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OVERVIEW AND MODEL ANALYSIS OF THE 25-26 JANUARY 2004 CAROLINA COASTAL PLAIN ICE STORM

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Abstract

Ice storms in the coastal plains of the Southeast United States are often difficult to forecast given limitations in modeling the very shallow subfreezing air masses typical in cold air damming scenarios east of the Appalachian Mountains. This subfreezing layer of air is particularly shallow in close proximity to the synoptic boundary separating much warmer maritime air to the east.

Operational tools used by forecasters to diagnose the potential for freezing rain events across the Piedmont of the Carolinas (Fig. 1a, 1b) are known to be of limited utility in coastal areas. This case study is intended to identify operational tools that will be useful in assessing freezing rain potential in the coastal plain of the Carolinas. A very damaging ice storm occurred across portions of the eastern Carolinas on 25-26 January 2004. Operational forecast models had difficulty resolving the very shallow subfreezing air mass present during these two days. A review of this event indicated that although model trends were in error, there were several parameters suggesting there would be precipitation type problems. Useful forecasting tools were identified, including pattern recognition, surface wet bulb temperature, and shallow-layer (1000-950 hPa) partial thicknesses.

1. Introduction

During 25-26 January 2004 a substantial ice storm affected the coastal plains of northeast South Carolina and southeast North Carolina. During the course of the two day event considerable tree damage occurred across a large portion of the Weather Forecast Office (WFO) Wilmington, NC (ILM) County Warning Area (CWA) (Fig. 2). The total monetary loss in the WFO ILM CWA was estimated to be $41.7 million and thousands of residents in the hardest hit areas were without power for a couple weeks (National Climatic Data Center 2005).

Across WFO ILM's CWA, ice accumulations generally ranged from 0.50 to 0.75 inch. At one point on 25 January 2004, freezing rain occurred at surface observation stations along the coast. In addition, there were several reports of freezing rain at some of the barrier islands. A band of ice accumulations exceeded 1 inch across Columbus County, NC (Fig. 2). It is fairly uncommon that an ice event of this magnitude occurs within close proximity to the coast. In fact, the highest frequency for ice events in the Carolinas occurs from the Appalachians to the Piedmont region (Gay and Davis 1993), as opposed to the coastal plains.

Before and during this event, model forecasts and techniques developed for inland sections of the Carolinas were of limited utility due to proximity to the coast, and the very shallow depth of the cold surface layer. Forecasters used surface wet-bulb temperatures to better diagnose the initial precipitation type. However, the duration of the event was not accurately forecast, and lead times were limited to approximately 8 hours each day. This paper will provide forecasters with information on how the Eta Forecast and the Global Forecast System (GFS) numerical models handled the synoptic and thermal characteristics leading up to and during this event. Specific consideration will be given to the handling of the extremely shallow cold air mass and evaporative cooling that locked the cold air in place over the region through the duration of the episode. The main purpose of the study is to demonstrate the application of nontraditional partial thickness schemes and surface wet-bulb temperatures as winter weather precipitation type forecasting tools. The awareness of these applications will help forecasters produce more accurate predictions of precipitation type in coastal areas of the Carolinas, and in situations when the subfreezing layer is very shallow.

2. Synopsis

During the evening of 24 January 2004, a cold front moved across the Carolinas. After the passage of the cold front, surface high pressure became established between the Appalachian Mountains of the western Carolinas and the western Atlantic Ocean (Fig. 3) by 25 January 2004. As a result, a very shallow wedge of cold air, as seen in the vertical profile of the Eta Binary Universal Form for the Representation of Meteorological Data (BUFR) sounding (Fig. 4), extended to the southeastern North Carolina coast. During this time an upper level closed low over the Baja California region opened and lifted northeast across the Southern Plains (not shown). The upper level low's position favored deep moisture advection across the southeast United States (not shown). Meanwhile, a strong area of confluence (Fig. 5) aloft became situated north of the Carolinas. This confluent zone supported a 1036 hPa parent surface high pressure center, the subsequent low level cold air, and advection of single digit dew points (^{o}F) into the Carolinas. The very low dew points, ensuing evaporative cooling, isentropic lift, and very strong low-level moisture transport helped to set the stage for the first part of the ice storm that commenced on 25 January 2004 (not shown).

The initial area of upward vertical motion (not shown) progressed away from the WFO Wilmington CWA the night of 25 January 2004. The second part of the event on 26 January 2004 was marked by another upper level impulse that passed over the region as well as a large swath of upper diffluence, which lead to strong upward vertical velocities. In fact, the upward motion was strong enough that embedded areas of convection developed, resulting in enhanced precipitation amounts across portions of the CWA. Meanwhile at the surface, the cold air wedge remained anchored in place with supporting strong upper level confluence persisting and surface parent high north of the region.

Finally, on 27 January 2004 an area of low pressure developed along the Carolina Coast and translated northward. The subsequent pressure falls that developed over North Carolina and Virginia as the low moved north reduced the influence of the parent high pressure. Thus, the evolution of the low gradually ended the cold air advection into the eastern Carolinas, which eventually lead to the demise of the wedge. Also, by this time the deep moisture plume had become displaced farther off the East Coast and the isentropic lift became neutral as winds backed in response to the area of low pressure bringing an end to the precipitation.

3. Data and Methodology

Several surface based observed parameters were compared to model guidance for five stations within the WFO ILM CWA, which includes portions of southeast North Carolina and northeast South Carolina (Fig. 2). The inland portion of the domain that was hardest hit during the event included three stations: Florence, SC (KFLO), Elizabethtown, NC (KEYF), and Lumberton, NC (KLBT). This domain also included two coastal stations, North Myrtle Beach, SC (KCRE) and Wilmington, NC (KILM) where the ice accretion had the least impact. Other observation stations in the area were not considered due to complete or substantial loss of data during this episode.

Six hourly observations of temperature, dewpoint, liquid precipitation amount, and precipitation type were examined for each station. Surface wet-bulb temperature was calculated directly from the observations (NWS 2006). Forecasts of the same parameters were examined from the Eta and GFS model, and the GFS based Model Output Statistics (MAV MOS) bulletins for each station. As with the observations, the MAV forecast surface wet-bulb temperature was calculated using the temperature and dewpoint from the bulletins.

4. Model Performance – Temperatures, QPF, and Overall Trends

Model performance was poor overall with chronic warm biases evident in forecast thermal profiles across the Eastern Carolinas. The GFS was initially the better model in successfully predicting a potential ice event several days in advance. GFS model runs from 06 UTC, 12 UTC and 18 UTC on 24 January 2004 all showed the potential for an ice storm over interior sections of the Carolinas, based on forecast surface wet-bulb temperatures across the northwestern counties in the WFO ILM CWA. As the event drew closer, the GFS initialization became more inaccurate with each subsequent run (Fig. 6). The Eta performed very poorly at first, but was later the model that was able to resolve the extremely shallow cold air mass trapped at the surface throughout the event. By 06 UTC on 25 January 2004, the Eta was able to resolve a shallow subfreezing surface layer for 24 hours before scouring it out (not shown). In fact, it took until the 00 UTC run on 26 January 2004, nearly halfway through the ice event, for the Eta to adequately maintain the shallow cold air mass.

Both models were too fast in eroding the shallow layer of cold air in place across the area. Even at the onset of the freezing rain between 1400 and 1700 UTC on 25 January, model surface temperature initialization errors of 10° F were common in portions of the forecast area. These errors rapidly increased during the model run with errors approaching 30° F in some GFS runs. With such poor handling of low-level temperatures (Figs. 7a and 7b), model thicknesses were also too high and were misleading to forecasters using traditional thickness-based precipitation type forecasting.

Temperatures from MOS forecasts were also inaccurate, particularly from MOS based off the GFS model. Reasons for the continued poor model initialization and performance (particularly in the GFS) were due to poor assimilation of such an extremely shallow layer of cold air in the model initialization scheme. With so few model layers located in the cold air near the surface, the model scoured out the shallow cold air mass and allowed warmer air from aloft to mix down to the surface. At the time of this event, the GFS contained 64 vertical layers, 13 of which were below the 850 mb level (National Centers for Environmental Prediction; http://www.emc.ncep.noaa.gov/gmb/STATS/tpb97/TPB02/html/v3.html). The Eta contained 60 vertical layers, 24 of which were below 850 mb (National Centers for Environmental Prediction; http://www.emc.ncep.noaa.gov/mmb/mmbpll/eta12tpb/). Comparatively fewer of the GFS' vertical layers were located near the surface which gave the Eta an advantage in maintaining the cold boundary layer.

Despite generally poor performance with low-level temperatures, the models performed reasonably well with Quantitative Precipitation Forecasts (QPF). It is worth noting that at the time of this event Automated Surface Observing System (ASOS) and Automated Weather Observing System (AWOS) units were not equipped with all-weather heated rain gauges, which can accurately measure all forms of precipitation including freezing rain and sleet. Considerable under measurement of precipitation occurred in inland areas where precipitation fell almost exclusively as freezing rain; therefore the accuracy of model QPF is difficult to assess in these locations. The two coastal ASOS sites, KILM and KCRE, measured liquid storm total precipitation amounts of 0.60 and 1.49 in respectively (Fig. 8a and 8b). This was very close to forecast precipitation amounts at KILM, and was partially above model forecast amounts at KCRE. It is a common forecaster rule-of-thumb that the first one to two tenths of an inch of precipitation falling into a dry air mass will evaporate and modify the thermal moisture profile of the lower atmosphere. Since all locations received more than enough precipitation to fully take advantage of available evaporative cooling, it is not believed QPF issues played a significant role in determining the outcome of this winter weather event. Locally enhanced precipitation amounts resulted from embedded elevated convection inland during the daylight hours on 26 January 2004.

5. Useful Forecasting Techniques

a. Surface Wet-bulb Temperatures

In freezing or frozen precipitation events, a potentially useful tool in temperature forecasting is the surface wet-bulb temperature. As precipitation falls into a dry near-surface layer, the layer will be cooled by evaporation. In the absence of other processes, the temperature will approach the wet-bulb temperature as saturation is reached. Janish et al. (1996) used the surface wet-bulb temperature as an approximation of the surface air temperature within a few hours after the onset of precipitation. However, after precipitation has been falling for several hours, evaporative cooling becomes a smaller factor due to low-level saturation and other processes, including thermal advection and adiabatic cooling due to ascent, begin to dominate (NWS 2005).

Immediately preceding this event, forecasters used model forecasts of surface wet-bulb temperatures to identify the potential for freezing precipitation. Beginning with the 0000 UTC 24 January 2004 run, the Eta and GFS forecasted that surface wet-bulb temperatures would be near freezing at the time of expected precipitation onset between 1200 and 1800 UTC 25 January 2004 (Fig. 9). At 1200 UTC, observed surface temperatures in the WFO Wilmington CWA were near freezing, with dewpoints around 20^{o} F. By 1800 UTC, a few hours after precipitation onset, surface temperatures had dropped to between 28 and 30^{o} F. The forecast surface wet-bulb temperatures from the Eta and GFS were better predictors of the temperature at onset of precipitation than any MOS forecast temperatures (Fig. 10). However, both the Eta and GFS forecasts of surface wet-bulb temperatures in later periods exhibited similar biases to each model's temperature forecast (GFS shown in Fig. 11a, 11b).

Model forecasts of surface wet-bulb temperatures were useful in forecasting the precipitation type at the onset of this event. However, forecast wet-bulb temperatures should be used with caution, just as any other numerical model forecast. Observed surface wet-bulb temperatures can also be used as a nowcasting tool.

b. Low-level Partial Thicknesses

An often used tool in forecasting precipitation type is the model forecast low-level (1000-850 hPa, and 850-700 hPa) thickness (the thickness of a layer is proportional to the mean temperature). Studies of precipitation events in the northeastern, mid-Atlantic, and southeastern United States (Keeter and Cline 1991; Heppner 1992) have identified critical 1000-850 hPa thicknesses near 1310 m, below which freezing or frozen precipitation is likely. Keeter and Cline (1991) suggested that critical thicknesses should be used with caution near the coast, because the marine influence was not accounted for in their study. Gay and Davis (1993) found a spatial variation in the mean 1000-850 hPa thickness associated with freezing rain events that occurred in the southeastern United States between 1949 and 1989. The mean thickness for freezing rain events increased from approximately 1290 m over the inland portion of the WFO ILM County Warning Area to approximately 1320 m near the southeast North Carolina coast. This variation might suggest that the critical thickness for freezing precipitation near the coast is slightly higher than suggested for the Piedmont by Keeter and Cline (1991).

The low-level thickness forecasts from successive Eta and GFS runs showed the 1000-850 hPa thickness near the critical 1310 m threshold at the time of precipitation onset between 1200 UTC and 1800 UTC on 25 January 2004. Each run also showed the 1000-850 hPa thicknesses increasing well above this critical threshold at 0000 UTC 26 January 2004 and beyond. If the 1000-850 hPa thicknesses had been the only forecasting tool used, forecasters would likely have predicted no more than a brief period of freezing or frozen precipitation at onset.

Another situation limiting the utility of the 1000-850 hPa thickness would be that of a very warm layer near 850 hPa overlying a cold but shallow near-surface air mass, as was the case on 25-26 January 2004. In this unusual case, it would be possible to observe near-surface temperatures below freezing, when the 1000-850 hPa thickness would otherwise suggest temperatures above freezing throughout the layer. In this case, the partial thickness of a shallower layer would likely be more useful in forecasting precipitation type. Souza (1994) developed the "TOP DOG" (Type of Precipitation: Descriptive and Objective Guidance) approach, which examined thicknesses of shallower layers, and found critical 1000-950 hPa thicknesses between 415 and 420 m, below which freezing or frozen precipitation is likely in the cold air damming regions of the southeastern United States.

Even though the 1000-850 hPa thicknesses were indicative of temperatures above freezing throughout the layer, the Eta forecast 1000-950 hPa thicknesses remained near critical values through 0000 UTC on 27 January 2004 at all three inland sites examined. At the two coastal sites, the 1000-950 hPa thicknesses were in the critical range at 1800 UTC on 25 January 2004, then, increased above the threshold for the remainder of the event. Both coastal stations did observe a brief period of freezing rain just after precipitation onset. In Fig. 12 the contour plot of Eta forecast 1000-950 hPa thickness for 1800 UTC 26 January 2004 shows the 416 m thickness contour extending from southeastern Florence County, northeast across portions of Marion, Horry, and Columbus Counties, and into eastern Bladen County. At the time of the event, GFS forecast 1000-950 hPa thickness was not available. This contour roughly coincides with the region of heaviest ice accumulation shown in Fig. 2. In this event, the shallow-layer partial thicknesses would have enabled forecasters to better predict the duration of the freezing precipitation. However, at the time of this event, this information was not readily accessible to operational forecasters.

6. Discussion

The ice storm that impacted the eastern Carolinas on 25-26 January 2004 was a very rare event, as freezing rain only occurs on the order of once per year in the coastal counties of the Carolinas (Gay and Davis 1993). Numerical model guidance was of limited utility in forecasting this event due to model limitations, which include the handling of a very shallow cold air mass and evaporative cooling processes.

Because of the limitations of numerical models in handling coastal freezing rain events, situation awareness is essential to correctly forecast these events. Forecasters should be cognizant of the initial temperatures and dewpoints in place across the forecast area, the timing of precipitation onset, and the intensity at onset. Forecasters should apply conceptual models to assess whether numerical guidance is representative. For example, in this event, strong upper confluence north of the region supported a persistent surface cold layer that was not depicted well by the MAV guidance.

Two forecasting tools were found to be more effective than MOS guidance or the more traditionally used 1000-850 hPa thickness for predicting precipitation type. In situations in which evaporative cooling is expected to be an important factor due to a dry low-level air mass, observations and forecasts of surface wet-bulb temperature can be an approximation of surface temperature at the onset of precipitation. When the cold near-surface air mass is expected to be especially shallow, the thickness of a shallower layer (e.g., 1000-950 hPa) is likely to be more useful in forecasting precipitation type than more widely used low-level thicknesses (e.g., 1000-850 hPa). However, forecasters must still recognize that model forecasts of wet-bulb temperature and low-level thickness are subject to the same limitations as other model guidance, and therefore use this information with caution.

7. Conclusion

Substantial icing near the Carolina coast is an extreme event, and one that tests limitations of numerical models. Forecasting tools developed for use in inland locations also suffer from limitations in coastal areas because of marine influences, and when the surface cold layer is especially shallow. Forecaster understanding of these limitations is critical. Through pattern recognition, forecasters can identify events in which numerical model guidance is unrepresentative, and the utility of other forecasting techniques may also be limited. Forecasting tools such as the surface wet-bulb temperatures and shallow-layer low-level thicknesses can be used to improve the accuracy and lead time of forecasts, watches, warnings, and advisories in freezing rain events.

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Figures

http://cgia.cgia.state.nc.us/ncgdc/

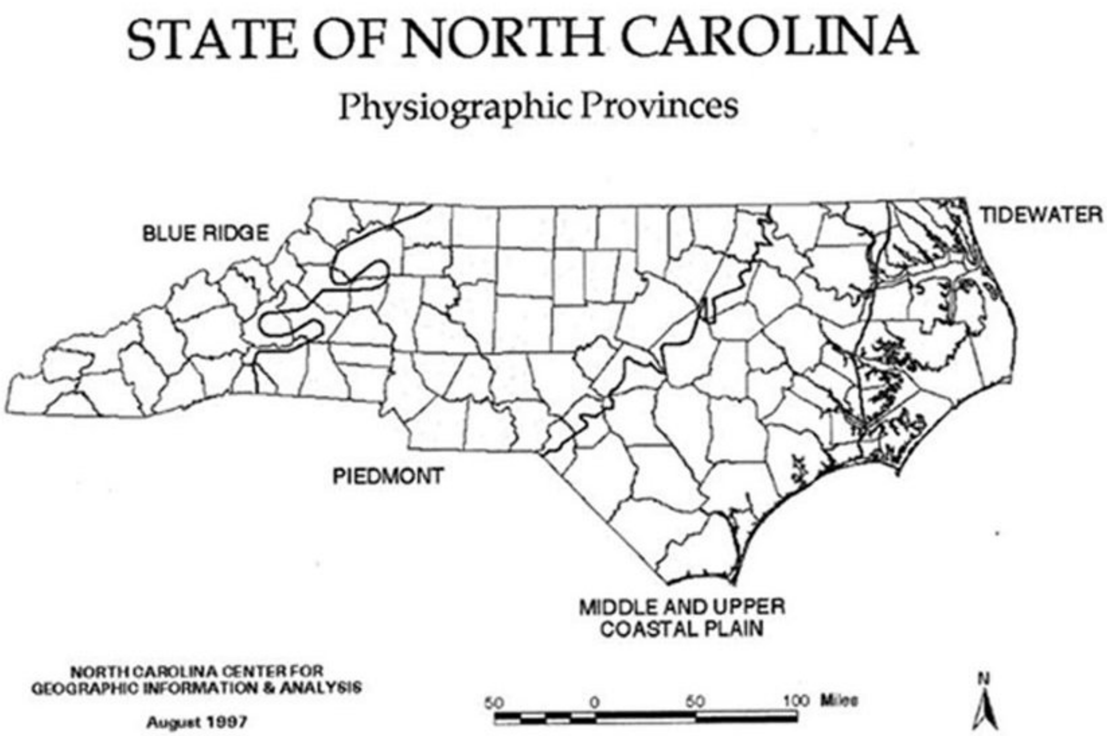

Figure 1a. North Carolina geographical regions map from the North Carolina Center for Geographic Information & Analysis.

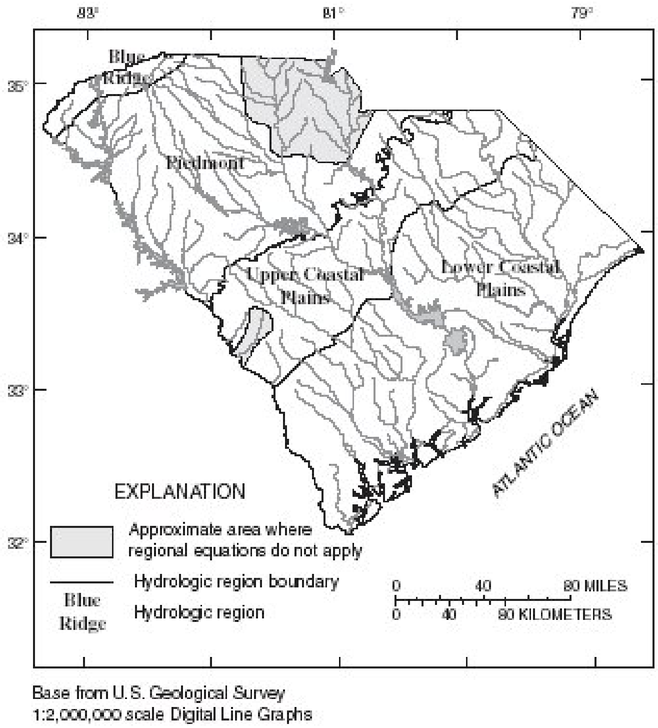

Figure 12. South Carolina geographical regions map from the United States Geological Survey.

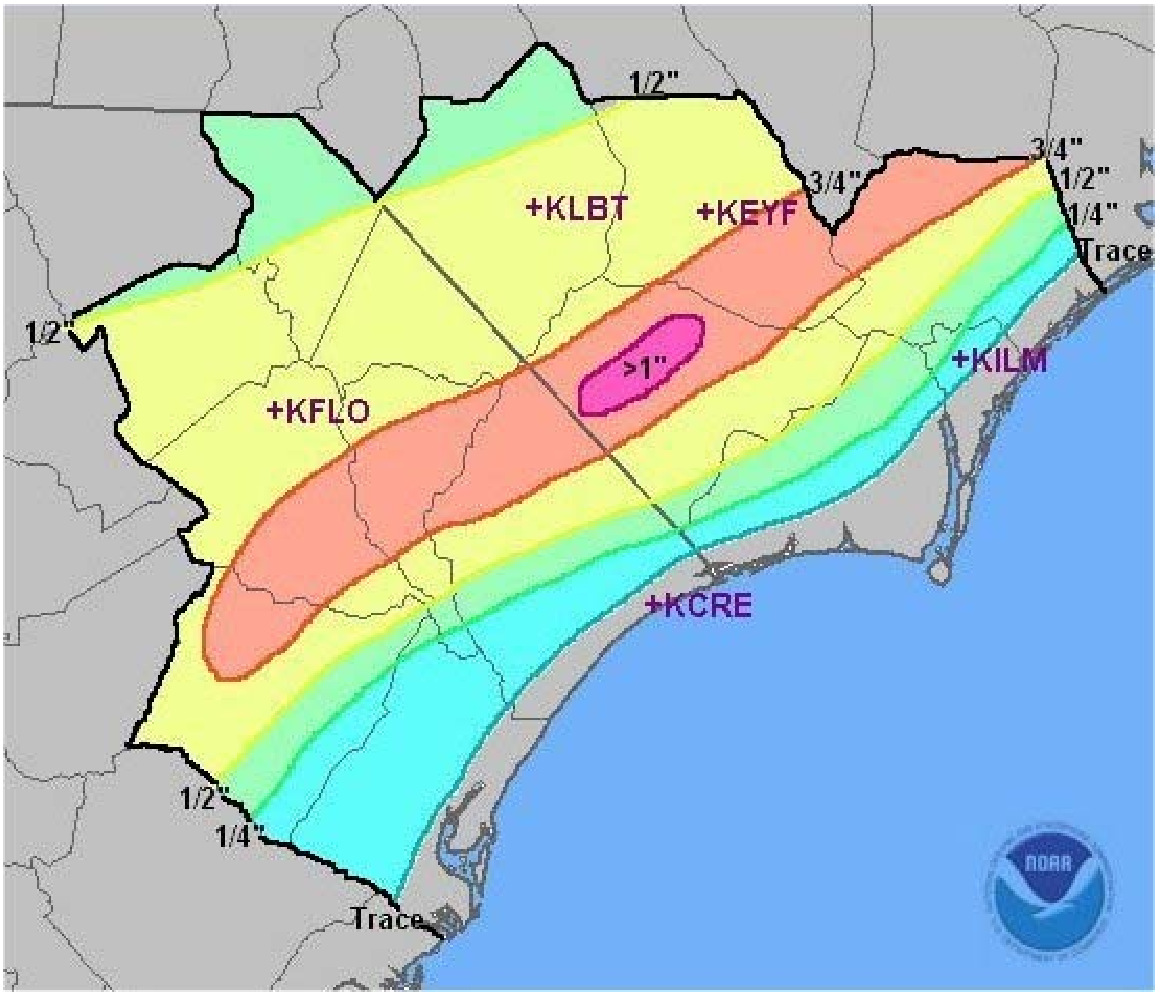

Figure 2. Total Ice Accumulations across the WFO ILM County Warning Area 25-26 January 2004.

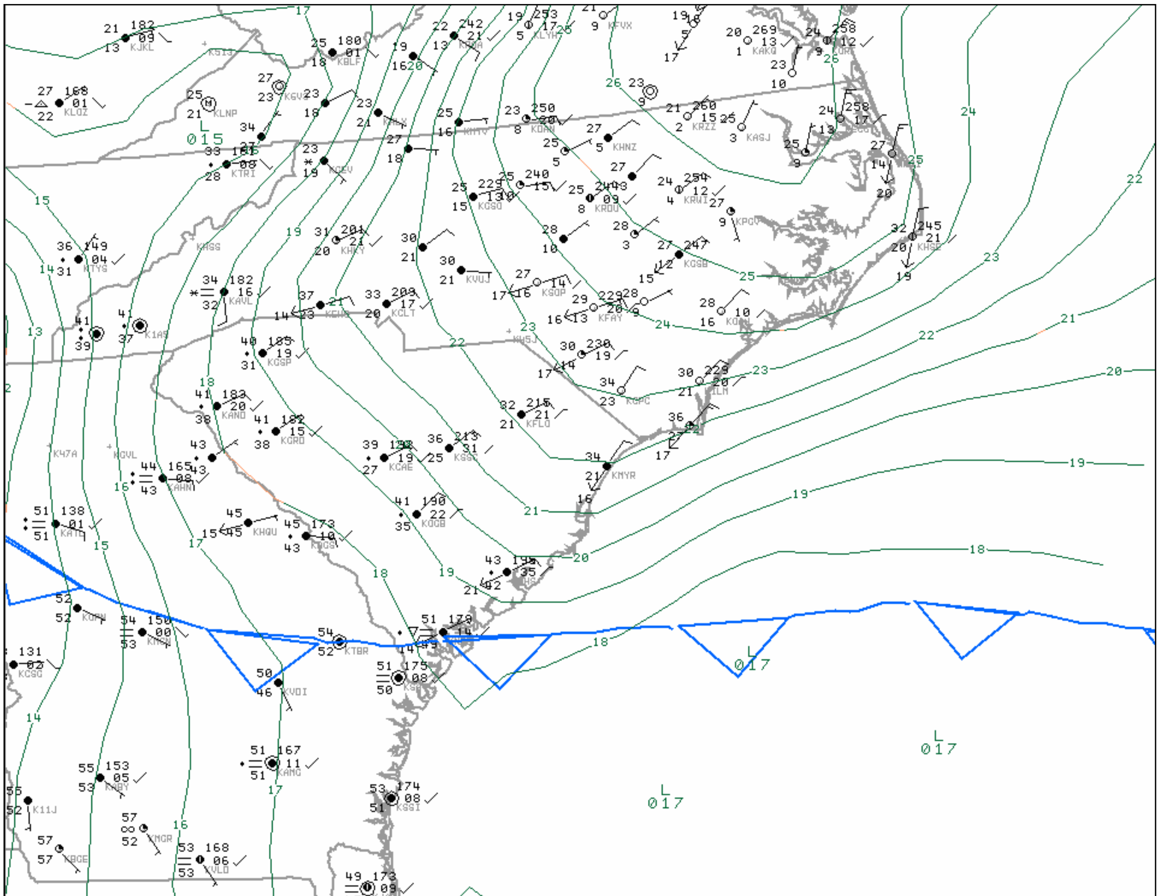

Figure 3. Surface plot, MSAS mean sea level pressure analysis (every 1 hPa) and Hydrometeorological Prediction Center (HPC) frontal analysis valid 1200 UTC 25 January 2004.

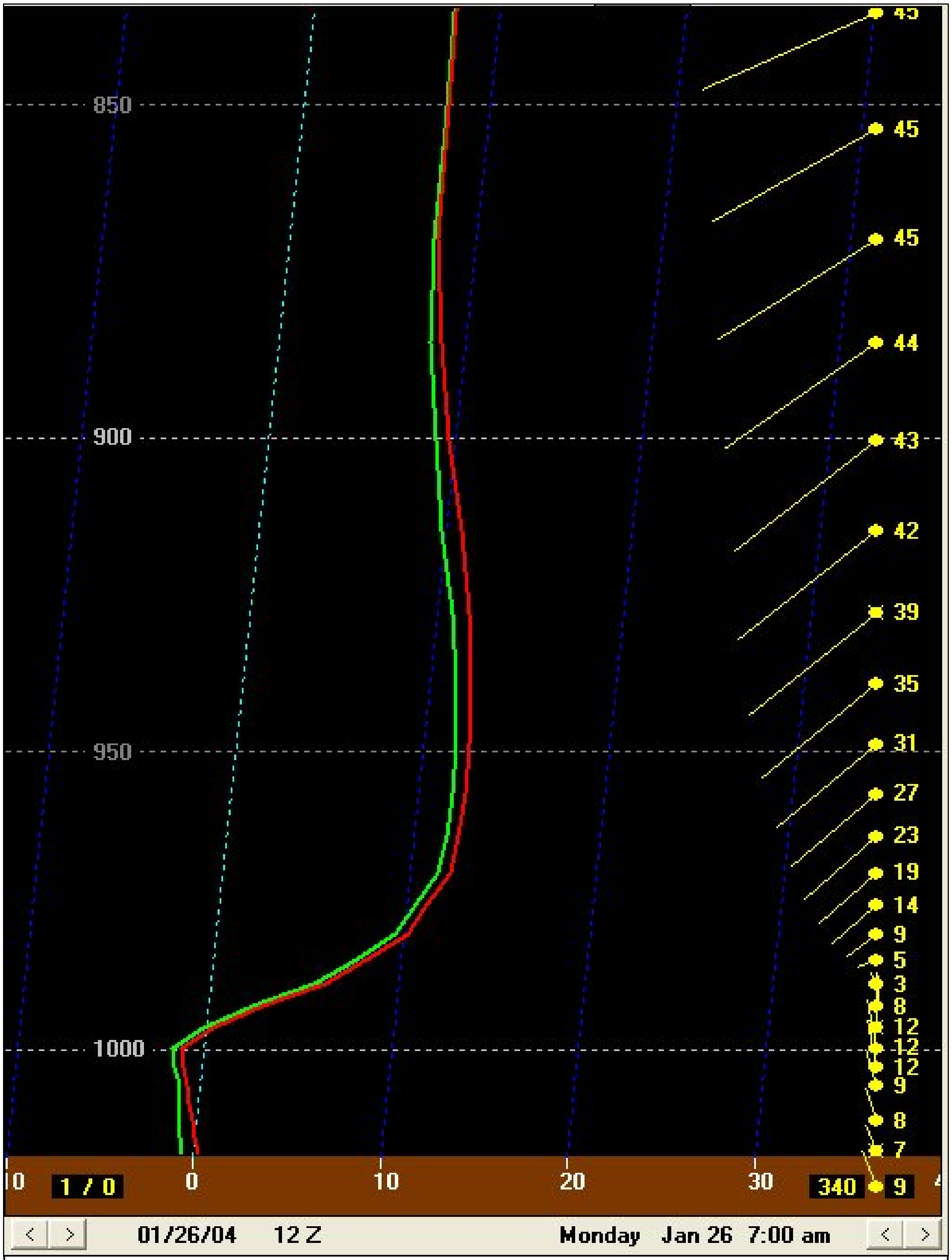

Figure 4. 1200 UTC 26 January 2004 initialized BUFR sounding for Wilmington, NC. This sounding shows the depth of the freezing layer confined from the surface to around 1000 hPa.

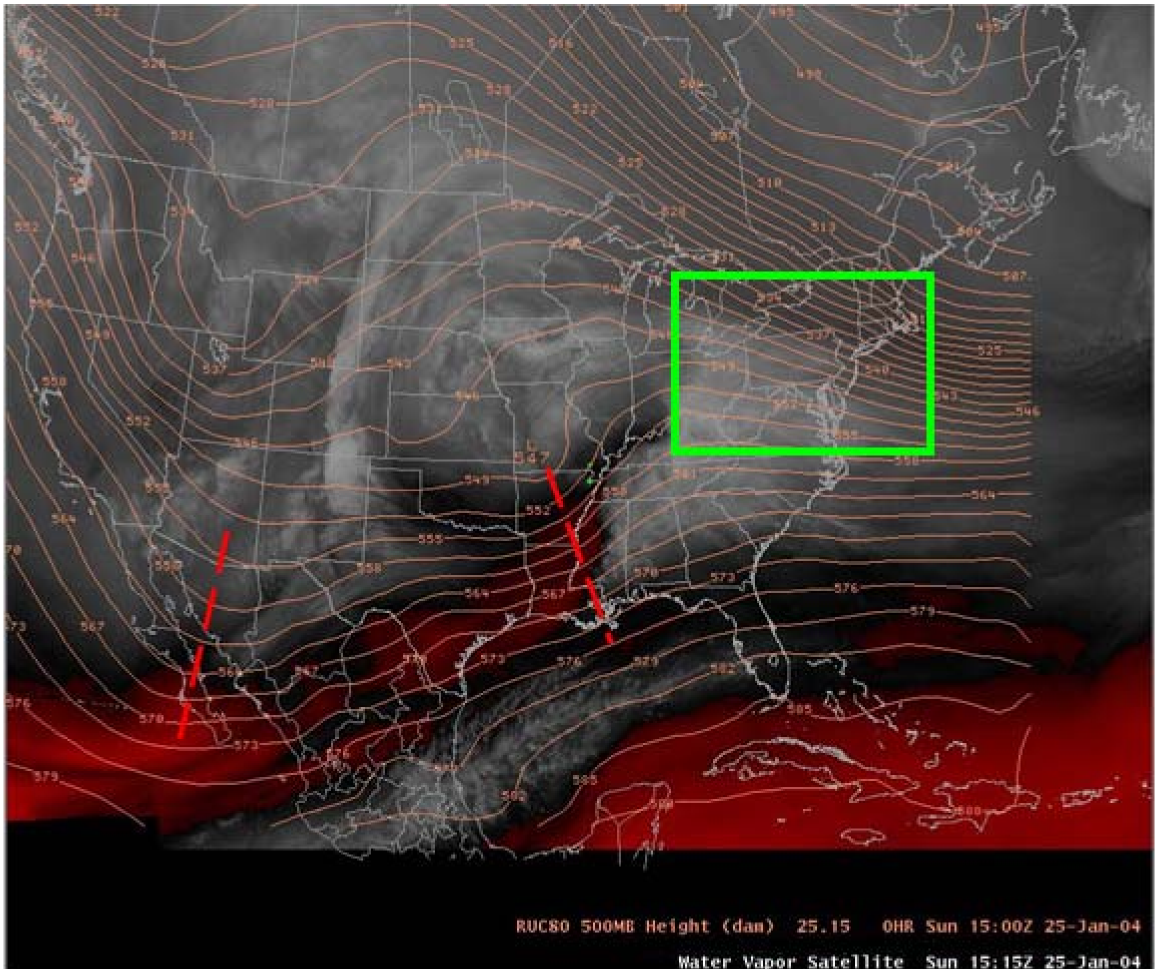

Figure 5. 1500 UTC 25 January 2004 water vapor imagery highlighting the area of upper confluence over the Ohio and Mid Atlantic regions (green box). Other features of note include

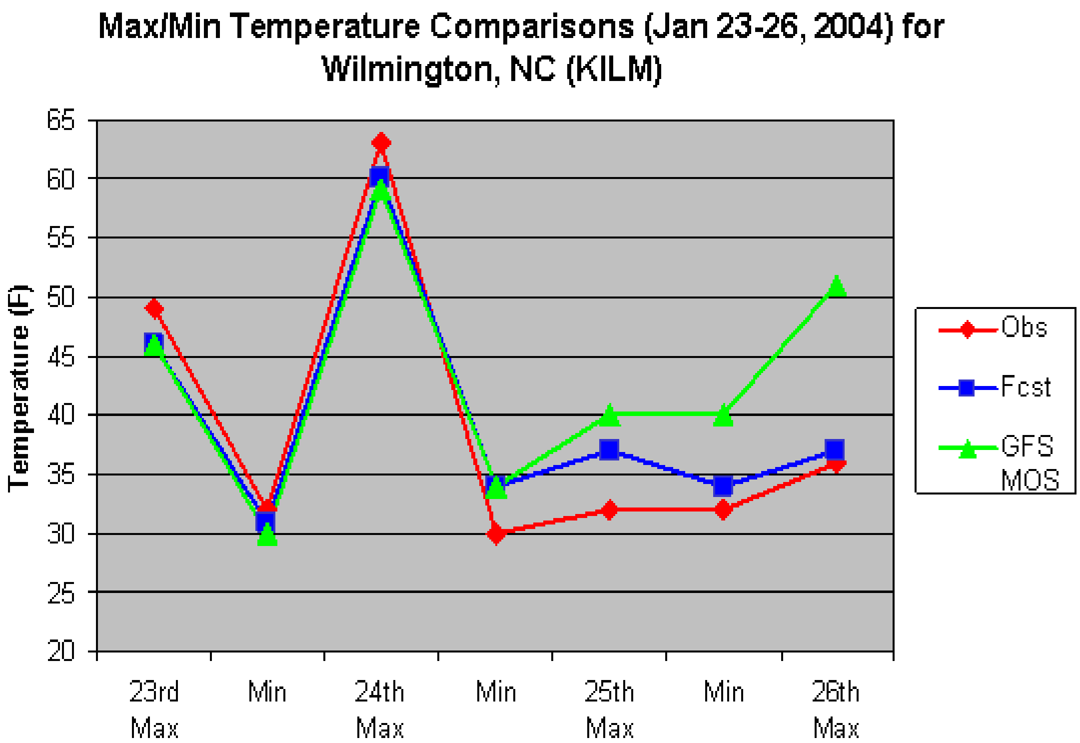

Figure 6. Comparison of GFS MOS model runs, WFO ILM forecast, and observed maximum and minimum temperatures for Wilmington, NC (KILM) through 23-26 January 2004. Note the separation between GFS MOS and actual forecast temperatures beginning with the maximum temp

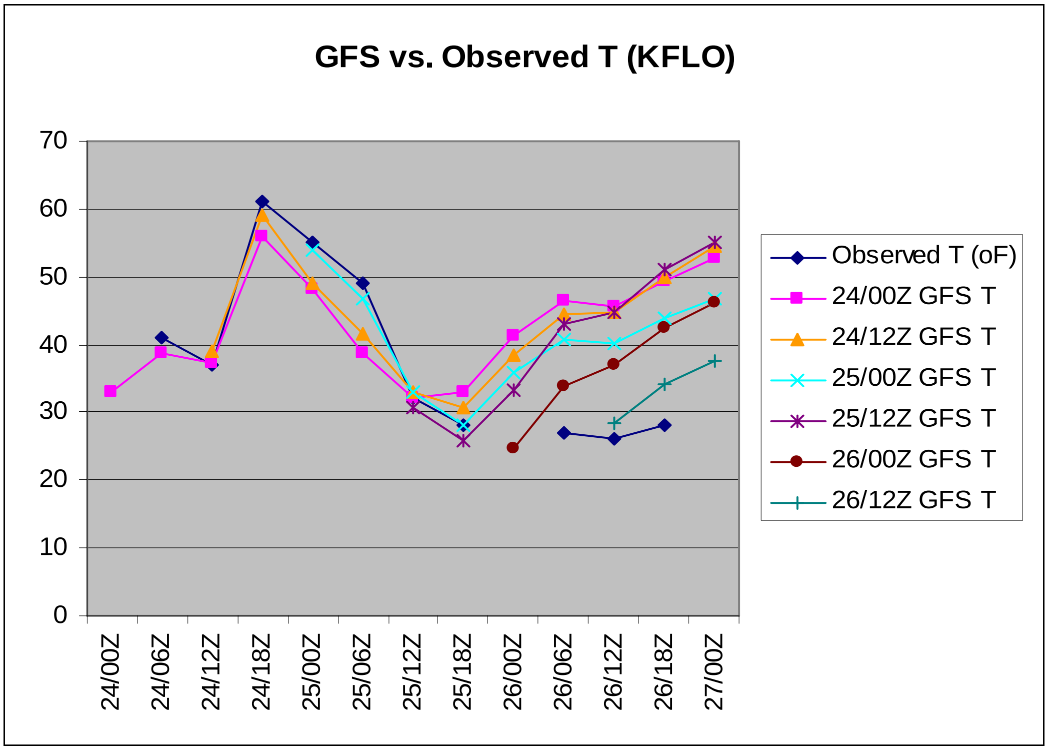

Figure 7a. GFS vs. Observed surface temperatures for various model runs leading up to the ice event at Florence, SC (KFLO). Date/time shown on the x-axis.

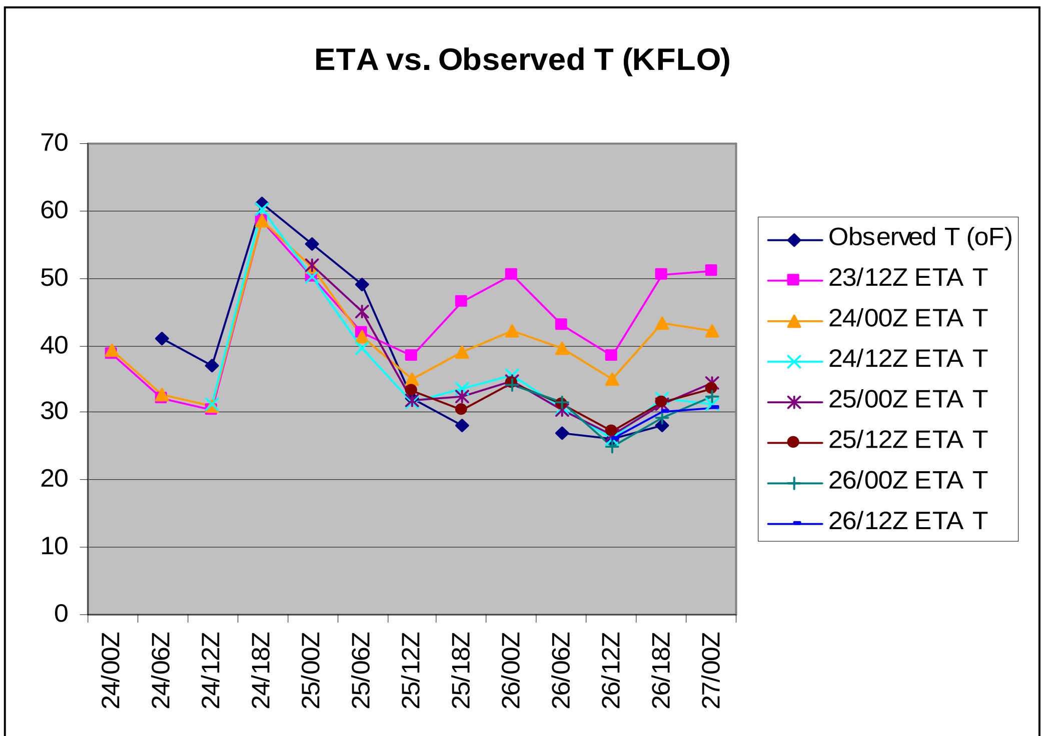

Figure 7b. Eta vs. Observed surface temperatures for various model runs leading up to the ice event at Florence, SC (KFLO). Date/time shown on the x-axis.

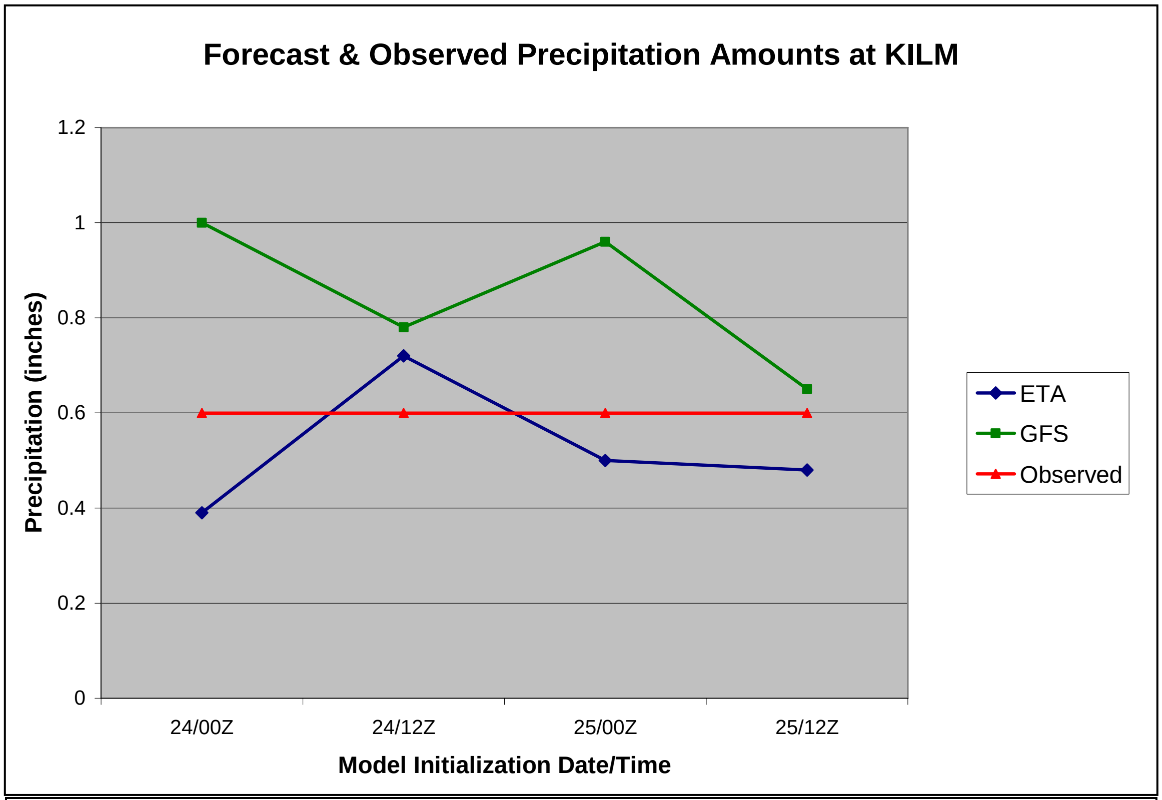

Figure 8a. Each Eta and GFS model run compared to the observed total QPF (liquid) at Wilmington, NC (KILM).

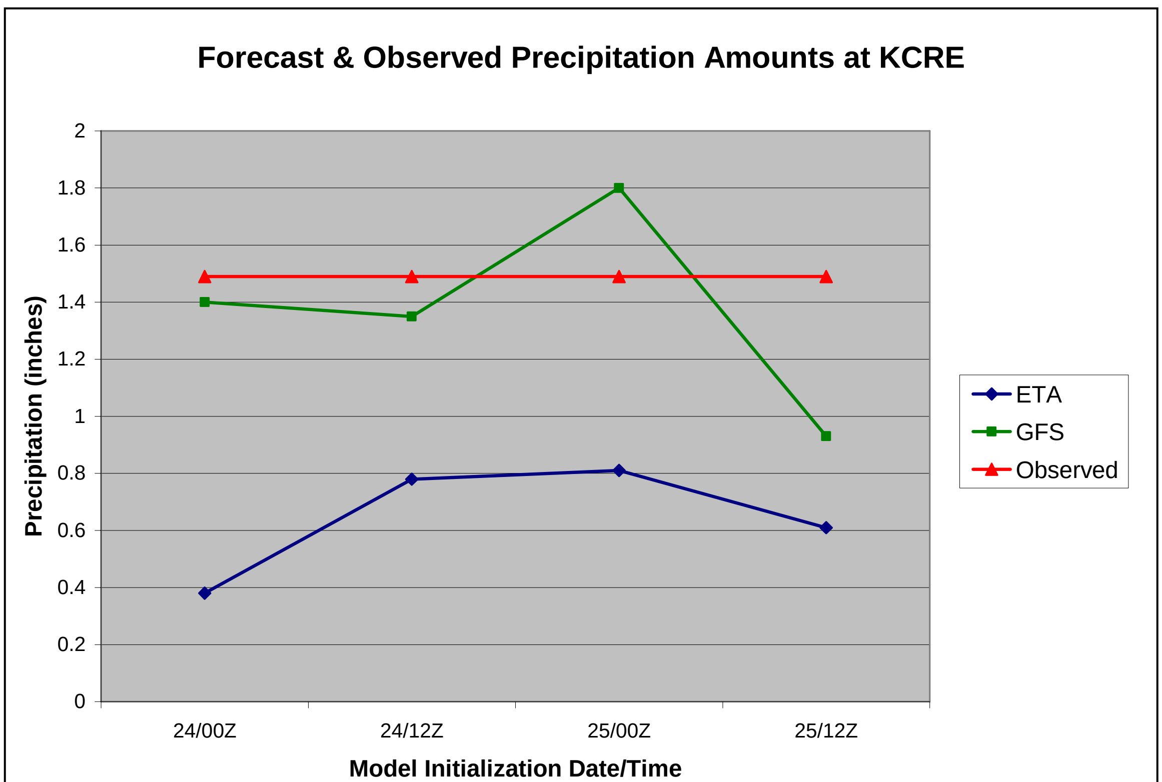

Figure 8b. Each Eta and GFS model run compared to the observed total liquid equivalent QPF at North Myrtle Beach, SC (KCRE).

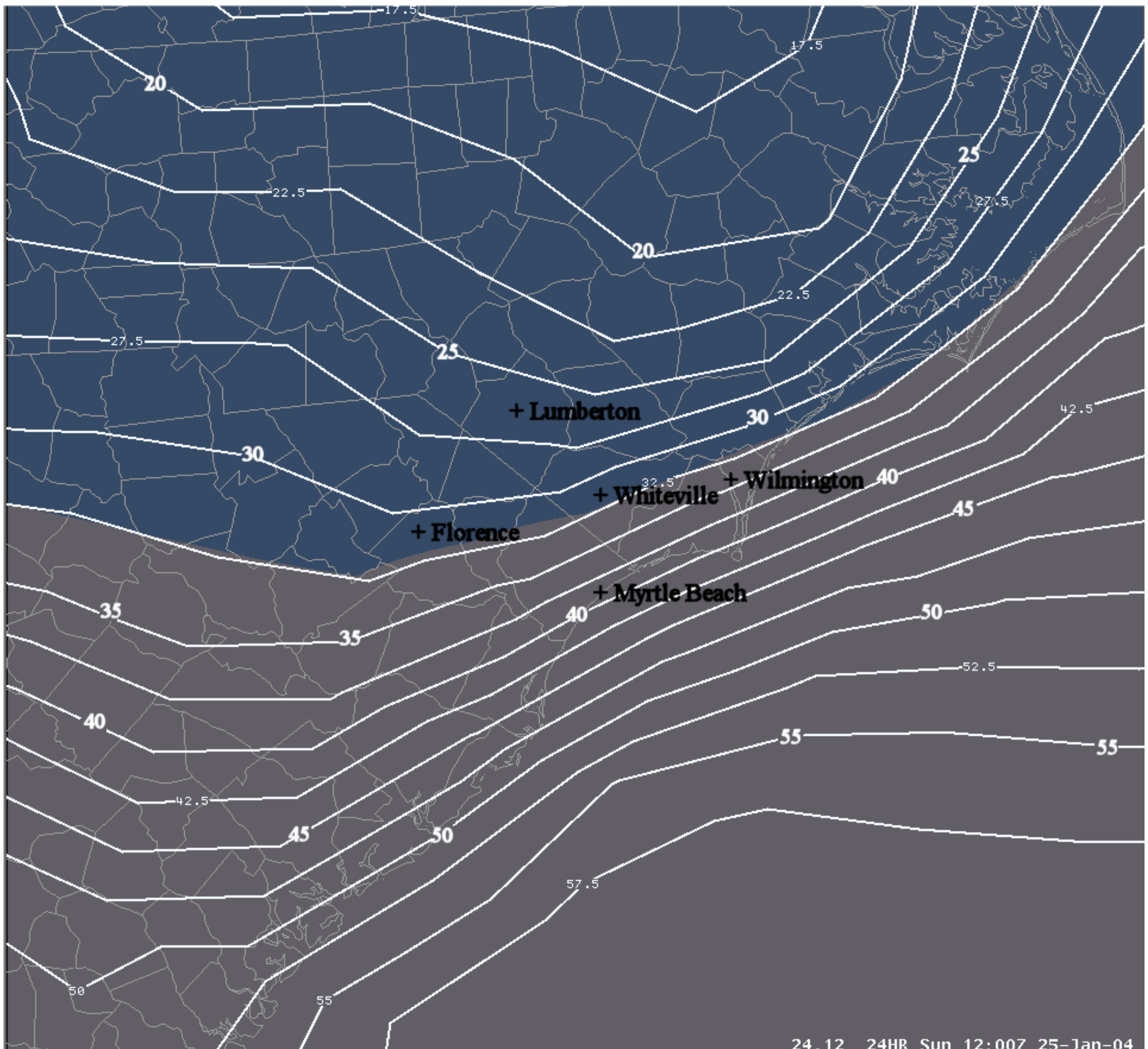

Figure 9. 24 hour forecast Surface Wet-bulb Temperature (°F) from the 1200 UTC 24 January 2004 GFS model run, valid 1200 UTC 25 January 2004. Temperatures below freezing are blue shaded area and the contours are every 2.5 °F.

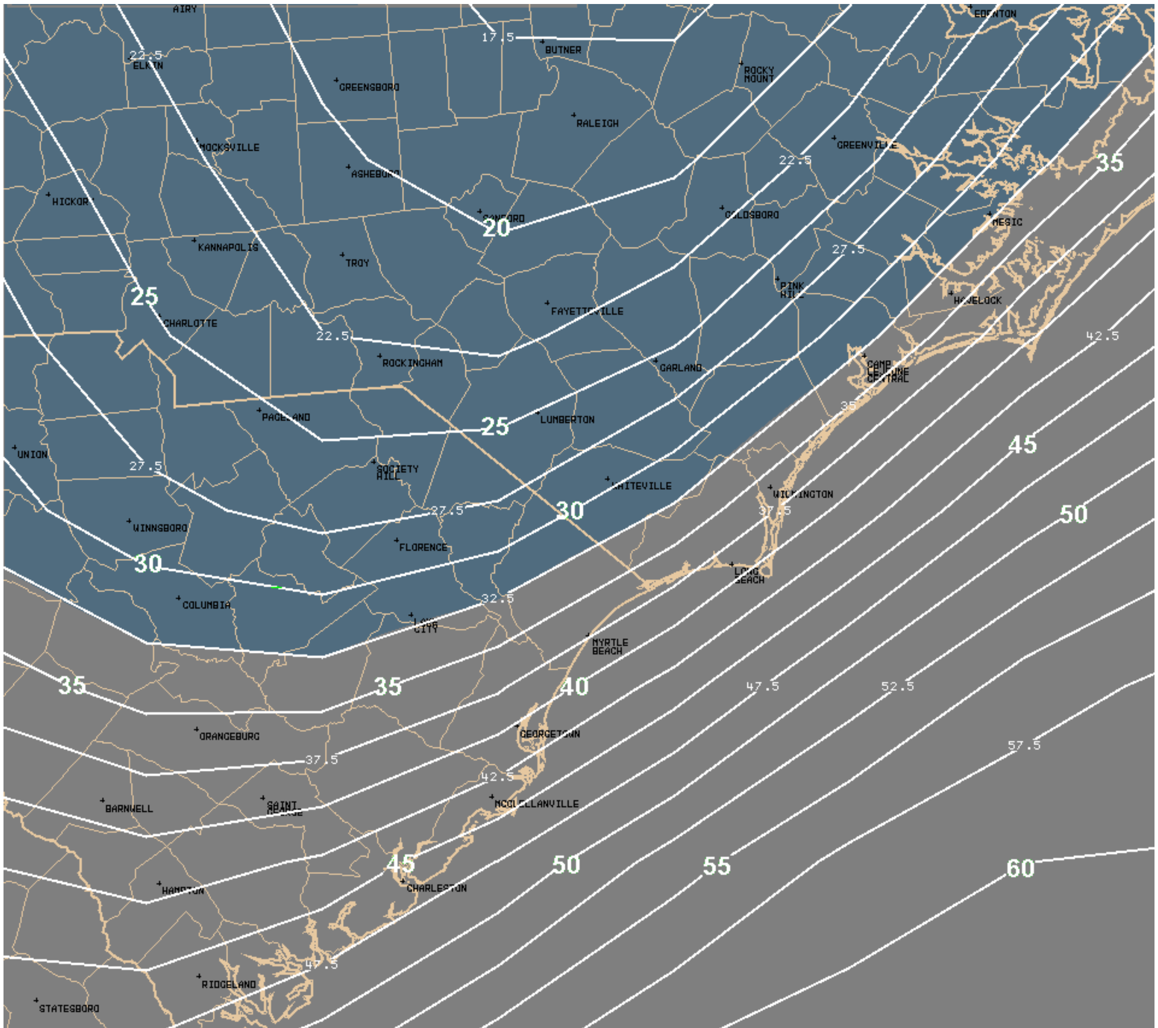

Figure 10. 12 hour forecast Surface Wet-bulb Temperature (°F) from the 0000 UTC 25 January 2004 Eta model run, valid 1200 UTC 25 January 2004. Temperatures below freezing are blue shaded area and the contours are every 2.5 °F.

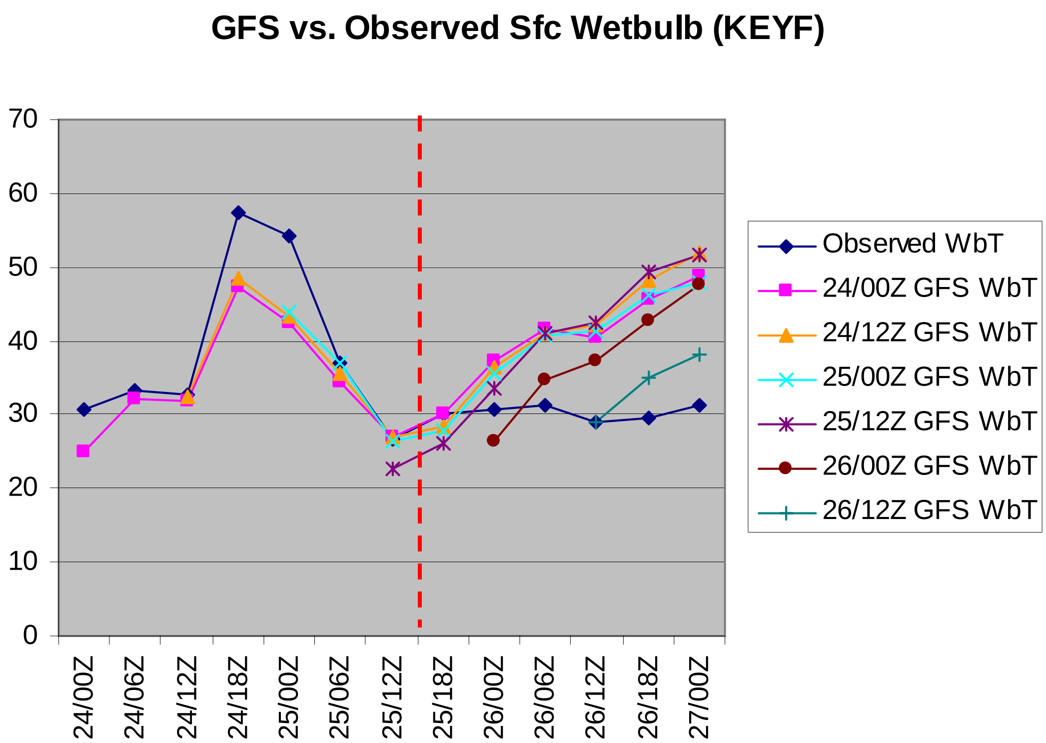

Figure 11a. GFS forecast vs. observed surface wet-bulb temperatures for KEYF. Dashed vertical line indicates approximate time of precipitation onset.

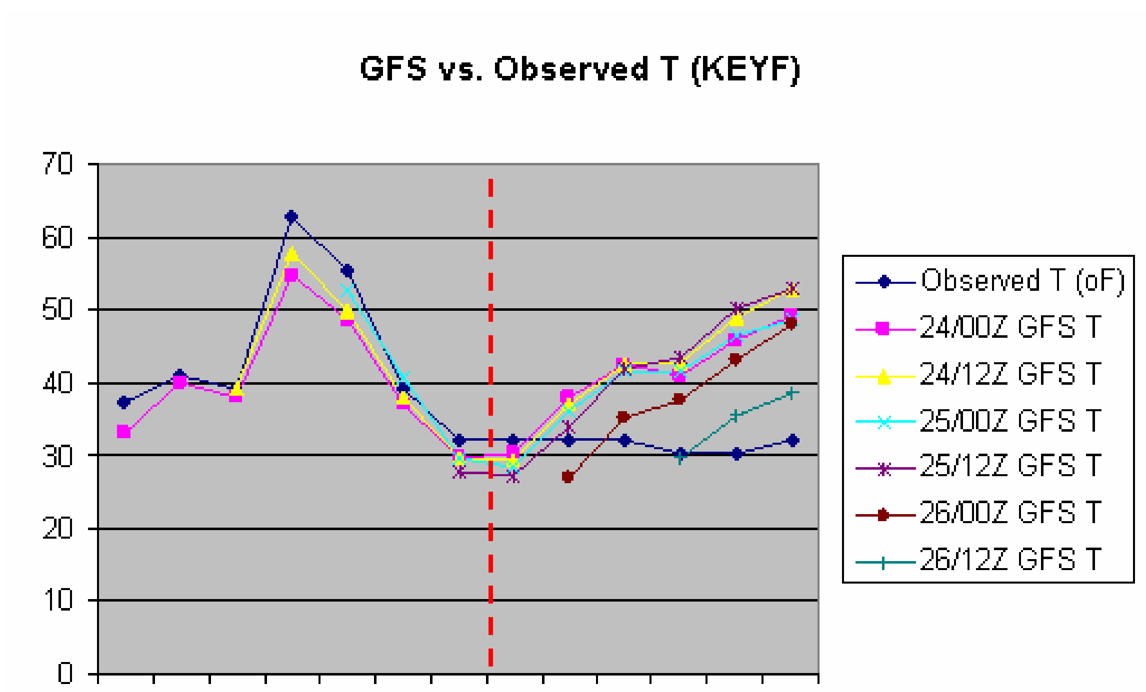

Figure 11b. GFS forecast vs. observed surface temperatures for KEYF. Dashed vertical line indicates approximate time of precipitation onset.

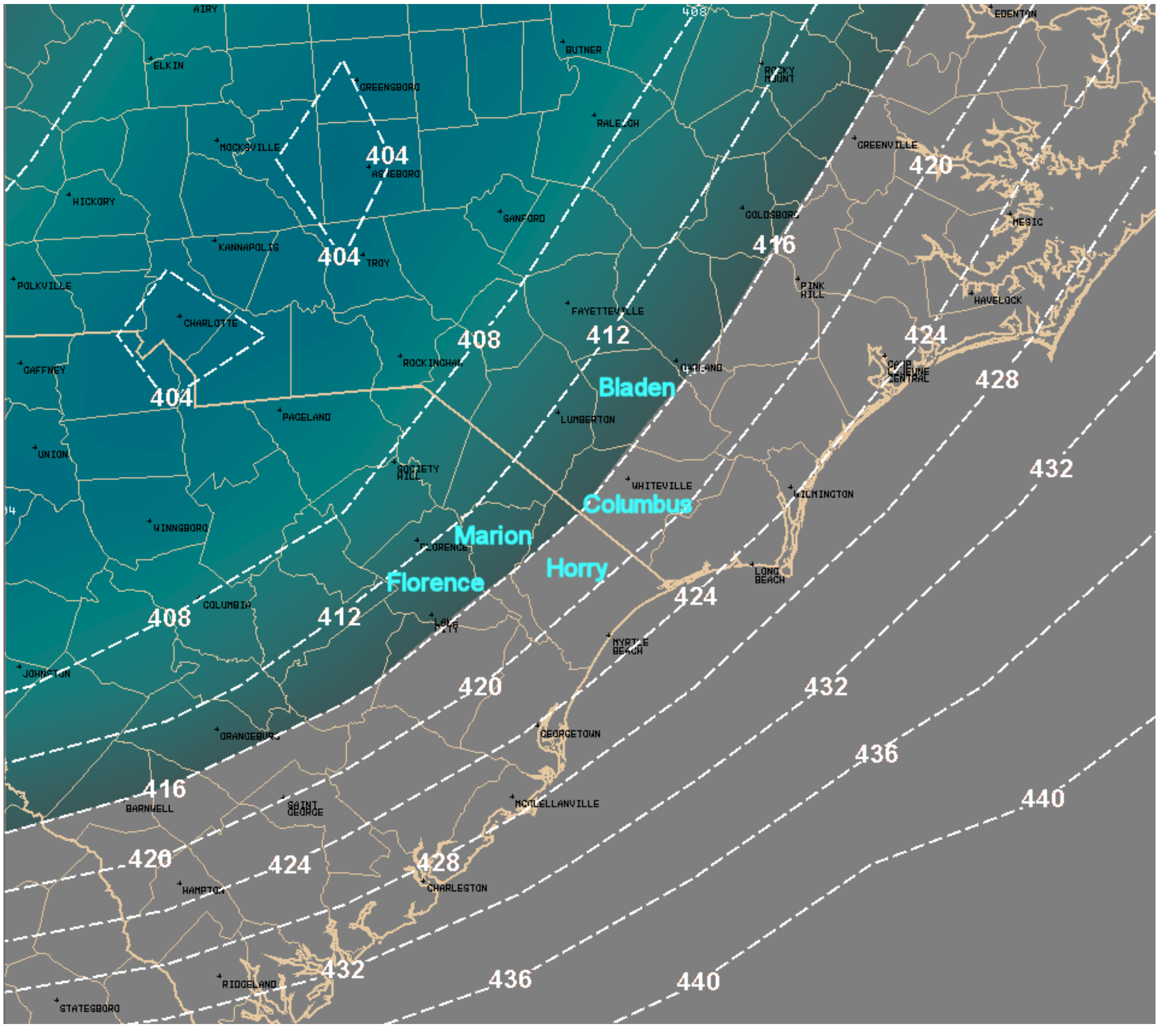

Figure 12. 18 hour forecast of 1000-950 hPa thickness from the 0000 UTC 26 January 2004 Eta, valid at 1800 UTC 26 January 2004. Thickness values less than or equal to 416 m shaded in blue and the contours are every 4 m.