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# WSR-88D OBSERVATIONS OF CONDITIONAL SYMMETRIC INSTABILITY SNOWBANDS OVER CENTRAL PENNSYLVANIA

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## 1. INTRODUCTION

On October 30, 1993 a developing surface cyclone along the East Coast produced a combination of rain and snow over Pennsylvania and New York. This storm was accompanied by some unseasonably cold air which produced snow during the Chicago Marathon and a white Halloween across northern Pennsylvania and southern New York. Most of the precipitation over central Pennsylvania fell from organized bands which were aligned nearly parallel to the thermal wind. This storm was the first winter-type storm observed by the recently installed (October, 1993) National Weather Service (NWS) Doppler Weather Surveillance Radar (WSR-88D) in central Pennsylvania.

The banded nature of precipitation associated with extratropical cyclones has been well documented (see Browning and Reynolds 1994; Browning 1986; Bennetts and Hoskins 1979; Hobbs 1978; Houze et al. 1976). Hobbs (1978) noted that regions of locally heavy precipitation associated with oceanic cyclones occurred on a mesoscale. The bands were classified into five types, including warm-frontal, warm sector, cold frontal, pre-frontal cold surge and post frontal bands. The bands were typically 1000 km in length but contained smaller features on the order of 100 km embedded within them.

Conditional Symmetric Instability (CSI) (Emanuel 1983; Snook 1992), often referred to as **"slantwise"** convection, is one mechanism which can create banded precipitation. It has been shown by Wolfsberg et al. (1986), Moore and Blakley (1988), and Sanders (1986) that areas conducive to CSI often are located north of an approaching warm front or developing surface cyclone. The CSI bands appear as distinct mesoscale precipitation bands embedded in a larger area of synoptic scale ascent and precipitation. Due to the enhanced ascent within these mesoscale bands, areas which experience CSI often receive additional precipitation relative to surrounding areas which receive only the larger scale forcing.

Kreitzberg and Brown (1970) examined mesoscale precipitation bands within an occluding cyclone, using a dense network of raingages within a radar network. They found that inertial instability near an upper-level jet streak entrance region may have played a significant role in the formation of these bands. They observed that the bands were aligned parallel to the 700 to 500 mb shear vector and that the orientation of these bands changed as the shear vector changed. Initially, the bands were parallel to the warm frontal baroclinic zone and wind shear. Later bands paralleled the cold frontal baroclinic zone. The multibanded structure of the precipitation associated with the cyclone was attributed to presence of multiple hyper-baroclinic zones. These zones collectively give the warm frontal precipitation area a leafed appearance and demonstrate how the surface cold front typically comes in multiple surges of cold air. The presence of these mesoscale bands leads to marked differences in precipitation associated with occluded cyclones. However, subsequent studies have shown that CSI is essentially an inertial instability on a slantwise surface, rather than a horizontal surface characteristic of atmospheric vertical motions. The quasi-isentropic requirements for the onset of CSI are less restrictive than those for pure inertial instability.

The most significant contribution of Kreitzberg and Brown (1970) was to note that mesoscale precipitation bands could occur in layers of weak static stability but appreciable potential instability, which upon being lifted would destabilize. These bands were in effect shallow convection, a possible second major causal mechanism for mesoscale precipitation bands.

The purpose of this paper is to demonstrate how the WSR-88D was able to identify mesoscale precipitation bands, how these radar data and standard observational and model data can then be used to improve short term forecasts, and how the operational meteorologist can anticipate both band formation and orientation.

## 2. METHODOLOGY

The WSR-88D data used in this case is from the Central Pennsylvania (KCCX) radar. The Radar Data Acquisition (RDA) site, where the physical transceiver is located, is in Black Moshannon State Park in Centre County, Pennsylvania. The radar is operated and maintained by the Central Pennsylvania Weather Service Office (KCTP), located about 17 km to the southeast of the RDA site. During the event the KCCX radar had no digital archive level II data available. All of the WSR-88D data used in this case came from the archive level III data base which is created on the Radar Products Generator (RPG). The RPG is located at KCTP.

The WSR-88D archive level III data available for this case included the lowest elevation scan of reflectivity, velocity, and spectrum width, along with vertical wind profiles and radar estimates of precipitation.

Surface and upper-air data for this case were obtained from the Pennsylvania State University (PSU) Department of Meteorology archives of real-time data distributed by the National Meteorological Center (NMC). Analysis of these fields was accomplished on the Penn State Research, Operational Meteorology, Education, and Training System (PROMETS, Cahir et al.

1981). In addition, model data was obtained from the National Meteorological Center (NMC) and displayed using GEMPAK (desJardines et al. 1991).

Detailed 6- and 24-hour precipitation data were obtained from the Middle-Atlantic River Forecast Center (MARFC) database. These data were plotted and displayed on PROMETS.

## 3. LARGE SCALE OVERVIEW

On 30 October a general area of precipitation moved across Pennsylvania from the south and west. The northern and western edge of the precipitation was primarily in the form of snow. This area of snow extended from northern West Virginia across western Pennsylvania and into southern New York State. Pittsburgh and Binghamton received heavy snow on 30 and 31 of October. Most of the East Coast received significant rain from the system.

As shown in Fig. 1, the conditions across Pennsylvania were setting up for a large-scale precipitation event. At 250 mb there was one jet downstream from Pennsylvania located over the northeastern United States, and an upstream jet over the southern United States. The entrance region of the downstream jet and the approaching exit region of the upstream jet acted to produce a coupled jet circulation from the Ohio Valley to the mid-Atlantic coast. A shortwave lifting out over northern New England and a shortwave approaching from the southwest (Fig. 1b) produced a large area of mid-level convergence over the northeastern United States. This convergence has been shown (Forbes 1987) to be a necessary condition to produce low-level cold air damming. At 850 mb (Fig. 1c), a low height center was moving across eastern Tennessee, with the flow resulting in strong low-level warm advection over the mid-Atlantic region. The flow at 850 mb was highly ageostrophic (Fig. 2d) over Pennsylvania with a strong northerly ageostrophic component. At 300 mb there were strong southerly ageostrophic winds over eastern Tennessee and southern New York State (Fig. 2a) associated with the previously mentioned approaching jet exit and departing jet entrance circulations, respectively. The large area of upper-level divergence located to the south of Pennsylvania (Fig. 2b) was associated with the approaching jet exit region. A small area of upper-level divergence was present over northern Pennsylvania and southern New York, in the departing jet entrance circulation.

The surface chart at 1200 UTC 30 October is shown in Fig. 3a. A developing surface cyclone was located in western North Carolina and a weak area of high pressure was located over New England, with strong low-level ridging along the east slopes of the Appalachian mountains. The winds were highly ageostrophic over most of Pennsylvania and the mid-Atlantic region. Snow was falling in the cold air northwest of the surface cyclone center across eastern Indiana, Ohio and western Pennsylvania. Further south and east rain was falling over a broad area from West Virginia to the Atlantic coast. By 1800 UTC (Fig. 3b), a new surface low was developing just south of the Delmarva Peninsula. The re-developing surface cyclone along the coast insured that Pennsylvania would remain in the cold air. The temperatures across central Pennsylvania had fallen into the low 30s °F and the snow had spread northeastward into the southern tier of New York State.

The 1200 UTC sounding from Pittsburgh, and an interpolated sounding (from Buffalo, NY and Sterling, VA) for central Pennsylvania, are shown in Figs. 4a and 4b, respectively. Both soundings show that the atmosphere was relatively stable over central Pennsylvania. The winds at Pittsburgh show the shallow cold air and northeasterly flow near the surface and increasing southwesterly flow aloft. Although the surface temperature was above freezing at Pittsburgh, the wet bulb temperature was below freezing, indicating that shortly after the precipitation began, evaporative cooling would rapidly cool the entire sounding to below freezing, supporting snow. Furthermore, the relatively stable atmosphere and the proximity of the downstream jet entrance circulation increased the potential for the development of Conditional Symmetric Instability (CSI) over the region.

The thermally direct transverse circulation in the jet entrance region supported low-level northerly ageostrophic winds which continued to reinforce the low-level cold air over the region. By 1800 UTC the surface low (Fig. 3b) was located in the region of the southern stream jet exit region, upstream from the jet entrance region over the northeastern United States (Fig. 5). At that time strong upper-level divergence was evident over coastal portions of the mid-Atlantic region (Fig. 5b). Figure 5c shows that there was a region of strong deformation of the 850 mb wind field over the mid-Atlantic region, with a weaker region extending from southwest to northeast across Pennsylvania. At 300 mb the flow was convergent over most of Pennsylvania. By 0000 UTC 31 October the upper-level forcing had shifted north of Pennsylvania and the 850 mb deformation had shifted to the Atlantic Coast (Fig. 6c).

## 4. RADAR OBSERVATIONS OF CSI PRECIPITATION BANDS

As the precipitation developed over Pennsylvania on the morning of October 30, the central Pennsylvania (KCCX) radar velocity pattern showed the classic warm air advection "S" signature at the lower elevation angle (Figs. 7a and 7b). Close examination of the data reveals a strong low-level northeasterly jet which intensified between 1406 and 1510 UTC. The winds slowly veer with height with southwesterly winds appearing over southern Pennsylvania and northern Maryland in the southeastern quadrant of the radar volume aloft.

The corresponding vertical wind profiles ending at 1417 UTC are shown in Fig. 8. These data show low-level northeasterly winds which veered with height, becoming southerly around 1.7 km (6000 ft) above ground (AGL) and southwesterly further aloft. A similar vertical wind structure was observed by the Pennsylvania State University (PSU) Department of Meteorology 50 MHz wind profiler (Fig. 9). The profiler is located at McAlvey's Fort, approximately 37 km south-southeast of the RDA.

The profiler data cover a longer period of time than the radar vertical wind profiles. These data reveal that from the period 1200 UTC to 2100 UTC on 30 October, the upper-level jet circulation built downward with time. The shear vector between 1.5 and 5.5 km was from the west-southwest.

Although only a few select radar observations from 30 October are shown, time loops of the data were examined. At 1204 UTC (Fig. 10a, note that all 15 dBZ and lower values have been filtered out for clarity) a broad area of precipitation was occurring over central Pennsylvania. Two distinct southwest to northeast oriented bands were present over central Pennsylvania. These bands were nearly parallel to the shear vector in Fig. 9. A weaker band was present over northwestern Pennsylvania. By 1300 UTC (not shown) the band which extended from near Pittsburgh northeastward across the RDA and over Williamsport had become the largest and most significant band on the KCCX radar. At 1417 UTC (Fig. 10b) this band had intensified and developed a very distinct linear appearance which reached its peak intensity around 1423 UTC (Fig. 10c). Two weaker bands with a similar orientation were present over southern (not shown) and south central Pennsylvania. The band just to the south of the main band nearly attained the degree of linearity and organization that the main band had achieved. After this time the size, strength and organization of the bands steadily decreased. At times as many as six bands were present over central Pennsylvania. By 1510 UTC (Fig. 10d) the bands had decreased in size and intensity, but maintained the overall southwest to northeast orientation.

The northern band was in an area that experienced snow, the central band was composed of mixed precipitation and the southern bands produced rain. Higher elevation scans (not shown) revealed a bright band signature near the radar. The effects of this bright band can also be seen in the precipitation estimates (Figs. 7c and 7d), which show concentric bands of high amounts about the RDA. The verifying 6-hourly precipitation valid at 1800 UTC 30 October is shown in Fig. 11. These data reveal distinct southwest to northeast oriented precipitation maxima similar in orientation and location to the bands shown in Fig. 10.

## 5. DISCUSSION

The precipitation bands observed over central Pennsylvania on 30 October 1993 were oriented parallel to the shear vector in the 1.5 to 5.5 km layer. Similar to Wolfsberg et al. (1986), the larger bands persisted for several hours while the smaller bands persisted for 30 minutes to about one hour. Throughout the day the bands remained oriented about 30 degrees from east extending from about 240 to 060 (west-southwest to east-northeast). As the day progressed the bands became less organized and smaller in size, but they had a significant impact on the distribution of precipitation across the state.

The bands are believed to have formed in an atmosphere which was conducive to the formation of conditional symmetric instability bands. The atmosphere over central Pennsylvania was relatively stable (Fig. 4). Geostrophic momentum ($M_g$) surfaces computed from the 1200 UTC NGM model grids are shown in Fig. 12. These data reveal that the atmosphere over central Pennsylvania was conducive to the formation of CSI bands near 40 degrees north in the layer between 650 and 550 mb. The 850 mb frontogenesis valid at 1200 UTC 30 October, 1993 is shown in Fig. 13. An area of frontogenesis, which extends from central Pennsylvania northeastward across New England, was parallel to the 850 mb axis of dilatation (not shown) and the observed precipitation bands (Figs. 10a-d). Low-level frontogenetic forcing was present over the region where the precipitation bands formed. It is likely that the sub-synoptic-scale frontogenesis also played a significant role in the formation of the bands. The strongest 850 mb frontogenetic forcing was located further south, extending from eastern Kentucky and Tennessee eastward to the western Atlantic, in a warmer and conditionally unstable atmosphere.

The circulation resulting from conditional symmetric instability (CSI) is often referred to as "**slantwise**" convection (Wolfsberg et al. 1986). From a forecasters' perspective, diagnosing conditions favorable for the instability means the circulation is likely to exist. Thus, these terms are used interchangeably in this article. Areas conducive to CSI often are located north of an approaching warm front or developing surface cyclone and in close proximity to the anticyclonically sheared, downstream jet entrance region. It is easy to identify synoptic-scale regions which are conducive to the potential formation of CSI bands, but it is difficult to forecast the exact mesoscale location where the bands will form. Once the band forms, forecasters can improve the short term nowcasts of locally heavy rain or snow based on the presence of CSI bands on radar.

Bands of slantwise convection typically form and dissipate over a time scale on the order of 3 to 4 hours. The length and width of the bands is on the order of hundreds and tens of kilometers respectively. They tend to form in regions of strong vertical wind shear (near jet entrance regions) with near-neutral static stability. If the atmosphere is conditionally unstable, less organized, upright or vertical convective elements will develop, though these can also be in lines. The CSI bands in this case formed and dissipated over a three-hour period (Figs. 10a-d).

On the synoptic scale, in an area of strong vertical wind shear, with near-neutral stability, bands of slantwise convection tend to occur in areas of weak synoptic scale ascent and oriented nearly parallel to the 1000 to 500 mb thickness lines and the 850 and 700 mb isotherms. The bands in Figs. 10b and 10c are nearly parallel to the isotherms in Fig. 1c. Frontogenetic forcing is also believed to play a role in the development of these bands (Moore and Blakley 1988); hence, the proximity of a strong jet entrance circulation is believed to play a significant role in identifying areas conducive for the development of CSI. This is also true from the perspective of the role of inertial instability in CSI. The right rear quadrant of the jet is the location where the inertial term can become unstable. The shear of the u-component of the wind in the y direction can be greater than the Coriolis parameter because of the anticyclonic shear. Strong anticyclonic curvature may also contribute to the likelihood of CSI.

Operationally, forecasters should learn to identify when the synoptic-scale environment is conducive for the development of slantwise convection. Once precipitation begins to develop, radar data should be examined to identify the development of these bands. The atmospheric adjustment which produces these bands typically lasts on the order of 4 to 6 hours (Reuter and Yau 1990). Short term forecasts and nowcasts can be modified to address the enhanced potential for heavy precipitation for locations near these bands. Furthermore, forecasters should anticipate changes in the orientation of the thickness patterns with time. If little change is expected, then band orientation and location is less likely to change, increasing the potential for heavy precipitation in areas near the bands. However, if model guidance suggests a change in the orientation of the thickness patterns, it is likely that new band orientations will develop reflecting these changes in the vertical wind shear. At the current time, these bands are not readily resolvable in numerical models, and accurate forecasting falls into the realm of the 0- to 6-hour time frame. However, extensive use of six-hourly model gridded data to see short term changes in the thickness pattern, thermal fields, and vertical wind shear is of great value. Furthermore, the analysis of relative vorticity on theta-e surfaces (Hoskins et al. 1985) may further assist in identifying regions conducive for the formation of CSI bands.

## 6. CONCLUSION

The KCCX WSR-88D did an excellent job detecting the CSI bands which formed over central Pennsylvania on the morning of 30 October, 1993. The model and observational data indicated that the atmosphere was conditionally stable for the most part, and that the necessary conditions were met to produce CSI bands. The available rawinsonde data, along with diagnostics generated from model gridded data, presented in this case showed the potential for CSI band formation, and the forecaster could anticipate the orientation of the bands prior to their appearance on radar. Once the bands form, the forecaster can anticipate areas susceptible for locally heavy precipitation and make improvements to the short term forecast. In this particular case the bands were quasi-stationary and lasted only a few hours, but they still played a significant role in the event total precipitation. The key is to be aware of the conditions where CSI bands are likely to first appear so they can be readily identified.

As more WSR-88D's are installed throughout the United States, more cases of CSI will be observed which will lead to more detailed analyses of CSI cases. Several factors which limited the scope of this study included the lack of both detailed short term precipitation data and access to useful digital radar data. We are in the process of examining a longer-lived transient CSI event which produced heavy rainfall, using the digital archive level II data from the Sterling, Virginia WSR-88D, and graphical archive level III data from the KCCX radar. Eventually, all National Weather Service WSR-88D sites will have digital data archiving capabilities.

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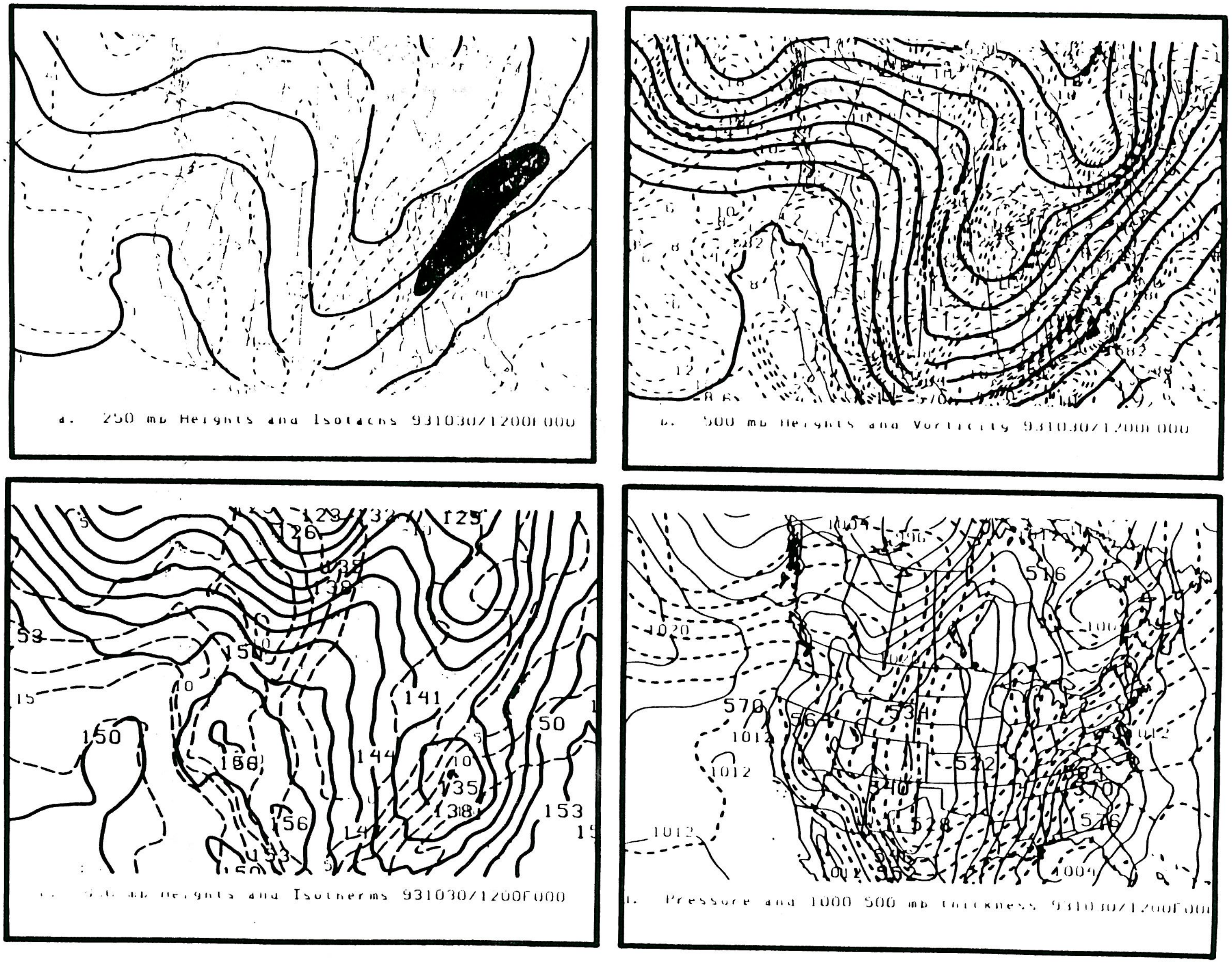


**Figure 1.** Nested Grid Model 00-h forecast valid 1200 UTC 30 October, 1993 of a) 250 mb heights and isotachs, b) 500 mb heights and vorticity, c) 850 mb heights and isotherms, and d) surface pressure and 1000 to 500 mb thickness. Isotachs are every 20 m $s^{-1}$, isotherms are every 5°C, 500 mb heights and thickness values are every 60 m, pressure is every 4 mb, and vorticity is every $2x10^{-5}$ $s^{-1}$. Shading denotes wind speed in excess of 70 kt.

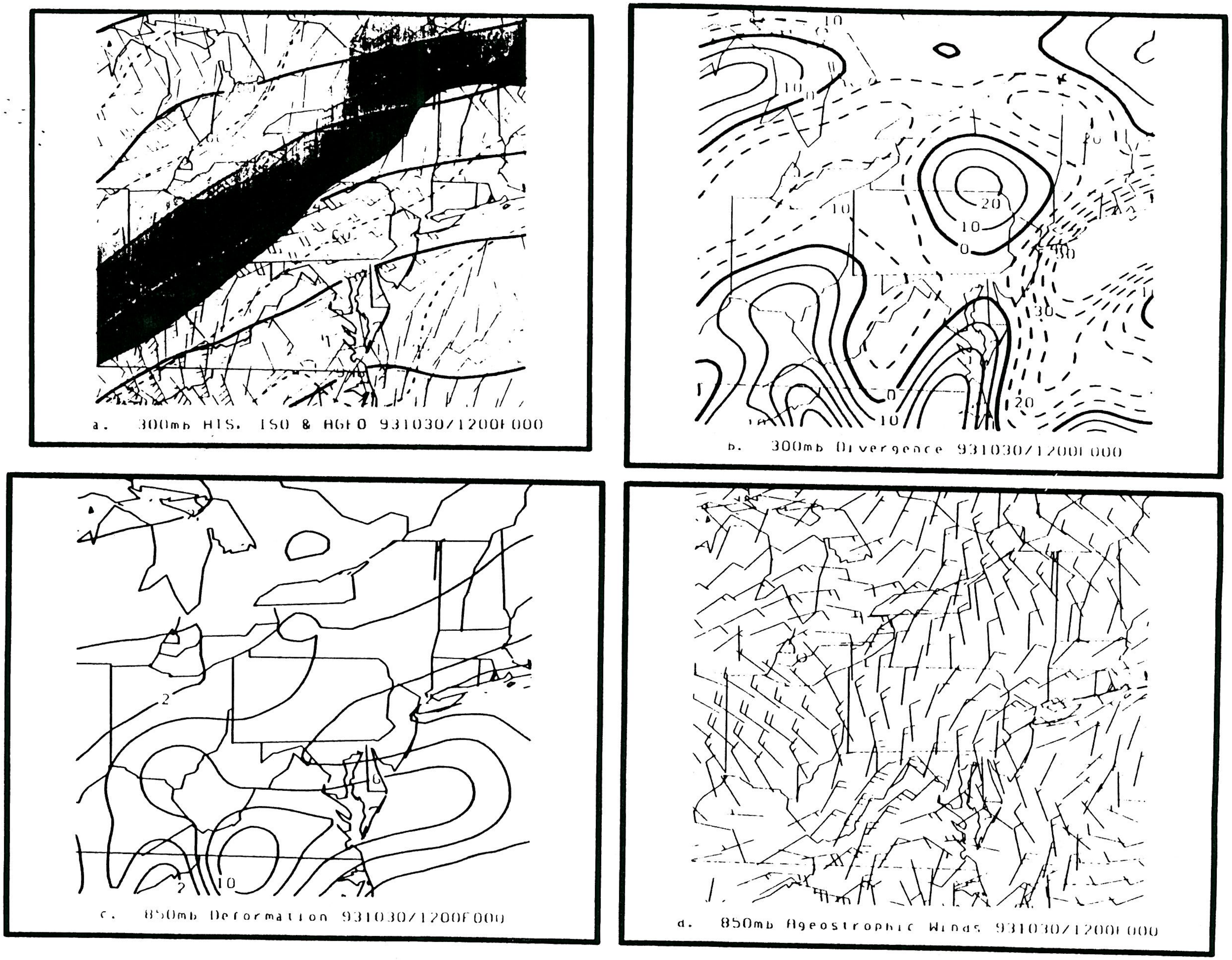


**Figure 2.** As in Figure 1 except for a regional display centered over Pennsylvania of a) 300 mb heights, isotachs and ageostrophic wind, b) 300 mb divergence ($10^{-6}$ $s^{-1}$), c) 850 mb deformation, and d) 850 mb ageostrophic wind.

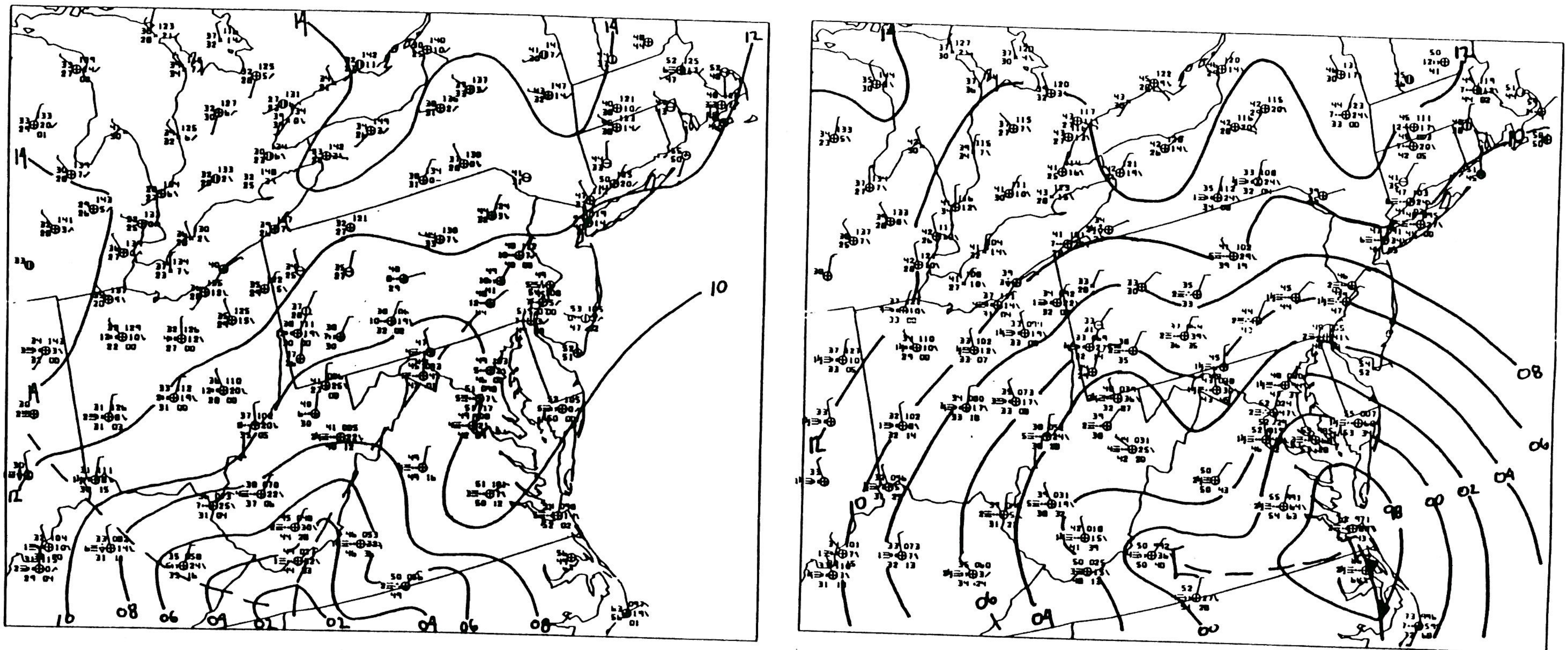


**Figure 3**. Surface analyses for a) 1200 UTC, and b) 1800 UTC 30 October, 1993. Contour increment is every 2 mb.

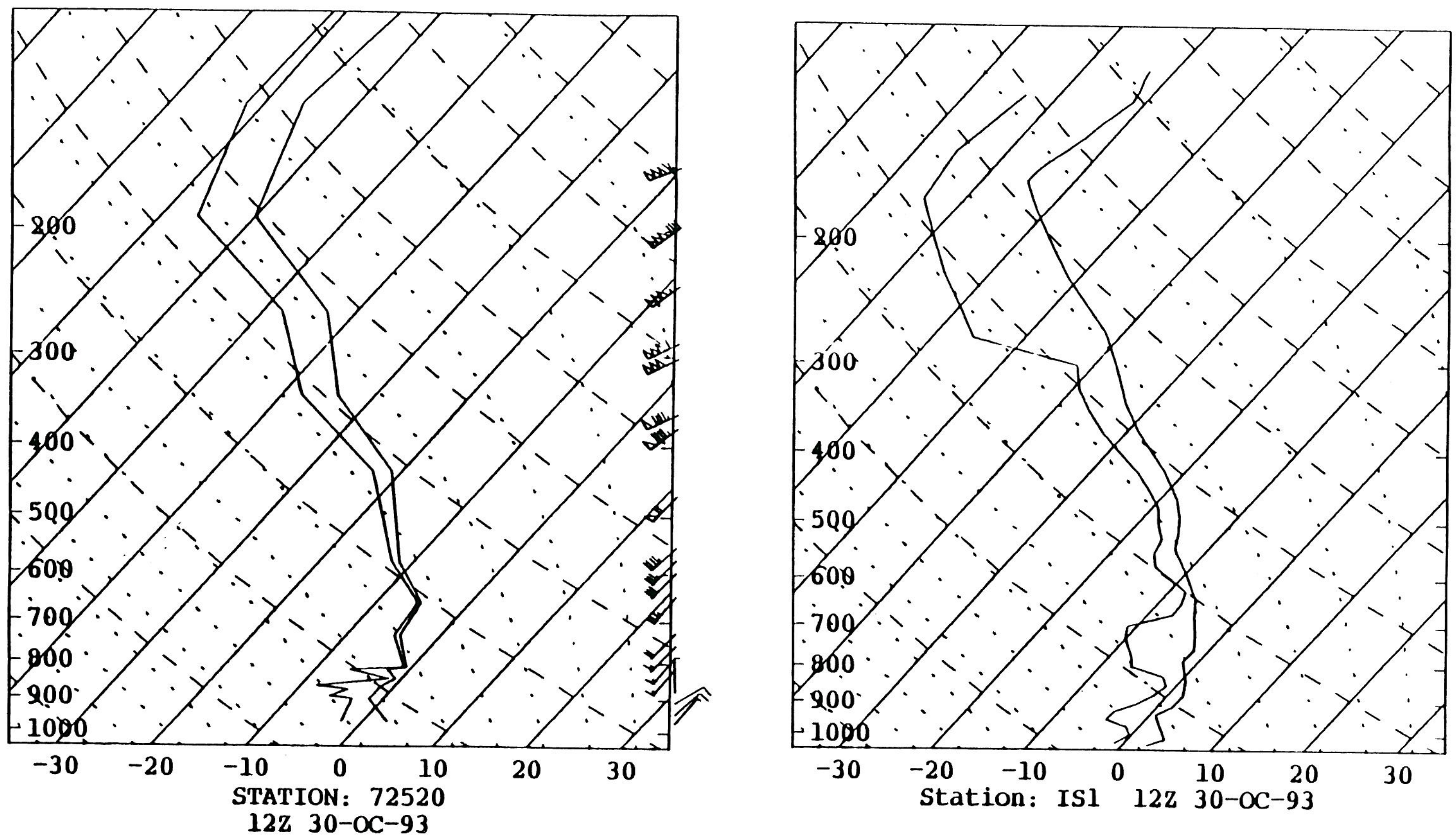


**Figure 4.** Atmospheric sounding valid 1200 UTC 30 October, 1993 for a) Pittsburgh, and b) central Pennsylvania (derived).

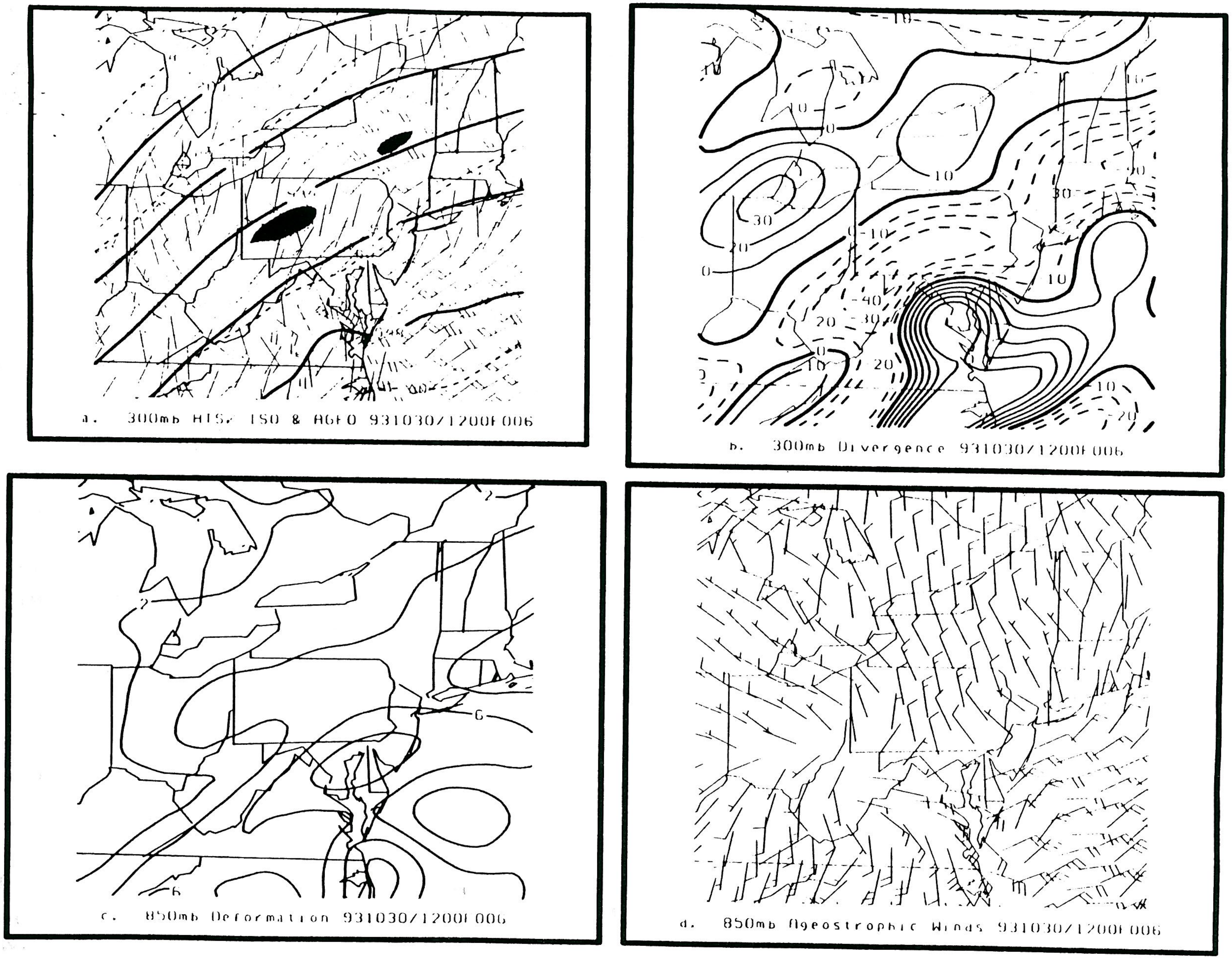


Figure 5. As in Figure 2 except a 6-h forecast valid at 1800 UTC 30 October, 1993.

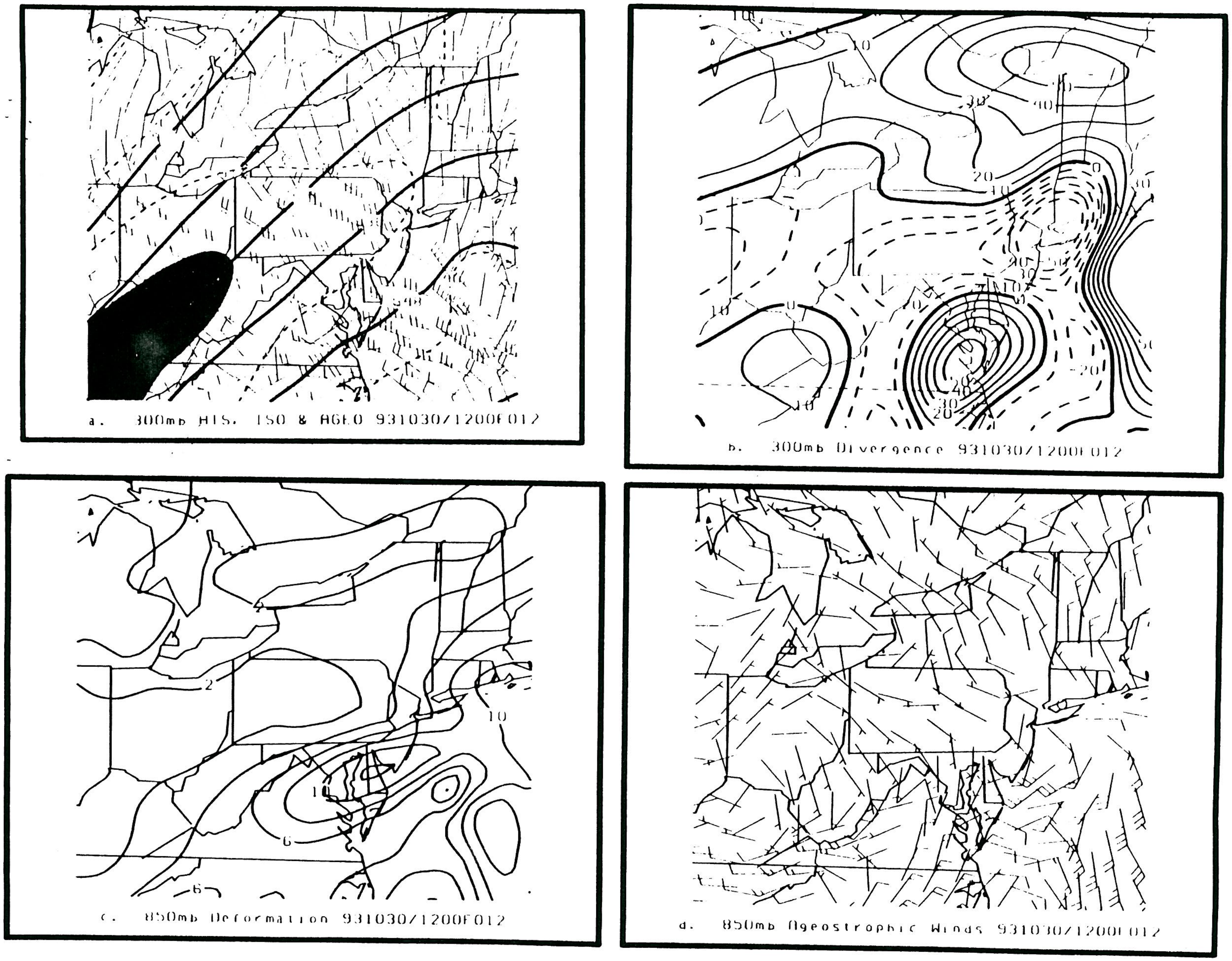


**Figure 6.** As in Figure 2 except a 12-h forecast valid at 0000 UTC 31 October, 1993.

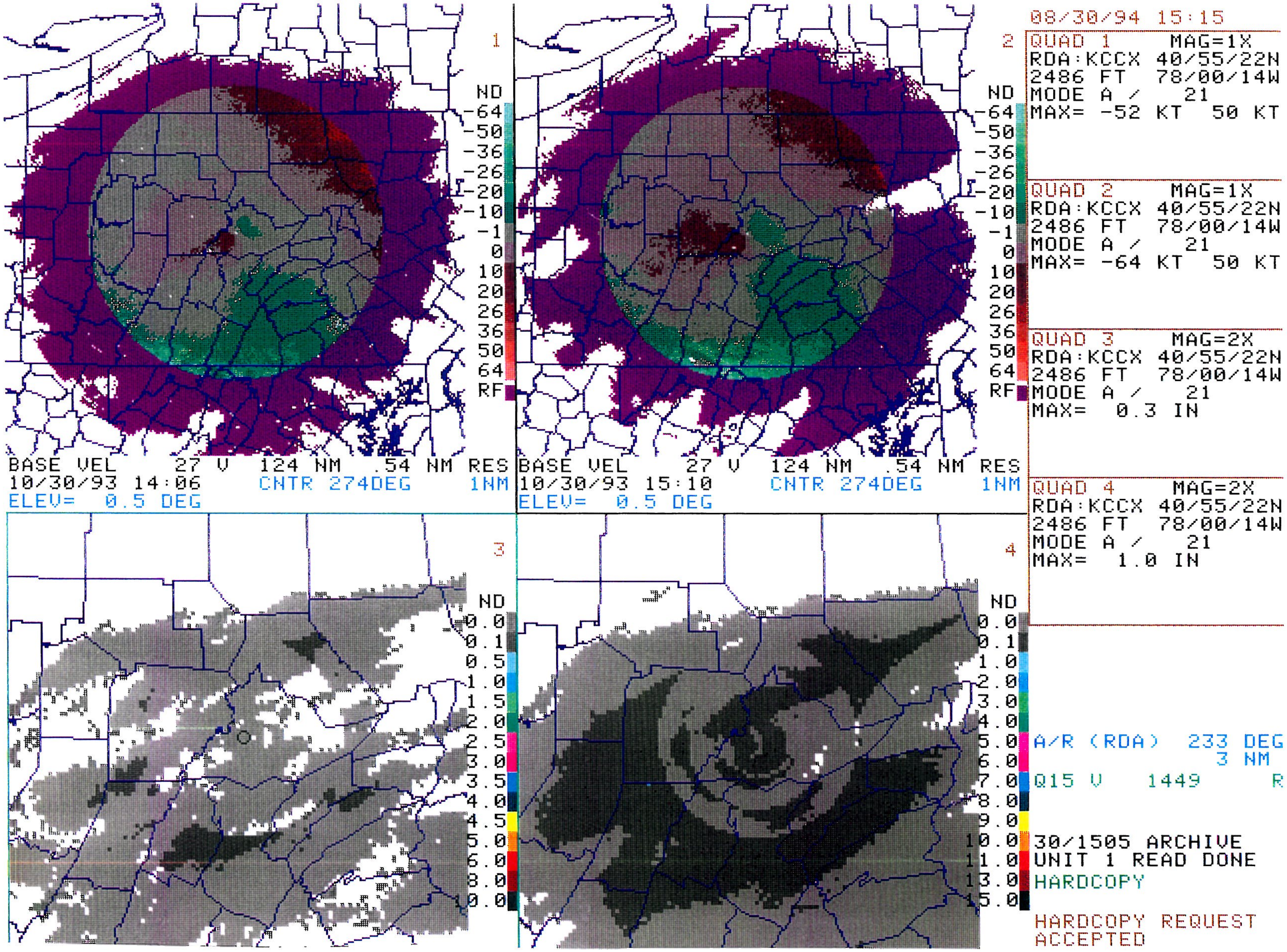


**Figure 7.** Four-panel display from the KCCX Doppler radar for base velocity at the 0.5° elevation angle valid at a) 1406 UTC, and b) 1510 UTC 30 October, 1993, and radar-estimated precipitation amounts ending at 1545 UTC 30 October, 1993 showing c) 1-hour and d) storm total products. Wind speeds are in knots, with cold colors being inbound and warm colors being outbound velocities. Rainfall estimates are in tenths and inches as per the scale associated with the panels.

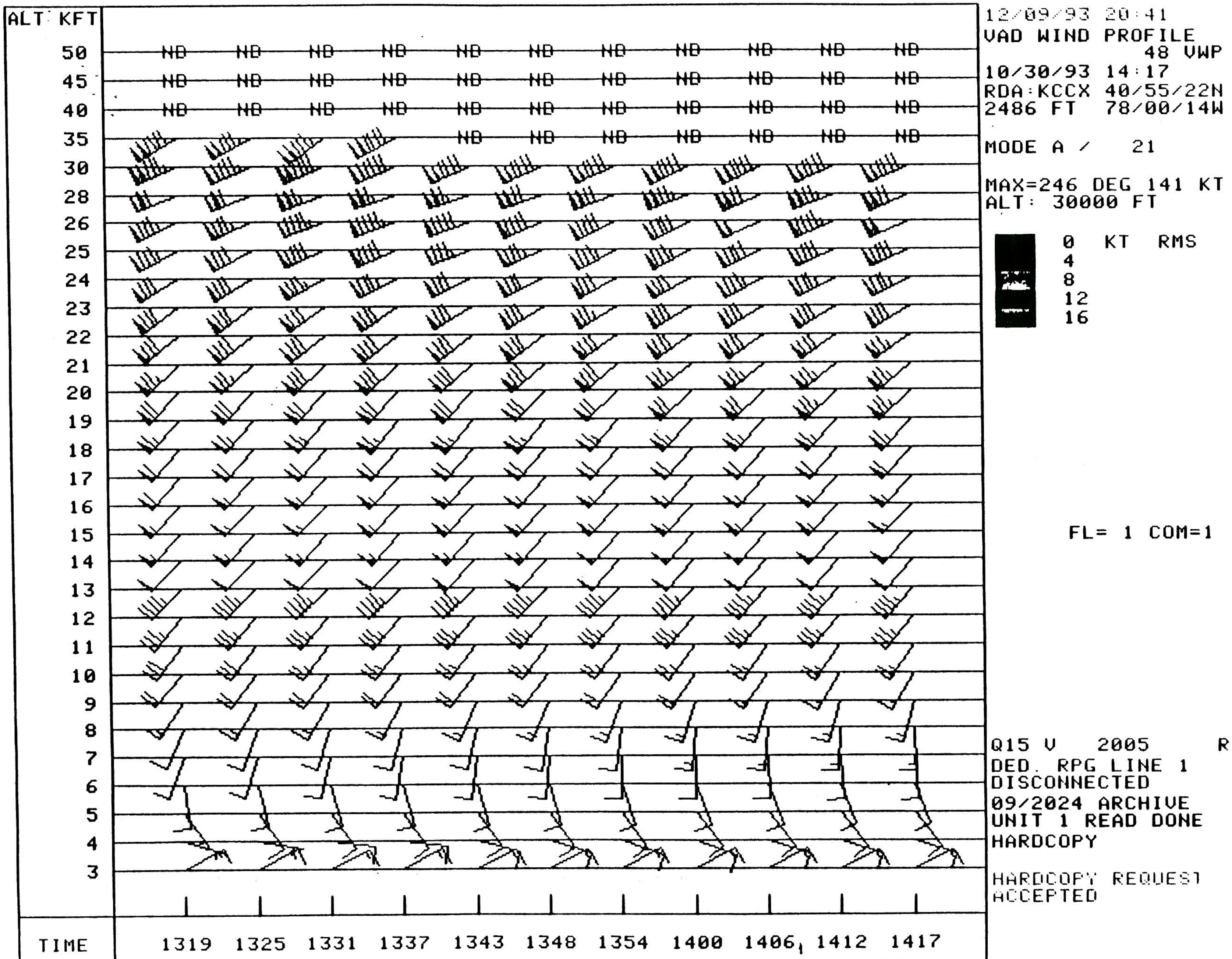


**Figure 8.** Vertical wind profile from KCCX radar valid at 1417 UTC 30 October, 1993. Wind speed is in knots, height scale is in thousands of feet, and the time interval is every 6 minutes.

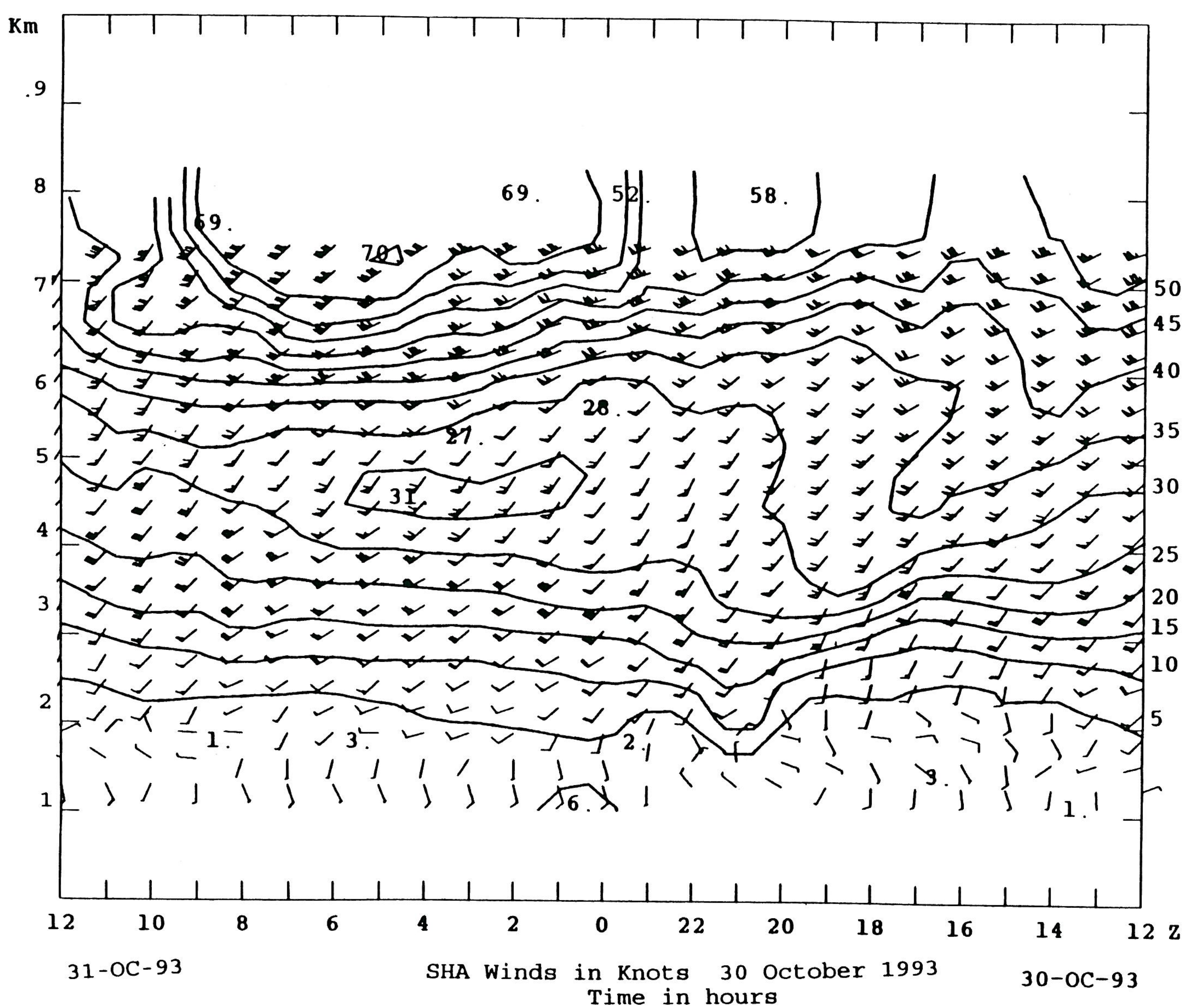


**Figure 9.** Maclevys Fort profiler data for the period 1200 UTC 30 October through 1200 UTC 31 October, 1993. Wind speeds are in meters per second, velocity contours are every 5 m $s^{-1}$, and the vertical scale is in kilometers.

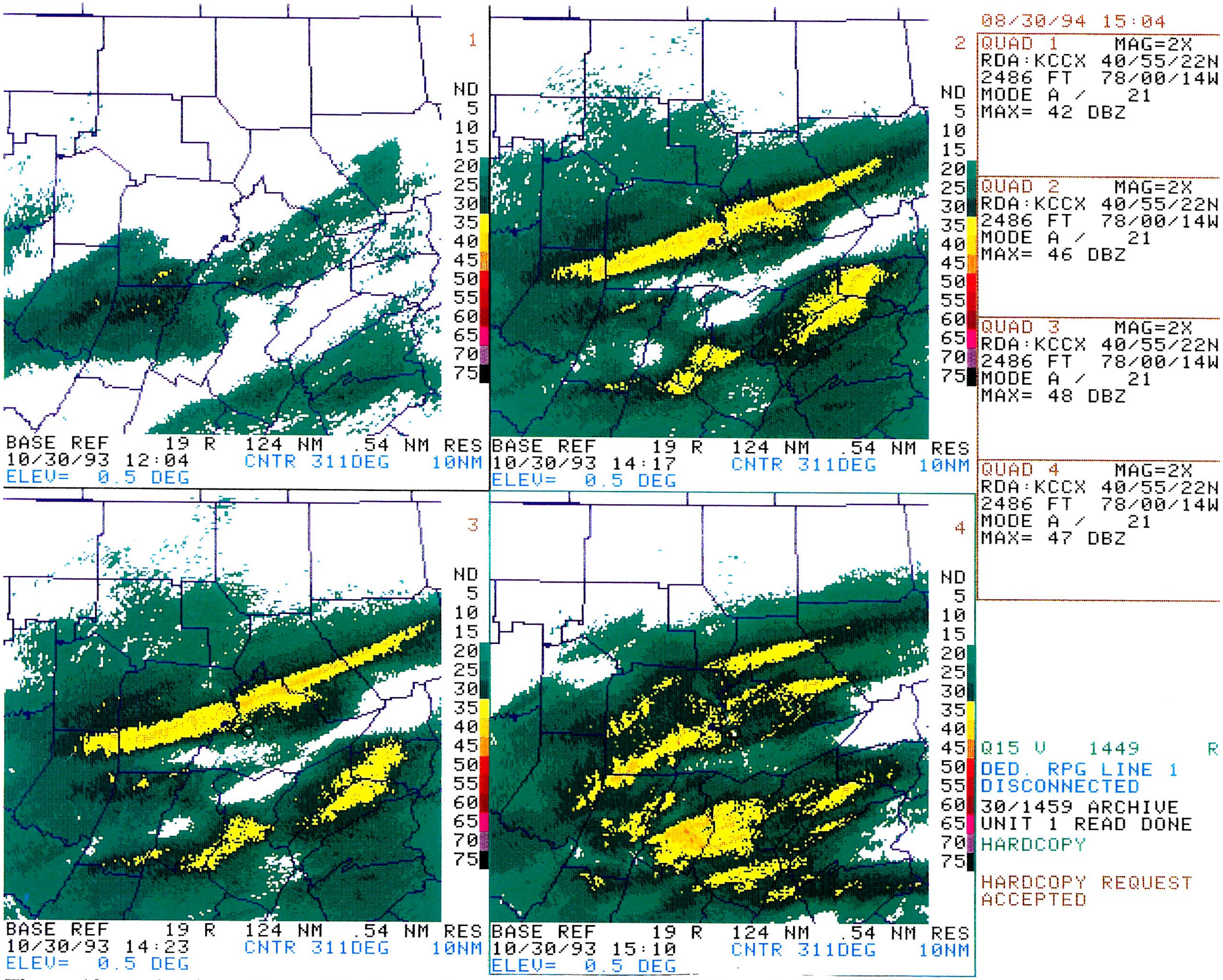


**Figure 10.** As in Figure 7 except for base reflectivity data valid at a) 1204 UTC, b) 1417 UTC, c) 1423 UTC, and d) 1510 UTC 30 October, 1993. Reflectivity values range from 20 to 75 dBZ, as shown on the scale to the right of the image. Values less than 15 dBZ have been filtered out for clarity.

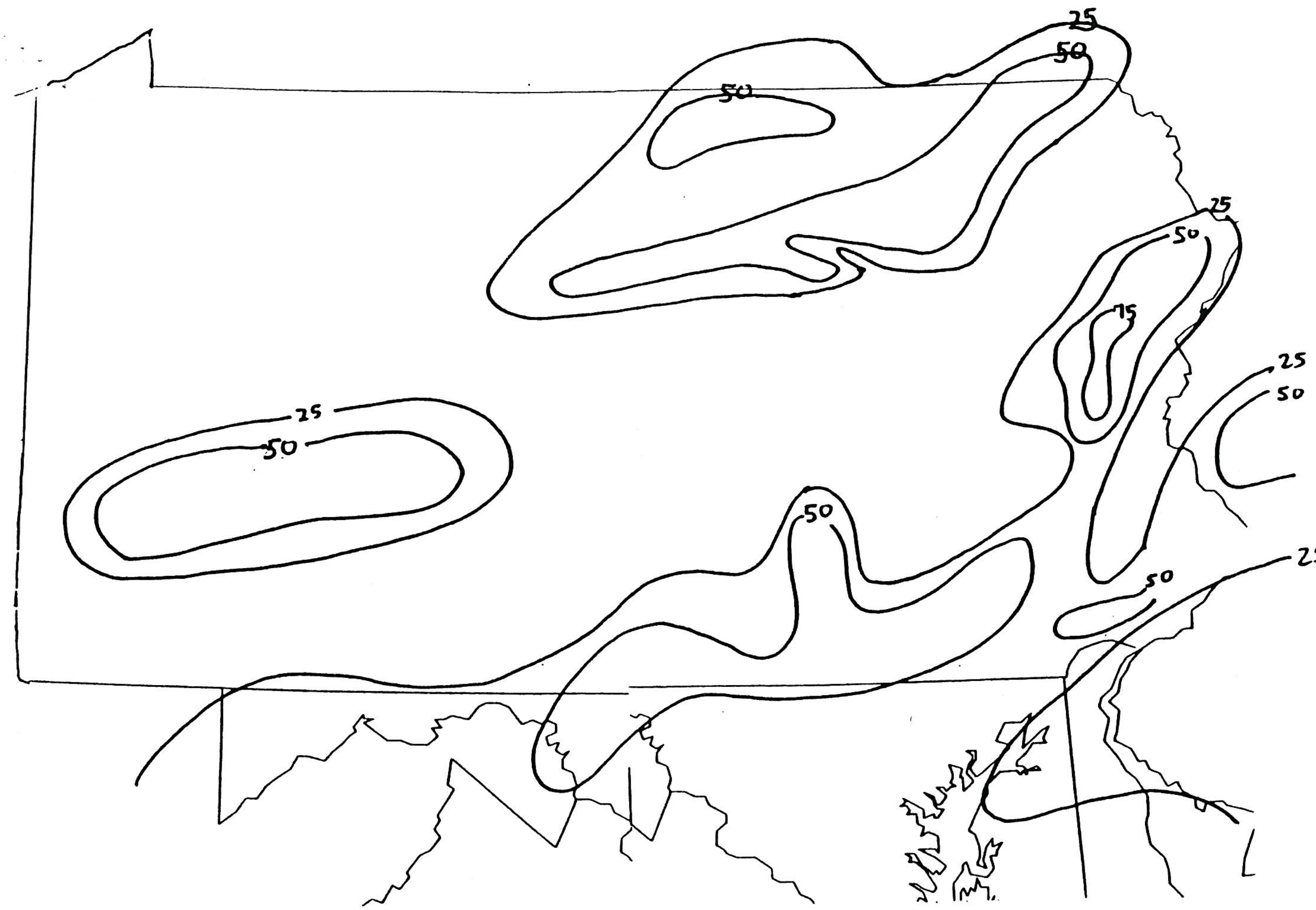


**Figure 11.** Total observed precipitation (mm) for the 6-h period of 1200 through 1800 UTC 30 October, 1993. Contours are in 25 mm increments.


**Figure 12.** Vertical cross section from the 6-h NGM forecast valid at 1800 UTC 30 October, 1993, showing geostrophic momentum ($M_g$) surfaces (dashed), and equivalent potential temperature (K; solid). Cross section is taken along 76°W longitude from 39°N to 41°N latitude. Contour intervals are every 4° for equivalent potential temperature and every 5 m s$^{-1}$ for $M_g$ surfaces.

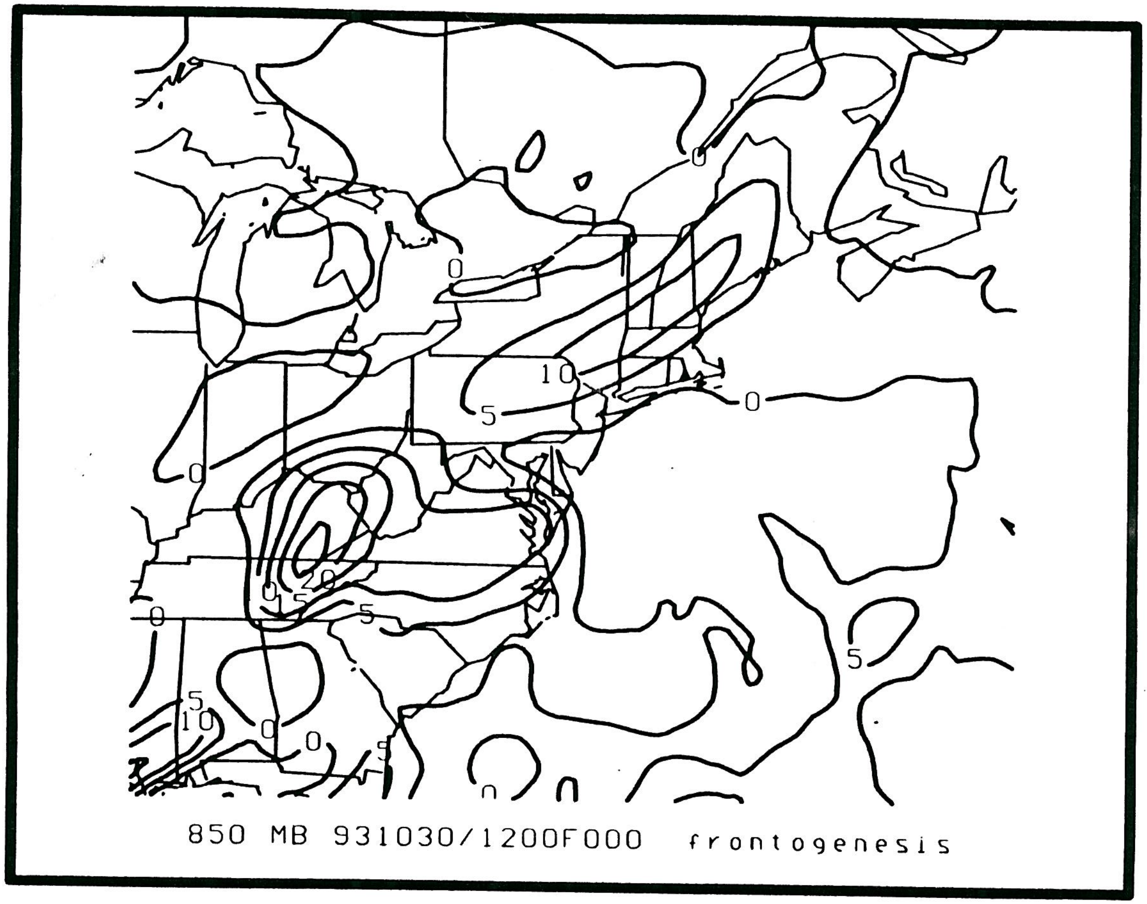


**Figure 13.** 850 mb frontogenetic forcing, taken from the NGM analysis valid at 1200 UTC, 30 October 1993. Contour increment is $5 \times 10^{-10}$ K $m^{-1}$ $s^{-1}$.