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AN INVESTIGATION OF THE 4 FEBRUARY 1995 NORTHEASTERN SNOWSTORM AND A RESULTING SNOWFALL MAXIMUM IN THE LOWER PART OF THE DELAWARE RIVER VALLEY

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1. INTRODUCTION

On 4 February 1995, a significant snowstorm affected a large part of the northeastern United States. One of the resulting snowfall maxima extended across parts of central Bucks County in southeastern Pennsylvania, and extreme southern Hunterdon County and northern Mercer County in west central New Jersey (Figure 1). The greatest totals reported were 16 inches at Princeton, New Jersey (Mercer County), and 15 inches at Doylestown, Pennsylvania (Bucks County). Philadelphia International Airport (PHL) received 8.8 inches of snow. The effects of the event were lessened by the fact that the heaviest of the precipitation occurred late on a Friday night into the early part the weekend. However, like many snowstorms that influence the northeastern megalopolis, it had a significant financial impact and created a great deal of inconvenience for area residents (Maglaras et al. 1995).

Computer model forecasts and the conditions prior to, and during, the storm will be reviewed. An examination of the model forecasts will focus on the 1200 UTC February 3, 1995 (hereafter referred to as 03/1200) aviation run of the global spectral model (AVN). This will be followed by an investigation of the evolution of the surface and upper air features, and the development of the heavy snow event. Finally, mesoscale and terrain effects in the study area will be considered in the hope of arriving at an explanation for the location of the snowfall maximum. In this paper, the term "study area" will refer to the lower part of the Delaware River valley around the cities of Trenton, New Jersey (TTN) and Philadelphia (PHL).

2. NUMERICAL MODEL FORECASTS

The AVN was chosen over the Nested Grid Model (NGM) and the Eta model for the following reasons: first, the PC-GRIDDS (PC-Gridded Interactive Display and Diagnostic System) data set for the AVN has the greatest horizontal resolution; second, the AVN handled the overall event somewhat better than the NGM; and third, data from the Eta model was unavailable for the period of interest (04/0600 to 04/1200).

a. Conventional Parameters

The 03/1200 run of the AVN indicated that a surface low with a central pressure of 1002 mb would be centered over eastern Kentucky at 04/0000, filling overnight as it moved to the northeast. The model then forecast the development of a secondary low near the coast of the Delmarva Peninsula by 04/1200. At 500 mb, a trough was forecast to extend from Lake Superior to Mississippi on the evening of February 3, and was expected to take on a negative tilt during the night as it amplified. By 04/1200, the trough axis was expected to extend from Michigan to Georgia.

The 0° C isotherm at 850 mb was projected to extend from the Ohio River Valley, across West Virginia and southern Virginia, to near the mouth of the Chesapeake Bay at 04/0000. Temperatures at 850 mb over the study area were forecast to be about -6° C. The model indicated that warm air advection would take place at that level during the night, bringing the 0° C isotherm north to Wilmington, Delaware (ILG) by 04/1200.

The AVN indicated that there would be an 850 mb wind maximum of 40-45 kt over the Great Plains, on the back side of a trough, at 04/0000. The forecast wind maximum also extended around the base of the trough, and up into the central Appalachians. With the trough forecast to deepen, the wind speeds were expected to strengthen on its east side. The model indicated that, by 04/1200, a wind maximum of approximately 60 kt would extend over the ocean waters, from about 200 mi east of Wilmington, North Carolina (ILM), north to about 50 mi east of Ocean City, Maryland. Meanwhile, a 100-kt jet maximum at 300 mb was forecast to extend from southern Pennsylvania eastward over the ocean at 04/0000. By 04/1200, the model showed that the initial jet would move well to the east and that a 110-120 kt jet streak would round the base of the 300 mb trough during the night. The jet would extend along the southeast and mid-Atlantic coasts by 04/1200, placing the study area under its left front quadrant, an area of enhanced vertical motion associated with a transverse ageostrophic circulation (Keyser and Shapiro 1986; Moore and VanKnowe 1992).

The AVN predicted light snow would be falling throughout the study area by 04/0600, with liquid precipitation totals reaching 0.5 - 0.6 inches by 04/1200. For the following 6-hour period it showed an additional 0.4 - 0.7 inches in the study area. The forecast storm total at PHL was 1.1 inches.

b. Conditional Symmetric Instability (CSI)

One of the many uses of PC-GRIDDS involves the diagnosis of areas that may be favorable for conditional symmetric instability (CSI), or "slantwise" convection (Emanuel 1983). CSI typically results in mesoscale banding of moderate to heavy precipitation that may occur north of an approaching warm front (Grumm and Forbes 1994). The procedure used in this study to determine CSI potential involved two steps (Moore and Lambert 1993; Browning and Foster 1995). First, a cross section was taken through the study area, perpendicular to the forecast 1000-500 mb thickness lines for 04/1200 (Figure 2). Second, contours of angular momentum (m s^{-1}) and theta-e (K) were overlaid on the cross section. The resulting product was then examined to determine if an area existed in which the slope of the theta-e isotherms was greater than that of the contours of angular momentum (Figure 3). This would indicate that the atmosphere was expected to be unstable with respect to saturated, slantwise displacements (Bluestein 1993).

The cross section shows that the region with the greatest potential for CSI during the period of interest was an area between 40° North latitude, which runs through the city of Philadelphia, and 41° North latitude, which extends through Westchester County, New York, extreme northern New Jersey, and into the Pocono Mountains of eastern Pennsylvania. Actually, the model indicated a region of concern extending north from the developing coastal low all the way up to near the northern border of Pennsylvania (42° North latitude). Output from the 04/0000 AVN (not shown) supported the forecast of the previous run regarding the potential for CSI.

3. ANTECEDENT CONDITIONS

At 04/0000, a 1002 mb surface low was located over eastern Kentucky, with a trough extending east northeast into West Virginia (Figure 4). The greatest surface pressure falls in the region were centered over western Pennsylvania, eastern Kentucky, and north central North Carolina and south central Virginia. The isallobaric pattern suggested that the low would move toward western Pennsylvania and that a trough would develop over or near the piedmont of North Carolina and Virginia.

By 04/0600, the surface low had moved to north central West Virginia with a central pressure of 1000 mb. A trough had begun to develop well to its east, extending northeast from the piedmont of North Carolina across the central part of the Chesapeake Bay to extreme southern New Jersey. A maximum pressure fall of 8.1 mb over 3 hours was located at Richmond, Virginia (RIC), indicating the development of a secondary low.

By 04/1200, the low over the central Appalachians had filled, while the secondary low, now slightly east of the southern Delmarva Peninsula, had deepened to 992 mb (Figure 5). As the morning progressed, the secondary low intensified off the New Jersey coast as it moved to the northeast.

Surface temperatures in the study area averaged around 30°F just prior to the onset of the snow late on February 3, and dew points were around 10°F. Evaporative cooling caused temperatures to fall quickly into the mid-20s (°F), then they recovered to around 32°F by daybreak on February 4. The 850 mb temperatures over the study area at 04/0000 were around -8°C. Strong warm air advection took place during the next 12 hours, and by 04/1200 the temperature at 850 mb rose to about -1°C. At that time the rain-snow line in southern New Jersey coincided fairly well with the 850 mb 0°C isotherm. The 03/1200 AVN's 850 mb temperature forecast for the morning of February 4 verified quite well for the study area and its vicinity.

At 04/0000, an 850 mb wind maximum of 45 kt extended from western Minnesota to northern Arkansas, on the back side of the trough. Wind speeds of 30-40 kt extended around the base of the trough and up into the central Appalachians as far north as south central Pennsylvania, the eastern extent of the snow at that time. As the trough moved east during the night, a 60-kt wind maximum at 850 mb developed along the coast. At 04/1200, this maximum extended from around Wilmington, North Carolina to the mouth of the Delaware Bay, farther west than the AVN had forecast.

Within the study area, the increase in upper level winds was detected by the Weather Surveillance Radar-88 Doppler (WSR-88D) located at Fort Dix, New Jersey (KDIX). At approximately 850 mb (4000-5000 ft), the radar detected a southerly wind of 20-30 kt at 04/0600, with little change during the following 3-4 hours (not shown). By 04/1030, the wind at that level became more southeasterly, and increased to 35-40 kt. The wind profile also showed that the wind direction began to veer significantly with height between 3000 and 6000 ft, an indication of strong low-level warm advection.

Based on the 300 mb analysis for 04/1200, the study area was apparently under the left rear quadrant of a 125-kt jet streak during the period of heaviest snow, from 04/0800 to 04/1200, which would have enhanced upward motion, and subsequently, the snowfall accumulations (Manuel and Rolinski 1995). The initial analysis from the 04/1200 run of the NGM (not shown) also indicated strong upward motion at 700 mb.

4. EVOLUTION OF THE SNOW EVENT

By 04/0000, the leading edge of the snow had already reached south central Pennsylvania and central Maryland. The snow overspread the study area between 04/0100 and 04/0300. During the early morning of February 4 there were two periods of heavy snow at PHL, each lasting from 1 to 2 hours, and thunder was reported at Maguire Air Force Base (WRI) near Wrightstown, New Jersey at 04/0955.

The reflectivity data from the WSR-88D at KDIX was quite intriguing. Between 04/0600 and 04/1100, the radar detected five distinct mesoscale bands of moderate to heavy precipitation, all of which drifted from south to north. The bands paralleled the thermal wind in the 1000-500 mb layer, maintaining a general east-to-west orientation across New Jersey and bending to the southwest as they extended into Pennsylvania. The bands were well organized and they occurred in a region which was shown to be conducive to CSI (Figure 3). The most well-defined band was the fourth (Figure 6), which reached PHL around 04/0800, coinciding with the onset of heavy snow at that location. The isolated report of thunder was associated with the fifth band.

With the development of the secondary low and the resulting strong onshore flow over New Jersey, the rain-snow line narrowed and quickly progressed inland, as often occurs with secondary development (Gurka et al. 1995). The change to rain occurred at PHL at 04/1158 and at TTN shortly after 04/1300. Light rain continued in the study area until around 04/1700, when it changed over to snow showers with little or no additional accumulation.

Snowfall totals in and around the study area ranged from about 8 to 16 inches. Water equivalent values generally ranged between 0.8 and 1.5 inches, in line with the 03/1200 forecast run of the AVN. Additional storm precipitation totals are listed in Table 1 (U.S.

Department of Commerce 1995).

5. MESOSCALE AND TERRAIN EFFECTS

As numerical model forecasts continue to improve, forecasters are able to focus more attention on mesoscale events; for example, why did the heaviest of the snow fall where it did in this event? The answers may lie in an examination of the combined effects of the orientation of the CSI-induced snow bands and the area's topography (Keeter et al. 1995).

As stated earlier, the CSI bands extended from east to west across New Jersey. As the bands drifted to the north through the southern and central parts of the state, moisture was drawn directly off of the ocean in the lowest layers of the atmosphere. The moist air then crossed relatively flat terrain before encountering the fall line (the boundary between the coastal plain and the piedmont, extending through the northwestern part of the city of Philadelphia, and continuing northeast to Trenton and New Brunswick, New Jersey). The rise in elevation across the fall line likely enhanced the precipitation in locations to its immediate west. This area includes both Princeton, New Jersey and Doylestown, Pennsylvania, the sites of the greatest snowfall reports. In addition, the bands moved into colder air while progressing north, which would have resulted in a greater snow-to-liquid ratio. If these were the only important factors in explaining the heavy snowfall, one would have expected a continued increase in snowfall amounts up into the hills of north central and northeastern New Jersey. However, this did not take place.

An abrupt change in the surface features along the length of the snow bands offers an explanation for the slight decrease in snowfall amounts to the north and northeast of the maximum. As the CSI bands moved over northern New Jersey, they began to be drawn across Long Island, New York, and moisture was no longer coming directly off of the Atlantic in the lowest layers of the atmosphere. Also, at this latitude the fall line is farther east and very near the ocean, crossing Staten Island and western Long Island, New York. On Staten Island, terrain of about 300-400 ft above sea level exists within just a few miles of the ocean. With this in mind, one might initially expect the maximum to shift to the east; however, the infusion of warmer marine air at that point would likely have caused a decrease in the snow-to-liquid ratio. As a result, it seems the maximum in the lower part of the Delaware River valley occurred at a location where the elements of topography, temperature, and moisture availability combined most efficiently to enhance the snowfall totals.

6. CONCLUSION

As is the case with all winter storms affecting densely populated areas, the most difficult and important aspects of the forecast are the timing, the precipitation type, and the precipitation amounts. Based on climatology, "nor'easters" such as this one (moving off the coast near the Delmarva Peninsula), tend to be heavy snow producers for areas from the Pocono Mountains of eastern Pennsylvania, northeast into the mountains of New England. While heavy snow did fall in those usual locations, the equally significant snowfall totals in the study area were not initially anticipated. This suggests that other factors, such as the mesoscale banding of precipitation and its interaction with the local terrain, played a role in enhancing the snowfall amounts.

There continues to be a great deal of uncertainty in the prediction of snowfall totals. Concepts such as CSI have proven useful, and in this case the AVN's forecast of the potential for CSI was helpful. Nevertheless, it was not evident beforehand exactly where CSI bands would develop, or that the heaviest snow would fall in Bucks, Hunterdon and Mercer Counties. Additional studies of this storm, and others like it, will help in better understanding the intricacies involved in snow forecasting.

7. ACKNOWLEDGMENTS

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Table 1. Storm-total snowfall amounts and water equivalents for selected locations in and near the lower part of the Delaware River valley.

Location	County	Water Equivalent (inches)	Snowfall (inches)
Palm, PA	Montgomery	0.80	8.5
Springtown, PA	Bucks	1.06	10.0
Neshaminy Falls, PA	Bucks	0.96	12.5
Conshohocken, PA	Montgomery	1.25	12.0
Philadelphia, PA	Philadelphia	1.04	8.8
Mount Holly, NJ	Burlington	1.43	9.0
Hightstown, NJ	Mercer	1.14	11.8
New Brunswick, NJ	Middlesex	1.09	11.5
Somerville, NJ	Somerset	1.22	13.0
Flemington, NJ	Hunterdon	1.24	12.0

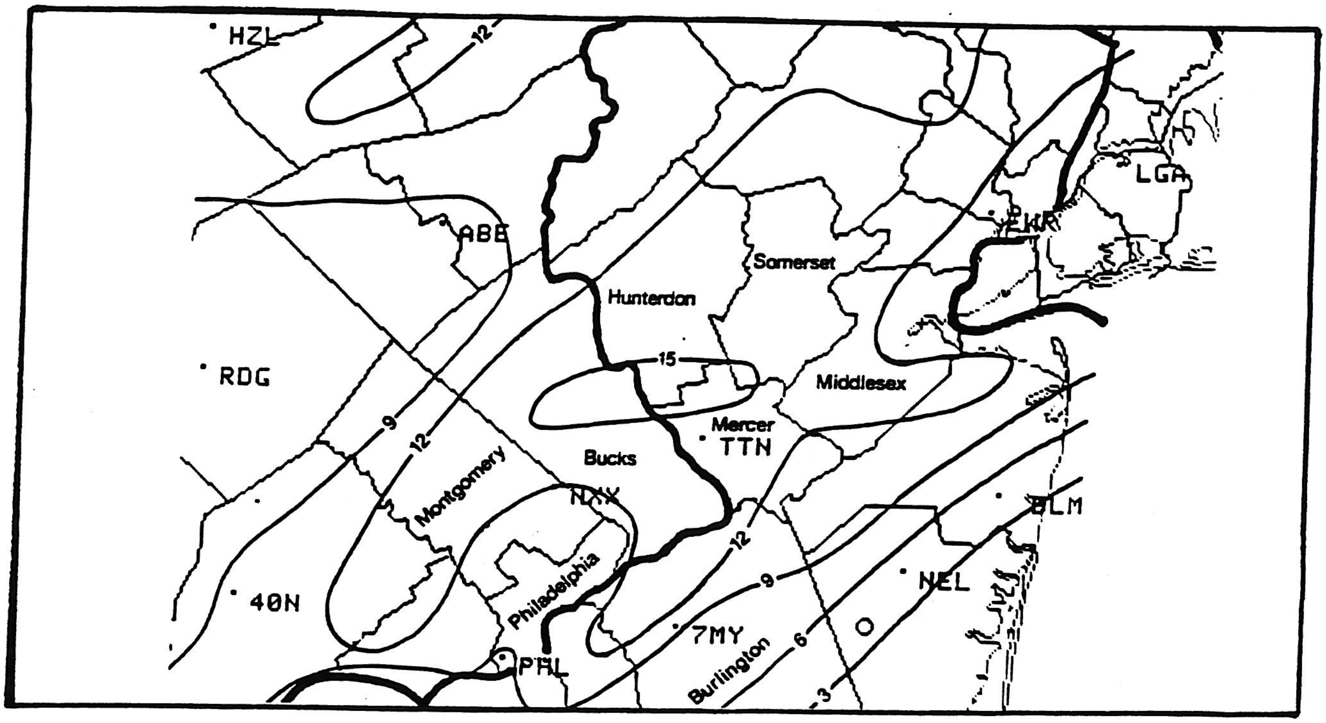

FIGURE 1. Snowfall totals for the February 4, 1995 storm. Contours every 3 inches (Based on an original analysis by Anthony F. Gigi, NWSFO Philadelphia, Pennsylvania).

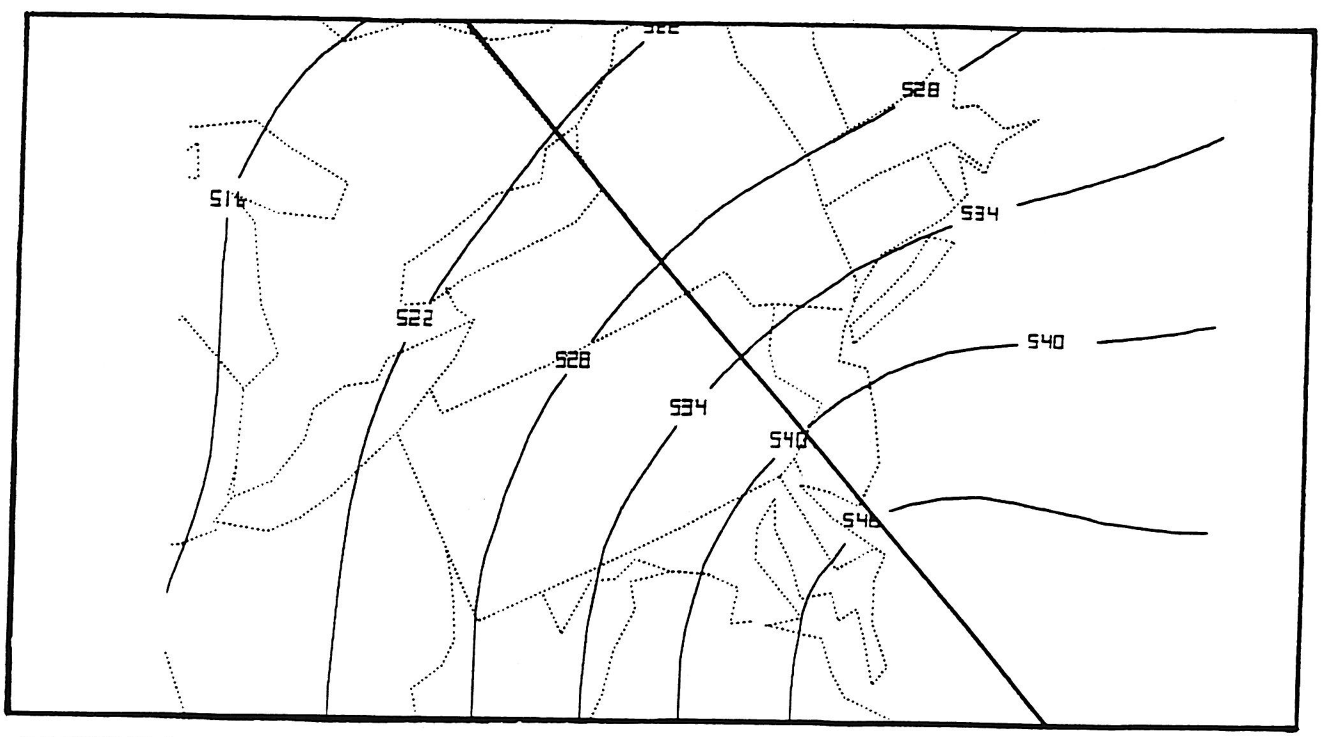

FIGURE 2. AVN 1000-500 mb thickness forecast valid for 1200 UTC February 4, 1995. Contours every 60 m. Cross section from 46°N-77°W to 35°N-74°W.

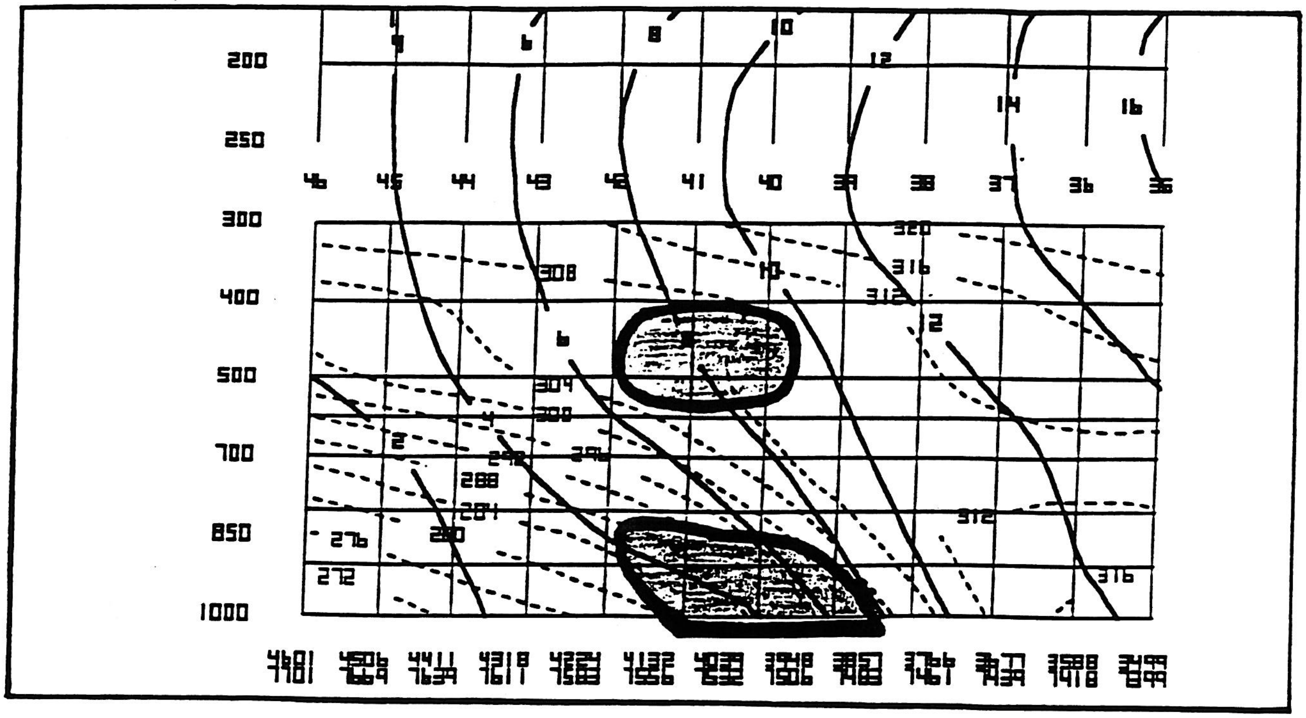

FIGURE 3. AVN forecast cross section of absolute angular momentum (m/s, solid) and theta-e (K, dashed) valid 1200 UTC February 4, 1995. Highlighted areas indicate CSI potential.

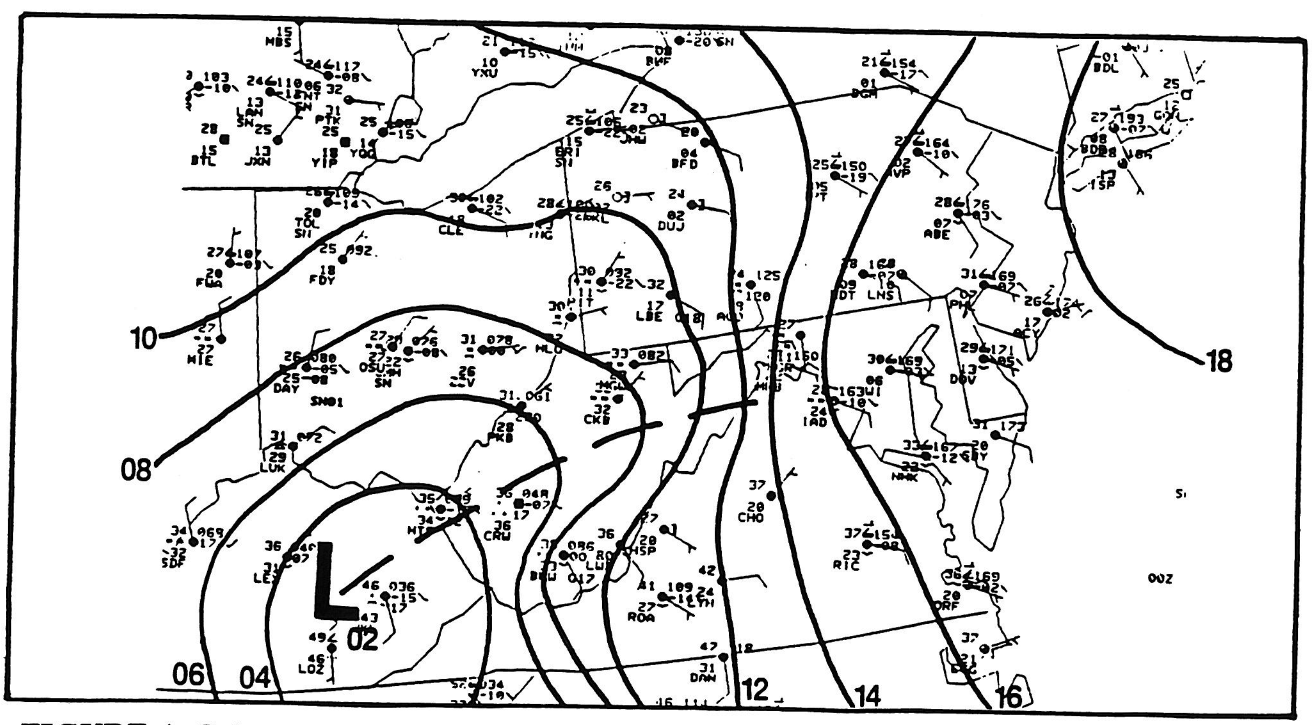

FIGURE 4. February 4, 1995 0000 UTC surface analysis. Isobars every 2 mb.

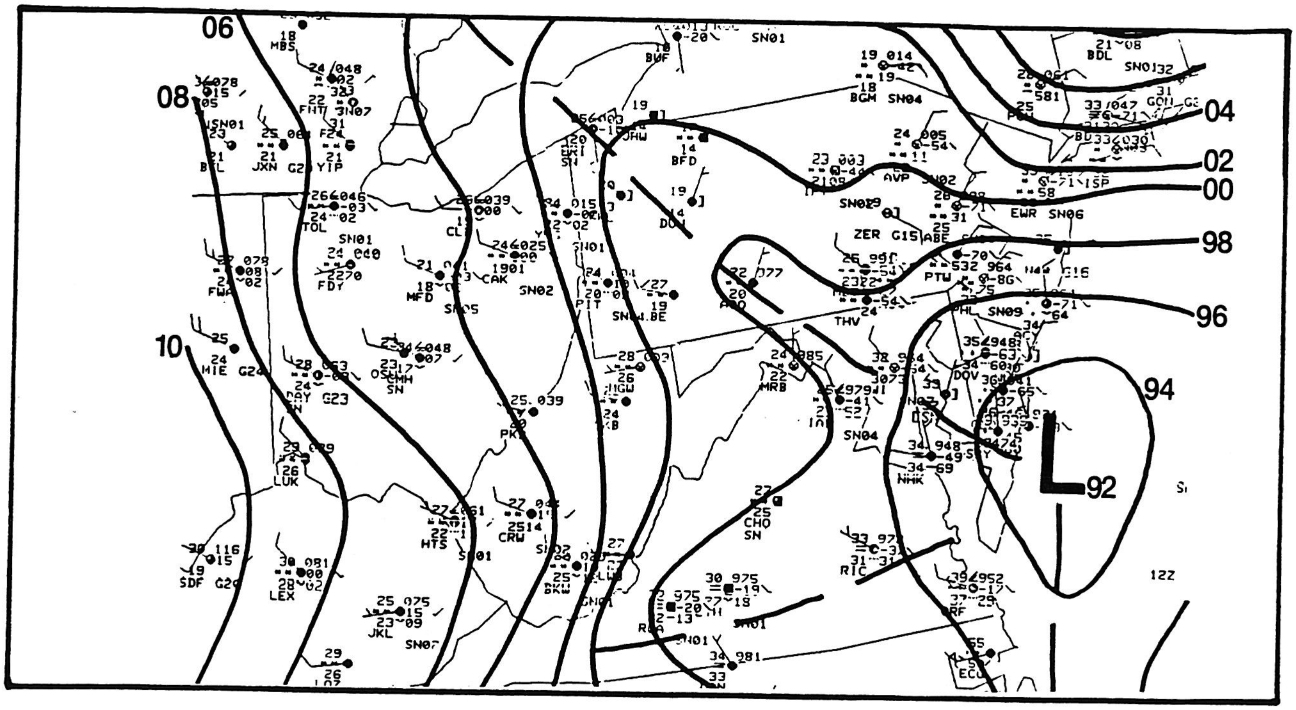

FIGURE 5. February 4, 1995 1200 UTC surface analysis. Isobars every 2 mb.

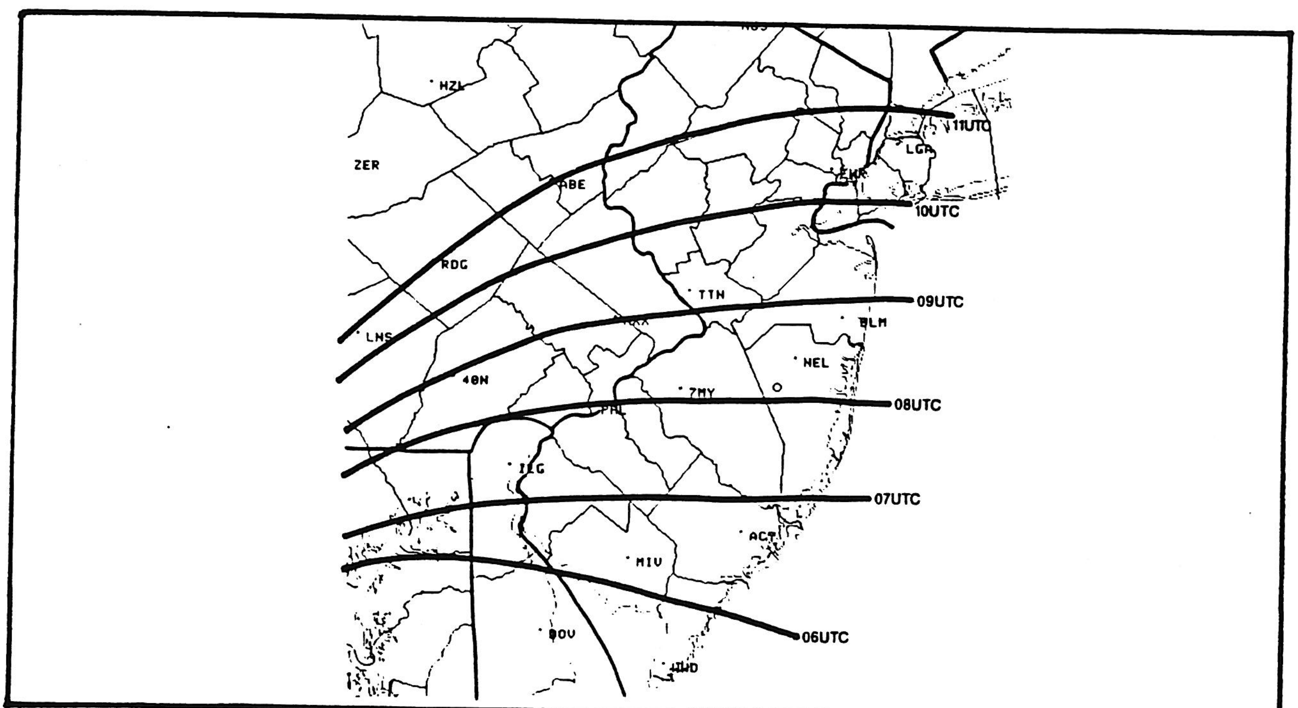

FIGURE 6. Northward progress of the center line of the fourth CSI band in one hour intervals from 0600 to 1100 UTC February 4, 1995.