

A MID-ATLANTIC STATES RAIN EVENT: A REVIEW AND COMPARISON OF TECHNIQUES FOR ASSESSING VERTICAL MOTION FIELDS

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Abstract

Techniques for assessing vertical motion fields are reviewed and compared within the context of a moderate mid-Atlantic states rain event. These include conventional methods such as 500-mb positive vorticity advection (PVA), positive isothermal vorticity advection (PIVA), isentropic analyses, and numerical weather prediction (NWP) vertical motion fields. In addition, quasi-geostrophic diagnostic and predictive fields at various levels are utilized, as well as vertical cross sections of theta surfaces and ageostrophic secondary circulations. The physical basis for each technique is reviewed, and the relative merits and utility of each explored and compared when applied to a typical weak, warm season synoptic scale environment. It was determined that the rain event was principally the product of events occurring at jet stream level, but that no single technique gave clear signals as to the extent and intensity of the precipitation, especially since most of the techniques focus on levels at 500 mb and below. However, by incorporating and integrating all the available data sets, it was found that better delineation of the affected area on smaller scales than numerical models alone were able to resolve, might be possible. Utilizing a variety of diagnostic and predictive fields can aid in resolving differences and conflicts between model forecasts and reinforce a forecast decision process based upon more complete and sound dynamic principles.

1. Introduction

Forecasters throughout the National Weather Service (NWS) and at many other U.S. military and civilian weather offices are being introduced to a wide variety of sophisticated and highly specialized data sources and forecast tools as state-of-the-art observing, diagnostic, and forecast systems come on-line. There are literally hundreds of new interactive graphic fields, many based upon gridded numerical model output, that will become available in this era of modernization. Forecasters will need to develop new strategies and methodologies for incorporating and selectively utilizing these tools in the forecast decision process.

This paper will review and compare conventional techniques for assessing vertical motion within the context of an eastern United States rain event which produced unexpected heavy rainfall. In so doing, the basic dynamic and thermodynamic principles of a quasi-geostrophic system, upon which many of the new diagnostic and predictive programs are based, will be reviewed. Traditional forecast methods and approaches for determining upward vertical motion will be compared to newer techniques and alternative data sources. The intent is to present alternative analysis techniques that

might have provided additional useful information for this and future events in which forecasters are faced with differing or conflicting model solutions, and to encourage forecasters to develop effective forecast methodologies and decision processes based upon the application of sound dynamic principles.

Some of the traditional methods for determining vertical motion will be presented as they are currently available in the NWS AFOS (Automation of Field Operations and Services) operational environment. A few of the new diagnostic and derived fields available on a prototype NWS Advanced Weather Interactive Processing System (AWIPS)-90 workstation in Denver, Colorado [Denver AWIPS-90 Risk Reduction and Requirements Evaluation (DAR³E-II)] will be shown to demonstrate their potential utility in this eastern United States rainfall event.

The NWS PC-based GRidded Information Display and Diagnosis System (PCGRIDDS) graphics routine was used to construct vertical cross sections derived from Nested Grid Model (NGM) data. The PCGRIDDS program is a software display and diagnostic system for model gridded data (R. Petersen, personal communication). The system utilizes gridded model output to provide a wide variety of diagnostic and forecast fields. In addition, various operations and manipulations can be performed on the data sets for initial analyses and forecast periods. The Upper Air (UA) program (Foster 1988), which performs thermodynamic and kinematic calculations on upper air data, will be utilized in analyzing the divergence of Q-vectors as well as frontogenetical forcing.

A brief overview of the event and the synoptic scale setting is presented in Sections 2 and 3 respectively, followed by a comparison of available analyses, conventional numerical weather output, and alternative data sources in Section 4. Section 5 concludes the paper with a discussion of the results.

2. The Rain Event of 13 September 1990

On 13 September 1990, significant rains fell over portions of the mid-Atlantic states. The event was centered over northern Virginia between the hours of 0600 and 1500 UTC where 1 to 3 inch amounts were measured (Fig. 1). The heaviest rains during this period fell just east of the Blue Ridge Mountains, which extend along a NNE-SSW line across western Virginia. The rain subsequently spread over the eastern shore of Maryland with similar amounts being reported. The event was by no means extraordinary (i.e., not the rare occurrence that is so often the subject of case studies), but rather a situation that could be faced by forecasters on any given day during the warm season.

The 1200 UTC 12 September NWP model runs apparently had difficulty in predicting this event and created a dilemma

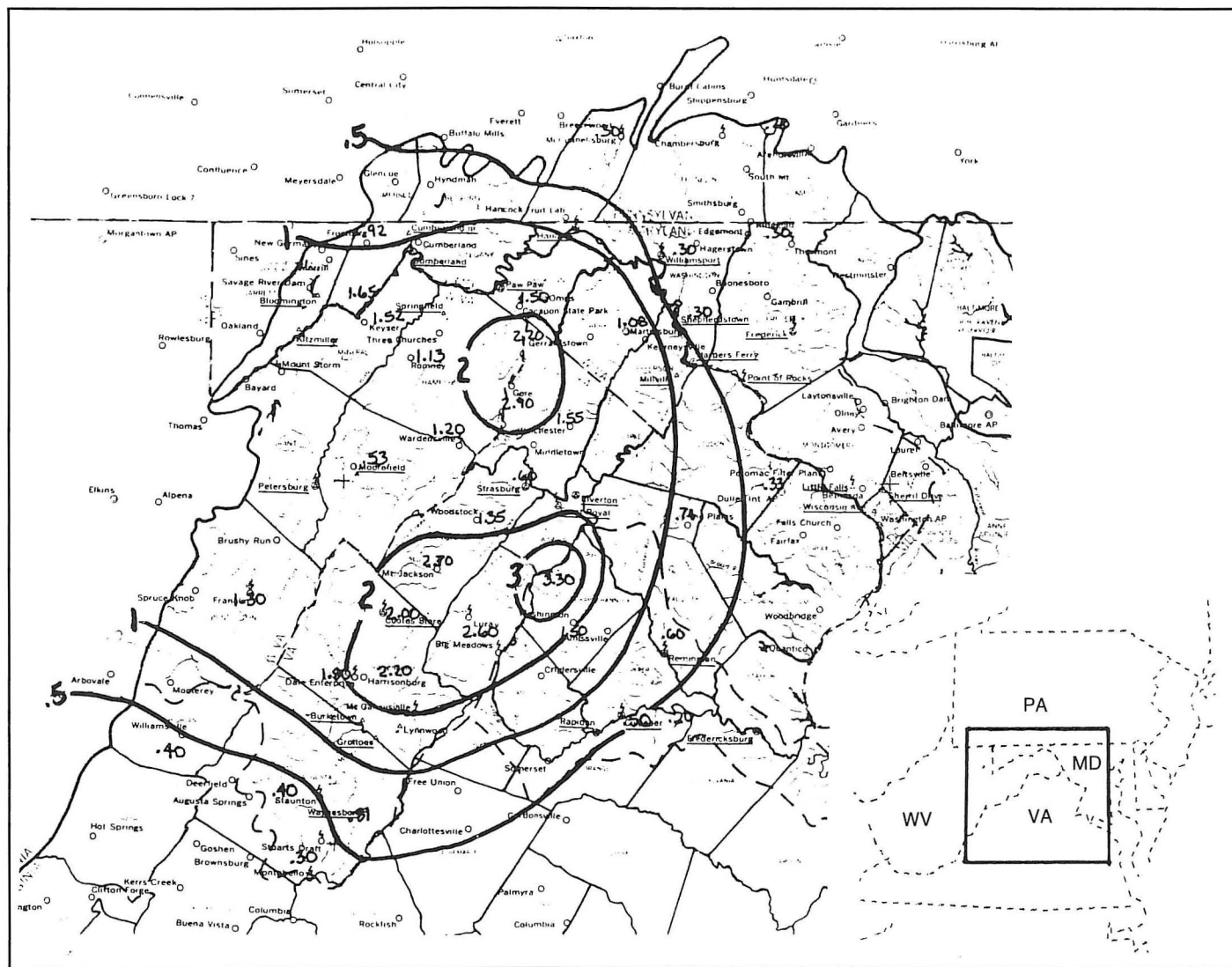


Fig. 1. Rainfall totals ending at 1200 UTC 13 September 1990. (Area shown is expanded from inset.)

in which the evening forecaster was forced to choose between conflicting solutions. Since the 1200 UTC 12 September upper air data and model runs were utilized to update the evening forecast, we will examine analyses and forecasts based on these data. However, the 0000 UTC 13 September data provided clues concerning the development of the heavy rains, so we will also examine analyses and model forecasts based on these data.

The 24-h forecasts of NGM and LFM-derived Model Output Statistics (MOS) and quantitative precipitation valid at 1200 UTC 13 September differed considerably. LFM MOS forecasts gave 30–40% probabilities of measurable rain, with model generated amounts generally under 0.10 inches. Corresponding NGM MOS forecasts indicated 50–70% probabilities of measurable rain. The NGM quantitative precipitation forecast showed some skill with regard to location and areal extent for 6-h amounts (Fig. 2), but substantially underestimated the rainfall totals, particularly in northern Virginia. The dynamic models have displayed limited success in predicting mesoscale rainfall events and severe weather, despite

improved forecasts of synoptic scale flow patterns (Keyser and Uccellini 1987).

Weak impulses in the westerly flow had failed to produce much precipitation over Virginia during the previous 24 h and the approaching system appeared to be similar in nature. The apparent lack of dynamic forcing for this event, as suggested by the numerical models, would belie the eventual extent and intensity of the precipitation. With very mixed signals from the models and no compelling arguments one way or another, the day and evening shift public forecaster at the Washington, D.C. area NWS Forecast Office chose to take a middle-of-the-road, compromise approach. The forecast for northern Virginia called for a chance of showers and thunderstorms, but did not mention the possibility of a more significant moderate to heavy rain event.

3. The Synoptic Setting

The 500-mb analyses prior to (0000 UTC 13 September 1990; Fig. 3a) and during (1200 UTC 13 September 1990;

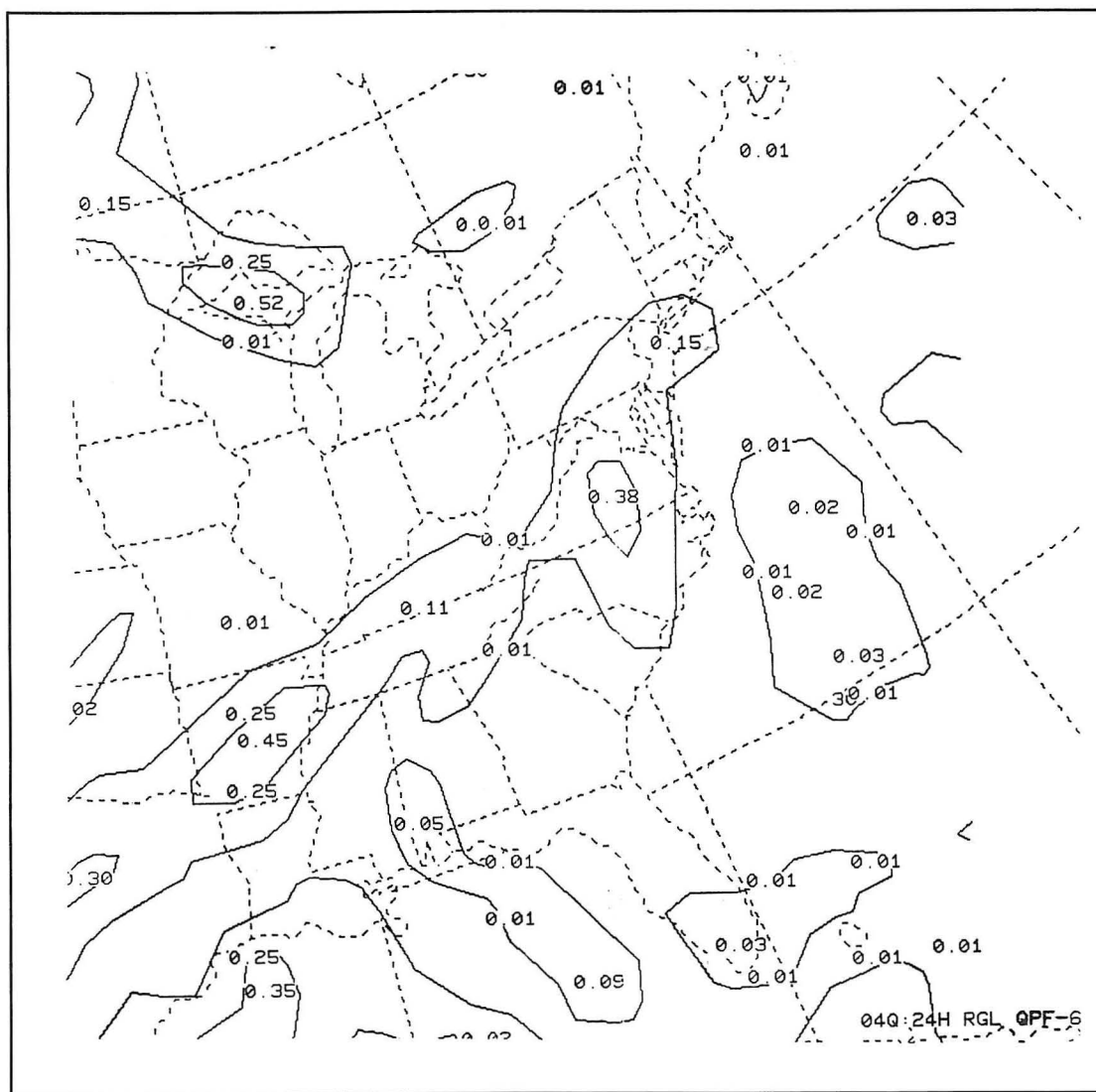


Fig. 2. 24-h NGM quantitative precipitation forecast for the 6-h period ending 1200 UTC 13 September 1990.

Fig. 3b) the event revealed a synoptic pattern typical of the warm season; moderate westerly mid-tropospheric flow along the U.S.-Canadian border with relatively light winds over the continental United States. A weak short wave trough over Ohio at 0000 UTC 13 September had moved southeast and extended from central Pennsylvania into West Virginia by 1200 UTC. The 200-mb analysis at 1200 UTC 13 September (Fig. 4) showed a jet streak stretching from the Ohio Valley to New England with winds of 70 kt. Beebe and Bates (1955), among others, have shown that areas of divergence (convergence) and enhanced upward (downward) vertical velocities often accompany these jets due to ageostrophic transverse circulations which develop in the entrance and exit regions of these features. As will be seen, this jet streak and its attendant circulation helped enhance vertical motion over the mid-Atlantic states during this event.

Most obvious of the features that would eventually contribute to the rain event was a large area of subtropical moisture spreading anticyclonically northeastward from the Gulf of Mexico through the Ohio Valley. This moisture, apparent as a widespread area of cloudiness and embedded showers on the 0001 UTC 13 September GOES-East IR satellite image

(Fig. 5), was also indicated by the relatively higher 850-mb dew points extending across the Gulf coastal states and the Carolinas (Fig. 6). This moisture had spread into northern Virginia by 1200 UTC, evidenced by precipitable water of 1.62 inches from the IAD sounding (Fig. 7). The anticyclonic flow of moisture seen in Fig. 6 conformed to one of the five categories of Subtle Heavy Rainfall Signatures (SHARS) on GOES imagery identified by Spayd and Scofield (1983). In this situation, warm-top thunderstorms are embedded in a large anticyclonic flow of cirrus (indicating large-scale over-running).

The 1200 UTC 13 September IAD sounding (Fig. 7) revealed some weak instability between 850 and 660 mb. Above this layer, the sounding was moist adiabatic, indicative of the embedded convection which, at this time, was beginning to shift to the east over eastern Maryland. Winds below 600 mb were relatively light (less than 10 kt) and variable, with the exception of a 15 kt southeast wind at 900 mb. At upper levels winds were westerly and increased to 70 kt at 200 mb, reflecting the upper-level jet near IAD.

High pressure building across New England was the dominant synoptic scale surface feature during the event (Fig. 8).

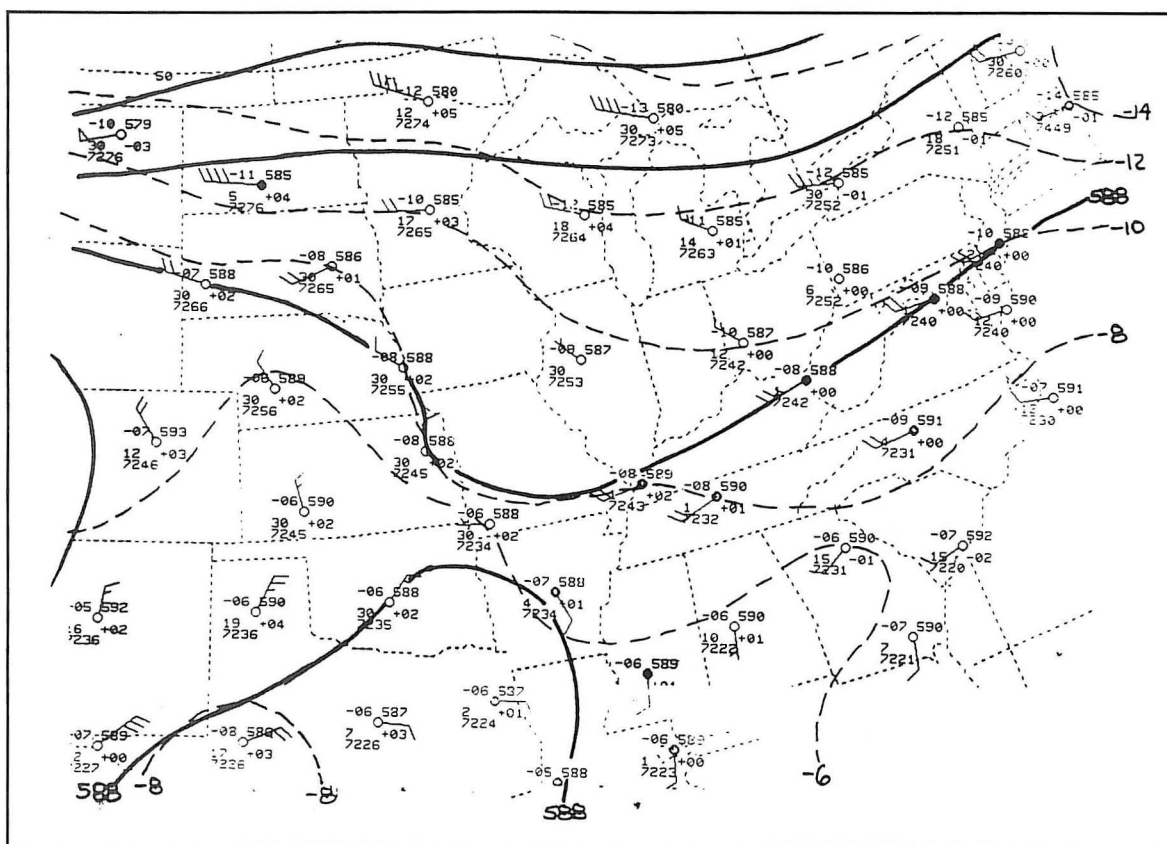


Fig. 3a. 500-mb analysis for 0000 UTC 13 September 1990.

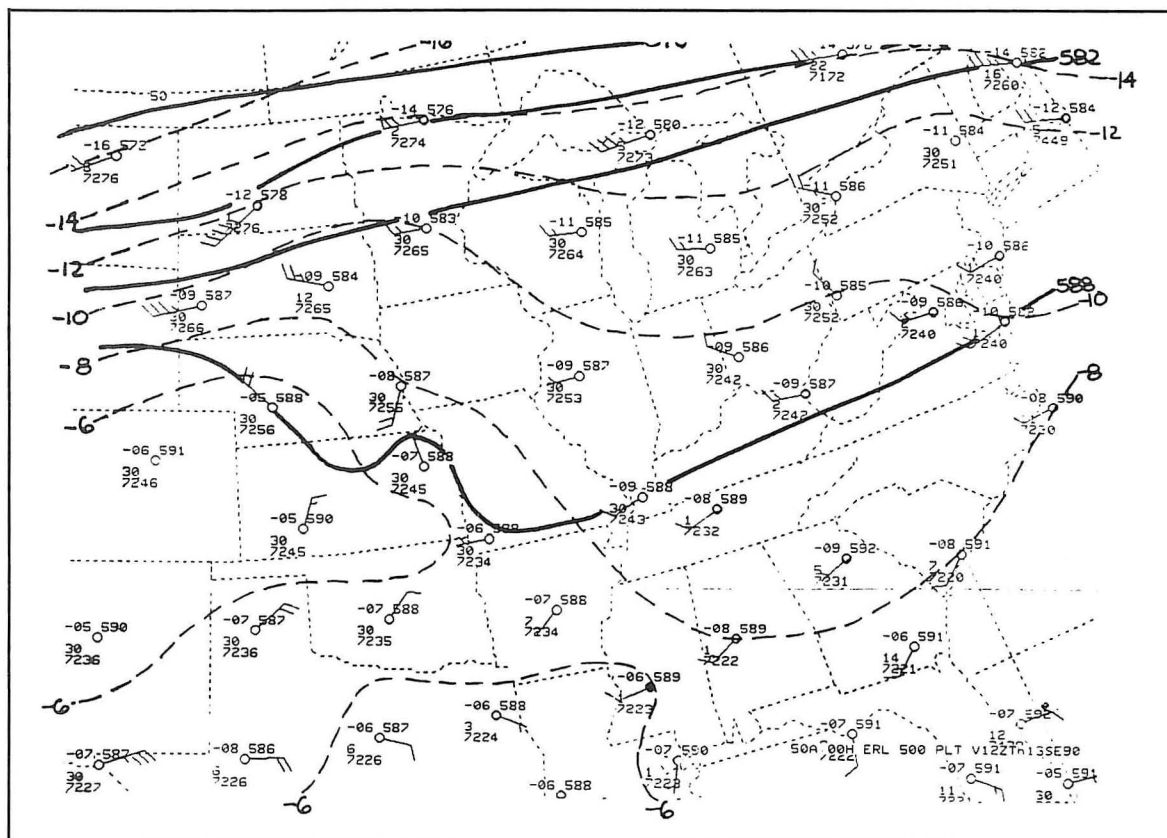


Fig. 3b. 500-mb analysis for 1200 UTC 13 September 1990.

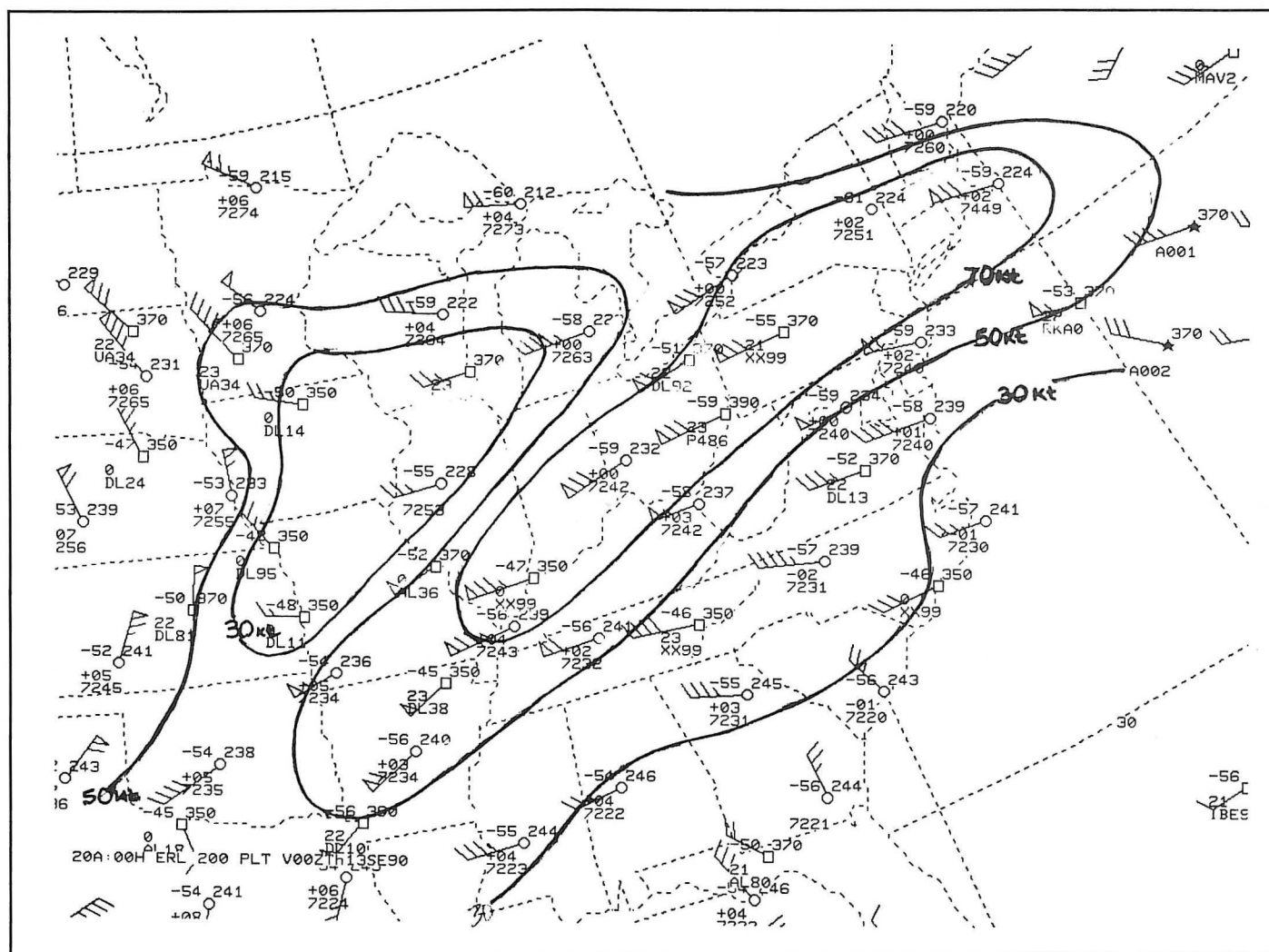


Fig. 4. 200-mb analysis for 0000 UTC 13 September 1990.

The associated ridge extended southward along the eastern slopes of the Appalachian Mountains. This pattern displayed some characteristics of weak cold air damming (Richwien 1980), with light east to northeast surface winds at most locations east of the Blue Ridge Mountains at 1200 UTC 13 September.

4. Comparison Of Techniques For Assessing Vertical Motion Fields And Precipitation Potential

In an attempt to assess vertical motion fields and related precipitation mechanisms, one must apply fundamental dynamic principles that yield accurate and sound conclusions in the forecast decision process. One of the most useful conceptual models available to forecasters for doing just that is the omega equation, which is the fundamental basis for the quasi-geostrophic system. Holton (1979) shows that for frictionless, adiabatic, synoptic scale flow, vertical motion is forced by differential (the rate of change with height) vorticity advection and the Laplacian of thickness advection. In other words, positive vorticity advection increasing with height and warm advection result in rising motion. However, an important point to remember is that,

within the quasi-geostrophic system, all advection is done by the geostrophic wind, and the readjustment process is accomplished through ageostrophic wind components. Consequently, quasi-geostrophic theory is deficient within regions of frontogenesis and near jet streaks, where advection by, and the rate of change of, the ageostrophic wind are important.

Therefore, the fundamental challenges facing precipitation forecasters are: 1) a diagnosis of the vertical motion field as a result of both vorticity and thermal advection contributions (the omega equation); 2) the effects of the atmosphere's subsequent responses to this forcing on other fields such as moisture, stability, and precipitation; and 3) other factors that contribute to vertical motion, such as ageostrophic wind components, diabatic heating, and orographic effects. In addressing these questions, the forecaster can first utilize traditional approaches, and supplement those with techniques and tools that give a more complete and meaningful solution to the omega equation. The following topics will be discussed with respect to the 13 September case:

- 1) 500-mb Positive Vorticity Advection (PVA)
- 2) Positive Isothermal Vorticity Advection (PIVA)

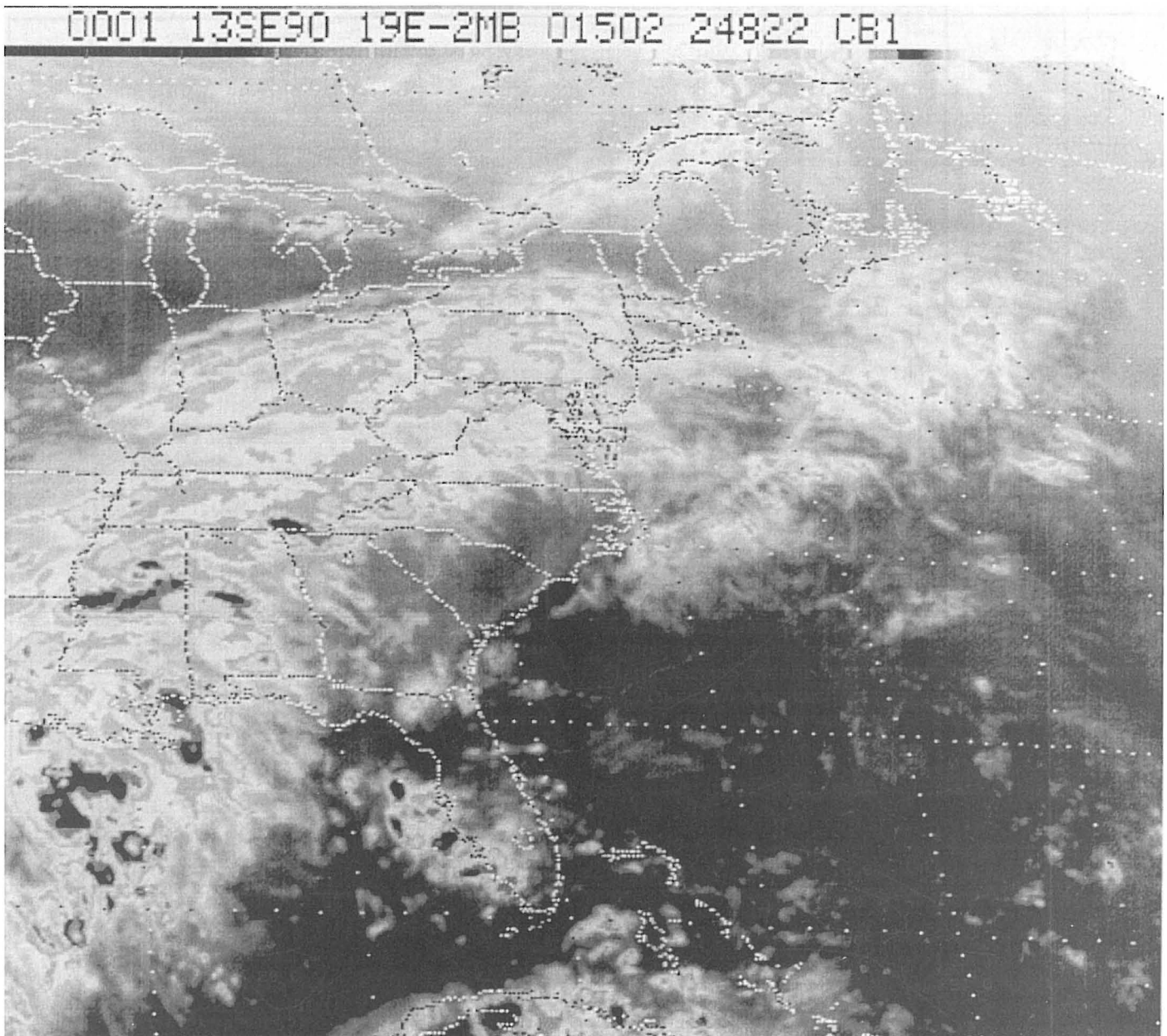


Fig. 5. GOES-East infrared imagery for 0001 UTC 13 September 1990.

- 3) Isentropic Analyses and Secondary Ageostrophic Circulations
 - 4) Quasi-Geostrophic Diagnostic Fields (Q-vectors and DIV-Q)
 - 5) Quasi-Geostrophic Predictive Fields (Progged Deep-Layer DIV-Q)
 - 6) NWP Vertical Motion Fields
- 4.1 500-mb Positive (Cyclonic) Vorticity Advection (PVA)

In the operational forecast environment, overlaying 500-mb heights with vorticity contours has been a quick and simple method to delineate areas where vertical motion may be enhanced by the advection of vorticity. By overlaying the 500-mb height contours with the vorticity, PVA is implied

over areas in which the two contours cross at angles (sole-noids) and in which absolute vorticity increases upstream. With this method, it is assumed (often incorrectly) that when PVA is present at 500 mb, upward vertical motion will result. Indeed, one can infer PVA at a single constant pressure height, but it is at best a crude one-dimensional estimate which tells nothing of the forcing through a deep layer resulting from the rate of change with height of vorticity advection (i.e., differential vorticity advection). Moreover, this technique neglects the combined effect of both vorticity and thermal advection which often negate each other in the real atmosphere. Finally, in weak flow situations more typical of warm season synoptic settings, vertical motion contribution by 500-mb PVA is much less apparent. In these cases, it is more typical to find dynamic forcing at levels above 500 mb.

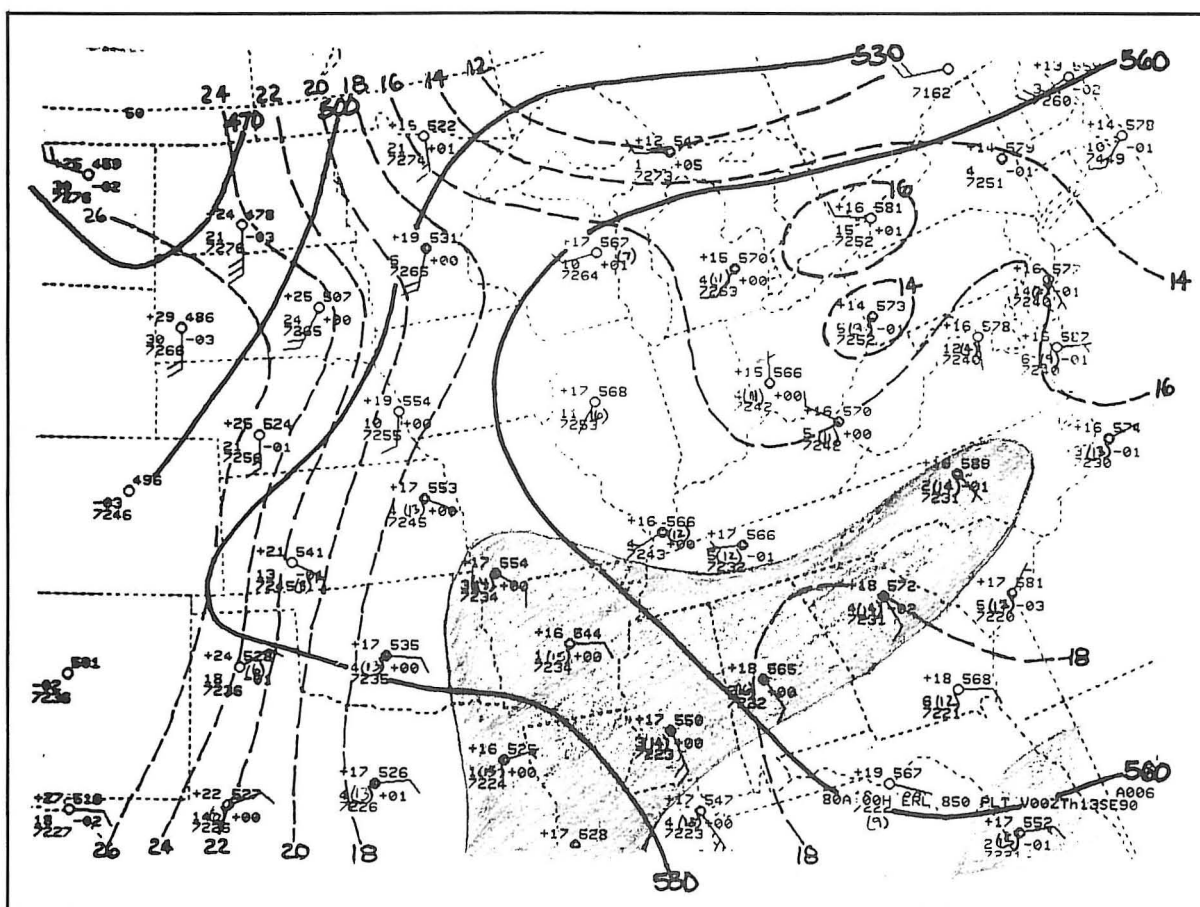


Fig. 6. 850-mb analysis for 0000 UTC 13 September 1990. Heavy solid lines represent height contours at 30 m intervals. Dashed lines represent isotherms at 2°C intervals. Shaded area represents surface dew points of 14°C or higher with dew points in parentheses.

Little insight into the impending rain event was revealed by the NGM 500-mb height and vorticity analyses (Fig. 9a) and 24-h forecasts (Figs. 9b, and 10) valid at 1200 UTC 13 Sept. Indeed, the advection pattern indicated by these charts was nearly neutral. Furthermore, a vorticity maximum analyzed over northern West Virginia at 1200 UTC 13 September (Fig. 9a) was apparently poorly forecast by the NGM 24 hours earlier (Fig. 9b). This feature may have been convectively induced, but whatever the source, subtle features such as these which are often poorly forecast by NWP models during the warm season can result in heavy precipitation.

Spayd (1982) produced composites of flash flood producing warm-top thunderstorms, in which most of the storms occurred to the north and east of a surface, 850-mb, and 500-mb low center. The vorticity center seen over northern West Virginia in Fig. 9a, had it been well forecast, might conform to some degree with the 500-mb composite, but little else either at the surface or 850-mb level bears much resemblance to the flash flood composite. Thus, few clues were provided by the 500-mb PVA technique, as to the extent and intensity of the impending rain event.

4.2 Positive Isothermal Vorticity Advection (PIVA)

The PIVA technique is a somewhat more recent and less utilized method for assessing vertical motion fields. It is

unfortunate this technique has not gained wide acceptance, since the method of advecting vorticity by the thermal wind rather than by the geostrophic wind provides a physically more complete and meaningful solution of the omega equation. Trenberth (1978) showed that differential vorticity advection and the rate of change, or Laplacian, of thermal advection (terms in the omega equation) can be represented by the advection of cyclonic vorticity by the thermal wind, and that this approximates the forcing function for synoptic scale vertical motion. Therefore, in advecting the 500-mb vorticity by the thermal wind, one obtains an approximation of the vertical motion field resulting from the combined effects of vorticity advection and thickness advection through the layer.

In an operational (e.g., AFOS) forecast environment this can be accomplished to some degree by overlaying the 500-mb vorticity contours with the 1000-500-mb thickness contours. (The thermal wind "blows" parallel to the thickness contours with cold air on the left looking downstream.) The estimation of PIVA is similar to 500-mb PVA except the solenoids are produced by intersecting thickness and vorticity contours. The beauty of this technique lies in its simplicity in incorporating the most important terms of the omega equation. However, employing only the 1000-500-mb thickness as a representation of the thermal wind and the 500-mb vorticity is a less than ideal approach (Dunn 1991).

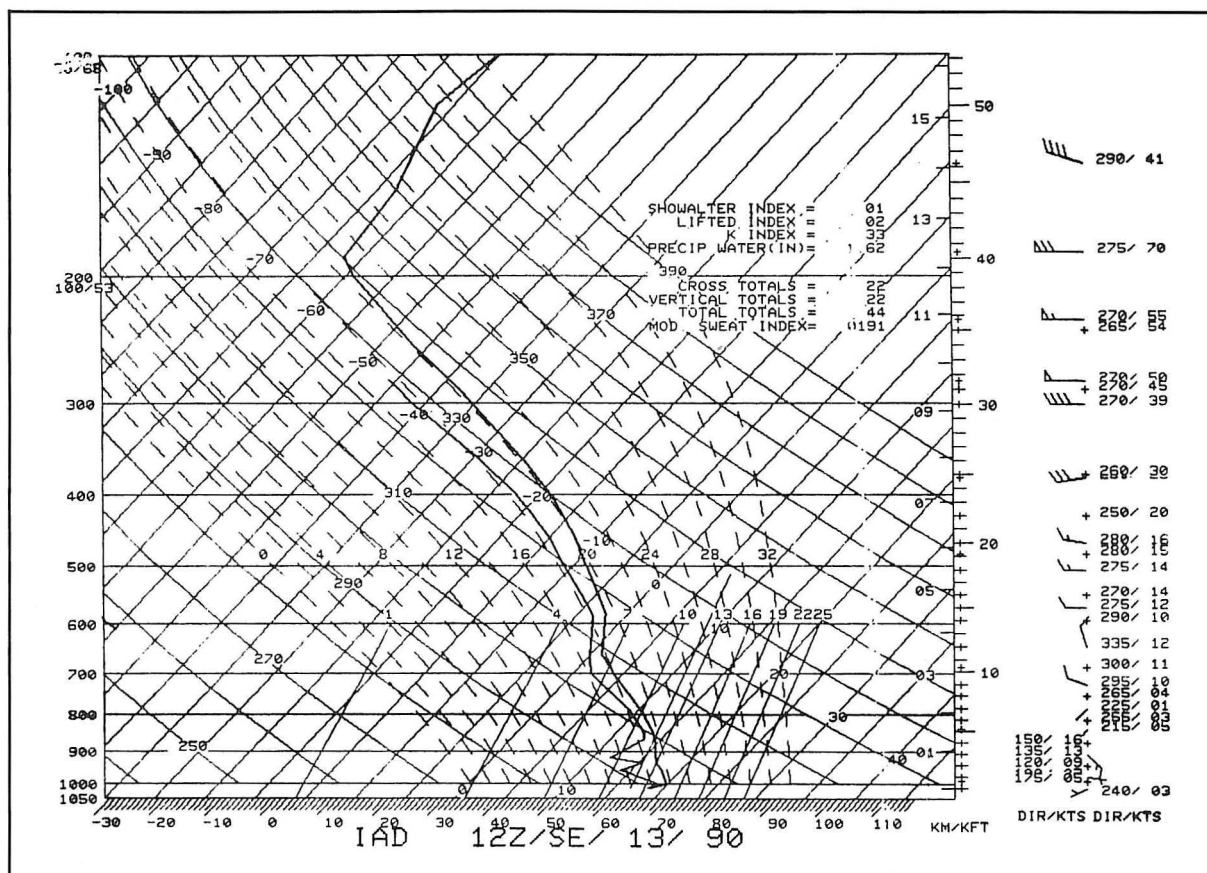


Fig. 7. Dulles Airport (IAD) sounding for 1200 UTC 13 September 1990.

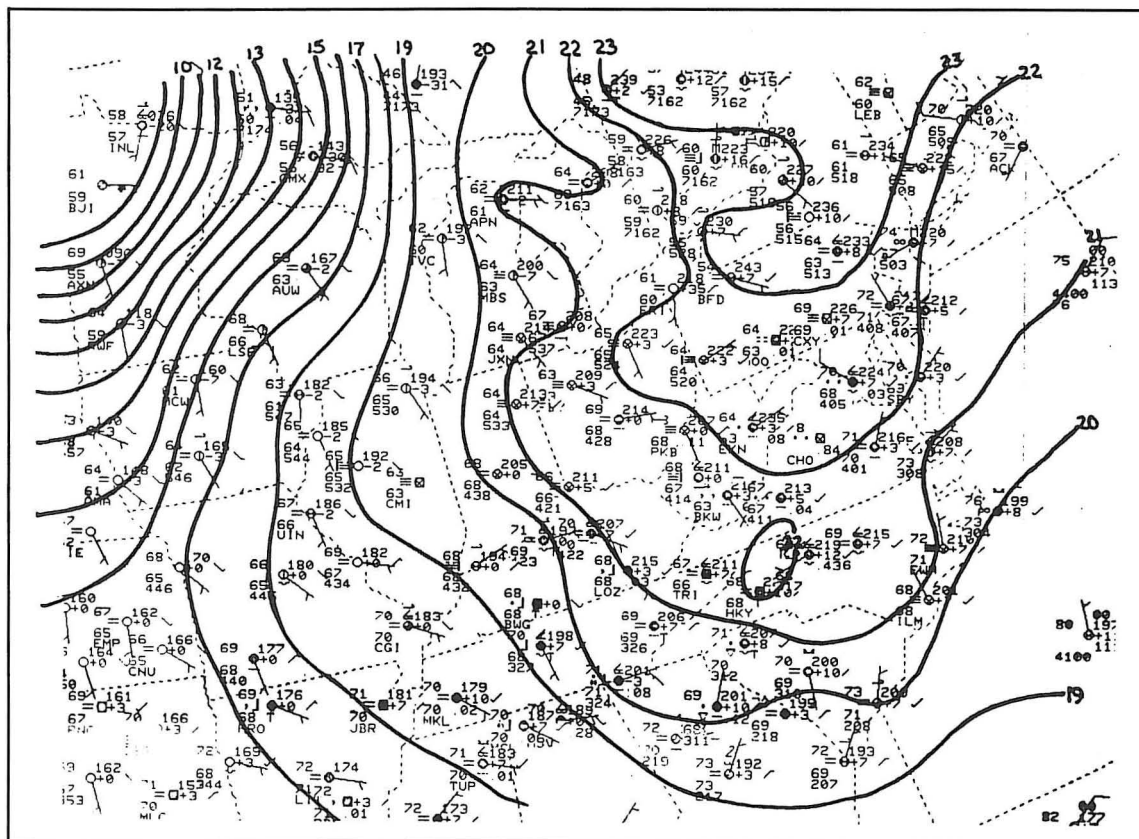
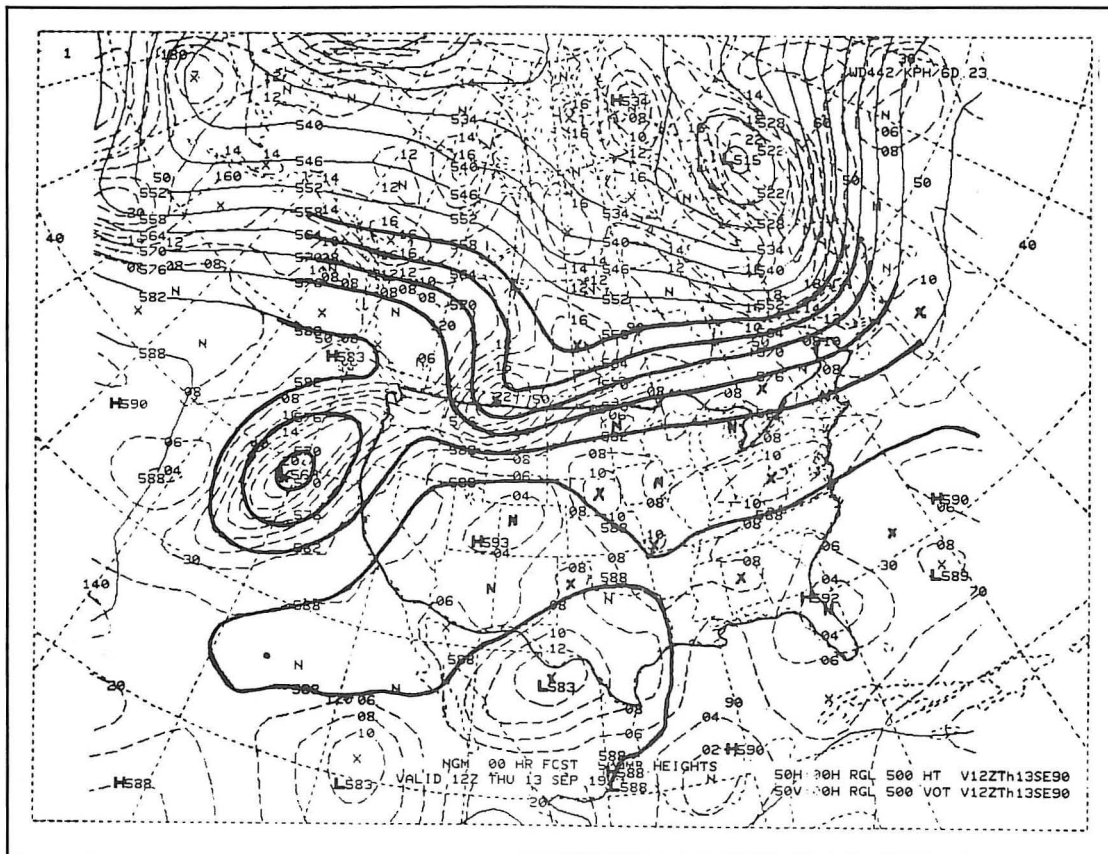


Fig. 8 MSL pressure analysis for 1200 UTC 13 September 1990.



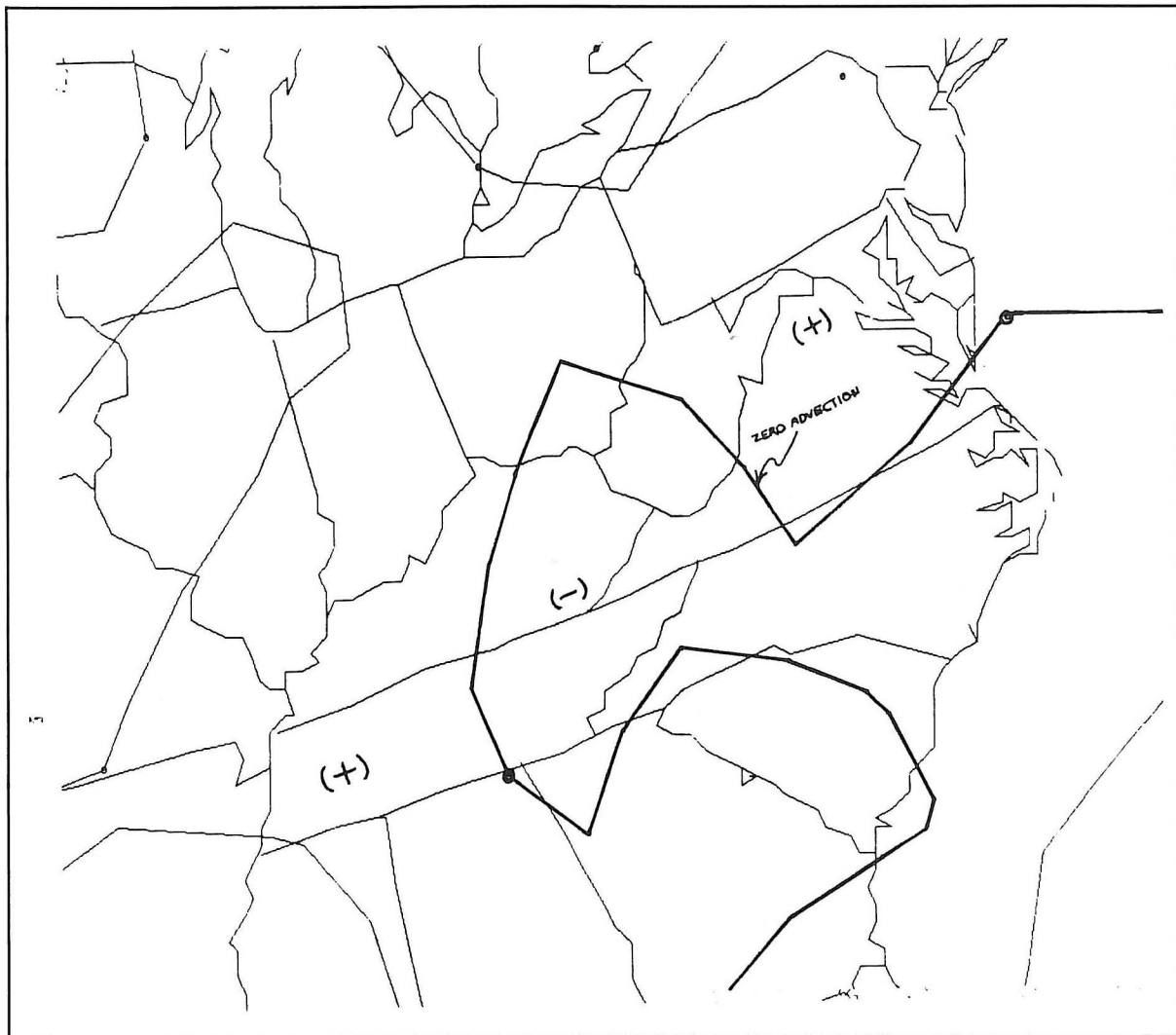


Fig. 10. 24-h NGM-derived forecast of 500-mb vorticity advection valid 1200 UTC 13 September 1990 (from DAR³E-II family graphics).

Unlike the 500-mb PVA method, PIVA can reveal potential upward vertical forcing in areas of warm advection, as well as the forcing resulting from the advection of cyclonic vorticity. Unfortunately, however, employing the 1000-500-mb thickness and 500-mb vorticity charts is not a true application of Trenberth's approximation (National Weather Service, 1991b) since it is the thermal wind at mid-levels, say in the 600-400-mb layer, that one is most interested in knowing. It is at mid-levels nearest the level of non-divergence where estimates of vertical motion are most crucial in developing baroclinic systems. Employing the 700-300-mb thickness analysis and 500-mb vorticity analysis available in the PC-based UA program (Foster 1988) may yield a truer application of Trenberth's approximation, but only for initial conditions.

Another disadvantage to the PIVA technique is that it neglects smaller scale but important advection and deformation effects (ageostrophic components) with frontal zones and in the vicinity of jets. In applying the PIVA technique to the 13 September event (Fig. 11), it appears that there

might be some weak synoptic scale forcing, but there is little to suggest a substantial rain event over a large area. The fact that the atmosphere is somewhat barotropic during the warm season results in thickness and vorticity contours that closely parallel one another, similar to the 500-mb height and vorticity contours in the PVA method. Consequently, little may be revealed by employing either technique in typical warm season situations.

4.3 Isentropic Analysis and Secondary Ageostrophic Circulations

An often neglected technique that dates back to the 1930s (Rossby 1937), isentropic analysis is again coming into favor as a useful and valid approach. Largely abandoned when pressure became the accepted vertical coordinate system, isentropic analysis is based upon the principle that in dry adiabatic flow, potential temperature is conserved. This becomes a convenient means for tracing the actual paths of individual parcels following the flow. The benefits of using

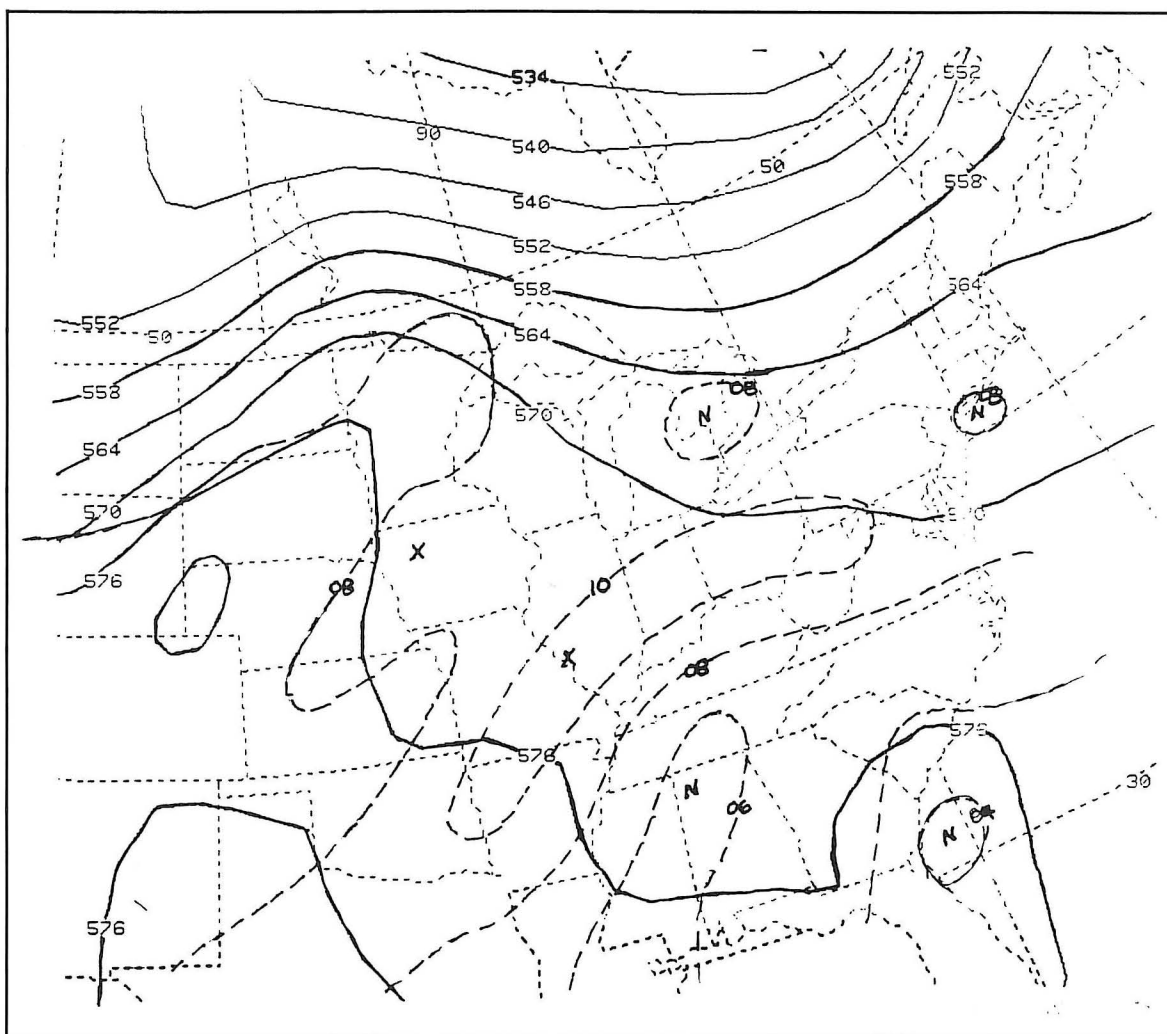


Fig. 11. 24-h NGM 1000-500-mb thickness (solid lines) and 500-mb vorticity (dashed lines) forecast valid 1200 UTC 13 September 1990.

isentropic analysis have been summarized by Uccellini (1976):

- 1) A more coherent three dimensional depiction of moisture transport can be attained than by using 850-mb or 700-mb analyses.
- 2) A simple means for directly estimating vertical motions is readily available.
- 3) Physical insight is provided into the juxtapositions of the vertical motion field, moisture transport, and the upper tropospheric jet stream.

The reader is also referred to a more detailed discussion of the advantages and disadvantages of isentropic analysis by Moore (1992).

Unlike the two dimensional perspective of an isobaric coordinate system, an isentropic approach gives a more realistic, three dimensional view in which isentropic surfaces slope through a significant depth of the atmosphere. In a situation of warm advection (e.g., southerly flow), a parcel will follow an isentropic surface (its potential temperature and entropy are conserved), undergoing adiabatic cooling as

it arrives at a higher level (lower pressure) at some point (further north). In this way, the atmosphere compensates for the warm advection through adiabatic cooling. Stated another way, air flowing on an isentropic surface from high pressure to low pressure represents upward vertical motion. If parcels ascend enough to reach their condensation levels, clouds and precipitation are a by-product of the process, and the parcels may end up at a higher (warmer) isentropic surface due to the release of latent heat. Isentropic analyses can be particularly useful during the warm season when dynamical forcing is typically weaker, and thermal and moisture advection are more important precipitation triggering mechanisms.

There are, at present, only a few widely available AFOS or PC-based applications programs at the NWS forecaster's disposal for evaluating isentropic lift, but the situation should improve greatly in the near future. The 0000 UTC and 1200 UTC 13 September 306°K isentropic analyses from the DAR³E-II Mesoscale Analysis and Prediction System (MAPS; Benjamin 1989) are illustrated in Figs. 12a,b. Isentropic analyses of pressure and wind on the 310°K surface

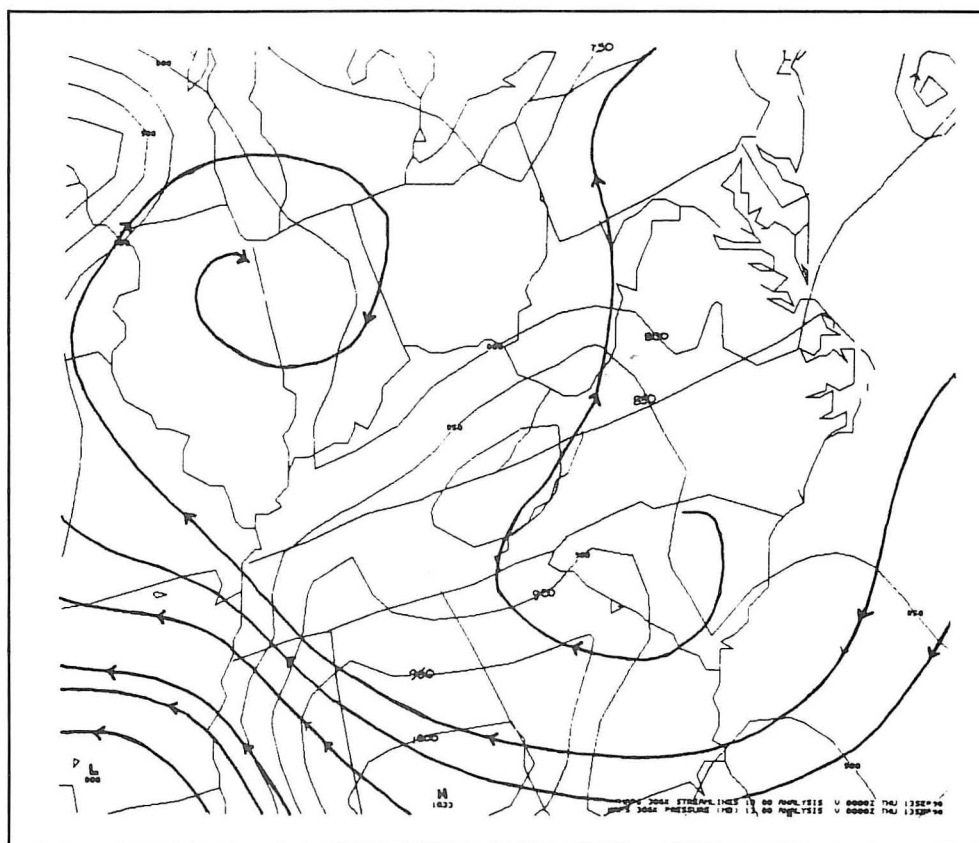


Fig. 12a. MAPS (Mesoscale Analysis and Prediction System) streamlines (solid lines with arrows) and pressure analysis for 306°K surface for 0000 UTC 13 September 1990 (from DAR³E-II family graphics).

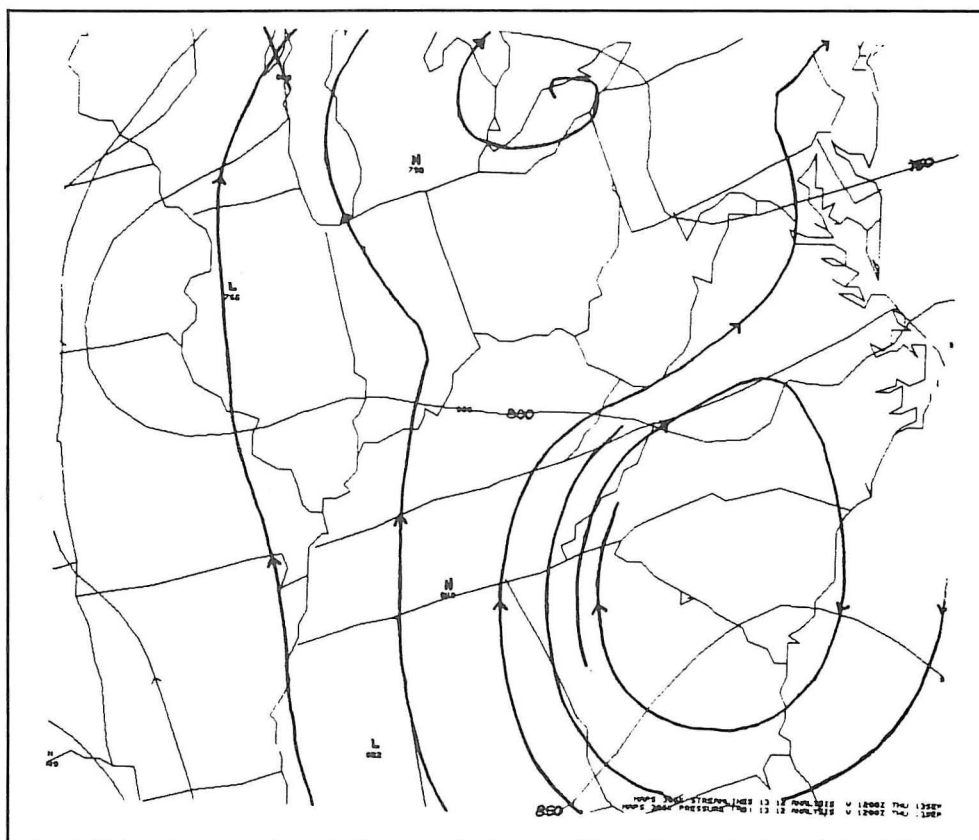


Fig. 12b. As in Fig. 12a except for 1200 UTC 13 September 1990.

from the PCGRIDDS program are also presented in Figs. 12c,d. These analyses indicate that a parcel trajectory underwent considerable upward vertical displacement moving northward through the lower and mid-Mississippi Valley and northeastward into southwest Virginia and southern West Virginia. The air mass was quite moist, and this ambient moisture in combination with isentropic lift appears to have been at least partially responsible for relative humidities exceeding 90% over southwest Virginia and West Virginia by 0000 UTC 13 September (Fig. 12c). In spite of seemingly weak synoptic scale dynamic forcing, these analyses revealed the presence of a significant, eastward translating vertical motion field in the form of isentropic lift.

The PCGRIDDS graphics routines were employed to generate a vertical cross section of pressure and isentropic surfaces, as well as winds in the plane of the cross section, from the lower Mississippi valley (point A) to off the mid-Atlantic coast (point B) at 1200 UTC 13 September (Fig. 13). This cross section showed a gradual upslope flow from southwest to northeast with isentropic uplift most pronounced at upper levels (i.e., between 200 and 300 mb along the 340k surface).

Even more revealing was a vertical cross section of secondary ageostrophic circulations constructed from point C to point D (Fig. 14). This cross section clearly shows the ascending branch of a thermally indirect transverse vertical circulation centered over northern Virginia. The structure and nature of jet stream circulations is described in greater detail by Uccellini and Kocin (1987), among others. Figure 14 is particularly unique in that it is a 12-h forecast utilizing data from the 0000 UTC 13 September NGM model run, which, as stated earlier, had a better handle on the impending rain event.

The associated 250 mb jet streak (32 m s^{-1}) is illustrated in Fig. 15. It is apparent that at 1200 UTC northern Virginia was situated under the left exit region of the jet. Therefore, it appears that upper-level jet dynamics were one of the primary triggering mechanisms in the 13 September rain event. The jet stream likely aided in maximizing or concentrating warm air advection in the region corresponding to the ascending branch of a thermally indirect transverse vertical circulation as illustrated in Fig. 14.

As stated by Moore (1992): "With the advent of faster computers and interactive graphic capabilities in the forecast office, the time seems right to re-introduce the isentropic viewpoint to the forecast community." Indeed, his advice has not gone unheeded. New DAR³E-II interactive analysis and forecast products have included the development of isentropic multi-level fields and cross sections, with analyses and forecasts at 3-h intervals. Diagnostic software such as the PCGRIDDS program have similar capability, and can be utilized quickly and in near real-time, which is important to operational forecasters. Hopefully, in the future, wider access to gridded model output will speed the rebirth of the isentropic coordinate system.

4.4 Quasi-Geostrophic Diagnostic Fields (Q-vectors and DIV-Q)

As noted earlier, the differential vorticity advection and Laplacian of thermal advection terms in the omega equation are often out of phase in the real atmosphere. This tendency for the terms to cancel each other can create difficulties for the forecaster attempting to estimate the relative contribution of each term. Trenberth's (1978) method is an alternative for estimating quasi-geostrophic forcing. Hoskins et al. (1978), and Hoskins and Pedder (1980) went a step further by mathe-

matically combining the two terms of the omega equation into a complete solution for the total quasi-geostrophic forcing. This simple vector quantity is known as the Q-vector. Unlike Trenberth's method, Q-vector analysis includes the effects of the geostrophic deformation of horizontal temperature gradients, and is therefore applicable throughout a deeper portion of the troposphere. Barnes (1985) and others have since demonstrated the utility of Q-vectors as a diagnostic tool.

Q-vectors are a convenient way of graphically depicting the combined effects of differential vorticity and thermal advection. Q-vectors are proportional to the component of the ageostrophic wind resulting from baroclinic adjustment processes in the presence of the horizontal advection of temperature and vorticity by the geostrophic wind. Where Q-vectors converge, upward motion is inferred; and where Q-vectors diverge, downward motion is inferred. In other words, the divergence of Q-vectors (DIV-Q) yields a solution for the forcing in the quasi-geostrophic vertical motion field. Therefore, for DIV-Q charts, negative values (convergence of Q-vectors) imply upward motion, while positive values (divergence of Q-vectors) imply downward motion.

Hoskins and Pedder (1980); Barnes (1985); Keyser, Reeder, and Reed (1988); and Barnes and Colman (1989) have demonstrated that Q-vectors and isotherms also provide the components from which the frontogenetic tendency of a system can be inferred. Q-vectors perpendicular to isotherms are an indication of the frontogenetical tendencies of induced ageostrophic secondary circulations. More specifically, Q-vectors pointing from cold air to warm air are indicative of frontogenesis, and an associated thermally direct circulation. While advection by ageostrophic components is not contained within quasi-geostrophic theory, Barnes (1985) has suggested that geostrophic frontogenesis provides the organizing environment in which ageostrophic frontogenetic components operate. In utilizing QG diagnostic graphics, Barnes has recommended a comparison with constant pressure analyses, moisture and stability analyses, model forecasts, and satellite imagery. Barnes has also suggested forecasters examine the vertical variation of DIV-Q (e.g. 300 and 700-mb DIV-Q) as possibly being indicative of the phasing of upper troughs and low-level systems. The phasing of DIV-Q fields at different levels or the development of DIV-Q couplets, may indicate a developing system. He also suggests that frontogenetic forcing implied by cross-isotherm Q-vectors seems to relate well to developing cloud patterns associated with deformation fields.

QG theory is the basis for the PC-based Upper Air (UA) program (Foster 1988) now widely used throughout the National Weather Service. This easy-to-use application program includes computations of Q-vectors and DIV-Q at two constant pressure levels from rawinsonde network data. Data from this program at 0000 UTC 13 September (Fig. 16a) showed 500-mb convergence of Q-vectors (negative values) over the lower and mid-Mississippi valley and the western Great Lakes. Another convergence maximum, coinciding with the mid-Atlantic rain area, extended from central Pennsylvania into northern Virginia. It is important to remember that these implied vertical motion fields were revealed in a very weak 500-mb vorticity field, suggesting that the combination of increasing vorticity advection with height and warm advection were producing substantial vertical lift at this time.

As suggested earlier, it is also possible to ascertain the geostrophic frontogenetic function with the UA program. Utilizing the 850-500-mb mean temperature and the 700-mb

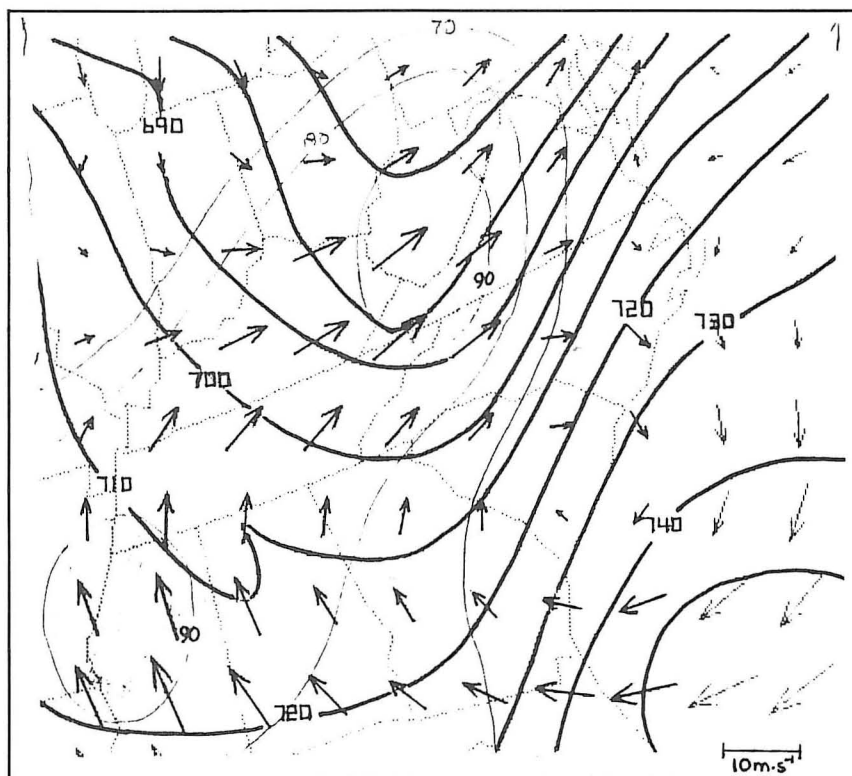


Fig. 12c. PCGRIDDS isentropic analysis of pressure and wind on the 310°K surface at 0000 UTC 13 September. Shaded area depicts 700-mb relative humidity > 90%. Magnitude of wind vectors shown at lower right.

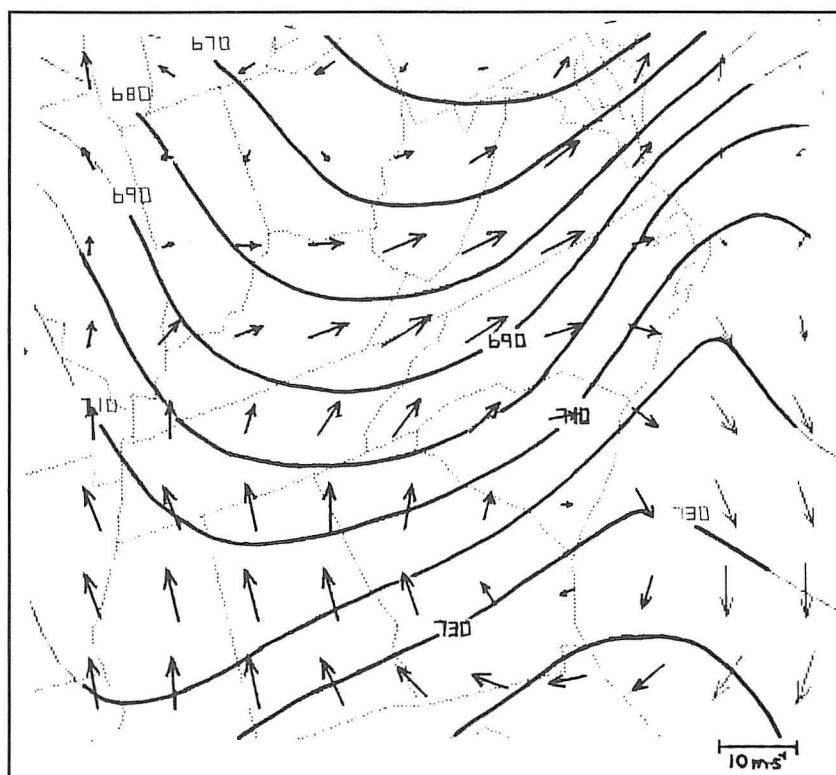


Fig. 12d. PCGRIDDS isentropic analysis of pressure and wind on the 310°K surface at 1200 UTC 13 September. Magnitude of wind vectors shown at lower right.

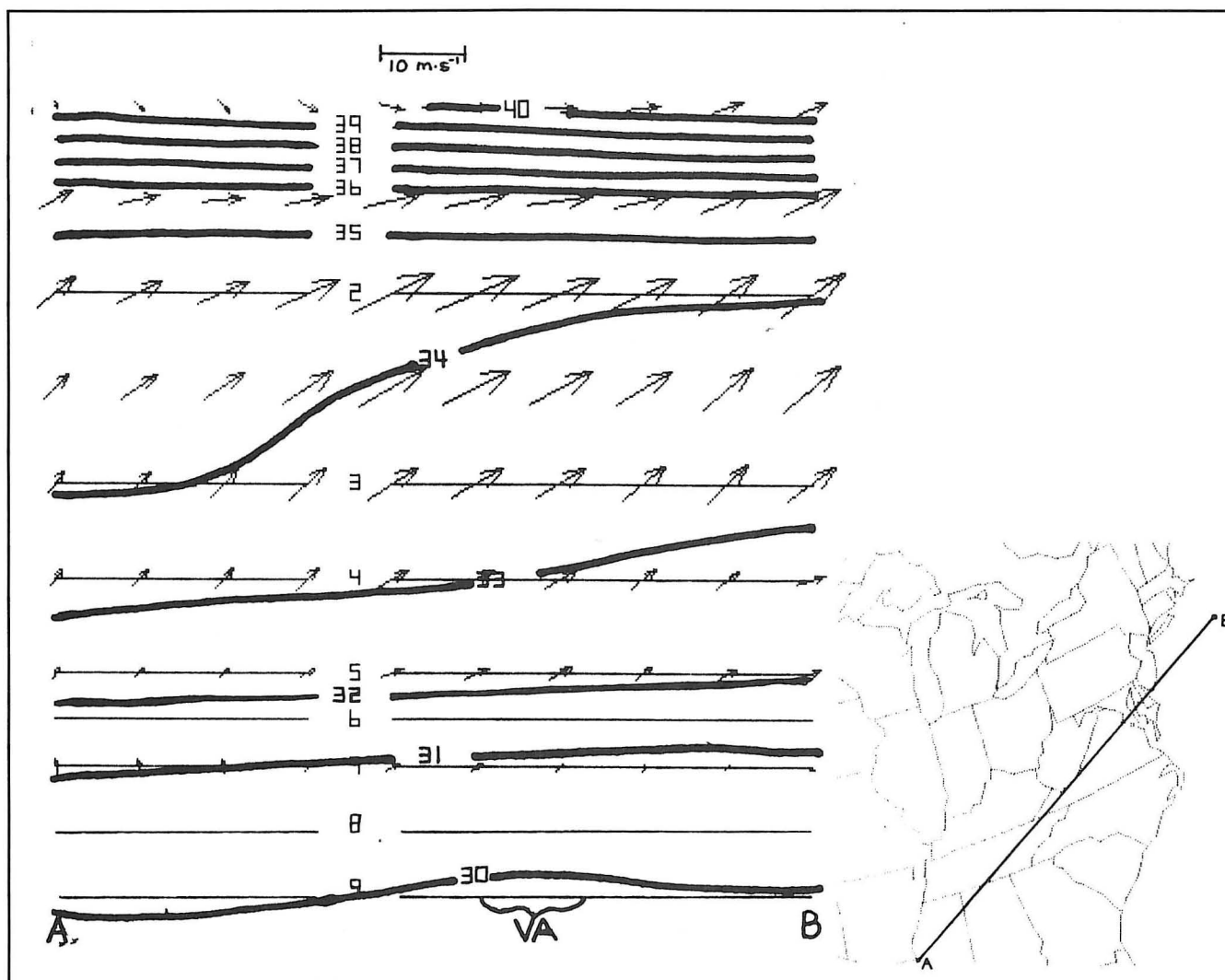


Fig. 13. Vertical cross section of pressure, isentropic surfaces (heavy solid lines; $^{\circ}\text{K} \times 10$), and wind at 1200 UTC 13 Sept. Cross section constructed from point A to point B as shown in inset. Horizontal lines represent pressure surfaces (mb $\times 10$). Magnitude of wind vectors shown at top.

Q-vectors, the results for the 0000 UTC 13 September case are illustrated in Fig. 16b. The Q-vectors are pointing from cold air to warm air from the Ohio valley through the middle and lower Mississippi valley implying weak frontogenetic forcing for this region. This is roughly coincident with the upward motion inferred in Fig. 16a. Physically, this means that the horizontal temperature (density) gradient in this region was increasing with time. In order to maintain geostrophic balance, a secondary thermally direct circulation was likely induced with air rising on the warm (south) side of the baroclinic zone and sinking on the cool (north) side.

4.5 Quasi-Geostrophic Predictive Fields (Progged Deep-Layer DIV-Q)

Advection by ageostrophic wind components is not contained within quasi-geostrophic theory, nor is the rate of change of the ageostrophic wind. Both factors become very important in areas where motion exceeds that predicted by quasi-geostrophic processes, especially on smaller temporal

and spatial scales. This is particularly true along narrow frontal zones and in the vicinity of jet streaks, where ageostrophic flow is a major component of the total wind. In addition to these inherent limitations, the UA program Q-vector and DIV-Q analyses are only available at 700-mb and 500-mb levels. Examining the Q-vector and DIV-Q charts at these two levels may not give a clear picture of deep-layer forcing and provides no insight into what is occurring above 500 mb. Finally, the UA program is diagnostic and not predictive. To fill these needs, experimental, predictive, NGM-derived deep-layer DIV-Q charts are being evaluated.

Figure 17a is an analysis of the 700-300 mb deep-layer DIV-Q from the DAR³E-II workstation for 0000 UTC 13 September. The regions of upward forcing over the middle and lower Mississippi river valley and the mid-Atlantic states correspond closely to those depicted on the UA diagnostic chart valid for the same time period (Fig. 16a). This suggests that deep-layer Q-vector convergence and its implied upward motion was in place by 0000 UTC over the northern mid-

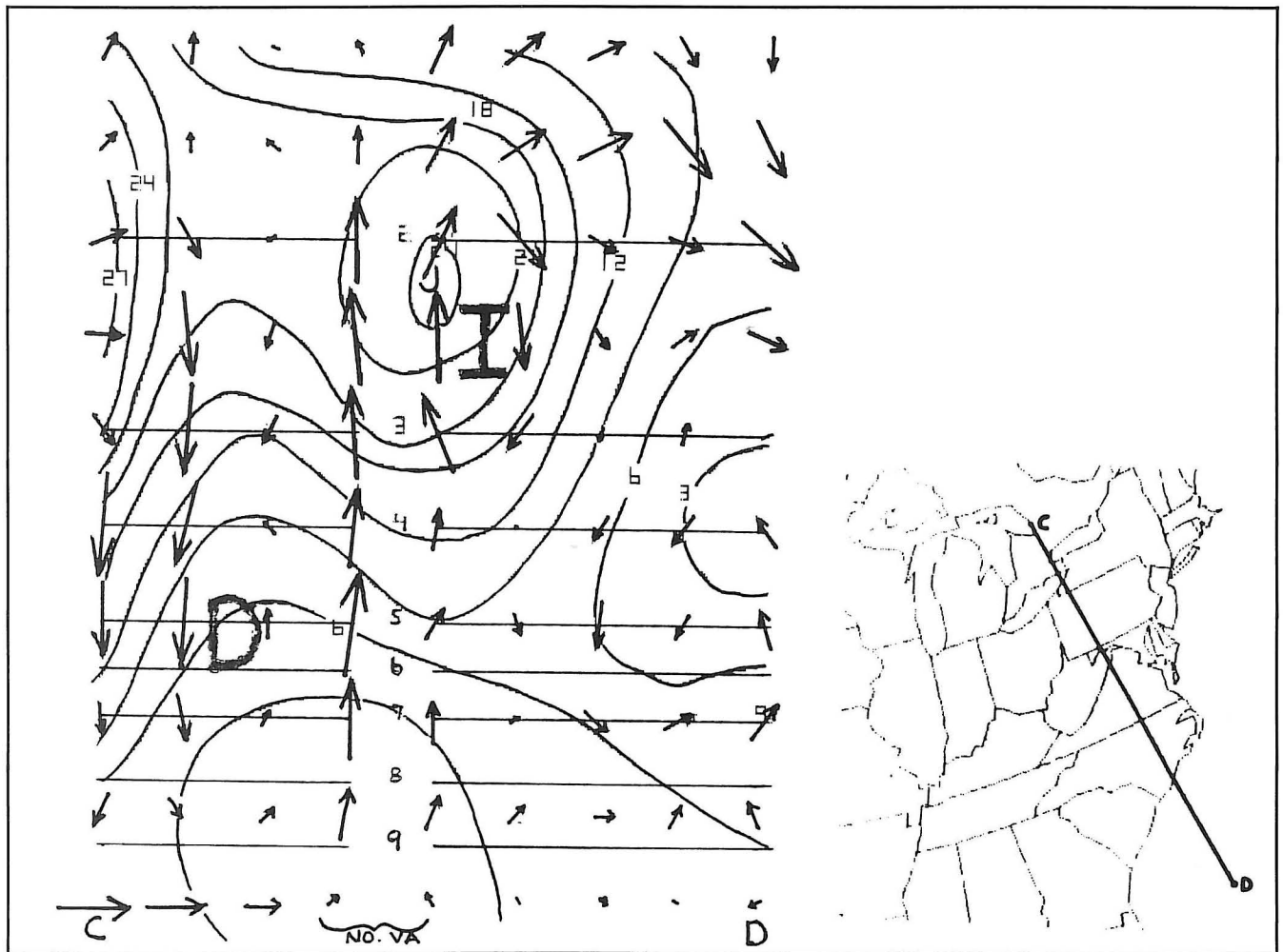


Fig. 14. Vertical cross section of ageostrophic secondary circulations constructed from point C to point D in inset. Cross section is a 12-h NGM-based forecast valid at 1200 UTC 13 September. Vectors represent the vertical motions and ageostrophic winds in the plane of the cross section. Solid lines are forecast wind speeds (m s^{-1}). Horizontal lines are pressure surfaces ($\text{mb} \times 10$). Bold-faced letters D and I represent thermally direct and indirect circulations, respectively.

Atlantic states. Figure 17b is a 12-h NGM-based forecast of the deep-layer DIV-Q valid for 1200 UTC. This convergent Q-vector field was forecast to persist while slowly translating eastward towards the coast. One might conclude that if the moisture and stability fields were favorable in a region of persistent upward vertical motion, precipitation should be the end result, giving added weight to a wetter forecast. Figure 17c shows the analysis of the deep-layer DIV-Q for 1200 UTC 13 September, indicating the persistent upward motion did occur over northern Virginia and eastern Maryland.

4.6 NWP Vertical Motion Fields

There are those who would argue that forecasters should dispense with these various techniques for assessing vertical motion and go directly to the vertical motion fields generated by the numerical models. Indeed, the primitive equations include both advections by, and the local rate of change of geostrophic and ageostrophic wind components. The NWP

models, therefore, have some capability for representing forcing even in regions such as frontal zones in which there are large departures from geostrophy. This, some would argue, has diminished the need to rely upon individual techniques for assessing vertical motion. However, Dunn (1991) makes a case for the continuation of subjective evaluations of vertical motion fields by the forecaster. He argues that such analyses are powerful tools in understanding and supplementing numerical model output that better enable the forecaster to judge the relative merit of the various model solutions.

The 24-h 700-mb vertical velocity forecasts from the NMC Nested-Grid Model (NGM) and Aviation (AVN) models, valid at 1200 UTC 13 September indicated very weak vertical motion (Fig. 18a,b). These charts provided few, if any clues as to the likelihood of a significant rainfall event over the mid-Atlantic states region. However, NWP output based on 0000 UTC 13 Sept data showed enhanced vertical velocities over portions of the mid-Atlantic states. Figure 19 shows

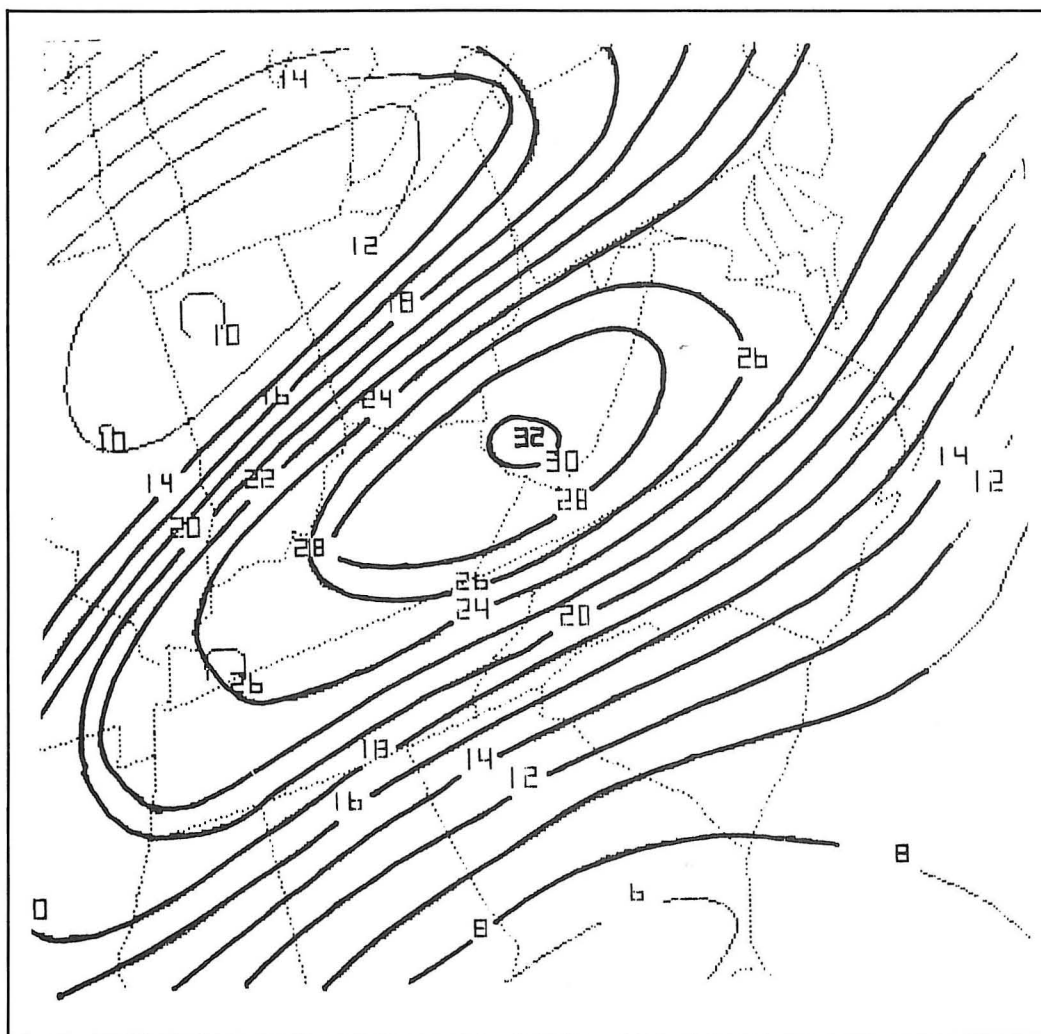


Fig. 15. Analysis of 250-mb winds (m s^{-1}) for 1200 UTC 13 September.

the 12-h forecast of 700-mb vertical velocity from PCGRIDDS valid at 1200 UTC 13 September. (Recall that PCGRIDDS utilizes model gridded data). These data showed an area of rising motion over northern Virginia, central Maryland and southern Pennsylvania.

5. Discussion

This paper has described a mesoscale rainfall episode which, due to the weakly-forced and subtle nature of the event, presented a challenge to forecasters. An attempt was made to determine the mechanisms responsible for upward vertical motion and the subsequent precipitation through an analysis of surface, upper-air, and numerical model output data via a variety of diagnostic methods.

Numerical model output based on 1200 UTC 12 September data did not show the potential for the heavy rain event. However, the 0000 UTC 13 September models handled the event quite well and were instrumental in determining what factors played a role in the organization of the mesoscale heavy rain area. Unfortunately, these data were not available for the evening forecast update on 12 September. The reason for the flip-flop behavior of the models can only be speculated

upon. Perhaps the morning model runs were not initialized well, or certain features such as the upper level jet streak were not sampled by the rawinsonde network or were just beginning to develop and strengthen. It may also have been due to mesoscale developments on temporal and spatial scales too small for the models to resolve (i.e., sub-grid scales).

It is apparent that several factors contributed to the enhanced rainfall event. One of the main contributing factors in the development of the enhanced precipitation appears to have been forcing at jet stream level due to a thermally indirect transverse circulation, which the 0000 UTC model runs successfully depicted. However, it appears that mesoscale features were responsible for focusing the heavier rains. One such feature was the cool air trapped at the surface. Warm and moist air overriding this low level cool air probably helped to enhance the rainfall. The axis of the heaviest rain was also situated along the eastern slopes of the Blue Ridge Mountains, implying that the low-level easterly upslope flow may have also contributed to the enhanced rainfall (recall that 900-mb winds were from the southeast at 15 kt from the 1200 UTC 13 September IAD sounding). In addition, there

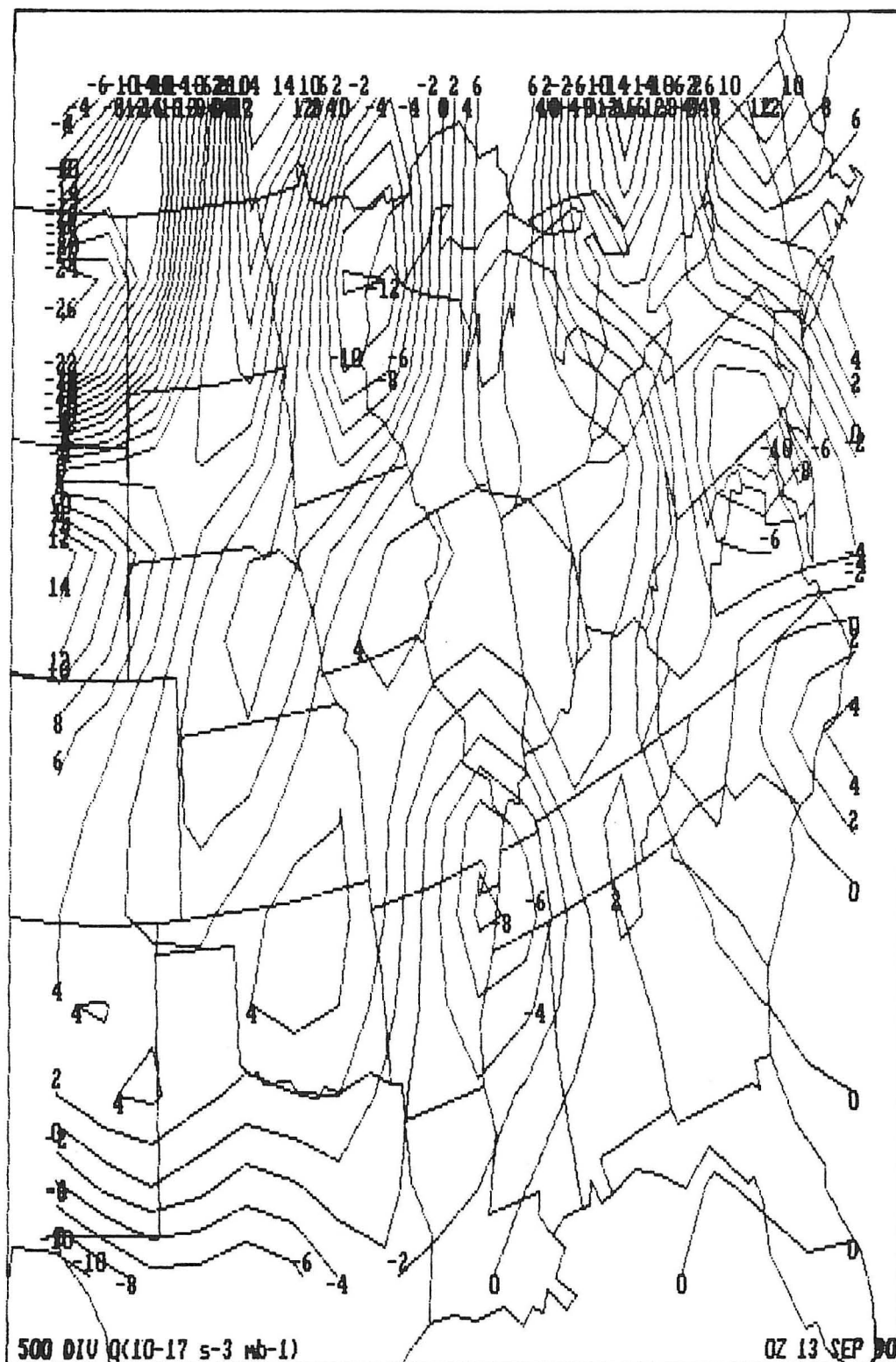


Fig. 16a. 500-mb DIV-Q analysis (5QD) for 0000 UTC 13 September 1990 (from Foster PC-based UA program).

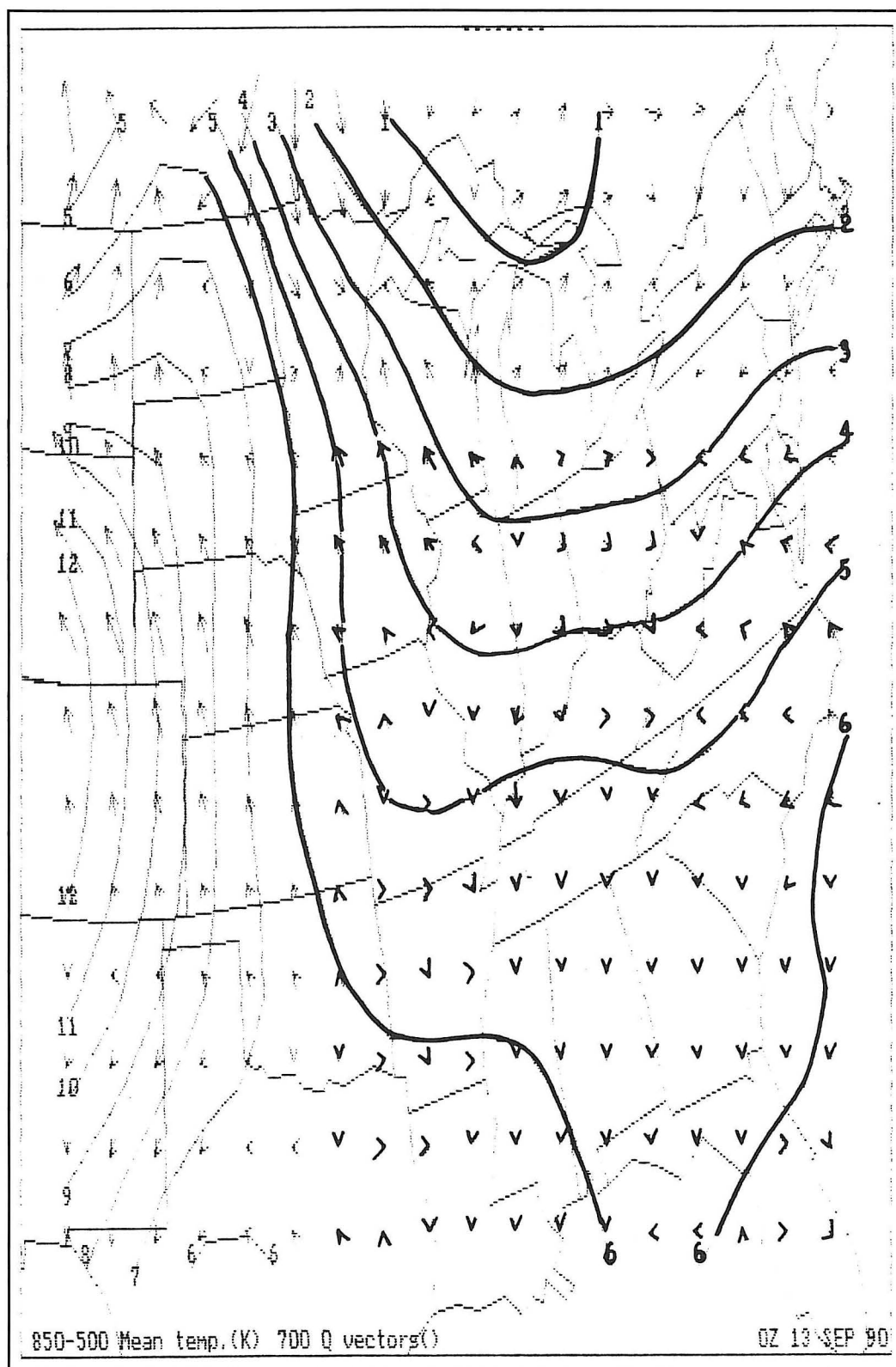


Fig. 16b. 850-500-mb mean temperature analysis (7QT, solid lines), and 700-mb Q-vector analysis (7QQ, arrows), for 0000 UTC 13 September 1990 (from Foster PC-based UA program).

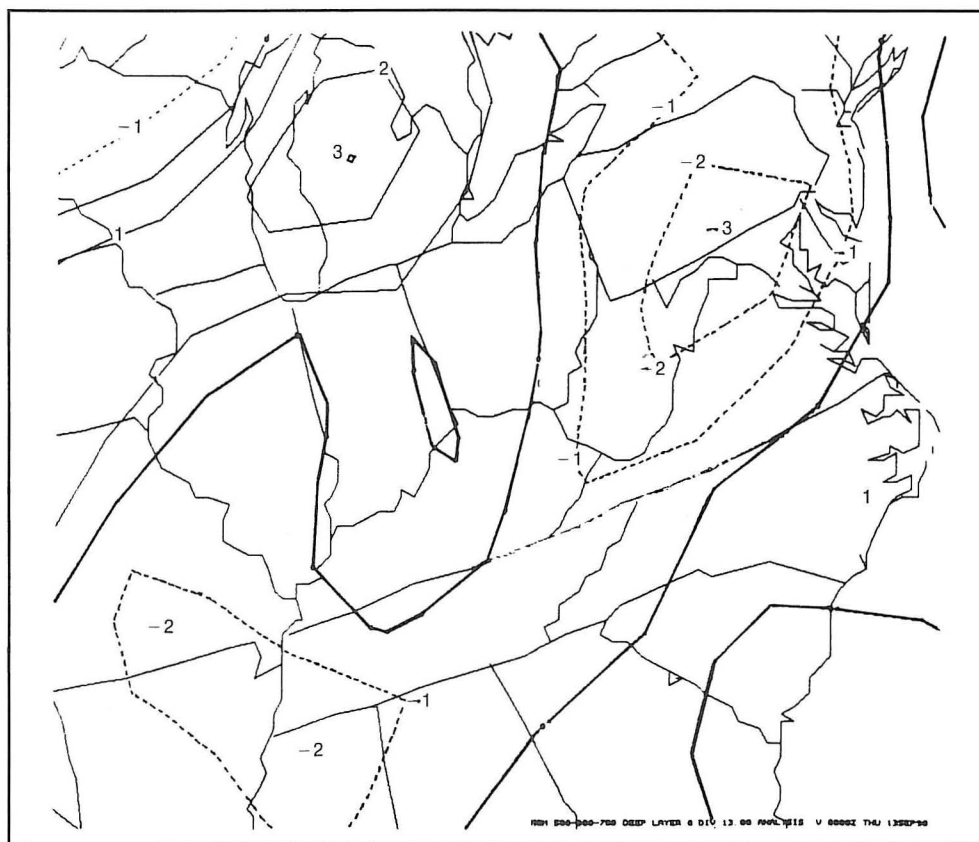


Fig. 17a. NGM-derived deep-layer (700-300 mb) DIV-Q analysis for 0000 UTC 13 September 1990 (from DAR³E-II family graphics).

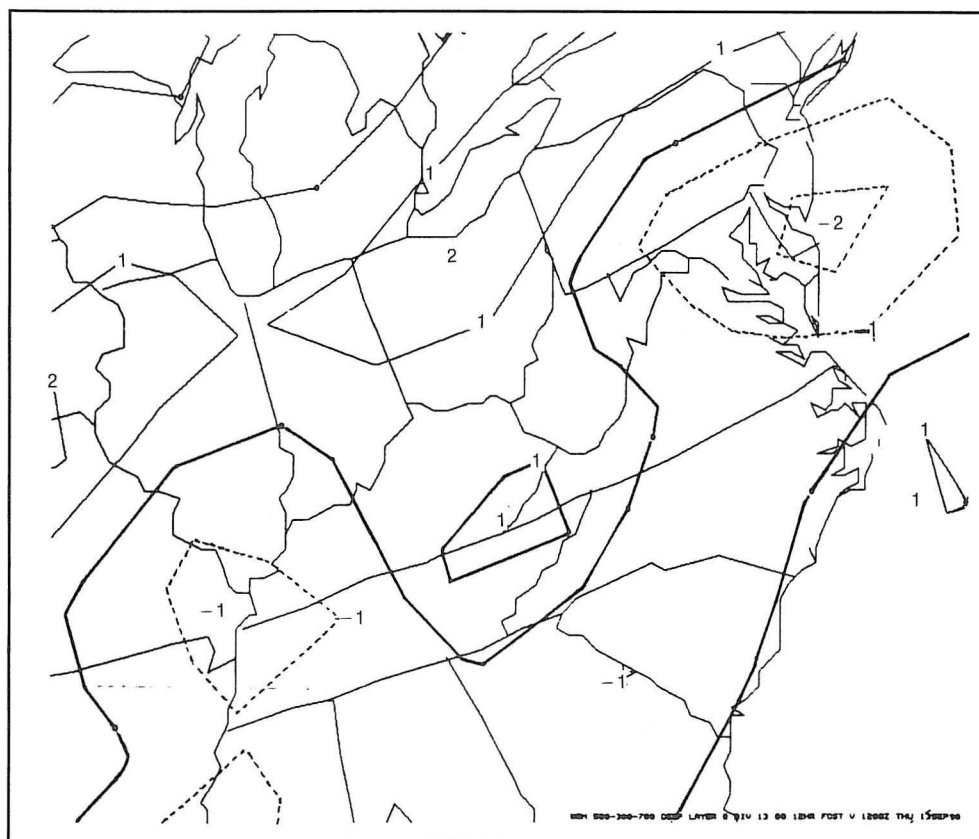


Fig. 17b. 12-h NGM-derived deep-layer (700-300 mb) DIV-Q forecast valid 1200 UTC 13 September 1990 (from DAR³E-II family graphics).

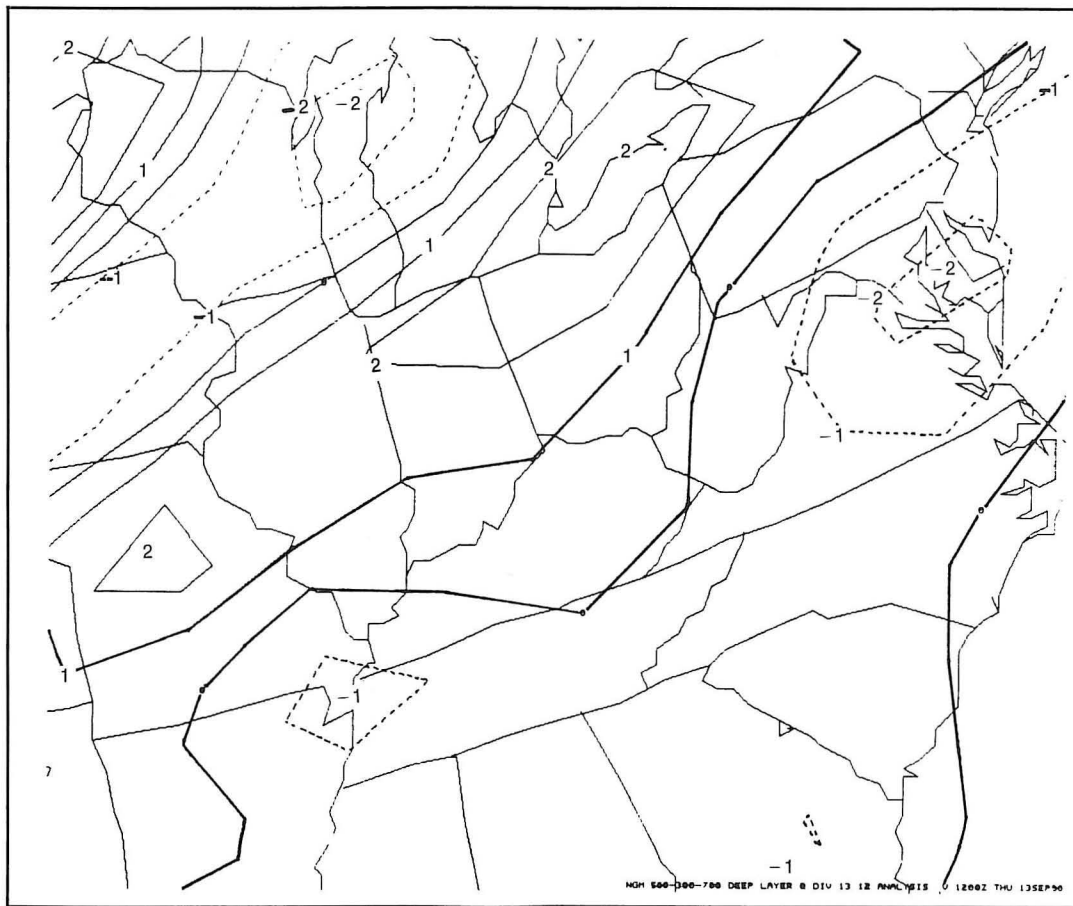


Fig. 17c. NGM-derived deep-layer (700-300 mb) DIV-Q analysis for 1200 UTC 13 September 1990 (from DAR³E-II family graphics).

were indications of weak low-level frontogenesis in the vicinity.

The PCGRIDDS program, as well as quasi-geostrophic DIV-Q analyses and 12-h forecasts were very useful in diagnosing the features leading up to the heavy rain event. It is questionable that any of these data or analyses would have alerted the forecaster to potential rainfall amounts of between 2 and 3 inches. However, vertical motion fields associated with secondary ageostrophic circulations and the QG analyses and forecasts would have more accurately delineated the area of enhanced rainfall by showing a coherent and apparently well organized area of upward vertical motion, which in combination with other methods described, might have resulted in an improved forecast weighted more heavily toward precipitation.

When using QG data in either a diagnostic or prognostic mode, the operational forecaster should be alert for features displaying continuity in both time and space. More credence can be given to longer-lived features than to those which are shortlived, and therefore may be spurious. Although nothing has been said concerning the magnitude of the DIV-Q features, it is known that cool season systems usually display larger values than their warm season counterparts. However, it appears that the continuity and trends in the magnitudes of these features are more important than the actual magnitudes themselves. In addition, the phasing of DIV-Q fields at differ-

ent levels or the development of DIV-Q couplets may indicate a developing system.

Other data should be analyzed in order to determine the atmosphere's response to upward vertical motion. The stability of the atmosphere in areas of converging Q-vectors should be investigated. Static stability can be ascertained to some degree by the 700-500-mb temperature lapse rate. Visible and IR satellite imagery, along with water vapor data, can give important clues as to the atmosphere's response. For example, cooling and/or expanding cloud tops would be indicative of upward motion, and these trends should be carefully compared with the various diagnostic products and model forecasts. The integration and assimilation of all available data types is extremely important in producing an accurate forecast.

In spite of the merits of the various diagnostic programs such as the divergence of Q-vectors, experience in Denver has shown (Dunn 1991) that these applications do not enjoy wide acceptance and routine application by operational forecasters until they become available in model-derived prognostic fields. Gridded model output will make possible the availability of a virtually limitless variety of prognostic fields at high spatial and temporal resolution, and this is already a possibility with such programs as PCGRIDDS and GEMPAK (Koch et al. 1983). On the pre-AWIPS workstation at the NWS Forecast Office Norman, Oklahoma, gridded data from

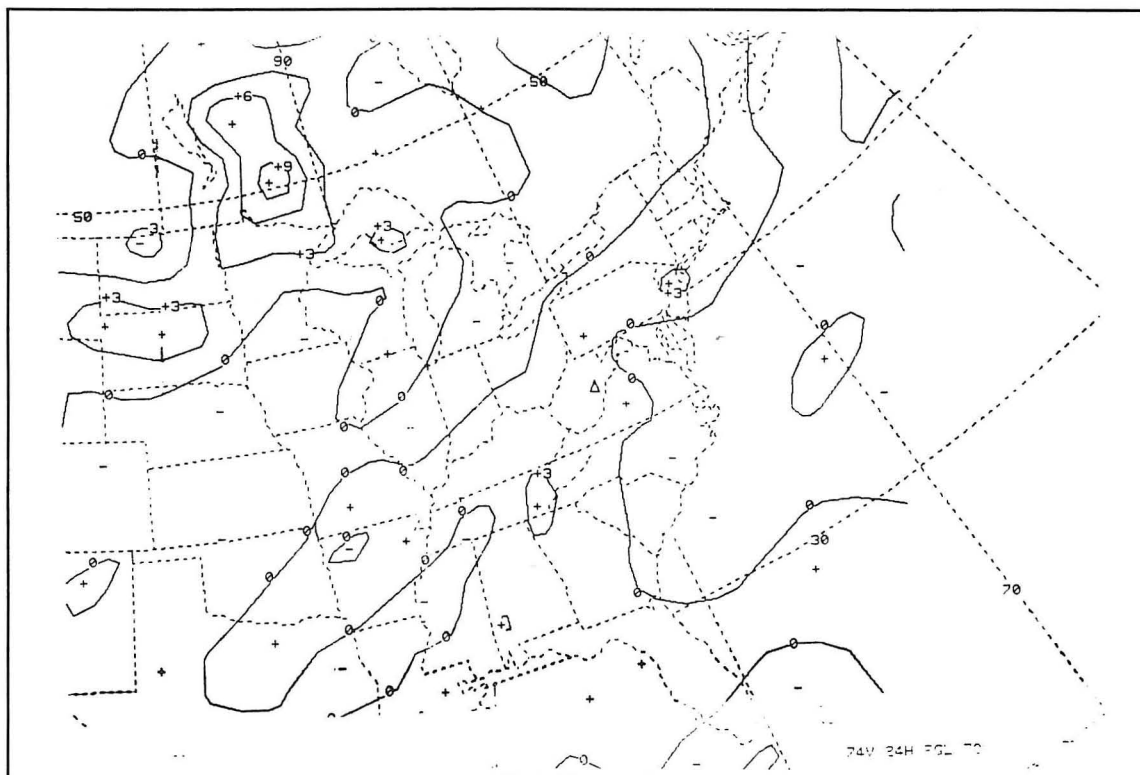


Fig. 18a. 24-h NGM forecast of 700-mb vertical velocity valid 1200 UTC 13 September 1990.

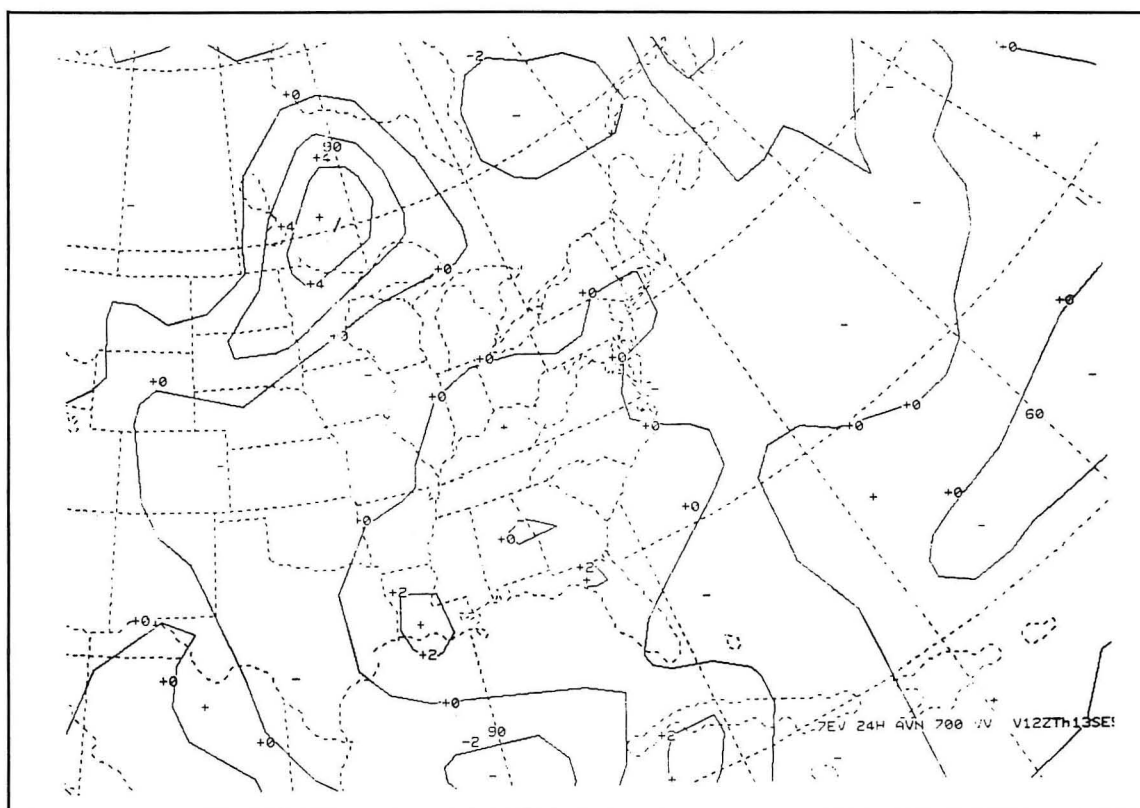


Fig. 18b. 24-h AVN forecast of 700-mb vertical velocity valid 1200 UTC 13 September 1990.

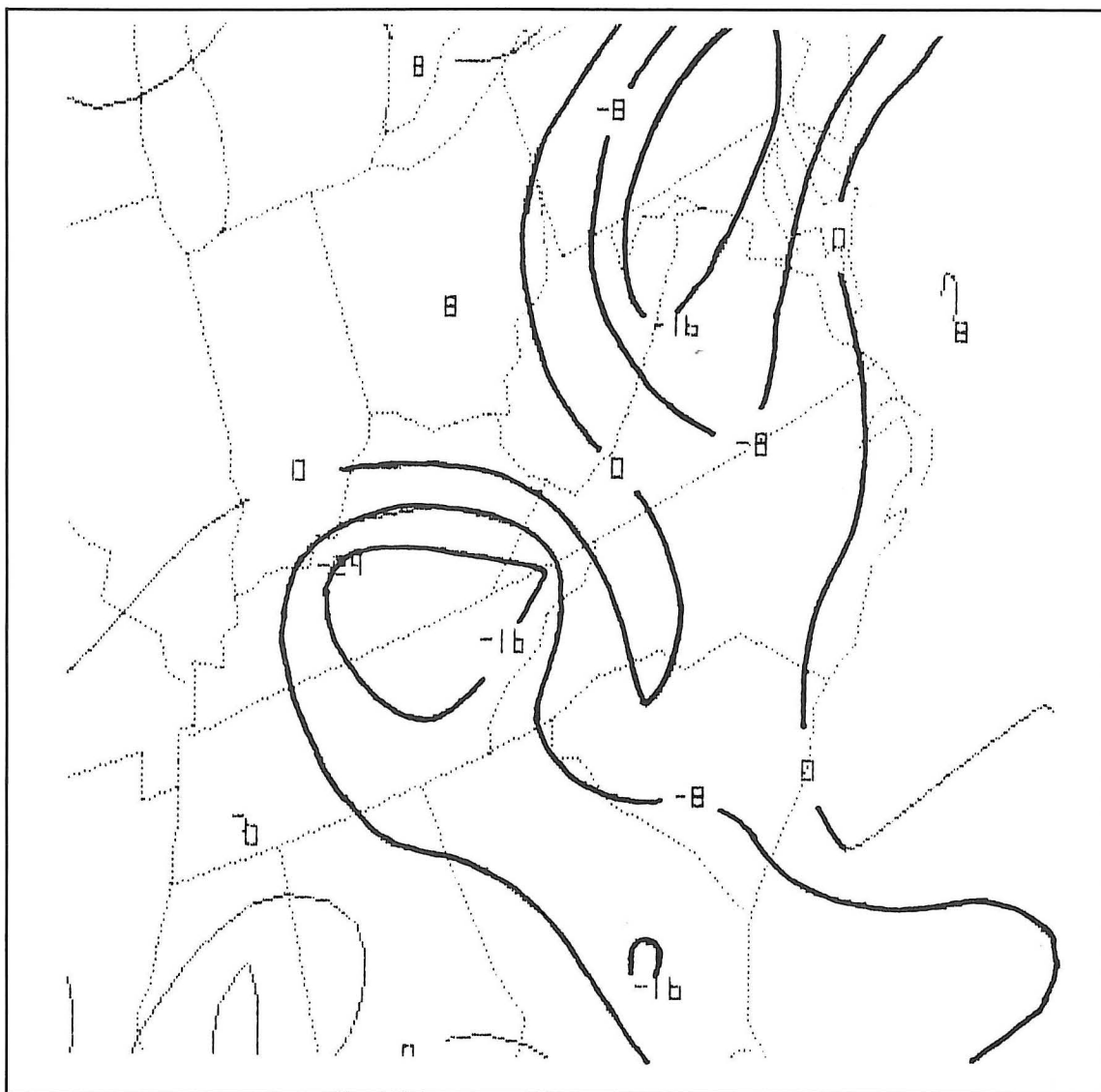


Fig. 19. 12-h NGM forecast of 700-mb vertical velocity valid at 1200 UTC 13 September 1990 from PCGRIDS. Units in microbars per second with negative values corresponding to upward motion.

the NGM model are available at 6-h forecast increments with a vertical resolution of 50 mb (Ruthi 1991). This workstation provides 22 forecast fields at the 850-mb level alone! With the flood of information that will become available in the future, it is important that forecasters learn to focus on data pertinent to the forecast problem of the day, and to have clear ideas of what to look for, where, and how to interpret the displays (Hoffman 1991).

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