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SYNOPTIC AND MESOSCALE SEVERE WEATHER: A TWO DAY CASE STUDY OF A DERECHO AND LOCAL HAILSTORMS

by

KIMBERLY WILLIS KREIS

A thesis submitted to the Graduate Faculty of
North Carolina State University
in partial fulfillment of the
requirements for the Degree of
Master of Science

MARINE, EARTH AND ATMOSPHERIC SCIENCE

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DEDICATION

I would like to dedicate this work to my family. My parents, Albert and Linda Willis, as always were wonderfully supportive. I stopped counting the number of times Dad jokingly asked “Is it done yet?”. My greatest support came from my husband, Andrew, and he receives my greatest thanks and all my love. Thank you, Mr. Pilot, for understanding why your meteorologist wife could not tell you what the weather would be like tomorrow. I promise to stop living in the past and get back to the present; both the weather’s and ours.

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BIOGRAPHY

Captain Kimberly W. Kreis was born 10 June 1967 in Fayetteville, North Carolina to Linda and Albert Willis. She has a brother, Kenneth, and a sister, Kelly. She married Andrew R Kreis 12 March 1994.

Captain Kreis received a Bachelor of Science degree in Physics from Tulane University in 1989. She was commissioned a second lieutenant in the United States Air Force in May 1989. Her first assignment was to the Air Force Institute of Technology at Pennsylvania State University. She received a Bachelor of Science degree in Meteorology from Pennsylvania State University in 1990. Her second assignment was to Cheyenne Mountain Air Force Base, Colorado where she served as a Space and Environmental Forecaster. She also served as the Command Weather Briefer for the Commander in Chief of Air Force Space Command. Captain Kreis spent four months in Taif, Saudi Arabia in support of Desert Storm. Her present assignment is to the Air Force Institute of Technology at North Carolina State University where she is pursuing a master's degree in meteorology.

TABLE OF CONTENTS

PAGE

LIST OF FIGURES

Page

The 4 June 1993 Derecho: Synoptic Evolution, Damage Analysis, And Possible East Coast Influences

LIST OF FIGURES (cont)

Page

Multiscale Analysis Of The 5 June 1993 Severe Hailstorms In North Carolina

1.0 THE 4 JUNE 1993 DERECHO: EVOLUTION, DAMAGE ANALYSIS, AND POSSIBLE EAST COAST INFLUENCES

1.1. Introduction

Thunderstorms occur on average 60 to 80 days throughout most of the United States, excluding the Pacific Coast states (Kessler, 1982). These storms provide beneficial rainfall, especially in the summer. However, convective thunderstorms present hazards such as tornadoes, damaging winds, and hail that can be produced in association with them. Damage to people and property from severe weather can be extensive. Severe weather is defined by the National Weather Service as any tornado, winds or wind gusts with speeds 50 knots or greater, and hailstones with diameters greater than 3/4 inch. Severe wind damage has been associated with convective downdrafts. Isolated thunderstorms, squall lines, or supercells can all produce straight line winds or downbursts.

Fujita (1981) described the bow echo, a squall line radar signature, and its relationship to severe winds. An intense downburst warps the squall line causing it to bow out at the point of strongest winds. There are cases where a bow echo squall line has developed and propagated over a large area, producing severe wind damage along a long path. Johns and Hirt (1987) have defined this long duration convective windstorm as a derecho.

They identified and defined a derecho as "any family of downburst clusters produced by an extratropical mesoscale convective system (MCS)." Johns and Hirt set forth detailed criteria for a storm to be called a derecho. They required the existence of a concentrated area of severe wind damage that covers more than four hundred kilometers. There must be a non random pattern to the damage and the damage path must show a chronological pattern. This will indicate whether the damage is from one storm, the derecho, or is caused by different, separate storms. There must also be three or more reports of individual wind gusts greater than sixty-five knots. Each of these reports must be separated by sixty-four kilometers. This shows that the strength of the derecho stays constant for a relatively long period of time. There must be less than three hours between wind damage reports. If more than three hours elapsed between severe weather reports storm continuity would be questionable. The convective system must have spatial and temporal continuity. This eliminates an areal severe thunderstorm complex from being included in the derecho database. Lastly, multiple swaths of damage must be part of the same mesoscale system. This last criterion eliminates the inclusion of damage reports from singular storms that might be generated near or by the derecho but not become a part of the derecho MCS.

Johns and Hirt (1987) cataloged and analyzed seventy derecho cases that occurred in the contiguous United States over a four year period. This extensive database of derecho storms suggests many synoptic factors that are significant for derecho initiation. Johns and Leftwich (1988) analyzed a tornadic supercell thunderstorm outbreak that evolved into a derecho. They focused on the differing upper air stability parameters between supercell and derecho evolutionary environments. Johns et al. (1990) provided an operationally oriented study that identified typical flow patterns and moisture fields for derecho initiation. The most current operational study of derechos was done by Duke and Rogash (1992). The derecho they studied had significant differences from the derecho data set developed by Johns and Hirt.

Observational studies of the radar structure of derechos have given significant insight into the storms intrinsic structure. Przybylinski and DeCaire (1985) cataloged four types of radar signatures for derechos. They pointed out the occurrence of the weak echo channel along the rear of the derecho squall line. Their studies indicate that the channel is an indication of where severe winds are occurring. Burgess and Smull (1990) tracked a derecho using Doppler radar. They again noted the importance of the weak echo channel as a signature for the location of strongest winds.

Theoretical studies of derechos have centered on the dynamics of squall lines and bow echoes. Schmidt et al. (1990) produced a numerical simulation of a derecho event. They found that a gravity wave circulation played a role in developing the rear to front flow. In the model, the gravity wave circulation helped develop a strong mesohigh aloft that blocked upper-level flow and channeled that flow downward toward the squall line. They suggest that the role of upper level shear and static stability be investigated to determine their part in the development of the rear inflow jet.

A severe convective windstorm developed near the Missouri-Kentucky border in the early morning of 4 June 1993. The storm originated in thunderstorms that developed in eastern Nebraska and northern Missouri between 0000 UTC and 0200 UTC. By 1300 UTC a bow echo structure was evident in southeastern Missouri. Over the next 20 hours, the bow echo squall line propagated through central Kentucky, southern West Virginia, Virginia and finally moved off the North Carolina coast. The storm produced damaging winds, hail, and several tornadoes. Damage in Virginia alone totaled more than 60 million dollars. (Storm Data, 1993)

This paper will present a detailed analysis of the 4 June 1993 derecho. The first section of the paper will analyze the synoptic environment in which the derecho formed and propagated. We will then compare the environment to that of previously documented derechos. The second part of the paper will provide a discussion of the radar structure and evolution of the derecho. The last part of the paper will focus on convective events associated with the derecho as it crossed the Appalachian mountains and approached the east coast. These events will be analyzed in order to supplement derecho studies that have previously focused on the central and southern plains (Przybylinski, 1995).

1.2. Data and Methods

Surface and upper air data are from the National Weather Service (NWS) Automation of Field Offices and Services (AFOS) and the NWS Records Retention System. Hourly surface observations and 12 hourly upper air data were utilized. Radar data was obtained from the NWS radar summaries with some data obtained from NOWRAD weather summaries from Weather Services Incorporated (WSI). Doppler radar images from the St. Louis WSR-88D, courtesy of Ron Przybylinski, were also used.

GEMPAK Meteorological and Analysis Software (5.0) was used to plot all hourly observations and gridded data fields. GEMPAK was also used to plot all standard rawinsonde sounding data. The software was used to objectively analyze other meteorological fields such as convergence. For these analyses a 50 X 50 surface grid was established. The upper air grid is 40 X 40. Both grids have a mean grid spacing of .8 degrees latitude. A Barnes Objective Analysis scheme was used with a two pass criterion and a convergence factor of 0.3 (Barnes, 1964, 1973).

1.3. Synoptic Analysis

Johns (93) described two basic synoptic patterns for bow echo events. Those patterns are the warm season pattern and the dynamic pattern. The warm season pattern centers around a low level thermal boundary oriented east- west (Fig 1.1a). The polar jet is westerly or northwesterly. The low-level jet approaches the thermal boundary from the south eventually becoming nearly parallel to the boundary. The dynamic synoptic pattern (Fig. 1.1b) is characterized by a strong, migrating low pressure system and is very similar to the classic Great Plains tornado outbreak pattern. However, in contrast to the Great Plains pattern where the low level jet is nearly perpendicular to the polar jet, the low level jet in the dynamic pattern for bow echo development is usually more parallel to the polar jet. Johns noted that this pattern is more common in cooler months, i.e., fall and spring.

The 4 June 1993 derecho is most similar to the warm season bow echo pattern. At 1200 UTC 4 June 1993 the NMC surface analysis (Fig. 1.2a) shows a stationary front extending eastward from a weak low pressure system in southwestern Missouri. South of the stationary front there is evidence of a low level jet. Winds throughout Tennessee, Mississippi, and Alabama are from the south with speeds near 10 knots. The polar jet is located to the north of the boundary at 1200 UTC 4 June 1993. This can be seen in the 200 mb NMC analysis (Fig 1.2b).

Johns and Hirt (1987) determined several meteorological features often that are present during warm season derecho initiation. The aforementioned thermal boundary is relatively strong in this case. For example, at 1200 UTC 4 June 1993 (Fig. 1.2a) the temperature at St. Louis, Missouri, located north of the stationary front, is 61 F. South of the front at Jackson, Tennessee the temperature is 74 F. This is a 13 F temperature gradient per 400 kilometers in the general vicinity of derecho initiation. Another synoptic feature in most warm season pattern cases is a mid level trough approaching the area of derecho initiation. A trough is shown on the 1200 UTC 4 June 1993 500 mb analysis just west of Missouri extending from Nebraska through Oklahoma (Fig. 1.3).

In the derecho database (Johns and Hirt, 1987), 86 percent of the cases had 500 mb winds from the direction 240 degrees or greater with an average speed of 41 knots. At 1200 UTC 4 June 1993 the winds at Monett, Missouri are southwesterly at 55 knots. Paducah, Kentucky winds are also southwesterly but at 40 knots. Farther east along the derecho's track the winds become even more westerly with Greensboro, North Carolina and Huntington, West Virginia both having winds that are due west (Fig. 1.3). Their wind speeds are 35 and 40 knots respectively. This gives a 500 mb wind speed average of 42 knots for this case. The derecho database average for the 700 mb wind speed is 34 knots. Using the same four stations we get an average 700 mb wind speed for this case of 31 knots, just less than the derecho database average. Surface winds are usually south or southwest and light in the warm season derecho composite. Along the derecho track surface winds for this case (Fig. 1.2a) are all southerly or southwesterly with speeds between 5 and 10 knots.

The derecho database (Johns and Hirt, 1987) indicates that low level moisture from the surface through 850 mb tends to be pooled along and just to the south of the east - west boundary. The 4 June 1993 1200 UTC surface dewpoint analysis illustrates this quite well (Fig. 1.4). A large area of regionally highest dewpoints is situated to the south of the stationary front. At 850 mb (Fig. 1.5), the area of highest dewpoints is centered near the derecho track. The 500 mb moisture levels are relatively low. The derecho database composite for 500 mb (Johns et al.) indicates a dewpoint depression at the midpoint of the derecho track of 22 C. For the 4 June 1993 case at 1200 UTC 500 mb is not as dry as the composite. Along the midpoint of the derecho track the dewpoint depressions are only (Fig. 1.6). It is interesting to note that the highest depressions, or the driest air at 500 mb, is on the eastern side of the Appalachians in Virginia.

Warm advection at both 850 mb and 700 mb is important to derecho development. Johns and Hirt found that in all 70 cases in the database, 850 mb warm advection was occurring within 320 kilometers of the derecho initiation point. Also 96 percent of the cases showed 700 mb warm advection in that same region. Warm advection near the thermal boundary would be expected. On 4 June 1993 at 1200 UTC strong warm advection at 850 mb can be seen in southern Missouri and decreasing in strength eastward along the derecho's path (Fig. 1.7a). A similar pattern can also be seen in the 700 mb temperature advection fields (Figs. 1.7b).

Derecho movement is often related to the thermal gradient at 850 and 700 mb. Derechos in the database appeared to move along the tightly packed isotherms, just to the north of a thermal ridge (Johns et al., 1990). Figure 1.8 shows both 850 and 700 mb temperature gradients, along with the layer averaged temperature gradient. The path of this derecho seems to most accurately follow the 850 mb isotherms.

Warm, moist air at low levels and cool dry air at upper contribute to strong convective instability. Johns and Hirt reported an average Showalter Index of -5.9 for the 70 cases. Showalter index values between -4 and -6 denote unstable atmospheres. Extreme instability is indicated with Showalter values -6 or less (Showalter, 1953). The average lifted index (LI) is -9.0 for the derecho database. Any LI value of zero or less indicates the increasing instability of the atmosphere (Galway, 1956). Johns et al.(1990) analyzed the instability parameter Convective Available Potential Energy (CAPE) and its relationship to derecho formation. CAPE is a measurement of the positive buoyancy of an adiabatically rising parcel and thus indicates the latent instability of the atmosphere. Larger CAPE values would suggest stronger convection, though the shear environment can also affect convective development (Doswell et al., 1990). In their composite study using standard 1200 and 0000 UTC rawinsonde data, Johns et al. (1990) found an average CAPE values of 2400 Jkg^{-1} near the derecho's genesis area. CAPE values were maximized near the midpoint of the derecho track. The average CAPE value at the midpoint was $4500Jkg^{-1}$.

Figure 1.9 shows a map of the 4 June 1993 derecho path along with nearby upper air reporting stations. Shown on the map are the CAPE, Showalter index, and LI for each station. Figure 1.10 shows the associated upper air soundings for those same stations. Paducah, Kentucky is the closest rawinsonde station to the derecho initiation area in southwestern Missouri; the derecho actually went through Paducah near 1530 UTC 4 June 1993. At 1200 UTC Paducah's sounding indicated a Showalter index of -7 and a LI of -8 (Fig. 1.10a). The Showalter value indicates more instability than the database average, but the LI is slightly more stable than the average. Another reporting station along the derecho track is Huntington, West Virginia, which the derecho passed around 1930 UTC. Huntington's values for the Showalter and LI are -1, and 2 respectively (Fig. 1.10b). The derecho passed just to the north of Greensboro, North Carolina. Greensboro had a Showalter of -2, and a LI of -3 (Fig. 1.10c). Most of the CAPE values along the 4 June 1993 derecho track reflect the composite values. Paducah has a CAPE value at 1200 UTC of 2726 Jkg^{-1}. This is representative of previous genesis area CAPE values. Cape Hatteras, North Carolina, is at the end of the derecho track. At 1200 UTC 4 June 1993 Cape Hatteras has a CAPE value of 1466 Jkg^{-1} at (Fig. 1.10d). The midpoint of the derecho track where the composite CAPE value is 4500 Jkg^{-1}, occurs near the Appalachian mountains. Huntington, West Virginia has a CAPE value of 0.0. Because Huntington is in the mountains many of the stability index calculations are not representative. Nashville, Tennessee is somewhat close to the midpoint location and has a reported CAPE value at 1200 UTC 4 June 1993 of 2492 Jkg^{-1} (Fig. 1.10e).

The synoptic environment of the 4 June 1993 derecho reflects many classic derecho features. Surface features reflect those in the warm season pattern. The stationary front, strong thermal gradient, and low level moisture are all usually present in warm season derecho cases. Movement of this storm is very similar to storms in the Johns and Hirt (1987) database. This storm travels along the 850 mb isotherms, and mid-level warm advection is also present. Departures from the classic derecho signatures occur mostly in upper air features. The 4 June 1993 derecho crosses the Appalachian mountains. Because of this many upper air signatures, such as 500 mb moisture, show differences from the derecho cases in the database. Stability indices are also affected by the mountains.

1.4 Radar Analysis

After studying the 70 derecho cases, Johns and Hirt (1987) identified two distinct radar echo patterns. These are the serial and progressive derecho patterns. The serial derecho consists of one extensive squall line with several small bow echoes and Line Echo Wave Patterns (LEWP) moving along the squall line (Fig. 1.11a). The squall line is oriented nearly parallel to the mean wind and moves perpendicular to it. The progressive derecho consists of one bow echo shaped squall line (Fig. 1.11b). The progressive derecho moves parallel to the mean flow and nearly parallel to the associated thermal boundary. The 4 June 1993 derecho follows the progressive pattern. The one bowing squall line is shown in the 1835 UTC 4 June 1993 NWS radar summary chart (Fig. 1.12). The mean wind is from the west as is shown in Paducah, Kentucky's 1200 UTC 4 June 1993 sounding (Fig. 1.10a).

Derechos have been shown to develop from both multicellular convection and from supercells. Johns and Leftwich (1988) detailed a derecho that developed from a tornadic supercell. The transition occurred as the supercell moved into an environment where the level of free convection (LFC) was significantly lower than the environment in which the supercell formed. The lower LFC could indicate that outflow from the supercell could more easily initiate new convection. Smith (1990) also documented a case where supercells evolved into a derecho. Burgess and Smull (1990) tracked a derecho that moved across the National Severe Storms Laboratory (NSSL) special observational network. The derecho in their study formed in north Texas as multiple cells, developing into a squall line as the storms approached Oklahoma City.

The 4 June 1993 derecho appears to have developed from multiple cells that originated in northwestern Missouri. Figure 1.13 shows a series of NWS radar summaries that document the development of the derecho. At 0035 UTC 4 June 1993 a large area of rain showers is depicted in eastern Nebraska and Kansas. One thunderstorm is shown in south central Kansas, and is moving toward the northeast. By 0235 UTC a second thunderstorm has developed from the rain shower area and is on the Kansas - Missouri border. The storm from central Kansas has continued to move northeastward and is approaching the cell on the Kansas border. A significant thunderstorm has developed in extreme southwestern Missouri. By 0535 UTC, a squall line oriented north-south has developed in southern Missouri. This area of thunderstorms is indicated by point “A”. Several storms have continued moving northeastward across Missouri, with a large cell moving into Illinois. This large cell is noted by point “B”. There is another area of thunderstorms in extreme southwestern Indiana. This area is noted by point “C”.

By 0935 UTC the northeastern portion of the squall line has moved across Missouri, point “A”. The squall line extends to the Missouri - Oklahoma border. Several large thunderstorms have developed near the southern tip of the squall line in Kansas and Oklahoma. The northern thunderstorms have moved into southern Indiana near the Kentucky border and extend across Illinois. The eastern most cell in this group of thunderstorms, point “B”, appears to have weakened. The storms at point “C” have slowly moved eastward.

At 1235 UTC the squall line shows some evidence of breaking up (point “A”). The storms on the northern end seem to be moving away from the line as the southern end becomes dominated by the large cells that moved east from Oklahoma and Kansas. The storm at point “B” has intensified with tops approaching 52,000 feet as it moves through central Illinois. The storms at point “C” are still strong with tops from 41,000 feet to 48,000 feet. These storms have moved into north central Kentucky.

The 1435 UTC radar summary is the first to show a bow echo signature. The leading edge of the bow is pushing into extreme southern Illinois. The indicated speed of movement for the bow echo is 40 knots with one individual cell moving at 50 knots. Storm tops in the middle and southern end are all above 52, 000 feet. Thunderstorm cluster “B” has moved eastward into central Indiana. Meanwhile, thunderstorm cluster “C” has shown no significant movement and is still located in north central Kentucky.

There is a noticeable notch at the back edge of the bow echo signature at 1435 UTC. Przybylinski and DeCaire (1985) first identified these signature notches in derechos called them weak echo channels (WEC). Much research has been done on the cause of these WEC features. Przybylinski and Gery (1983) determined that the location of the WEC, or rear inflow notches (RIN), coincided with the area of strongest downburst winds. Burgess and Smull (1990) noticed a strong rear inflow jet passing through the trailing stratiform region approaching the surface and producing a WEC in a squall line. The WEC developed just before significant bowing occurred in the squall line. Smull and Houze (1987) studied several squall line systems with trailing stratiform precipitation and analyzed the inflow of environmental air into the rear of the storm. They found the rear inflow jet composed a continuous channel from middle levels in the trailing stratiform region through the lower levels near the leading convective region. This rear inflow jet actually helped strengthen the gust front. Weisman et al. (1988, 1990) and Weisman (1990) have performed numerical simulations of long lived squall lines. They have found that the rear inflow jet is an important feature in long lived squall line such as derechos. Weisman (1990) also noted two vortices developing at either end of the bowing squall line. He described them as book end vortices since they developed on either end of the bowing squall line.

A WEC can be seen in WSR-88D reflectivity radar data from WSFO St. Louis for the 4 June 1993 case. The 1448 UTC reflectivity scan shows one WEC, indicated by the arrow (Fig. 1.14a). Cape Giradeau, Missouri, located just to the north of the WEC and shown as point “A” on Figure 1.14a, reported in *Storm Data* 55 knot winds at the

Cape Giradeau Airport at 1453 UTC. By 1518 UTC the WEC has progressed even further into the convective line and the squall line has moved further into Kentucky (Fig. 1.14b). McCracken County, Kentucky, located at point “B” on Figure 1.14b, reports a wind damage path 10 to 20 miles wide at 1525 UTC. The 1529 UTC radar image suggests the development of two WECs, one in Kentucky and the other in southern Illinois (Fig. 1.14c). At 1535 UTC Marshall County, Kentucky, point “C” on Figure 1.14c, reported an F0 tornado. This tornado could be associated with the book end vortices suggested by Weisman. There is some evidence at points “D” and “E” to suggest book end vortices. The 1547 UTC radar reflectivity shows no signs of WECs, just a strong bowing squall line with no cells stronger than 40 dbZ (Fig. 1.14d). However, wind severe wind damage is still occurring. The derecho producing squall line moves rapidly to the east and by 1651 UTC (Fig. 1.14e) leaves the range of the St. Louis radar.

Przybylinski and DeCaire (1985) defined four radar signatures associated with derechos. All four of these signatures have some similarities (Fig. 1.15). They all eventually show a bow echo shape. They have a strong low level reflective gradient along the leading edge of the storm. They also all have WECs along the back edge of the derecho. The type I storm begins as individual convective elements covering a large area, up to 250 kilometers. At maturation the storms organize into a line echo pattern with several bow echoes. The type II storms resemble the progressive derecho from Johns and Hirt (1987). They have a short line of convective elements that eventually form one bow echo. Notable about this storm is that individual convective cells develop downwind of the bow echo. These cells can develop as far ahead of the bow echo as 80 kilometers. Type III storms are similar to type II storms except they lack the down wind cell development. They are also characterized by the presence of a strong convective cell on the upwind flank but embedded in the bow echo. This cell can often reach supercell status and can remain active even as the bow echo goes through several regenerations. Type IV storms begin with a single severe storm, possibly a supercell. During the severe storm's lifecycle, new convective elements form along the rear flank downdraft. These new cells organize into an ill defined bow echo.

The Przybylinski and DeCaire (1985) type II pattern has also been associated with a band of scattered to broken convection, seen northeastward of the bulging squall line. This is similar to the LEWP associated with the progressive derecho radar pattern. Przybylinski (1995) noted that this broken convection is usually associated with a surface frontal boundary or warm advection zone. Smith (1990) documented a “warm advection wing” with the 4 May 1989 derecho. This wing was a radar echo that developed along the north end of the bow echo and formed in an area of strong warm advection.

The 1815 UTC NOWRAD radar summary presents an interesting picture (Fig 1.16). The bow echo can be seen in central Kentucky, south of Lexington. Another line of thunderstorms is shown extending from Huntington, West Virginia back to the leading edge of the derecho squall line. This can be described as an arrow feature emanating from the bow echo.

There are several possible causes of this interesting alignment. A surface analysis for 1800 UTC shows areas of warm advection (Fig. 1.17). The change in sign of the advection values in east-central Kentucky defines somewhat the location of the stationary front. Station spacing limits more accurate placement of the front, however. Strong warm advection is occurring in southeastern Kentucky near the stationary frontal boundary. Several areas of thunderstorms are occurring in the same geographical region where warm advection is shown.

The 1435 UTC NWS radar summary showed two areas of thunderstorms, "B" and "C", ahead of the derecho convective system. Area "B" was in southern Indiana and area "C" was in central Kentucky moving towards West Virginia. At 1635 UTC area "B" has moved south to the Kentucky-Indiana-Ohio borders (Fig. 1.18a). Area "C" has moved rapidly southeastward and is nearing the West Virginia border, and by 1735 UTC (Fig. 1.18b) area "C" is moving through southern West Virginia. However, area "B" is decreasing in strength and appears to be merging with the derecho convective system, and by 1815 UTC, as shown in Figure 1.16, appears to have formed part of the arrow echo.

The large geographical extent of the arrow echo is greater than any other documented type II convective band. The thunderstorms in area "B" appeared to be losing strength as they approached the area of strong warm advection. Assuming a type II derecho with a developing warm advection wing, these preexisting thunderstorms could have merged with the derecho convective system to produce this extensive arrow echo.

By 2100 UTC the derecho is moving out of the Appalachian mountains into Virginia (Fig. 1.19). NWS summary charts (not shown) indicate that the intense convective cell in south central Virginia is thunderstorm complex “C”. This storm has produced significant damage in Virginia. The damage path for both this storm and the subsequent derecho illustrates why Virginia suffered 60 million dollars of damage (Fig. 1.20). Przybylinski and DeCaire’s (1985) type II storm pattern includes isolated convective cells that develop downwind from the bow echo system. However, as previously documented, this cell originated in Indiana, well away from the influence of the derecho convective system. The storm’s movement is similar to the derecho convective system’s movement since it also tracks along the stationary boundary.

A high pressure area off the Florida coast is inducing strong, moist flow from the Gulf of Mexico. Southwest surface winds are strong from Florida through North Carolina. The increased convergence along the stationary boundary could help reinvigorate convection (Fig. 1.21). Both the Greensboro and Cape Hatteras soundings provide evidence that the air mass in southern Virginia and North Carolina was convectively unstable (Fig. 1.10c,d,e). The cell’s intensification in Virginia could thus be caused by increased convergence and decreased stability.

At 2200 UTC a third convective element has developed in Virginia (Fig 1.22a). This cell resembles a type II downwind convective element. The cell merges with the bow echo by 2245 UTC (Fig. 1.22b). Meanwhile, the leading cell continues its movement southeastward along the stationary boundary. The thunderstorm development on the North Carolina coast along the stationary front suggests that convergence is strong along the entire boundary. A second type II cell appears to have developed at 2330 UTC (Fig. 1.22c). The cell formed on the stationary boundary, apparently in the wake of the leading cell. This second downwind cell merges with the derecho convective system by 0000 UTC (Fig. 1.22d) forming an intense, convective cell on the southern end of the squall line. Finally at 0100 UTC (Fig. 1.22e) the leading cell merges with the squall line as it begins to move off the coast.

1.5 Summary and Discussion

The synoptic environment over the initiation area of the 4 June 1993 derecho compares favorably to those already documented for warm season derechos. The convective system resembled a warm season progressive derecho. The derecho appears to have originated in a band of thunderstorms that developed in southern Missouri and Kansas. The bow echo squall line associated with the derecho developed many signature features found in previous derecho studies such as WECs and bookend vortices. An extensive arrow echo developed in western Kentucky and has been compared to the much smaller warm advection wings seen in the type II derecho radar signatures (Przybylinski and DeCaire, 1985). One preexisting thunderstorm crossed the Appalachians before the derecho and rapidly intensified into a strong convective cell. This storm continued to track ahead of the derecho along the stationary front. Several other cells developed between the derecho and the leading convective cell. These storms resemble the downwind convective cells also seen in the type II derecho radar signature (Przybylinski and DeCaire, 1985).

Future study could focus on modeling this event. Modeling the interaction of the derecho convective system and the preexisting thunderstorms could determine the true cause of the arrow echo. A model of this event could further understanding of rear to front flow and their relationship to WECs. A model analysis of the upper air stability over the mountains and the east coast could provide insight into how the derecho and the leading convective cell successfully crossed the Appalachians, intensifying as they did.

A comparison modeling study of other derechos that cross the Appalachians might determine a signature geographical distance from the mountains that derecho genesis can occur and mountain crossing will be successful. A similar modeling comparison could be performed to determine an average lifetime expended for a successful crossing of the mountain range.

1.6 References

Barnes, S.L., 1964: Atechnique for maximizing details in numerical weather map analysis. *J. Appl. Meteor.*, **3**, 396-409.

_____, 1973: Mesoscale objective map analysis using weighted time-series observations. *NOAA Technical Memorandum ERL NSSL-62*, Norman, OK, 60 pp.

Burgess, D.W., and B.F. Smull, 1990: Doppler radar observations of a bow echo associated with a long track severe windstorm. Preprints, *16th Conf. Severe Local Storms*, Kananaskis Park, Alberta, Canada, Amer. Meteor. Soc., 203-208.

Doswell, C.A., III, R. Davies-Jones, and D.L. Keller, 1990: On summary measures of skill in rare event forecasting based on contingency tables. *Wea. Forecasting*, **5**, 576-585.

Duke, J. D., and J. A. Rogash, 1992: Multiscale review of the development and early evolution of the 9 April 1991 derecho. *Wea. Forecasting*, **7**, 623-635.

Fujita, T.T., 1981: Tornadoes and downbursts in the context of generalized planetary scales. *J. Atmos. Sci.*, **38**, 1511-1534.

Galway, J. G., 1956: The lifted index as a predictor of latent instability. *Bull. Amer. Meteor. Soc.*, **37**, 528-529.

Johns, R.H., and W.D. Hirt, 1987: Derechos: widespread convectively induced windstorms. *Wea Forecasting*, **2**, 32-49.

_____, and P.W. Leftwich, Jr., 1988: The severe thunderstorm outbreak of July 28- 29 1986... A case exhibiting both isolated supercells and a derecho producing convective system. Preprints, *15th Conf. Severe Local Storms*, Baltimore, Amer. Meteor. Soc., 448-451.

____, K.W. Howard, and R.A. Maddox, 1990: Conditions associated with long lived erechos- An examination of the large scale environment. Preprints, *16th Conf. Severe Local Storms*, Kananaskis Park, Alberta, Canada, Amer. Meteor. Soc., 4 08-412.

____, 1993: Meteorological parameters associated with bow echo development in convective storms. *Wea. Forecasting*, **8**, 294-299.

Kessler, E., ed., 1982: Thunderstorms: a social, scientific, and technological documentary Vol. 2, thunderstorm morphology and dynamics.

Przybylinski, R.W., and D.M. DeCAire, 1985: Radar signatures associated with the derecho, a type of mesoscale convective system, Preprints, *14th Conf. Severe Local Storms*, Indianapolois, Indiana, Amer. Meteor. Soc., 171-174.

____, and W. J. Gery, 1983: The reliability of the bow echo as an nimportant severe weather signature. Preprints, *13th Conf. On Severe Local Storms*, Tulsa, OK, Amer. Meteor. Soc., 270-273.

____, 1995: The bow echo: observations, numerical simulations, and severe weather detection methods. *Wea. Forecasting*, **10**, 203-218.

Schmidt, J.M. C.J. Tremback, and W.R. Cotton, 1990: Numerical simulations of a derecho event: Synoptic and mesoscale components, Preprints, *16th Conf. Severe Local Storms*, Kananaskis Park, Alberta, Canada, Amer. Meteor. Soc., 422-427.

Showalter, A.K., 1953: A stability index for thunderstorm forecasting. *Bull. Amer. Meteor. Soc.*, **34**, 250-252.

Smith, B.E., 1990: Mesoscale structure of a derechoproducing convective system: The southern great plains storm of May 4, 1989. Preprints, *16th Conf. Severe Local Storms*, Kananaskis Park, Alberta, Canada, Amer. Meteor. Soc., 455-460.

Smull, B.A., and R.A. Houze, 1987: Rear inflow in squall lines with trailing stratiform precipitation. *Mon. Wea. Rev.*, **115**, 2869-2889.

Weisman, M.L., 1990: The numerical simulation of bow echoes. Preprints, *16th Conf. Severe Local Storms*, Kananaskis Park, Alberta, Canada, Amer. Meteor. Soc., 428-433.

_____, J.B. Klemp, and R. Rotunno, 1988: Structure and evolution of numerically simulated squall lines. *J. Atmos. Sci.*, **45**, 1990-2013.

_____, R. Rotunno, and J.B. Klemp, 1990: The role of rear inflow jets in the production of long lived meso-convective systems. Preprints, *16th Conf. Severe Local Storms*, Kananaskis Park, Alberta, Canada, Amer. Meteor. Soc., 652-657.

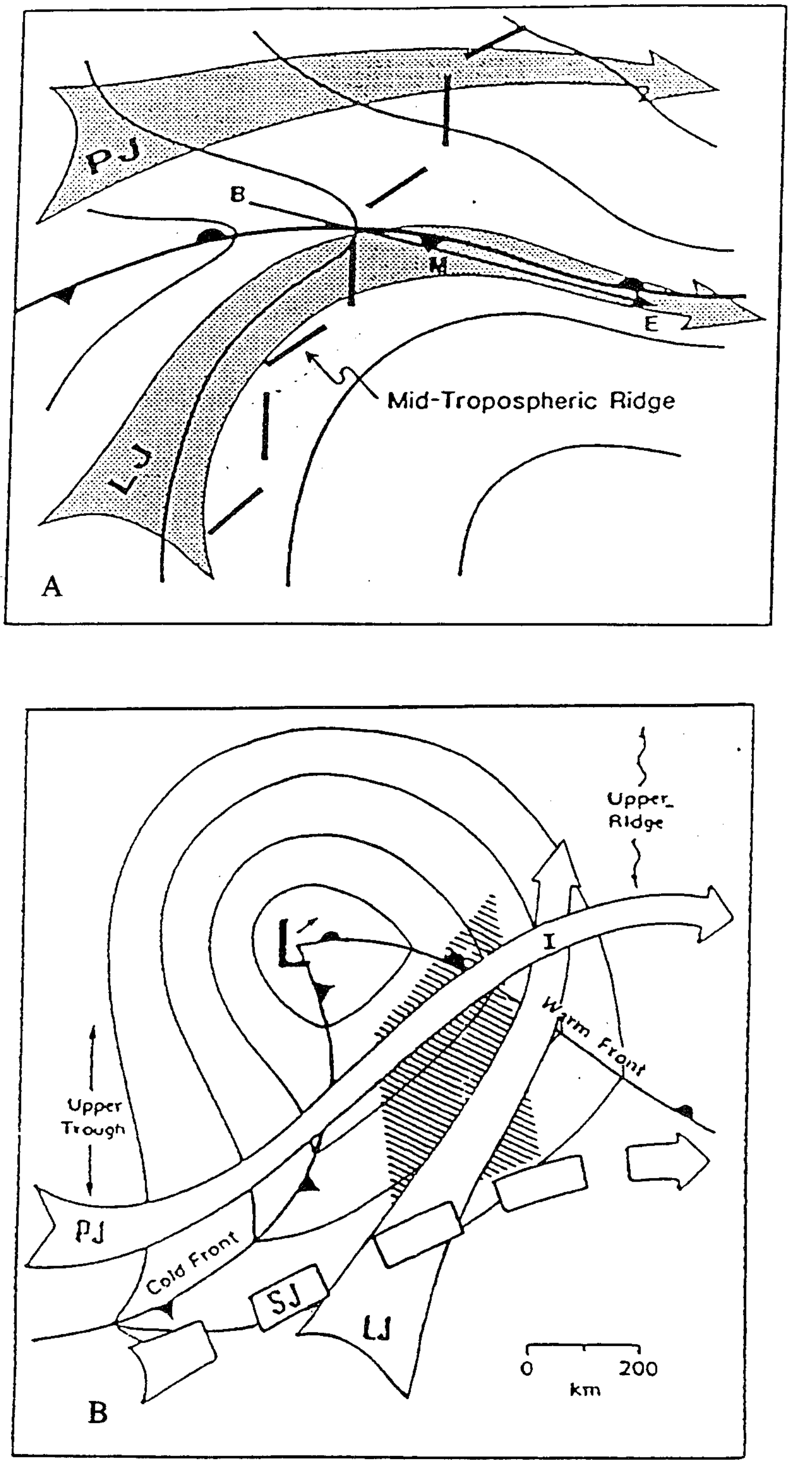


Figure 1.1. A) Warm season pattern favorable for progressive bow echo complexes. B) Dynamic synoptic pattern favorable for squall line development. Broad arrows are the polar jet (PJ), low level jet(LJ), and the upper subtropical jet. The thin lines are sea level pressure and all other symbols are standard in meteorology. The line B-M-E represents the bow echo track. (Johns, 1993)

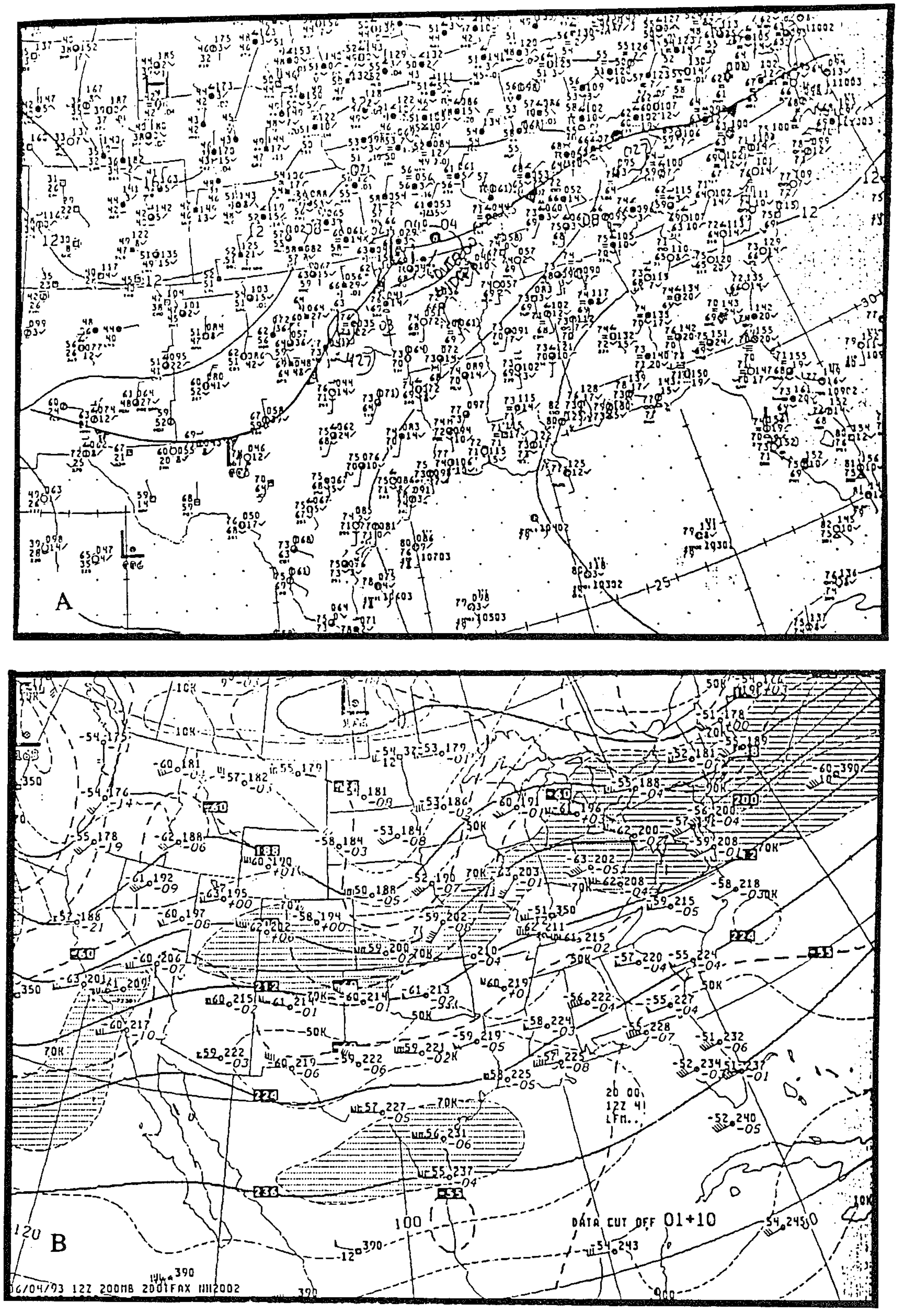


Figure 1.2. Warm season pattern on 4 June 1993. A) NMC surface analysis for 1200 UTC 4 June 1993. B) NMC 200 mb analysis. Shaded areas denot wind speeds greater than 70 knots.

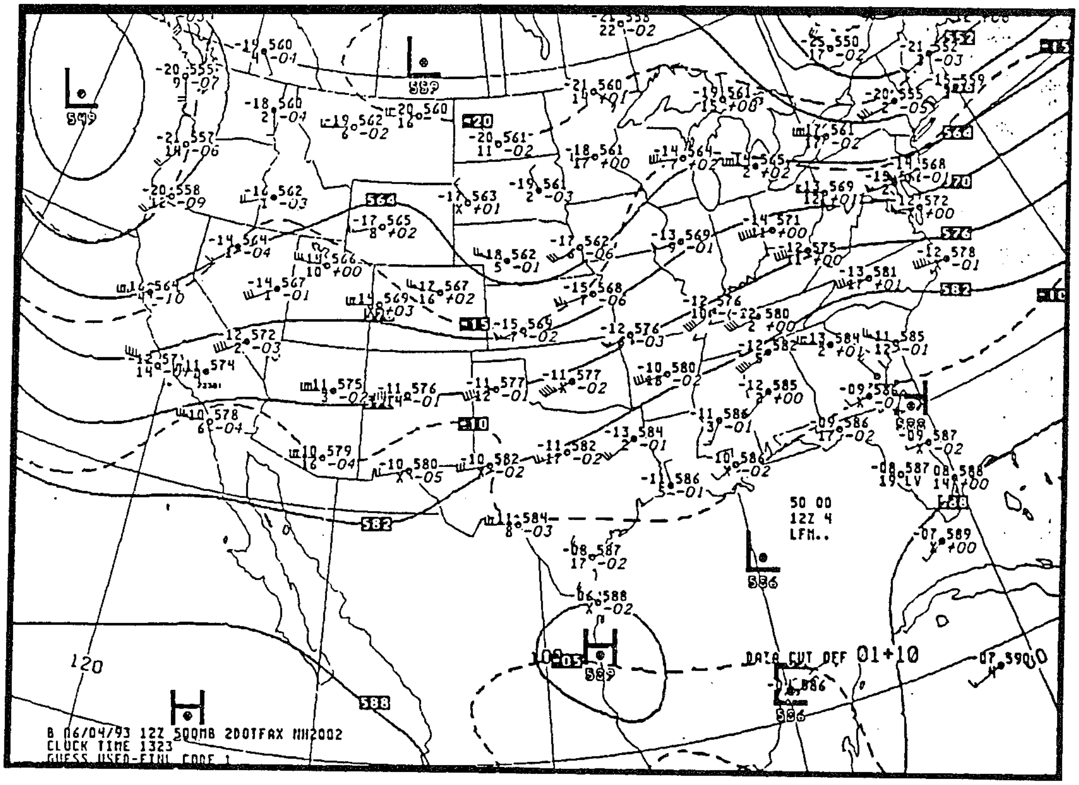


Figure 1.3. NMC 500 mb analysis for 1200 UTC 4 June 1993.

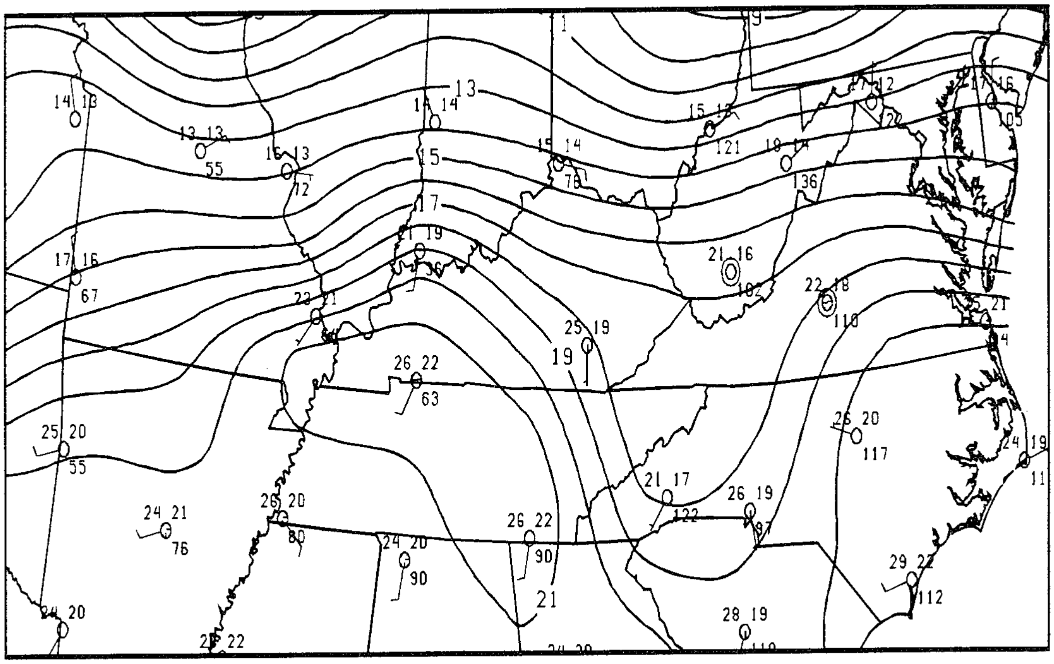


Figure 1.4. Surface dewpoint analysis for 1400 UTC 4 June 1993. Values are in degrees Celsius and are contoured every degree.

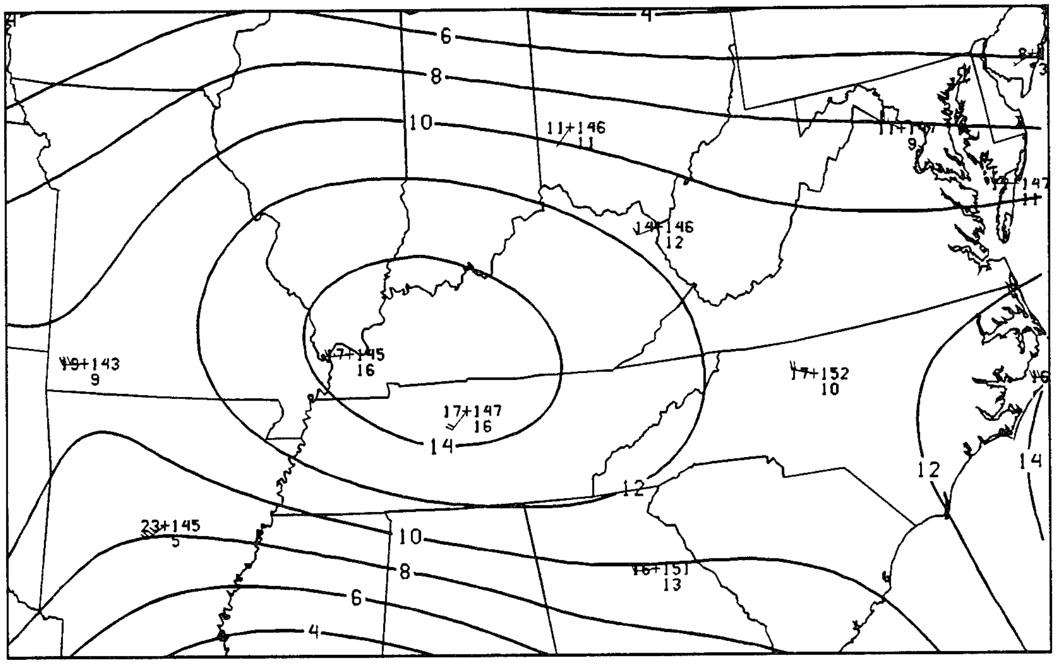


Figure 1.5. The 850mb dewpoint analysis for 1200 UTC 4 June 1993. Conturs are every 2 degrees Celsius.

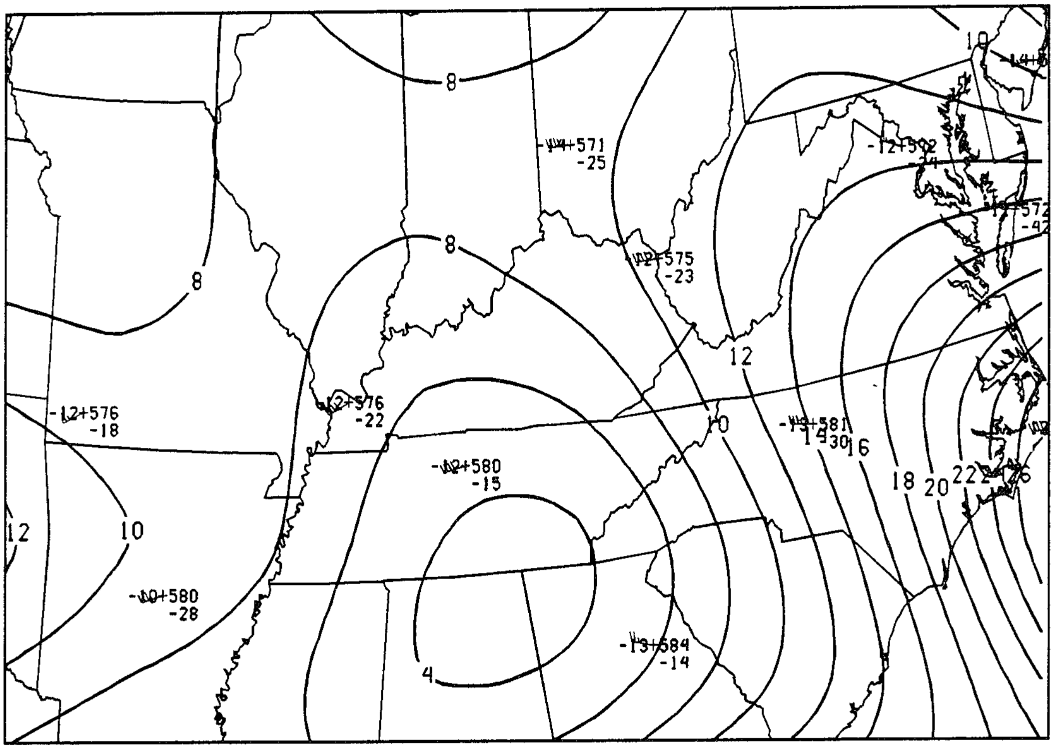


Figure 1.6. The 500 mb depoint depression analysis for 1200 UTC 4 June 1993. Copnturs are every two degrees Celsius.

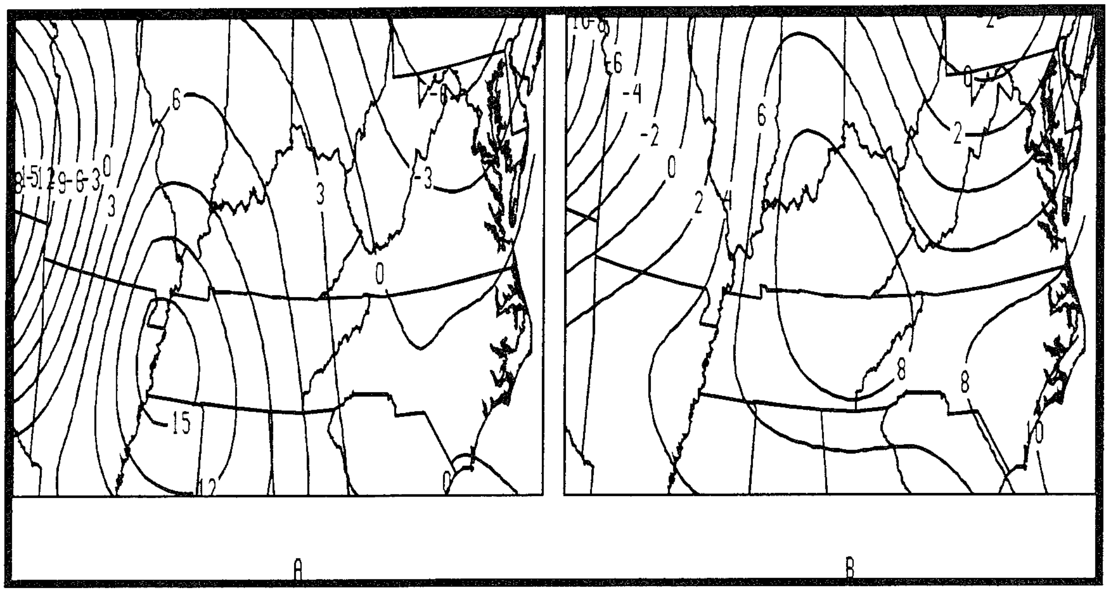


Figure 1.7. Temperature advection at 1200 UTC 4 June 1993 a) 850mb, b) 700 mb. Units are 10^{-5} Ks^{-1}.

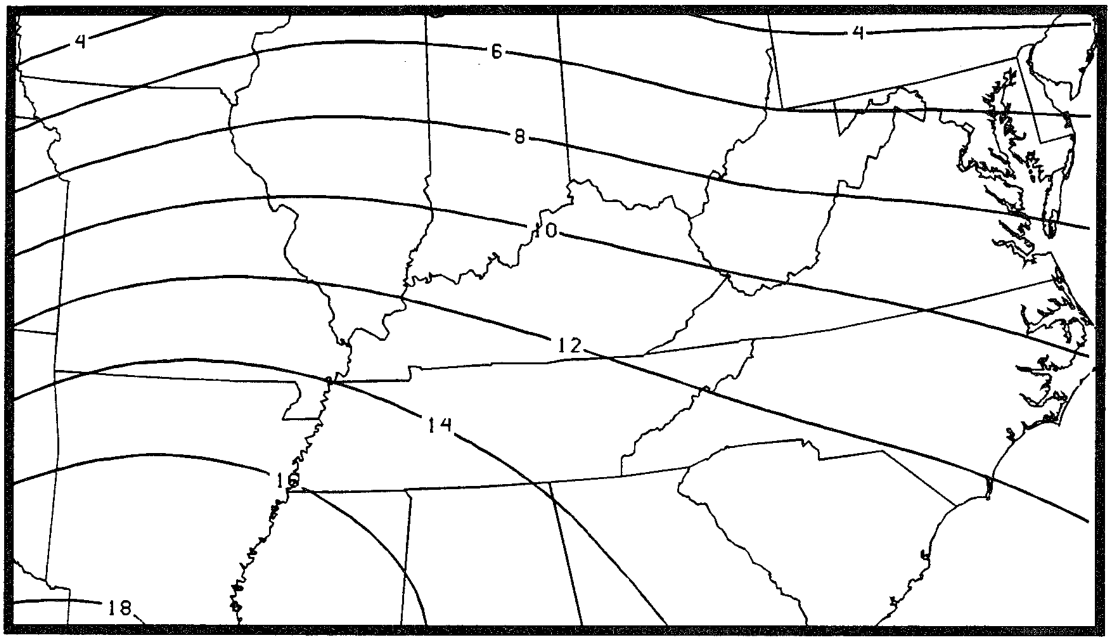


Figure 1.8. The 850 - 700 mb layer average temperature gradient at 1200 UTC 4 June 1993. Conturs are every 2 degrees Celsius.

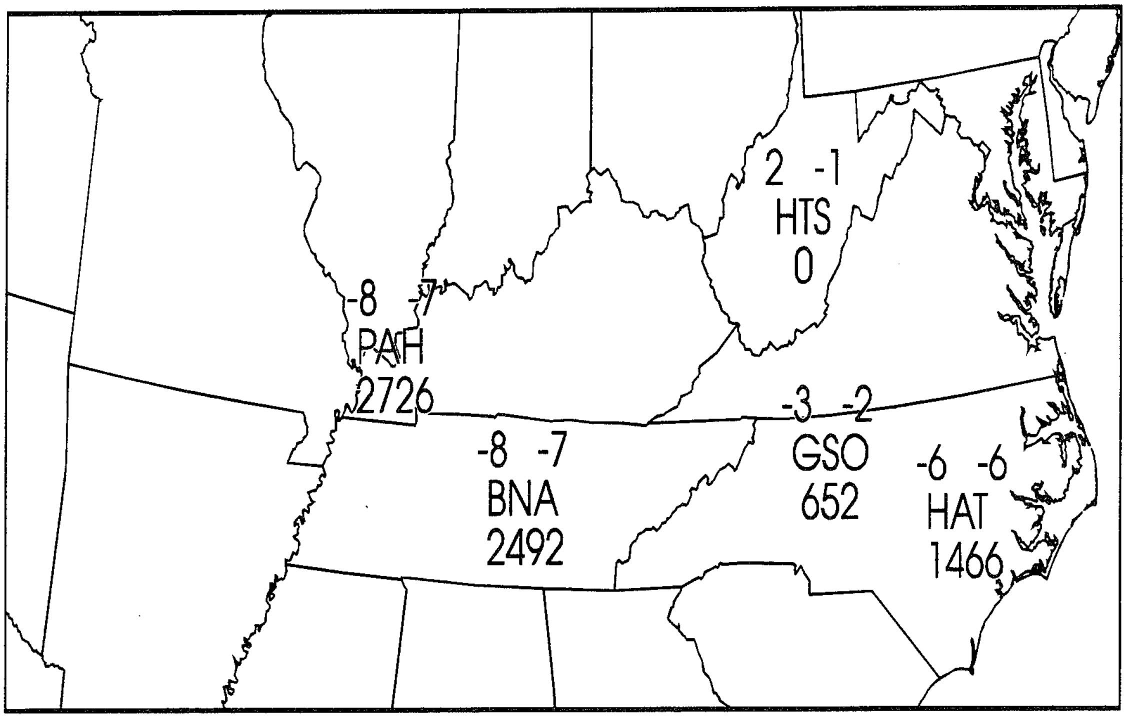


Figure 1.9. Stability indices along derecho track at 1200 UTC 4 June 1993. Station identifiers are shown along with Lifted Index on the upper left, Showalter index on the upper right, and CAPE value below.

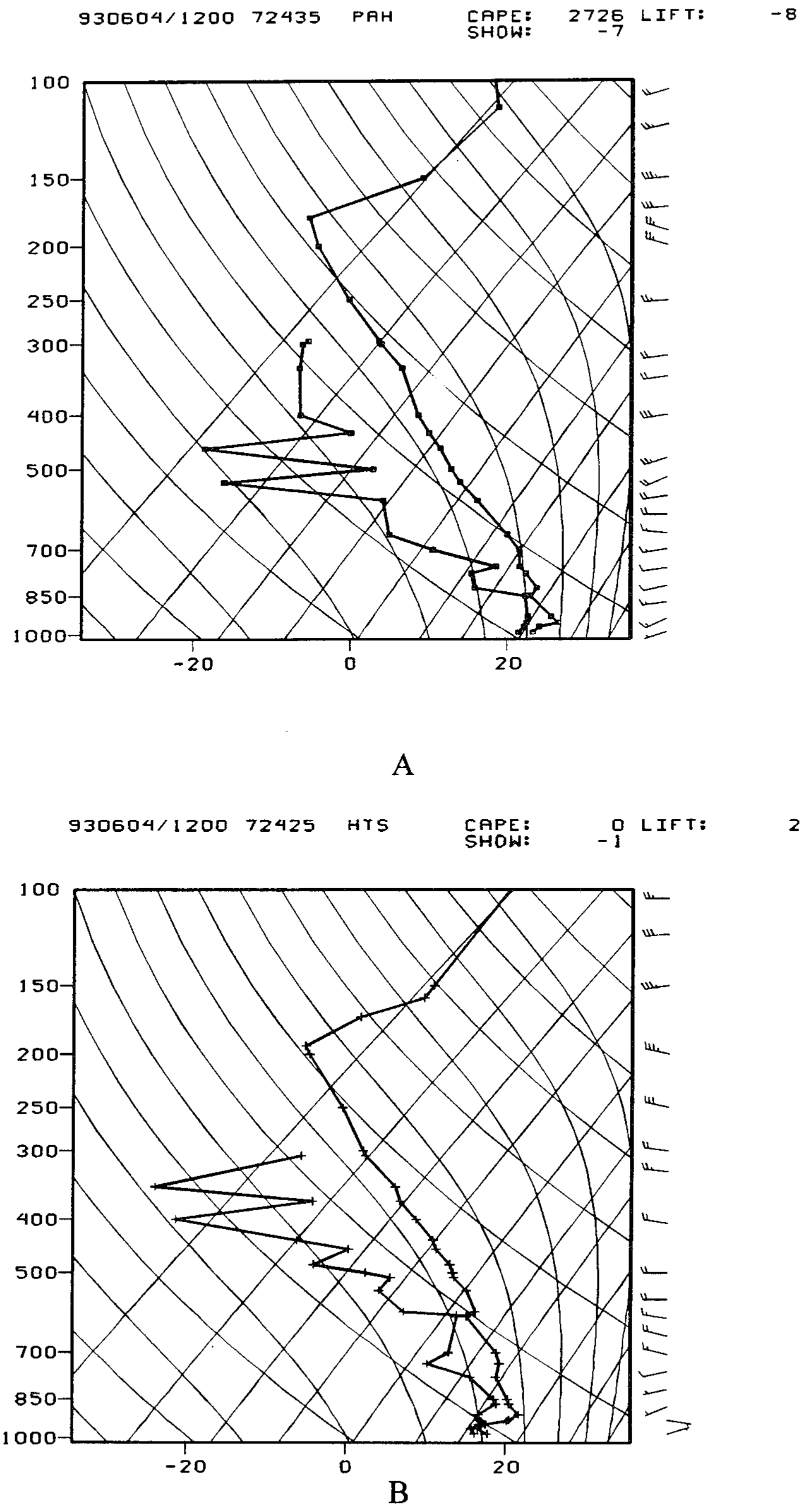
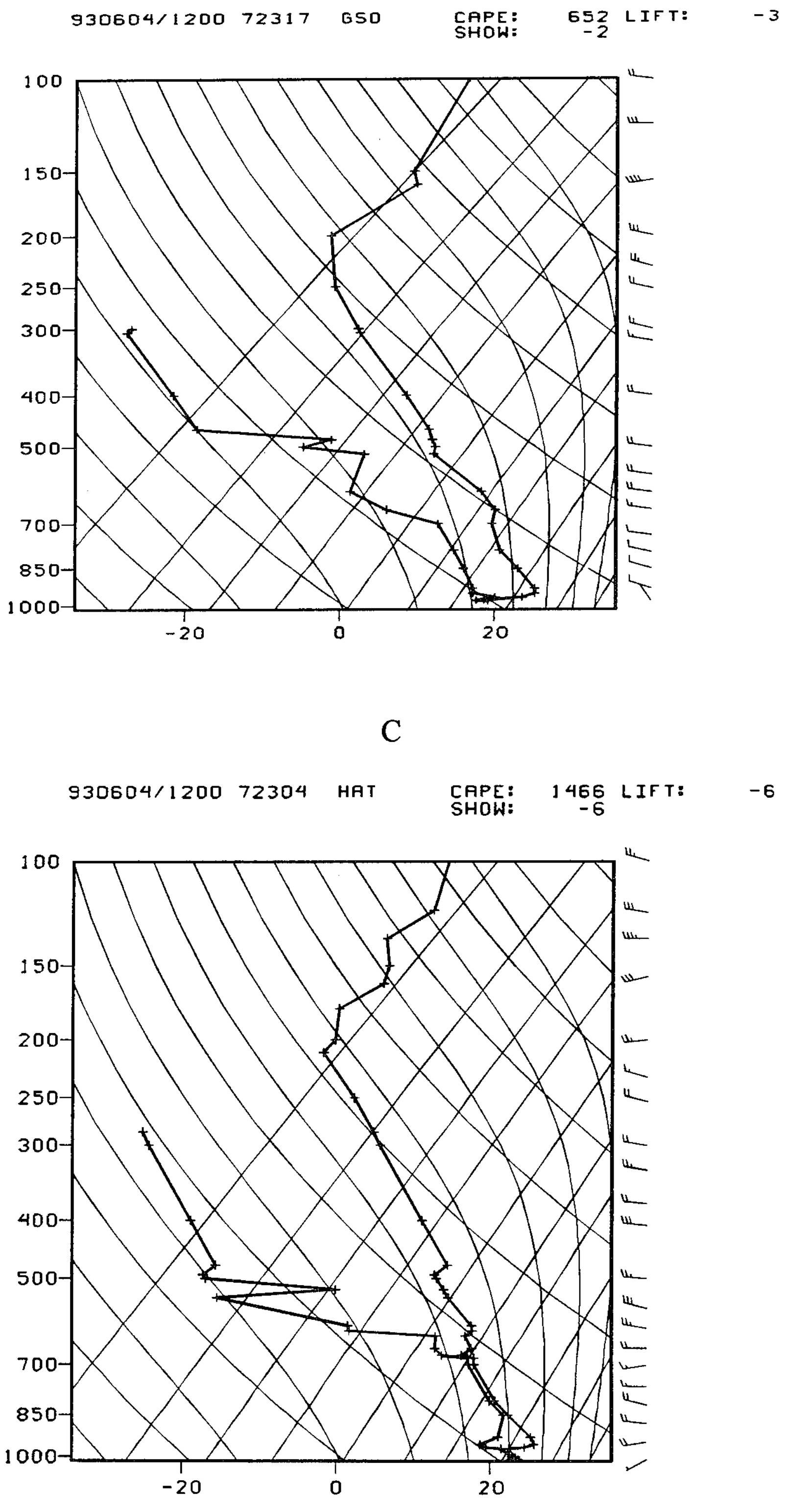


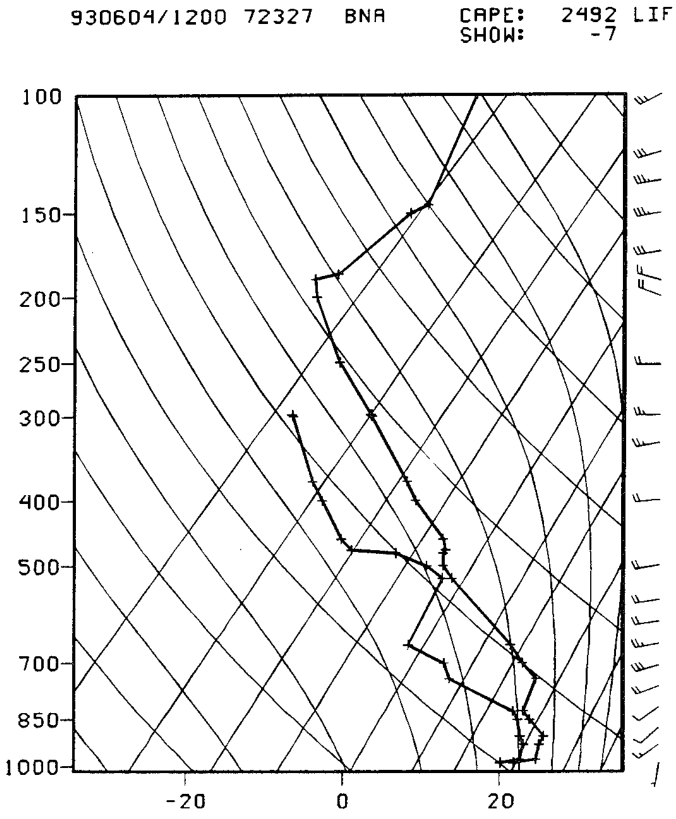
Figure 10. Upper air soundings from 1200 UTC 4 June 1993 for A) Paducah, Kentucky and B) Huntington, West Virginia.



C

D

Figure 10. Upper air soundings from 1200 UTC 4 June 1993 for C) Greensboro, North Carolina and D) Cape Hatteras, North Carolina.



E

Figure 10. Upper air soundings from 0000 UTC 4 June 1993 for E) Nashville, Tennessee.

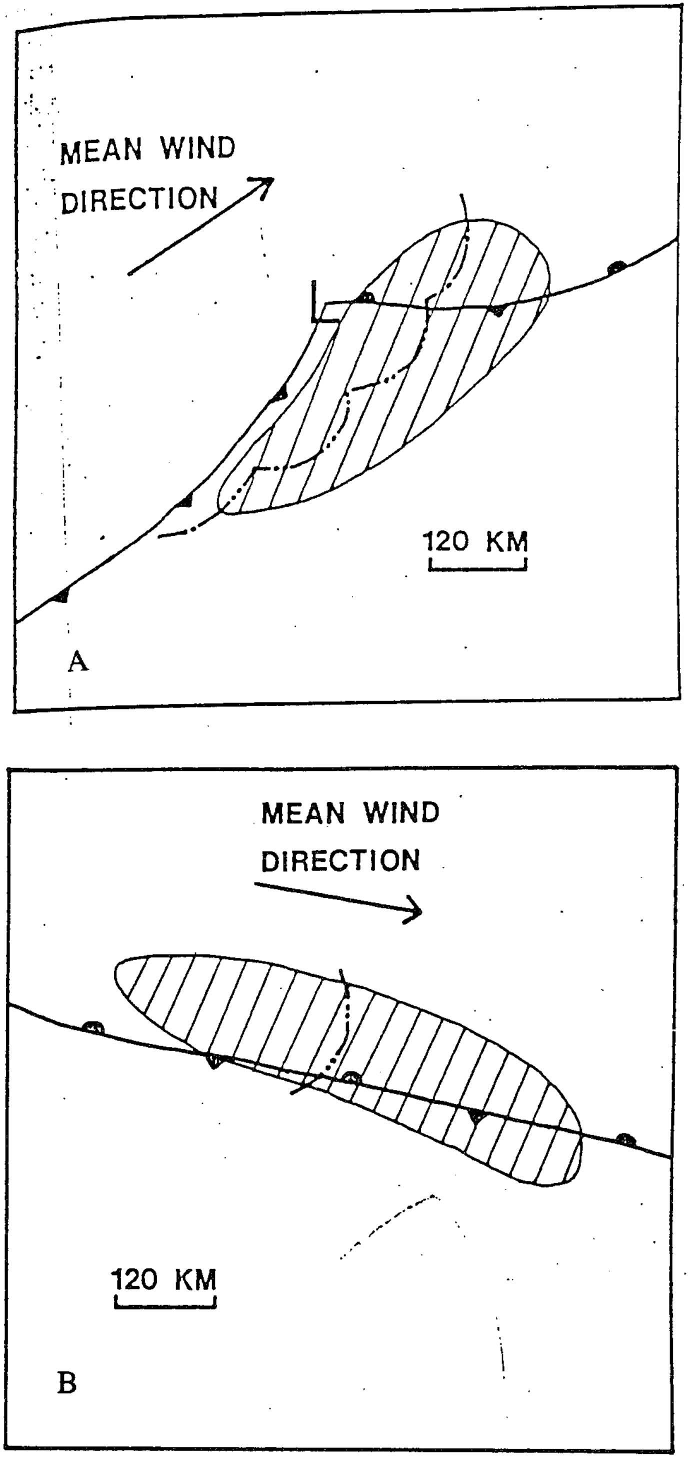


Figure 1.11. Primary radar signatures for derecho convective complex. A) Serial derecho. B) Progressive derecho. (Johns and Hirt, 1987)

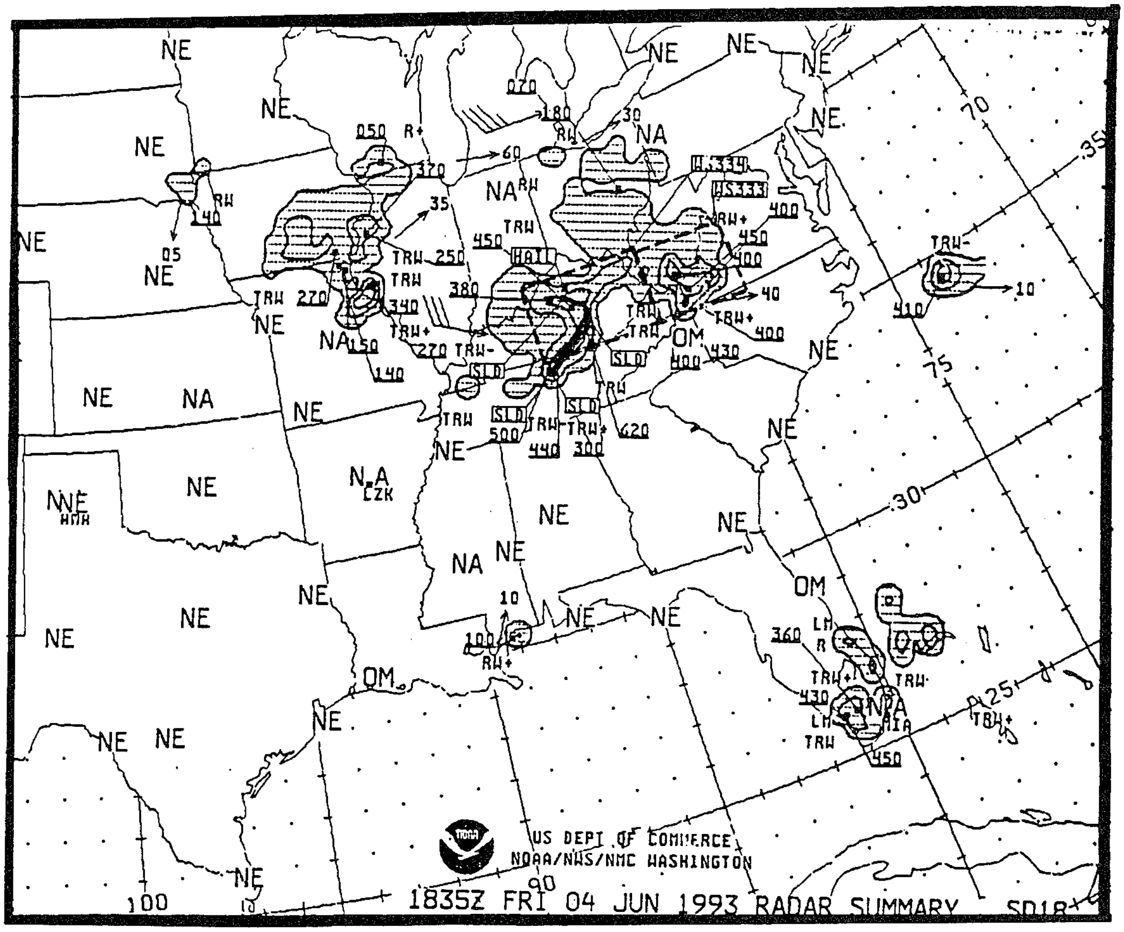
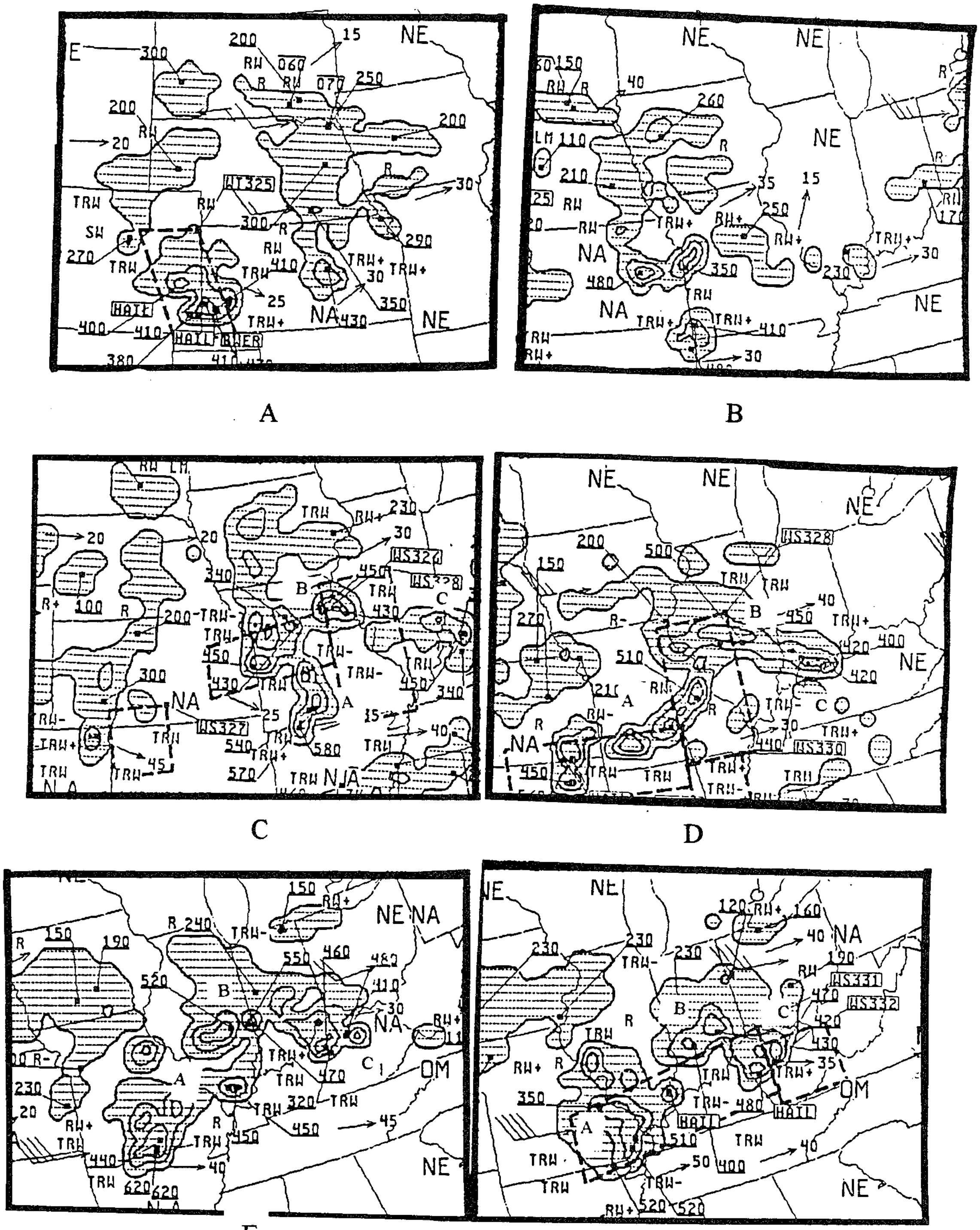


Figure 1.12. NWS radar summary from 1835 UTC 4 June 1993.


A

B

C

D

E

F

Figure 1.13. NWS radar summaries from a) 0035, b) 0235, c) 0535, d) 0935, e) 1235, f) 1435 UTC 4 June 1993.

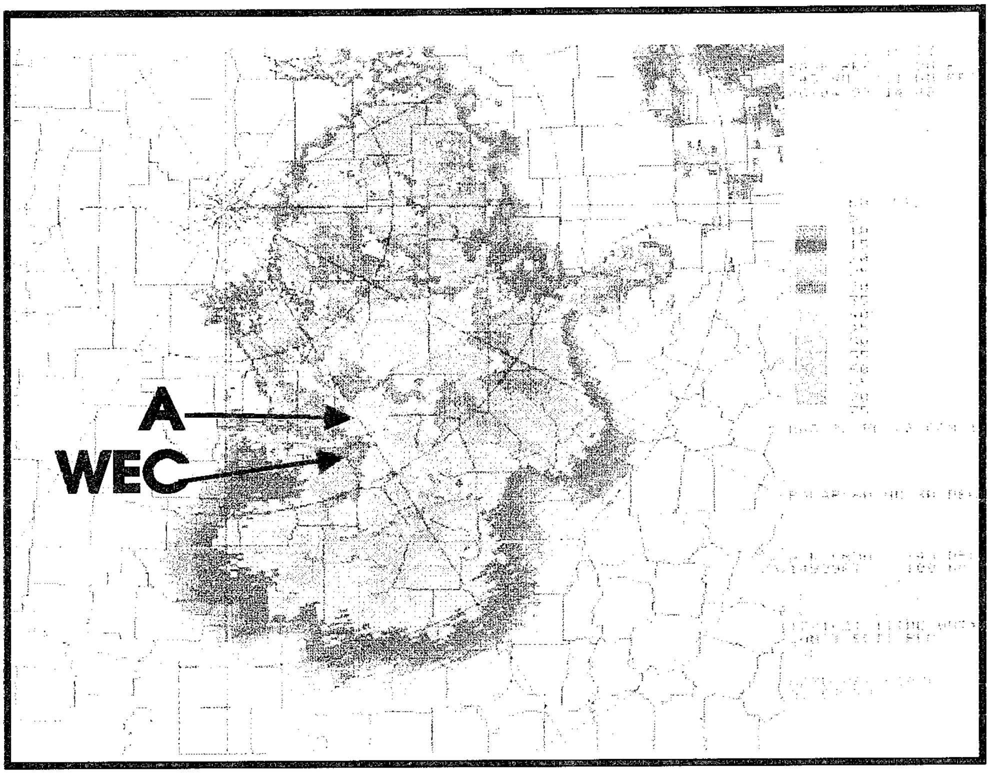


Figure 1.14a. WSFO Doppler radarreflectivity data from 1448 UTC 4 June 1993.

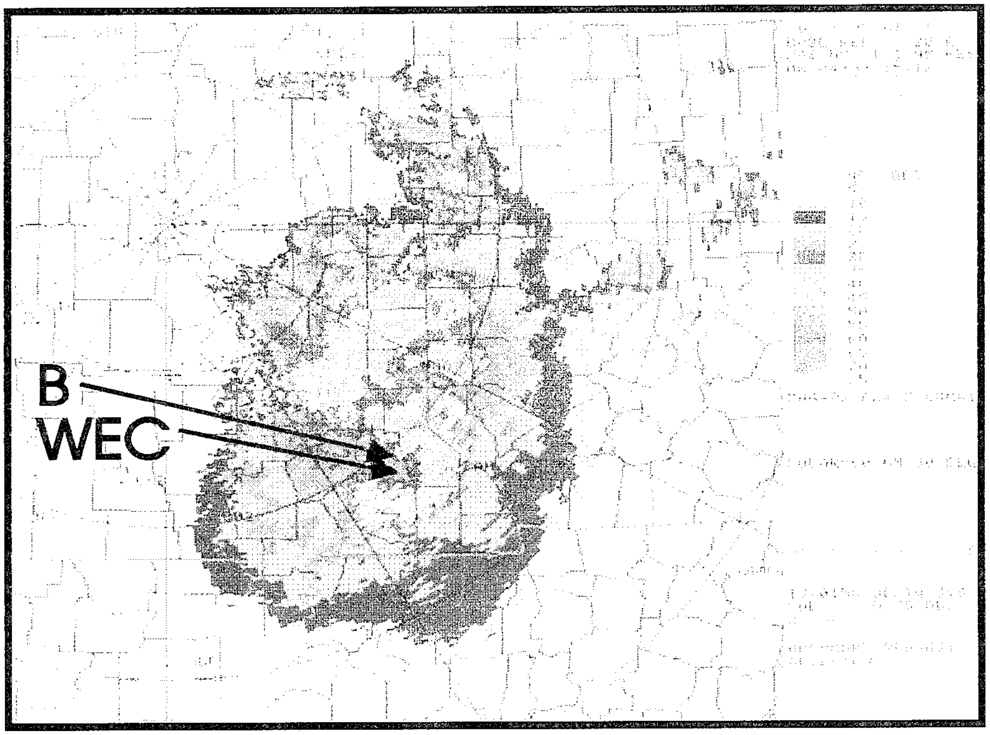


Figure 1.14b. WSFO Doppler reflectivity radar datafrom 1518 UTC 4 June 1993.

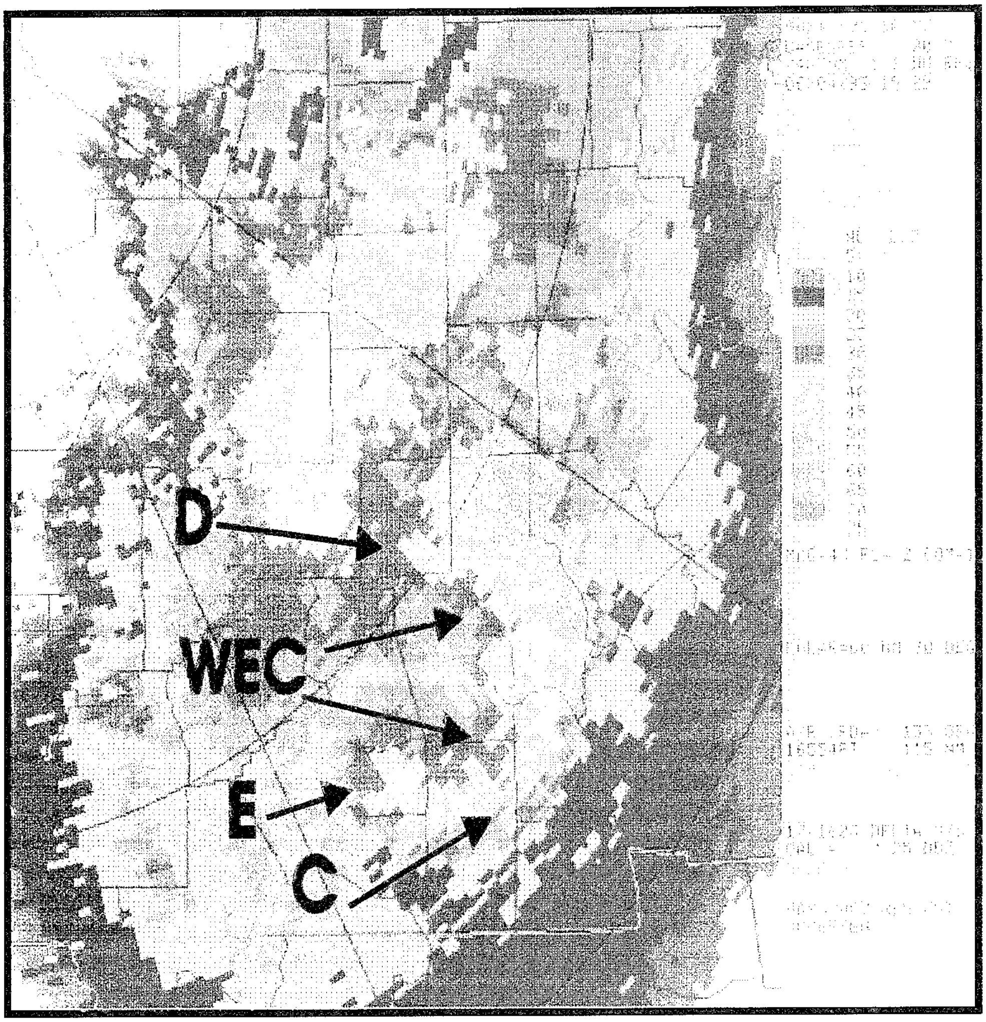


Figure 1.14c. WSFO Doppler reflectivity radar data from 1529 UTC 4 June 1993.

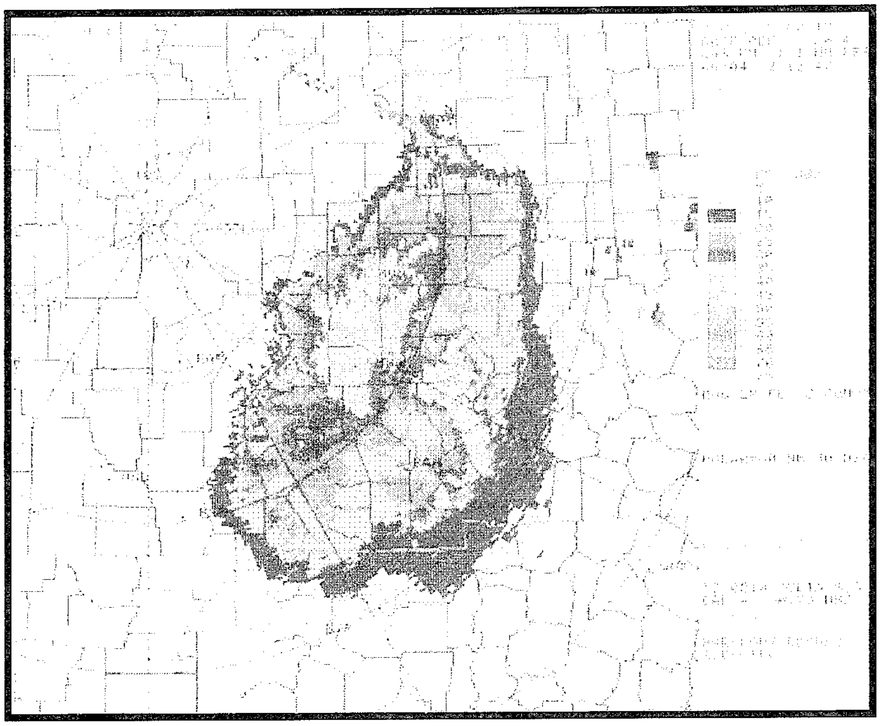


Figure 1.14d. WSFO Doppler radar reflectivity data for 1547 UTC 4 June 1993

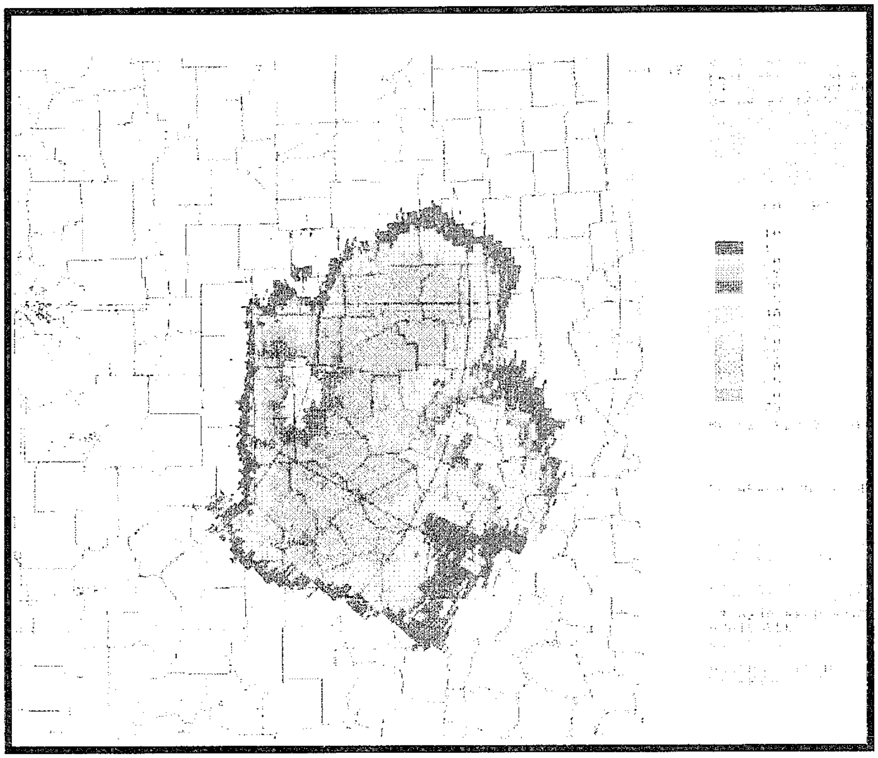


Figure 1.14e.WSFO Doppler radar reflectivity data for 1651 UTC 4 June 1993

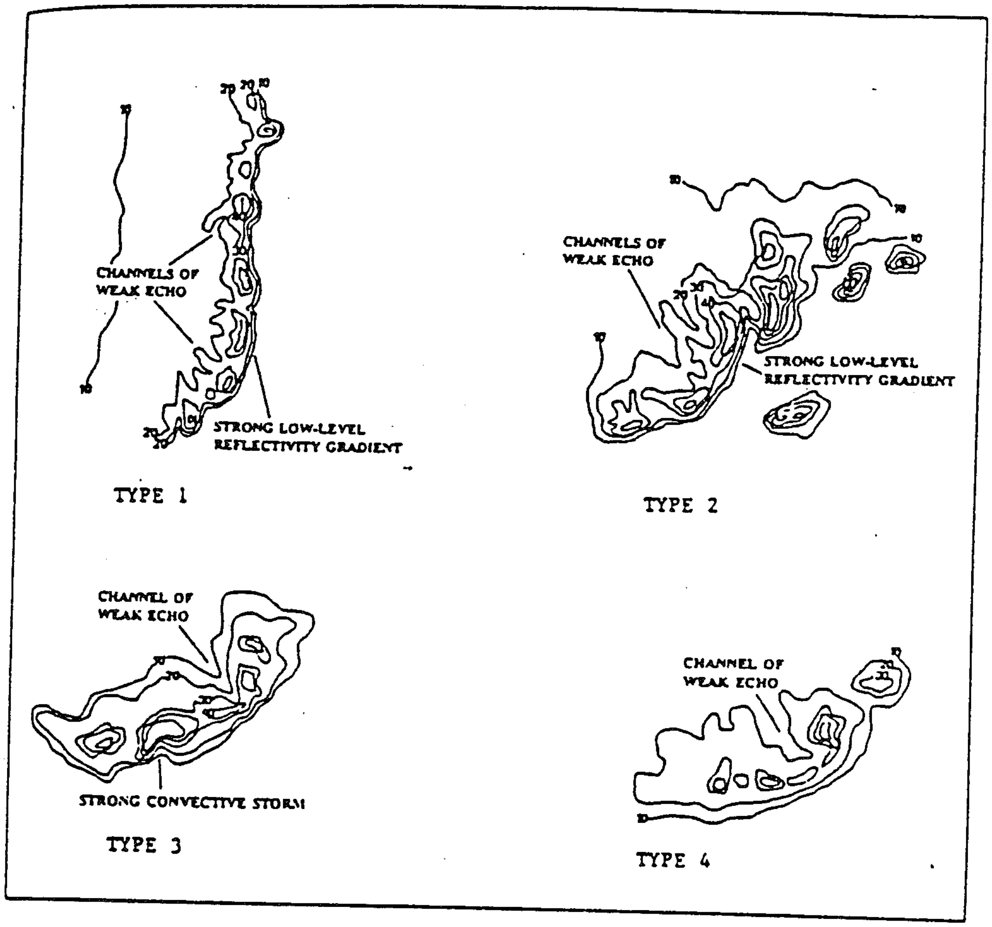


Figure 1.15. Radar signatures associated with derechos. (Przybylinski and DeCaire, 1985)

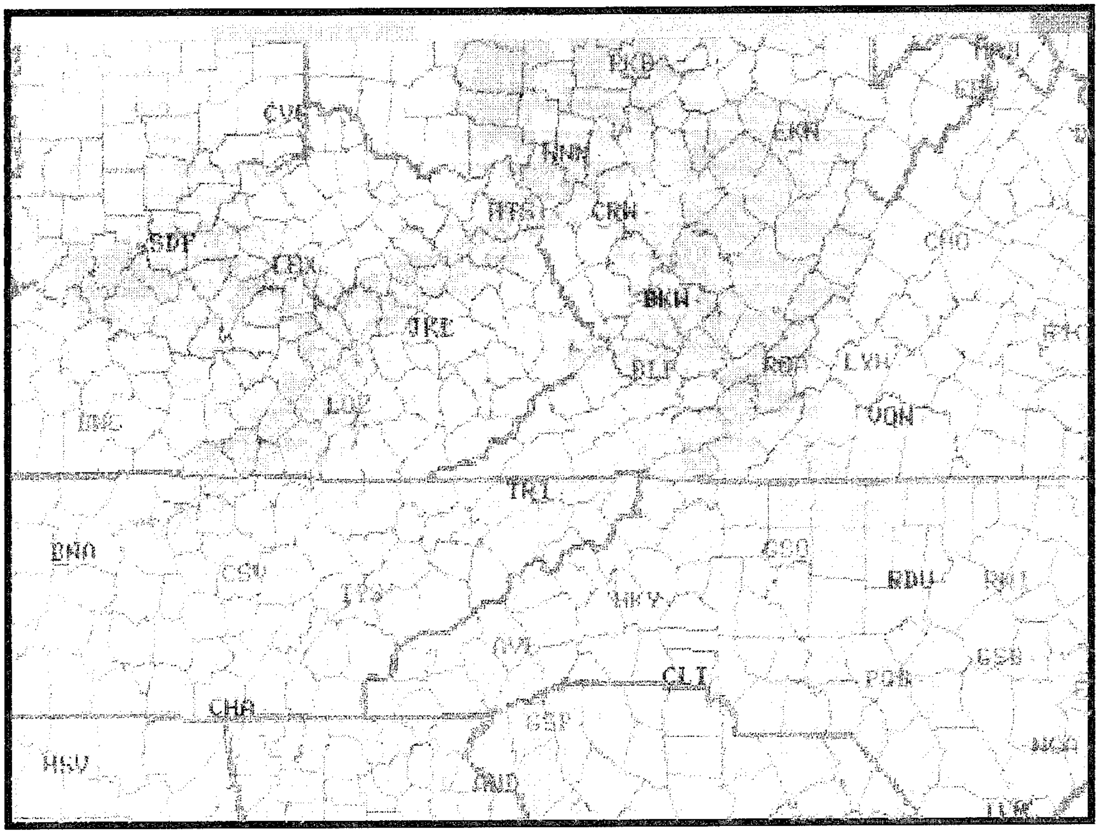


Figure 1.16. NOWRAD radar summary from 1815 UTC 4 June 1993.

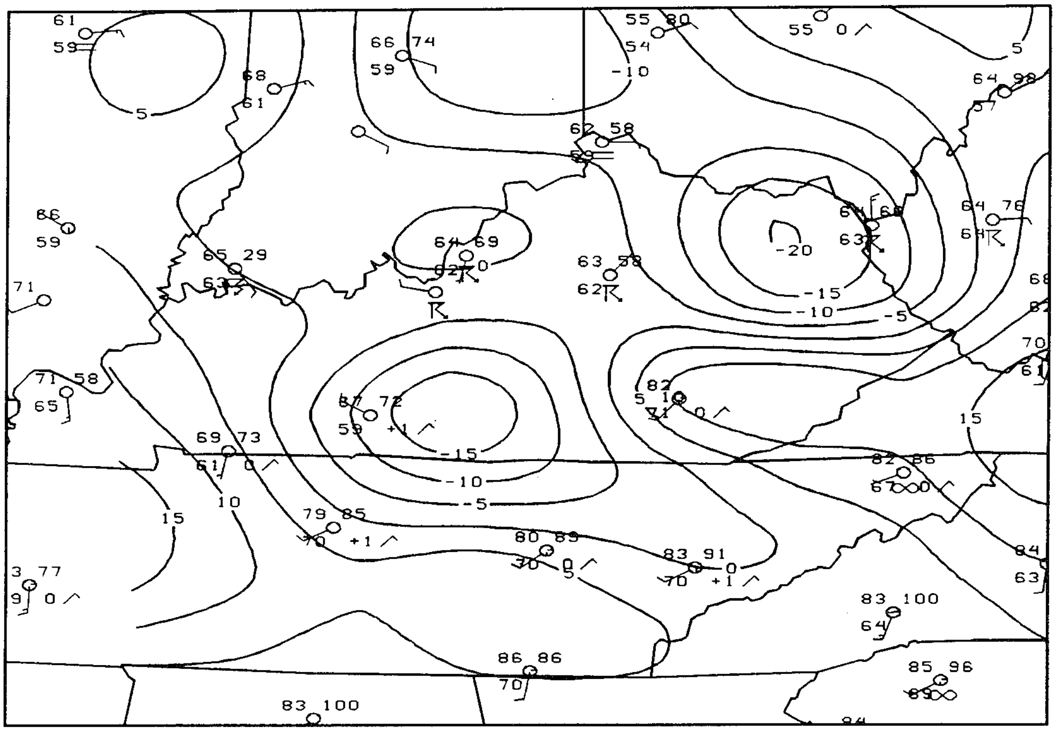


Figure 1.17. Surface observations and temperature advection at 1800 UTC 4 June 1993. Units are 10^{-5} Ks^{-1}.

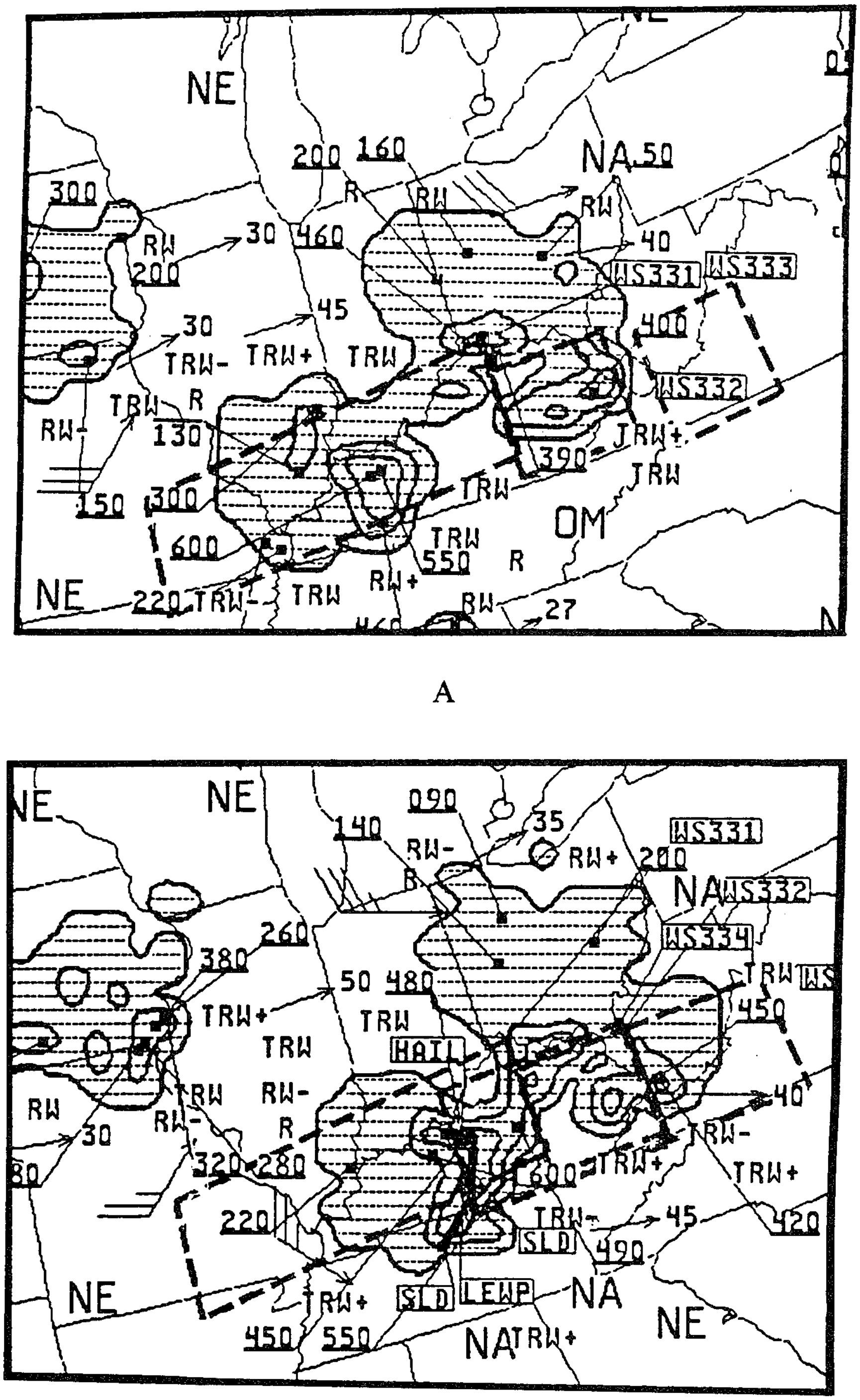


Figure 1.18. NWS radar summaries from a) 1635 and b) 1735 UTC 4 June 1993.

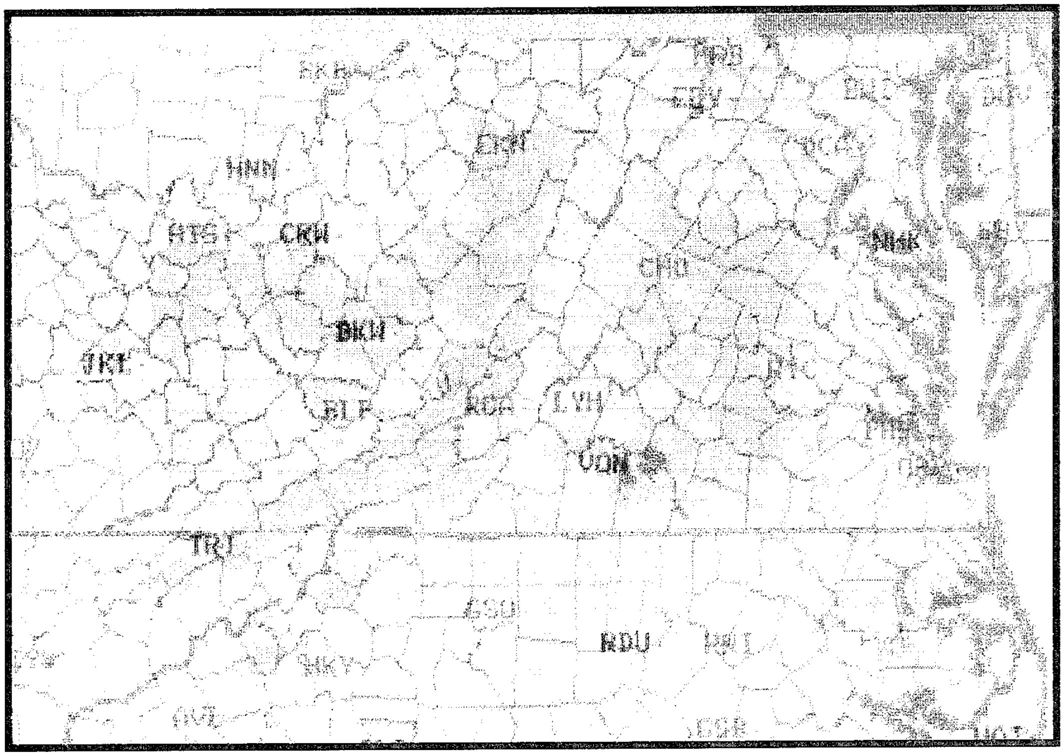


Figure 1.19. NOWRAD radar summary from 2100 UTC 4 June 1993.

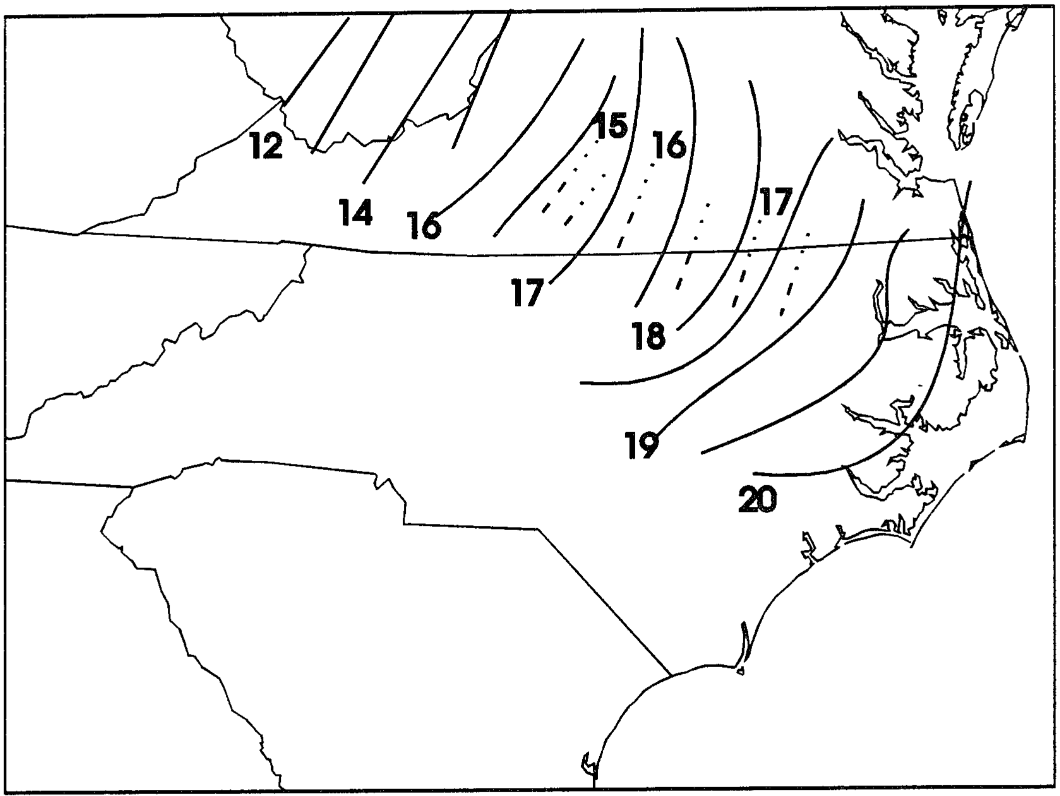


Figure 1.20. Damge path for 4 June 1993 derecho. Solid lines denote damage isochrones for the derecho. Dashed lines denote damage isochrones for the leading intense convective cell. All damage is severe winds.

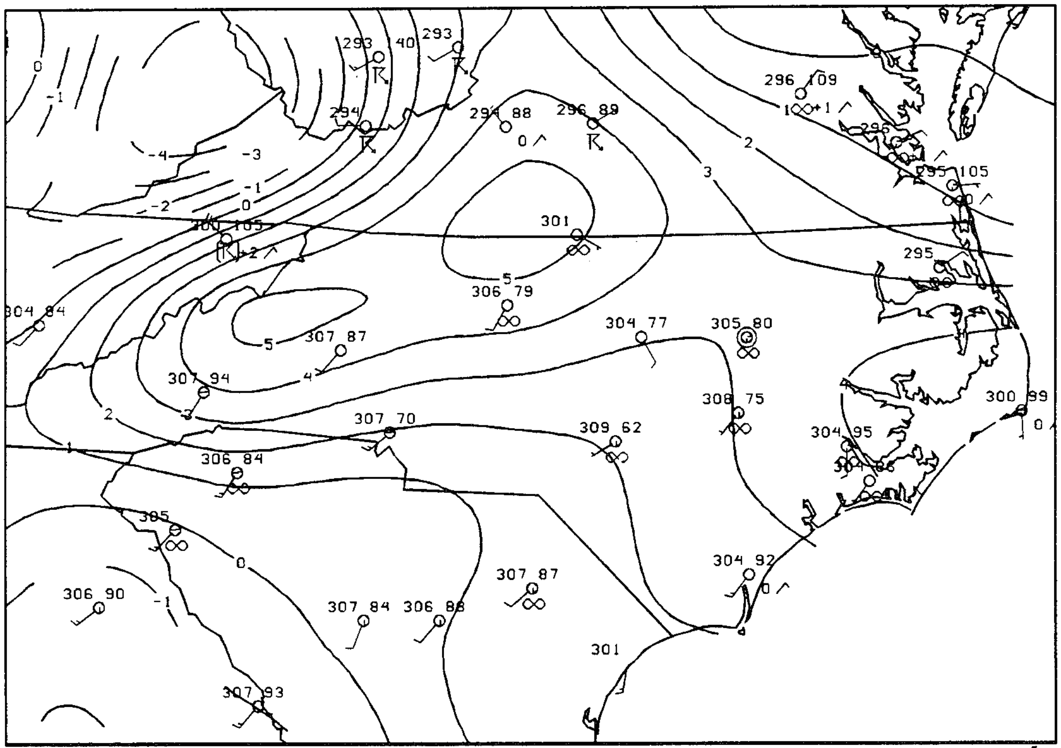


Figure 1.21. Surface mass convergence at 2100 UTC 4 June 1993. Units are $10^{-5}\,s^{-1}$.

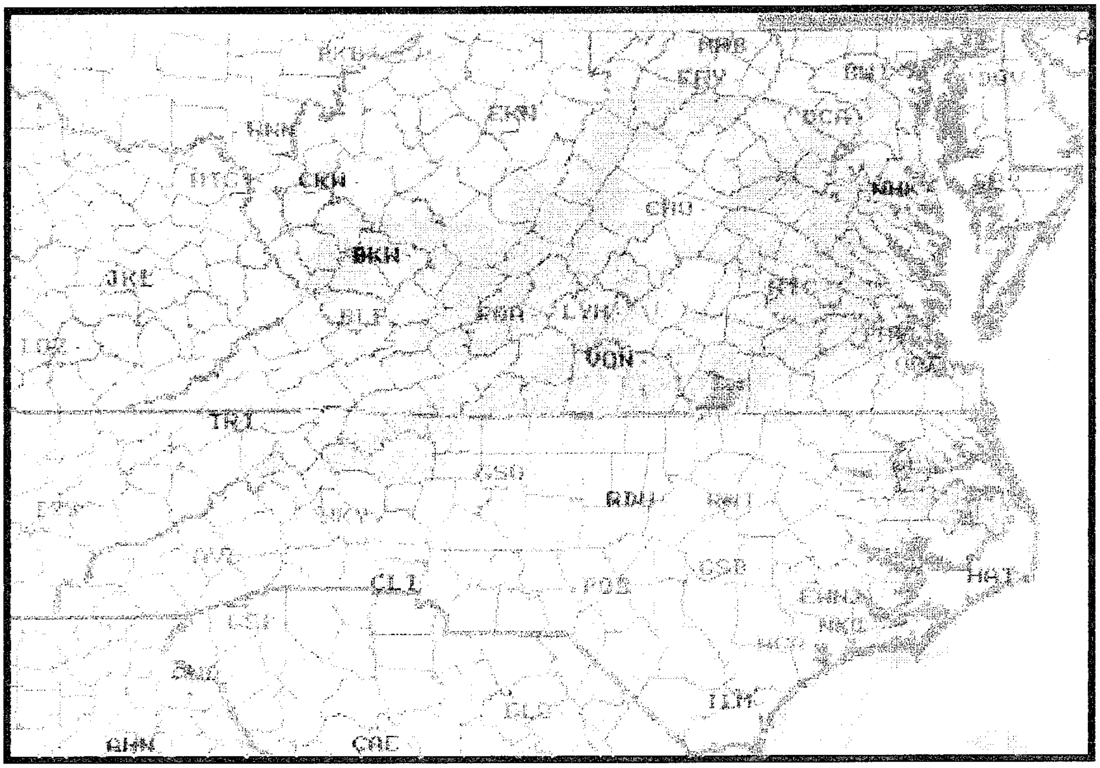


Figure 1.22a. NOWRAD radar summary from 2200 UTC 4 June 1993.

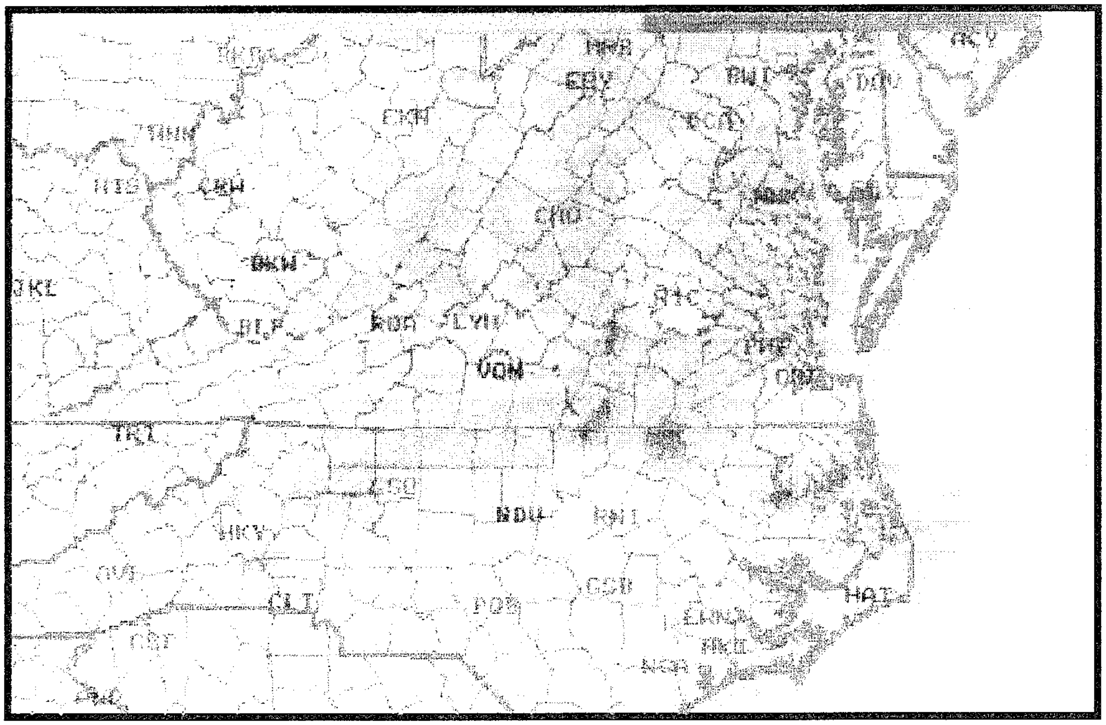


Figure 1.22b. NOWRAD radar summary from 2245 UTC 4 June 1993.

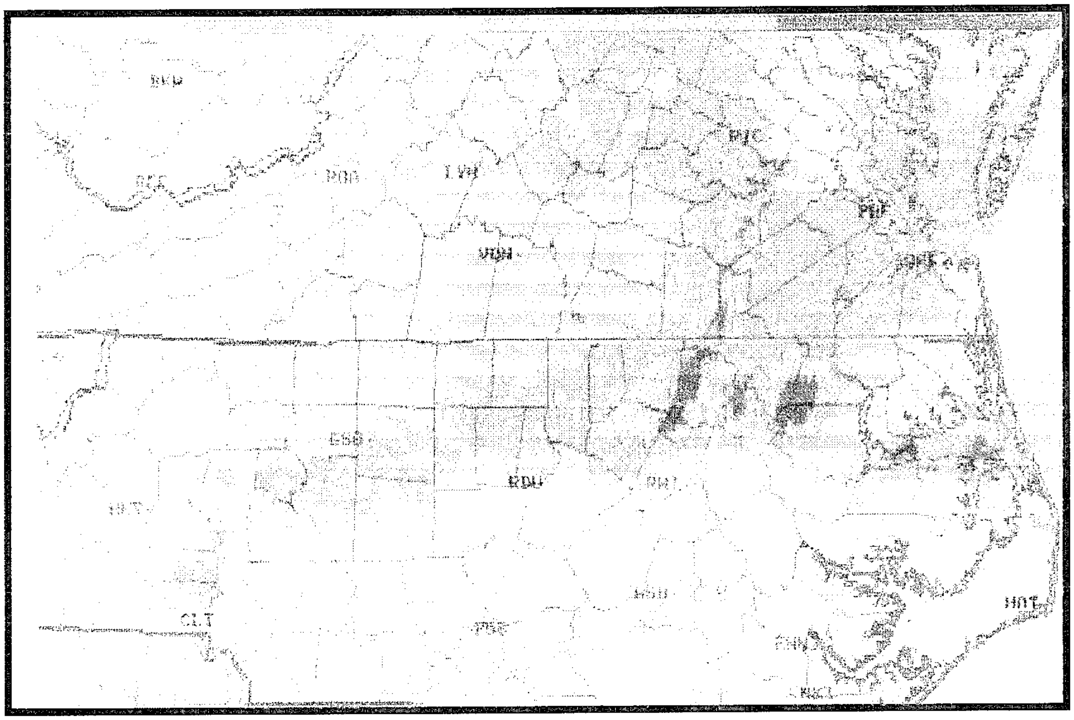


Figure 1.22c. NOWRAD radar summary from 2330 UTC 4 June 1993.

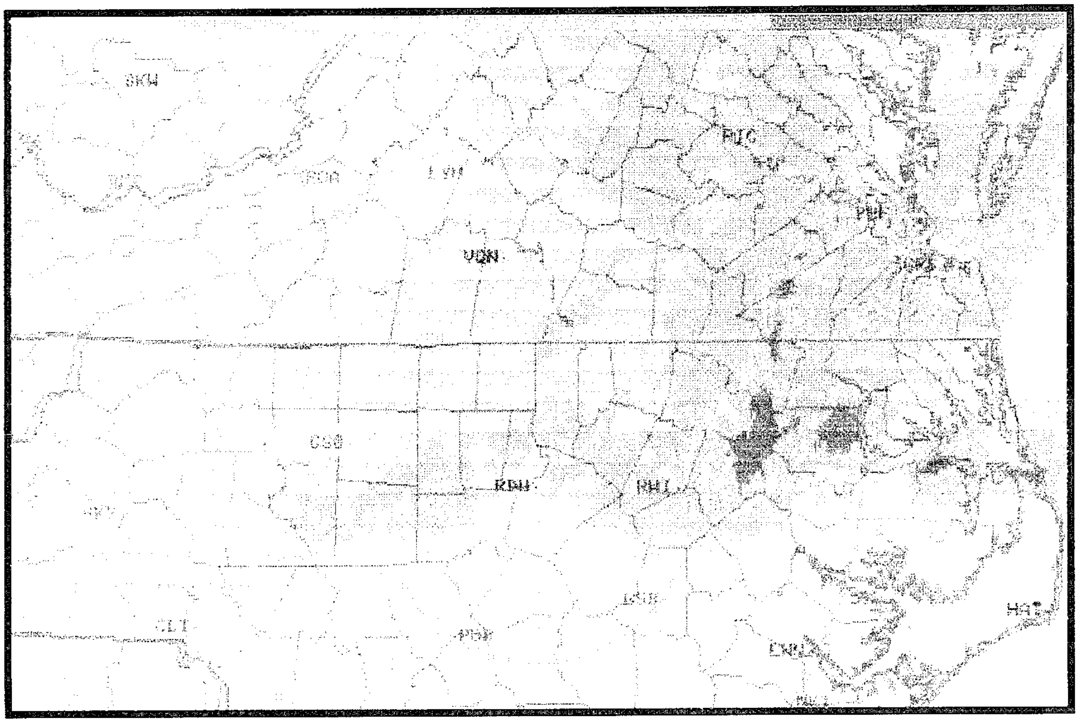


Figure 1.22d. NOWRAD radar summary from 0000 UTC 5 June 1993.

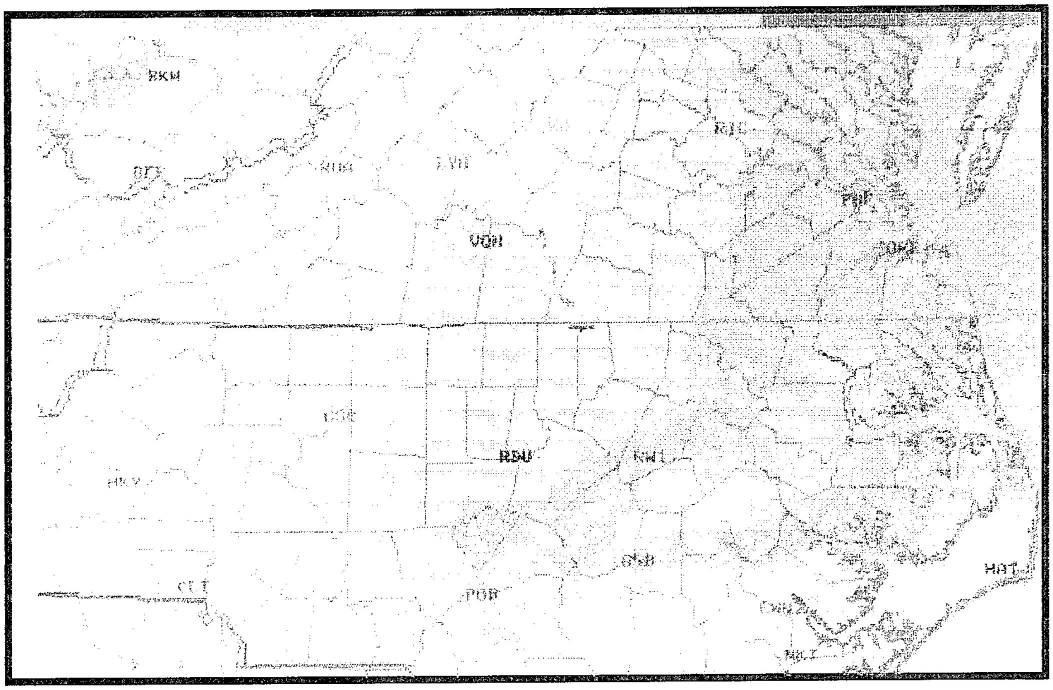


Figure 1.22e. NOWRAD radar summary from 0100 UTC 5 June 1993.

2.0 MULTISCALE ANALYSIS OF THE 5 JUNE 1993 SEVERE HAILSTORMS IN NORTH CAROLINA

2.1. Introduction

Across the United States, hail damage to both property and crops can be substantial. Studies from the National Hail Research Experiment (NHRE) reported that there is an average hail related crop loss in the United Sates of 680 million dollars (Knight and Squires, 1982). NHRE studies also found that the ratio of crop damage to property damage is 10:1. This gives a national yearly average for hail damage near 750 million dollars.

The role of mesoscale boundaries in the initiation of thunderstorm convection has been known for sometime. Many modern tools are being used to identify these boundaries. Weaver (1979) studied thunderstorms that appeared to be anchored to low - level convergence areas that affected formation and movement of these storms. This study was accomplished using standard meteorological data enhanced by subsynoptic surface and upper air data. Purdom (1976) and Purdom and Weaver (1982) observed convective boundaries and their interactions in satellite imagery. Purdom noted the frequent initiation or regeneration of convection when boundaries collided. Identifying convergence boundaries such as thunderstorm outflows, sea breezes and drylines in satellite data and tracking those boundaries allows forecasters to locate with higher precision the areas of possible convective outbreaks.

With the advent of Doppler radar a new method for identifying boundaries was identified. Convergence boundaries were detected in the radar as thin lines of enhanced reflectivity or as convergent Doppler velocities. Wilson and Schreiber (1986) performed a study in eastern Colorado using Doppler radar where they identified thunderstorm initiation triggers, and found that 79 percent of the thunderstorms they observed were associated with convergence boundaries. Wilson and Mueller (1993) reaffirmed that monitoring convergence boundaries was useful for identifying areas where convection could occur but that smaller scale features as yet not resolvable determined the precise location of the convection.

Mueller et al. (1993) used high spatial and temporal thermodynamic soundings to determine the location on a convergence boundary where convection would originate. Unfortunately they found that this increase in thermodynamic data was only marginally helpful to forecasting convection. So at this point it seems that a forecaster should identify convergence boundaries and monitor them as a key to later convective activity.

North Carolina has on average 45 thunderstorm days per year (Knight and Squires). The majority of those thunderstorm days occur during the summer. On average, 39 summer days have thunderstorms while there are only 6 thunderstorm days occurring during the winter. Of all of those thunderstorm days, less than two are associated with hail. When hail occurs it is most likely not severe (i.e., the hail is less than 3/4 inch in diameter).

North Carolina has a unique mix of geographical features, i.e., the Appalachian mountains, the coastal region, and the Gulf Stream flowing just off the coast (Keeter *et. al.*, 1995). These features generate a myriad number of boundaries across the state. Sea breeze fronts from the Atlantic coast can penetrate well into the piedmont area of the state. The Appalachian mountains can cause eastward moving cold fronts to stall and can induce lee side troughing (Weisman, 1990). Boundaries can be situated across the state when back - door fronts approach from the north. These aforementioned boundaries are synoptic scale but the mesoscale boundaries also need to be understood. Identifying mesoscale boundaries in North Carolina can help forecasters more accurately predict areas of initiation and evolution of convection.

In an effort to increase knowledge and understanding of thunderstorm development in North Carolina, the Raleigh NWS office and researchers from North Carolina State University (NCSU) have initiated a unique collaboration program. During periods of severe weather, researchers from NCSU supplement the Raleigh NWS staff. The researchers also document the severe weather case for further research.

One of these collaborative cases occurred on June 5 1993. On the previous day a derecho had passed through central and northeastern North Carolina. On June 5, severe hailstorms developed throughout the central part of North Carolina. The hailstorms produced severe hail damage over a large portion of the state (Fig. 2.1). One hailstorm in particular produced hail approximately 7.5 cm in diameter and caused at least three million dollars in damage to the town of China Grove. These storms moved very slowly, thus localizing the damage. For example, severe hail reports were received from Mecklenburg county from 2100 UTC through 2300 UTC. Extensive hail damage was reported with most of the storms that developed in North Carolina that day.

In this paper we take a detailed look at the mesoscale environment of the severe hailstorms that occurred in North Carolina on 5 June 1993. The first part of the paper presents detailed mesoscale analyses that document the evolution of the thermal, pressure, and wind fields associated with a derecho convective complex the previous night. It also focuses on the formation of a persistent thermal boundary. The second part of the paper focuses on the factors that lead to the initiation of the convection. The third part of the paper will discuss the factors affecting the type of convection that was produced. Lastly, the detailed analyses will help answer the question: operationally can boundaries be resolved with enough precision to allow for nowcasting of convective development and evolution?

2.2. Data and Methods

Surface and upper air data are from the National Weather Service (NWS) Automation of Field Offices and Services (AFOS) and the NWS Records Retention System. Hourly surface observations and 12 hourly upper air data were utilized. Radar data for this study were obtained from the NWS radar summaries with some data from NOWRAD weather summaries from Weather Services Incorporated (WSI). GOES 7 visible and infrared satellite data were obtained through the McIDAS system. The visible satellite data have 1 kilometer resolution while the infrared data have 8 kilometer resolution. Barogram traces for all reporting stations in Virginia and North Carolina were also used. 24 hour rainfall data were obtained from both the Virginia and North Carolina State Climatologist Office.

Detailed hourly surface mesoscale analyses were completed by hand for the period 2000 UTC 4 June - 0300 UTC 6 June 1993. These analyses were performed using the protocol of Fujita (1963). The area of analysis is shown in Figure 2.2 along with station identifiers and pertinent geographical regions. All mesoscale analyses were done over an area larger than that shown. Thus, details at the edge of the analyses are consistent. Time and space continuity of important mesoscale features was established for the entire time period using barograph traces, radar data, and satellite data in support of the surface observations. This was necessary since the hourly station maps do not have the spatial density to adequately resolve important mesoscale features. A small degree of subjective smoothing was also applied to the surface analysis.

Rawinsonde observations were analyzed using the Skew-T/Hodograph Analysis and Research Program (SHARP) Workstation (v 1.50) (Hart and Korotky, 1991). This program provided a multitude of thermodynamic stability indices that helped interpret the detailed thermodynamic status of the atmosphere at each NWS station. The program also allowed for modification of the individual soundings. This feature enabled us to produce forecast soundings more representative, both geographically and temporally, of the atmosphere near where convection initiated.

GEMPAK Meteorological and Analysis Software (5.0) was used to plot all hourly observations received from the National Weather Service. The software was also used to objectively analyze other meteorological fields. These objective analyses were used as first guess guidance for the mesoscale hand analysis and to generate convergence fields. For these analyses a 50 X 50 grid was established with a mean grid spacing of 0.8 degrees latitude. A Barnes Objective Analysis scheme was used with a two - pass criterion and a convergence factor of 0.3 (Barnes, 1964, 1973).

2.3. Synoptic Overview

Synoptic conditions at 0000 UTC 05 June 1993 focus on a low pressure system in the center of the country. In Figure 2.3a, a surface cold front can be seen extending from near the Illinois-Indiana border southward through extreme southeastern Missouri, across Arkansas, and into central Texas. A stationary front extends from the Illinois - Indiana border through northern

Kentucky, southern West Virginia and along the Virginia-North Carolina border. There are two areas of significant weather. The first is near the Virginia-North Carolina border associated with the derecho. The second is a line of prefrontal thunderstorms developing in Kentucky and Tennessee.

Figure 2.3b shows the upper air analyses. At 850 mb there is a closed low centered over Illinois and Indiana. There is also a thermal trough west of the low extending south from Nebraska into Texas. The strongest winds are to the south of the low; Paducah has southwest winds at 40 knots. The low remains closed at 700 mb but is located on the Illinois- Wisconsin border. Winds are again strongest south of the low; Paducah has southwest winds but at 55 knots. There are no significant thermal features.

At 500 mb the low is no longer closed. A trough and coincident thermal trough are evident from northern Wisconsin south through Kentucky. Flow near and east of the trough axis is strongest; Paducah and Dayton, Ohio both have winds that are southwest at 60 knots. The 300 mb analysis shows a weak trough from southern Manitoba south through Illinois, and again the thermal trough is very nearly aligned with the trough in the height field. A small area of greater than 70 knot winds is centered in Missouri.

2.4. Mesoscale Analysis

0000 UTC 05 June 1993

The mesoscale analysis begins at 0000 UTC 05 June 1993. Figure 2.4 shows the composite analysis. Figure 2. 5 is the accompanying NOWRAD radar composite. The most striking feature is the derecho and its gust front. The derecho convective system is affecting most of southern

Virginia and northern North Carolina. The outflow boundary extends from near Richmond, Virginia to Hickory, North Carolina. The synoptic scale stationary front can be seen extending off the North Carolina coast. Derechos develop near and travel parallel to east - west thermal boundaries such as this stationary front (Johns and Hirt, 1987). Streamline analysis indicates winds from the southwest flowing across southern North Carolina and towards the derecho convective system.

A tight thermal gradient is seen near the outflow boundary and to the north of the stationary front. A broad area of higher temperatures can be seen throughout most of southern North Carolina centered near the sandhills area of the state. This area of higher temperatures actually extends southwest through the sandhills areas of South Carolina and Georgia (analysis not shown). This thermal zone is a prevalent afternoon feature throughout the summer months.

0200 UTC 05 June 1993

Two hours later the derecho has moved off the coast but the storm's mesohigh is still evident west of Cape Hatteras (Fig. 2.6). The tight thermal gradient has a northwest to southeast orientation. Near Hickory and Charlotte there has been little southward movement of the thermal boundary associated with the derecho outflow. The strength of the sandhills thermal ridge appears to have hindered movement of this weaker back edge of the outflow boundary. The sandhills thermal area is retaining most of its daytime heat well into evening. The southeastern portion of the thermal gradient somewhat follows the southeastward movement of the derecho as it moved off the coast.

An area of higher pressure can also be seen near Asheville and Hickory. This high pressure area remains throughout the rest of the analysis period. The stations to the east will be affected by the intense thermal gradient and will show continued pressure falls throughout the analysis period.

As early evening approaches the wind field is apparently dominated by diurnal stabilization of the lower atmosphere. Most winds become light and variable with much weaker synoptic or mesoscale pressure control. The stronger winds at the coastal sites are still under the influence of the mesohigh associated with the derecho. The only other coherent feature in the wind field is the continued southwest flow from Georgia and South Carolina. Overall, the winds are light, but the synoptic directional flow pattern is still present.

0400 UTC 05 June 1993

The 0400 UTC analysis shows the outflow thermal gradient in central North Carolina extending southeastward to Wilmington (Fig. 2.7). Southward movement of the western portion of the thermal gradient is affected by the region of higher temperatures. These higher temperatures are associated with the sandhills thermal area. This area is centered east of Charlotte and has a northeast-southwest orientation. The persistence of this thermal area appears to be the primary factor affecting moderation and movement of the outflow thermal gradient.

The pressure field shows an east-west trough in the southern portion of North Carolina. There is also evidence of weak ridging from the northeast coast into the central part of the state near Raleigh. This ridging is probably associated with the rain cooled air that remains from the derecho's passage over this broad area. This area can be seen in the 24 hour total rainfall map in Figure 2.8. Sea surface temperatures off the Virginia coast are cool and northeast flow from over the ocean can often advect these cooler temperatures into southern Virginia. However, flow during this period is not from the northeast, thus eliminating this as a source for the cool air in this area. The pressure trough also appears to be thermally induced since its axis coincides more with the thermal ridge than with the gradient. However at this point the exact location of the trough axis is hard to resolve.

The wind field remains basically similar to that of the previous analysis. The coastal stations still show strong onshore winds. Since the convective system is well offshore it is probably not the cause of these winds. Sea surface temperatures along the North Carolina coast are relatively warm (Fig. 2.9). The warm temperatures enable the planetary boundary layer over the coast to remain well mixed. Over inland sections of North Carolina winds are light and variable, and weak southwesterly flow continues in South Carolina.

The 0400 UTC IR regional satellite image shows two large cloud areas (Fig. 2.10). The first cloud area that is moving off the Virginia - North Carolina coast is associated with the derecho. The second is associated with prefrontal thunderstorms, none of which move into North Carolina. It is interesting to note the thin band of clouds trailing from the derecho cloud complex crossing the North Carolina coast just north of Wilmington. The cloud band follows very closely the outflow boundary, but takes on a more east west orientation south of Greensboro whereas the boundary continues northwestward. Also notable is the fact that South Carolina and extreme southern North Carolina are free of mid and upper - level clouds. These areas will cool more rapidly than those to the north with cloud cover.

0600 -1000 UTC 05 June 1993

The thermal gradient significantly changes during the five hour period from 0600 UTC through 1000 UTC (Fig. 2.11 a,b,c). The 300 K isotherm is no longer evident throughout the analysis area, because the strength of the sandhills thermal area is decreasing; probably associated with diurnal cooling. The western portion of the thermal gradient moves south giving the gradient an east west orientation by 1000 UTC. The 290 K isotherm has remained relatively stationary throughout this period. That isotherm marks the edge of coolest surface air. The lack of any strong temperature gradient in northeastern North Carolina and southern Virginia suggests there exists a broad area of cool air that has been modified by the derecho.

The pressure field over the next six hours shows a strengthening of two main elements. The pressure trough continues to deepen and by 1000 UTC there is even a closed isobar near Charlotte. The orientation of the trough changes subtly during this time period. At 0600 UTC the trough has a northwest southeast orientation, very similar to the thermal gradient orientation. Then by 1000 UTC the trough has settled south into an east west orientation. At the same time, the ridging in the northeast portion of North Carolina is still prominent. There is no significant change in either the strength or orientation of the ridging. This again seems consistent with the idea that this pressure area is associated with the cool moist air mass resultant from the derecho precipitation. Throughout the rest of the paper the thermal gradient and pressure trough system will be referred to as the sandhills boundary.

The steady flow from the southwest into southern North Carolina remains the dominant feature in the streamline analysis. Throughout this six hour period there does appear to be some evidence of convergence near the sandhills boundary. This can be seen in convergence calculations at 1000 UTC (Fig. 2.12 a) when there is even some indication of anticyclonic flow near Raleigh and Greensboro, two cities that are close to the sandhills boundary (Fig. 2.11c)

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1200 UTC 05 June 1993

With sunrise the mesoscale boundaries react to solar heating and increasing destabilization of the atmosphere (Fig. 2.13). The eastern part of the thermal gradient appears to be moving northward. The temperature at Goldsboro has increased 5 K over the past two hours while that at Fort Bragg, located south of the sandhills boundary, has not changed. The western portion of the thermal gradient has not undergone any significant changes, except in northwest North Carolina. A strong temperature gradient associated with a synoptic scale cold front is evident on the western side of the Appalachian mountains.

The movement of the sandhills boundary's thermal gradient is mirrored in the pressure field. Pressure analysis shows an impressive low pressure area centered near Fort Bragg, where previously the center had been near Charlotte. The ridging to the north is not as prominent in this analysis but still shows evidence of significantly higher pressures such as the 1012 mb observation at Rocky Mount. This feature might be better resolved if the area north of Rocky Mount were not so data sparse.

Streamline analysis indicates a large area of convergence coincident with the sandhills boundary. The flow from the southwest has strengthened and can probably be described as prefrontal flow at this time. Meanwhile flow over most of northern North Carolina is from the northeast thereby intensifying the convergence area along the thermal gradient (Fig. 2.12b). The alignment of the convergent axis and the thermal boundary establishes an area of strong frontogenesis (Fig. 2.14). The frontogensesis associated with the cold front can be seen to the west of the mountains. The frontogenesis in the area of interest aligns almost perfectly with the sandhills boundary. This suggests that the combination of the thermal gradient and convergence is producing a true frontal boundary.

As daytime heating increases the rainfall produced by the derecho will undoubtedly become important. The boundary for significant rainfall, shown in Figure 2.8, lies just to the northeast of the sandhills boundary. This broad area of moisture should hinder dissipation of the thermal gradient since much of the early insolation will be used in evaporating surface moisture and not in heating the atmosphere. McCumber and Pielke (1981) reported that when soil moisture is plentiful and skies are clear, up to 90 percent of the solar energy is used for evaporation. They also indicated that dryer surfaces will have a much greater sensible heat flux than moist ones. It can be determined from daily precipitation totals for North Carolina that the southern portion of the state has received little to no precipitation in the previous three days. Additionally, the thermal properties of the sandy soils characteristic of that area also suggest rapid temperature rises in southern North Carolina. Thus the dry area to the south of the sandhills boundary will heat more quickly than the moist areas to the north. The thermal gradient will actually intensify throughout the morning as temperatures rise south of the boundary and remain somewhat constant to north of the boundary.

Thermodynamic soundings for this time show an atmosphere with the ability to sustain convection. Unfortunately, soundings from Greensboro are missing from 1200 UTC 4 June 1993 through 1200 UTC 6 June 1993. However the Athens, Georgia sounding is representative of the air mass that has been transported into North Carolina (Fig. 2.15a). Also shown is the Cape

Hatteras sounding (Fig. 2.15b), one that should represent the airmass on or near the thermal boundary. A detectable lid at 800 mb is indicated in both soundings. In fact, all of the upper air soundings in the southeast have lids with the strongest lids in Louisiana and Mississippi. The thermodynamic indices from these two soundings all reflect the convective potential of the atmosphere. The lifted index for both soundings even without modification is -9 and CAPE values are above 2400 Jkg-1. Johns and Doswell (1992) report CAPE values for severe storms ranging from 200 to 5300 Jkg^{-1}. Severe storms with larger CAPE values usually have weak wind shear in the low levels. Low CAPE values are usually associated with strong shear environments. The wind profiles on both soundings show little low level wind shear. Speed and directional shear occur in the midlevels.

1400 UTC 05 June 1993

The synoptic forcing of the approaching cold front is beginning to interact with and influence the mesoscale environment (Fig. 2.16). The sandhills thermal area is reemerging with the Fort Bragg temperature increasing by 5 K in two hours. That is the northern extent of a large area of higher temperatures denoted by the 302 K isotherm. Another area of rapid warming is seen near Asheville in the eastern foothills of the mountains. Asheville's temperature increased 5 K in two hours. Evidently, Asheville's early morning cloud cover, remnant of the thunderstorms that dissipated in eastern Tennessee, has decreased much faster than surrounding stations allowing Asheville to warm faster.

The pressure field is undergoing significant synoptic changes. The 500 mb wind flow is from the west and since that is perpendicular to the mountain range, lee side troughing should be present. Weisman (90) observed that lee troughs were present over the Appalachians during the summer 40 percent of the time. The sandhills boundary's pressure trough now appears to be interacting with the synoptic scale dynamics that are generating a lee side trough.

The interaction of the pressure trough associated with the sandhills boundary and the synoptic scale lee side trough is suggested in the analysis. Even though the sandhills frontal boundary maintains an east-west orientation, the pressure trough moves into a southwest-northeast orientation over western South Carolina. The 1011 mb isobar on the Virginia coast also shows some semblance of troughing. Interrupting the trough is the area of persistent ridging, now evident as a mesoscale high pressure area in central North Carolina.

The synoptic scale flow is beginning to dominate in North Carolina. Pre-frontal flow is now from the west-southwest. The stronger flow from the southwest is forming a convergence boundary along the southern side of the thermal gradient (Fig. 2.12c). However this convergence is significantly weaker than at 1200 UTC because the winds to the north of the gradient are beginning to swing to a southerly direction. Some convergence is occurring at the extreme western portion of the thermal gradient, with Asheville's northwest wind, also.

1600 UTC 05 June 1993

Moderation of the thermal gradient is now beginning to occur (Fig. 2.17). The gradient is rapidly moving to the northeast. The temperature at Rocky Mount has increased 7 K in two hours. The sandhills area is also experiencing significant heating with an average temperature increase of 4 K. Asheville is still a local maximum due in part to full solar heating and subsident warming.

The mesohigh in central North Carolina has shown significant dissipation. As the cloud cover clears and the thermal gradient moves through the area, the pressures begin falling. The rapid heating is removing the last vestiges of the derecho modified air mass. However, the remnant mesohigh is still obscuring the trough signature in central North Carolina. The cold front appears to have crossed the mountains in Virginia but still lags behind the mountains in Tennessee.

The only sign of any streamline boundary is some convergence in western North Carolina (Fig. 2.12d). This convergence is occurring near the trough where the synoptic southwesterly flow converges with local mountain induced northwesterly flow from around Asheville. Synoptic flow dominates the rest of the wind field. Due to the pressure gradient force, the strong flow from the southwest should weaken on the southwest side of the mesohigh, and strengthen on the northeast side. This is not evident in the available reporting stations but data is sparse in this general area. The diverging streamlines near the mesohigh suggest its presence somewhat, however.

1800 UTC 05 June 1993

The thermal gradient remains tight as it moves even farther northeastward (Fig. 2.18). The broad area of high potential temperature air has increased encompassing most of southern and western North Carolina. The potential temperatures in the foothills of the Appalachians are still much higher than those anywhere else in the state. Since Asheville's dry bulb temperature is similar to surrounding stations this maximum in the potential temperature field is probably due to lower station pressures in the mountains. The axis of the thermal trough has changed slightly from north-south to northeast southwest. This occurs as the tightest part of the thermal gradient continues to lift northeastward and the gradient associated with the cold front rapidly approaches from the west.

The cold front has entered North Carolina and the pressure trough remains fairly stationary. The two features are becoming quite close to each other near Asheville. Previously the mesohigh appeared to be rapidly dissipating, but the pressure at Raleigh-Durham appears to have steadied and remains significantly higher than at surrounding stations.

Convergence in the wind field continues in the southwestern portion of North Carolina (Fig. 2.19a). The convergence area reinforces the sandhills - outflow boundary. Effects of the mesohigh pressure gradient is still evident in the streamlines near the mesohigh. The increased confluence to the northeast of the mesohigh suggests acceleration of the winds as would be expected from pressure gradient force considerations.

A modified thermodynamic sounding was generated for Charlotte using the SHARP program (Fig. 2.20) as an attempt to obtain representative afternoon thermodynamic profile over central North Carolina. The 1200 UTC Athens sounding was used and the lowest 100 mb was modified to reflect 1800 UTC Charlotte surface moisture data. The Athens sounding indicated an environment conducive to convection, and that has not changed considerably with the significant surface heating at Charlotte. There is still a capping inversion but as mixing occurs it is slowly being eroded. Modification has not changed the stability indices; the LI is -8, and the CAPE value is 2349 Jkg^{-1} , and as before they still reflect values for strong convection.

1900 UTC 05 June 1993

Thunderstorms began to develop between 1800 UTC and 1900 UTC. These can be seen in the 1900 UTC visible satellite image (Fig. 2.21). The strongest cell is located north of Charlotte along with a curved line of cumulus development to the southwest. Evidence for an east west boundary is indicated in this image by cloud development from the coast extending to the thunderstorm cloud mass. There is a region of clear air just to the north of this cloud line extending northeast toward Norfolk, Virginia. An area of widespread uniform cloud to the south is consistent with the presence of the capping inversion.

The temperatures in the sandhills region have risen rapidly, as much as 3 K in the past hour (Fig. 2.22). This rapid increase in temperature has reintensified the thermal gradient, and reestablished an east - west orientation for the gradient. The cloud line seen on the satellite picture aligns quite well with the southern edge of the sandhills boundary.

The sandhills boundary's pressure trough's position has not changed. The northeast end of the trough is very near the western edge of the mesohigh. The pressures at the stations within the mesohigh are falling but still not as quickly as other stations. The geographical area of the mesohigh is the same as that for the region of clear skies in the satellite picture. The cold front's movement is steady but slow.

The streamline analysis is showing the re-establishment of a convergence boundary. The western edge of this boundary lies where convergence has been occurring over the past hours between Asheville and Charlotte. Convergence continues to occur across the state nearly coincidental with the thermal gradient boundary. The western edge of the convergence boundary is illustrated in the satellite picture by the curved line of cumulus clouds just west of the first thunderstorm cell.

Hailstorm Development

By 2100 UTC thunderstorms dominate central and eastern North Carolina as shown in the NOWRAD radar composite and mesoscale analysis (Figs. 2.24, 2.25). *Storm Data* reports that 2.75 inch hail was reported at 1940 UTC at China Grove in Rowan county where the first cell developed. The storms near the coast are also producing severe hail. Greenville in Pitt county also reported 2.75 inch hail at 2045Z and at 2115Z Franklinton in Franklinton county reported 1.75 inch hail. The radar indicates that the storms are developing along the sandhills - outflow frontal boundary. From earlier satellite data (not shown) it can be seen that the cells developing near Raleigh-Durham and Greensboro are triggered by an outflow boundary from the first developed cell.

The question that arises at this point is; Why are all the storms severe hail producers. Hail research has determined four items necessary for hail development. They are, 1) strong convective instability, 2) abundant moisture, 3) strong wind shear and 4) a dynamical mechanism to release the convective instability (Knight and Squires, 1988). All four of these requirements exist for this case. From the modified Charlotte sounding the convective instability and wind shear are evident. The wind profile shows significant veering of the winds in the midlevels. Wind direction changes from 260 degrees at 700 mb to 290 degrees at 300 mb. No low level veering is evident, which suggests that supercells will not develop. The CAPE, 2349 Jkg^{-1}, and lifted index, -8, values all support the convective instability of the air mass.

The sandhills boundary acts as the trigger. The lifting produced at the boundary should be able to overcome the lid, which in the modified sounding has a strength of 4.2 C. This value could be lower since the only modifications of the sounding were done on the lowest 100 mb. The derecho convective system would have significantly modified the mid-levels of the atmosphere, to include significantly depleting the lid. However, this effect is not able to be depicted with the data available. The Cape Hatteras sounding at 0000 UTC 5 June 1993 was taken just prior to passage of the derecho convective system. The lid strength at Cape Hatteras is 2.2. A capping inversion stronger than 2 C usually will prohibit development of deep convection (Graziano, 1985). However, it has been noted (Kessler, 1986) that a capping inversion allows for an intense buildup of surface heat and moisture, so that when a storm eventually does break the inversion, rapid, and possibly severe convection can develop.

The strength of the convergence, and subsequent lifting, at the boundary is shown in Figure 2.20b. The storms generate on and are anchored to the boundary. The prefrontal air flow from the southwest continues to flow into and over this boundary providing an unlimited supply of new inflow air. Soil moisture is readily available from the derecho precipitation.

A strong updraft is necessary to support hailstones as they grow. In Weisman and Klemp (1986) the maximum strength of the updraft (w_{max}) can be estimated from CAPE values. The equation is

$$w_{max} = (2 \text{ x CAPE})^{1/2}.$$

They noted that w_{max} could be decreased by as much as 50% due to water loading, vertical pressure gradients, and mixing effects. Using the most conservative CAPE value from the unmodified 1200 UTC Athens sounding we get a w_{max} of 69.3 ms^{-1} and a 50 % reduced value for

w_{max} of 34.65ms^{-1}. NHRE studies of the Grover, Colorado hailstorm showed 20 ms^{-1} updrafts associated with 3/4 inch hail. Either value for this case is sufficient to support hailstone development.

Fawbush and Miller (53) identified the wet bulb zero (WBZ) height as a good indicator of hail development. They determined that a hailstone can experience approximately 9000 feet of free fall through air at temperatures above freezing before rapid melting commences. From their research they determined a range of WBZ height values for severe hailstorm development. The WBZ height above ground ranges from 8000 - 11000 feet. The Athens sounding shows a WBZ height of 10752 feet, near the top of the range but definitely within it.

2.5. Summary and Conclusions

Severe hailstorms developed in central North Carolina on 5 June 1993 and seemed to have originated near an intense thermal boundary that was the remains of an outflow boundary from a derecho that had transversed the northern part of North Carolina the previous evening. The wind field aligns into a convergence boundary along the thermal boundary, extending from the foothills to off the Carolina coast. The pressure field responds to the thermal forcing with troughing in and around the thermal boundary throughout the evening and early morning. The combination of thermal boundary, convergence boundary, and pressure trough are referred to as the sandhills boundary.

A slow moving cold front approaching the Appalachian mountains seems to affect both the wind and pressure fields. Strong, prefrontal, southwest winds approaching the sandhills boundary produce even stronger convergence. A prefrontal trough interacts with the pressure field associated with the sandhills boundary changing its orientation. With diurnal destabilization the interaction of the lee side trough and the increased convergence with the sandhills boundary initiates the convection. The severe weather is in the form of large hail. Thermodynamic soundings present very classic signatures for severe hailstorm development.

The recurrence and consistency of the sandhills thermal boundary suggests that this thermal area might play a part in forcing thunderstorms. Air mass thunderstorms that previously had no known trigger might actually be triggered by the thermal gradient associated with the sandhills thermal area. Further study of this feature is warranted

All of the mesoscale features that contributed to the sandhills boundary were located with standard operational data. This study was performed without many of the modern tools a National Weather Service office has or will have soon due to modernization. Several of the boundaries responsible for this severe weather might have been detected by Doppler radar. That detection would have helped forecasters focus on where convection would initiate.

2.6. References

Barnes, S.L., 1964: A technique for maximizing details in numerical weather map analysis. *J. Appl. Meteor.*, **3**, 396-409.

_____, 1973: Mesoscale objective map analysis using weighted time-series observations. *NOAA Technical Memorandum ERL NSSL-62*, Norman, OK, 60 pp.

Daniels, R. B., H.J. Kleiss, S. W. Buol, H. J. Byrd, and J. A. Phillips, 1984: Soil systems in North Carolina. North Carolina Agricultural Research Service , Bulletin 467.

Fawbush, E. J., and R. C. Miller, 1953: A method for forecasting hailstone size at the earth's surface. *Bull. Am. Meteor.* Soc., **34**, 235-244.

Fujita, T. T., 1963: Analytical mesometeorology: A Review. In *Severe Local Storms*, Meteor. Monogr. **5**(27), American Meteorological Society, Boston, 77-125.

Hart, J. A., and J. Korotky, 1990: The SHARP Workstation v1.50. NOAA, NWS Eastern Region, unpublished report.

Johns, R. H., and W. D. Hirt, 1987: Derechos: widespread convectively induced windstorms. *Wea. Forecasting*, **2**, 32-49.

______, and C. A. Doswell, 1992: Severe local storms forecasting. *Wea. Forecasting*, 7, 588-612.

Kessler, E., ed., 1982: Thunderstorms: a social, scientific, and technological documentary Vol. 2, thunderstorm morphology and dynamics.

Keeter, K. K., S. Businger, L. G. Lee, and J. S. Waldstreicher, 1995: Winter weather forecasting throughout the eastern United States. Part III: The effects of topography and the variability of winter weather in the Carolinas and Virginia. *Wea Forecasting*, **10**, 42-60.

Knight, C. A., and P. Squires, Ed., 1982: Hailstorms of the Central High Plains, Vol. 1. Co. Assoc. Univ. Press, 12.

McCumber, M. C., and R. A. Pielke, 1981: Simulation of the effects of surface fluxes of heat and moisture in a mesoscale numerical model. Part I: Soil layer. *J. Geophys. Res.*, **86**, 9929-9938

Mueller, C. K., Wilson, J. W., and N. A. Crook, 1992: The utility of sounding and mesonet data to nowcast thunderstorm initiation. *Wea. and For.*, **8**, 132-145.

Purdom, J. F. W., 1976: Some uses of high-resolution GOES imagery in the mesoscale forecasting of convection and its behavior. *Mon. Wea. Rev.*, **104**, 1474-1483.

_____, and J. F. Weaver, 1982: Nowcasting during the 10 April 1979 tornado outbreak: A satellite perspective. Preprints, 12th Conference on Severe Local Storms, San Antonio, American Meteorological Society, Boston, 467-470.

Weaver, J. F., 1979: Storm motion as related to boundary-layer convergence. *Mon. Wea. Rev.*, **107**, 612-619.

Weisman, R. A., 1990: An observational study of warm season southern Appalachian lee troughs. Part I: Boundary layer circulation. *Mon. Wea. Rev.*, **118**, 950-962.

Weisman, M. L., and J. B. Klemp, 1986: Characteristics of isolated convective storms, In: *Mesoscale Meteorology and Forecasting*, Ray, P. S., Ed., 331-357.

Wilson, J. W., and C. K. Mueller, 1993: Nowcasts of thunderstorm initiation and evolution. *Wea and For.*, **8**, 113-131.

______, and W. E. Schreiber, 1986: Initiation of convective storms by radar-observed boundary layer convergent lines. *Mon. Wea. Rev.*, **114**, 2516-2536.

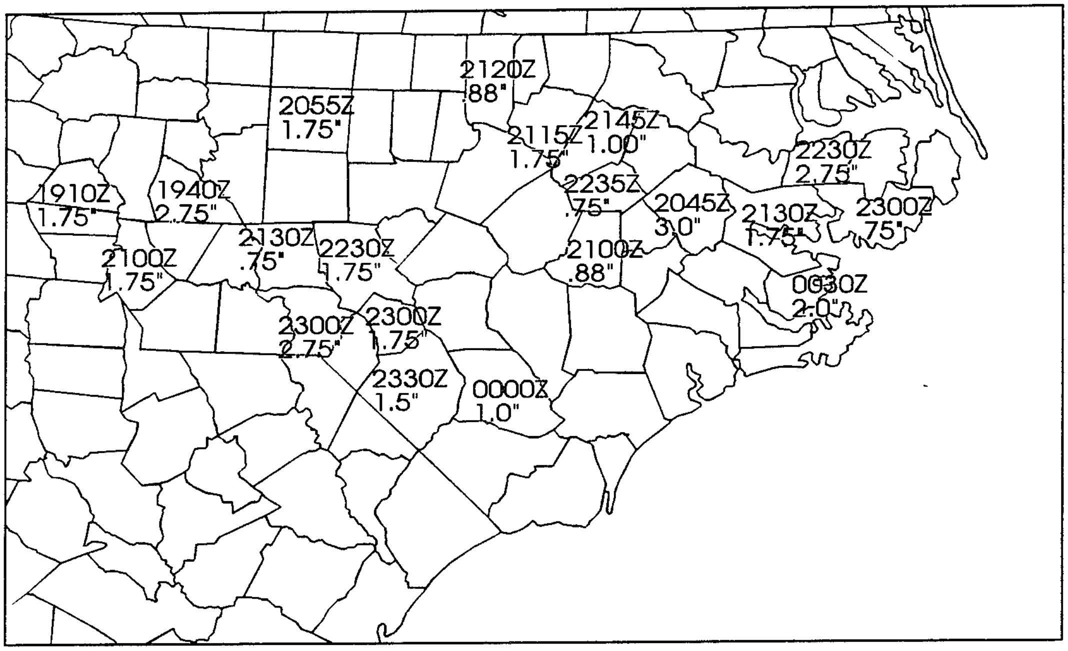


Figure 2.1. Damage reports from the severe hailstorms on 5 June 1993. The first time severe hail occurred is shown along with the size of the largest hail reported in that county.

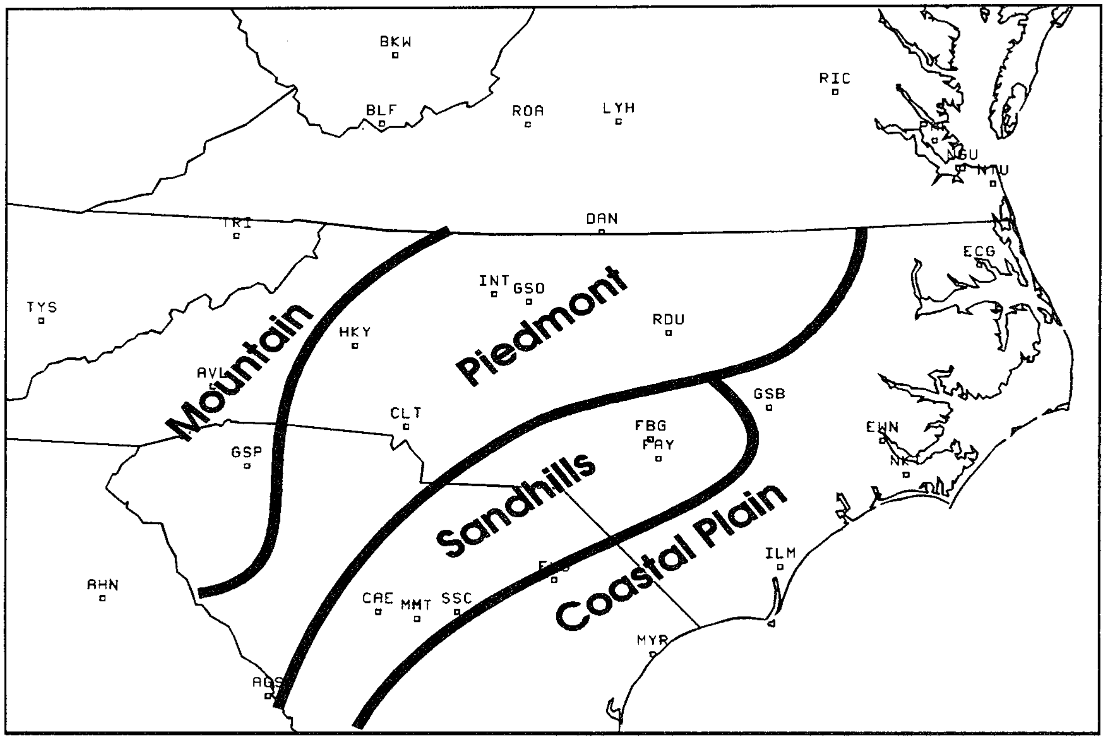


Figure 2.2. Analysis area with station identifiers and pertinent North Carolina geographical areas (Daniels et al, 1984).

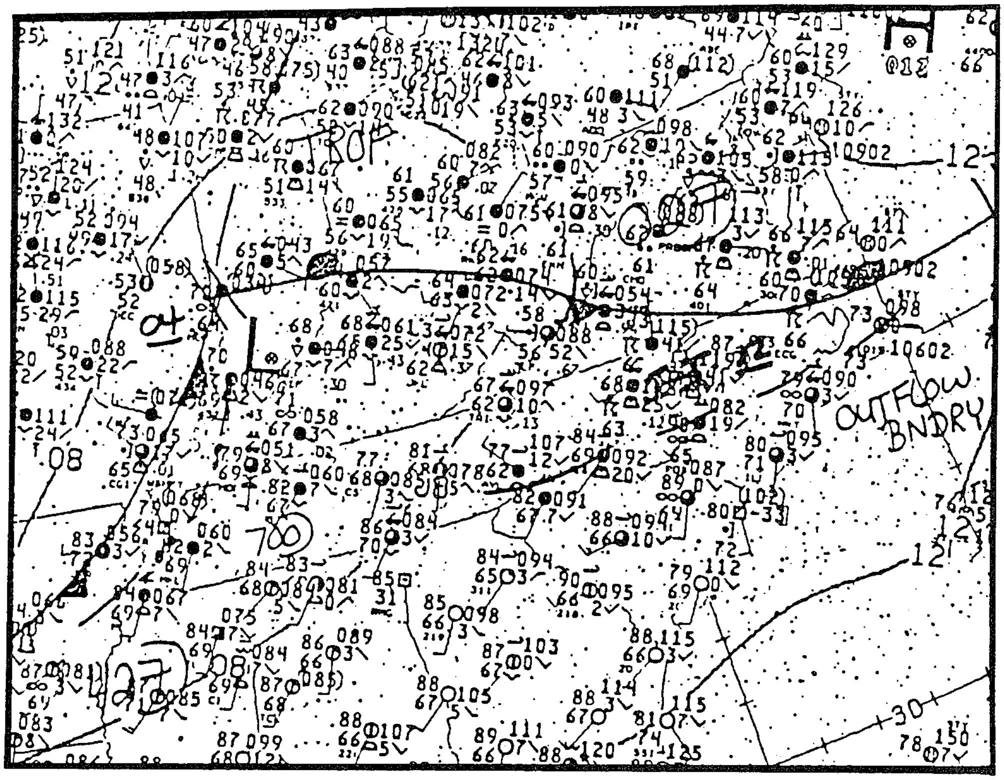


Figure 2.3a. NMC surface analysis for 0000 UTC 5 June 1993.

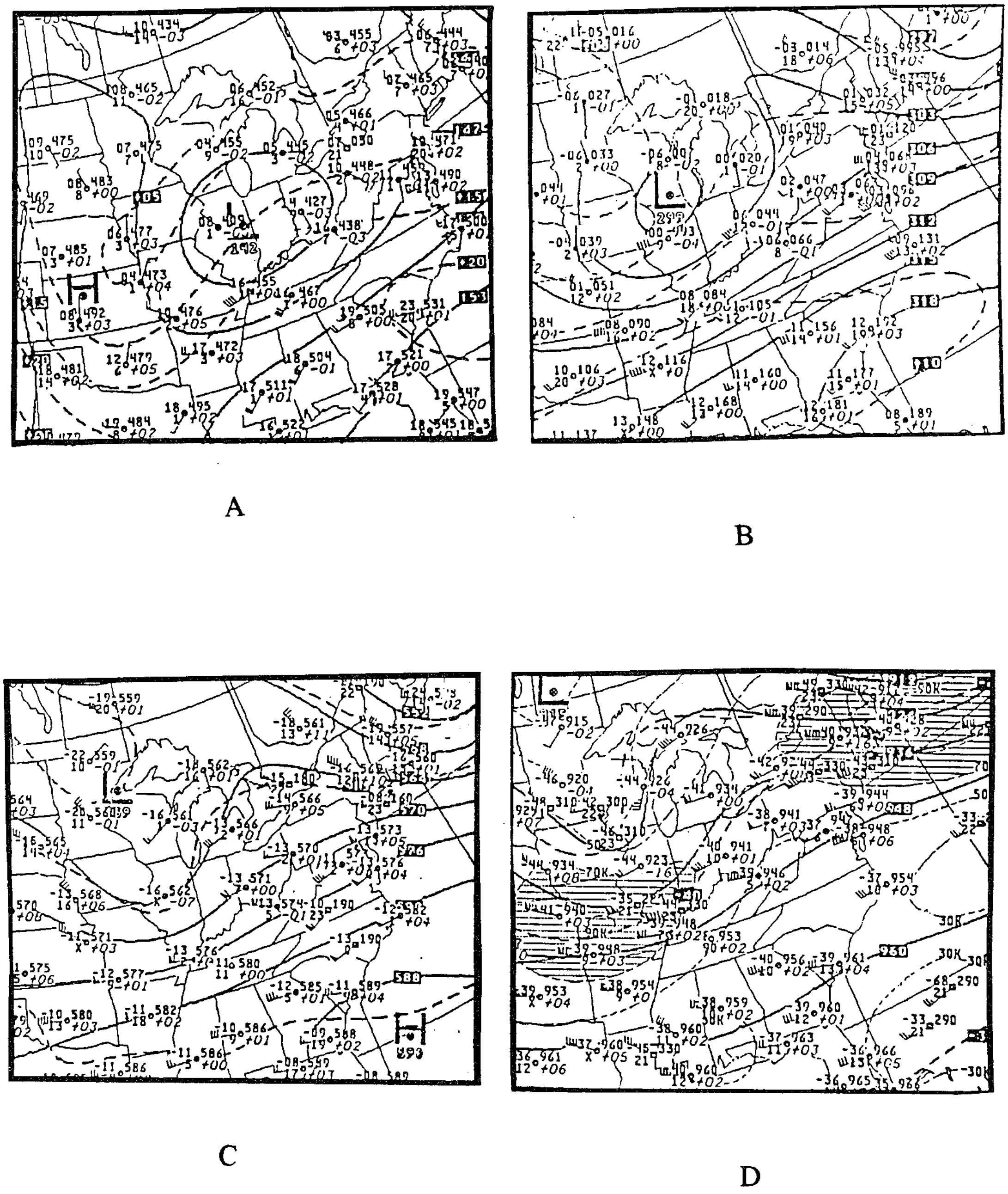


Figure 2.3b. NMC upper air analysis for 0000 UTC 5 June 1993. A) 850 mb, b) 700 mb, c) 500 mb, d) 300 mb.

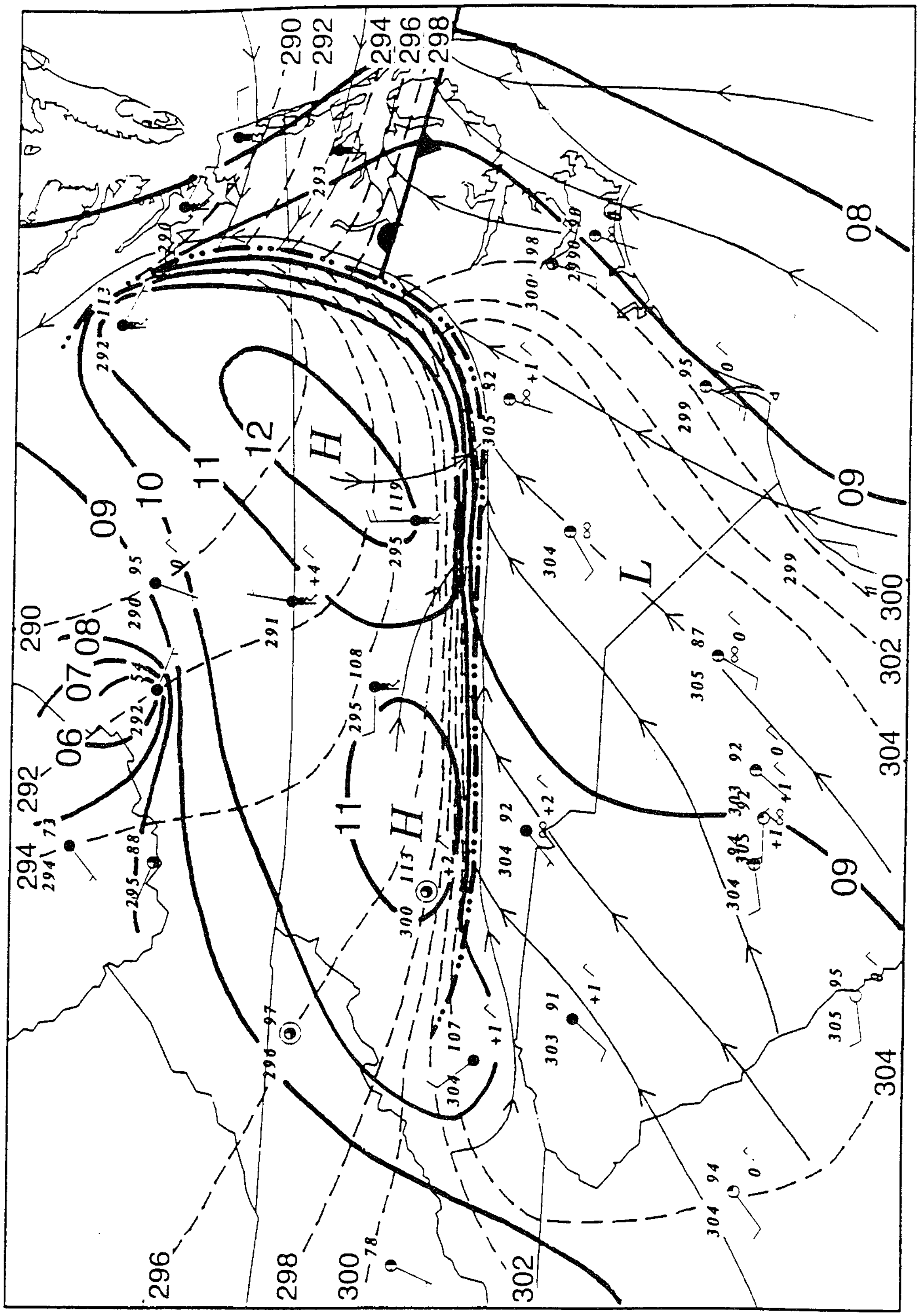


Figure 2.4. Subjective surface mesoanalysis for 0000 UTC 5 June 1993. Surface reporting stations are shown along with 1 mb isobars and potential temperature analyzed every 2^0K. The arrows are streamlines for the observed surface winds.

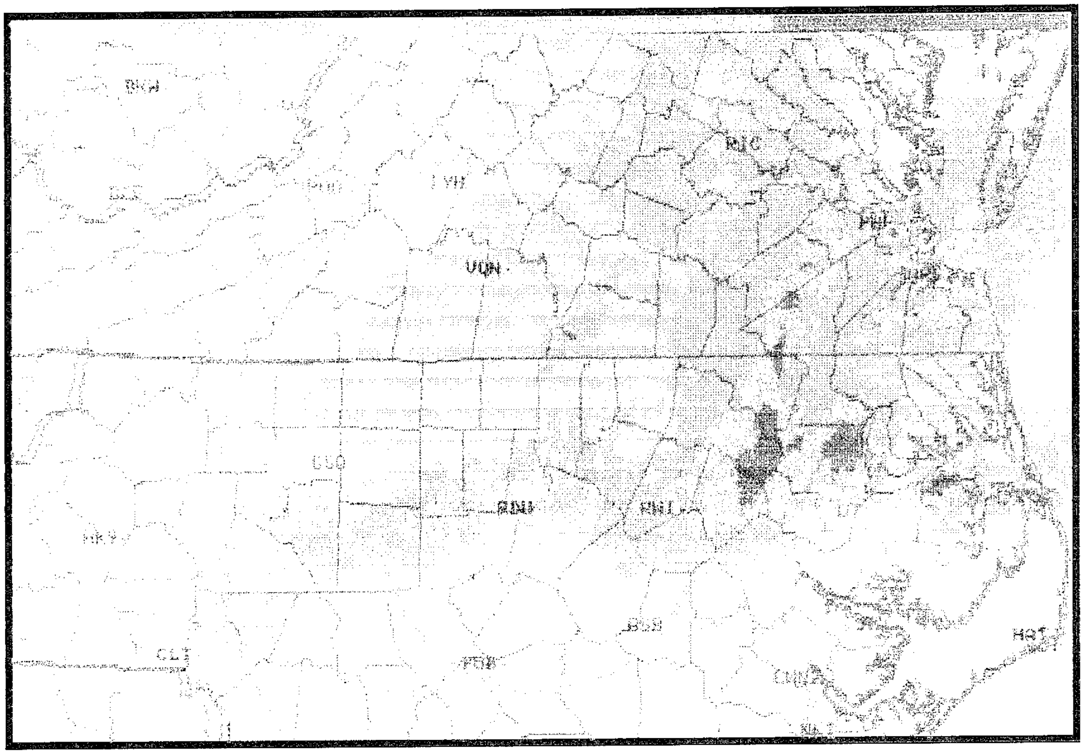


Figure 2.5. NOWRAD radar image for 0000 UTC 5 June 1993.

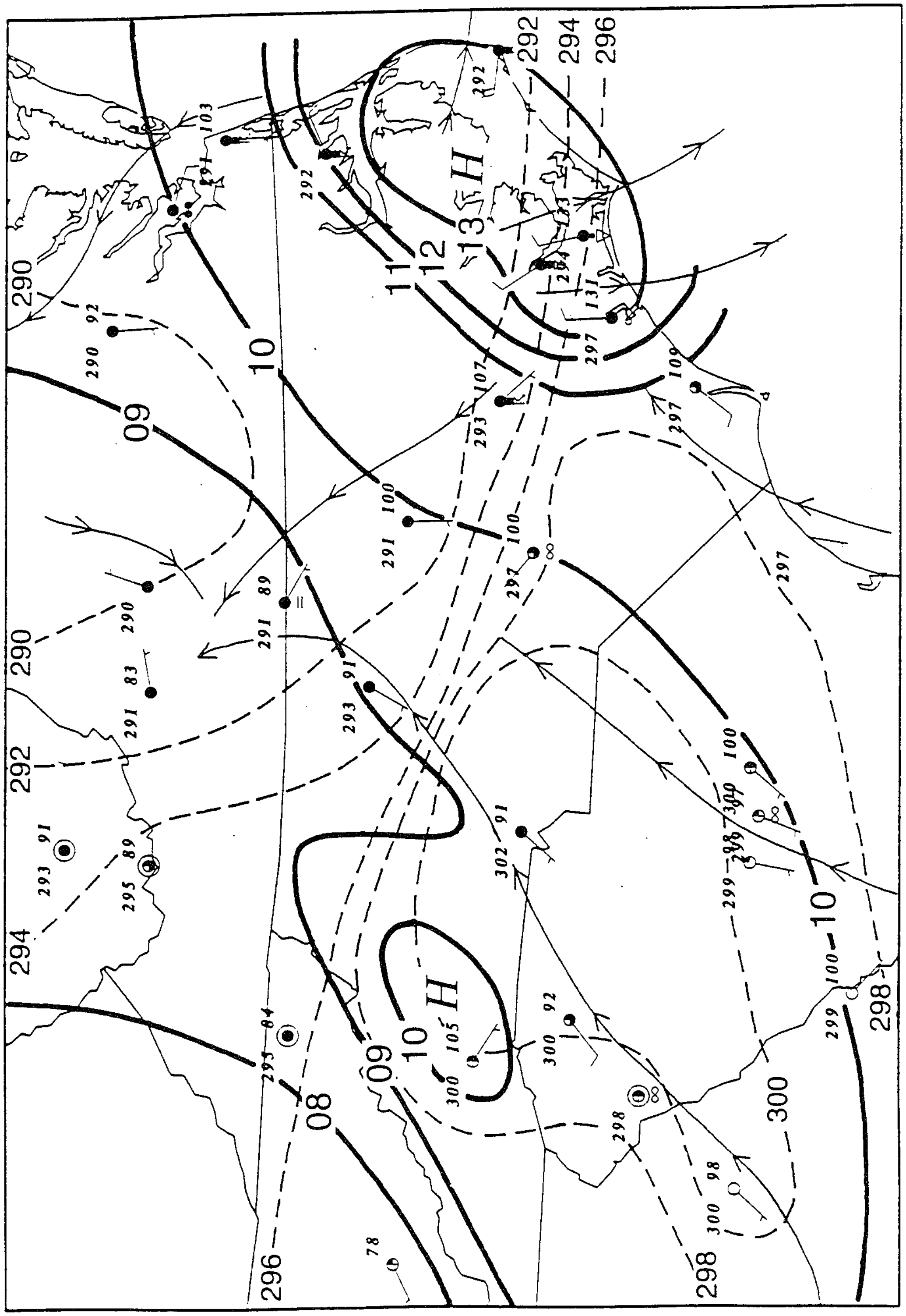


Figure 2.6. Same as Fig. 2.4 except for 0200 UTC 5 June 1993.

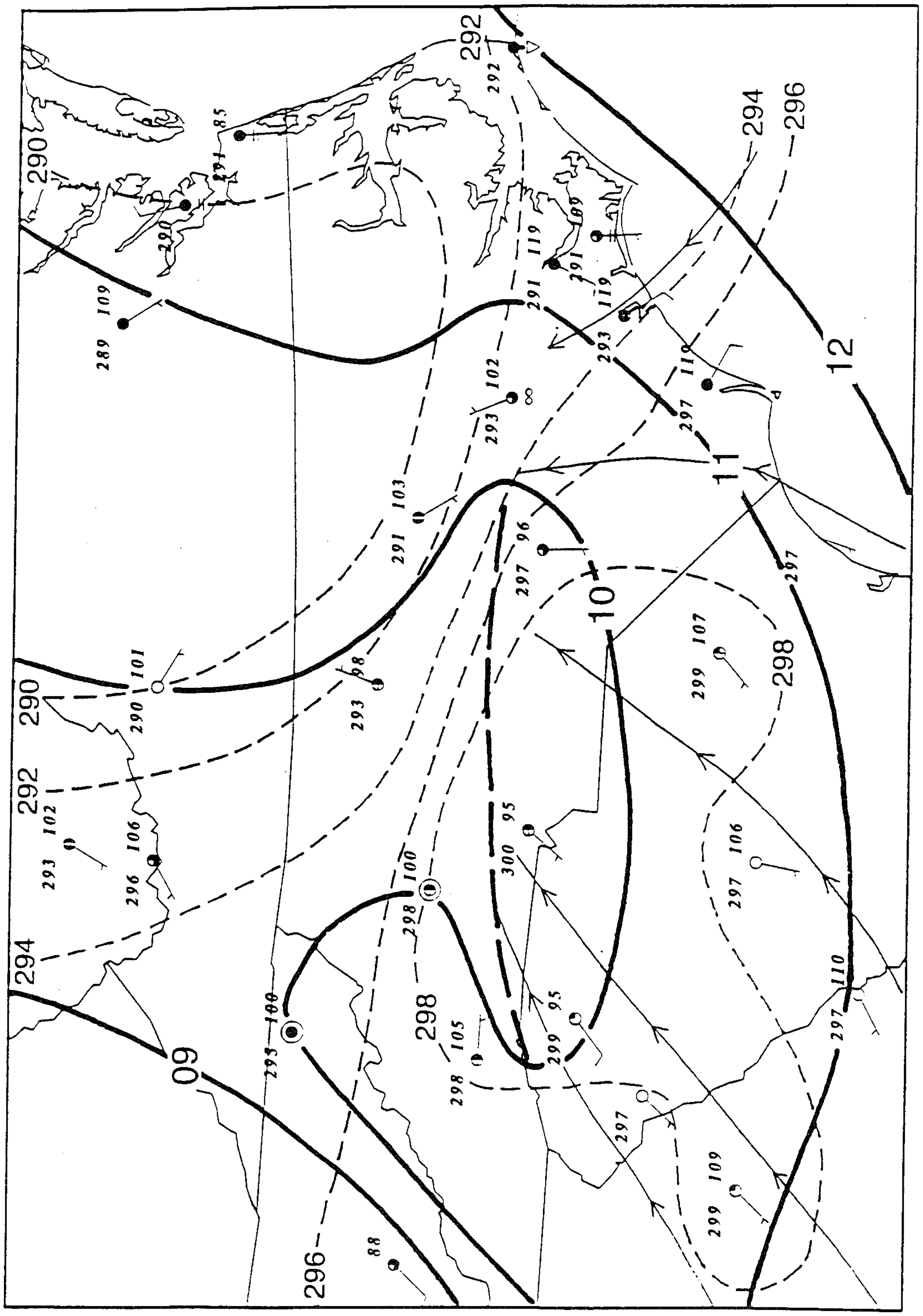


Figure 2.7. Same as Fig. 2.4 except for 0400 UTC 5 June 1993.

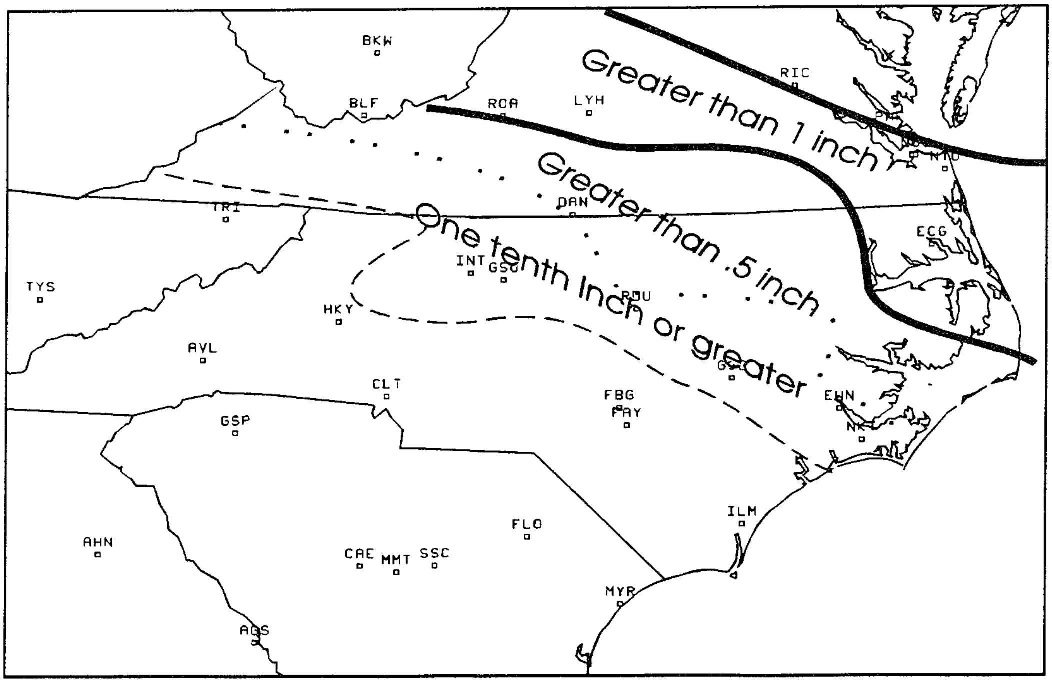


Figure 2.8. 24 hour precipitation totals from 1200 UTC 4 June 1993- 1200 UTC 5 June 1993.

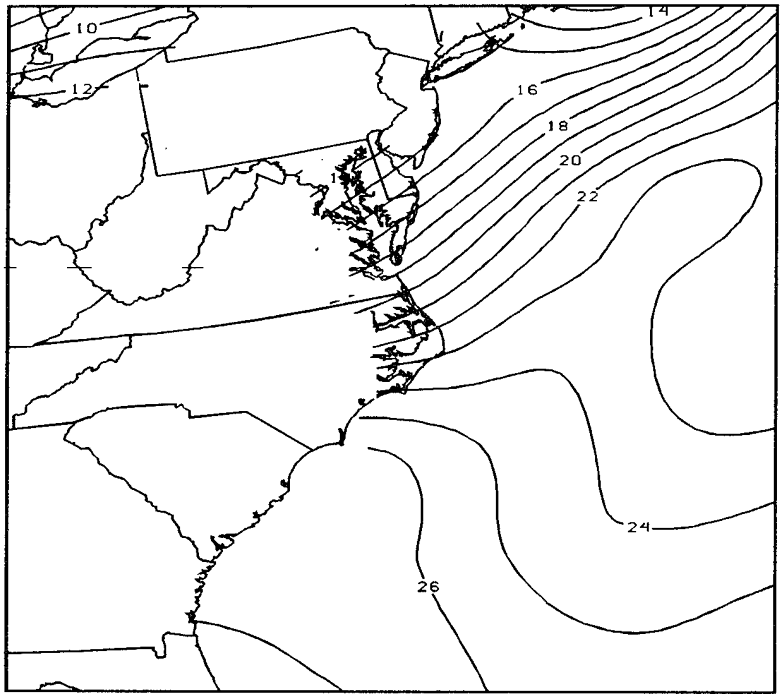


Figure 2.9. Weekly averaged sea surface temperatures for the week ending 6 June 1993. Temperatures are in degrees Celsius.

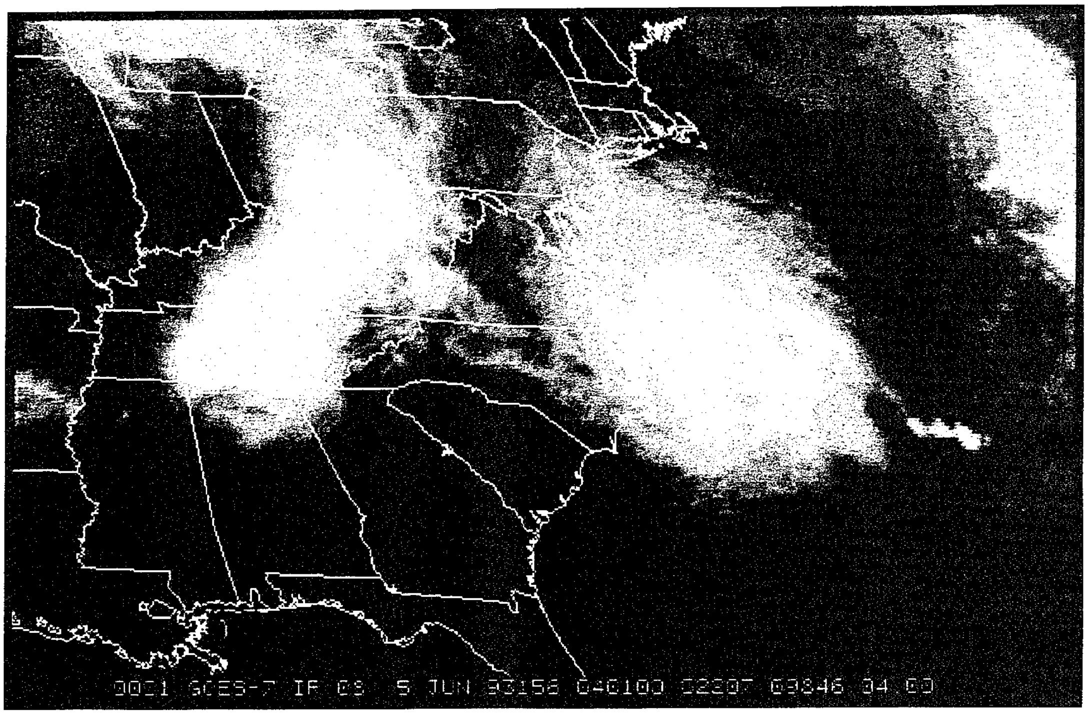


Figure 2.10. Infrared satellite imagery at 0400 UTC 5 June 1993.

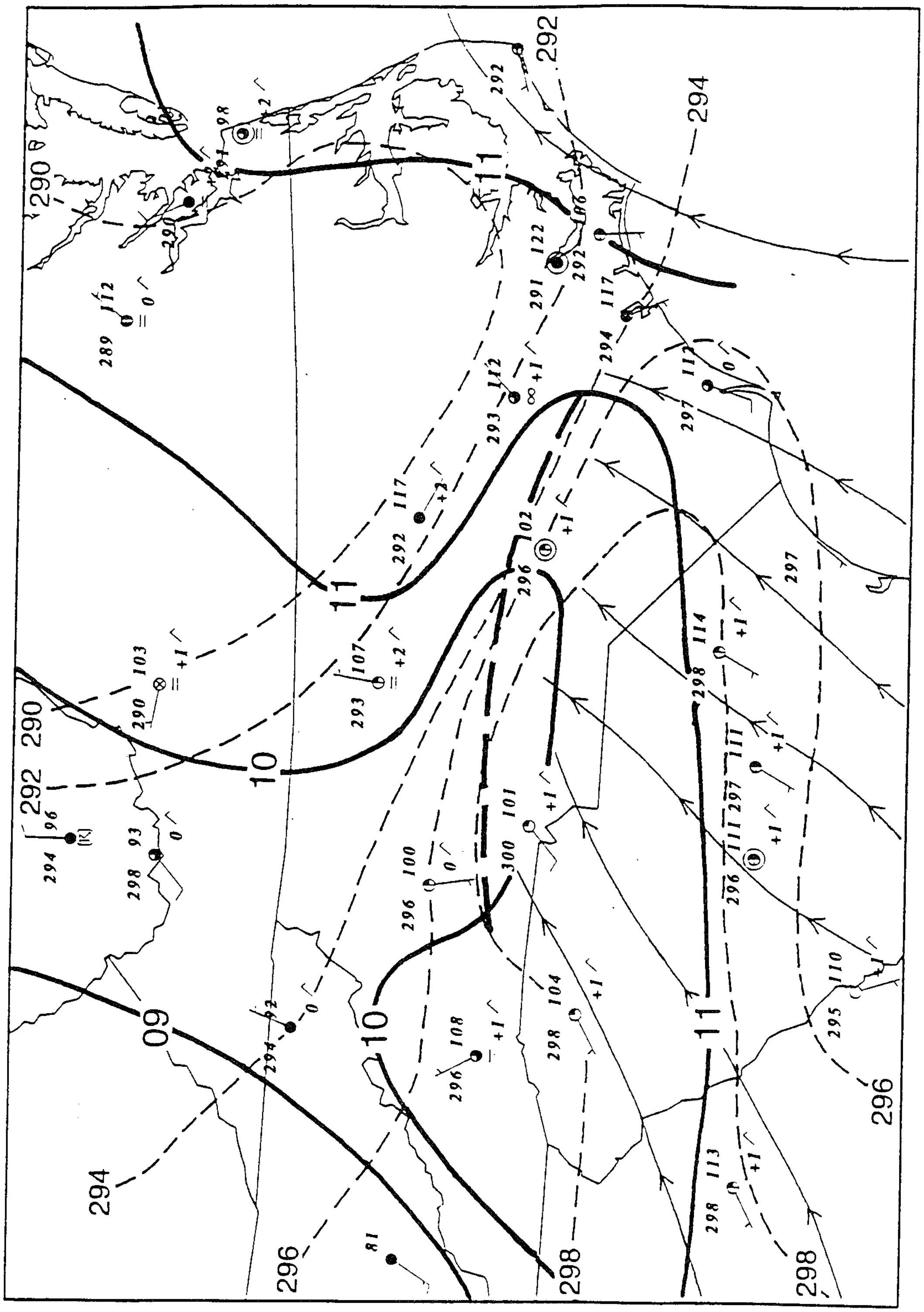


Figure 2.11a. Same as Fig. 2.4 except for 0600 UTC 5 June 1993.

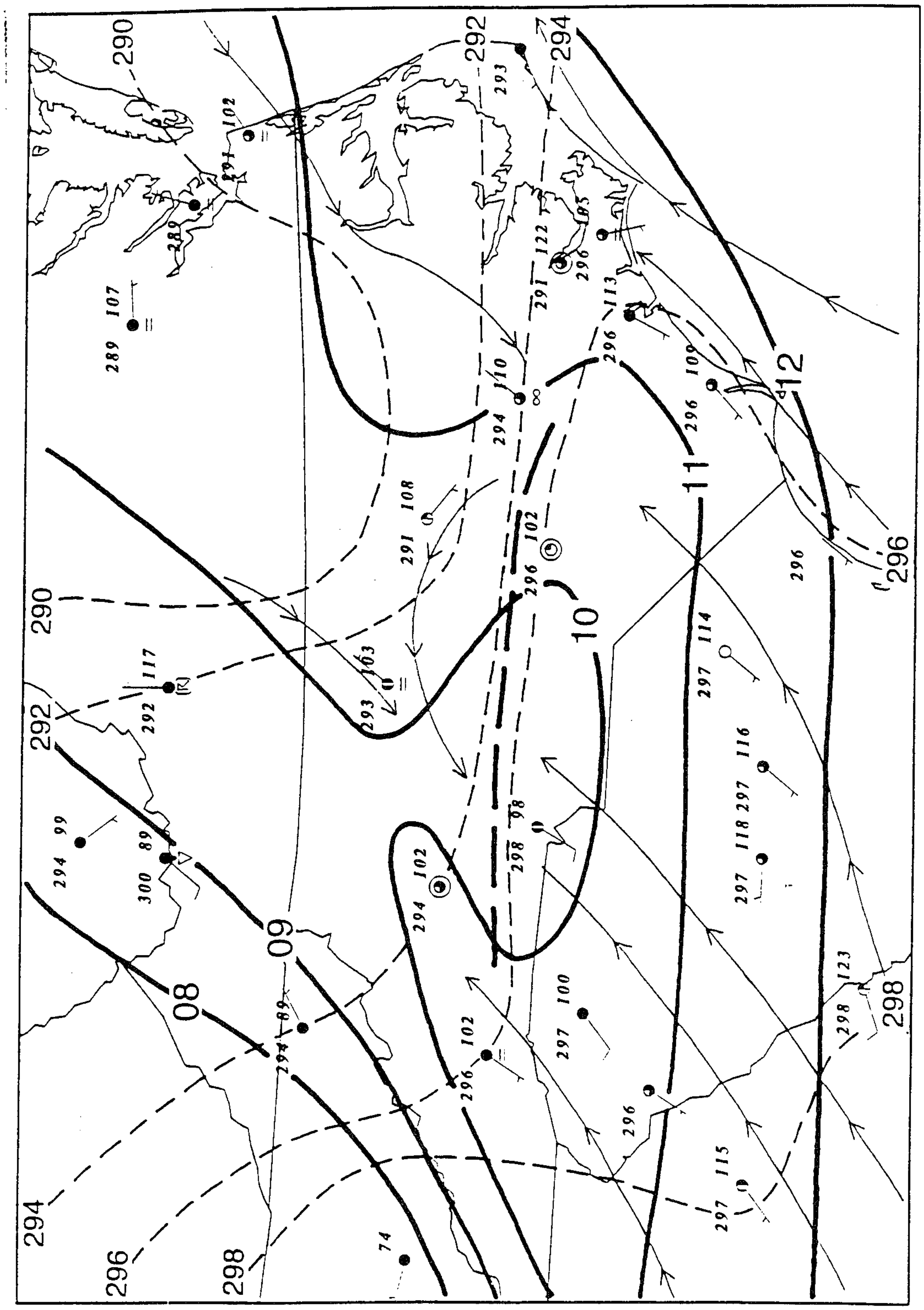


Figure 2.11b. Same as Fig. 2.4 except for 0800 UTC 5 June 1993.

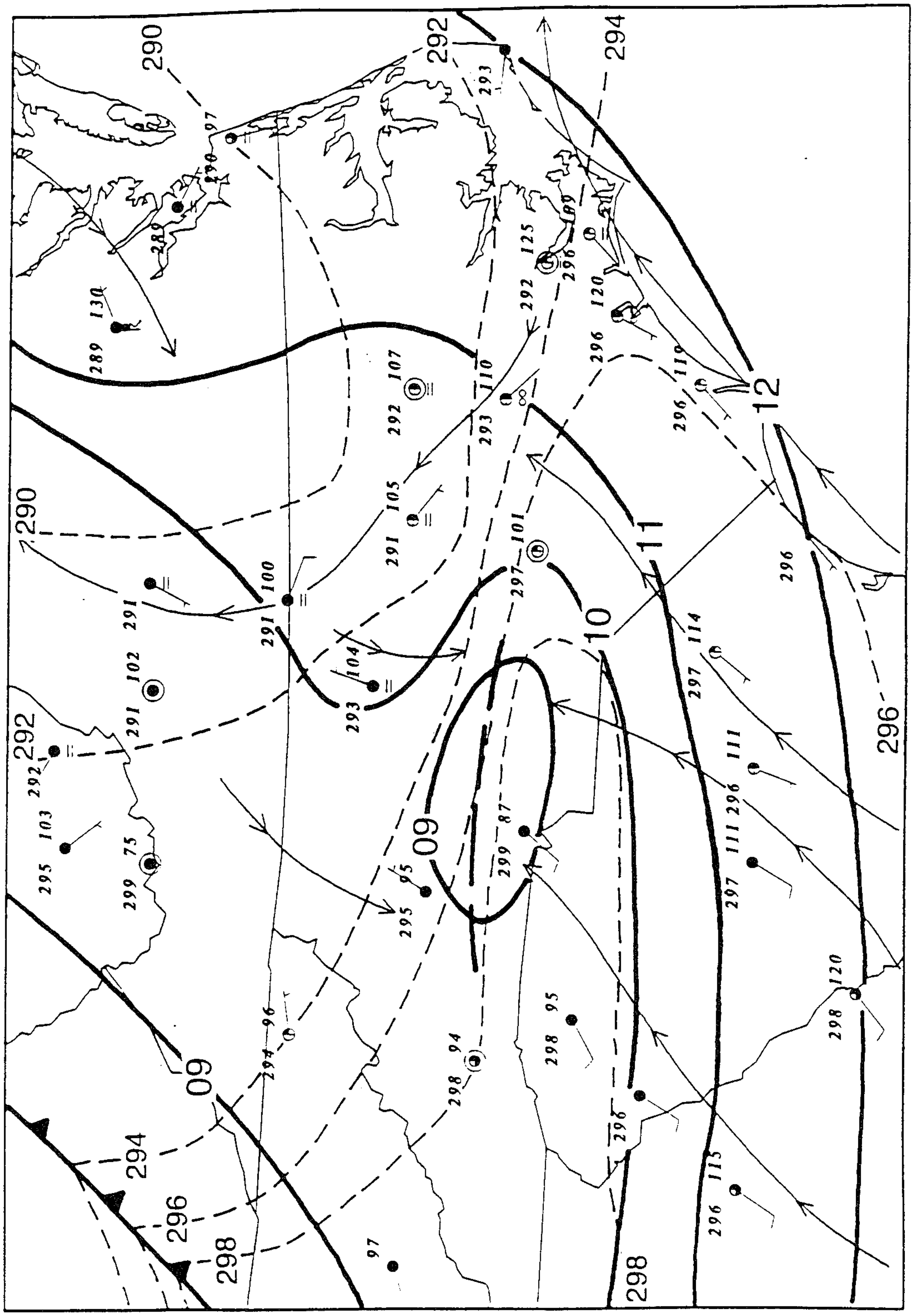


Figure 2.11c. Same as Fig. 2.4 except for 1000 UTC 5 June 1993.

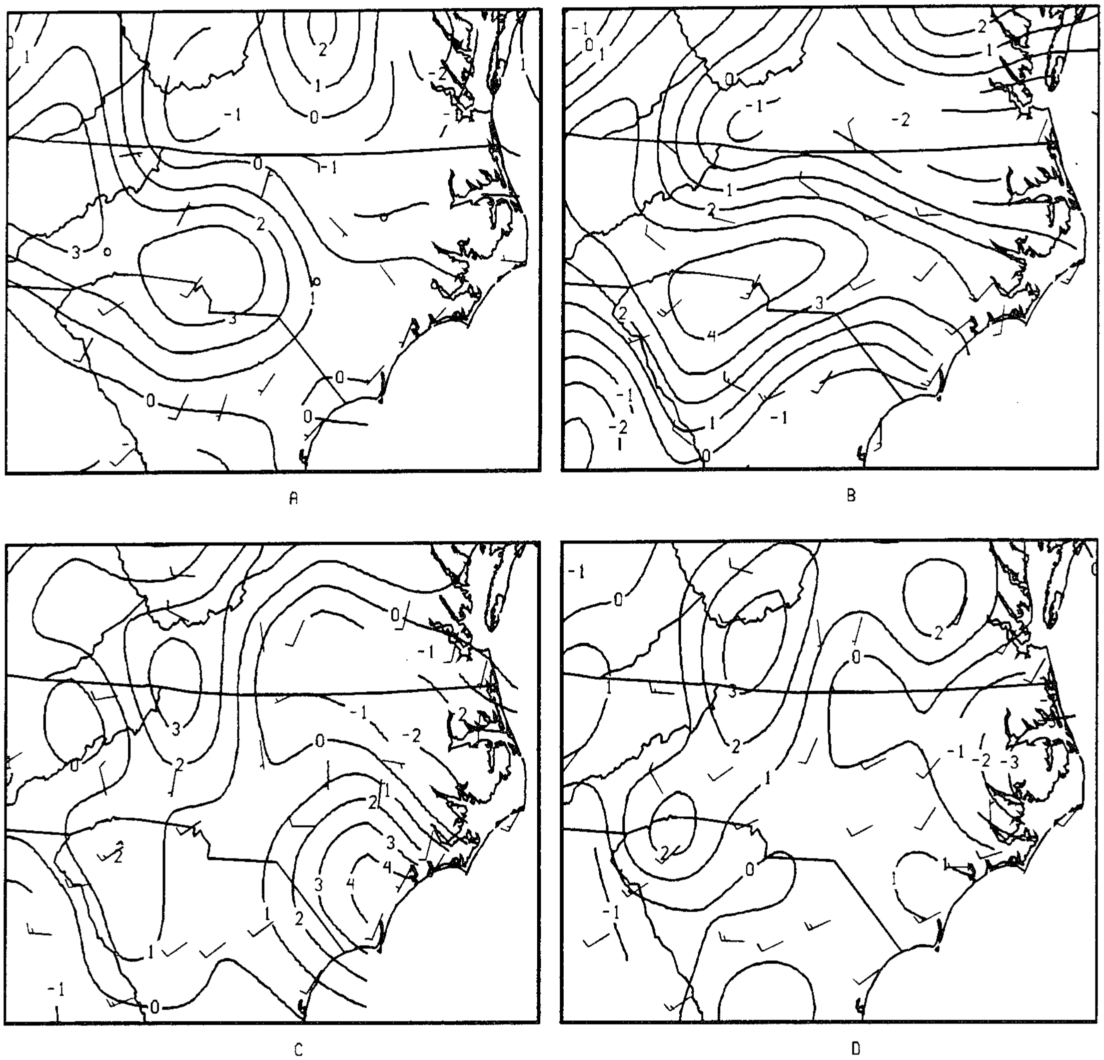


Figure 2.12. Surface mass convergence calculations a)1000, b) 1200, c) 1400, d) 1600 UTC. Units are 10^{-5} s^{-1}.

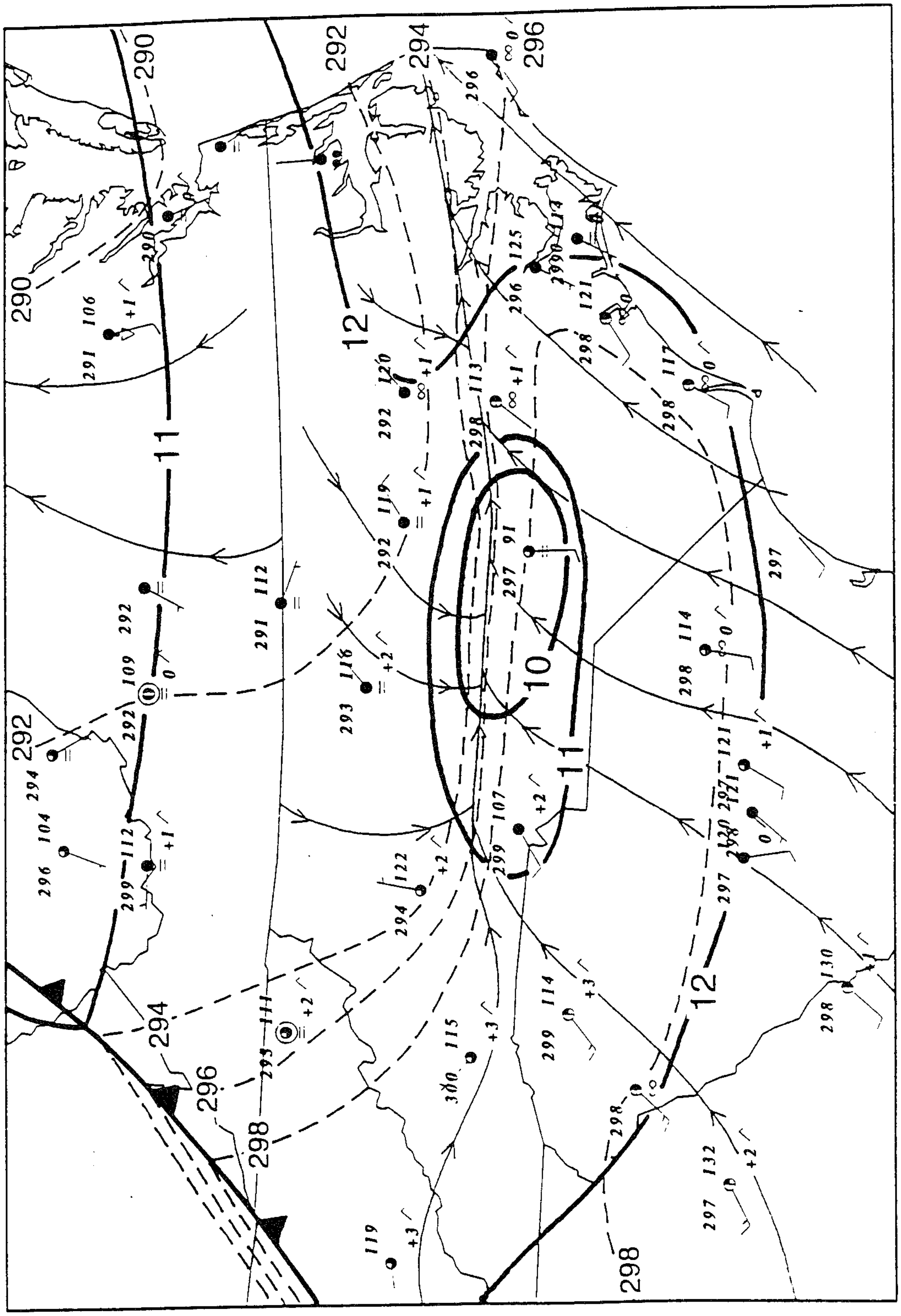


Figure 2.13. Same as Fig. 2.4 except for 1200 UTC 5 June 1993.

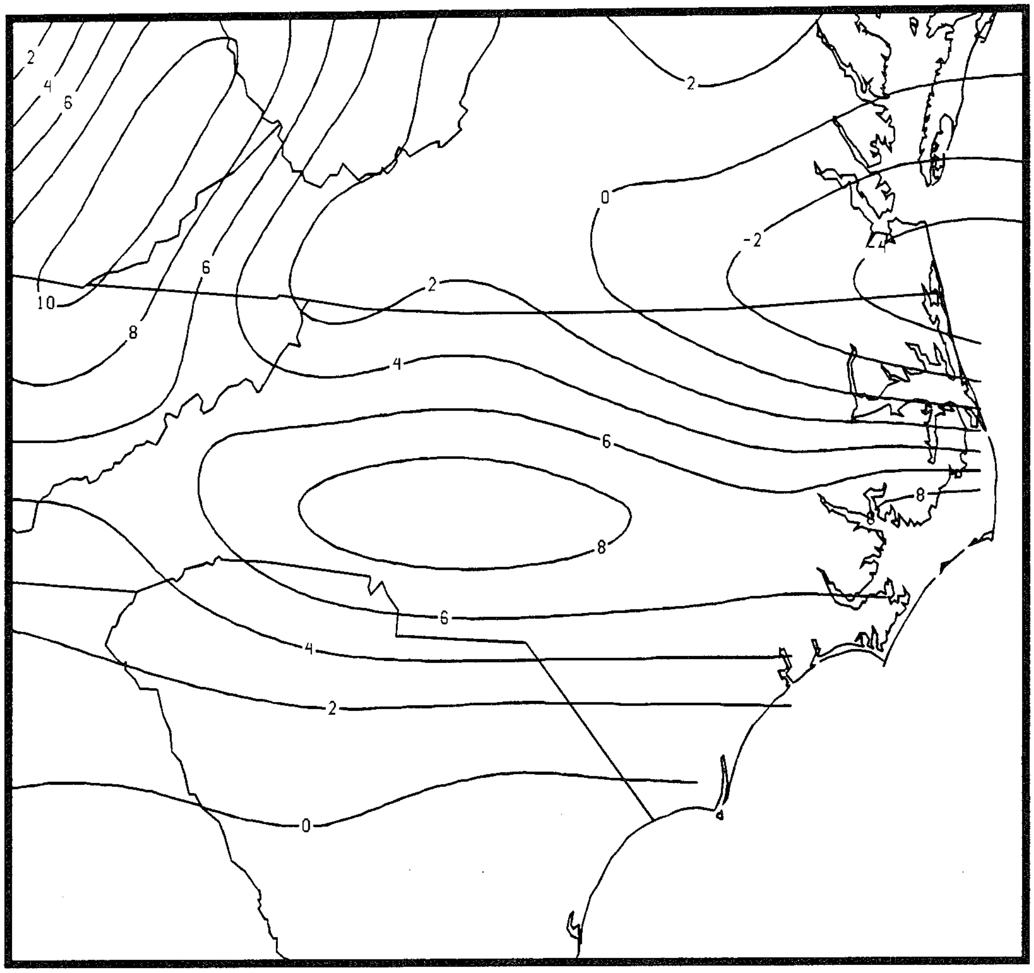


Figure 2.14. Total adiabatic frontogenesis for 1200 UTC 5 June 1993. Units in Kelvin/100 Kilometer/3 hours x 10^5

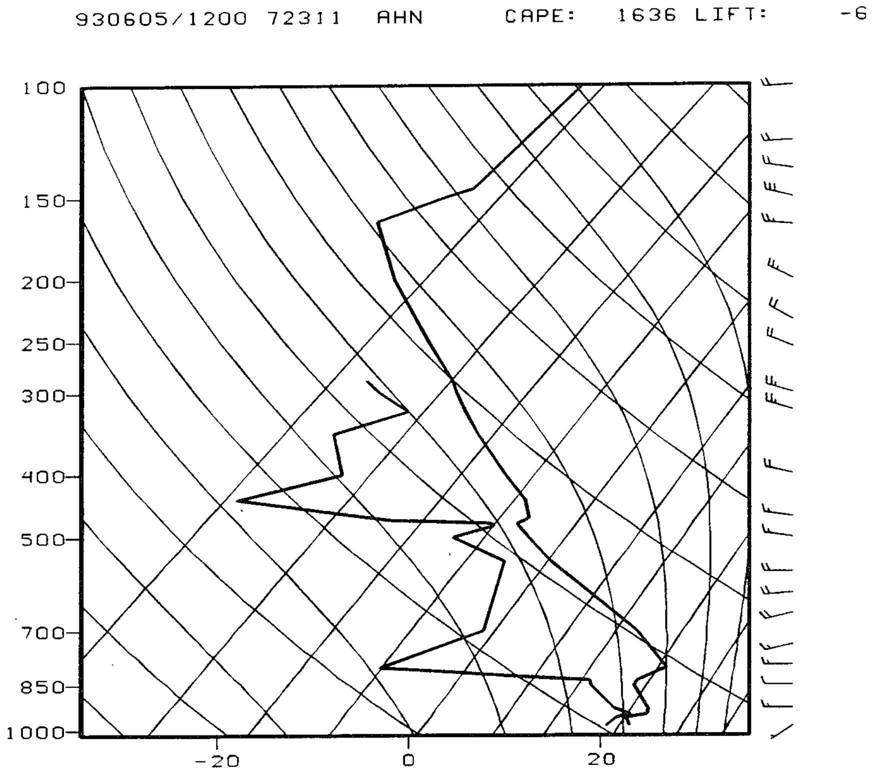


Figure 2.15a. 1200 UTC 5 June 1993 skew T-log *p* plot of Athens, Georgia (AHN), rawinsonde observation.

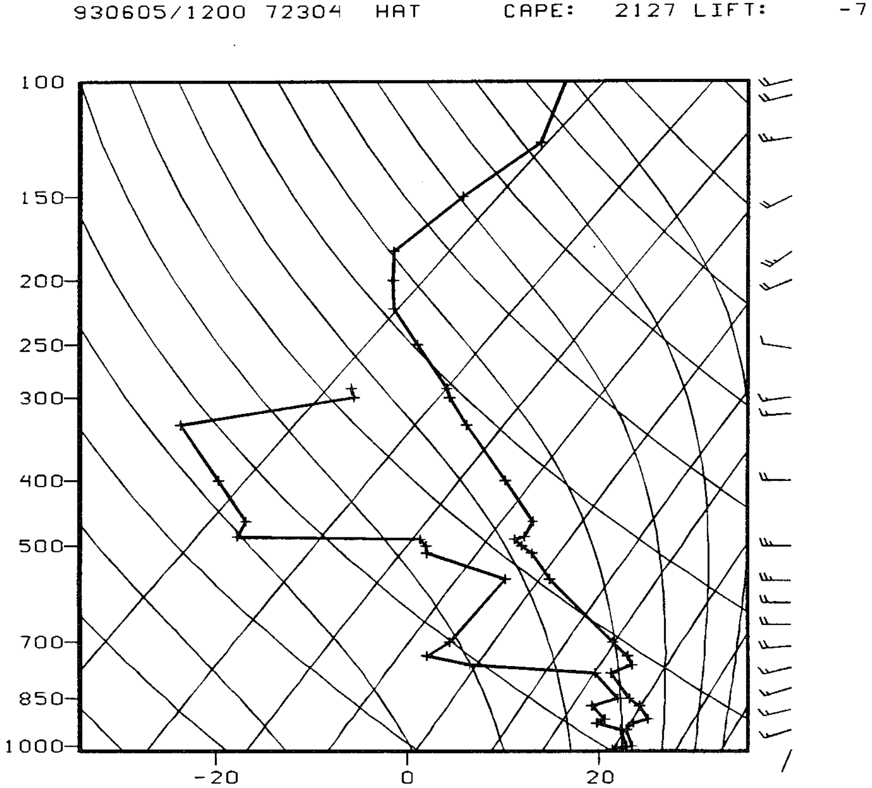


Figure 2.15.b. As in 2.15a except for 1200 UTC 5 June 1993 at Cape Hatteras, North Carolina (HAT).

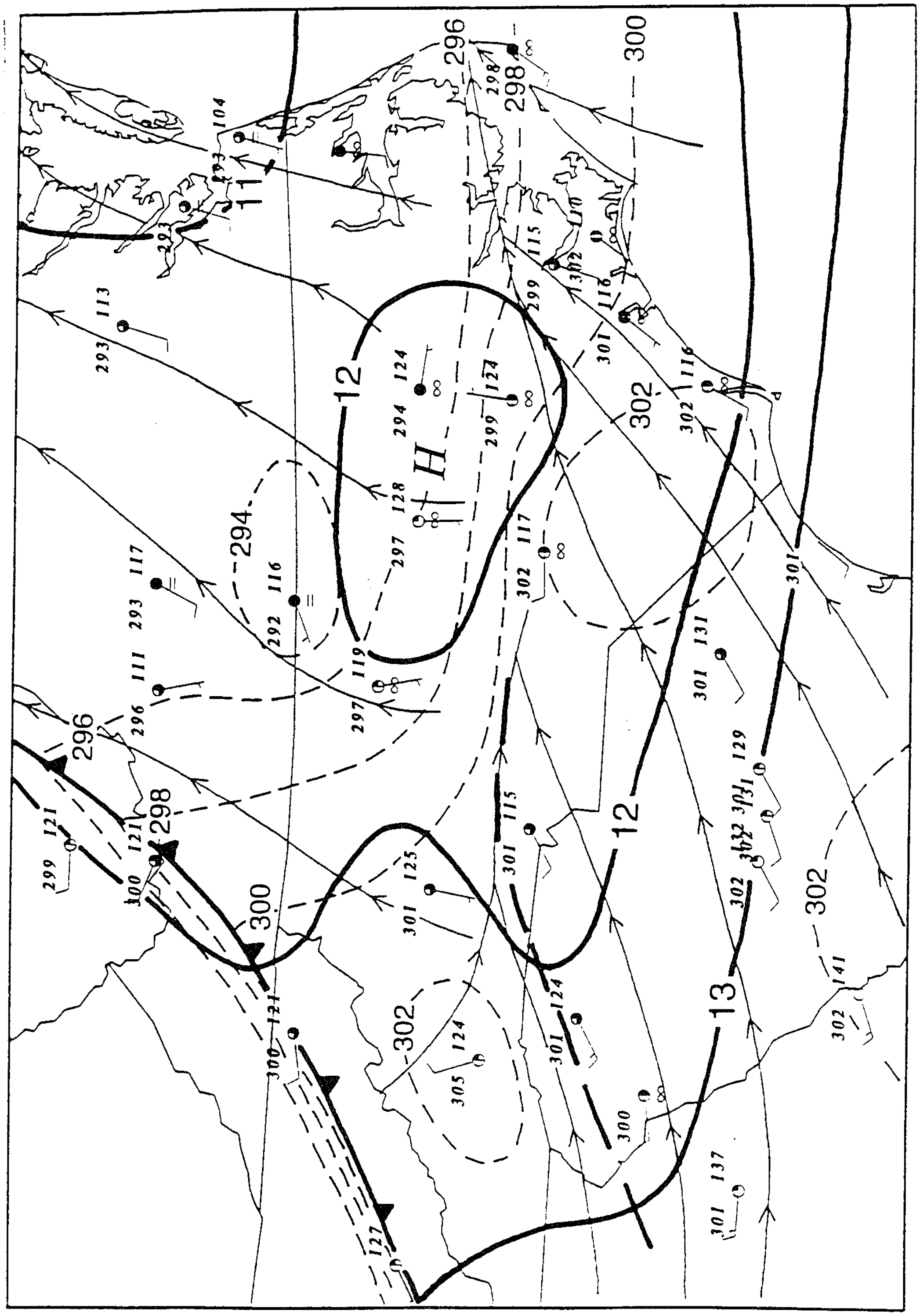


Figure 2.16. Same as Fig. 2.4 except for 1400 UTC 5 June 1993.

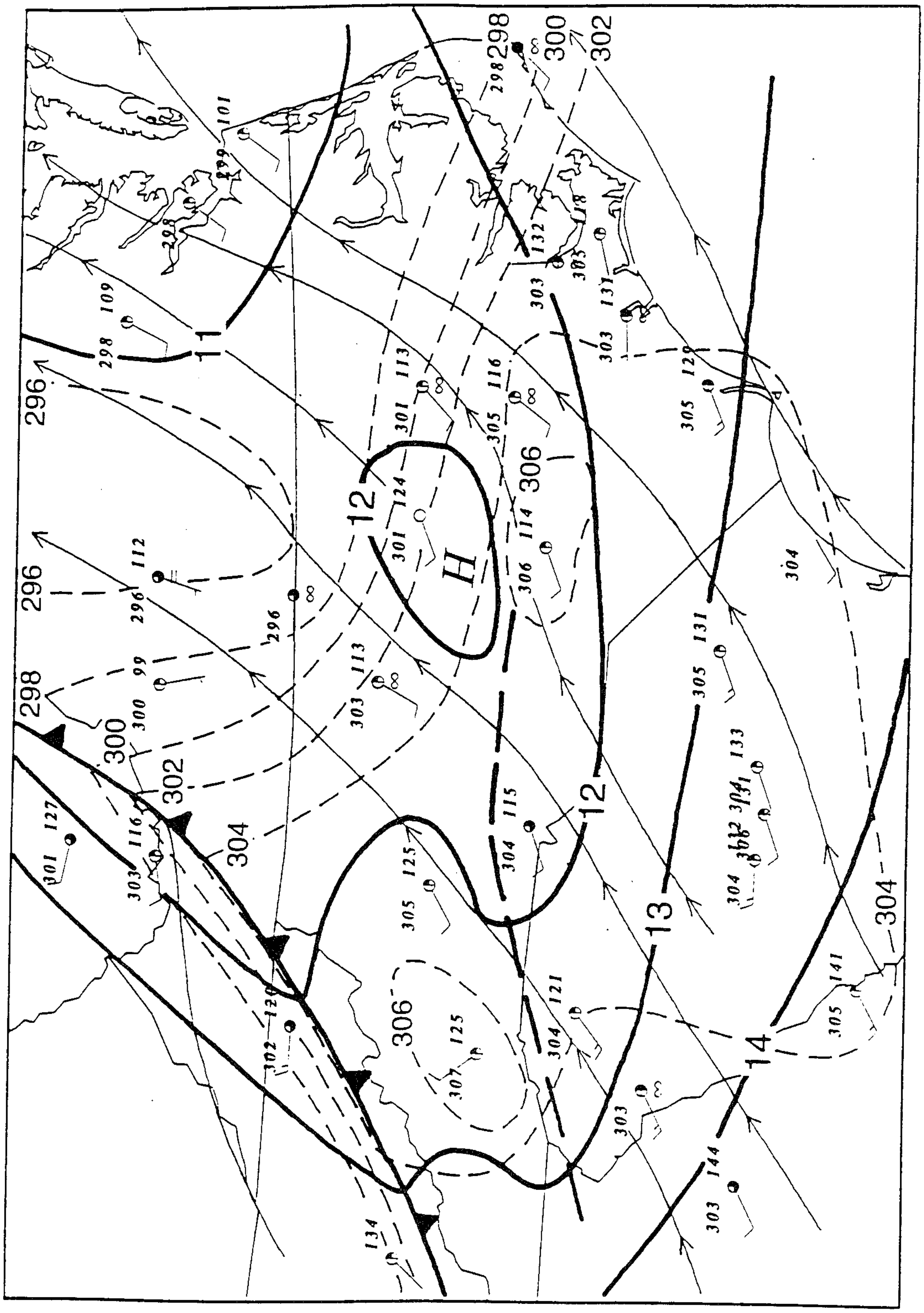


Figure 2.17. Same as Fig. 2.4 except for 1600 UTC 5 June 1993.

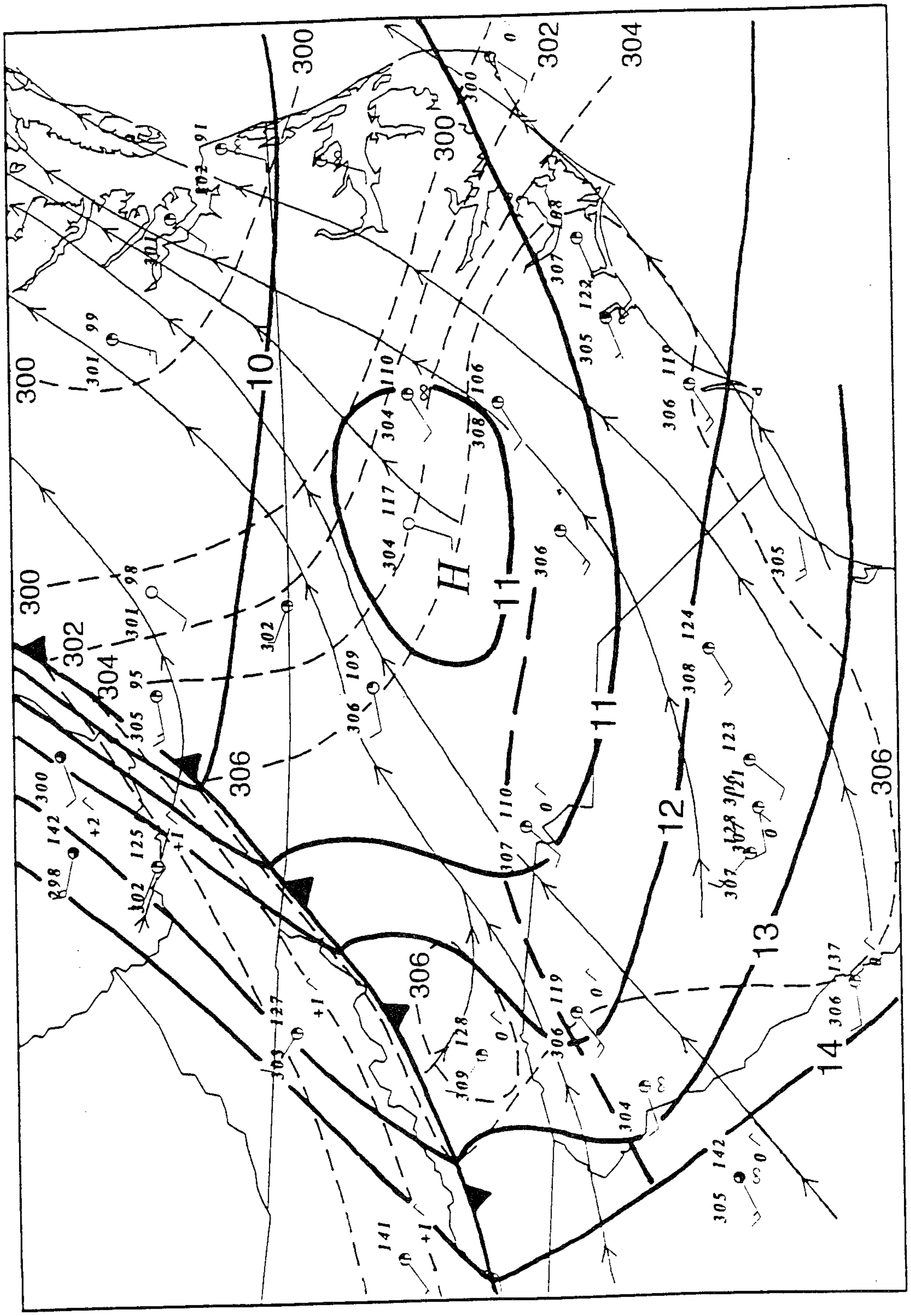


Figure 2.18. Same as Fig. 2.4 except for 1800 UTC 5 June 1993

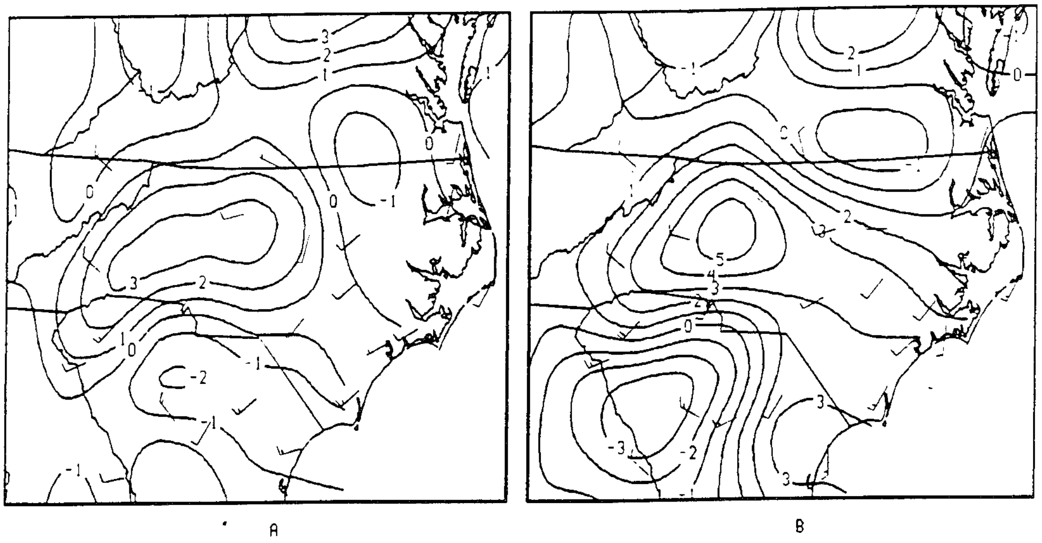
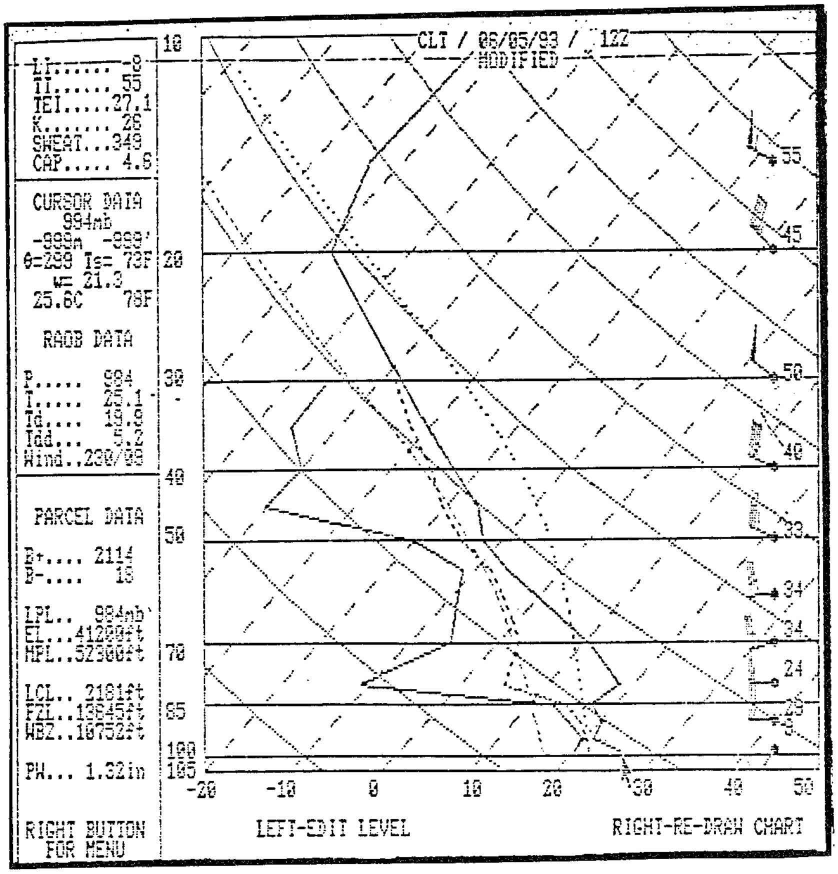


Figure 2.19. Same as Fig. 12 except for a)1800, b) 2000 UTC 5 June 1993



```
LI......  -8
TI......  55
TEI.....27.1
K.......  26
SWEAT...349
CAP..... 4.6

CURSOR DATA
  994mb
 -999m  -999'
θ=299 Ts= 73F
   W= 21.3
 25.6C    78F

RAOB DATA

P.....   994
T.....  25.1
Td....  19.9
Tdd...   5.2
Wind..230/09

PARCEL DATA

B+.... 2114
B-....   18

LPL..  994mb
EL...41200ft
MPL..52300ft

LCL..  2181ft
FZL..13645ft
WBZ..10752ft

PW... 1.32in
```

Figure 2.20. Same as Fig. 15 except lower 100 mb modified to reflect surface data from 1800 UTC 5 June 1993 at Charlotte, North Carolina.

Figure 2.21. Visible satellite imagery for 1900 UTC 5 June 1993.

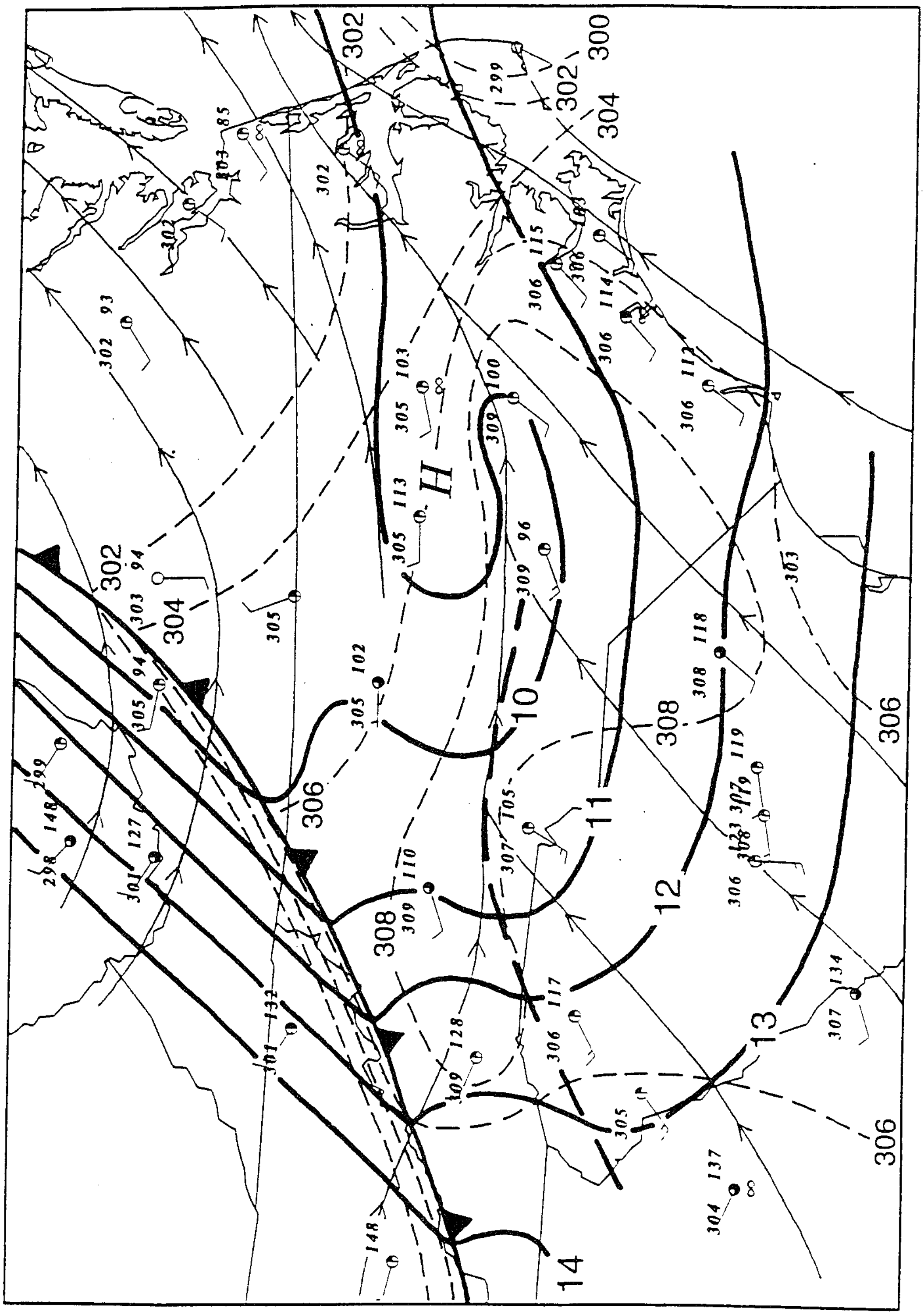


Figure 2.22. Same as Fig. 2.4 except for 1900 UTC 5 June 1993.

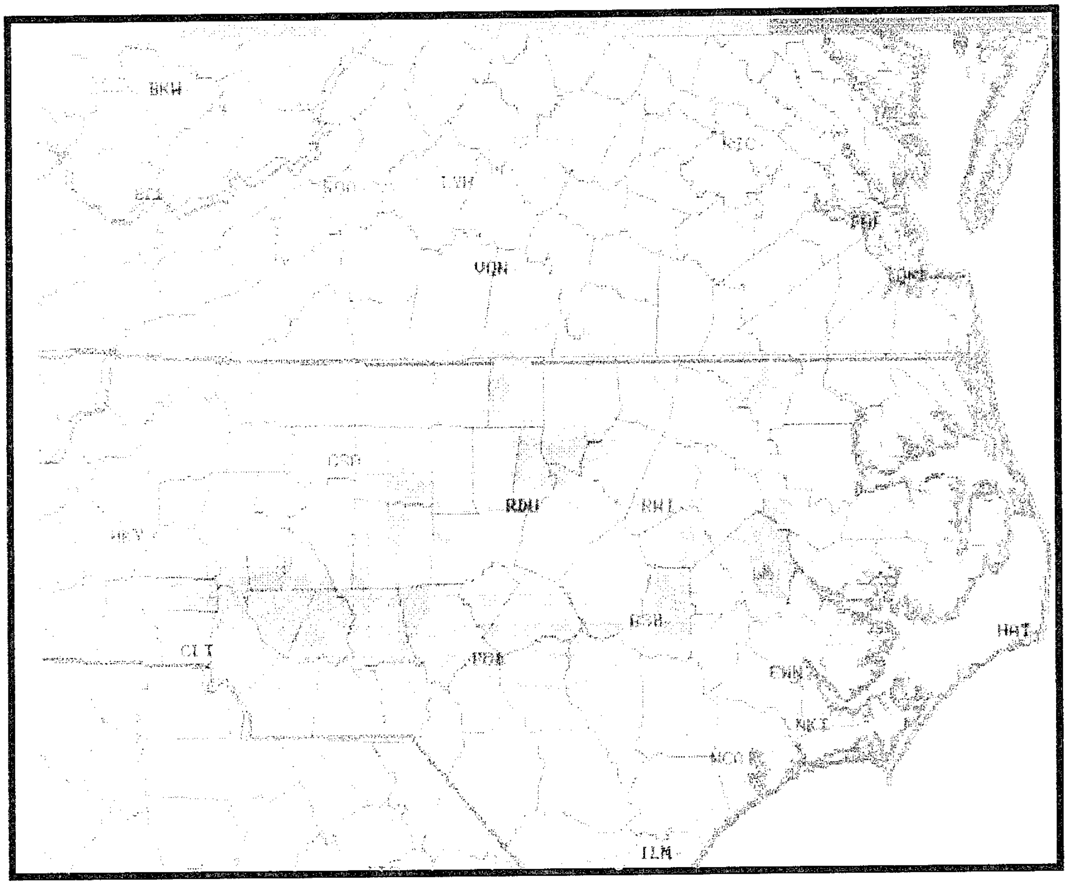


Figure 2.23. NOWRAD radar image for 2100 UTC 5 June 1993.

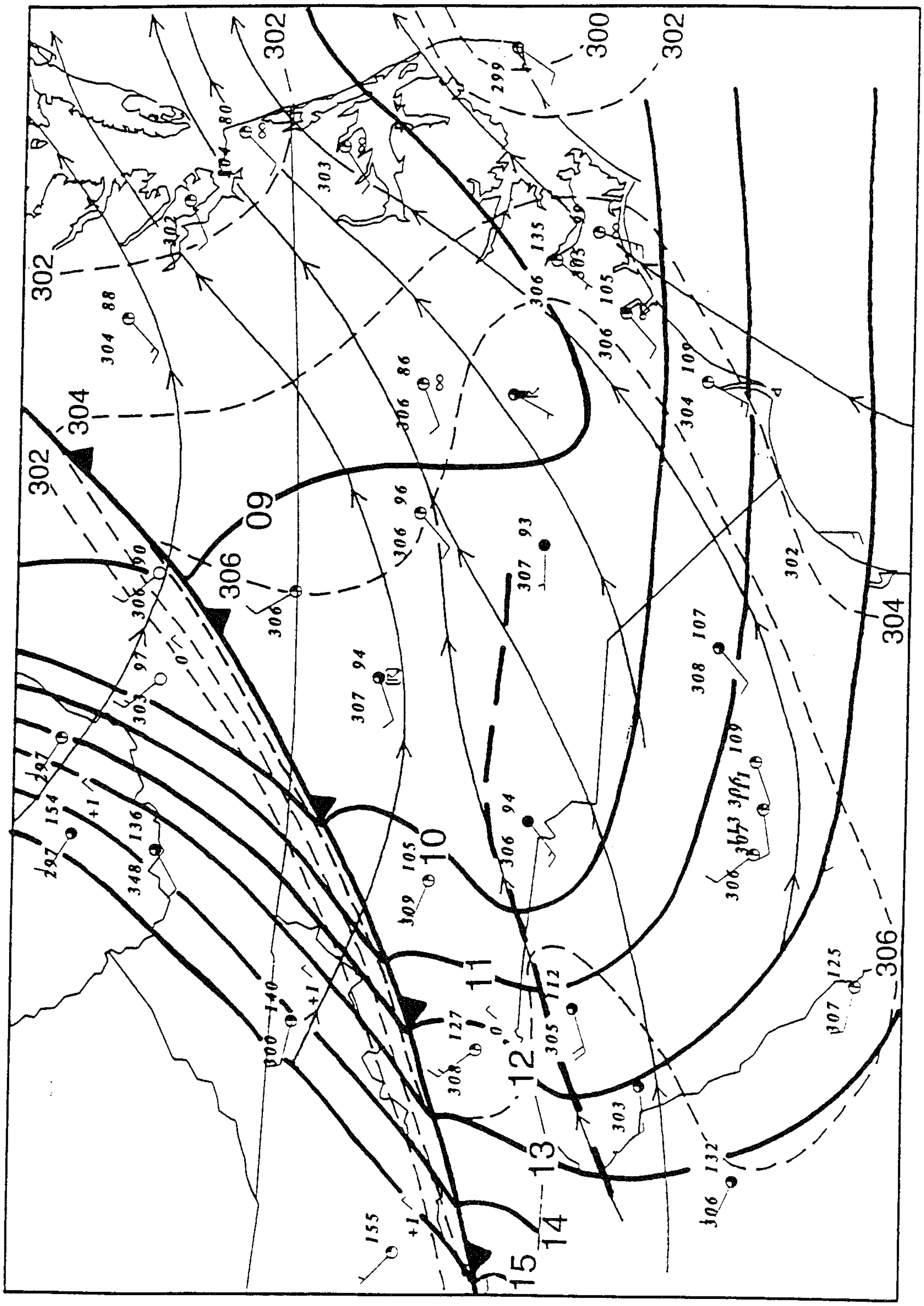


Figure 2.24. Same as Fig. 2.4 except for 2100 UTC 5 June 1993

Bibliography

Barnes, S.L., 1964: Atechnique for maximizing details in numerical weather map analysis. *J. Appl. Meteor.*, **3**, 396-409.

_____, 1973: Mesoscale objective map analysis using weighted time-series observations. *NOAA Technical Memorandum ERL NSSL-62*, Norman, OK, 60 pp.

Burgess, D.W., and B.F. Smull, 1990: Doppler radar observations of a bow echo associated with a long track severe windstorm. Preprints, *16th Conf. Severe Local Storms*, Kananaskis Park, Alberta, Canada, Amer. Meteor. Soc., 203-208.

Daniels, R. B., H.J. Kleiss, S. W. Buol, H. J. Byrd, and J. A. Phillips, 1984: Soil systems in North Carolina. North Carolina Agricultural Research Service , Bulletin 467.

Doswell, C.A., III, R. Davies-Jones, and D.L. Keller, 1990: On summary measures of skill in rare event forecasting based on contingency tables. *Wea. Forecasting*, **5**, 576-585.

Duke, J. D., and J. A. Rogash, 1992: Multiscale review of the development and early evolution of the 9 April 1991 derecho. *Wea. Forecasting*, **7**, 623-635.

Fawbush, E. J., and R. C. Miller, 1953: A method for forecasting hailstone size at the earth's surface. *Bull. Am. Meteor.* Soc., **34**, 235-244.

Fujita, T. T., 1963: Analytical mesometeorology: A Review. In *Severe Local Storms*, Meteor. Monogr. **5**(27), American Meteorological Society, Boston, 77-125.

Fujita, T.T., 1981: Tornadoes and downbursts in the context of generalized planetary scales. *J. Atmos. Sci.*, **38**, 1511-1534.

Galway, J. G., 1956: The lifted index as a predictor of latent instability. *Bull. Amer. Meteor. Soc.*, **37**, 528-529.

Hart, J. A., and J. Korotky, 1990: The SHARP Workstation v1.50. NOAA, NWS Eastern Region, unpublished report.

Johns, R. H., and W. D. Hirt, 1987: Derechos: widespread convectively induced windstorms. *Wea. Forecasting*, **2**, 32-49.

______, and C. A. Doswell, 1992: Severe local storms forecasting. *Wea. Forecasting*, **7**, 588-612.

_____, and P.W. Leftwich, Jr., 1988: The severe thunderstorm outbreak of July 28- 29 1986... A case exhibiting both isolated supercells and a derecho producing convective system. Preprints, *15th Conf. Severe Local Storms*, Baltimore, Amer. Meteor. Soc., 448-451.

____, K.W. Howard, and R.A. Maddox, 1990: Conditions associated with long lived erechos- An examination of the large scale environment. Preprints, *16th Conf. Severe Local Storms*, Kananaskis Park, Alberta, Canada, Amer. Meteor. Soc., 4 08-412.

____, 1993: Meteorological parameters associated with bow echo development in convective storms. *Wea. Forecasting*, **8**, 294-299.

Kessler, E., ed., 1982: Thunderstorms: a social, scientific, and technological documentary Vol. 2, thunderstorm morphology and dynamics.

Keeter, K. K., S. Businger, L. G. Lee, and J. S. Waldstreicher, 1995: Winter weather forecasting throughout the eastern United States. Part III: The effects of topography and the variability of winter weather in the Carolinas and Virginia. *Wea Forecasting*, **10**, 42-60.

Knight, C. A., and P. Squires, Ed., 1982: Hailstorms of the Central High Plains, Vol. 1. Co. Assoc. Univ. Press, 12.

McCumber, M. C., and R. A. Pielke, 1981: Simulation of the effects of surface fluxes of heat and moisture in a mesoscale numerical model. Part I: Soil layer. *J. Geophys. Res.*, **86**, 9929-9938

Mueller, C. K., Wilson, J. W., and N. A. Crook, 1992: The utility of sounding and mesonet data to nowcast thunderstorm initiation. *Wea. and For.*, **8**, 132-145.

Purdom, J. F. W., 1976: Some uses of high-resolution GOES imagery in the mesoscale forecasting of convection and its behavior. *Mon. Wea. Rev.*, **104**, 1474-1483.

______, and J. F. Weaver, 1982: Nowcasting during the 10 April 1979 tornado outbreak: A satellite perspective. Preprints, 12th Conference on Severe Local Storms, San Antonio, American Meteorological Society, Boston, 467-470.

Przybylinski, R.W., and D.M. DeCAire, 1985: Radar signatures associated with the derecho, a type of mesoscale convective system, Preprints, *14th Conf. Severe Local Storms*, Indianapolois, Indiana, Amer. Meteor. Soc., 171-174.

____, and W. J. Gery, 1983: The reliability of the bow echo as an nimportant severe weather signature. Preprints, *13th Conf. On Severe Local Storms*, Tulsa, OK, Amer. Meteor. Soc., 270-273.

____, 1995: The bow echo: observations, numerical simulations, and severe weather detection methods. *Wea. Forecasting*, **10**, 203-218.

Schmidt, J.M. C.J. Tremback, and W.R. Cotton, 1990: Numerical simulations of a derecho event: Synoptic and mesoscale components, Preprints, *16th Conf. Severe Local Storms*, Kananaskis Park, Alberta, Canada, Amer. Meteor. Soc., 422-427.

Showalter, A.K., 1953: A stability index for thunderstorm forecasting. *Bull. Amer. Meteor. Soc.*, **34**, 250-252.

Smith, B.E., 1990: Mesoscale structure of a derechoproducing convective system: The southern great plains storm of May 4, 1989. Preprints, *16th Conf. Severe Local Storms*, Kananaskis Park, Alberta, Canada, Amer. Meteor. Soc., 455-460.

Smull, B.A., and R.A. Houze, 1987: Rear inflow in squall lines with trailing stratiform precipitation. *Mon. Wea. Rev.*, **115**, 2869-2889.

Weaver, J. F., 1979: Storm motion as related to boundary-layer convergence. *Mon. Wea. Rev.*, **107**, 612-619.

Weisman, M.L., 1990: The numerical simulation of bow echoes. Preprints, *16th Conf. Severe Local Storms*, Kananaskis Park, Alberta, Canada, Amer. Meteor. Soc., 428-433.

_____, J.B. Klemp, and R. Rotunno, 1988: Structure and evolution of numerically simulated squall lines. *J. Atmos. Sci.*, **45**, 1990-2013.

_____, R. Rotunno, and J.B. Klemp, 1990: The role of rear inflow jets in the production of long lived meso-convective systems. Preprints, *16th Conf. Severe Local Storms*, Kananaskis Park, Alberta, Canada, Amer. Meteor. Soc., 652-657.

Weisman, R. A., 1990: An observational study of warm season southern Appalachian lee troughs. Part I: Boundary layer circulation. *Mon. Wea. Rev.*, **118**, 950-962.

Wilson, J. W., and C. K. Mueller, 1993: Nowcasts of thunderstorm initiation and evolution. *Wea and For.*, **8**, 113-131.

______, and W. E. Schreiber, 1986: Initiation of convective storms by radar-observed boundary layer convergent lines. *Mon. Wea. Rev.*, **114**, 2516-2536.

ABSTRACT

KREIS, KIMBERLY WILLIS. Synoptic and Mesoscale Severe Weather : A Two Day Case Study of a Derecho and Local Hailstorms. (Under the direction of Allen J. Riordan.)

A case study was conducted on the evolution and damage path of the 4 June 1993 derecho and several severe hailstorms in central North Carolina that occurred the following day. Both events produced significant damage. Wind damage from the derecho totaled over 60 million dollars in Virginia alone. The following day, hailstones greater than three inches fell on China Grove, North Carolina causing at least three million dollars in damage there, and six hundred thousand dollars elsewhere in North Carolina.

The synoptic environment over the initiation area of the 4 June 1993 derecho compares favorably to those already documented for warm season derechos. The convective system resembled a warm season progressive derecho. The derecho appeared to originate in a band of thunderstorms that developed in southwestern Missouri and Kansas. The bow echo squall line associated with the storm developed many signature features such as weak echo channels and bookend vortices. An extensive arrow echo developed in western Kentucky and is compared to the much smaller warm advection wings seen in the type II derecho radar signatures (Przybylinski and DeCaire, 1985). One preexisting thunderstorm crossed the Appalachians ahead of the derecho and rapidly intensified into a strong convective cell. This storm continued to track ahead of the derecho along the stationary front. Several other cells developed between the

derecho and the leading convective cell. These storms resemble the downwind convective cells also seen in the type II derecho radar signature.

Severe hailstorms developed in central North Carolina on 5 June 1993 and seemed to have originated near an intense thermal boundary that was the remains of the derecho outflow boundary. This thermal boundary extended from the foothills to off the North Carolina coast. The pressure field apparently responds to the thermal forcing with troughing in and around the thermal boundary throughout the evening and early morning. A persistent convergence zone aligned with the trough. This combination of thermal boundary, convergence boundary, and pressure trough are referred to as the sandhills boundary.

A slow moving cold front approaching the Appalachian mountains seemed to affect both the wind and pressure fields. A prefrontal trough interacted with the pressure field associated with the sandhills boundary changing its orientation. With diurnal destabilization the interaction of the lee side trough and the increased convergence with the sandhills boundary initiated the convection which led to the large hail event. Thermodynamic soundings present very classic signatures for severe hailstorm development.