EVALUATION OF AN UNUSUAL WINTER WEATHER *NON*-OCCURRENCE IN NORTH CAROLINA ON 24 JANUARY 1991

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Abstract

On 24 January 1991, heavy snow was forecast for much of the Piedmont of North Carolina. Very little snow actually fell in this region; however, a few inches of snow fell over parts of the Sandhills and southern Coastal Plain, where it was not expected. This paper first examines the watch and warning process from an operational forecasting perspective. Then, in an attempt to explain why heavy snow did not fall over the warned area, the paper describes pertinent 500-mb and 850-mb features, surface high pressure center location, and low-level thickness values. Special emphasis is placed on the roles of upward vertical motion, melting snow, and evaporational cooling. Ultimately, the main limiting factors for significant snow across the Piedmont were: 1) the storm taking a more southerly track than forecast and 2) the lack of cold air advection within the lowest levels of the atmosphere.

1. Introduction

It is not very often that snow falls in the Southern Coastal Plain and Sandhills regions of North Carolina while rain falls in the northern Piedmont. (Please refer to map of North Carolina, Fig. 1.) But that is what happened during an unusual winter weather event that occurred on 24 January 1991. Winter Storm Watches and subsequent Warnings were issued for this "storm," yet only a few inches of wet, slushy snow occurred—mainly outside of the warned areas. This paper will discuss the synoptic setting and reasoning behind the forecasts. A hypothesis will be presented to explain some of the thermodynamic processes (especially melting and vertical motion) that could have caused the changeover to snow in the southeastern part of the state.

In this paper, there are several instances where assumptions are made based on limited available data. But, forecasters must deal with "missing" information all of the time. From a scientific viewpoint, this approach may evoke more questions than answers. However, in the operational world, it is important to be able to produce the best possible product within time constraints and to be able to learn from "busted" forecasts.

2. The Synoptic Setting

On Tuesday, 22 January 1991, the National Weather Service (NWS) National Meteorological Center's (NMC) numerical models began to suggest a rapid return of moisture to the southeastern United States from the Gulf of Mexico. These model runs were consistent with previous extended-range model runs. High pressure, which was over North Carolina at that time, was forecast to move offshore with a weak inverted trough of low pressure developing along the Gulf Coast—spreading precipitation northward. The high had already provided very dry air—dew points were in the teens statewide on Tuesday. The 48-hour, 700-mb net vertical displacement prognostic field from the NMC Nested Grid Model (NGM) depicted an impressively large, >100 mb maximum area over northern Georgia and western South Carolina.

Just how the weather pattern would unfold for North Carolina was not clear-cut, however. None of the dynamical models showed a well-organized low pressure system. The area of upward vertical motion (depicted by NGM) was forecast to move straight east across South Carolina and then offshore. Forecast thicknesses were cold enough for snow, except in southeastern North Carolina, where 36- to 48-hour mid-level thicknesses (850-700 mb) warmed substantially.

The 0000 UTC cycle model runs on 23 January were quite similar. Despite the lack of a surface low, the NMC models continued to indicate high mean relative humidity with high probabilities of precipitation. The potential existed for a cold front to move from the Ohio Valley into the state on Thursday, the 24th, bringing a reinforcing shot of cold air. However, ahead of this front, surface winds over North Carolina were from the southwest—not normally a direction associated with snow. In fact, Cantin and Bachand (1990) found that winds with a southerly component had a negative impact on the probabilities of frozen/freezing precipitation.

During the day on Wednesday, 23 January, the forecast shift became hectic and interesting! The 1200 UTC 23 January model runs began to look more ominous for a heavy snow event. Model thickness values, which had warmed slightly on the previous runs, were colder and forecast mean relative humidity values of >90% covered most of the state from 24-36 hours. At the surface, dew points remained low. However, southwest winds continued out ahead of the advancing cold front (approaching the Appalachians) and behind the departing high. There was a good deal of doubt at that time as to whether the cold front would make it as far south as North Carolina on Thursday. If it did, would it arrive late in the day? Also, a slight eastward trend was noted in the cloud band on the satellite imagery, which might limit the amount of precipitation that would fall in the mountains. At 500 mb, a strong positively-tilted trough in the southwestern United States (Fig. 2) was forecast to eject eastward, but not to become negatively-tilted (a more favorable pattern for snow).

With these reservations in mind, shift forecasters evaluated NMC's heavy snow discussion and forecast. NMC was forecasting a large swath of 4 to 8 inches of snow over the North

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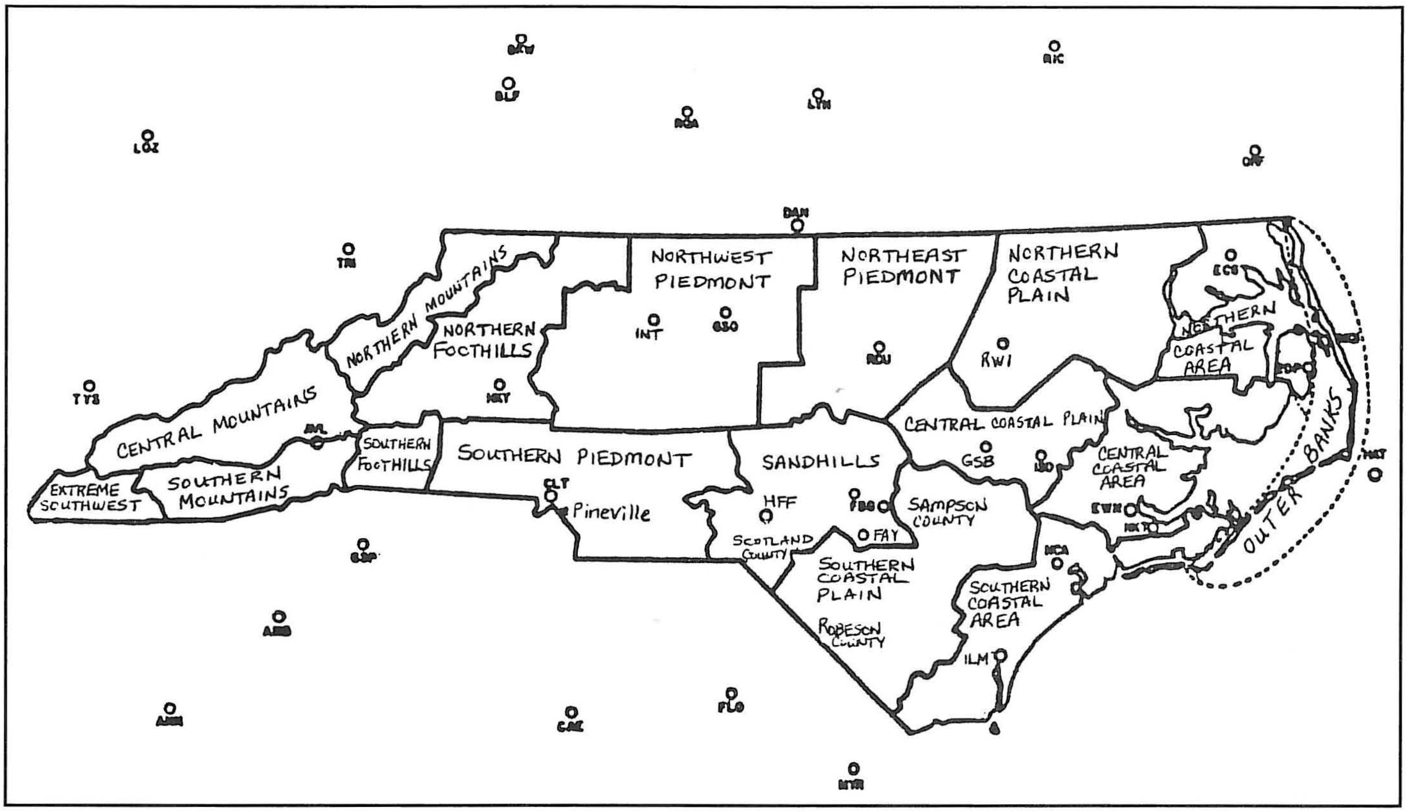

Fig. 1. Map of North Carolina's public zones (with corresponding geographical descriptions) as they existed in 1991.

Carolina Piedmont with greater than 8 inches centered over Charlotte. Precipitation was expected to begin late at night in the south and early in the morning in the north, which raised the possibility that it would begin as snow. Forecasters also used an applications program entitled "Local Objective Guidance for Predicting Precipitation Type," which is based on thickness values for different layers. It was developed at the National Weather Service Forecast Office (NWSFO) in Raleigh (Keeter et al. 1988, 1991). For Greensboro, the NGM forecast a 1000-850 mb thickness of 1300 m and an 850-700 mb thickness of 1520 m. Based on regression equations, this indicated a 55% conditional probability that measurable frozen precipitation would be observed at Raleigh between 0000 and 1200 UTC Thursday.

3. The Decision to Issue Watches and Warnings

In North Carolina, a Winter Storm Warning is required for 4 or more inches of snow. Even a forecast of 2 to 4 inches requires that a Warning be issued. Snow Advisories are issued for 1 to 3 inches of snow. Winter Weather Advisories are issued when a mixture of precipitation types is expected, provided that total sleet accumulation is less than 1/2 inch and freezing rain accumulation is less than 1/4 inch.

As of Tuesday afternoon, a 70% chance of snow was forecast for Wednesday night into Thursday for the southern Piedmont (including Charlotte), with 50-60% probabilities for the western areas and lesser chances in northeastern North Carolina. A Winter Storm Watch was issued Wednesday afternoon for all of the west and north for Thursday. Winter Storm Warnings were issued for the southern and central mountains, since snow was expected to begin there after midnight Wednesday night. The headline "Winter Weather Advisory May Be Needed Thursday" was added to the central Coastal Plain and Sandhills forecast. Sleet was mentioned in this transition area as well.

On Wednesday night at 0300 UTC, the leading edge of the precipitation slowed its northward progress and still was only in southern Georgia (Fig. 3). Warnings were continued as previously forecast, except "after midnight" was changed to "toward daybreak" in the mountains. Watches continued as previously forecast. A new Special Weather Statement was issued that continued to express a high degree of uncertainty. It stated, "With the low expected to take a more southerly track and remain as a relatively weak system . . . the Winter Storm criteria of 4 inches of snow is by no means a sure bet for those areas in the Winter Storm Watch."

On the midnight shift Thursday, 24 January, precipitation had progressed to northeast Georgia, and it appeared likely that it would overspread the North Carolina Piedmont early in the first period of the upcoming forecast. According to National Weather Service policy, Watches generally should be issued for events in the second, third, and occasionally fourth forecast periods. Therefore, the decision had to be made whether to upgrade the Watch to either Warnings or Advisories, scrap the whole thing, or continue the existing watch (if the precipitation was not expected to begin until late in the first period).

a. Positive factors for heavy snow:

1) The 0000 UTC Limited-Area Fine Mesh Model(LFM) run depicted a coherent 850-mb low moving from southern Mississippi to eastern North Carolina by late Thursday afternoon (Fig. 4). The corresponding LFM quantitative precipitation forecast gave Raleigh more than 11 inches of snow (based on a 10:1 frozen/liquid ratio).

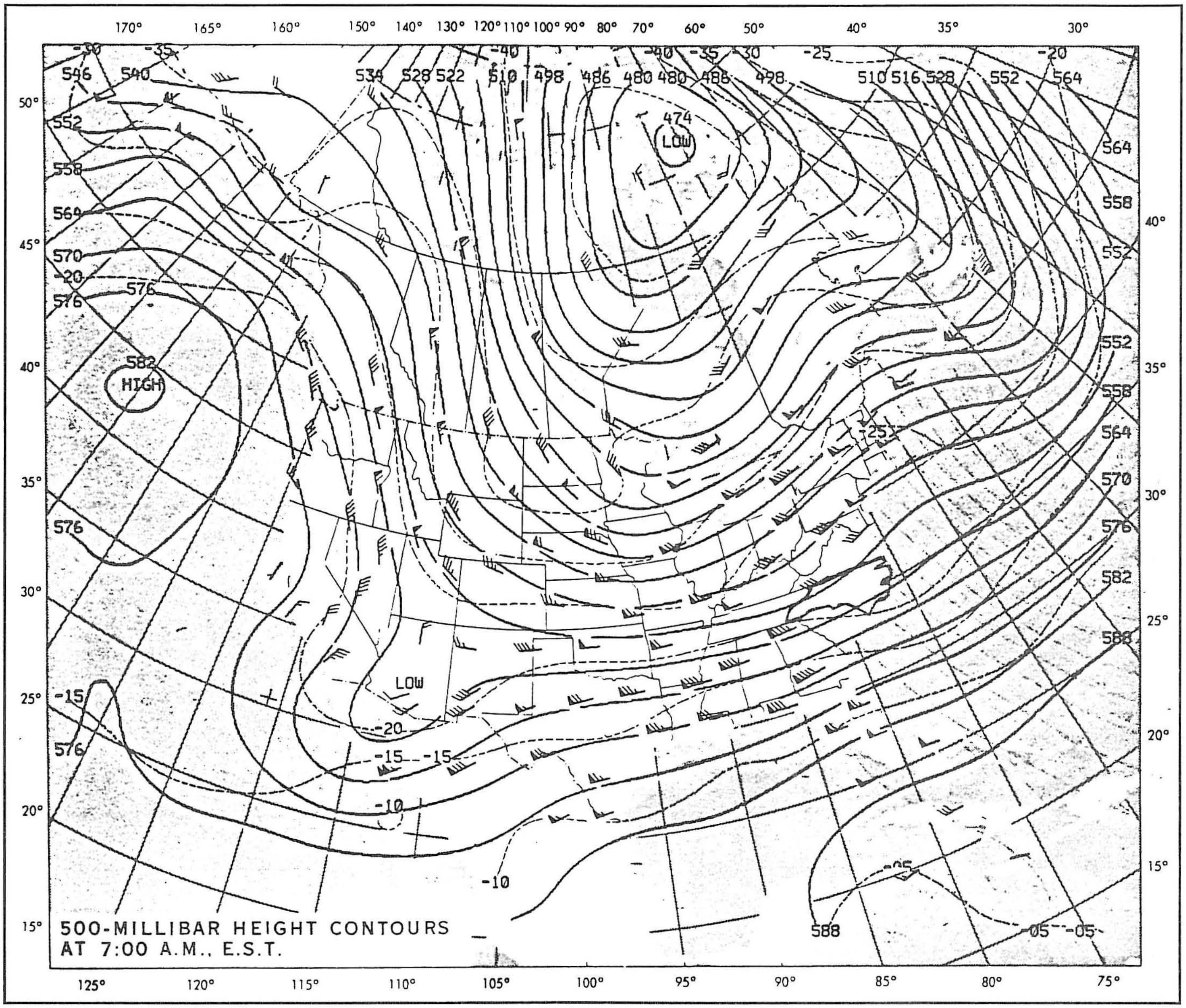

Fig. 2. 500-mb height contour analysis and winds for Wednesday, 1200 UTC 23 January 1991. (Taken from "Daily Weather Maps, Weekly Series: 21–27 January 1991," NOAA Climate Analysis Center, Washington, D.C.)

2) The 0000 UTC NGM run was also very impressive with its moisture and precipitation. Its 90% area corresponded well to the radar echoes in southern Georgia at 0600 UTC and Athens radar showed a steady northward progression of the rain with embedded VIP level 2's and 3's.

3) NMC forecast guidance showed a large swath of 4 to greater than 8 inches of snow over the North Carolina Piedmont, with the maximum centered over Charlotte.

4) Hourly NGM profile data,[1] which the NWSFO Raleigh is able to retrieve from the NAS 9000 computer (Fig. 5), clearly showed the onset of precipitation to be early—between 1300 and 1400 UTC at Charlotte and 1400 and 1500 UTC at Raleigh. This seemed reasonable per radar data extrapolation. The NGM forecast precipitation amounts of 0.74 inches for Greenville-Spartanburg, South Carolina, 0.54 inches for Charlotte, and 0.42 inches for Raleigh.

5) The effects of evaporative cooling usually offset some of the low level warming. As of 0900 UTC Thursday, the surface temperature/dew point (°F) were 35/19 at Raleigh (RDU); 32/18 at Hickory (HKY); and 38/27 at New Bern (EWN). The 32°F wet-bulb temperature contour (determined by using a local applications program) ran from just east of Charlotte (CLT) to just south of Raleigh. Generally, the potential for the heaviest snowfall lies just north of the 32°F wet-bulb temperature, although the exact placement of this line was difficult to determine due to the poor spatial resolution of the reporting stations. This cooling effect was evident over Georgia, where moderate rain was falling at Macon, while snow had begun at Athens where the wet-bulb temperature was below freezing.

[1]The NGM profile data, as of now, are provided for the support of post-event analysis. However, these data can provide more insight into what the model vertical sounding looks like and, if accurate, are potentially useful as an operational tool.

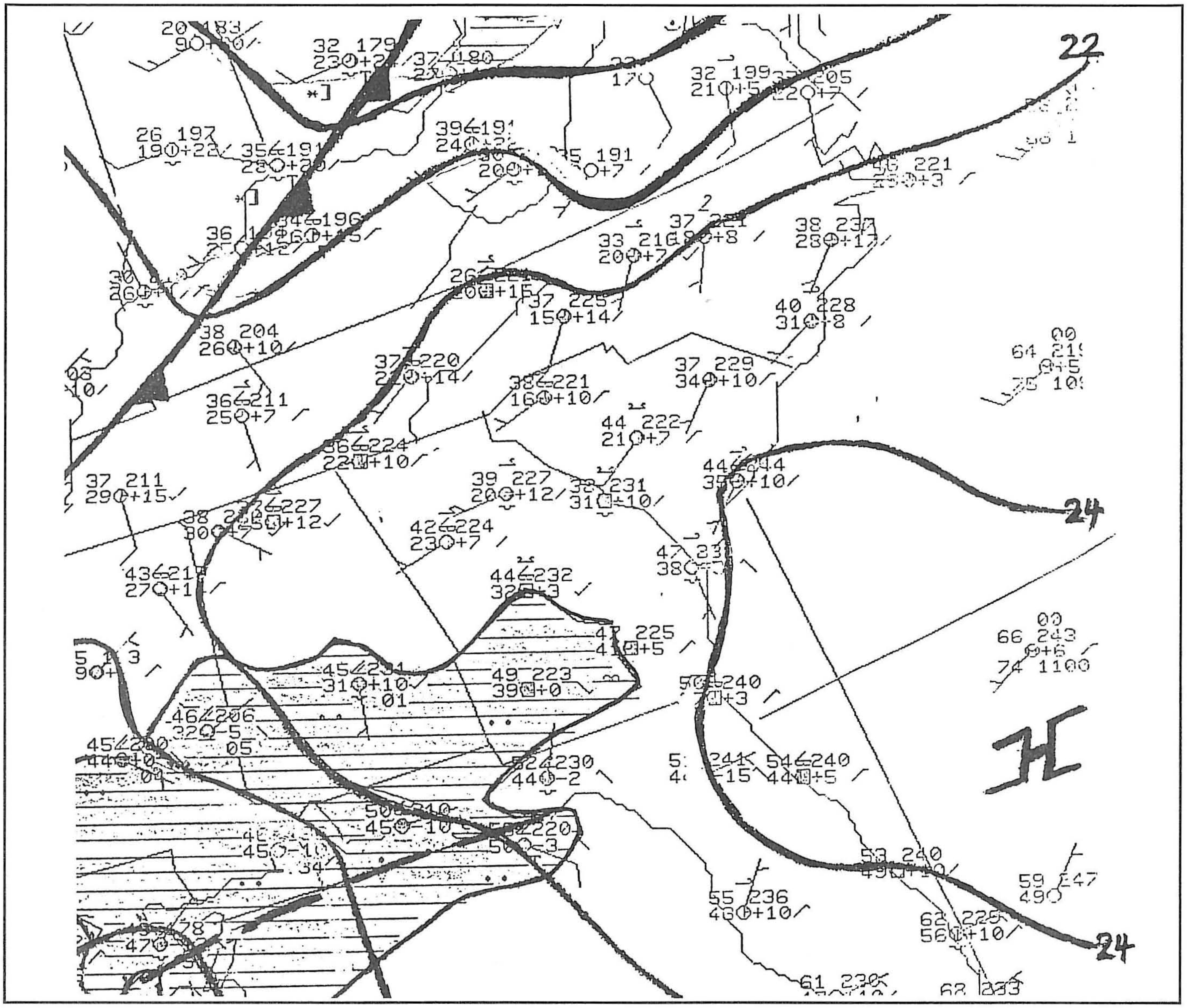

Fig. 3. Surface analysis for 0300 UTC 24 January 1991. Note the retreating high pressure, the advancing cold front, precipitation along the Gulf Coast, and low dew point temperatures over North Carolina.

b. The negative indicators for snow:

1) For the duration of the day at both Charlotte and Raleigh, the NGM profile data indicated the Layer 4 (roughly 850 mb) temperature would hold steady between −3 and −4°C, while the boundary layer (near 600 ft AGL) warmed to between +3 and +4°C.

2) Winds at Raleigh were forecast to remain from the unfavorable southwest direction all day, without any reinforcing shot of cold air.

c. The forecast decision

Taking into account all of this information, the decision was made to upgrade the Winter Storm Watch area to a Winter Storm Warning—with two exceptions. Due to the distance of the northern mountains from the expected storm track, only a Snow Advisory was issued there, while in the far northeast corner of the state, the Watch remained in effect for the afternoon. Winter Weather Advisories for a mixture of rain, sleet, and snow were issued for the central Coastal Plain and the Sandhills. Accumulations of 3 to 5 inches were forecast in the warned areas with an additional inch in the "tonight" period for a storm total of up to 6 inches. The only exception to this was for the southern Piedmont (Charlotte area) and southern Foothills, where storm totals of 7 to 8 inches were forecast (in complete agreement with the adjacent South Carolina zone forecasts).

However, as will be explained later in this paper, snow did not materialize as much as expected. Warnings were downgraded to Advisories and then dropped altogether by late in the day on Thursday. The only Winter Weather Advisory that was extended into Thursday evening was for the Sandhills and southern Coastal Plain region in the far southeast corner of the state.

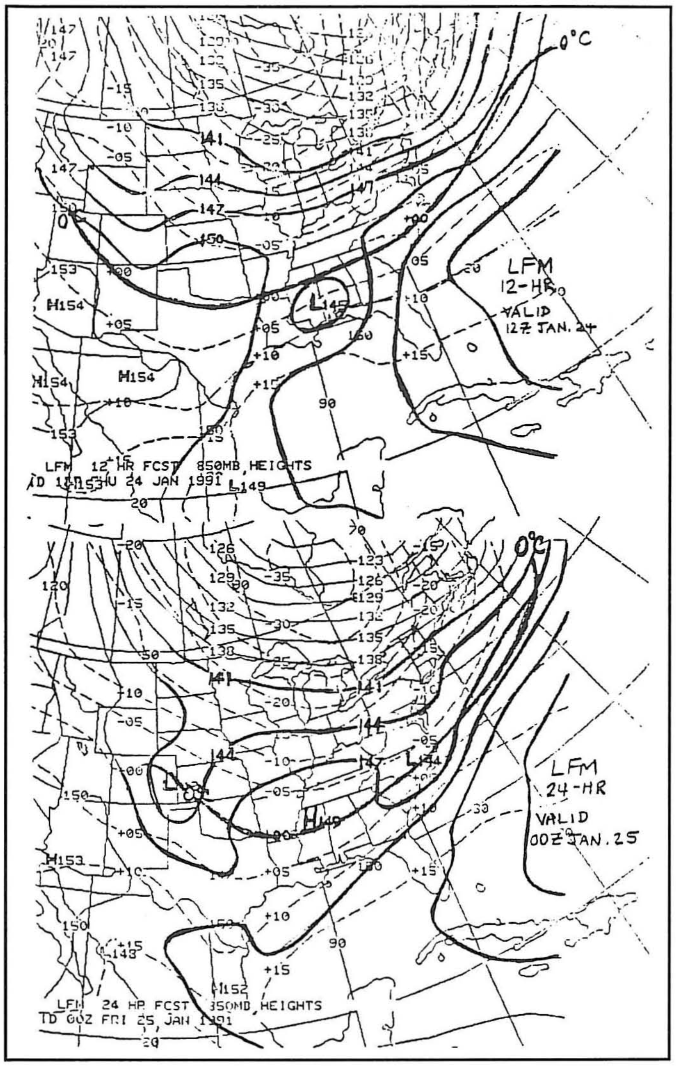

Fig. 4. LFM 12-hour (top) and 24-hour (bottom) 850-mb height and temperature forecasts from the 0000 UTC 24 January 1991 run. Note the track of the 850-mb low center across central North Carolina.

P	GMT	HR PRCP	TOT PRCP	TEMPERATURE BL	L4	L6	L9	L12	RELATIVE HUMIDITY 123456789ABCDEFG	AV	SFC PRES	K*	85-70 DDSS	BL DDSS
0	0	.000	0.00	2.9	-2.4	-8.2	-17.2	-43.7	3456631123478410	40	996	-9	2734	2313
1	1	.000	0.00	3.1	-2.0	-7.3	-17.2	-44.2	3346621124678510	38	996	-14	2732	2313
2	2	.000	0.00	3.2	-2.2	-6.9	-17.3	-42.7	3346721246626510	40	995	-14	2731	2415
3	3	.000	0.00	3.3	-2.4	-6.5	-17.7	-42.6	3347722247647510	43	995	-11	2730	2417
4	4	.000	0.00	3.4	-2.6	-5.9	-18.1	-43.9	3347723357566410	46	995	-9	2730	2517
5	5	.000	0.00	3.4	-2.9	-5.4	-18.6	-44.5	3347724468[illegible]7410	49	996	-8	2731	2617
6	6	.000	0.00	3.4	-3.1	-4.8	-19.1	-43.8	334872467***8310	52	996	-8	2731	2716
7	7	.000	0.00	3.3	-3.2	-4.4	-19.8	-43.5	33486248*****210	54	996	-9	2731	2816
8	8	.000	0.00	3.2	-3.5	-4.5	-20.1	-44.2	4358526******210	58	996	-10	2730	2816
9	9	.000	0.00	3.1	-3.6	-5.4	-19.8	-44.7	4358439******210	62	996	-6	2728	2814
10	10	.000	0.00	3.1	-3.7	-7.0	-18.9	-45.0	4358569******210	67	996	1	2726	28[illegible]
11	11	.000	0.00	3.3	-3.8	-7.8	-18.0	-45.6	435868******8210	73	996	5	2724	2812
12	12	.000	0.00	3.1	-3.6	-7.7	-17.3	-46.0	446889*****37210	81	996	6	2723	2812
13	13	.000	0.00	1.9	-4.0	-7.3	-16.9	-46.2	5799*******77210	93	997	8	2723	2915
14	14	.004	0.00	0.6	-3.8	-6.7	-16.6	-45.1	89*********37210	**	997	8	2723	30[illegible]
15	15	.016	0.02	0.8	-3.6	-6.2	-16.8	-44.4	9*9********36310	**	996	9	2722	32 5
16	16	.036	0.06	1.6	-3.5	-6.6	-17.5	-44.3	*99********76310	**	996	10	2619	35 3
17	17	.072	0.13	2.6	-3.6	-7.9	-17.0	-45.2	**9********95300	**	996	9	2619	32 2
18	18	.076	0.20	3.1	-3.5	-8.7	-16.0	-45.4	**9********97210	**	996	8	2719	31 2
19	19	.051	0.26	3.6	-3.4	-8.8	-15.7	-45.1	**99*******98310	**	996	8	2619	17 1
20	20	.051	0.31	3.7	-3.5	-8.8	-15.4	-45.4	**99*********310	**	994	8	2619	16 2
21	21	.061	0.37	4.2	-3.5	-8.4	-15.6	-45.3	9*9**********310	**	993	8	2618	15 2
22	22	.055	0.42	4.3	-3.6	-7.6	-15.9	-45.2	**9*********9410	**	993	8	2617	13 1
23	23	.042	0.46	4.4	-3.7	-6.7	-16.3	-45.4	**9*********9310	**	993	8	2717	10 1
24	0	.028	0.49	4.4	-3.8	-5.9	-16.6	-45.5	999*********8310	**	993	8	2717	10 2
25	1	.021	0.51	4.6	-3.9	-5.5	-17.3	-45.5	99*9********8310	**	993	9	2817	6 2
26	2	.012	0.52	4.5	-4.0	-5.2	-18.1	-45.1	99*99****9*98310	**	993	9	2816	4 4
27	3	.008	0.53	4.6	-4.1	-5.1	-18.7	-44.6	99999***98[illegible]7410	99	993	9	2816	3 7
28	4	.004	0.54	4.6	-4.2	-4.8	-19.1	-44.2	99999***97767410	97	993	8	2916	3 9
29	5	.001	0.54	4.4	-4.2	-4.7	-19.7	-44.2	9998899986558410	92	993	8	2917	310
30	6	.000	0.54	4.1	-4.0	-4.7	-20.3	-44.4	8997798[illegible]74457410	86	993	7	2918	311
31	7	.000	0.54	3.5	-3.9	-4.9	-20.6	-44.6	8897687752347410	78	993	5	2918	412
32	8	.000	0.54	2.7	-3.9	-5.1	-20.6	-44.9	8897675521236410	69	993	3	2918	41[illegible]
33	9	.000	0.54	1.6	-3.9	-5.2	-20.5	-45.1	8876564310126310	60	993	0	2817	4[illegible]
34	10	.000	0.54	0.5	-3.9	-5.2	-20.4	-45.3	8876453100125310	54	993	-1	2816	416
35	11	.000	0.54	-0.5	-3.9	-5.3	-20.3	-45.6	8876452011225310	50	993	-3	2714	417
36	12	.000	0.54	-1.5	-3.9	-5.4	-20.0	-46.1	8796441012224410	47	994	-5	2714	4[illegible]
37	13	.000	0.54	-2.3	-3.9	-5.7	-19.7	-46.7	8786440123234410	46	995	-6	2714	4[illegible]
38	14	.000	0.54	-1.8	-3.8	-5.9	-19.5	-47.1	7785440124134410	45	995	-7	2714	411
39	15	.000	0.54	-0.1	-3.6	-6.0	-19.2	-47.4	7785440124133400	43	996	-8	2615	5 7
40	16	.000	0.54	1.5	-3.4	-6.1	-18.9	-47.5	6785430123133400	42	996	-10	2615	5 6
41	17	.000	0.54	2.9	-3.3	-6.1	-18.7	-47.5	6784430123132410	41	995	-12	2616	6 5
42	18	.000	0.54	4.1	-3.4	-6.2	-18.5	-47.3	5684430123132410	40	995	-14	2617	6 5

Fig. 5. NGM hourly profile data for Charlotte (CLT), North Carolina from the 0000 UTC 24 January 1991 run. In this figure, the "P" column is the number of hours into the model run; the "GMT" column is the Greenwich Mean Time (or "UTC") hour; "HR PRCP" is hourly precipitation in inches; "TOT PRCP" is the cumulative precipitation total. Temperatures are listed for the BL (≈ 600 ft.), Layer 4 (≈ 5,000 ft.), Layer 6 (≈ 9,000 ft.), Layer 9 (≈ 18,000 ft.), and Layer 12 (≈ 32,000 ft.). Relative humidity, rounded to the nearest 10% with the zero dropped (* means >95%), is given for each of the NGM's 16 layers (which range from Columns 1 through G). Also shown are: "AV" which is the average relative humidity in Layers 1–9 (surface-500 mb); "SFC PRES", the surface pressure; "K*", the K Index computed with values from Layers 4, 6, and 9 (850, 700, and 500 mb, respectively); "85-70 DDSS", the mean of Layer 4, 5, and 6 winds (850-700 mb); and "BL DDSS", the Boundary Layer wind direction and speed.

Note that precipitation was forecast to begin at Charlotte about 1400 UTC Thursday (P = 14 hours) with a storm total precipitation of 0.54 in. Also, saturation occurs in mid levels between 0600 and 1200 UTC, then works its way to the surface between 1300 and 1400 UTC.

4. What Actually Occurred

Moderate to heavy snow spread northeastward into western sections of South Carolina Thursday morning. By late in the afternoon, 6 or more inches had fallen in the mountains and foothills of South Carolina. The moderate snow spread northeastward into the southern Piedmont of North Carolina. Charlotte picked up an inch of snow in the morning. The community of Pineville, in southern Mecklenberg County (just south of Charlotte), reported 2 inches on the ground at one point in the afternoon. But that is where the snow stopped its northeastward trek.

A mixture of snow, sleet, and mostly rain spread slowly northeast toward Raleigh, while rain overspread the southeast half of the state. Unfortunately, the northward movement of the precipitation slowed down to almost a halt—not reaching the Raleigh area until around noon instead of mid-morning, as had been expected. By then, the temperature had risen to the mid to upper 30s. In and around Raleigh, rain with scattered plops of wet snow on the windshield was observed, although no snow was officially reported at the airport. In fact, rain fell all the way westward into the Foothills during the afternoon. Light snow with little accumulation fell in the Southern Mountains, but accumulations of around an inch were reported above elevations of 5,000 ft.

During the early afternoon, pressures began to fall rapidly along the Carolina coasts, indicative of the upward vertical motion maximum that had been consistently forecast by the models (Fig. 6). NMC analyses showed a weak surface trough off the Carolina coasts at that time. It is possible that an organized surface frontal wave developed offshore, but a lack of data precluded its analysis. Suddenly, rain changed to snow in

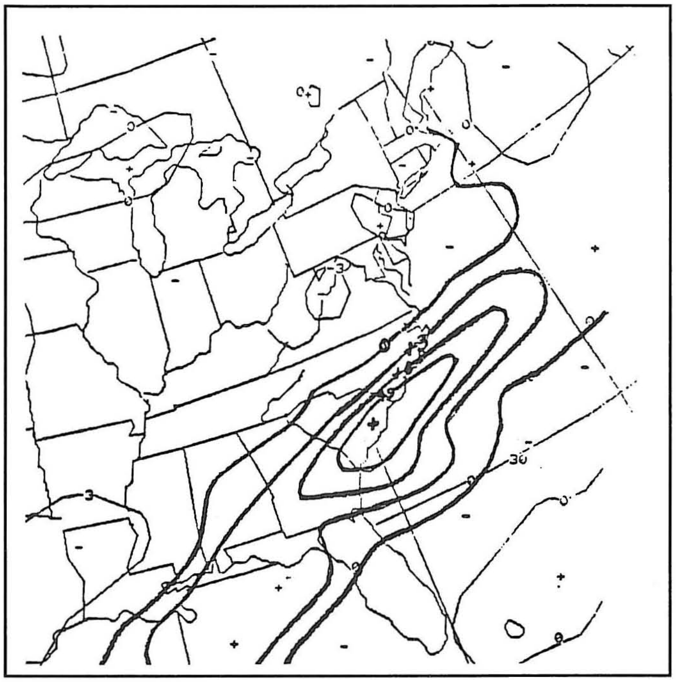

Fig. 6. NGM 24-hour, 700-mb vertical velocity forecast valid 0000 UTC 25 January 1991. Note the maximum upward motion along the southeast coast of North Carolina.

the southern Coastal Plain and Sandhills region, where the temperatures had risen to near 40°F. Two to three inches of snow fell (mainly on grassy surfaces) in Robeson County (between Fayetteville and Wilmington). One to two inches of snow were reported in Scotland and Sampson Counties—also in the southeastern part of North Carolina (see map—Fig. 1). Where the radar showed the heaviest precipitation (mainly VIP 3's) snow was observed. (Some of this higher reflectivity was likely due to large, melting snowflakes.) In Raleigh, the precipitation was very light and fell almost entirely as rain. However, a pilot flying over Raleigh reported snow falling down to 800 feet above the ground before changing to rain below.

The 500-mb analyses from 1200 UTC 24 January and 0000 UTC 25 January (Fig. 7) showed a weakening north-south oriented trough moving across the Gulf Coast states with weak positive vorticity advection spreading into North Carolina. At 0000 UTC 25 January, the 850-mb low was weaker (1480 m) than the LFM had forecast 24 hours earlier (1440 m) and about 275 miles farther to the southwest (compare Figs. 4 and 8). At both 1200 UTC 24 January and 0000 UTC on the 25th, the 850-mb temperatures were within a couple of degrees of what was forecast by the models. For the most part, the winds over eastern North Carolina were westerly and nearly parallel to the isotherms, thus minimizing temperature advection. However, toward 0000 UTC, there was a somewhat more pronounced area of warm advection over far southeastern North Carolina as the low tracked in that direction.

Figure 9 is an 850-mb analysis from 0000 UTC 25 January that utilized McIDAS (Man-Computer Interactive Data Access System) software to draw contour intervals every 5 m and isotherms every 2°C. This more clearly identifies the trough position and implied region of warm advection (where the height contours cross the isotherms). Notice that now the thermal forcing appears to be over South Carolina and extreme southeast North Carolina.

At 1200 UTC Thursday, the Greensboro sounding showed a 1000-850 mb thickness of 1310 m (warmer than the 1300 m that the NGM had forecast) and the 850-700 mb thickness was 1520 m (the same as the NGM had forecast). When these numbers were plugged into the precipitation type applications program that had predicted about a 55% conditional probability of measurable frozen precipitation for Raleigh based on the NGM forecast, the probability dropped to 37%. According to the scheme, this would indicate that if precipitation were to occur, there would only be a trace amount of frozen precipitation (Keeter et al. 1988, 1991).

5. Why it Didn't Turn Out as Expected

Many of the reasons for the "bust" have already been stated, but will be summarized here along with some additional discussion of thermodynamic processes that were at work. The authors' hypothesis is also presented.

a. Summary of reasons for the non-occurrence

1) The delayed onset of precipitation allowed the surface temperatures to warm into the upper 30s to near 40°F at most locations. This helped explain why the majority of the Piedmont area received mostly rain.

2) A reinforcing shot of cold air from the north never arrived. In fact, winds stayed from the southwest just about all day. In North Carolina, it is difficult to get a sustained snow event without a good deal of cold air in place and a northeast flow in the lowest layers, providing cold air advection.

3) In this study, the long wave pattern featured a broad trough over the central United States with two distinct jet streams west of the Rockies and generally confluent flow farther to the east. Typically, in these patterns, models have difficulty handling the interaction, phasing, and timing of shortwaves that are in separate streams. On 24 January 1991, the northern shortwave outran the southern system and helped suppress it farther to the south.

4) The increased upward vertical motion probably led to cooling and enhanced precipitation. According to the thermodynamic equation (from Penn 1957),

$$\frac{\delta T}{\delta t} = -V \cdot \nabla T - w(\gamma_d - \gamma) + \frac{1}{c_p}\frac{dQ}{dt}$$

(a) (b) (c)

the change in temperature over time is a function of (a) advection, (b) vertical motion, and (c) diabatic cooling (due to evaporation or melting). In the absence of a well-organized surface system (as in this event) and with light winds, the contribution of horizontal temperature advection is small. The temperature profile and associated precipitation type then becomes dependent on the processes of adiabatic cooling/warming (from increased upward/downward vertical motions) and diabatic processes.

Increased upward vertical motion (Fig. 6) was probably a major reason why rain changed to snow in southeastern North Carolina. This led to increased adiabatic cooling and increased precipitation rates. Without nearby radiosonde measurements, it is difficult to determine at what level(s) above the ground this cooling was maximized.

5) It is likely that the diabatic process (third term in the equation above) of melting (latent heat of fusion, which absorbs energy from the surrounding air) caused additional cooling of the lowest layers of the atmosphere over southeastern North Carolina.

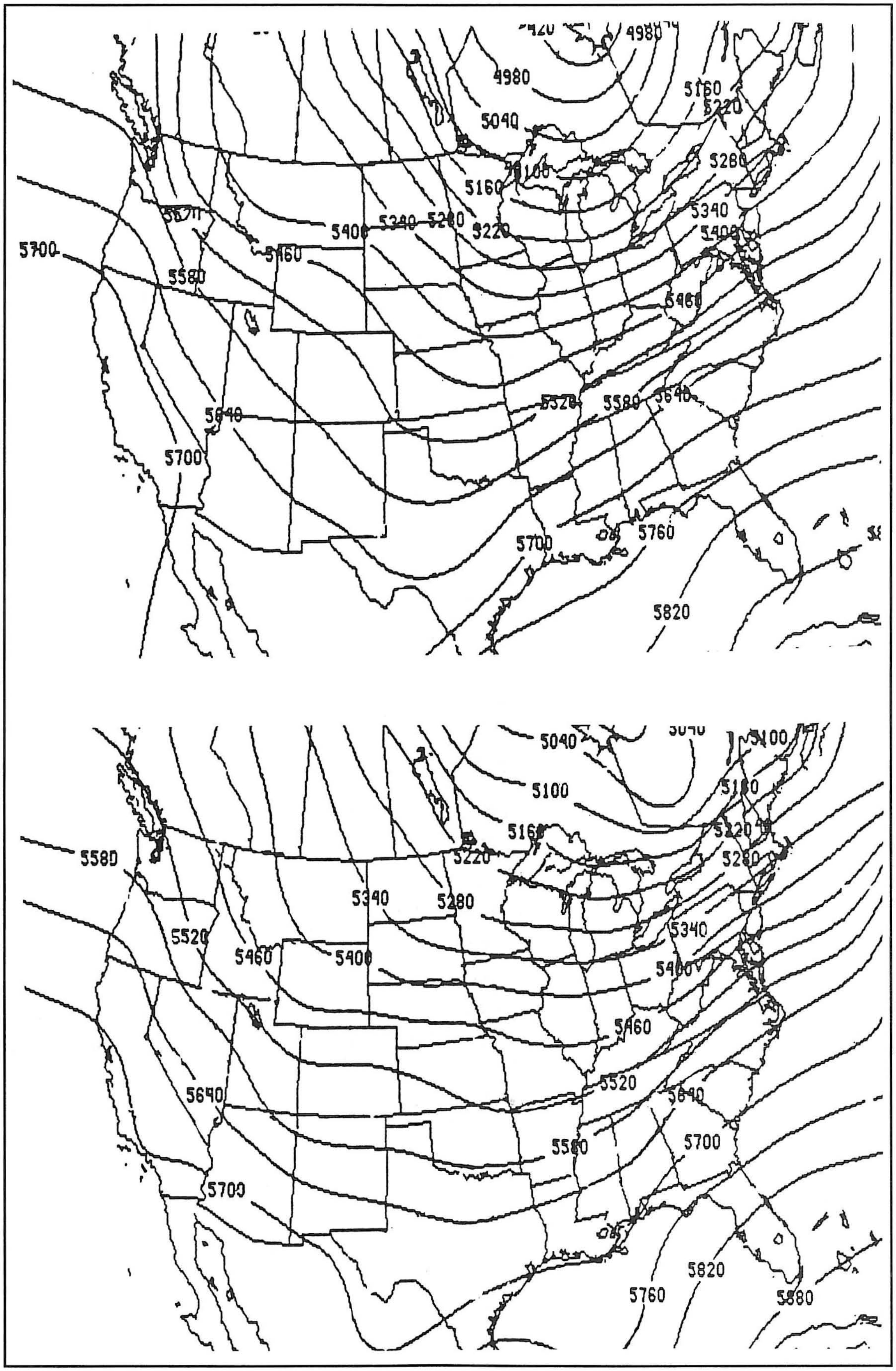

Fig. 7. 500-mb height analyses for 1200 UTC 24 January 1991 (top) and for 0000 UTC 25 January 1991 (bottom) (from McIDAS).

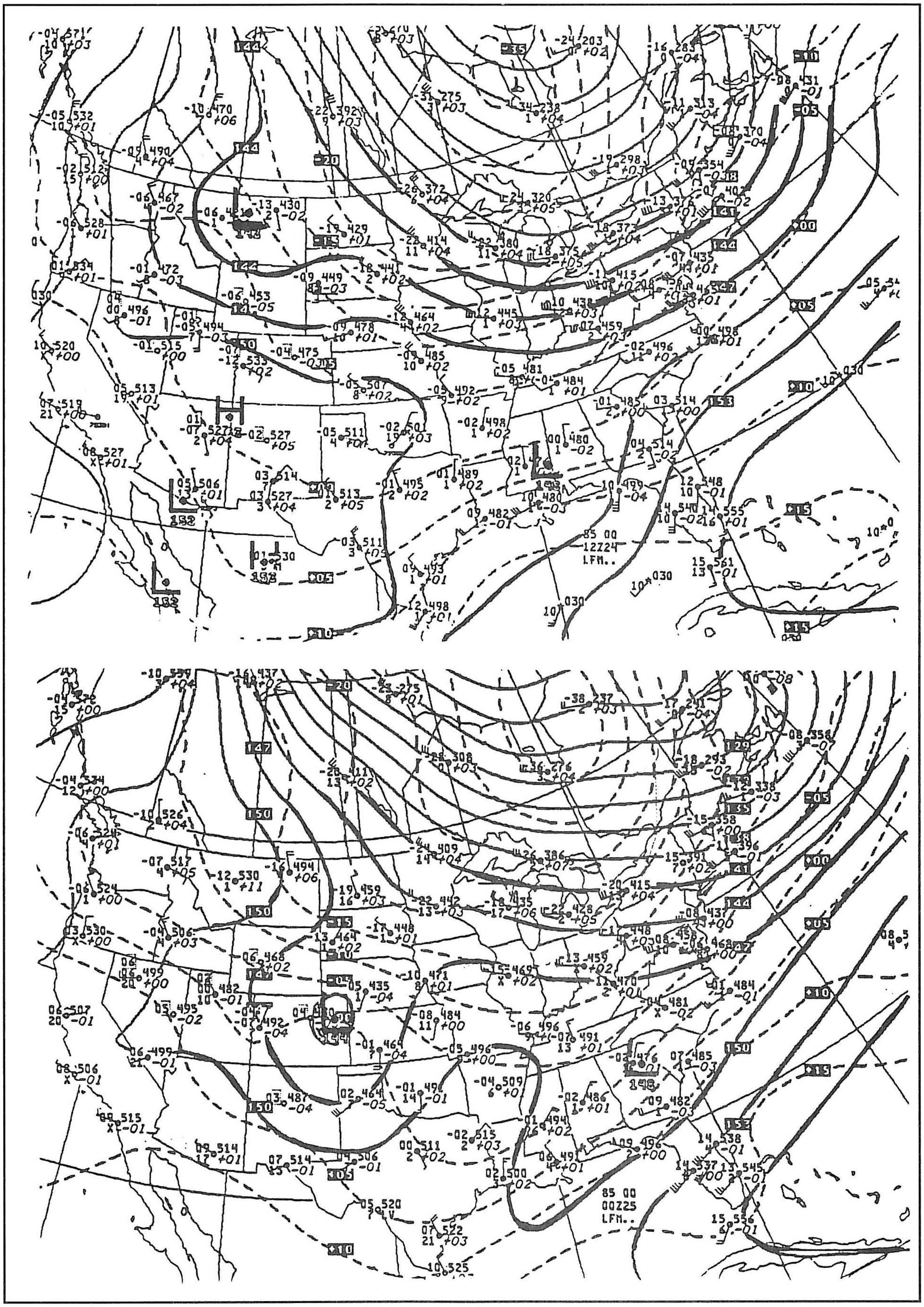

Fig. 8. LFM 850-mb height and temperature analyses from 1200 UTC 24 January 1991 (top) and 0000 UTC 25 January 1991 (bottom).

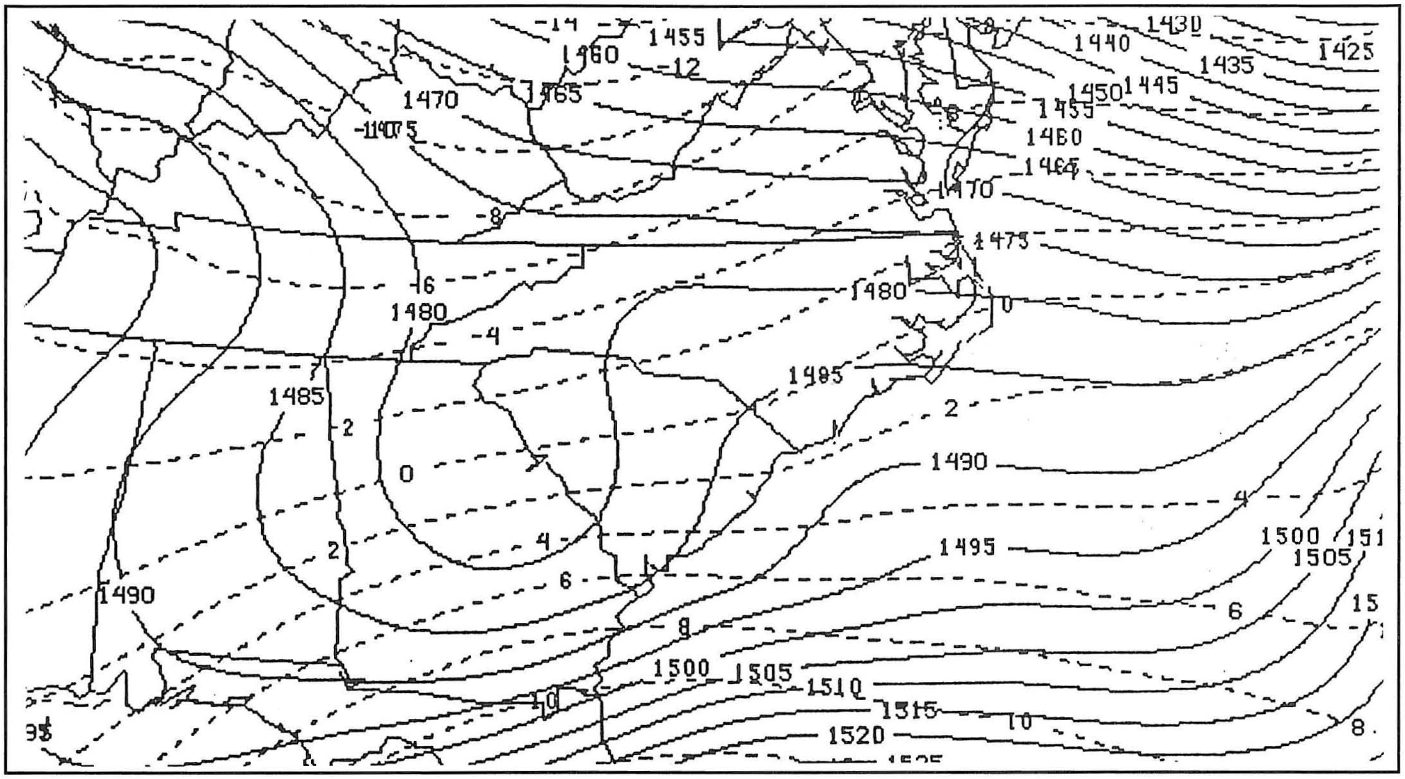

Fig. 9. McIDAS-derived, 850-mb height and temperature analyses for 0000 UTC 25 January 1991. Contour intervals: 5 m (heights) and 2°C (temperatures).

Normally, the role of melting is much less significant than the role of evaporation (since the latent heat of fusion is only 79.7 cal g^{-1} and the latent heat of evaporation is 597.3 cal g^{-1}). According to Penn (1957), "To obtain substantial temperature changes due to melting, it is necessary to have rather heavy amounts of precipitation falling and little warm air advection [to counteract it]." In addition, LaPenta (1988) noted, "Unlike evaporative cooling, the cooling due to melting is not dependent on the degree of saturation." Numerous studies have found melting of falling precipitation to be a key factor in determining precipitation type (Bosart and Sanders 1991; LaPenta 1988; Stewart and King 1987; and McGuire and Penn 1953).

In southeastern North Carolina, there were no strong gradients of temperature, there was significant precipitation, and the air had become almost totally saturated. Therefore, melting was very important. Rainfall amounts in excess of one inch (1.03 inches was reported at Wilmington) fell across southeast North Carolina in the area where the precipitation changed to snow. In Raleigh, farther northwest, only 0.03 inches of precipitation fell all day.

b. A hypothesis for what occurred

Based on the available information, the following is a hypothesis which explains what the authors believe happened (Fig. 10). From a pilot report above Raleigh (RDU), snow was changing to rain at 800 ft. Therefore, the melting/freezing level was probably several hundred feet higher—let's say around 1,500 ft. In the absence of real-time upper air data, it is reasonable to estimate that the freezing level sloped upward towards warmer air over the southeast and was perhaps 3,500 ft in the Sandhills/Southern Coastal Plain and 5,000 ft at Wilmington (ILM). (Wilmington's surface temperature was near 40°F all day and rain was the only type of precipitation observed.)

Increased upward vertical motion in the southeast led to cooling of the air in or above the boundary layer and enhanced precipitation rates. As a result, the melting snow began to cool the column of air down to near freezing. According to Wexler et al. (1954), the cooling rate due to melting is inversely proportional to the thickness of the layer cooled and directly proportional to the precipitation rate. They showed that 1 inch of precipitation melted in a layer 200 mb thick would produce a drop in temperature of 2.5°C within that layer. Cooling due to the process of melting would, in time, create a near 0°C isothermal layer. Deep layers of air that are near freezing are conducive to the formation of large snowflakes due to aggregation. These large snowflakes are more likely to reach the surface even if the freezing level is elevated because they must fall farther before they can melt completely.

Radar observations supported this scenario. Recall that high reflectivity VIP levels 2 and 3 were observed over the Sandhills during the time that the changeover occurred at the surface. According to Penn (1957), this "bright band" seen on radar is associated with the melting layer, whose depth can vary as much as 1,500 ft depending upon snowflake type, melted drop size, and the lapse rate.

So, after a few hours of precipitation, the cooling effect of the melting precipitation caused the freezing level in the Sandhills/Southern Coastal Plain to gradually lower to between 1,200 ft and 1,500 ft above the ground, a level from which the snow could reach the ground. The heavier precipitation rate allowed the snow to accumulate rapidly and 2-3 inches of snow accumulated on mainly grassy areas northwest of Wilmington—despite the above freezing surface temperature.

At Wilmington, the same processes were occurring, but the higher freezing level and warmer surface temperature prevented anything but rain from falling. At Raleigh, 0.03 inches of precip-

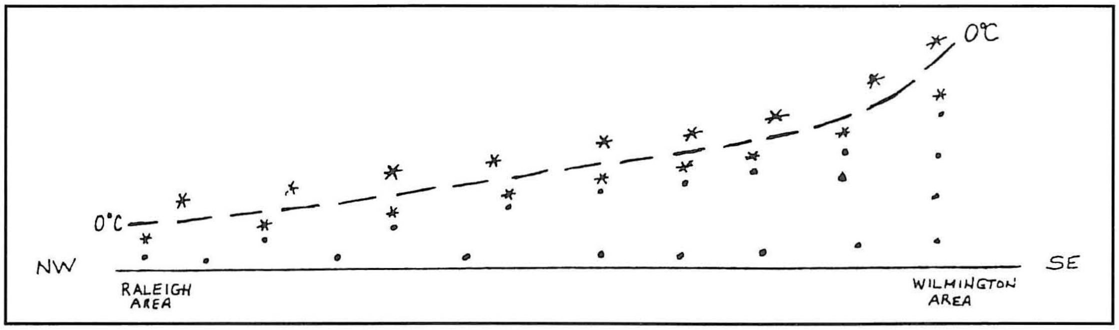

Fig. 10a. During the morning of 24 January 1991, precipitation generally was light; some heavier rain was occurring in parts of southeastern North Carolina. The freezing level (dashed line) showed a gentle slope and ranged from approximately 1,500 ft near Raleigh to about 5,000 ft near Wilmington.

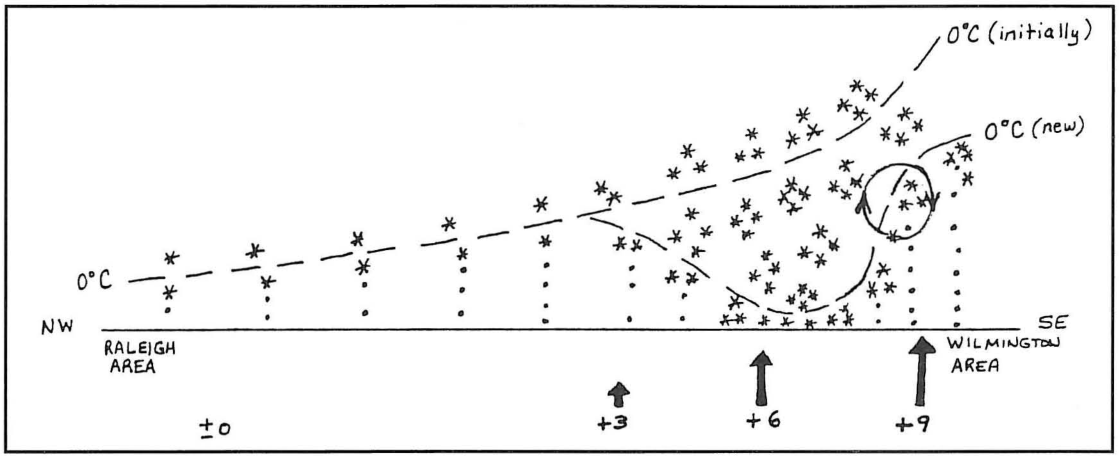

Fig. 10b. During the afternoon and evening of 24 January, increased vertical motion over southeast North Carolina led to increased precipitation rates (strength of NGM 24-hr forecast vertical motion valid for 0000 UTC 25 January is shown at bottom in microbars/second and by solid arrows). Cooling, mainly due to the process of melting, created a "deep" isothermal layer to the northwest of Wilmington. Deep, near 0°C layers are conducive to the formation of large snowflakes. Snow reached the ground and accumulated in the Sandhills/Southern Coastal Plain to the northwest of Wilmington. A possible mesoscale circulation initiated by the gradient of melting also is indicated aloft between Wilmington and the Sandhills.

itation was too insignificant for melting or evaporation to have been important (there was hardly anything to melt or evaporate). The NGM vertical motion forecast (Fig. 6) actually was negative (downward), so that, too, did not contribute to cooling.

Recent literature has discussed the fact that mesoscale circulations may develop as a direct result of the gradient of melting snow. According to Lin and Stewart (1986), a circulation develops due to an ''elevated temperature perturbation associated with non-uniform cooling in a melting layer.'' Similar to a sea breeze circulation, the elevated horizontal temperature gradient enhances the upward vertical motion in a favorable large scale environment. Actually, the idea of a mesoscale circulation due to the gradient of melting was first discussed by Atlas et al. (1969), but they had not included vertical motions in their modeling work. Stewart and King (1987) stated that in the case of a rain-snow boundary, the temperature gradient would be greatest near the boundary, as opposed to the rain region where melting is occurring everywhere or the snow region where it does not occur at all.

In this case study, we have already suggested that melting helped to lower the freezing level over the Sandhills. However, if the melting was not horizontally homogeneous and if a gradient of melting existed to the southeast of there (more melting aloft over Wilmington, less over the Sandhills), then a mesoscale circulation could have been initiated. Local downward motion associated with the air cooled from melting aloft in the Wilmington area would, by continuity, be compensated by local ascent northwestward into the snow area (see circulation shown in Figure 10b). This could have played a role in the enhanced snowfall rates in the Sandhills region.

6. Summary and Conclusions

The forecasters at the NWSFO Raleigh had a difficult forecast situation on 24 January 1991 and suffered a ''busted'' forecast. Although it would be easy to blame a bad forecast on bad guidance, we should be able to understand and recognize when the forecast scenario is not happening as expected and update the guidance. After all, we should be the experts for forecasting winter storms in North Carolina. But, this storm would have been tough for any person or large scale dynamical computer model to predict!

The upward vertical motion in this case study resulted from several factors: weak warm advection at the 850-mb level; an approaching 500-mb short wave trough (albeit very weak); possible warm frontogenesis along the coast; and an intense,

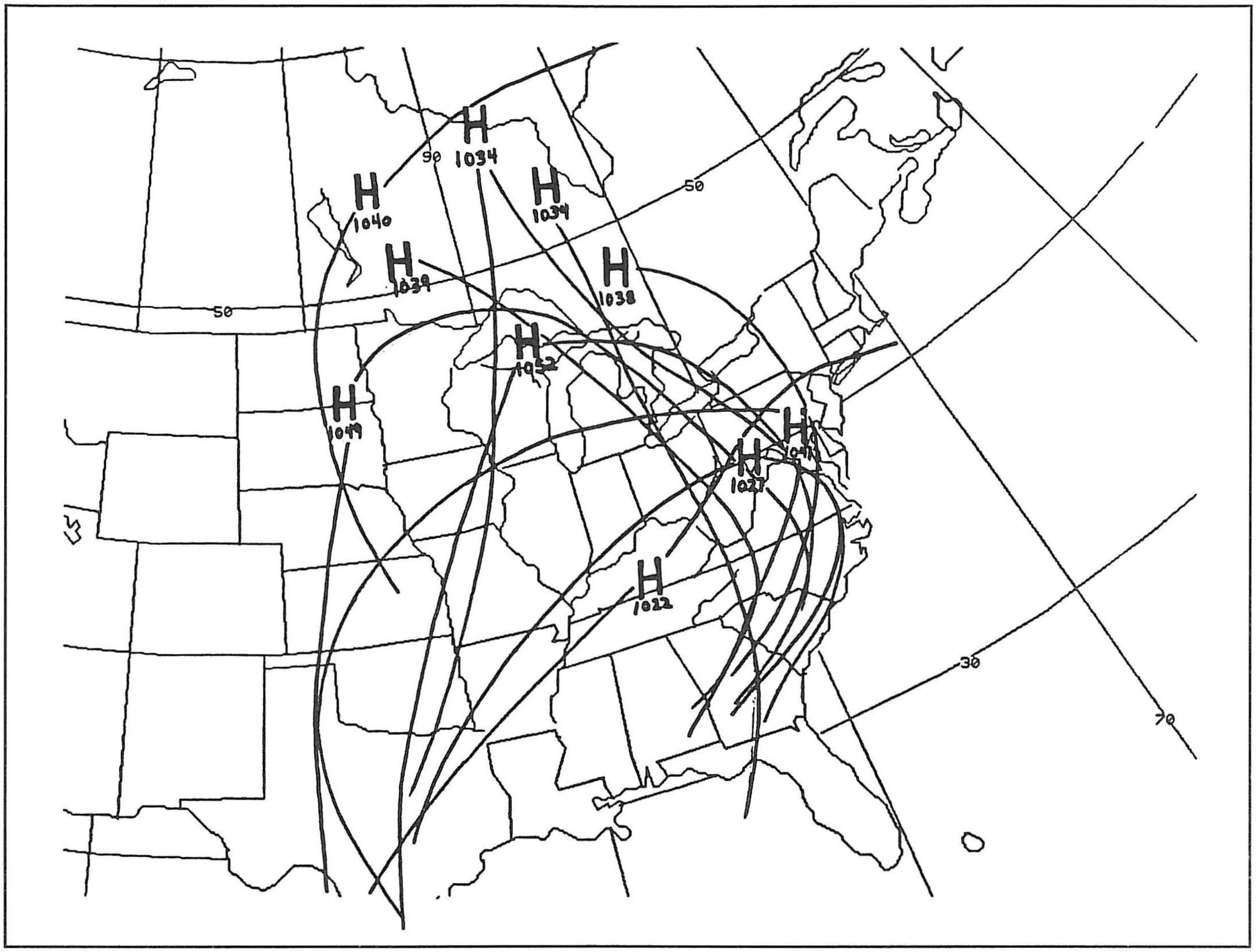

Fig. 11. Locations of high pressure centers within 24 hours of the onset of heavy snow events in North Carolina from 1970–1987. Solid lines indicate ridge axes.

small-scale temperature gradient near the rain-snow boundary. In these situations, guidance such as the NGM net vertical displacement and the 700-mb vertical velocities can give important clues about potential forecast problems. It has been hypothesized that in the presence of weak thermal advection combined with substantial precipitation amounts, melting and evaporation played important roles in the changeover to snow in southeastern North Carolina. With little vertical motion and insignificant precipitation amounts in the northern Piedmont, melting and evaporation played very minor roles, thus keeping the precipitation in the form of rain. A good overview of precipitation types, their formation, and spatial and temporal features can be found in Stewart (1992).

Since this event, an examination of 25 snow events over the eastern two thirds of North Carolina between 1970 and 1987 has shown that the position of the surface high pressure center is critical in determining the likelihood of heavy snowfall in this state. It was found that all but two snow events involved a surface high located to the northwest of the state within 24 hours of the onset of precipitation. In the other two cases, the surface highs were centered along the southeast coast, as in this case. In 10 heavy snow events (≥4 inches), none had high centers along the southeast coast (Fig. 11).

Perhaps, in the future, forecasters should use an "Advisory" rather than a "Warning" in situations where there is still a reasonable amount of doubt due to model disagreements or atypical synoptic patterns. Complete conservatism is not being advocated, however. If the forecaster feels that the Winter Storm Warning criteria could be met—even in the third period—and there is little conflicting evidence, he/she should not hesitate to go with the Watch/Warning.

Another lesson derived from this event is that NGM hourly profile data—while potentially useful in an operational sense—are only as good as the model from which they are run. The NGM temperature predictions of +3 to +4°C at the surface and −3 to −4°C at 850 mb were quite good. But, the timing and amount of precipitation were both incorrect.

Probably the most important thing that can come from this episode is the fact that this scenario has become a part of our collective forecast experience. Hopefully, if a similar situation arises in the future, this paradigm can be recalled.

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