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A CASE STUDY OF OROGRAPHIC ENHANCEMENT OF HELICITY IN THE LEE OF THE APPALACHIAN MOUNTAINS

Gregory T. Robbins
National Weather Service Office
Greensboro, North Carolina

Greg L. Dial
National Weather Service Forecast Office
Raleigh, North Carolina

1. INTRODUCTION

Low-level lee pressure troughs and the associated orographically induced circulations are common east of the southern Appalachian Mountains. These phenomena disturb the low-level local wind and pressure fields, and can have a significant impact on mesoscale weather features. Several investigations, such as Newton 1956, Palmen and Newton 1969, Chung et al. 1976, and Pierrehumbert 1985, have theorized on the initial formation and intensification of lee troughs.

On March 7, 1992, a convective storm with supercell characteristics developed and produced a damaging tornado near Lake Norman, NC. Enhanced mesoscale modification of the low-level wind flow associated with an Appalachian lee trough, is believed to have influenced the formation and evolution of the storm.

The objective of this paper, is to examine how *the synoptic and mesoscale environments can interact* with local topography to enhance severe weather potential in the foothills and western Piedmont of North Carolina. Similar studies of orographically enhanced severe weather in Northern California are documented by Braun and Monteverdi (1991).

2. MESO AND SYNOPTIC SCALE ENVIRONMENTS

During the afternoon of March 7, 1992, a quasi-stationary surface low pressure trough developed in the lee of the Appalachian Mountains (Figs. 1-3). This trough was well defined in the pressure and height fields from the surface to approximately 925 mb. It was much less pronounced at 850 mb and was indiscernible at and above 700 mb. The pressure trough was associated with an orographically modified low-level wind flow, which included backed boundary layer winds. Moisture flux convergence along the axis of the lee trough helped provide the low-level forcing needed to initiate convection. The modified low-level wind flow east of the lee trough enhanced the vertical directional wind shear, and produced an environment favorable for thunderstorms to evolve into organized multicells or supercells. At approximately 2128 UTC, a supercell-like storm developed near Lake Norman, NC that produced a damaging F1-F2 tornado on the Fujita tornado scale. The tornado was highly visible and extensive video coverage was obtained. The storm also produced tennis ball size hail and exhibited other characteristics of a supercell thunderstorm, including a rotating wall cloud and a rear flank downdraft.

Flow normal to the mountains in the lowest several thousand feet of the atmosphere is usually needed for initial lee trough formation, while future intensification is highly dependent upon the dynamics accompanying the upper-flow pattern (Newton 1956). The Appalachians in western North Carolina and Virginia, contain numerous mountains with heights up to 4000 ft above mean sea level, with some peaks in excess of 6000 ft. Therefore, westerly flow in the surface to 850 mb layer should have the most influence on Appalachian Mountain lee trough formation.

At 1200 UTC on March 7, 1992, the wind flow in the surface to 850 mb layer was from the southwest in western North Carolina, due to an approaching shortwave trough with its axis located over central Tennessee (Figs. 4-6). At 300 mb, a 100 kt jet streak was located over Alabama embedded within the subtropical jet stream (Fig. 7).

By 0000 UTC on March 28, the shortwave trough and accompanying 300 mb jet streak advanced northeast and moved over southeast North Carolina (Figs. 10 and 11). Figures 8 and 9 illustrate that as the shortwave trough approached the North Carolina Foothills, the wind in the surface to 850 mb layer veered to the west-northwest along and west of the Appalachians, inducing a flow normal to the mountains.

Evolution of the low-level lee trough examined in this study is considered to be a two stage process, which included formation and development. In the formative stage, downslope motion accompanying the augmented westerly wind flow induces low-level adiabatic warming, which causes the surface pressures to fall and increases the low-level thickness (Bluestein 1993). Figure 13 illustrates the process of lee trough formation. The forcing for upward vertical motion in this stage appears to be a result of the convergence associated with surface pressure falls.

In the development stage, upward vertical motion is induced by the approach of the left-front exit region of the 300 mb jet streak. The large scale forcing further lowers the surface pressure and increases the low-level cyclonic circulation. Vertical motion associated with the left front quadrant of a jet speed maximum is a result of supergeostrophic wind in the jet exit region. To achieve geostrophy, parcels must decelerate by turning south toward higher pressure. These southward moving parcels form the upper-level north-south oriented ageostrophic branch of the transverse jet streak circulation, and result in a net convergence in the jet streak right-front quadrant and a net divergence in the jet streak left-front quadrant (Kessler 1985). The divergence in the jet streak left-front quadrant induces the compensating upward vertical motion (Fig. 14). When the vertical motion from the jet streak dynamics came into phase with the orographic forcing, the lee trough and its cyclonic circulation were at maximum intensity (Fig 2).

The low-level lee pressure trough persisted throughout the afternoon and evening hours and remained nearly stationary. Between 1900 and 2100 UTC, the lee trough and its associated cyclonic circulation were at maximum intensity, with surface winds from the south and southeast over the Foothills and western Piedmont. At this time, the contributions to ascent were the combined effects of divergence aloft from the approaching upper-level jet streak, and the low-level convergence associated with the lee trough. However, Figure 3 also illustrates that by 0000 UTC, the lee trough had become stretched in a northeast-southwest orientation. This occurred as the vertical motion associated with the jet streak moved into the eastern third of North Carolina and caused pressure falls in the coastal plain. At this stage, the vertical motion from orographic forcing and the jet streak dynamics were no longer in phase and the lee trough subsequently weakened.

3. OROGRAPHIC INFLUENCE OF HELICITY

Helicity is defined as the component of horizontal vorticity parallel to the mean wind within the lowest few kilometers of the atmosphere (Davies-Jones 1984). Storm relative (SR) helicity gives a measure of how efficiently storm relative inflow transports vorticity to the developing storm updraft. Significant storm relative helicity in the 0 to 3 km layer has theoretically been shown to be effective in initiating thunderstorm updraft rotation (Lilly 1986). Empirical studies have shown a close correlation between helicity rich low-level environments and supercell formation, provided sufficient instability is present to support initial updraft development. Studies by Davies-Jones et al. (1990) suggest that most tornadoes developed in environments with helicities greater than 150 m^2/s^2. They found a range of helicities for weak, strong and violent tornadoes to be (150-299), (300-449), and (>450) respectively.

There was substantial vertical wind shear in the 0 to 3 km layer over North Carolina. Over the Foothills and southern Piedmont, the lee trough cause the low-level winds to back. The backing resulted in stronger veering in the 0 to 3 km layer, which suggested that warm air advection was occurring. Hodographs were generated by using the SHARP (Skew-T Hodograph Analysis and Research Program: Hart and Korotky 1991) workstation. Hodographs were generated for the northern Piedmont, and also for the southern Piedmont and Foothills, based on the 0000 UTC WSO Greensboro (GSO) radiosonde sounding. However, the GSO hodograph was unrepresentative of the low-level wind in the southern Piedmont and Foothills of North Carolina, due to the strong backing of the low-level flow to the lee of the mountains. Therefore, modification of the wind was made from the surface to 500 meters (m). The surface wind between Charlotte, (CLT) and Hickory, (HKY) NC prior to tornado touchdown, was between 160° and 180° at approximately 10 kt. For the helicity computation, a wind vector of 160° at 10 kt was used, and a 500 m wind vector of 200° at 16 kt was determined through linear interpolation. The influence of orography on backing the low-level winds decreased significantly above 500 m and were left unmodified.

The storm motion computed by SHARP was modified slightly to reflect the cell movement (300° at 15 kt) observed by the CLT WSR-57 radar. Figures 15 and 16 illustrate the observed and modified hodographs. The corresponding sounding (Fig. 12) depicts that the atmosphere was moderately unstable with a Convective Available Potential Energy (CAPE) of 1563 J/Kg. The SR helicity increased from 103 m^2/s^2 (observed hodograph) to 191 m^2/s^2 (modified hodograph). The storm relative inflow increased from 147° at 15 kt to 128° at 24 kt.

The Energy-Helicity Index (EHI) represents the potential strength of a tornado, based on storm relative helicity and convective available potential energy (Johns et al. 1990). An EHI of 1.22 was calculated using the 0000 UTC GSO sounding. An EHI greater than 1 may indicate a potential for strong tornadoes (F2-F3). However, use of this parameter is still experimental and the reliability of the EHI as a valuable forecasting tool is yet to be determined.

4. CONCLUSION

Results from this study imply that under certain conditions, local orographic effects can modify the low-level wind circulation and enhance the potential for severe storm development in the Foothills and western Piedmont of North Carolina.

The results also indicate that the lee trough and associated low-level convergence, can significantly alter the low-level wind direction and vertical wind shear profile. Furthermore, when large scale forcing (such as an approaching 300 mb jet streak) interacts with the local circulation, it can increase the potential for severe weather development. In the case examined in this study, it is apparent that the local low-level wind shear increased the SR helicity and contributed to the development of the tornado.

Initial Appalachian Mountain low-level lee trough formation, usually requires significant wind flow normal to the mountains in the lower several thousand feet of the atmosphere. A broad 300 mb trough with an embedded jet streak, will favor development and intensification of the lee trough, if the left front quadrant of the jet streak moves over the lee of the mountains, and phases with the low-level orographic component.

As the low-level lee trough intensifies, so does the ensuing low-level cyclonic circulation associated with geostrophic adjustment. This process can significantly increase the helicity, which can contribute to the development of rotation in thunderstorms. The degree of destabilization and the strength of the mid-level wind will further dictate the storm type. Since the conditions that favor low-level lee trough development in North Carolina do not frequently occur in conjunction with the conditions that promote severe weather, orographic enhancement of helicity in the lee of the Appalachian Mountains is not commonly associated with severe storm development.

Results from this study stress the importance of being able to identify local mesoscale features that can enhance severe weather potential, given an otherwise unfavorable or marginally favorable synoptic scale environment. In addition to the implementation of new technologies such as the WSR-88D and improved satellite information, future improvements in the forecasting of severe thunderstorms will rely on the meteorologists ability to assess the potential for severe weather development hours before it begins. This can only be achieved through increased forecaster training and an improved understanding of pre-storm mesoscale convective environments.

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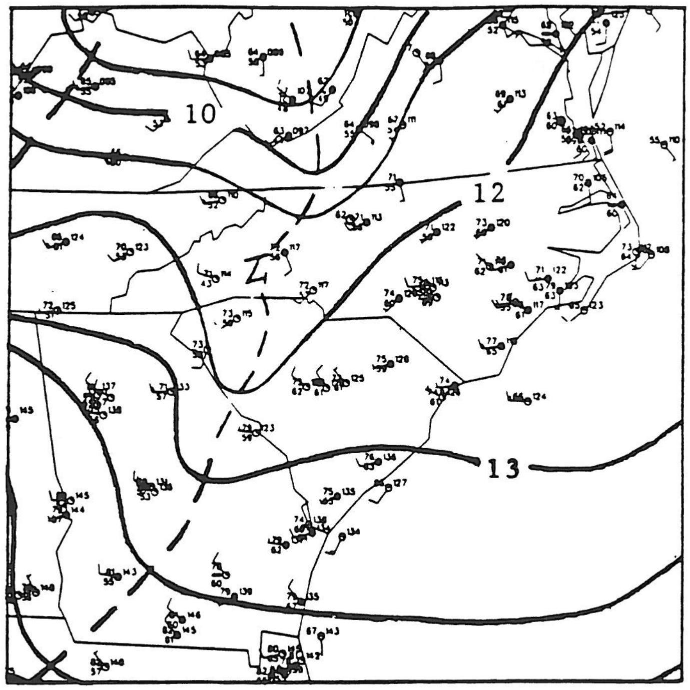

Figure 1. 1900 UTC March 7, 1992 surface pressure analysis. The solid lines are isobars contoured every 1 mb. The dashed lines are low-level lee pressure trough axes.

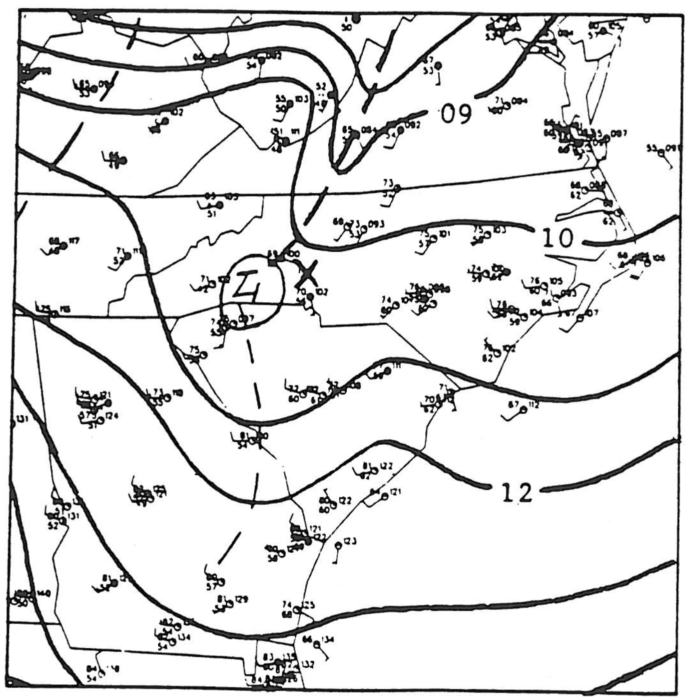

Figure 2. As in Figure 1 except for 2100 UTC March 7, 1992. The x denotes the location where the F1-F2 tornado occurred.

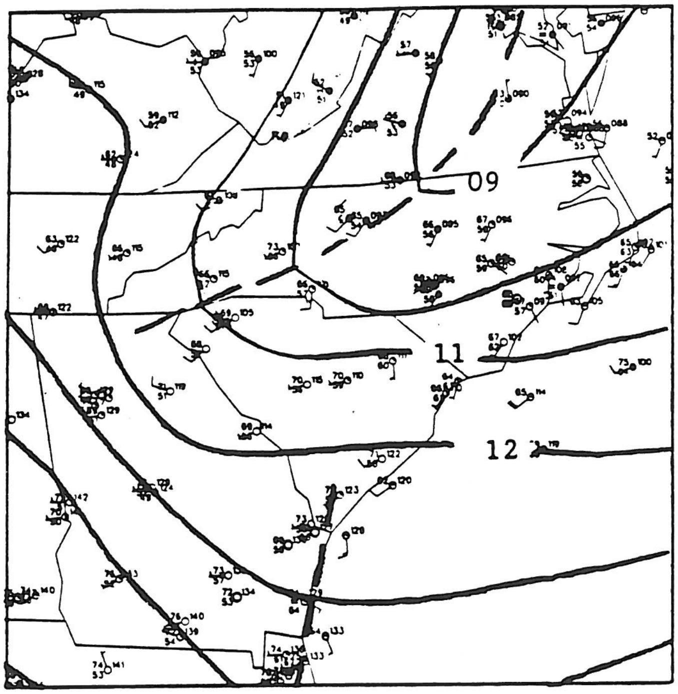

Figure 3. As in Figure 1 except for 0000 UTC March 8, 1992.

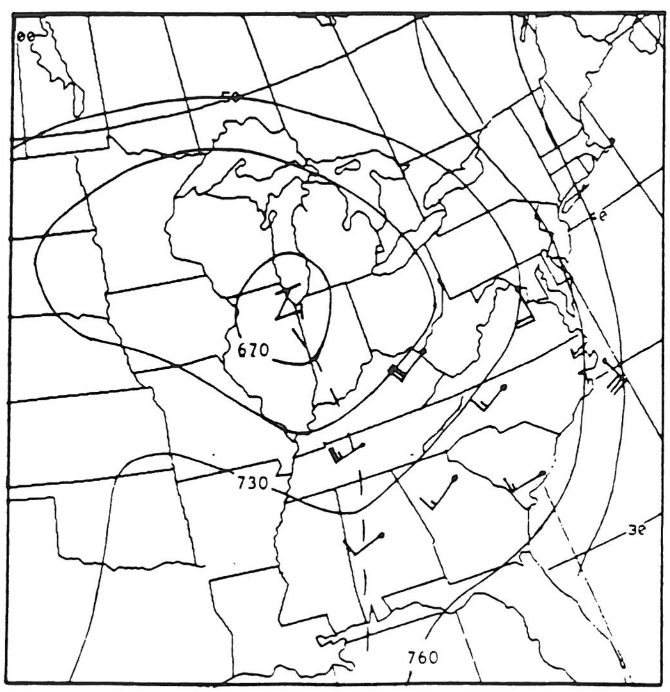

Figure 4. 1200 UTC March 7, 1992, 925 mb height analysis. The dashed line is the trough axis. The contour increment is 30 m.

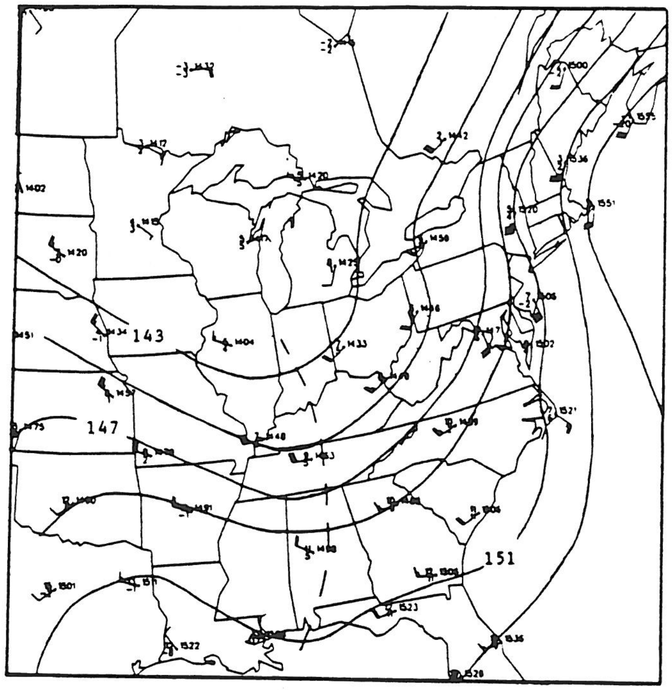

Figure 5. As in Figure 4 except for 850 mb heights. The dashed line is the trough axis. The contour increment is 20 m.

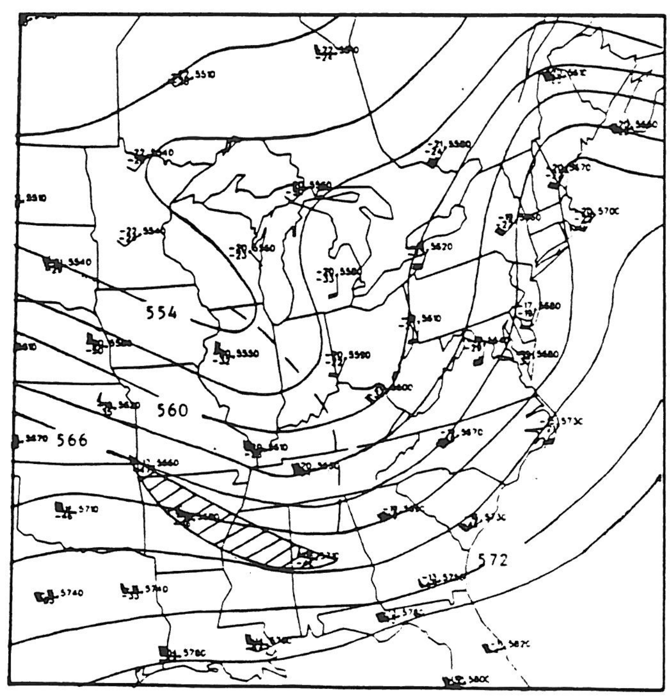

Figure 6. As in Figure 4 except for 500 mb heights. The hatched area denotes the max wind speed exceeding 60 kt. The dashed line is the trough axis. The contour interval is 20 dm.

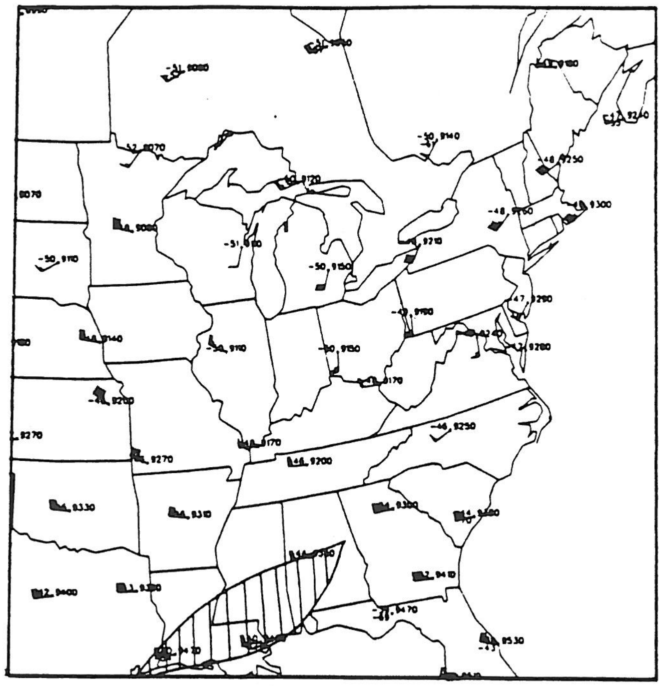

Figure 7. 1200 UTC March 7, 1992 300 mb station plot. The hatched area denotes the jet streak maxima where the wind speed exceeds 100 kt.

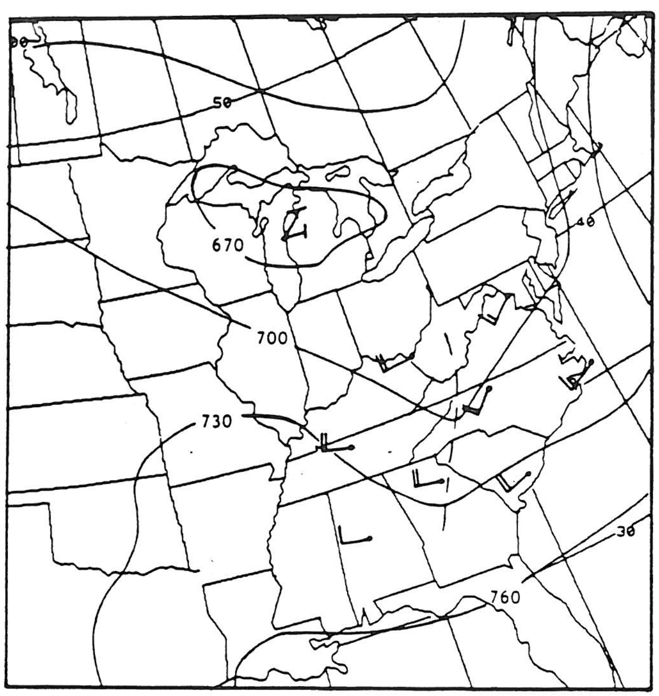

Figure 8. 0000 UTC March 8, 1992 925 mb height analysis. The dashed line is the trough axis. The contour increment is 30 m.

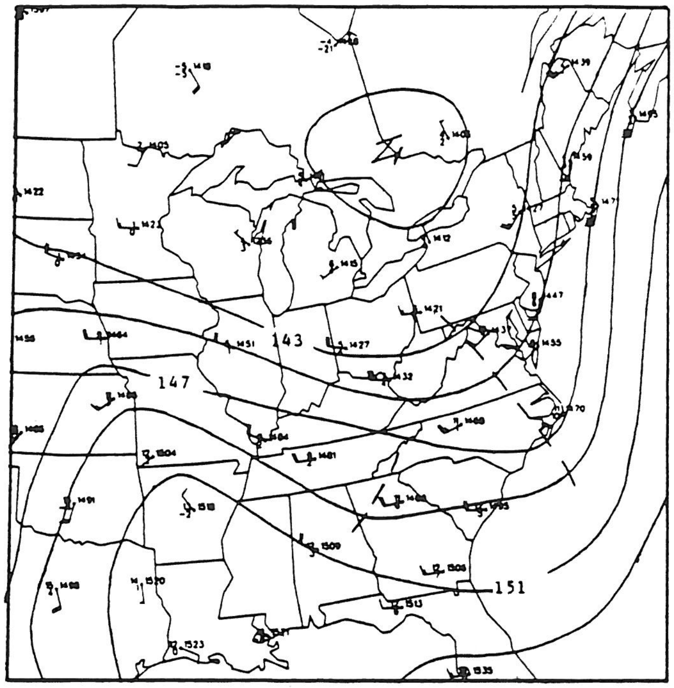

Figure 9. As in Figure 8 except for 850 mb heights. The contour increment is 20 m.

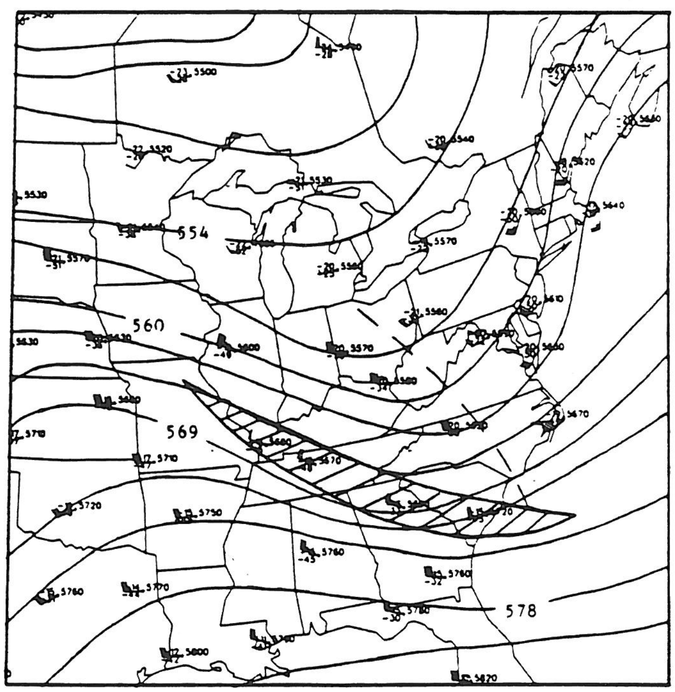

Figure 10. As in Figure 8 except for 500 mb heights. The hatched area denotes the max wind speed exceeding 60 kt. The dashed line is the trough axis. The contour interval is 20 dm.

Figure 11. As in Figure 7 except valid for 0000 UTC March 8, 1992. The hatched area denotes the jet streak maxima where the wind speed exceeds 90 kt.

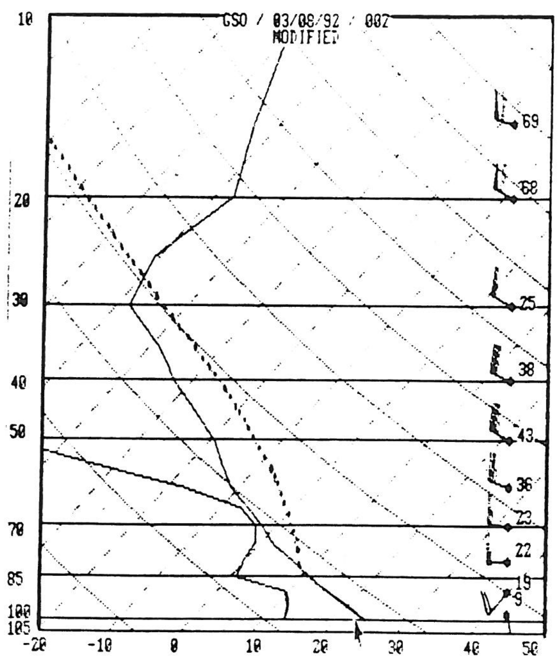

Figure 12. 0000 UTC March 8, 1992 Greensboro, NC radiosonde plot. From the SHARP Workstation (Hart and Korotky 1991). The dotted black line denotes the lifted parcel.

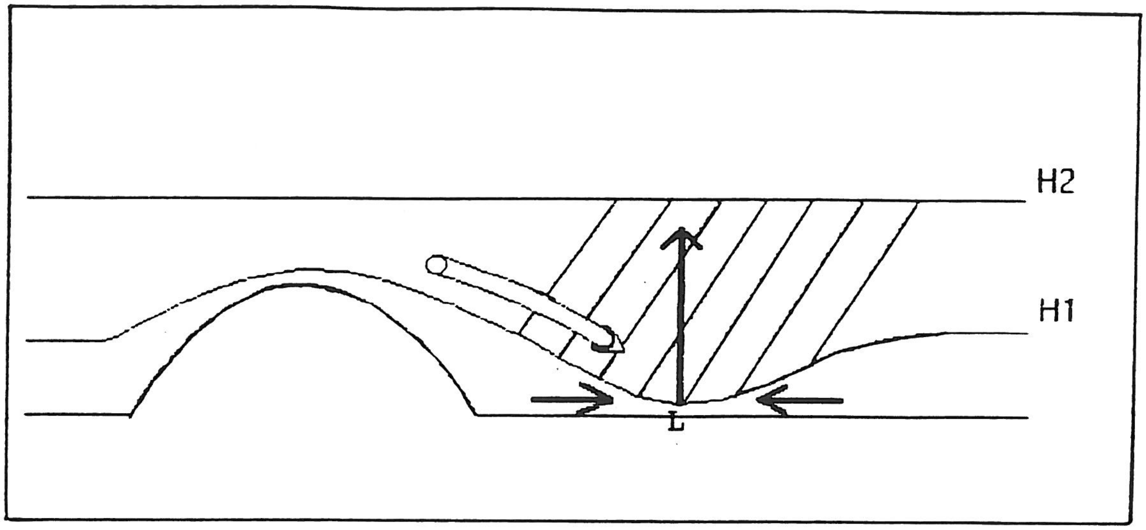

Figure 13. Illustration of a low-level lee trough induced by downslope motion. The solid white arrow denotes initial downslope wind flow. Solid black arrows denote response of wind to lowering heights (H1) induced by adiabatic warming. Hatched area is where adiabatic warming has occurred due to downslope motion. The "L" denotes axis of surface lee-side trough. Note that the black arrows imply surface wind convergence and net upward vertical motion in the vicinity of the lee trough axis (From Bluestein 1993, Newton 1956, and Pierrehumbert 1985b).

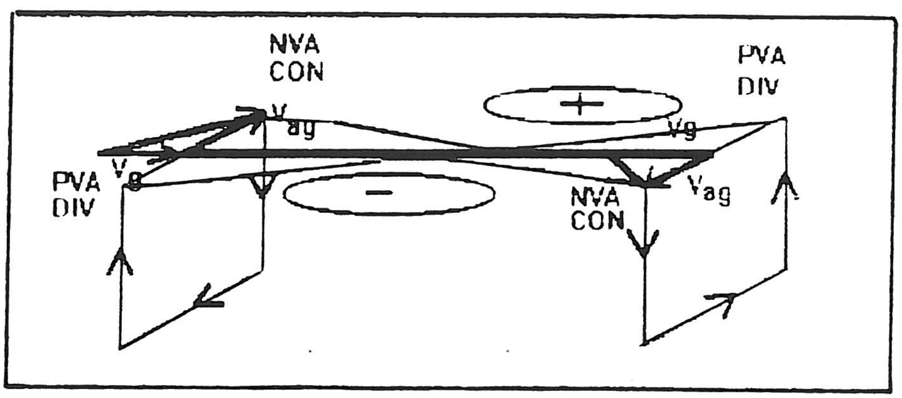

Figure 14. Illustration of the effect of jet streak dynamics on the development of atmospheric vertical motions. The dark horizontal line is an upper-level jet streak. The "+" and "-" circles represent positive and negative vorticity induced by speed shear along the axis perpendicular to the jet streak. The thick black arrows denote the geostrophic and ageostrophic components of the jet streak. The thin arrows are the response of wind to divergence (DIV) and convergence (CON) induced by the jet streak. Note the upward vertical motion in the left-front and right-rear quadrants of the jet streak (From Kessler 1985).

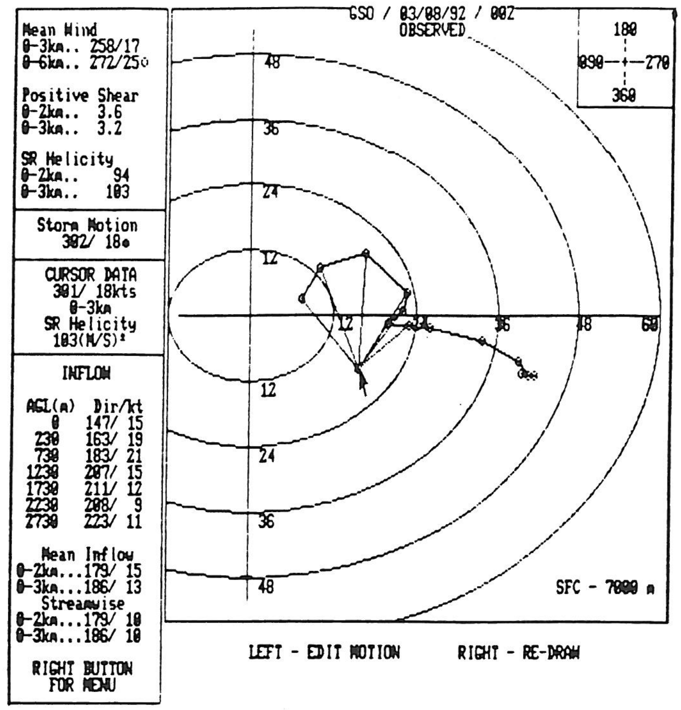

Figure 15. 0000 UTC March 8, 1992 observed WSO Greensboro, NC hodograph. From the SHARP Workstation (Hart and Korotky 1991).

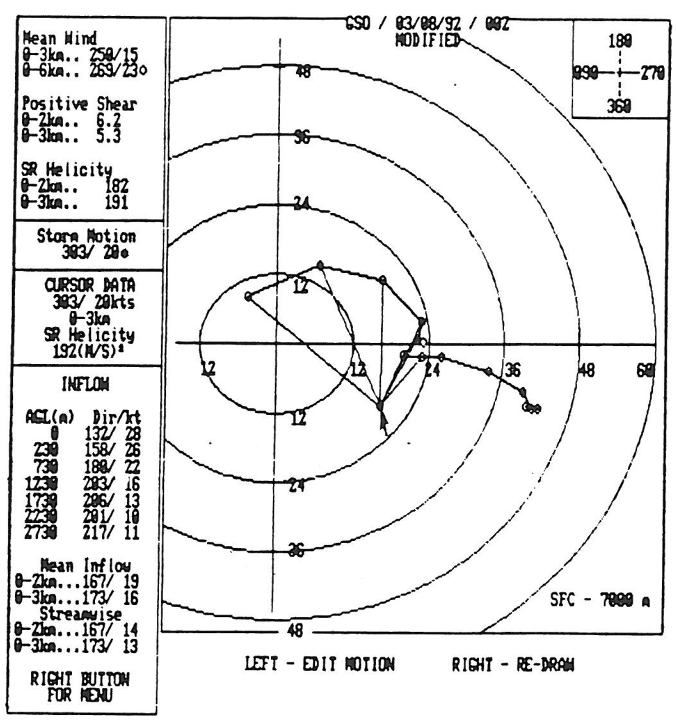

Figure 16. Same as Figure 15 except with the modified wind and storm motion. Modifications as explained in text.