8



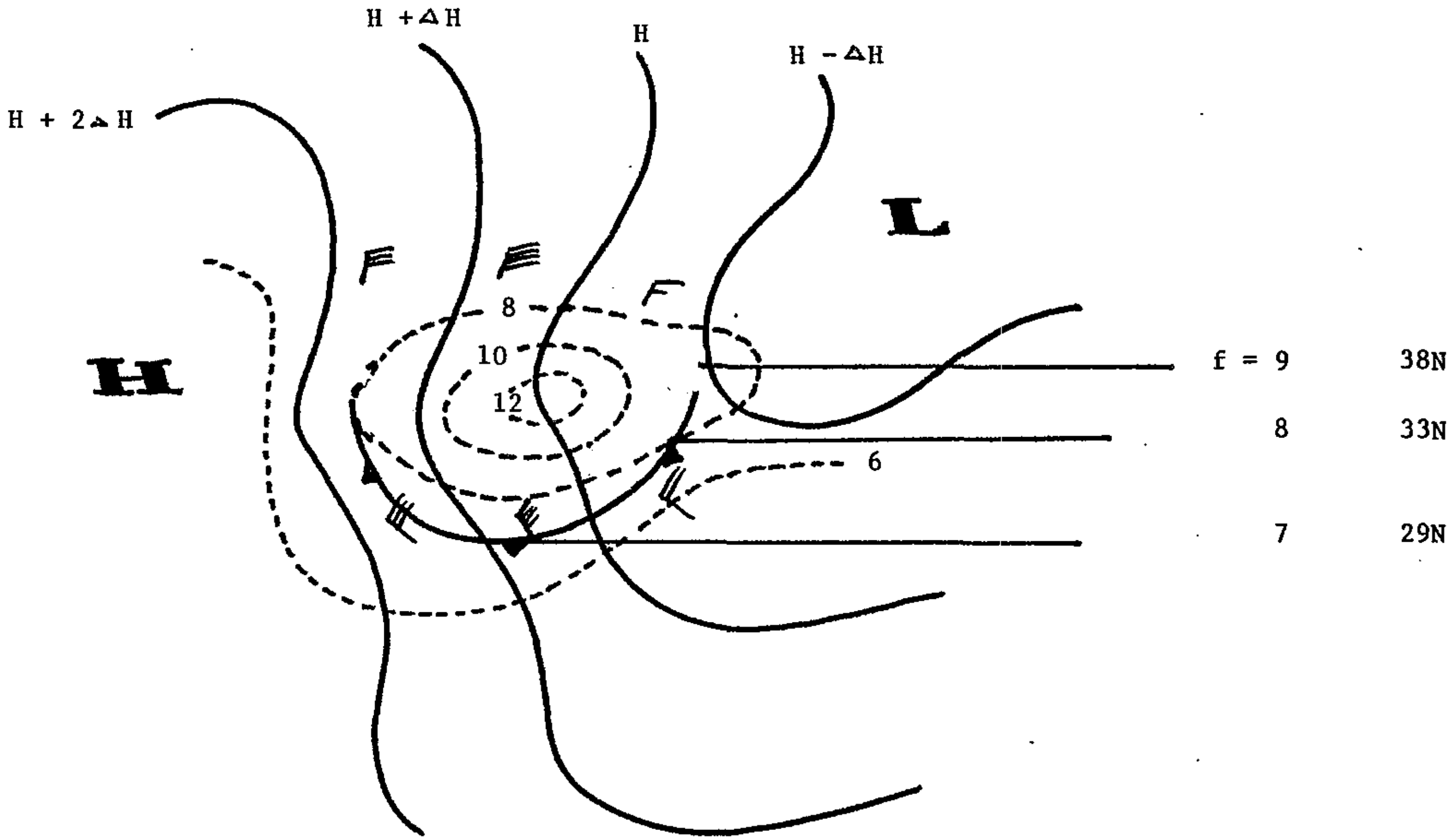
Vorticity field and "occluded ZRVL" with intense vertical cyclone. This type of cyclone may produce heavy snow along the east-west oriented segment of the ZRVL to the north of the center and severe thunderstorms in the moist air to the southeast. Being a vertical system the surface and upper centers will closely coincide with the vorticity isopleths. In this schematic case the heaviest precipitation relative to the center may occur 300 miles (5 degrees latitude) to the north.

Figure 9a



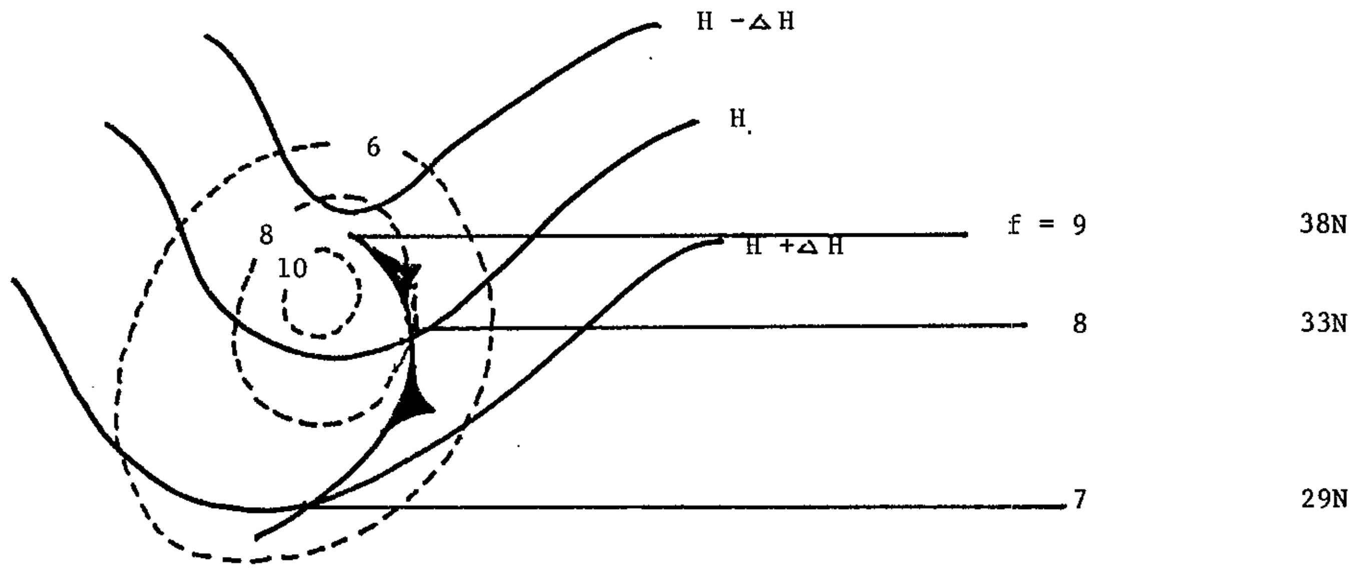
A disturbance in the easterlies with the associated ZRVL. The ZRVL in this case will approach from the east or southeast. Downward mixing of momentum may result in northeasterly surface winds as the showers approach from that direction.

Figure 9b



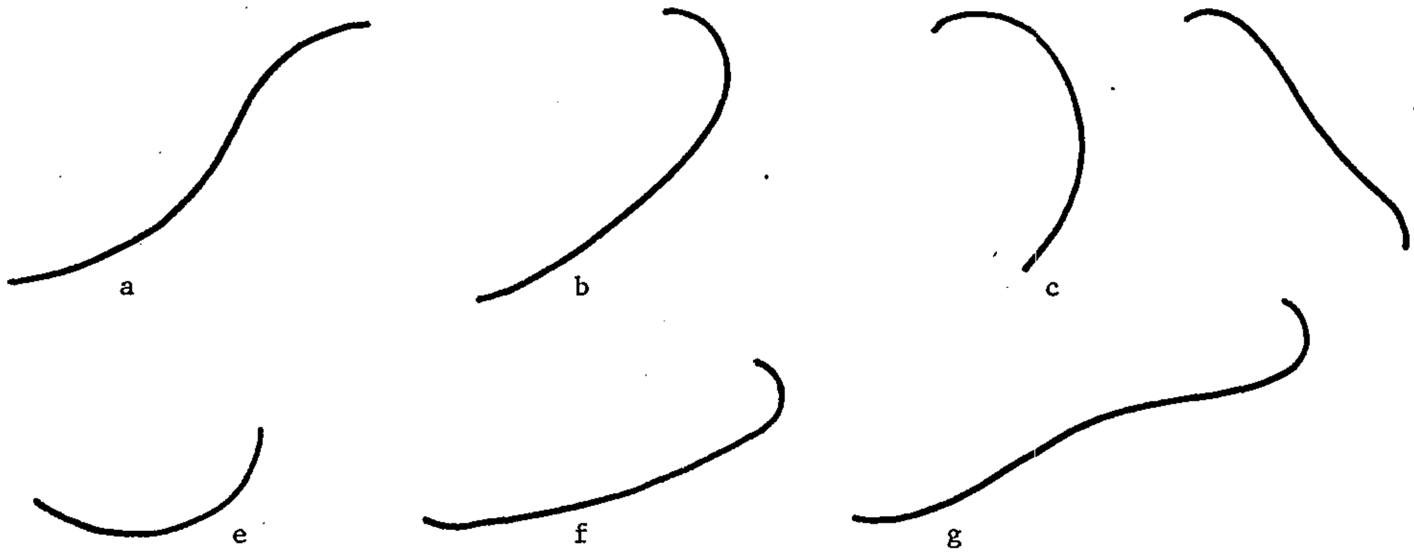
A disturbance moving southward from the Great Basin area in northerly flow. Much of this vorticity may be of the shear type. As this system moves into deeper "monsoon" moisture over Arizona, thunderstorms will intensify. In this case thunderstorms move into the deserts from northwesterly directions.

Figure 9c



A disturbance in westerly flow aloft moving into the southwest deserts from California. This type of flow is relatively rare in summer and moisture is often lacking with this pattern. However, very heavy rain of flash flood proportions may occur when large quantities of air moisture is available out ahead of this type of disturbance.

Figure 10



Some typical 500 mb ZRVL patterns and orientations. ZRVL with (a) sinusoidal wave pattern, (b) occluded front with closed circulation or sharp trough, (c) and (d) negative tilt systems which usually have strong PVA and heavy moisture supply, (e) frontal system or disturbance in northwesterly flow often of the "digging" variety, (f) system with weak PVA along most of front and high cirrus the predominant cloud type, (g) wave on a frontal band as two vorticity centers interfere.