

EAST COAST WINTER STORM: 4 FEBRUARY 1995

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Abstract

A winter storm developed along the east coast of the United States on 4 February 1995, producing a large area of heavy snow from near Washington, D.C. northward into northern New England. The three operational numerical weather prediction models from the NOAA/NWS National Centers for Environmental Prediction did a reasonable job in approximating the track and intensity of the surface cyclone. However, all three operational models forecast the cyclone to track farther west than the observed track. The forecast track error resulted in dynamic model forecasts of warmer air farther inland than was observed. Hence, the more eastward observed track of the cyclone produced a longer period of heavy snow over the major cities of the Northeast than the model forecasts suggested. This study adds to the knowledge of the capabilities and limitations of numerical weather prediction models that operational forecasters need to be aware of.

1. Introduction

Major east coast snowstorms are often associated with the interaction of the polar front jet, the subtropical jet, and warm moisture laden Atlantic air (Kocin and Uccellini 1990; Uccellini et al. 1984). Additionally, low-level cold air damming east of the Appalachian mountains can establish the necessary conditions to keep the precipitation from changing to rain and create a strong baroclinic zone along the East Coast (Riordan 1990). Frontogenetical forcing along this baroclinic zone often has a significant impact on the type and distribution of precipitation (Sanders 1986; Sanders and Bosart 1985). This coastal front often serves as an area where a surface low will track and rapidly deepen. Additionally, the coastal front often marks the boundary between rain and snow, with the heaviest snow just to the west (on the cold side) of the coastal front.

In classic east coast snowstorms, a strong surface anticyclone or ridge, relatively dry air that will support evaporative cooling, and downstream confluence in the upper troposphere (300 to 200 mb) are present over the northeastern United States (Kocin and Uccellini 1990). The confluence aloft is associated with an upper-level jet entrance region. The resulting ageostrophic circulations associated with the jet entrance region play a significant role in maintenance of low-level cold air along the eastern slopes of the Appalachian mountains. Additionally, many significant storms are associated with rapid cyclonic development which meet the "bomb" criteria (Sanders and Gyakum 1980).

Other factors that play a significant role in east coast snowstorms include a statically stable atmosphere, the local orographic effects of the Appalachian mountains, and the speed and track of the surface cyclone center. Generally, the faster the cyclone moves the less snow it will produce, and the more

westward the track of the cyclone center, the more likely it will allow warm Atlantic air to penetrate farther inland, changing the precipitation to rain. One critical aspect of using numerical weather prediction guidance to determine the likelihood of rain or snow is the track of the surface low. Coastal areas close to the cyclone track often ingest warm moist air from the western Atlantic.

The purpose of this study is to examine the meteorological and model forecast conditions that were associated with the east coast winter storm of 4–5 February 1995. This storm produced locally heavy snow (Fig. 1) from the Washington, D.C. area, northeastward across the Philadelphia, New York City, and Boston corridor, and interior sections of New York and New England. The fact that this storm impacted all the major metropolitan areas of the northeastern United States with heavy snow, would classify it as a major east coast snowstorm as defined by Kocin and Uccellini (1990). Most of the affected coastal cities received heavy snow, which eventually mixed with and/or changed to rain. The precipitation ended as snow in all the areas, as cold Arctic air moved in from the northwest behind the storm. Preliminary forecasts from the National Centers for Environmental Prediction (NCEP) short range forecast models suggested that many of the coastal cities would likely have snow mixed with rain and that the heaviest snow would occur farther inland. However, the axis of the heaviest snow occurred farther eastward than was originally forecast. In this study, it will be shown that model forecasts predicted the low center farther west than the observed track, which led to the forecast error in the location of the heaviest snow.

2. Methodology

The data used for this analysis included grid point data from the NCEP's three operational models. These include the stepped terrain model (Eta; Rogers et al. 1995; Black et al. 1994), the Nested Grid Model (NGM) output from the Regional Analysis and Forecast System (RAFS; Hoke et al. 1989), and the Aviation run of the global spectral model (AVN) component of the NCEP's Global Data Assimilation and Forecast System (GDAS), a description of which is given by Kanamitsu (1989). Gridded model data were available for the PC-Gridded Interactive Diagnostic and Display System (PC-GRIDDS), and the General Meteorological Package (GEMPAK; desJardines et al. 1991). The data for the AVN, 30 km Eta, and NGM were examined by using GEMPAK. Data from the 80 km run of the Eta model were examined by using PC-GRIDDS. The fields shown are similar to those used operationally at the Central Pennsylvania National Weather Service Office (NWSO CTP). Other meteorological data included observed surface and upper-air data obtained from The Pennsylvania State University (PSU) Meteorological system (Cahir et al. 1981).

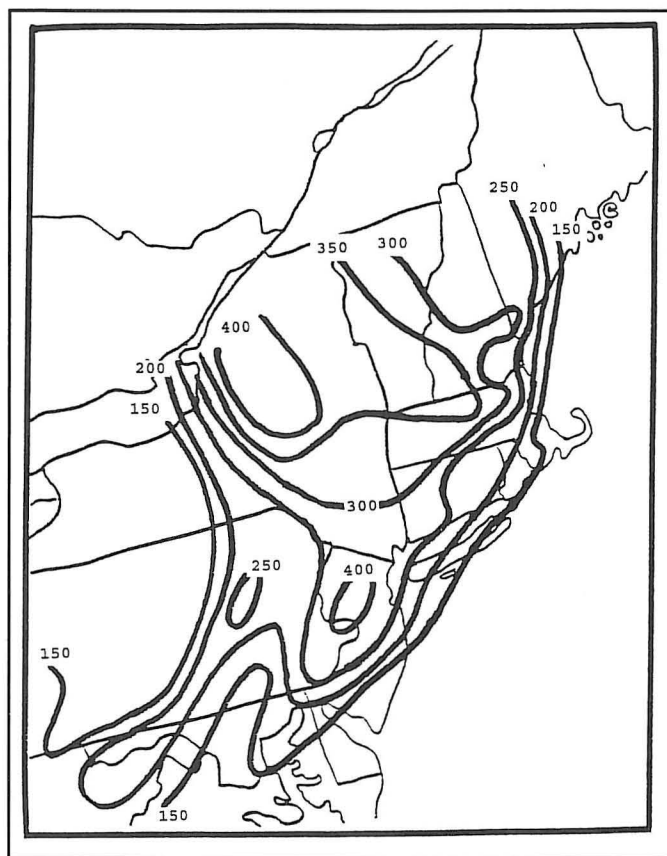


Fig. 1. Composite analysis of observed snowfall (mm). Data were derived from surface reports, cooperative observers, spotter reports, and SHEF observations. The contour interval is every 50 mm beginning at 150 mm.

The positions and track of the surface low were determined by analyzing synoptic and local scale surface charts. The synoptic scale charts revealed the origin of the surface low and were analyzed every 4 mb. The local area analyses were centered over Pennsylvania and analyzed every 2 mb. The latter charts were used to refine the position and central pressure of the surface cyclone.

In addition to these traditional data sources, the forecast and observed cyclone position, central pressure, 850 mb temperature, and 1000-500 mb thickness data for the NGM and AVN were obtained from the NCEP. These data were used to examine the systematic errors in cyclone central pressure and distance errors during the winter of 1994-95 (WI95), and for the month of February 1995 for comparison with this case. The geographic domain of the cyclones in these data sets encompass all of North America and the adjacent portions of the Atlantic and Pacific oceans (for the exact bounds, see Grumm and Siebers 1989). Unfortunately, data collection for the operational 80 km Eta was terminated on 1 January 1995. The December 1994 file was obtained for comparison purposes. The position of the model forecast cyclone tracks were obtained from these data and from 2 mb analysis on PC-GRIDDS.

Snowfall data were retrieved in real time from cooperative weather observers, snow spotter reports, and standard surface aviation observations (SAO's). Using the PSU Meteorological system, additional snowfall, snow depth, and precipitation data were obtained from Standard Hydrological Exchange Format

(SHEF) data. These data were manually analyzed to obtain subjective "ground truth."

3. Results

a. Overview

The upper-air pattern over North America was in a state of transition prior to the development of the 4-5 February 1995 storm. The mean 500 mb trough that had been present over the Pacific coast had retrogressed westward, while the mean ridge that had been in place over the eastern United States was located over western North America. A weak trough was present over eastern North America. A series of weak upper-level short waves had moved across the United States, lowering the 500 mb heights and deepening the upper-level trough over the western Atlantic. On 2 February, the third in a series of short waves moved over the ridge in the Pacific Northwest. This short wave was located over eastern Washington State at 1200 UTC 2 February (not shown) and moved into the western plains by 0000 UTC 3 February (Fig. 2a); it was located over southern Missouri at 1200 UTC 3 February (Fig. 2b). Another wave was over the southwestern North Atlantic at this time. This feature is best represented by the large scale jet entrance region over the southeastern United States and southwestern North Atlantic on 3 February (Figs. 3a and 3b). The first wave (not shown), which had produced snow over the mid-Atlantic States, had moved over the western North Atlantic. Each of these waves reinforced the trough and cold air along the east coast of the United States.

During the next 36 hours, the upper-level short wave that was located over northern Kansas and southern Nebraska (Fig. 2a) moved rapidly eastward across the Plains (Fig. 2b) and into the middle Mississippi Valley (Figs. 2c and 3c). This short wave reached the Atlantic coast by 1200 UTC 4 February 1995 (Fig. 2d and 3d). This short wave was responsible for the rapid cyclogenesis that occurred over the mid-Atlantic coast on 4 February 1995.

Three-hourly surface analyses beginning 1200 UTC 3 February through 0000 UTC 5 February, were constructed to track the position of the surface lows. The position of the manually analyzed surface cyclones beginning at 1200 UTC 3 February is shown in Fig. 4a. The corresponding manual surface analyses valid 1200 UTC 3 February, 0600 UTC 4 February, 1200 UTC 4 February, 1800 UTC 4 February, 0000 UTC 5 February, and 0600 UTC 5 February 1995 are shown in Figs. 5a-f, respectively. The initial surface low tracked from southeastern Missouri across Kentucky between 1200 UTC 3 February and 0300 UTC 4 February. A secondary low formed around 0600 UTC (Fig. 5b) along the border of North and South Carolina. This low moved northward to the North Carolina coast by 0900 UTC (Fig. 4a). By 1200 UTC, the surface observations suggested the presence of two surface lows (Fig. 5c). One low was located along the outer banks of North Carolina and the other low was at the mouth of Delaware Bay. Each low had an estimated central pressure of 992 mb. The western low, which maintained its identity as a closed circulation through 0900 UTC, was dissipating over the West Virginia Panhandle by 1200 UTC.

The coastal low tracked northeastward over the western North Atlantic between 1200 and 1800 UTC, was located south of Islip, NY (ISP) on Long Island by 1800 UTC (Fig. 5e) and crossed eastern Long Island at 2100 UTC (Fig. 4a). The low continued its northeastward track passing over eastern Long Island and was located over Boston, MA by 0000 UTC 5 February (Fig. 5f) with an estimated central pressure of 972

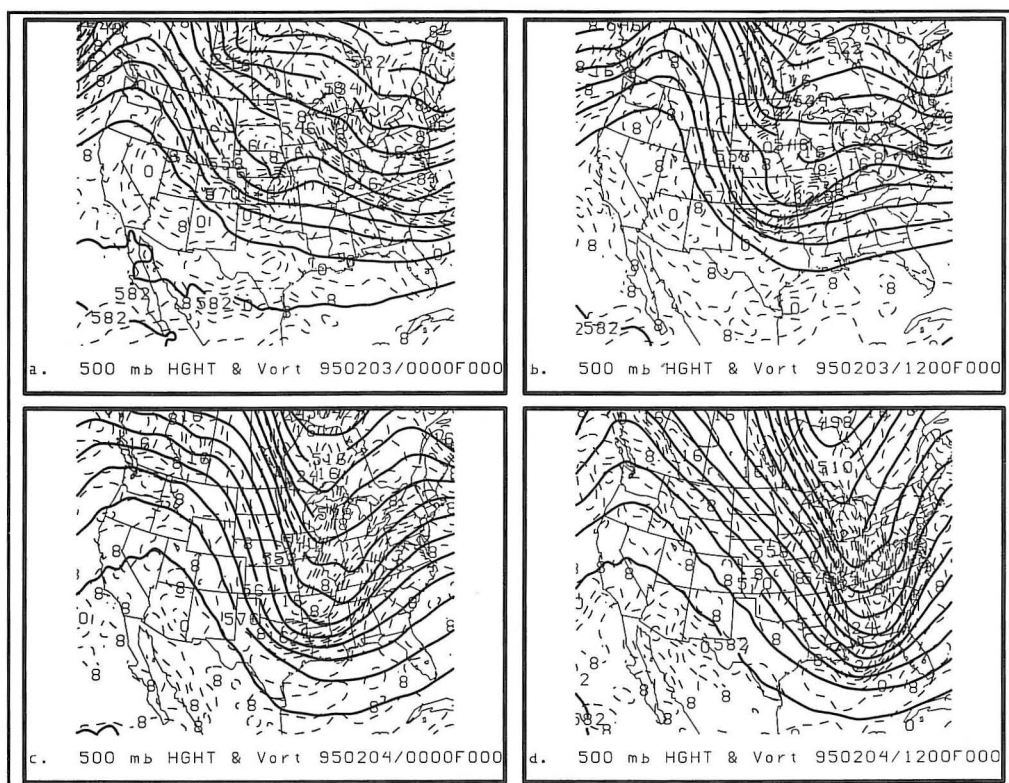


Fig. 2. Eta initialized analyses of 500 mb heights (dm) and vorticity (s^{-1}) valid at (a) 0000 UTC 3 February, (b) 1200 UTC 3 February, (c) 0000 UTC 4 February and, (d) 1200 UTC 4 February 1995. The height contours are every 6 dm and vorticity every $2 \times 10^{-5} s^{-1}$.

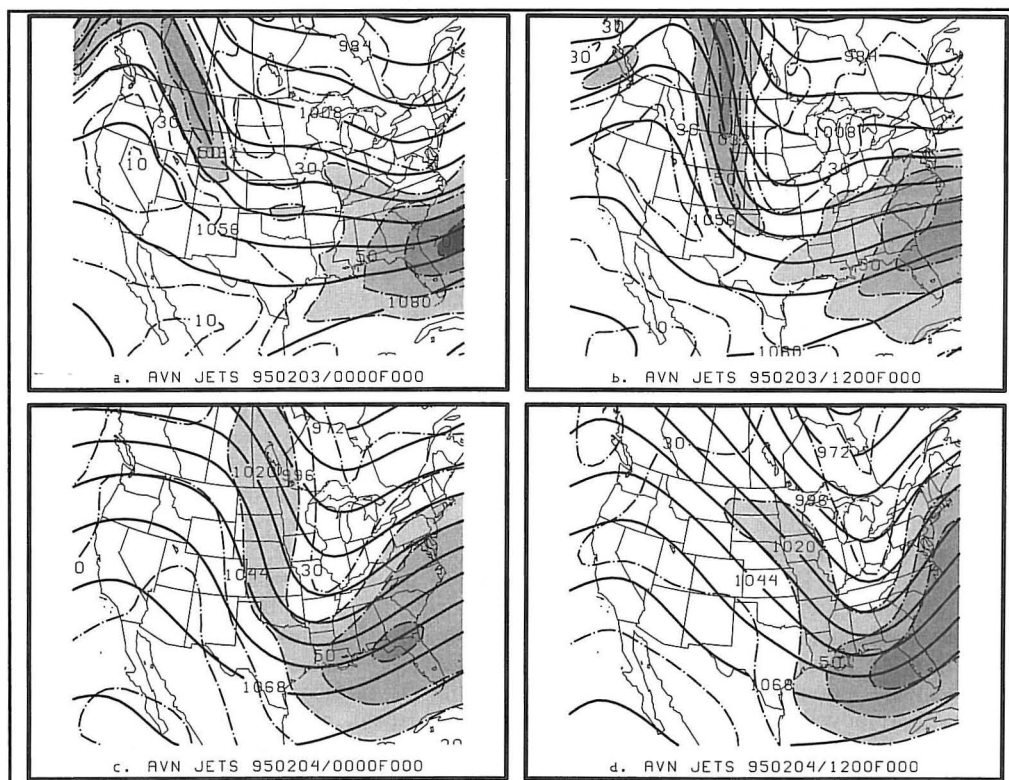


Fig. 3. As in Fig. 2, except for AVN 250 mb heights (dm) and isotachs ($m s^{-1}$). The height contour interval is every 90 m and the isotach contours are every $20 m s^{-1}$. The isotachs shading is every $20 m s^{-1}$ beginning at $30 m s^{-1}$.

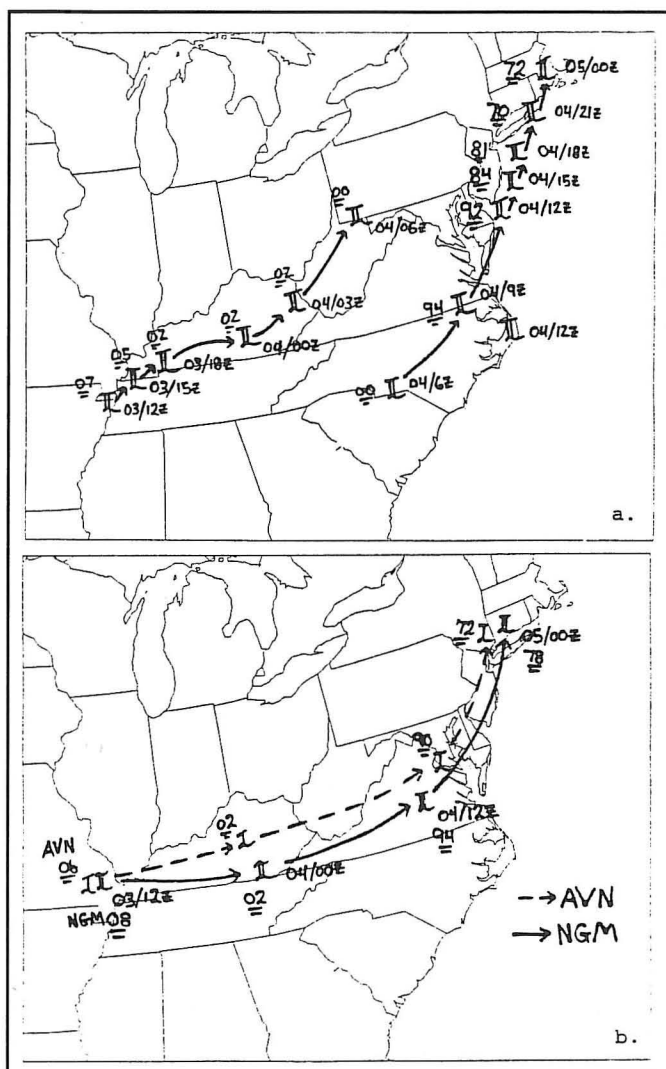


Fig. 4. Plot of the surface cyclones associated with the 3-5 February winter storm. Plot shows the location, time, and central pressure of the surface cyclone for (a) observed surface data and (b) NGM and AVN forecasts from the 1200 UTC 3 February forecast cycle.

mb. The surface low had deepened by 16 mb in 12 hours, as it moved from the coast of Virginia into eastern Massachusetts. The most rapid deepening (8 mb) occurred between 1200 and 1500 UTC. This storm achieved "bomb" status as defined by Sanders and Gyakum (1980) on 4 February 1995.

The 24 h liquid equivalent precipitation amounts produced during this event valid at 1200 UTC 4 and 5 February are shown in Figs. 6a and 6b respectively. By 1200 UTC 4 February (Fig. 6a), the 6.75 mm contour extended from Long Island westward across central Pennsylvania into Ohio and West Virginia. A 37.5 mm precipitation maxima was observed over central New Jersey and in the mountains of northern West Virginia. As the surface cyclone moved up the coast, the precipitation shifted northeastward into New England. By 1200 UTC 5 February (Fig. 6b) the 6.75 mm contour ran from the eastern shores of Lake Erie across western New York, northeastern Pennsylvania and across central New Jersey. Heavier precipitation amounts were confined to coastal New England and north-

eastern New York State. A 50 mm precipitation maxima was observed over southeastern Maine.

The snowfall produced by this storm (mm) is shown in Fig. 1. An area of 150 mm and greater snowfall occurred from West Virginia, western Maryland, and central Pennsylvania into central New York State. The eastern limit of the 150 mm snowfall area extended from near Washington, DC, northeastward across southern New Jersey and eastern Long Island, and then northward across southern Massachusetts and eastern Maine. Within this 150 mm area of snow, a band of 200 mm and greater snowfall occurred from the panhandle of West Virginia northward across Maryland, central Pennsylvania and into New York State. A few local areas within this band received in excess of 250 mm of snowfall. A second band extended northeastward from southeastern Pennsylvania into southern New England. Within this band there were several locations that received in excess of 400 mm of snow. The heaviest snowfall occurred across northern New York State, central New Jersey, and Vermont.

The Central Pennsylvania (KCCX) Weather Surveillance Radar-1988 Doppler (WSR-88D) observations (not shown), indicated north to south oriented bands of precipitation along the coast and inland as far west as Binghamton, NY, and Scranton, PA. The orientation of these bands and observations from the Binghamton and New York City Doppler radars were similar to those shown by Sanders (1986; Figs. 3 and 4). Additionally, the orientation of the axis of heavy snow on 4 February 1995, and the observed WSR-88D imagery were similar to the heavy snow orientation shown in Sanders (1986; Fig. 2). An examination into the cause of these bands is beyond the scope of this paper and will be the focus of a companion study.

b. Model performance

Overall, the operational Eta, NGM, and AVN models performed well during this storm. Within 48 h of the development of the surface cyclone, all three models had converged on a similar solution with each model indicating the rapid development of a significant east coast winter storm. Of course, there were some minor differences in the exact track and depth of the surface low. There were also differences in the amount and distribution of precipitation generated by each model. One of the significant errors associated with this storm was that the initial numerical model forecasts (especially at 36- and 48-h) tracked the surface cyclone farther west than the verifying track. As a result, the model quantitative precipitation forecasts (QPFs) generated liquid precipitation that would have produced heavy snow (using a simple ten to one ratio) over a larger area of Pennsylvania and central New York than what occurred. The combination of high QPF and a more westward forecast storm track, led to forecasts for the potential of heavy snow (30 to 900 mm) over a large area of central Pennsylvania, and for lower snowfall amounts over New Jersey and southern New England due to the potential for the snow to change to rain.

The forecast track of the surface cyclone from the 1200 UTC cycle of the 3 February AVN and NGM model forecasts is shown in Fig. 4b. Both models developed a surface cyclone in eastern Virginia, which tracked northeastward across the Delmarva Peninsula and into southern New Jersey. From this point the surface cyclone was forecast to move over western Long Island, northward into western Massachusetts. The 30 km Eta forecasts were similar (the 18- or 24-h forecasts from the 1200 UTC 3 February cycle were not available in gridded form) and are not shown. An ensemble solution, using a blend of the NGM, AVN, and 80 km Eta, would have tracked the surface cyclone over the Delmarva peninsula, along the coast

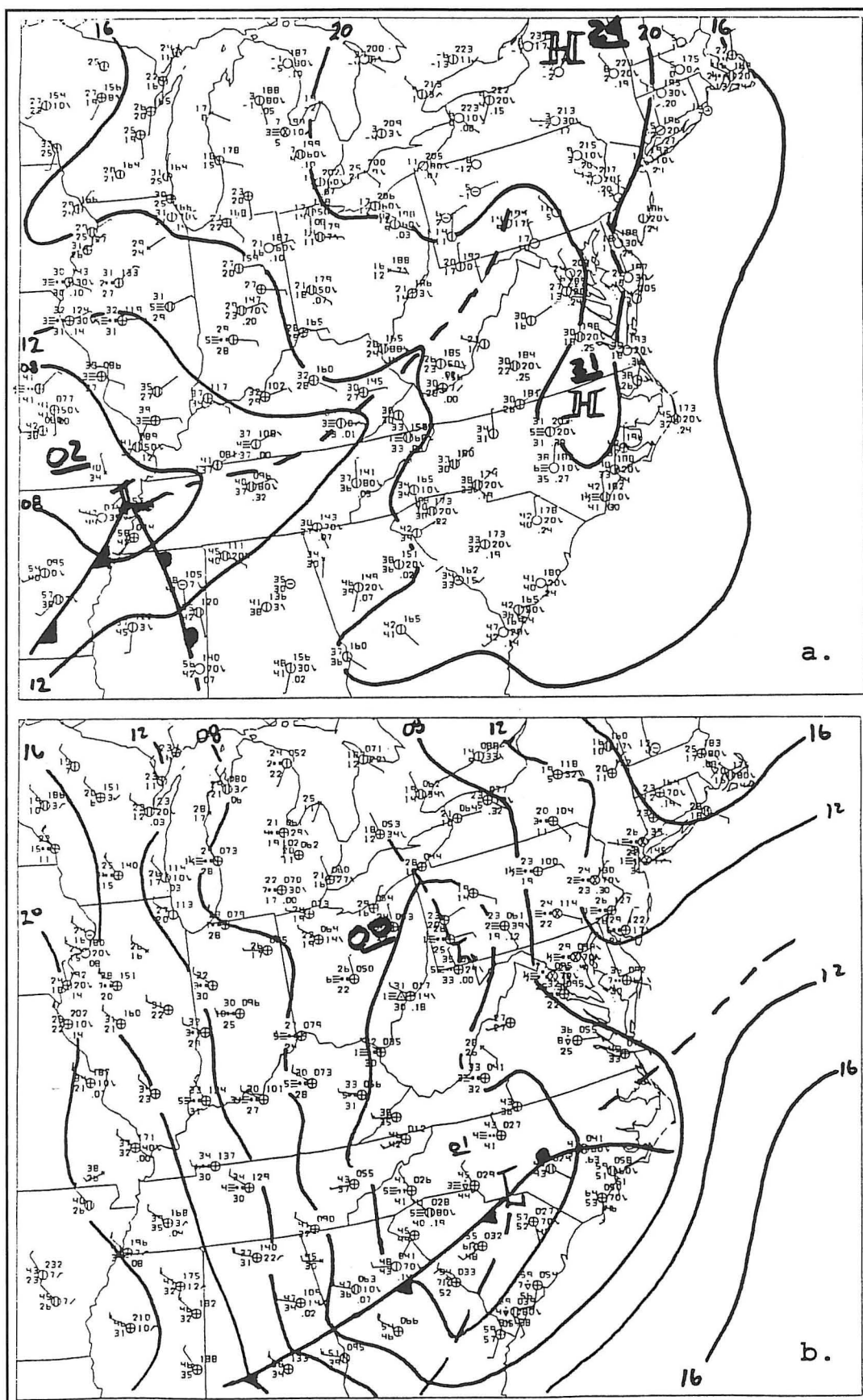


Fig. 5 (a-b). Surface observation plots and manual mean sea-level pressure (4 mb interval) and frontal analyses valid: (a) 1200 UTC 3 February and (b) 0600 UTC 4 February.

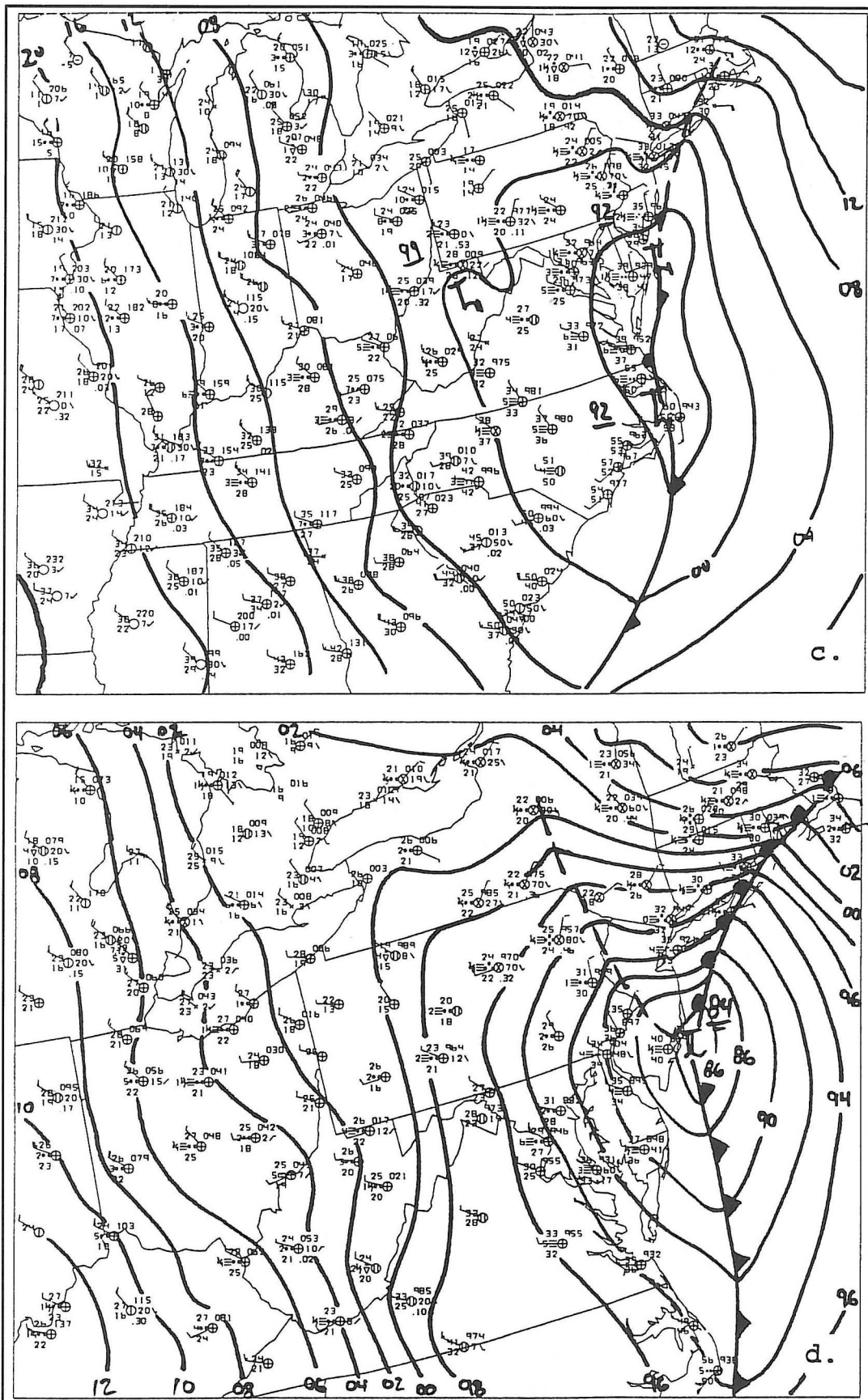


Fig. 5 (c-d). Surface observation plots and manual mean sea-level pressure (4 mb interval) and frontal analyses valid:(c) 1200 UTC 4 February and (d) 1500 UTC 4 February.

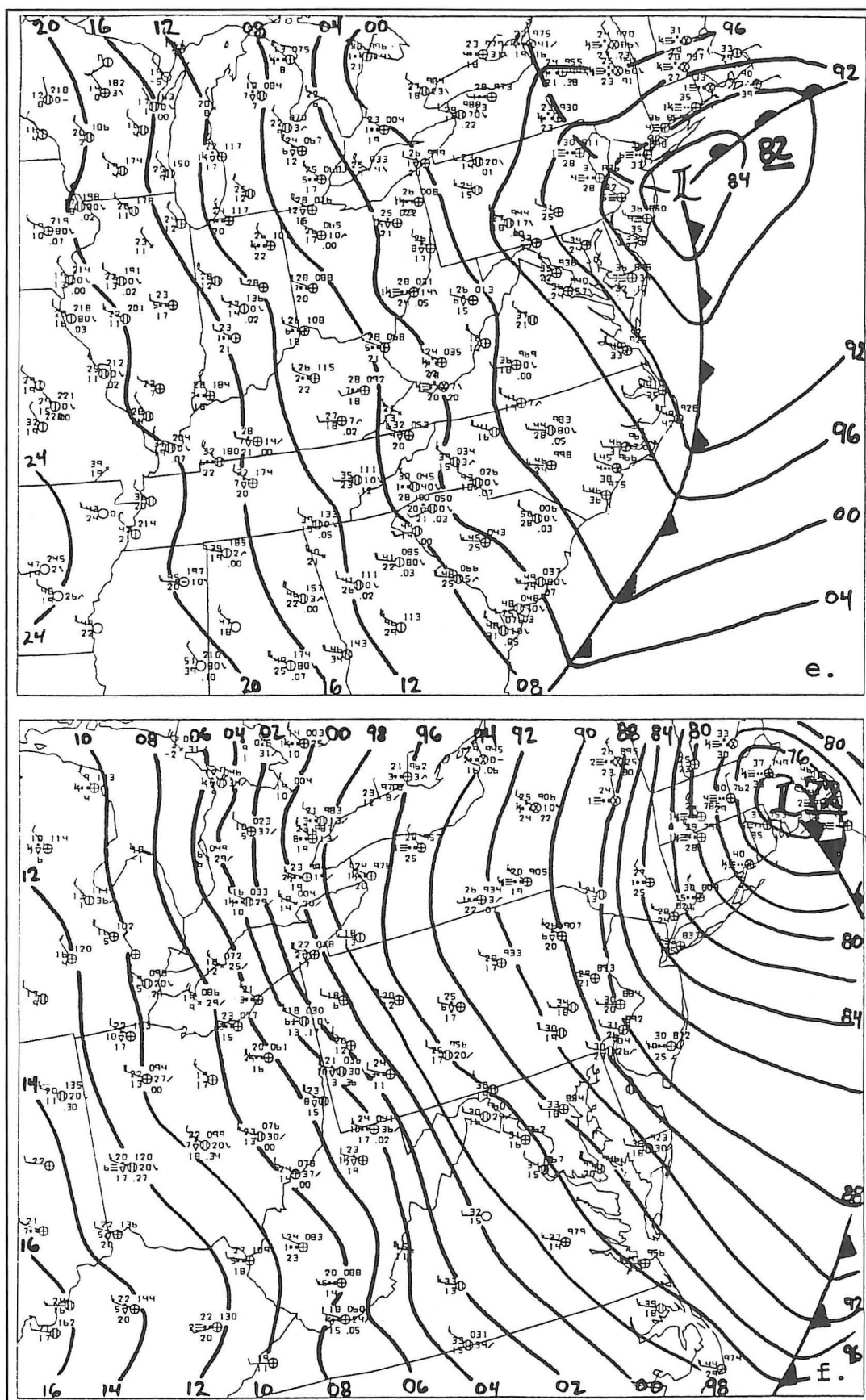


Fig. 5 (e-f). Surface observation plots and manual mean sea-level pressure (4 mb interval) and frontal analyses valid: (e) 1800 UTC 4 February and (f) 0000 UTC 5 February 1995.

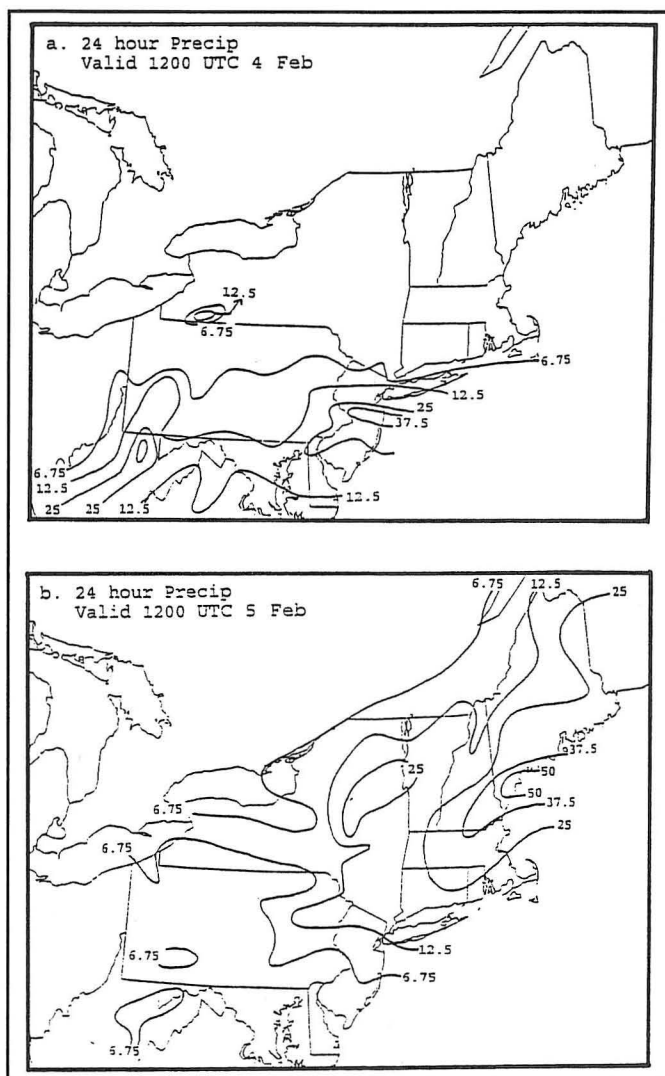


Fig. 6. Manually analyzed 24-h liquid equivalent precipitation (mm) valid at 1200 UTC (a) 4 February and (b) 5 February 1995. Contours are every 12.5 mm beginning at the 12.5 mm contour. The 6.75 mm contour is included for clarity.

of New Jersey, across western Long Island, and into western Massachusetts. Clearly, the NCEP's three operational models had converged on a similar solution.

The AVN forecasts of mean sea-level pressure and 1000–500 mb thickness (hereafter referred to as thickness) from the 1200 UTC 3 February cycle are shown in Figs. 7a–d. The display window was intentionally shifted to the west for the 00-h forecast period (Fig. 7a). The initialized analysis depicted the surface low over southeastern Missouri, which was forecast to deepen by 4 mb and track across Kentucky (Fig. 7b) during the next 12 hours. By 1200 UTC 4 February 1995, the AVN predicted a 990 mb low to be over southeastern Virginia (Fig. 7c). This new low was forecast to deepen an additional 18 mb and track northward into western Massachusetts during the next 12 hours. The corresponding 36-h forecasts from the NGM and the 30 km Eta valid 0000 UTC 5 February 1995 are shown in Figs. 8a and 9a, respectively. Both the Eta and AVN models were deeper than the NGM, and both models positioned the surface cyclone farther west than the NGM.

The NGM 36-, 24-, and 12-h forecasts and 00-h initialized analysis, all valid at 0000 UTC 5 February 1995 are shown in Figs. 8a–d. These data show that the NGM forecasts initially placed the surface cyclone too far west. However, subsequent forecasts positioned the surface cyclone farther to the east, closer to the verifying 00-h model analyzed position (Fig. 8d) and the manually analyzed position (Fig. 5f). The central pressure error at 36 h was at least +4 mb, compared to around –1 mb in the corresponding AVN forecast (Fig. 7d) valid at the same time. However, the 12- and 24-h forecast errors were relatively small when compared to the model initialized analyses and the manual surface analyses.

The 30 km Eta 36-, 24-, and 12-h forecasts and initialized analysis valid at 0000 UTC 5 February 1995 are shown in Figs. 9a–d. These show that the 30 km Eta forecasts had errors similar to those found in the AVN and NGM. Overall, the 30 km Eta produced a deeper cyclone, which was forecast to be farther to the west than the NGM, and slightly to the west of the AVN model forecasts.

The AVN and NGM forecasts of the 24-h accumulated precipitation valid at 1200 UTC 4 February and the 12-h accumulated precipitation valid at 0000 UTC 5 February are shown in Figs. 10a–d. Both models predicted local maxima in precipitation over portions of West Virginia, northern Virginia and Maryland between 1200 UTC 3 February and 1200 UTC 4 February (Figs. 10a and 10c). The AVN generated more precipitation than the NGM and had its precipitation maxima located farther east than the maxima in the NGM. The northern and western extent of the precipitation forecasts were quite similar in both models. Comparing these forecasts to the 24-h observed liquid equivalent precipitation valid at 1200 UTC (Fig. 6a) reveals that both models produced too much precipitation over West Virginia, Maryland and central Pennsylvania. Both models grossly underestimated the precipitation amounts over central New Jersey and eastern Pennsylvania. Using a 10 to 1 ratio, the AVN model forecast 150 to 200 mm of snow in a 12-h period over most of eastern Pennsylvania, northern Virginia, Maryland, and West Virginia. An additional 4 to 12 mm of liquid precipitation was forecast in the following 12-h period, which would have produced an additional 40 to 120 mm of snow over the region. By 0000 UTC 5 February, there should have been between 200 to 350 mm of snow throughout this region.

The AVN predicted approximately 32 mm of precipitation (about 320 mm of snow) in central New Jersey by 0000 UTC 5 February. The data in Fig. 6a suggest that the AVN was too slow to bring the heavy precipitation into the region. Both the AVN and the NGM did an inadequate job in estimating the snowfall amounts over northern New York and Vermont. The NGM also over estimated the snowfall over the western half of Pennsylvania. Twenty-four hour forecasts from the operational 80 km Eta were not available. However, the 36-h Eta forecast (not shown) valid 0000 UTC 5 February, produced a large area of 25 mm, and greater, of liquid precipitation over northeastern New Jersey and Long Island, northward into south central Massachusetts. This maxima area was farther west than the maxima produced in the AVN valid at the same time (Fig. 10b).

4. Discussion

The 4 February 1995 winter storm clearly illustrates how critical the *track* of a surface cyclone can be in determining the location of heavy snow. The Eta, NGM, and AVN forecasts predicted a more westerly track of the surface cyclone than

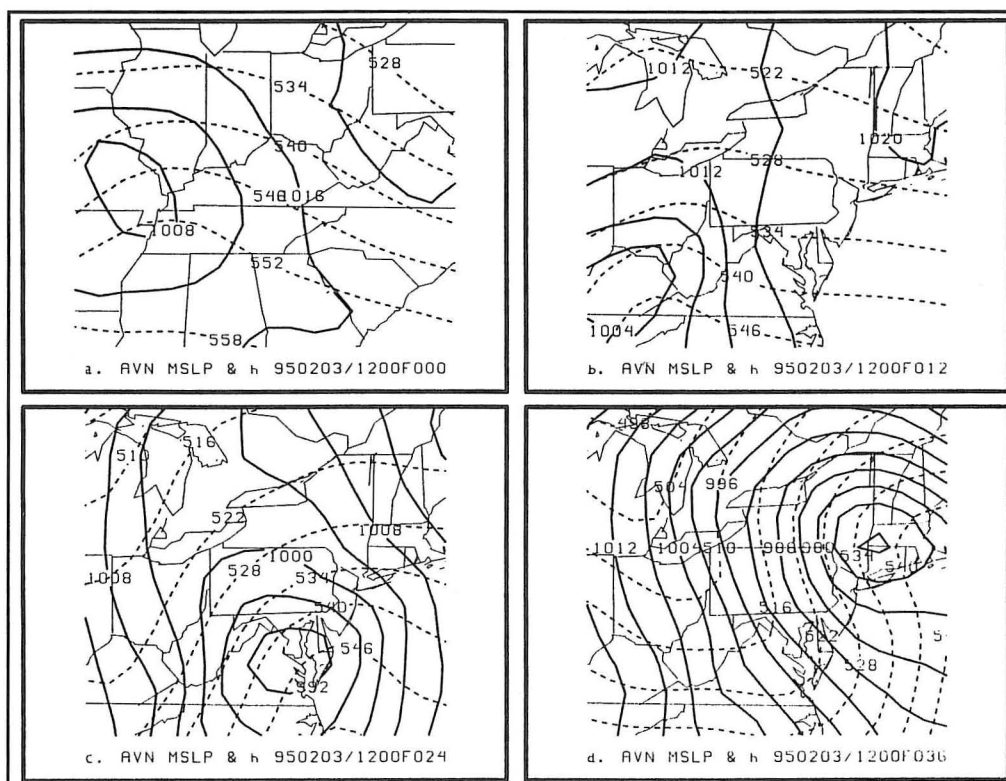


Fig. 7. AVN forecasts of mean-sea level pressure (mb) and thickness (dm) from the 1200 UTC 3 February forecast cycle for (a) 00-, (b) 12-, (c) 24-, and (d) 36-hours. The isobars are every 4 mb and the thickness is every 6 dm.

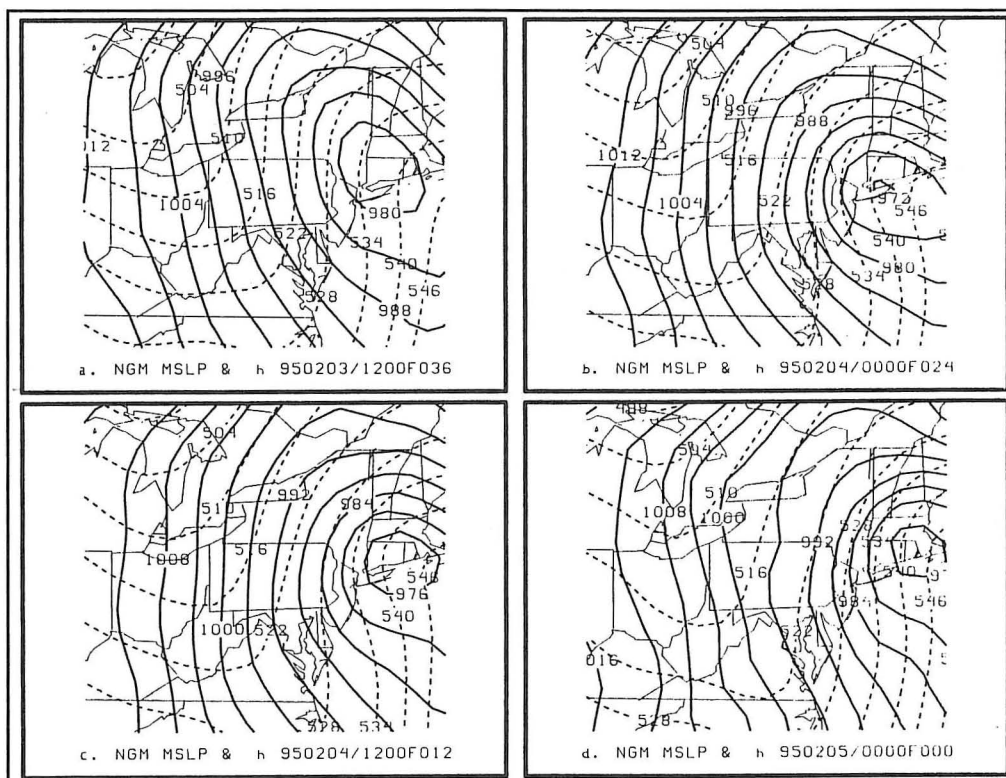


Fig. 8. NGM forecasts of mean-sea level pressure (mb) and thickness (dm) from (a) 1200 UTC 3 February, (b) 0000 UTC 4 February, (c) 1200 UTC 4 February, and (d) 0000 UTC 5 February 1995. All forecasts are valid at 0000 UTC 5 February 1995. The isobars are every 4 mb and the thickness is every 6 dm.

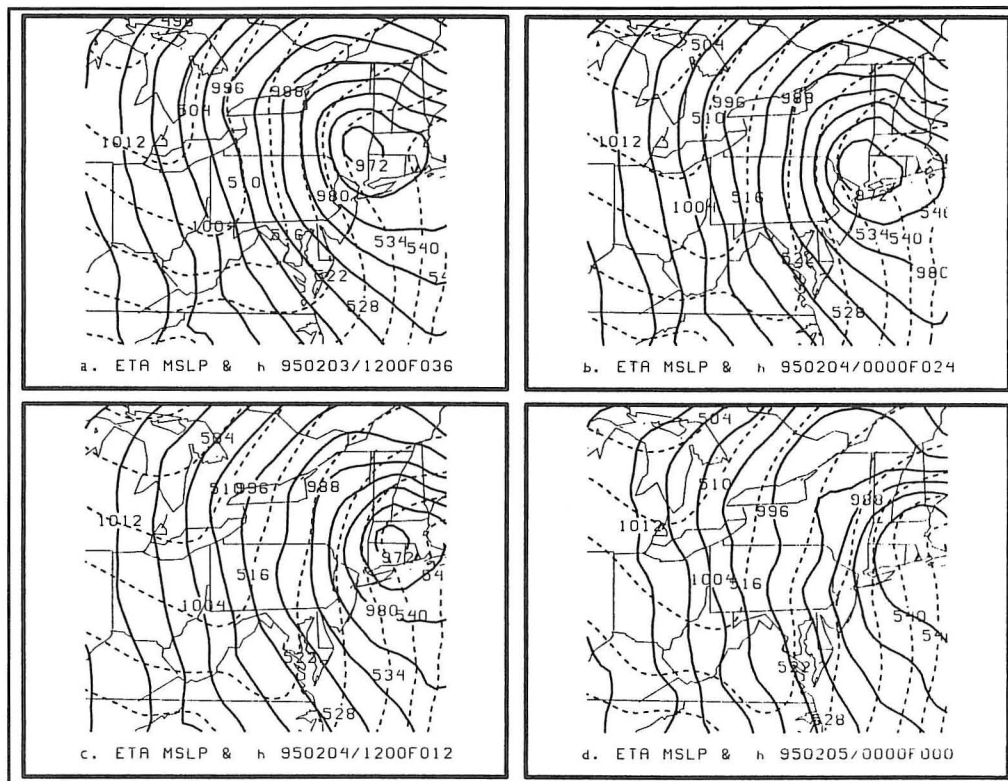


Fig. 9. As in Fig. 8, except for the 30 km Eta forecasts from (a) 1200 UTC 3 February, (b) 0000 UTC 4 February, (c) 1200 UTC 4 February, and (d) 30 km Eta initialized analysis valid 0000 UTC 5 February, 1995. All forecasts are valid at 0000 UTC 5 February, 1995.

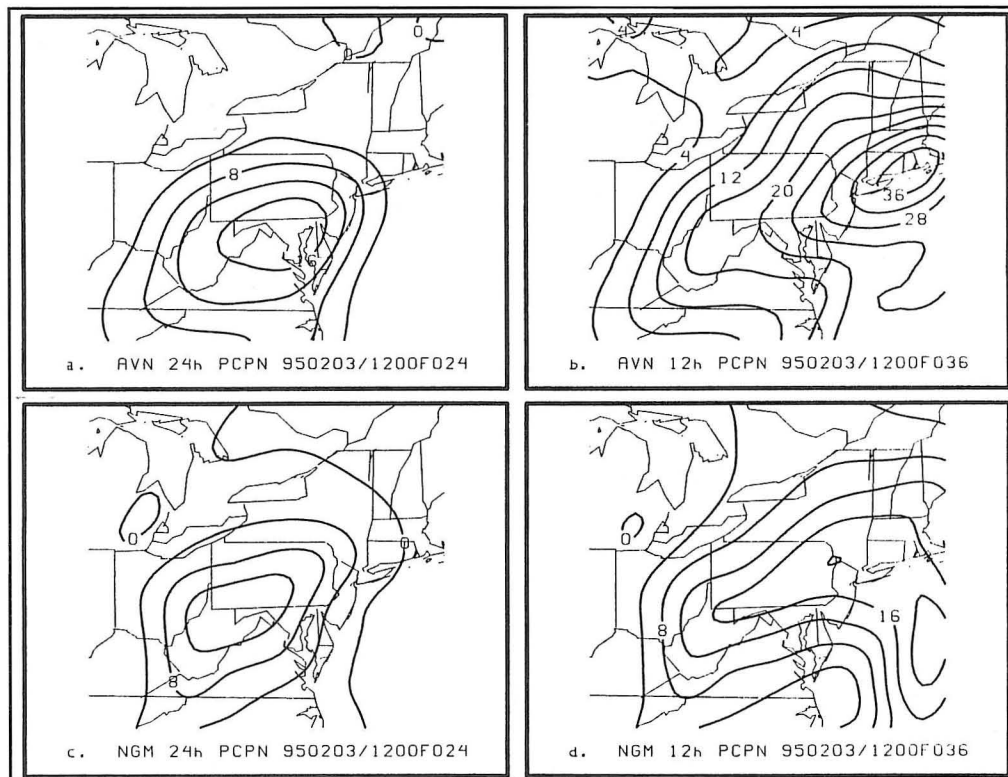


Fig. 10. Precipitation (mm) forecasts from the 1200 UTC 3 February cycle showing (a) AVN 24-h forecast valid 1200 UTC 4 February, (b) AVN 36-h forecast valid 0000 UTC 5 February, (c) NGM 24-h forecast valid 1200 UTC 4 February, and (d) NGM 36-h forecast valid 0000 UTC 5 February. The contour interval is every 4 mm.

what occurred. This would have favored heavy snow farther west, with the potential for less snow to the east due to the intrusion of warm moist Atlantic air. The errors in the model track were similar to those shown by Grumm (1993) and Oravec and Grumm (1993), which indicated that the NGM and AVN tended to position surface cyclones too far west of the verifying position along the east coast of the United States and the adjacent western North Atlantic. Also, similar to the findings of Grumm (1993) and Oravec and Grumm (1993), the NGM and AVN did an excellent job in predicting the *approximate location* and time of rapid development of this major east coast storm. At this time, published results as to the Eta model's ability to forecast cyclone central pressures and positions are not available. However, the 36-h Eta forecast from 1200 UTC 3 February had the largest westward bias in the forecast track of the surface cyclone. The central pressure forecast was similar to that produced by the AVN.

Surface cyclone errors for the NGM and AVN models during the WI95 are shown in Tables 1 and 2, respectively. These data include the forecast hour, the number of cyclones, the mean sea level pressure error (mb), mean thickness error (m) and mean distance error (km). Winter is defined as the months of December, January, and February and the domain of these data include all of North America and the adjacent portions of the Atlantic and Pacific Oceans (Grumm and Siebers 1989). Overall, mean 36-h distance errors for the NGM and AVN during WI95 were 297 and 226 km, respectively. The root-mean square distance error was smaller in the AVN than in the NGM at all forecast lengths. Similarly, the mean 36-h central pressure errors were -1.21 and -0.29 mb for the NGM and AVN, respectively. The root-mean square pressure errors were smaller in the AVN than in the NGM at all forecast periods. Both models showed a cold bias in the forecast of

1000–500 mb thickness over surface cyclones. The NCEP terminated tracking surface cyclone errors in the operational Eta model on 1 January 1995. Therefore, similar data for the Eta during WI95 were not available. A comparison of December 1994 data reveal that the Eta had larger cyclone position and central pressure errors than both the NGM and AVN beyond 12 hours.

The 100 to 150 km errors in the 36-h forecast position of the 4 February surface low in the AVN, NGM, and Eta were small relative to the overall surface cyclone distance errors in these models. The distance errors in the 36-h forecasts for this cyclone were comparable to those normally found for all cyclones in the 12-h forecasts. Grumm (1993) showed that the AVN was better able to forecast the central pressure and position of cyclones, which were both observed and forecast to deepen. During the winter of 1992, the mean distance errors for these cyclones were 102 and 158 km at the 12- and 24-h forecast periods, respectively. This cyclone exhibited comparable distance errors to those found in the Grumm (1993) study.

Another mechanism that may have concentrated the heaviest precipitation farther to the east was the presence of a coastal front (Bosart 1975 and 1981). Observations of coastal fronts in winter storms indicate that the heaviest precipitation typically occurs on the west (cold) side of the boundary. With a vertical thermal structure supporting snow, the heaviest snow typically falls just west of this boundary. Three-hour surface analyses, the local precipitation maxima in central New Jersey (Fig. 6a), and hourly surface observations from coastal locations (not shown) suggest that a coastal front developed along the coast of New Jersey and extended northward into southern New England (Fig. 5c). This boundary moved westward as the surface low moved northeastward. This may have provided the necessary conditions to produce heavy snow over New York City and northern New Jersey. It is believed that if the surface low had tracked closer to the model forecast track, both the coastal front and the heaviest precipitation would have likely occurred farther westward. In all likelihood, there would have been more rain than snow over most of the New York Metropolitan area. Atlantic moisture would have penetrated farther inland, producing heavier snow over a larger portion of Pennsylvania and New York State.

Another forecast error noted in the models was in the location and timing of where the surface cyclone would develop. Numerical model guidance indicated a secondary cyclonic development in eastern Virginia with a track across the Chesapeake Bay (Figs. 7b and 7d). Observed surface data indicated that the surface low developed about 160 km south of the predicted position, near the border of North and South Carolina. The track of the manually analyzed surface low was south and east of the forecast low. Unfortunately, the ensemble solution from the three models suggested that the low would develop in Virginia and track west of the observed track due to the relative similarity in the forecasts. Additionally, by 1200 UTC 4 February 1995, the surface low had moved off of the east coast, northeast of the forecast point of development.

This case clearly demonstrates how relatively minor errors in the forecast track of the surface cyclone can lead to significant differences in the observed weather. For example, Fig. 11 shows the NGM 850-mb temperature forecasts valid at 0000 UTC 5 February. The data at a model grid point over western Connecticut from the 36- and 24-h forecasts (Figs. 11a and b) would have reflected the more rapid intrusion of Atlantic air, the change over to rain, and the passing of the surface cyclone at or near the grid point. However, the 00-h initialized Eta analysis valid at this time (Fig. 11d) illustrates that the 850-

Table 1. NGM cyclone mean pressure, thickness, and distance errors by forecast period (FCST PD) during the winter of 1995. These data include the number of cyclones (Num), the mean pressure errors (mb), mean thickness errors (m), mean distance errors (km), and the root-mean-square errors (RMS).

FCST PD	Num	Pressure Errors		Thickness Errors		Distance Errors	
		MEAN	RMS	MEAN	RMS	MEAN	RMS
12	970	-0.73	2.86	-0.27	36.91	153	221
24	858	-0.73	4.53	-3.39	50.07	226	318
36	796	-1.21	5.44	-4.19	50.40	297	390
48	699	-1.38	6.32	-5.26	60.65	393	509

Table 2. As in Table 1, except for the AVN.

FCST PD	Num	Pressure Errors		Thickness Errors		Distance Errors	
		MEAN	RMS	MEAN	RMS	MEAN	RMS
12	671	-0.19	2.30	-4.02	41.35	106	148
24	591	-0.32	3.25	-0.72	32.51	164	216
36	543	-0.29	3.99	-0.35	41.49	226	290
48	483	-0.16	4.34	0.90	46.41	294	369
60	425	-0.21	5.21	-0.35	50.59	376	472
72	398	-0.32	6.17	0.81	54.13	431	522

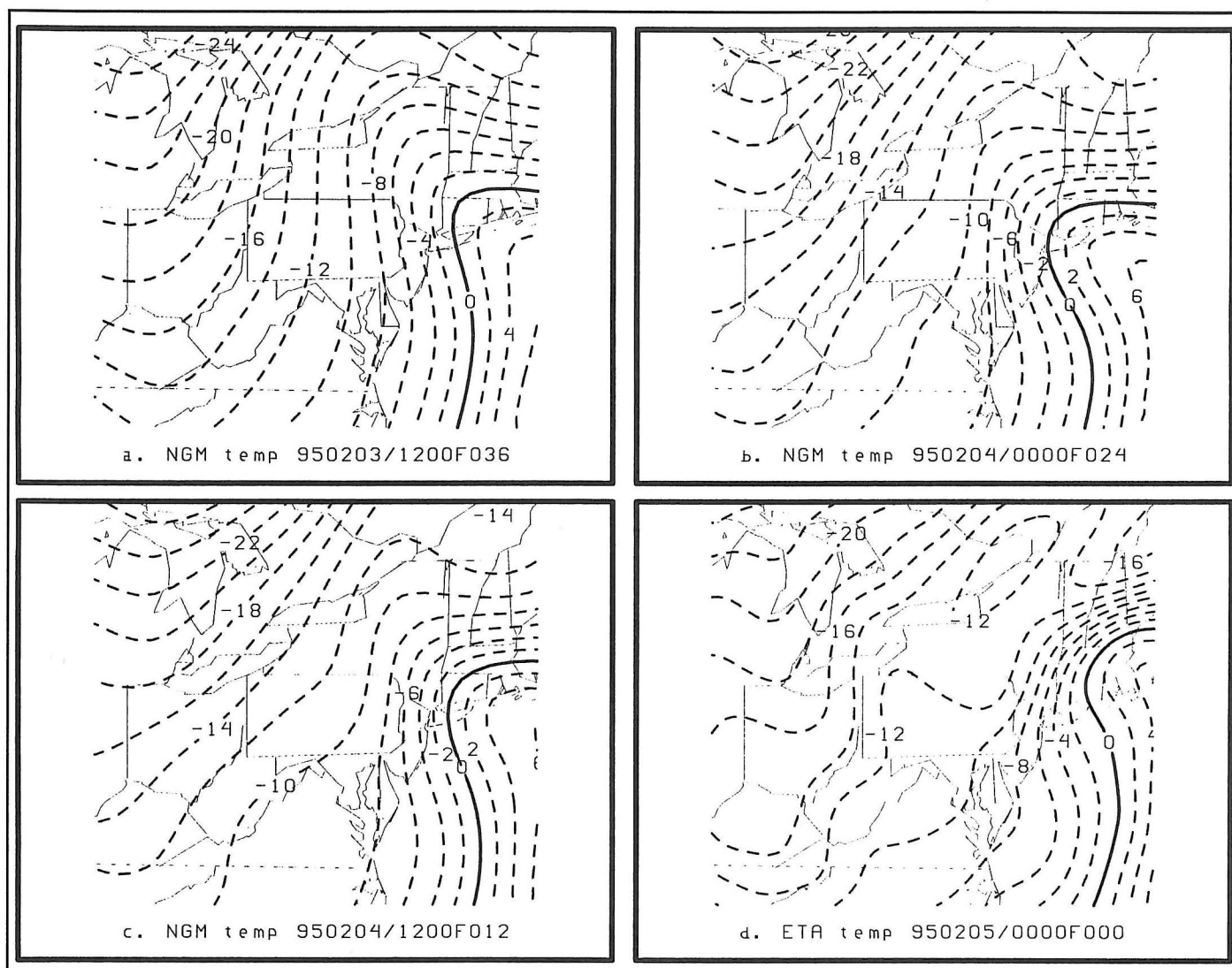


Fig. 11. NGM forecast of 850 mb temperature forecasts from (a) 1200 UTC 3 February, (b) 0000 UTC 4 February, and (c) 1200 UTC 4 February, and (d) 30 km Eta initialized analysis all valid at 0000 UTC 5 February, 1995. Contour interval is every 2°C with the 0°C isotherm highlighted in bold.

mb temperatures in western Connecticut were on the order of 4°C colder than forecast. The anticipated conditions were more likely to have been observed over eastern Connecticut.

5. Conclusions

The 4 February 1995, East coast winter storm revealed how numerical weather prediction models generally do a proficient job in forecasting the development and track of strong winter surface cyclones. Numerical weather prediction models are excellent *forecast tools* and have probably reached the state where it is unlikely that strong surface cyclones will go unpredicted. Errors in QPFs and the exact track of surface systems are complicated by the use of parameterization schemes, simulated terrain to fit the model coordinate system, the lack of horizontal and vertical resolution, and problems with model physics. Near the coast, differences between actual and model land-sea interfaces also contribute to forecast errors. Forecasters should be aware of biases in numerical models due to these factors.

Due to the error in the 4 February 1995, surface cyclone track, forecasters were faced with a difficult task in predicting the “sensible” weather that would occur over the heavily populated region along the east coast of the United States. Heavy snow was a potential forecast problem from Washington, D.C., northward to Boston, MA. In coastal locations (New York City and its surrounding airports), model forecast tracks 24-, 36- and 48-h prior to the event indicated the likelihood of an early change over from snow to rain. However, a longer period of heavy snow occurred, due to the more easterly track of the surface cyclone than forecast. The heavy snow disrupted the air traffic at the major metropolitan airports in the region, with many of them closing down during the period of heaviest snow-fall.

The key to making a good forecast for this case depended on knowing the systematic errors in the operational Eta, NGM, and AVN models. With a knowledge of these model errors, the predicted cyclone track could have been adjusted. This would have alerted forecasters to the potential of a slower change

over to rain in coastal sections and lesser amounts of snow farther to the west.

The 4 February 1995 winter storm also revealed that a convergence of model solutions does not always produce the best forecast. In the 36- and 48-h forecast period, the three operationally available models placed the surface cyclone farther west of the verifying track. Subsequent model runs gradually moved the surface cyclone track farther east, closer to the verifying position. This winter storm demonstrates that determining the position of the rain/snow line can still be in considerable question in the 12- and 24-h forecast periods.

The small, but significant error in the forecast track of the surface cyclone of 4 February 1995 illustrates the need for continued study and dissemination of known errors in operational numerical weather prediction model forecasts of surface cyclones and anticyclones. Hopefully, regional and national scale studies will continue to examine these errors and find ways to improve both the model forecasts and operational interpretation of these data.

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