Forecasting

DIFFERENTIAL RIDGE-AXIS DISPLACEMENT: APPLICATIONS TO FORECASTING THE ONSET OF PRECIPITATION

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ABSTRACT

Mass divergence in the upper troposphere that occurs upstream from a 500-mb ridge axis is associated with cyclogenesis. However, vertical motion throughout the 1000–500 mb layer can be significantly influenced by thermal advection in the lower troposphere. Consequently, precipitation may be observed well ahead of the 500-mb ridge axis if the same feature at 850 mb is displaced a considerable distance downstream. A case study is presented from December 14–15, 1987, which shows precipitation nearly 350 mi. east of the 500-mb ridge axis.

1. INTRODUCTION

The ability to diagnose the spatial fields of vertical motion in a developing cyclone is of essential importance to synoptic meteorologists. In the troposphere, regions of net upward vertical motion are associated with clouds and precipitation; whereas, net downward vertical motion suppresses the development of precipitation. While cyclones often exhibit a general signature of vertical motion at 500 mb related to mass divergence at that level, there can be *significant* deviations at other levels in the lower troposphere. Consequently, these deviations may promote vertical motion of varying magnitudes and *even opposing sign within a given column of air,* perhaps 1000–500 mb, over a particular location. Stated another way, strong upward motion can occur at 850 mb while the 500-mb level experiences weak downward motion. This dynamic scenario was observed in the cyclone of December 14–15, 1987, when the 850-mb ridge axis was displaced downstream from the 500-mb ridge axis, with precipitation advecting well ahead of that 500-mb feature.

2. DYNAMICS OF VERTICAL MOTION

Traditionally, the 500-mb ridge axis is widely regarded as a demarcation of regimes of vertical velocity: sinking motion associated with mass convergence is to the *east* of the ridge axis and rising motion associated with mass divergence is to the *west* of the same ridge axis (Palmen and Newton, 2, and Bjerknes, 3). In this conceptual model (Fig. 1), a surface low-pressure system will develop under the region of 500-mb divergence which is found west of the ridge axis (and east of the 500-mb trough). Using ω to denote vertical velocity, as defined in the *Omega Equation* (Carlson, 4 and Holton, 5), and isolating the effect of mass divergence only, $\omega<0$ (rising motion) in the region of upper-level divergence and $\omega>0$ (sinking motion) in the region of upper-level convergence. The 500-mb ridge and trough axes represent *change-over* points where $\omega=0$.

While this conceptual model is important for assessing the dynamics of cyclogenesis, the model can be far too simplistic in diagnosing the vertical-velocity fields of storms. Caught by the trap of rigorously using the 500-mb ridge axis as the leading edge of clouds and precipitation, many meteorologists have been surprised by precipitation events that advect well ahead of the ridge axis. One such example is the storm of December 14–15, 1987, where the leading edge of the precipitation was *350 mi* downstream of the 500-mb ridge axis, and more closely aligned with the ridge-axis at 850 mb.

3. THE OMEGA EQUATION

The Omega Equation (Holton, 5) is commonly used to diagnose the vertical motion of a hydrostatic atmosphere. This equation combines the geostrophic vorticity equation and the thermodynamic equation, and is written (after Carlson, 4):

$$\frac{R_d}{gp}\bar{s}\,\nabla^2\omega + \frac{\bar{f}^2}{g}\frac{\partial^2\omega}{\partial p^2} = -\frac{\bar{f}\,\partial}{g\partial p}(-V\cdot\nabla(\rho+f)) + \nabla^2\left(-V\cdot\nabla\frac{\partial z}{\partial p}\right) - \frac{R_d}{gp^{C_p}}\nabla^2\dot{Q} \quad (1)$$

The conventional symbols are defined in that text.

The Omega Equation uses fluid spin, or vorticity, as a means of measuring mass divergence when angular momentum is conserved. In a more simplified form, ignoring the influence of diabatic heating, Eq. (1) becomes:

$$\nabla^2\omega \equiv \underbrace{\frac{-\partial}{\partial p}(-V\cdot\nabla(\rho+f))}_{\mathbf{A}} + \underbrace{\nabla^2\left(-V\cdot\nabla\frac{\partial z}{\partial p}\right)}_{\mathbf{B}} \quad (2)$$

Term A represents differential vorticity advection and Term B represents thermal advection. Eq. (2) is used to diagnose only the *sign* of the components (terms A & B) because several constants have been neglected (those constants would be required to perform any quantitative analyses).

As diagnosed from Eq. (2), positive vorticity advection (PVA) that increases with height and warm-air advection

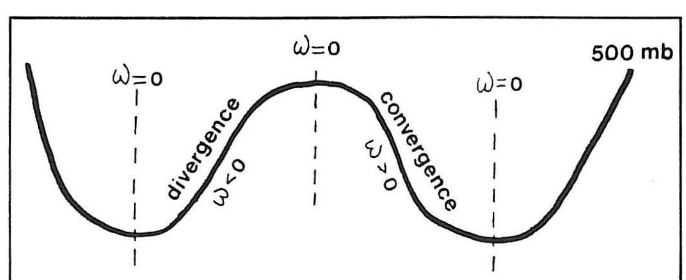

Fig. 1. Regions of mass divergence and convergence at 500 mb. Vertical motion expressed by ω.

(net) throughout the 1000–500 mb layer will each, individually, contribute to upward vertical motion ($\omega<0$). Referring to Figure 2, the greatest rising motion attributed to differential vorticity advection occurs at the inflection point east of the 500-mb/850-mb troughs and west of the 500-mb/850-mb ridges. The greatest thermal warm-air advection, and rising motion occurs near the ridge-axis position. Therefore, a combination of both the vorticity and thermal factors usually leads to the greatest magnitude of $\omega<0$ just *west* of the coincidental ridge axis. To the east of the ridge axes, negative vorticity advection (sinking motion) tends to be offset by warm-air advection in the 1000–500 mb layer. With the net vertical velocity in the column nearly zero (or very weak in magnitude), there is a lack of dynamical support for precipitation. So, when this configuration arises, the 500-mb ridge axis is usually a reasonable demarcation of the leading edge of mid-tropospheric clouds and precipitation associated with a synoptic-scale cyclone.

However, not all cyclones behave in such an idealized manner, evolving instead with a phase shift (horizontal) of the geopotential height field at various standard levels within the troposphere (Fig. 3). When the 850-mb ridge axis is displaced downstream from the 500-mb ridge axis, the fields of vertical motion will undergo a corresponding change. Strong warm-air advection in the lower troposphere *ahead* of the 500-mb ridge, in the presence of weak negative vorticity advection (NVA), can result in *net upward motion* throughout the 1000–500 mb column, which in turn would support the development of clouds and precipitation.

4. THE CASE OF DECEMBER 14–15, 1987

On December 14, 1987, a surface low-pressure system was intensifying over the lower Gulf Coast states and moving northeastward. At 0000 GMT on December 15, the storm center (999 mb) was situated near Little Rock, AR with a warm front stretched eastward to the coast of North Carolina (Fig. 4). Concurrently, a surface high-pressure system (1027 mb) was positioned near the coast of Delaware. Warm-air advection at the surface was overspreading western Pennsylvania and all of the Ohio Valley. The weather depiction chart (Fig. 5) for 0100 GMT on December 15 indicates light snow was falling at Altoona and Pittsburgh, PA. Light rain

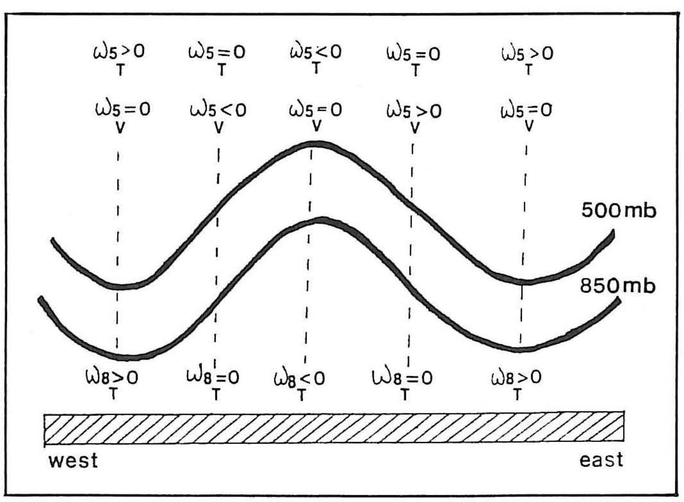

Fig. 2. Coincidental alignment of heights at 500 mb and 850 mb. Vertical motion contributions from thermal advection (T) and vorticity advection (V).

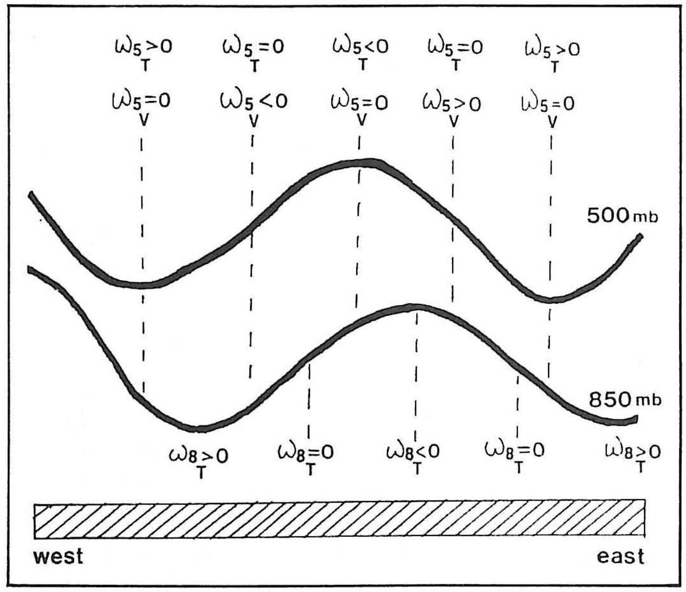

Fig. 3. Displaced alignment of the 500-mb and 850-mb heights. Same conventions as Fig. 2.

was observed at Hagerstown and Baltimore, MD with cloud bases at approximately 6500 ft (1970 m). Figure 6, the 500-mb analysis at 0000 GMT on December 15, clearly shows the ridge axis located over central Michigan through central West Virginia (dashed line). Precipitation (Fig. 7) was observed 350 mi. *east* of that axis, and more definitively aligned with the 850-mb ridge axis (Fig. 8) that was located over central Pennsylvania through eastern Virginia. This 850-mb ridge axis represented the leading edge of strong warm-air advection.

Figures 9a, 9b, 9c, and 9d show the following Nested Grid Model (NGM) analyses, respectively, at 0000 GMT on December 15: 1000–500 mb thickness/surface pressure, 500-mb heights/vorticity, 700-mb heights/relative humidity, and 850-mb heights/temperature. In Figure 9a, warm-air advection throughout the entire 1000–500 mb layer is indicated from central Pennsylvania westward to the Ohio Valley. Weak NVA (Fig. 9b) is featured over the same region. Most strikingly, the relative humidity at 700 mb over central Pennsylvania and Maryland is analyzed to be approximately 50% (Fig. 9c)—in a region where light precipitation was observed. Clearly, strong upward vertical motion was generated in the 1000–700-mb layer, primarily from warm-air advection, to form the lower-tropospheric clouds and precipitation.

A linearized version of Eq. (2), listed in the Appendix (after Carlson, 4), can be used to estimate the 700-mb vertical velocity over western and central Pennsylvania. With the magnitudes of vorticity and thermal advection specified by the advection boxes illustrated in Figs. 9a and 9b,

$$\omega \equiv -3.26 \times 10^{-2} \text{ mb} \cdot \text{s}^{-1}$$

This result confirms the hypothesis that warm-air advection, in conjunction with the 850-mb ridge-axis, generated the precipitation, even though the 500-mb ridge lagged several hundred miles upstream.

5. CONCLUSION

While the 500-mb ridge axis may represent the onset of upward vertical motion, induced by divergence at that level,

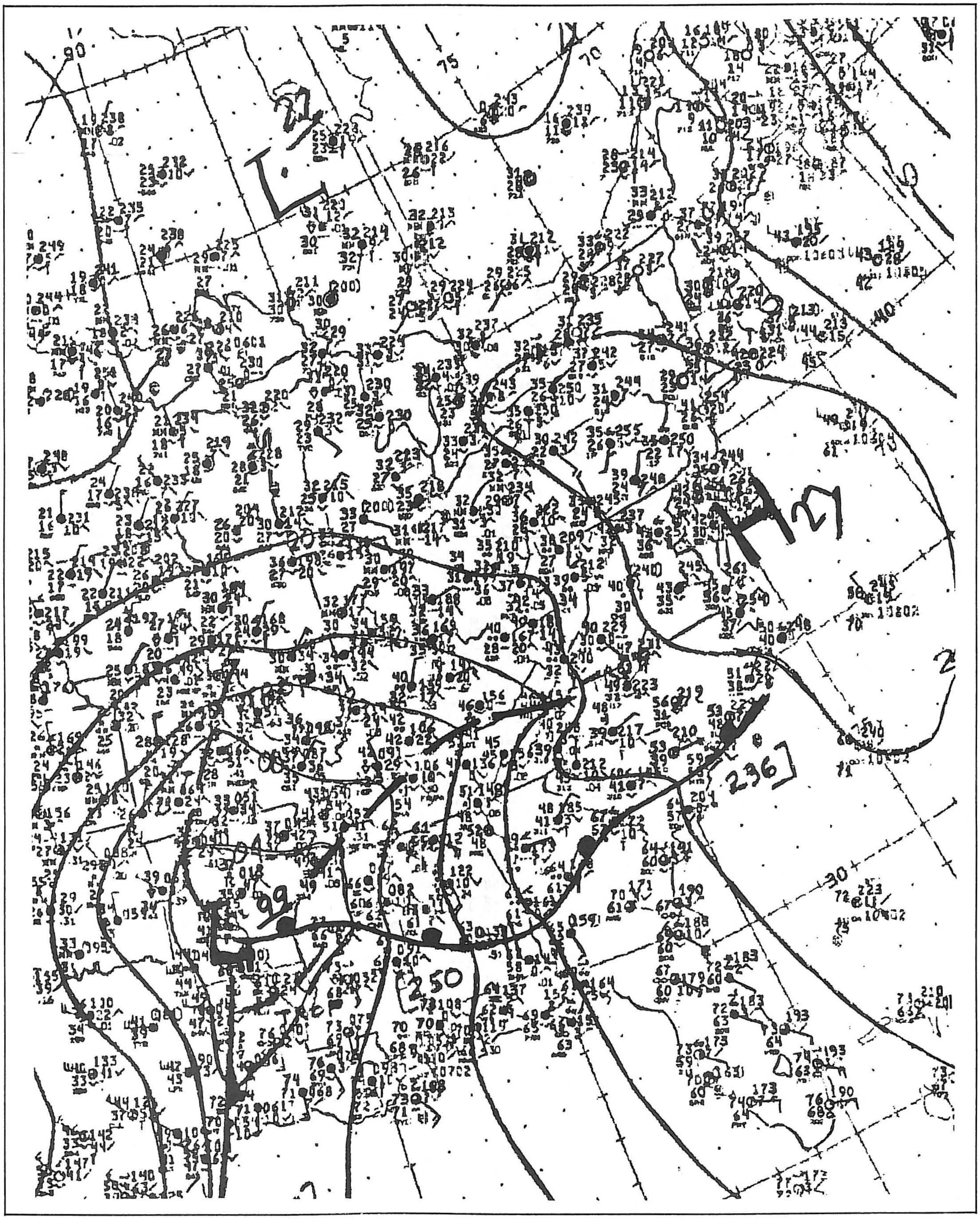

Fig. 4. Surface analysis at 0000 GMT on December 15, 1987.

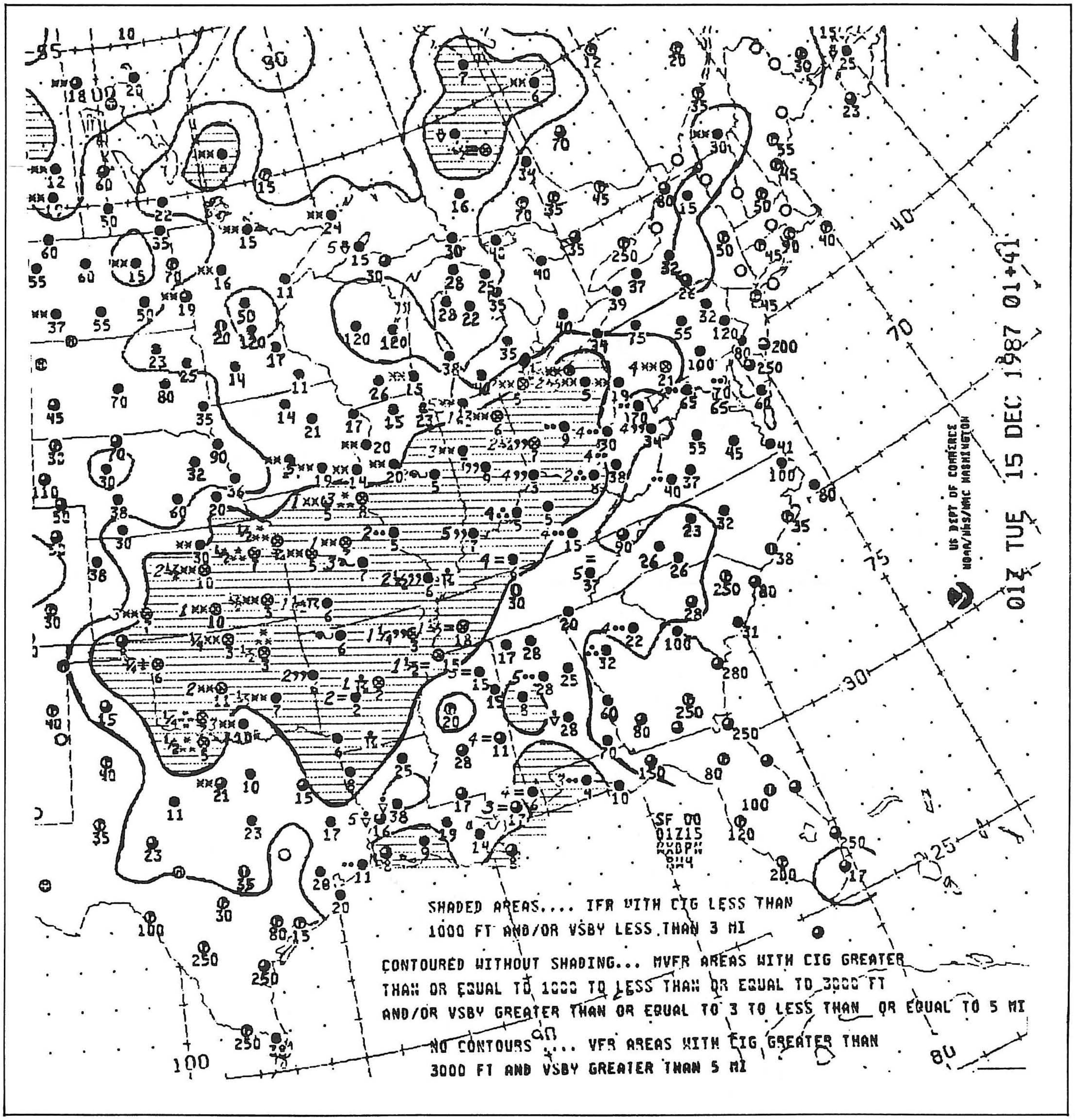

Fig. 5. Weather Depiction Chart at 0100 GMT on December 15, 1987.

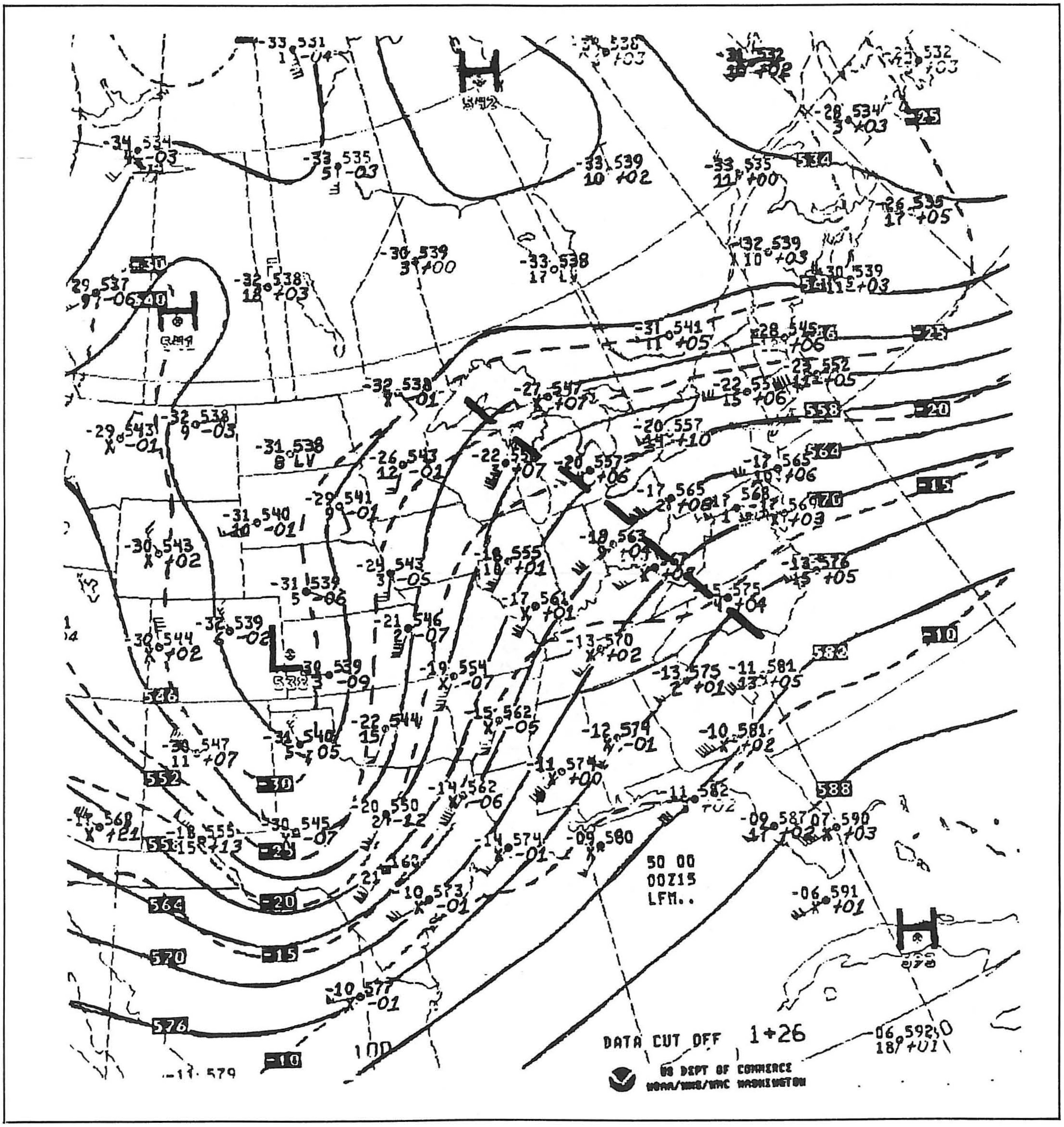

Fig. 6. The 500-mb analysis at 0000 GMT on December 15, 1987.

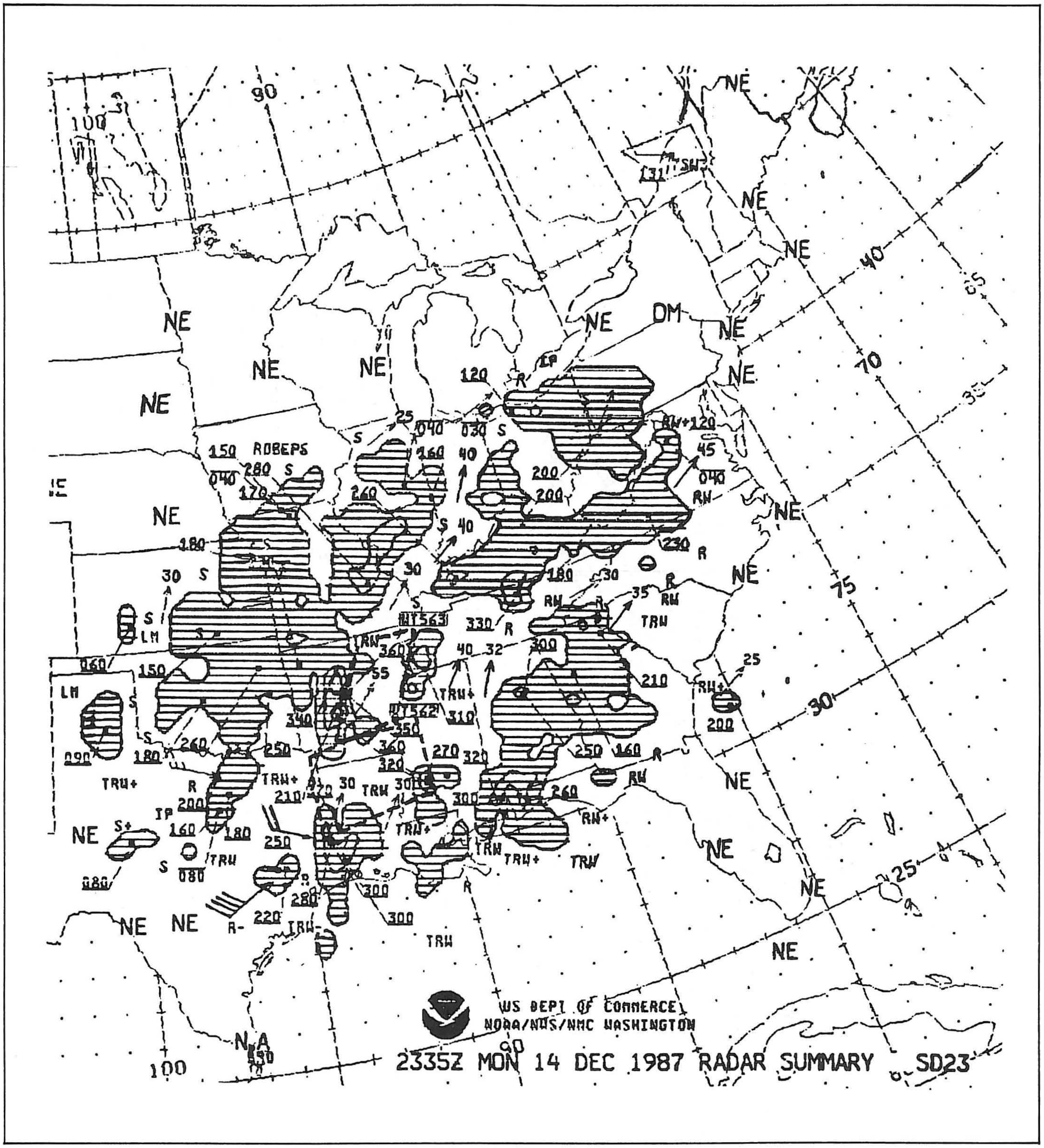

Fig. 7. Radar composite summary at 2335 GMT on December 14, 1987.

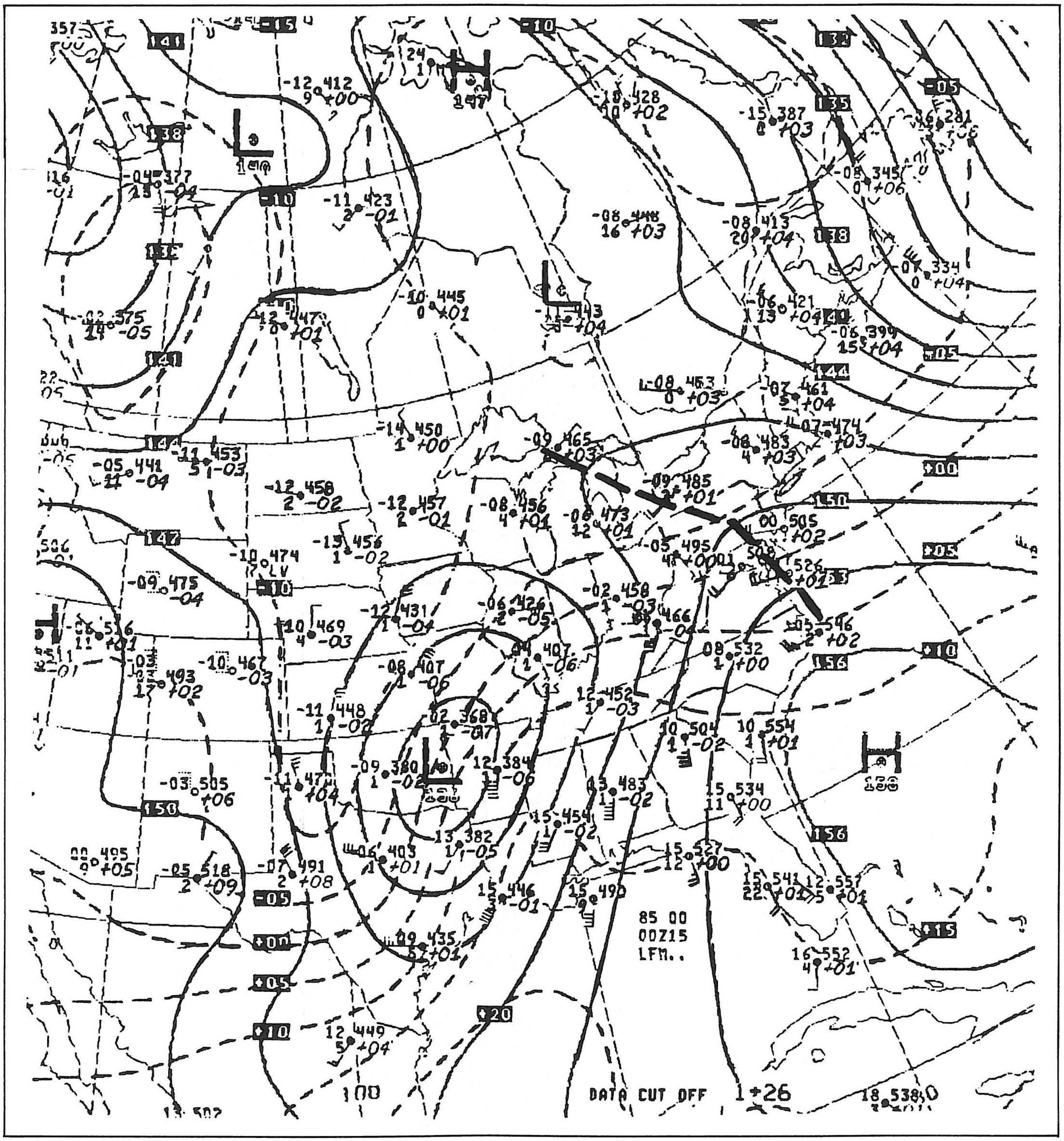

Fig. 8. The 850-mb analysis at 0000 GMT on December 15, 1987.

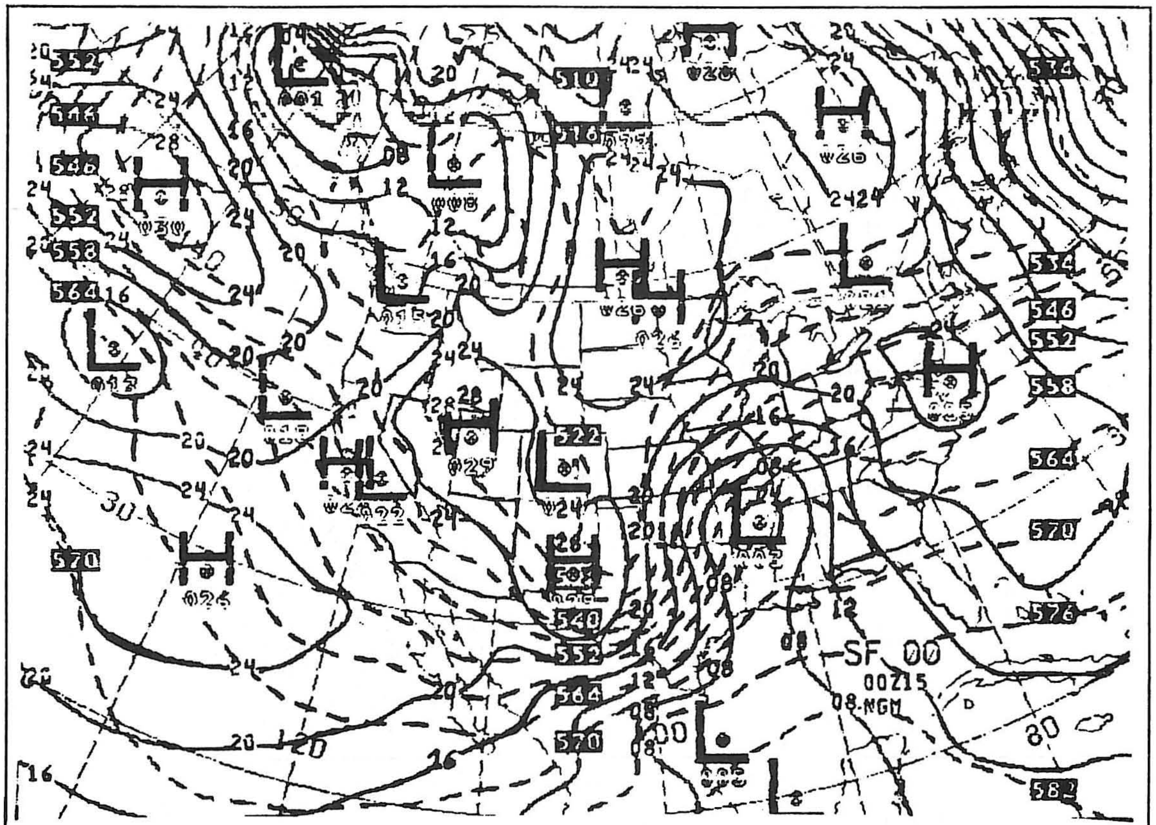

Fig. 9a. Nested Grid Model initial analysis of surface pressure and 1000–500-mb thickness valid 0000 GMT on December 15, 1987.

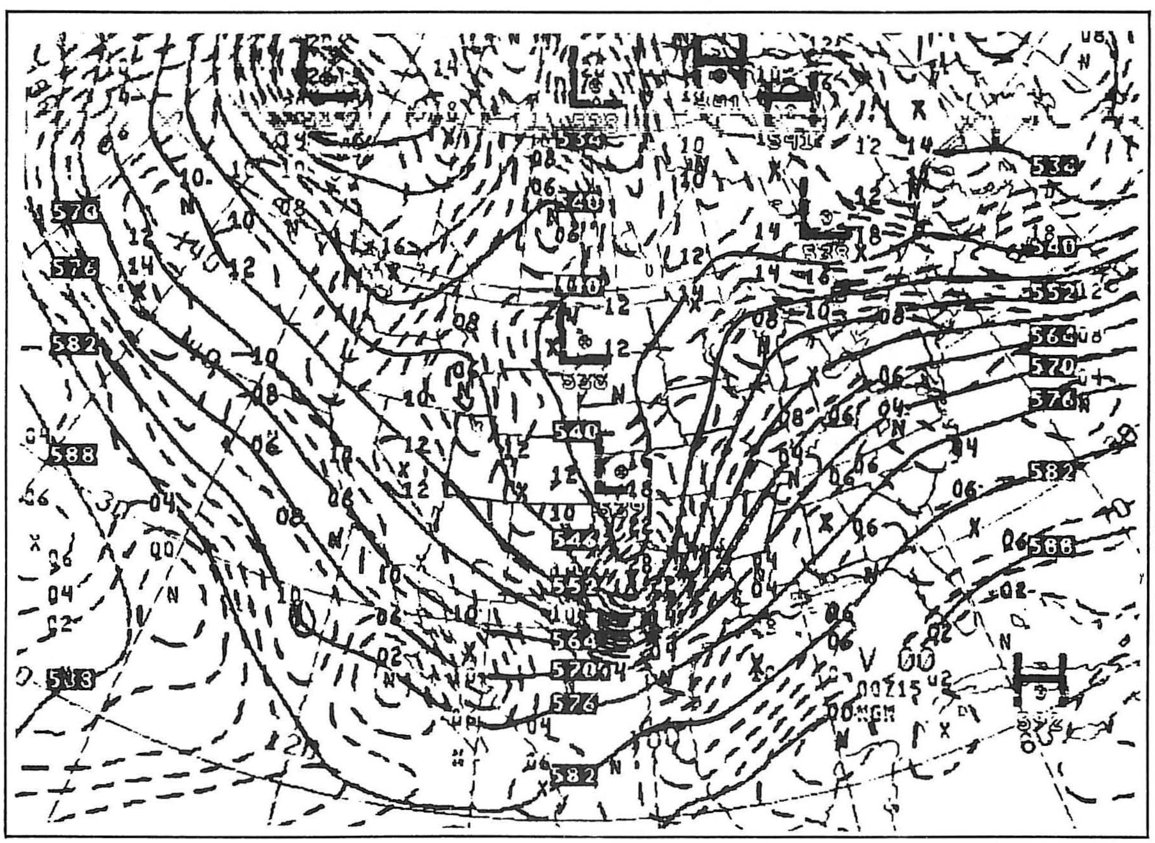

Fig. 9b. Nested Grid Model initial analysis of 500-mb heights and absolute vorticity valid 0000 GMT on December 15, 1987.

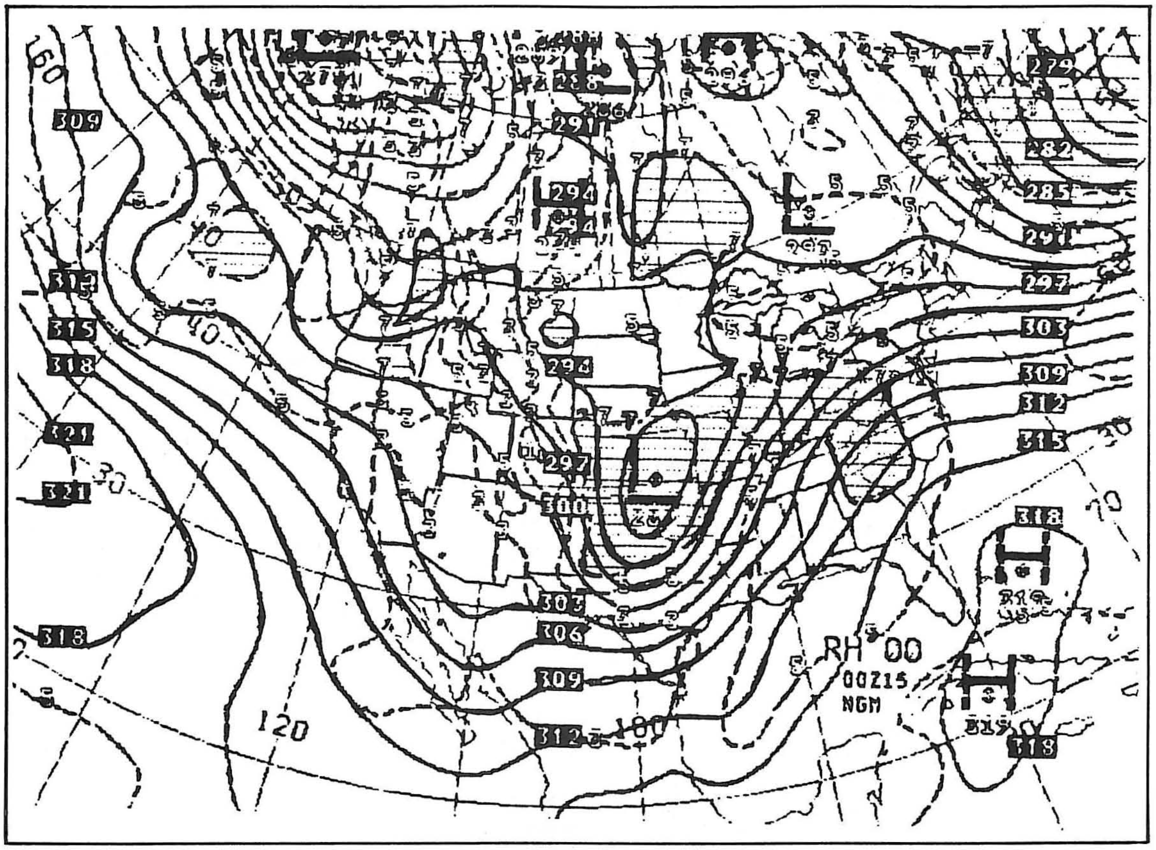

Fig. 9c. Nested Grid Model initial analysis of 700-mb heights and relative humidity valid 0000 GMT on December 15, 1987.

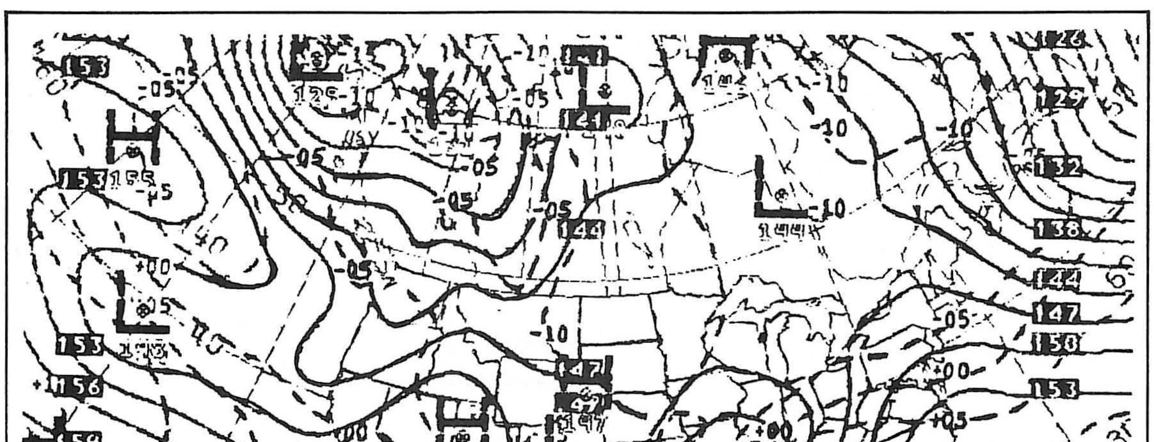

Fig. 9d. Nested Grid Model initial analysis of 850-mb heights and temperature valid 0000 GMT on December 15, 1987.

this parameter alone is insufficient to precisely define mid-tropospheric and lower-tropospheric vertical motion, which is also affected by thermal advection in the 1000–500 mb layer. When the 850-mb ridge axis is displaced downstream (east) of the 500-mb ridge axis, and assuming sufficient moisture available, adequate rising motion may exist to create clouds and precipitation. This scenario assumes that the lower-tropospheric warm-air advection is strong and the mid-tropospheric NVA is weak.

In a remarkable case, the storm of December 14–15, 1987 featured a large band of precipitation aligned with the 850-mb ridge axis, well in advance of the corresponding axis at 500 mb.

As a very brief digression, the concepts illustrated here are not inherent exclusively to synoptic-scale cyclones. Summertime mesoscale convection has been frequently observed to develop in regions of weak NVA and strong warm-air advection (Forbes et al., 6, Maddox, 7). Again, the thermal forcing is of critical importance as the primary source of net upward motion, even in the presence of weak NVA.

REFERENCES

1. Paul Heppner is chief meteorologist at WYOU-TV 22, Scranton, PA. He received a B S in Meteorology from Pennsylvania State University in 1982 and the M S in meteorology from the same institution in 1985. His current research interests are: using different predictors to determine the type of precipitation associated with winter storms and the development of nocturnal thunderstorms.

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The Cloud Chart 1, 2, 3 1-88

The Cloud Chart 1, 2, 3, NWA publication 1-88 is now available. It is composed of three 12 × 24 charts showing various cloud types, the weather they bring, cloud weatherlore and optical phenomena, and contains more than three dozen color photographs with accompanying text and state locations.

The three chart collection sells for $7.50 to NWA members and $9.00 to nonmembers. Shipping and handling charges are included in this special offer.

To order chart, send check to: The Cloud Chart 1, 2, 3, NWA, 4400 Stamp Road, Room 404, Temple Hills, MD 20748.

Script Slide Satellite Training 2-88

The training program, prepared by NESDIS, on "polar orbiter imagery interpretation" has been delayed, but should be available in early August. The Script-Slide Training Program, publication 2-88, contains 76 slides and a comprehensive script that addresses many aspects of basic satellite imagery interpretation from a polar orbiter perspective. However, the information can also be used for understanding geostationary satellite imagery, as well.

Worldwide examples show synoptic scale storm systems, jet streams, tropical cyclones, thunderstorms, land and ocean features, and basic cloud identification. One section describes the differences in imagery characteristics among various AVHRR channels. The package concludes with a "test" so viewers can determine how well they understood the material.

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