

AN EXAMINATION OF ETA MODEL FORECAST SOUNDINGS DURING MIXED-PRECIPITATION EVENTS

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Abstract

Eta Model forecast sounding data for 15 mixed-precipitation events over the northeastern United States are examined to test the utility of that data for forecasting precipitation type. In this study, when a single surface-based warm layer (defined as a layer characterized by wet-bulb temperatures above freezing throughout the layer) was forecast, rain typically occurred when the depth of the warm layer exceeded 100 mb, or when the maximum wet-bulb temperature within the warm layer exceeded 3°C. Snow typically occurred with forecast surface-based warm layers less than 100 mb deep, and maximum wet-bulb temperatures of 3°C or less. When a single warm layer was forecast aloft, sleet typically occurred when the depth of the warm layer ranged from 80 to 140 mb, the depth of the surface-based cold layer ranged from 90 to 150 mb, and the maximum wet-bulb temperature within the warm layer ranged from 1 to 5°C. When warm layers were forecast both at the surface and aloft, rain occurred whenever the depth of either warm layer exceeded 100 mb. Three case studies are presented to illustrate these findings. Comparisons of observations with the Eta forecast soundings indicate that the Eta frequently exhibited a warm bias in the boundary layer for the cases in this study. The warm bias was most pronounced when the Eta model predicted a relatively steep boundary layer lapse rate, instead of the isothermal lapse rate typically associated with saturated conditions. Several possible causes for this bias are proposed.

1. Introduction

For many years, forecasters have estimated the location of the rain-snow line in winter storms by examining plan view forecasts of thermal parameters, such as thickness and 850-mb temperature. Numerous studies have been conducted to find "critical values" of these parameters, in order to estimate the location where there would be equal chances of rain vs. snow (Lamb 1955; Wagner 1957; Bocchieri and Maglaras 1983; Maglaras and Goldsmith 1990; Heppner 1992; Keeter and Cline 1991). In effect, the use of these parameters is an attempt to estimate the forecast temperature profile of the atmosphere by examining parameters that are directly related to mean values of temperature at a given layer or level.

Recent computer software advances have resulted in the introduction of NWP model forecast soundings to the operational community. As a result, it is no longer neces-

sary to use a series of parameters to approximate the model forecast vertical temperature profile at any given point; the profiles are now readily available for viewing. Grumm and Hart (1998) demonstrated the potential for improved forecasts with this new technology by examining a case where lower-tropospheric model forecast thicknesses and 850-mb temperatures implied that the atmosphere would be cold enough for snow across central Pennsylvania. However, model forecast soundings also indicated a layer of warm air between 850 mb and 700 mb, which may not have been directly detectable by viewing only traditional rain/snow predictors. The result was a significant ice storm, with little snow.

For a numerical model to accurately forecast the thermal structure of the atmosphere in a storm, the model must accurately forecast the position of the associated surface cyclone. Oravec and Grumm (1993), and Grumm (1993) found several characteristic biases in both NGM and AVN forecast cyclone positions that should be considered before using soundings from those models. The Eta model can also be subject to cyclone track errors. For example, if a model forecast is expected to track a cyclone too far to the west, an adjustment to a cooler forecast temperature profile should be made at locations near the track. In addition to position errors, the potential for model forecast timing errors should also be considered when making a forecast.

Another potential source of error in a model forecast sounding is the localized effect of terrain, which is often poorly modeled. Examples of this type of effect include localized cooling resulting from cold-air damming (Forbes et al. 1987) or cold-air drainage associated with a gap wind (Steenburgh et al. 1997).

Finally, mesoscale details of the vertical motion field can have locally large effects on the temperature structure of the atmosphere, and may not be well modeled. Vertical motion directly affects the temperature structure of the atmosphere, with upward motion resulting in adiabatic cooling, and downward motion resulting in warming. Variations in vertical velocity can also indirectly affect the temperature profile by modifying precipitation intensity, which affects the rate of cooling due to melting or evaporation (Bluestein 1992). Examples of features associated with mesoscale variations of vertical motion include bands of enhanced precipitation associated with slantwise convection produced by the release of conditional symmetric instability (CSI, Nicosia and Grumm 1999; Schultz and Schumacher 1999), and areas of enhanced upward vertical motion associated with

mesoscale circulations near gradients of melting associated with rain-snow boundaries (Lin and Stewart 1984).

The purpose of this study is to examine the utility of model forecast temperature profiles in precipitation type forecasting. Sounding parameters from model forecasts will be examined from points located within areas of mixed-precipitation for 13 winter storms that occurred over the eastern United States from November 1997 through March 1999. In addition, two storms that occurred during 1995 are included. **All data will be taken from the NOAA/National Weather Service (NWS) National Centers for Environmental Prediction (NCEP) Eta stepped-terrain model (Eta; Black 1994) 48-km version through January 1998, and the 32-km version after January 1998.** The method for collecting the data will be summarized in Section 2 and the results will be given in Section 3. Three case studies will be shown in Section 4. A discussion is given in Section 5, and a summary and conclusion are given in Section 6.

2. Method

Data for this study were taken from Eta forecast soundings at locations near rain-snow lines or areas of mixed-precipitation from 13 winter storms that affected the eastern half of the United States from November 1997 through March 1999, plus 2 storms from 1995. For 13 of the 15 storms, points for study were located near the rain-snow line or within a mixed-precipitation area in the mid-Atlantic-states region. For the other 2 storms, points were taken farther west, over mixed-precipitation areas across the southern Great Lakes region. Each storm selected for the study was associated with a heavy (greater than 15 cm) snowfall.

For each storm, data were collected at times when 12 or 18-h Eta forecast data was available. In 3 of the cases, some 24-h forecasts were used when 12 or 18-h data was not available. Data were taken at locations corresponding to surface observation points, so that the forecasts could be compared and related to corresponding surface observations. The data were taken at locations in the vicinity of peak precipitation rates, as the surface low-pressure center was passing off to the south-southeast. In order to limit any one storm from having a disproportionately high representation in the database, no more than 2 times were used from each storm.

Data for the study were collected by archiving six-hourly model-forecast soundings generated by the General Meteorological PackAge, version 5.1 (GEMPAK 5.1) (DesJardins et al. 1991). GEMPAK soundings are generated from 6-hourly gridded model GEMPAK files, and are interpolated directly to any location within the 2D domain of the model grid. The data is interpolated to a vertical resolution of 50-mb. For storms after 1997, higher resolution hourly model sounding data was also available, in the form of BUFR files. This data was extracted from the native model grids by NCEP and maintains the native grid's vertical resolution, which is higher than 50-mb (Black 1994). Hourly soundings are shown in 2 of the 3 case studies in Section 4 using GRADS software (Hart et al. 1998).

Table 1. Location, date, time (UTC) and model forecast hour for data collected for each point in the study.

Location Snow pt. / Rain pt. / Sleet pt.	Date / Time	Eta Forecast hr
UNV / MDT /	11/14/95 1800	F18
HGR / BWI /	11/15/95 0000	F24
RDG / BWI / MDT	12/19/95 1200	F12
PIT / ACY / IAD	12/19/95 1800	F18
ERI / DUJ /	11/14/97 1200	F12
/ / IPT	11/14/97 1800	F18
TOL / MFD /	12/10/97 1200	F12
TOL / MFD /	12/10/97 1800	F18
AVP / ABE /	12/30/97 0600	F18
AVP / EWR /	12/30/97 1200	F24
AOO / HGR /	01/28/98 1200	F12
UNV / MDT / ABE	02/05/98 0000	F12
AOO / MDT /	02/24/98 0000	F12
JXN / TOL /	03/21/98 0000	F12
TOL / CLE /	03/21/98 1200	F24
PTK / PKB / BUF	01/03/99 0600	F18
BGM / PIT / UNV	01/09/99 0000	F12
POU / / AVP	01/15/99 0000	F12
BFD / DOV / IPT	01/15/99 0600	F18
PIT / AOO /	03/04/99 0000	F12
AVP / ABE /	03/06/99 1800	F18
BWI / DOV /	03/14/99 1800	F18
PHL / DOV /	03/15/99 0000	F12

Table 1 gives the location, time, and model-forecast hour for each data point in the study. Locations are given for points corresponding to observations of snow, rain, and sleet. In summary, data were recorded at 22 points during times of observed snow, 21 points during times of observed rain, and 8 points during times of observed sleet. In order to limit the scope of the project, freezing rain cases were not addressed in the study.

3. Results

Figures 1a-f show the relationship between observed precipitation type and several different parameters

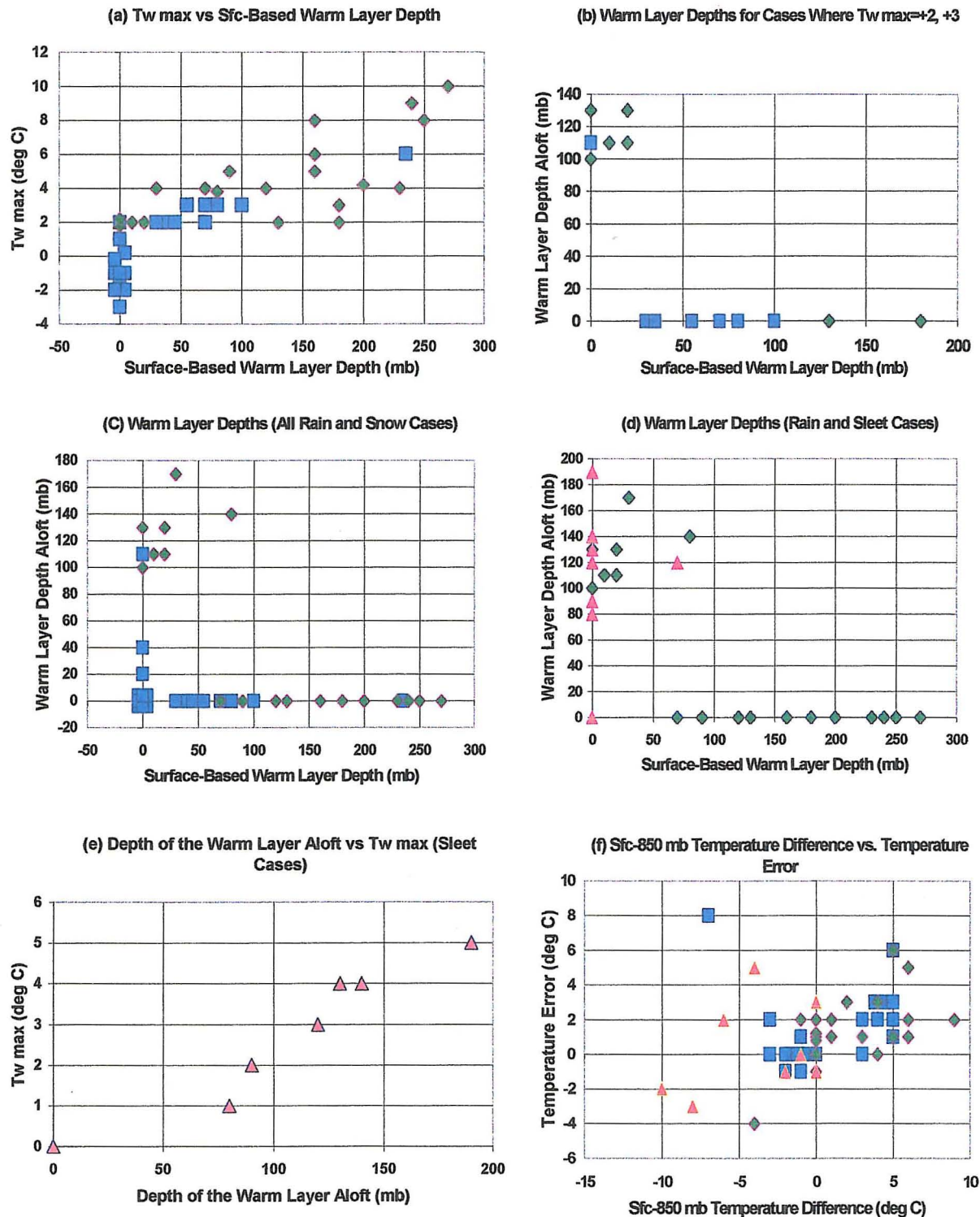


Fig. 1. Scatter diagrams of: a) Eta forecast depth of the surface-based warm layer vs. the maximum wet-bulb temperature within the entire sounding, for all rain and snow cases in the study, b) forecast depth of the surface-based warm layer vs. the forecast depth of any warm layer aloft for rain and snow points where the maximum wet-bulb temperature was 2 or 3°C, c) forecast depth of the surface-based warm layer vs. the depth of any warm layer aloft, for all rain and snow points, d) same as (c) but for all rain and sleet points, e) forecast depth of the warm layer aloft vs. forecast maximum wet-bulb temperature within the warm layer for sleet cases, and f) forecast surface-to-850 mb temperature differences (°C) vs. the difference between the forecast surface temperature and the observed temperature, for all points.

Layer depths are given in mb, wet-bulb temperatures are in °C, rounded to the nearest whole degree. Rain points are plotted with green diamonds, snow points with blue squares, and sleet points with red triangles.

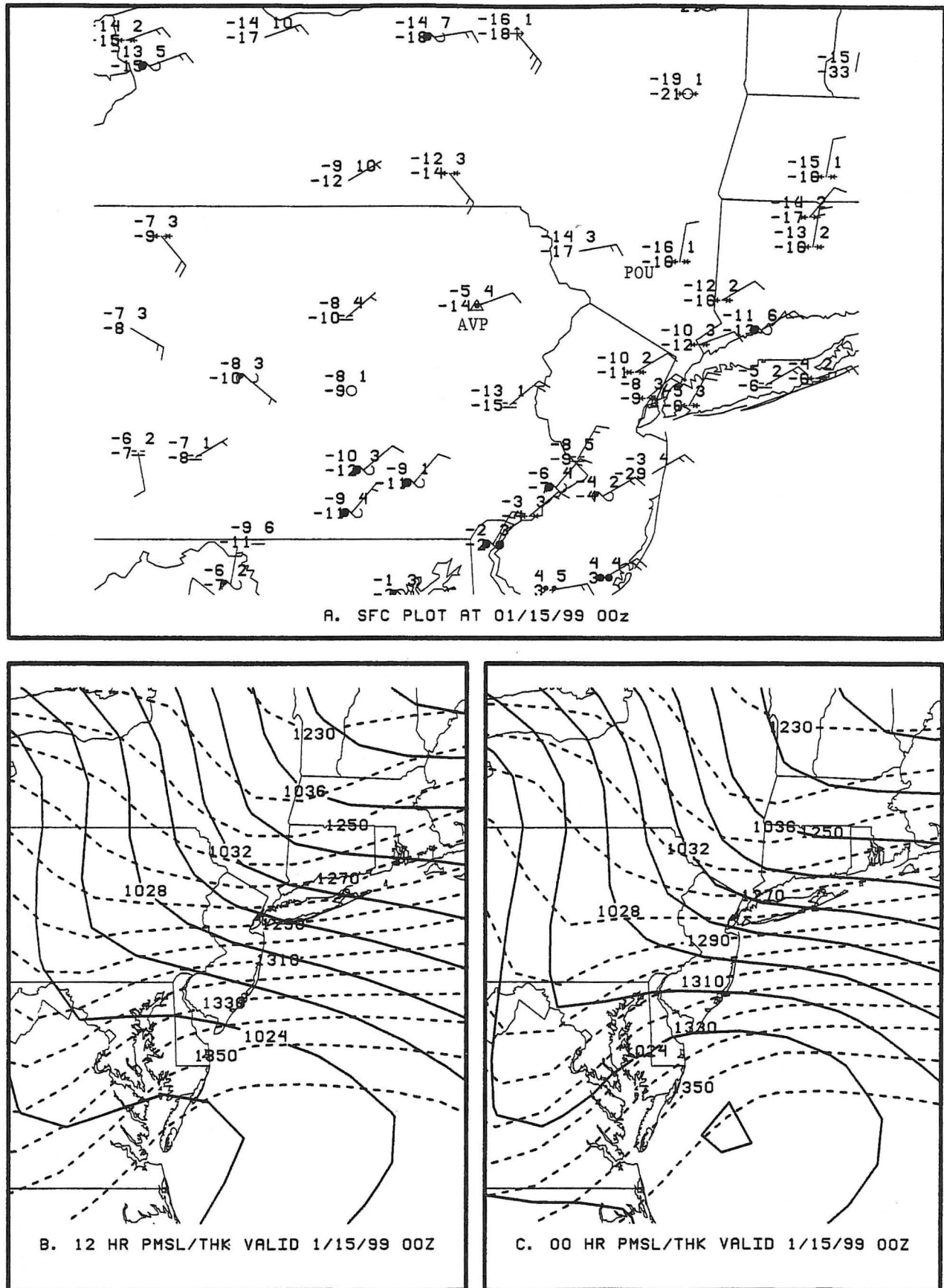


Fig. 2. a) A surface plot in standard notation valid at 0000 UTC 15 January 1999. Eta forecast mean sea-level pressure and 1000-850-mb thickness (m) valid 0000 UTC 15 January 1999 from: b) the 12-h and c) 00-h.

taken from Eta model forecasts (from the 6-hourly GEMPAK data), for the cases in this study. The reader should keep in mind that the values of the parameters shown on these figures are from model forecasts, not from observations. While it cannot be assumed that all of these forecasts were accurate, the primary goal of this study is to assess the utility of these model forecasts in predicting precipitation type. Imperfect forecasts can still theoretically be of value, if the errors reflect model biases that are consistent enough to be systematically accounted for. Therefore, comparing the model forecasts to observed precipitation type could be justified, even if the forecasts are not perfect. In the discussion section of this paper, some of the results from this section will be compared to results from similar studies where observational data was used, in order to assess the accuracy of the model data.

Figure 1a summarizes the relationship between the depth of any forecast surface-based warm layer, the maximum wet-bulb temperature within the entire forecast sounding (rounded to the nearest whole degree C), and the observed precipitation type, for each rain and snow point in the study. The surface-based warm layer for this study is defined as any surface-based layer where the wet-bulb temperature was forecast to be above freezing throughout the layer. Wet-bulb temperature is used to define warm layers, since temperatures typically approach the wet-bulb temperature during the saturated conditions typical of a mixed-precipitation regime. (For the cases in this study, the decision to define warm layer depth by wet-bulb temperature, as opposed to dry-bulb temperature, made little difference in the results, as the warm layers were typically saturated or near saturation). The combination of maximum wet-bulb temperature and warm layer depth was chosen as an estimate for the amount of warm air present in the sounding. Data from locations where snow was falling are plotted with blue squares, while data from locations where rain was falling are plotted with green diamonds.

With one exception, the data in Fig. 1a indicate that only rain occurred when the surface-based warm layer depth exceeded 100 mb. The exception will be examined more closely in Section 4c. When the surface-based warm layer depth was 100 mb or less, precipitation type was related to the maximum wet-bulb temperature (TwMax) within the sounding. For TwMax less than 2°C snow was observed, for TwMax of 2 or 3°C rain or snow was observed, and for TwMax greater than or equal to 4°C, only rain was observed.

The depth of any surface-based warm layer, the depth of any warm layer aloft, and precipitation type, for data points where the maximum wet-bulb temperature was +2 or +3°C, is summarized in Fig. 1b. The warm layer aloft for this study is defined as any layer, based above the ground, where the wet-bulb temperature was above freezing throughout the layer. The results indicate that the rain cases associated with surface-based warm layers of less than 100 mb in depth were all associated with deep (greater than 100 mb) warm layers aloft. With one exception, the snow cases were not associated with a forecast warm layer aloft.

A plot of surface-based warm layer depth, warm layer depth aloft, and precipitation type for all rain and snow

points, regardless of maximum wet-bulb temperature, is shown in Fig. 1c. These results indicate that when the surface-based warm layer depth was forecast to be 100 mb or less, snow was always observed if the elevated warm layer was less than 100 mb deep, with two exceptions. The two exceptions occurred with easterly flow at points near the Atlantic Ocean (Newark, New Jersey (EWR), and Dover, Delaware (DOV)). In those cases, a warm easterly flow from the nearby ocean corresponded with predicted maximum wet-bulb temperatures of 5°C at DOV and 4°C at EWR, within single surface-based warm layers. All of the rest of the rain cases occurred with at least one warm-layer deeper than 100 mb.

Forecast warm layer depths and precipitation type for all rain and sleet cases were also examined. The data indicate that 7 of the 8 sleet cases were associated with a forecast elevated warm layer (Fig. 1d). In 6 of those 7 cases there was no forecast surface-based warm layer. One sleet case occurred with both a surface-based and an elevated warm layer. Another sleet event occurred with a forecast sounding completely below freezing. Since some melting is required for sleet formation, it can be assumed that this sounding was either an incorrect forecast, or that the GEMPAK data did not resolve a relatively shallow forecast warm layer. For the 7 cases where a warm layer aloft was forecast, the depth of the warm layer ranged from 80 to 190 mb. In the 6 cases where the warm layers were located above a surface-based cold layer, the surface-based cold layer depths ranged from 90 to 150 mb (not shown).

The depth of the elevated warm layer vs. the maximum wet-bulb temperature within the warm layer, for the sleet cases in the study, is shown in Fig. 1e. These data indicate that maximum wet-bulb temperatures within the warm layers ranged from 1 to 5°C.

4. Case studies

a. 15 January 1999

At 0000 UTC 15 January (15/0000 UTC), low pressure over the central Appalachian Mountains was bringing a mix of snow, sleet, freezing rain and rain to the mid-Atlantic-states region. Sleet was falling over much of eastern and central Pennsylvania, with snow to the north, across New York State (Fig. 2a). Figures 2b and c show a comparison between the 12-h Eta forecast mean sea level pressure and 1000-850-mb thickness, verifying at 15/0000 UTC, and the verifying 00-h Eta mean sea level pressure and 1000-850-mb thickness from the 15/0000 UTC forecast cycle. Comparisons between the Eta forecast surface pressure and low-level thickness pattern, and the verifying 00-h pressure and low-level thickness pattern will be shown for each case study in this section, in order to give the reader an idea of how Eta model cyclone track errors could have impacted the model's resultant temperature forecast. Recall that a track error to the north and west of the verifying track could result in an erroneously warm forecast, while an error to the south and east could result in an erroneously cold forecast. In this case, both model forecasts indicate low pressure developing off the mid-Atlantic coast. The

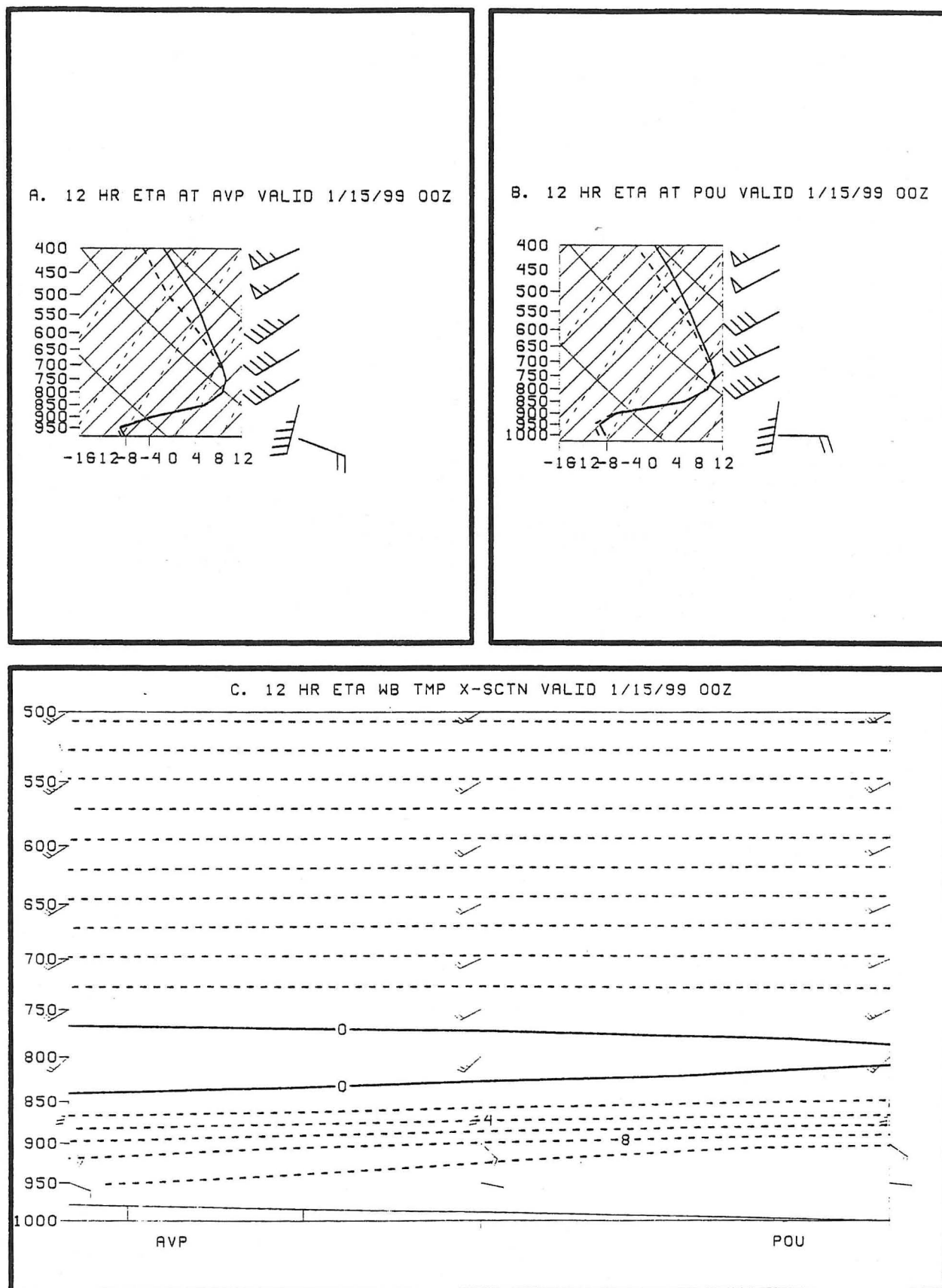


Fig. 3. The 12-h Eta forecast soundings at a) Avoca, Pennsylvania, and b) Poughkeepsie, New York valid at 0000 UTC 15 January 1999. Temperatures are plotted with a solid line, dewpoints are plotted with a dashed line. c) A 12-h Eta forecast cross section of wet-bulb temperature from Avoca eastward through Poughkeepsie, valid 0000 UTC 15 January 1999.

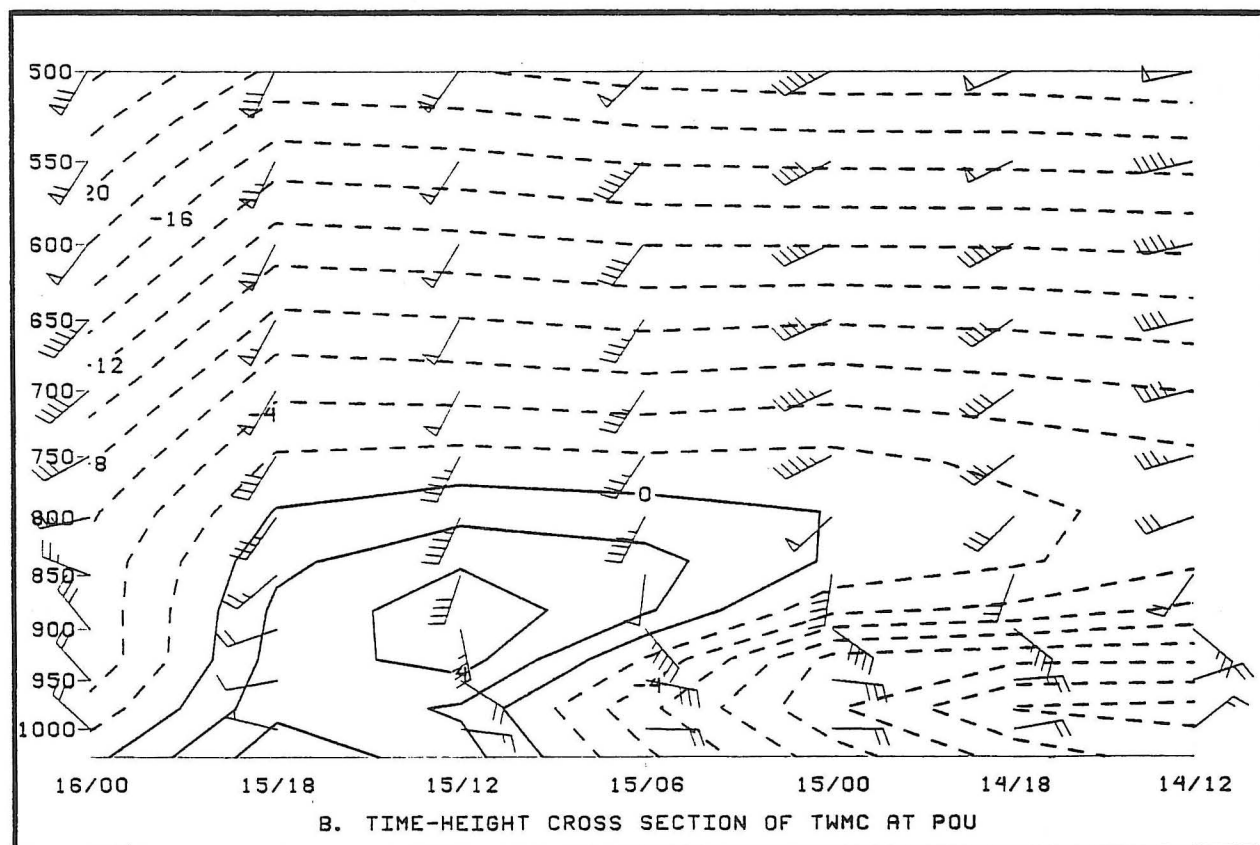
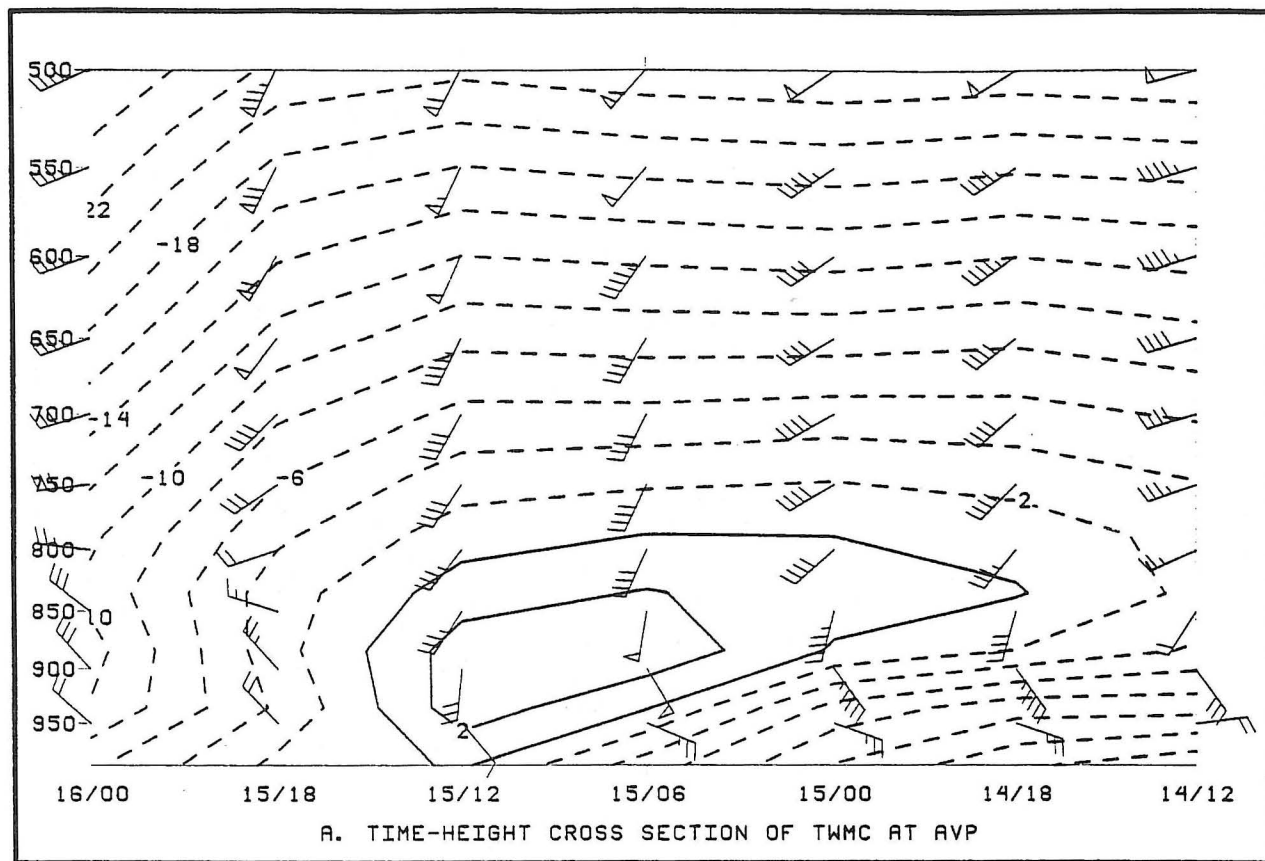


Fig. 4. An Eta forecast time-height diagram of wet-bulb temperature at a) Avoca, Pennsylvania, and b) Poughkeepsie, New York valid from 1200 UTC 14 January 1999 through 0000 UTC 16 January 1999. Note time axis increases from right to left.

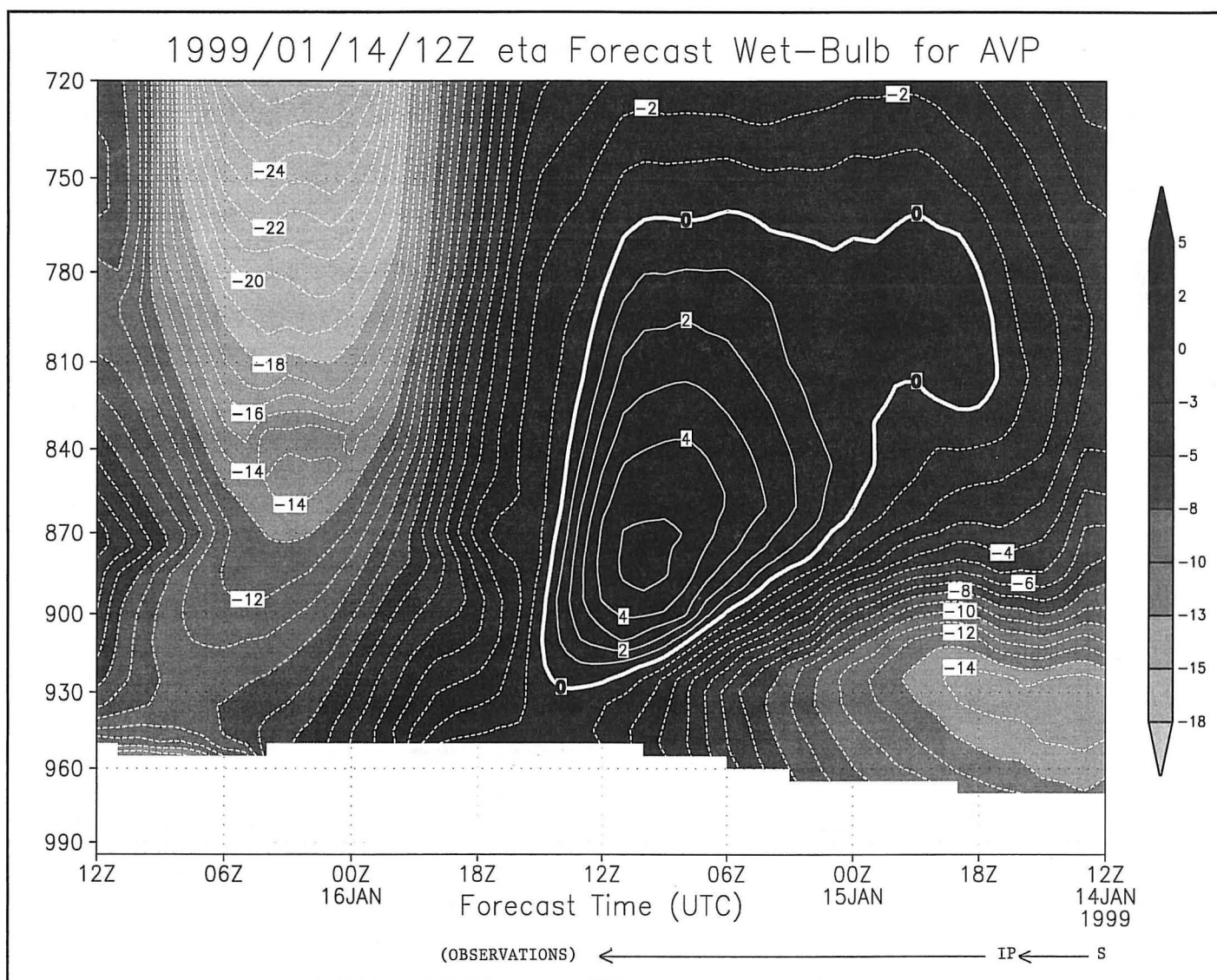


Fig. 5a. An Eta forecast time-height diagram of temperature using the hourly profile data at Avoca, Pennsylvania valid from 1200 UTC 14 January 1999 through 1200 UTC 16 January 1999. Note time axis increases from right to left.

secondary low is slightly stronger and thickness values are slightly lower along the mid-Atlantic coast in the 00-h forecast, indicating that the 12-h model forecast may have been slightly too warm. Overall however, no large errors are indicated.

Figures 3a & b show the 12-h Eta forecast soundings generated by GEMPAK for (a) Avoca, Pennsylvania (KAVP) and (b) Poughkeepsie, New York (KPOU), verifying at 15/0000 UTC. At KAVP, where a significant sleet event was occurring, the Eta model forecast indicated an elevated warm layer with a depth of approximately 70 mb and a maximum temperature of 1°C. Additionally, the model forecast a surface-based cold layer approximately 150-mb deep. This case illustrates the problem with associating the occurrence of a warm layer with temperatures at mandatory pressure levels, since the warm layer at KAVP developed between 850 mb and 700 mb. The forecast surface temperature of -8°C was 3°C colder than the observed temperature. At KPOU, where snow was falling, the GEMPAK data indicated a very shallow

(about 20-mb deep) warm layer located around 800 mb. The forecast surface temperature of around -8°C was 8°C warmer than the observation. (Note that the base of the KAVP sounding is located at a slightly lower pressure than the base of the KPOU sounding. This is due primarily to the higher elevation of the KAVP forecast point. Similar differences can be seen with other forecast sounding points throughout this section).

A GEMPAK-generated vertical cross section of wet-bulb temperature from KAVP east to KPOU, verifying at 15/0000 UTC, is shown in Fig. 3c. The elevated warm layer is clearly visible, becoming increasingly shallow from west to east. Figure 4 shows GEMPAK-generated time-height diagrams of wet-bulb temperature from the 14/1200 UTC run off the Eta at (a) KAVP and (b) KPOU from 14/1200 UTC through 16/0000 UTC. The development of the elevated warm layer is evident at both locations, with a relatively deep warm layer developing at KAVP between 14/1800 UTC and 15/0000 UTC, and between 15/0000 UTC and 15/0600 UTC at KPOU. Snow

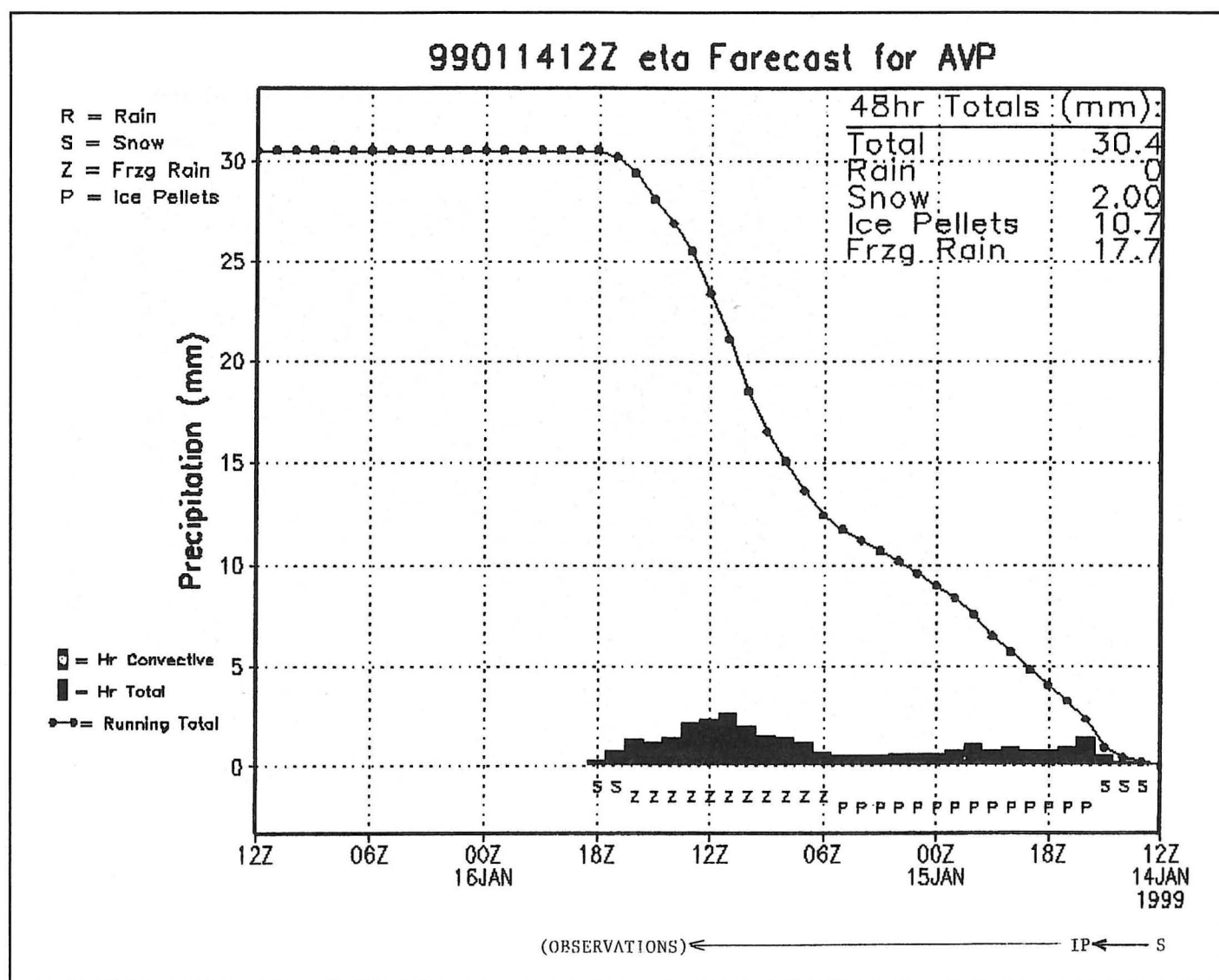


Fig. 5b. Eta model forecast quantitative precipitation and precipitation type (using the Baldwin method) at Avoca, Pennsylvania, from 1200 UTC 14 January 1999 through 1200 UTC 16 January 1999. Note time axis increases from right to left.

changed to sleet at KAVP at 14/15000 UTC and snow changed to freezing rain at KPOU by 15/0900 UTC.

A time-height diagram of wet-bulb temperature at KAVP from the hourly data from the 14/1200 UTC Eta, along with the observed precipitation type at KAVP, is shown in Fig. 5a. Figure 5b shows a corresponding time series of the model quantitative precipitation, precipitation type forecasts (as calculated by the Baldwin method (Baldwin et al., 1995)) and observed precipitation type. The Baldwin method changes snow to sleet based on the calculated area of the sounding with a wet-bulb temperature above -4°C . Recall that the hourly data are characterized by significantly higher temporal and spatial resolution than the 6-hourly data, shown in the previous figures. Because of the increased vertical resolution, the warm intrusion appears to develop initially over a greater depth on the hourly data, than on the GEMPAK data, at KAVP (compare Figs. 4a and 5a). The Baldwin method forecast the snow to change to ice pellets at 14/1600 UTC. In this case, the forecast precipitation type

matched the observations almost perfectly, since the observations indicated a change to sleet at 14/1500 UTC. This case clearly demonstrates the problems that can result with forecasting precipitation type by only examining temperature forecasts at the 850-mb level, when warm intrusions develop just above 850 mb. The high temporal resolution hourly data show that the Eta did not forecast an above-freezing wet-bulb temperature value at 850 mb until 15/0000 UTC, when 30% of the total precipitation was forecast to have fallen, and 9 hours after the warm intrusion first appeared just above 850 mb.

Figure 6 is the same as Fig. 5, except for KPOU, instead of KAVP. Figure 6a shows the elevated warm layer located at 800 mb arriving around 14/2000 UTC. The wet-bulb temperature in this layer did not exceed 2°C until around 15/0300 UTC. The Baldwin method indicates precipitation type in the model changing from snow to sleet due to the presence of a deep saturated layer from 0°C to -4°C around 14/1800 UTC. The obser-

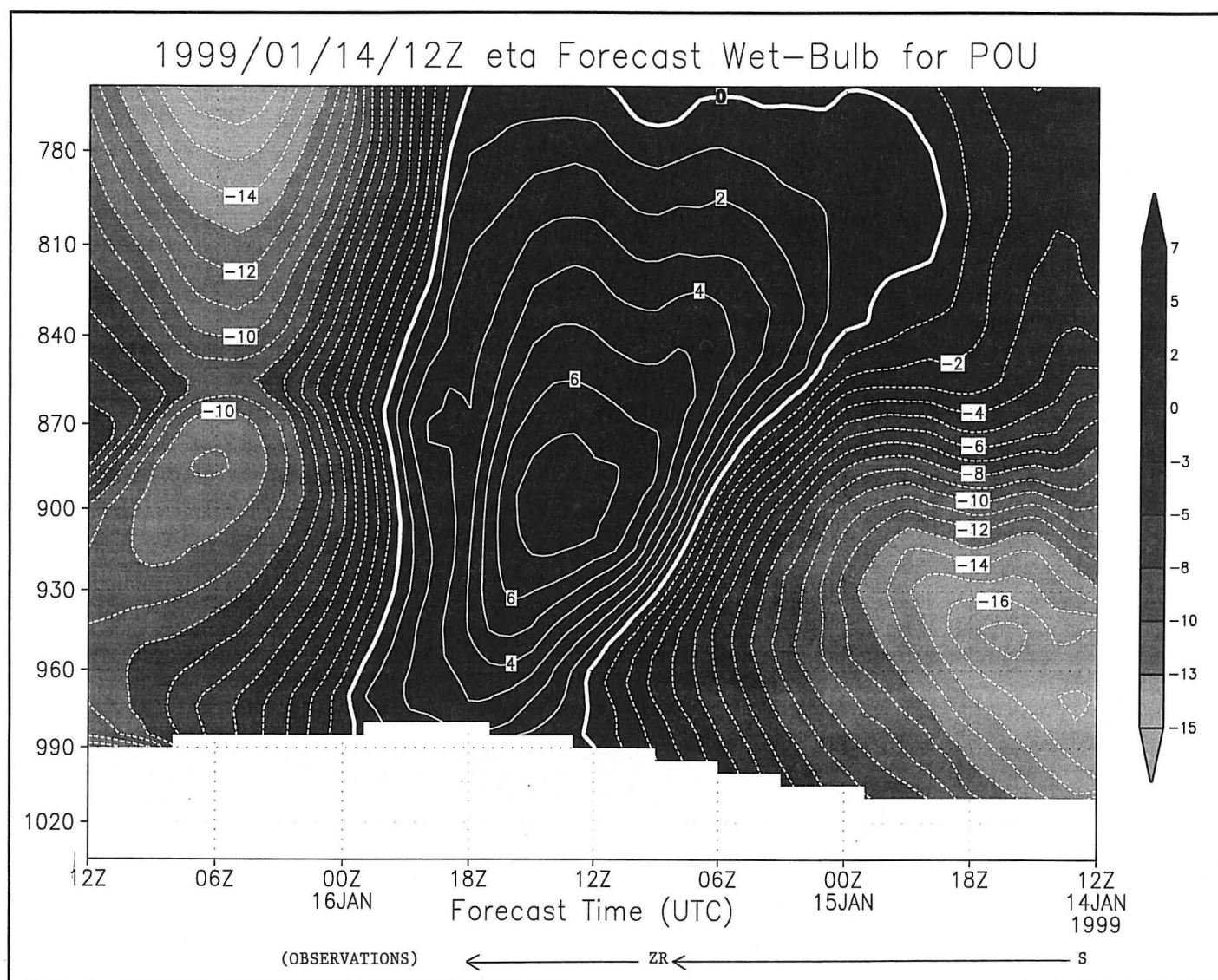


Fig. 6a. a) An Eta forecast time-height diagram of temperature using the hourly profile data at Poughkeepsie, New York valid from 1200 UTC 14 January 1999 through 1200 UTC 16 January 1999. Note time axis increases from right to left.

vations indicated that the precipitation remained all snow at KPOU until 15/0900 UTC, when it changed to freezing rain. Some possible reasons for this forecast error are discussed in section 5.

b. 24 February 1998

At 0000 UTC 24 February (24/0000 UTC), a deep low pressure area off the mid-Atlantic coast was bringing rain to eastern Pennsylvania, with snow over the central Appalachians from eastern West Virginia northward through central Pennsylvania (Fig. 7a). Figures 7b and c show a comparison between (b) the 12-h Eta model forecast mean sea-level pressure and 1000-850-mb thickness verifying at 24/0000 UTC, and (c) the corresponding "verifying" 00-h surface mean sea-level pressure and 1000-850-mb thickness from the 24/0000 UTC forecast cycle. Both models show low pressure off the mid-Atlantic coast, with the 12-h Eta forecast being a little farther west and not as deep as the 24/0000 UTC 00-h forecast.

Low-level thickness values are slightly lower over southern Pennsylvania on the 24/0000 UTC run, indicating that the 23/1200 UTC run may have had a slight warm bias.

Figure 8 shows GEMPAK-produced 12-h Eta model forecast soundings verifying at 24/0000 UTC, at (a) Altoona, Pennsylvania (KAOO) and (b) Harrisburg, Pennsylvania (KCHY). Heavy wet snow was observed at KAOO and rain was observed at KCHY. In contrast to the 15 January 1999 case in Section 4a, the primary warm layer in these soundings was located in the boundary layer. At KCHY, the Eta model forecast a surface-based warm layer approximately 90-mb deep. A secondary warm layer was also forecast just above the surface-based warm layer. The forecast surface temperature of 4°C was 1°C warmer than the surface observation. At KAOO, the Eta forecast a 30-mb deep surface-based warm layer, with no elevated warm layer. The surface temperature forecast of 3°C was 2°C warmer than the observation. Figure 8c shows a GEMPAK-generated 12-h

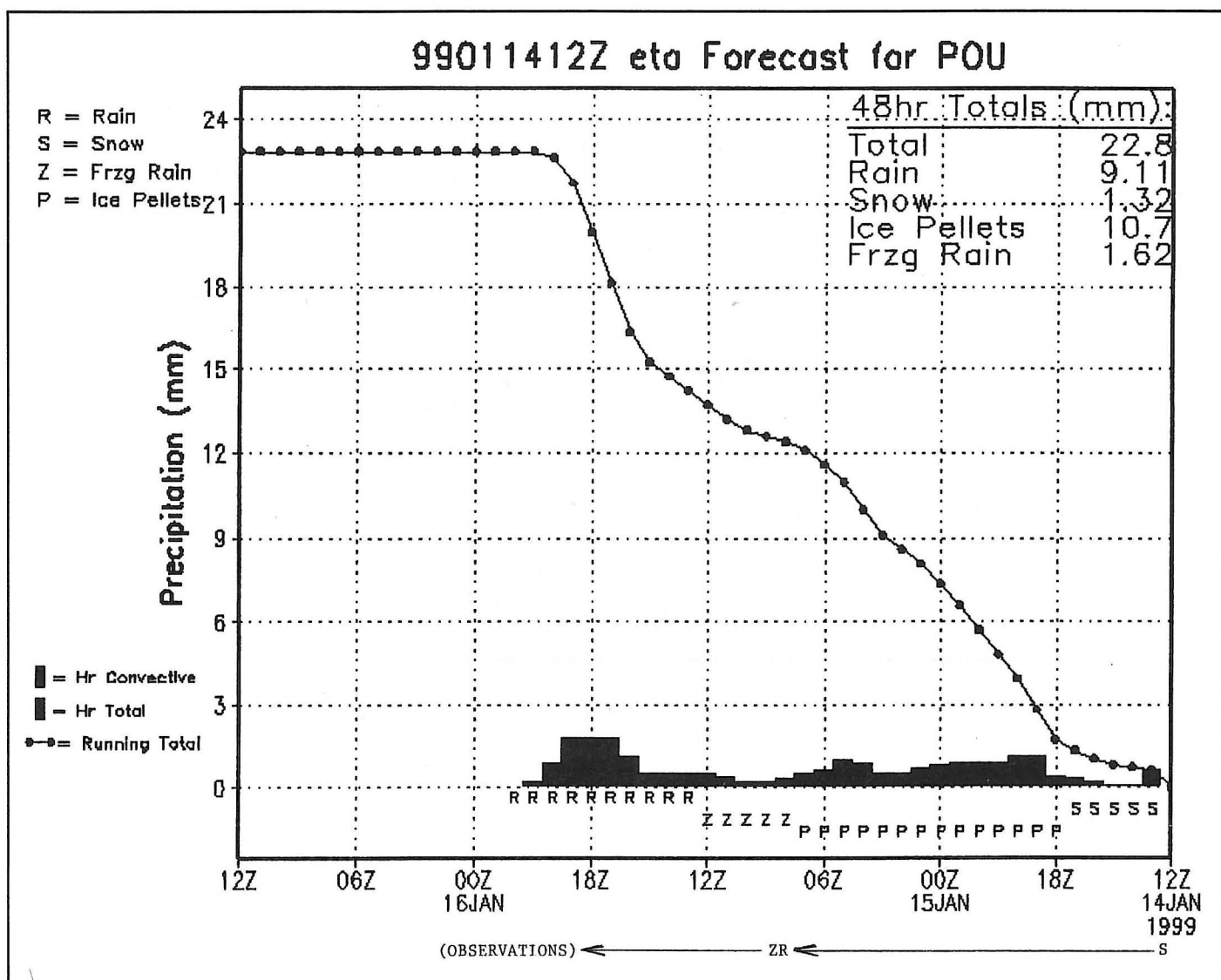


Fig. 6b. Eta model forecast quantitative precipitation and precipitation type (using the Baldwin method) at Poughkeepsie, New York, from 1200 UTC 14 January 1999 through 1200 UTC 16 January 1999. Note time axis increases from right to left.

Eta forecast cross section of wet-bulb temperature across the rain-snow line over Pennsylvania at 24/0000 UTC. The forecast cross section indicates that the freezing level remained nearly constant from KAOO east to just west of KCXY, then became much higher at KCXY.

A time-height diagram of wet-bulb temperature from the 23/1200 UTC run of the Eta is shown for KCXY in Fig. 9a, using the high-resolution hourly data. The deep surface-based warm layer is clearly evident, as is the double warm layer structure forecast around 24/0000 UTC. This diagram indicates that wet-bulb temperatures were above freezing through a depth of nearly 200 mb during much of the precipitation at KCXY. As a result, the quantitative precipitation forecasts from the hourly data (Fig. 9b) shows that the Baldwin technique forecast a nearly all rain event. Surface observations indicate that a nearly all rain event did in fact occur at KCXY (Figs. 9a, b). At KAOO, a time-height diagram of wet-bulb temperature from the hourly Eta forecast data (Fig. 10a) shows a shallower surface-based warm layer present throughout the

event, with the depth remaining around 30 mb. No double warm layer structure is indicated, although there is an increase in the depth of the layer from 0°C to -2°C around 24/0000 UTC. The combination of the warm surface-based layer, and the deep layer from 0°C to -2°C caused the Baldwin technique to forecast snow changing quickly to rain on the 23rd (Fig. 10b). Recall that the precipitation remained all snow throughout the event at KAOO (Figs. 10a, b). Some possible reasons for this forecast error are proposed in Section 5.

c. 15 November 1995

At 0000 UTC 15 November (15/0000 UTC), a deep area of low pressure was bringing a mix of rain and snow to the mid-Atlantic-states region, with rain along the coast, and snow over the Appalachian mountains (Fig. 11a). Figures 11b and c show a comparison between (b) the 24-h Eta forecast of mean sea level pressure and 1000-850-mb thickness verifying at 15/0000 UTC, and (c)

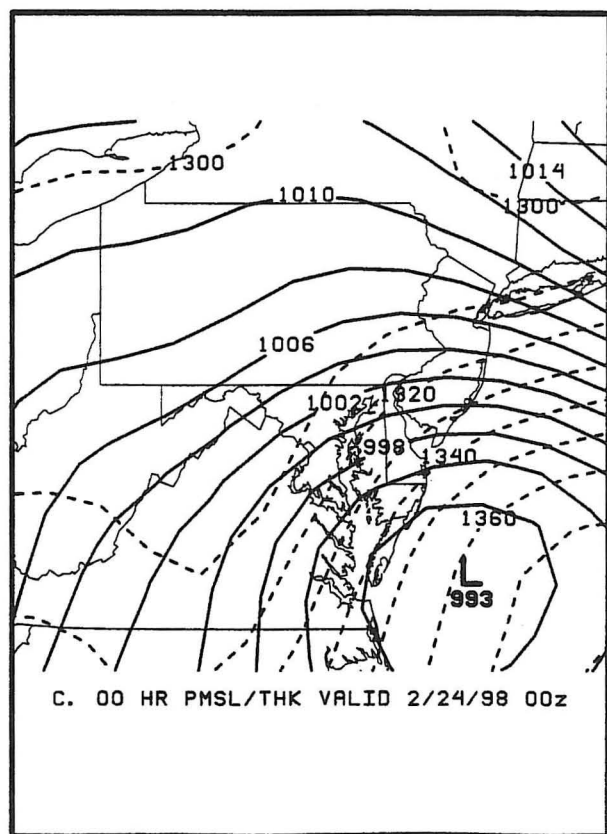
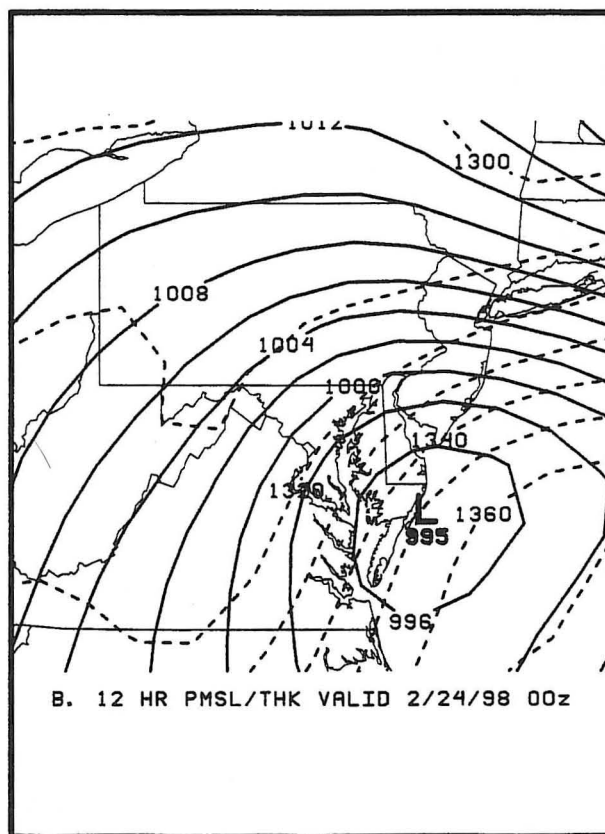
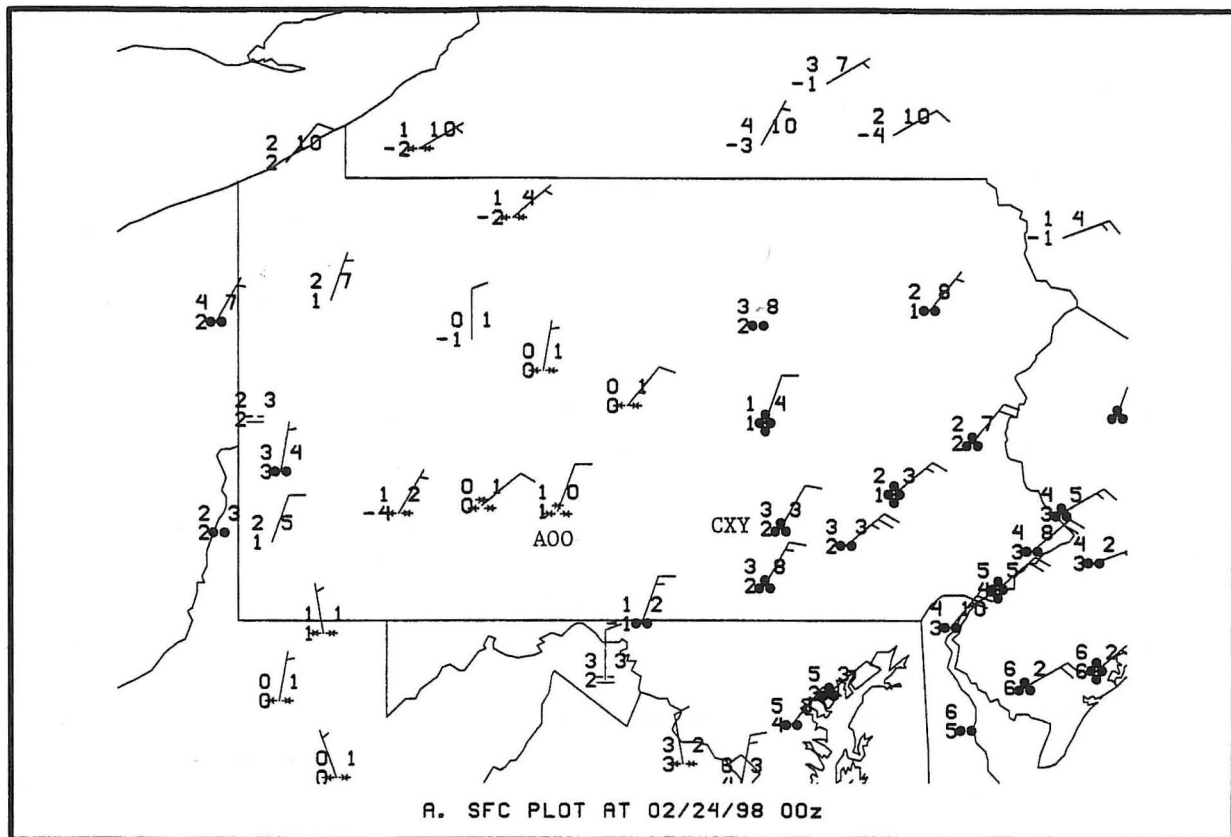


Fig. 7. a) A surface plot in standard notation valid at 0000 UTC 24 February 1998. Eta forecast mean sea-level pressure and 1000-850-mb thickness valid 0000 UTC 24 February 1998 from: b) 12-h and c) 00-h.

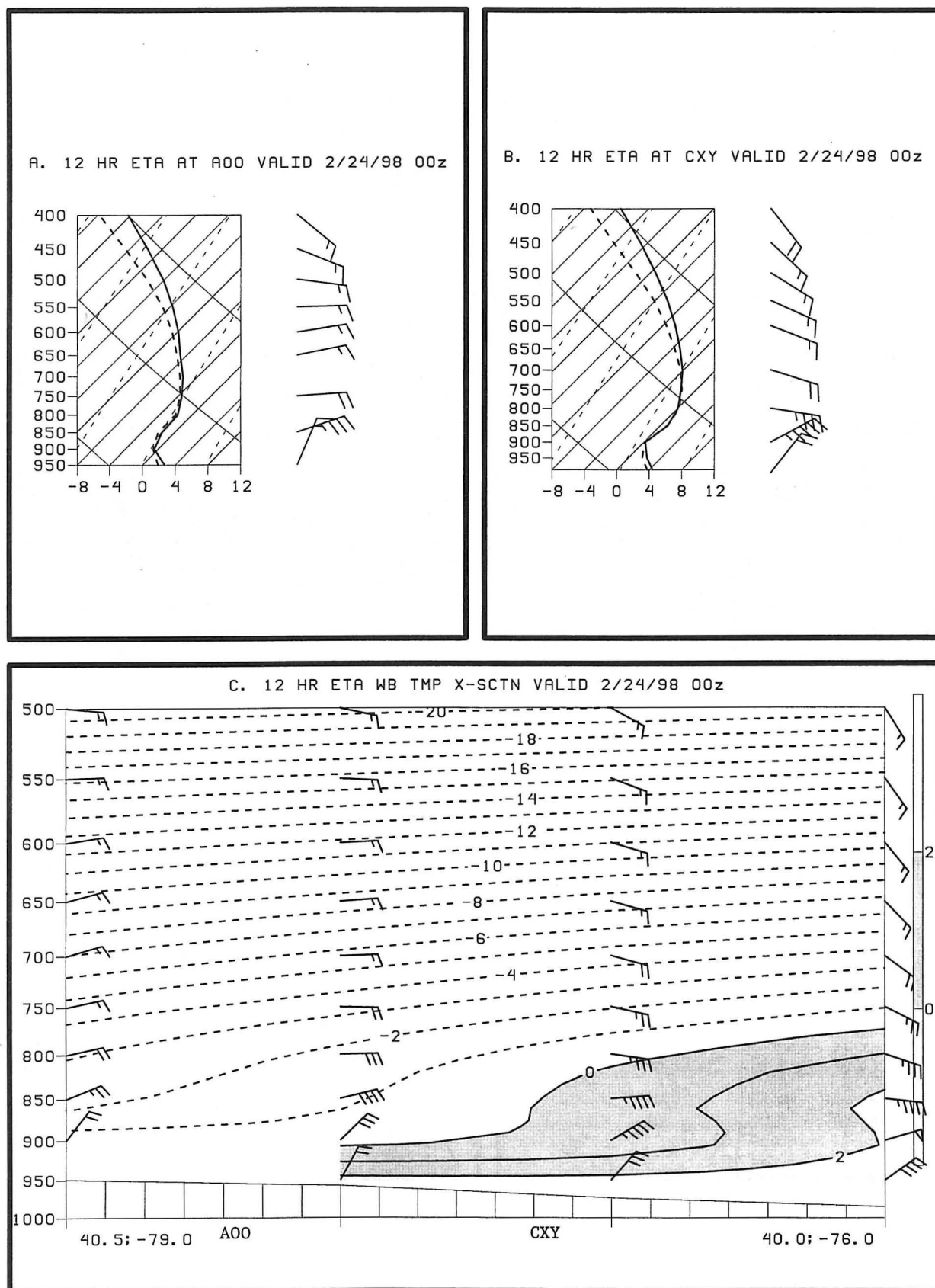


Fig. 8. The 12-h Eta forecast soundings at a) Altoona, Pennsylvania, and b) Harrisburg, Pennsylvania valid 0000 UTC 24 February 1998. Plotting conventions as in Fig. 3. c) A 12-h Eta forecast cross section of wet-bulb temperature across Pennsylvania valid 0000 UTC 24 February 1998.

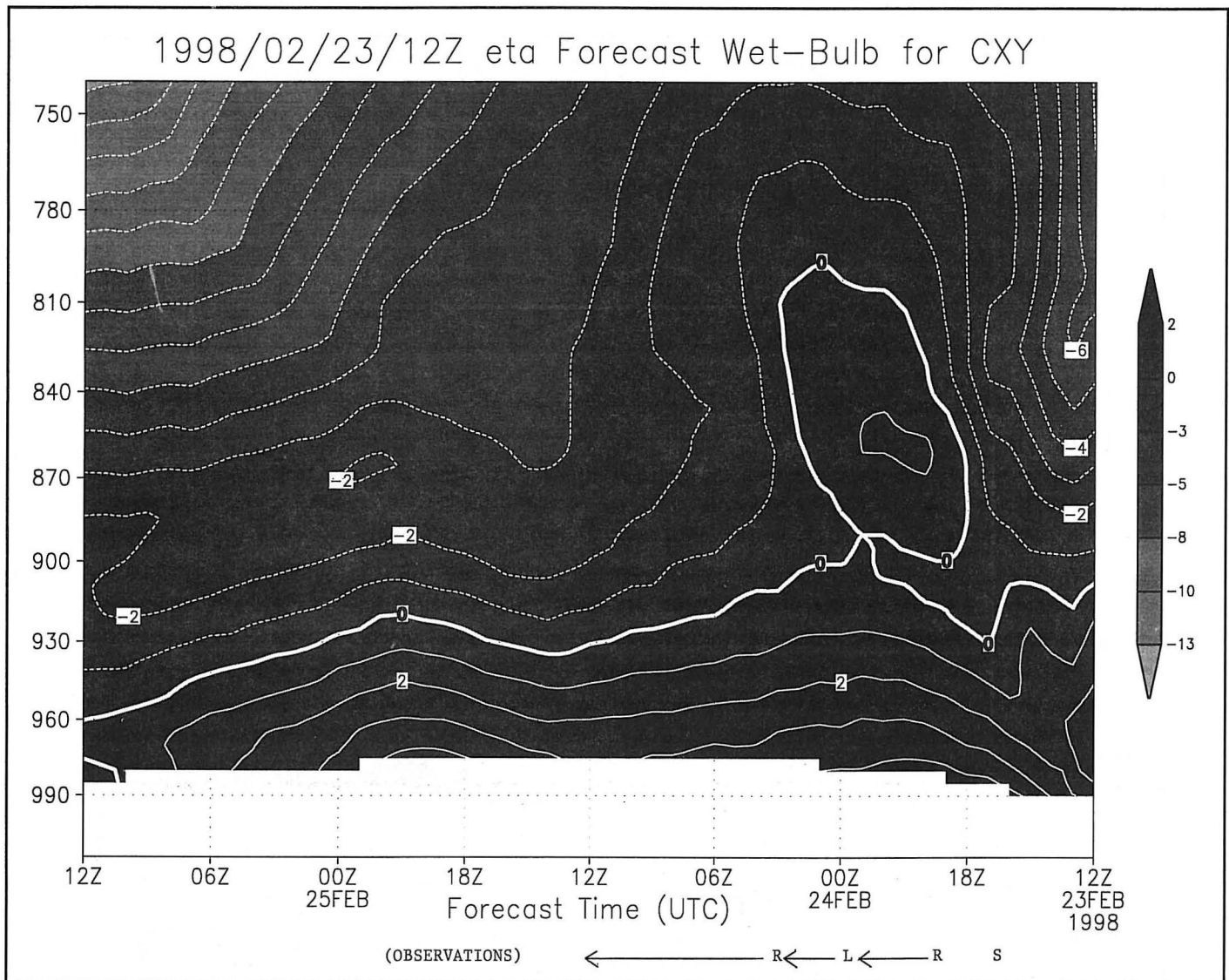


Fig. 9a. An Eta forecast time-height diagram of temperature using the hourly profile data at Harrisburg, Pennsylvania valid from 1200 UTC 23 February 1998 through 1200 UTC 25 February 1998. Note time axis increases from right to left.

the corresponding 00-h Eta forecast verifying at the same time. In contrast to the first two cases, a significant difference is noted between the two model forecasts valid at 15/0000 UTC, with the 24-h forecast being much farther west with the position of the surface cyclone than the 00-h forecast. Low-level thickness values were also significantly higher in the 24-h forecast, as would be expected with the low center located much farther to the west. In this case, successive model forecasts tended toward a more eastward track and a colder solution, but never fully captured the correct storm track, which remained east of all Eta forecasts.

Figure 12 shows GEMPAK-generated 24-h Eta model forecast soundings verifying at 15/0000 UTC at (a) Hagerstown, Maryland (KHGR), where a heavy wet snow was falling, and (b) Baltimore, Maryland (KBWI), where rain was falling. At KHGR, the forecast surface-based warm layer extended to around 750 mb. The forecast surface temperature was $+6^{\circ}\text{C}$, which was 6°C warmer than observed. At KBWI, an even deeper sur-

face-based warm layer was forecast, with the freezing level at 725 mb. The forecast surface temperature of $+10^{\circ}\text{C}$ was 4°C warmer than observed.

Figure 12c shows an Eta 12-h forecast cross section of wet-bulb temperature taken across the rain-snow line from western Maryland to Delaware. In this case, the cross section indicates a deep surface-based warm layer across the entire region, with a depth ranging from nearly 300 mb in the southeast, to over 200 mb in the northwest. Based on the fact that heavy snow was falling across central and western Maryland at this time, there seems to be little doubt that the model forecast in this case was simply too warm.

5. Discussion

a. Forecasting precipitation type

The results shown on Fig. 1a suggest that falling snow particles change to rain in association with Eta model

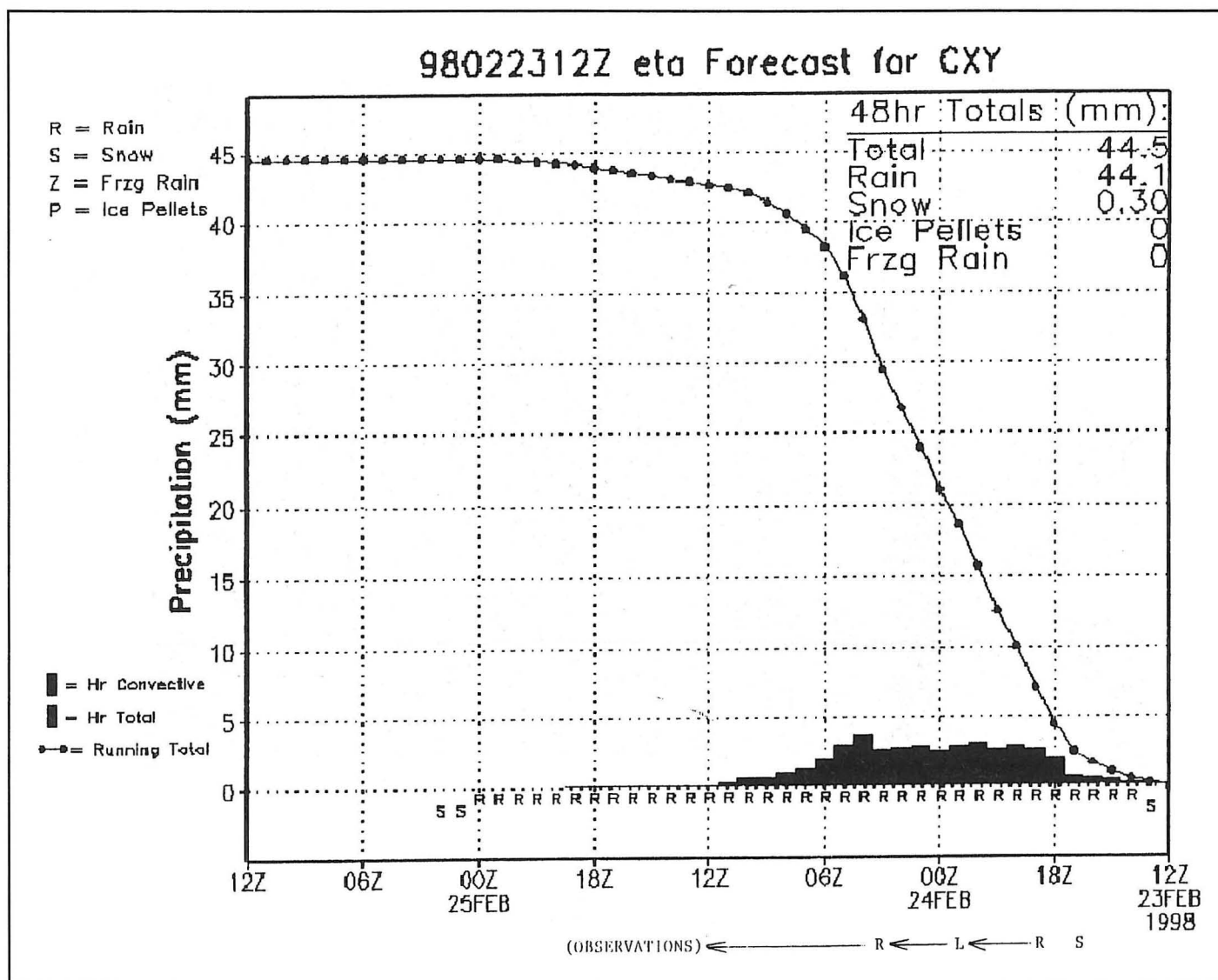


Fig. 9b. Eta model forecast quantitative precipitation and precipitation type (using the Baldwin method) at Harrisburg, Pennsylvania, from 1200 UTC 23 February 1998 through 1200 UTC 25 February 1998. Note time axis increases from right to left.

forecasts of surface-based warm layer depths (defined by wet-bulb temperature) greater than 100 mb, or maximum wet-bulb temperatures within the warm layer greater than 3°C. Lumb (1961) studied precipitation type in the British Isles and found that snow frequently occurs at the surface in that region with an observed wet-bulb zero level as high as 300 to 600 m. In addition, he found that, in rare cases with heavy convective snow, the wet-bulb zero level can be as high as 750 m. A depth of 750 m corresponds to approximately 85 mb in the lower troposphere (U.S. Standard Atmosphere, 1976). The fact that the results from this study indicate a slightly higher critical depth for Eta forecast surface-based warm layers (100 mb) suggests that the Eta may contain a slight lower-tropospheric warm bias in these cases. This possible warm bias will be discussed in more detail later in this section.

When warm layers were located at the surface and aloft, rain typically occurred when the depth of any warm layer exceeded 100 mb. Only 2 snow events from this

study occurred with a warm layer deeper than 100 mb; one case where snow fell with a forecast 110-mb deep warm layer aloft, and another case (presented in section 4c) where snow fell with a forecast 195-mb deep surface-based warm layer. Since previous research, including the findings in this study, indicate that such deep warm layers would melt any snow, it is likely that those two model forecasts were simply too warm, and significant adjustments would have been needed in order to make a good forecast.

In summary, the Eta-forecast warm layer critical depths suggested by the data in this study match the critical depths indicated by the observational work of Lumb fairly well, with a slight warm bias indicated in the model data. The reader should keep in mind that the forecasts in this study were mostly 12-h forecasts, with a few 18- and 24-h forecasts. Longer-range forecasts would probably have been less accurate, as cyclone track errors became more common and more significant.

When the Eta forecast a surface-based cold layer with

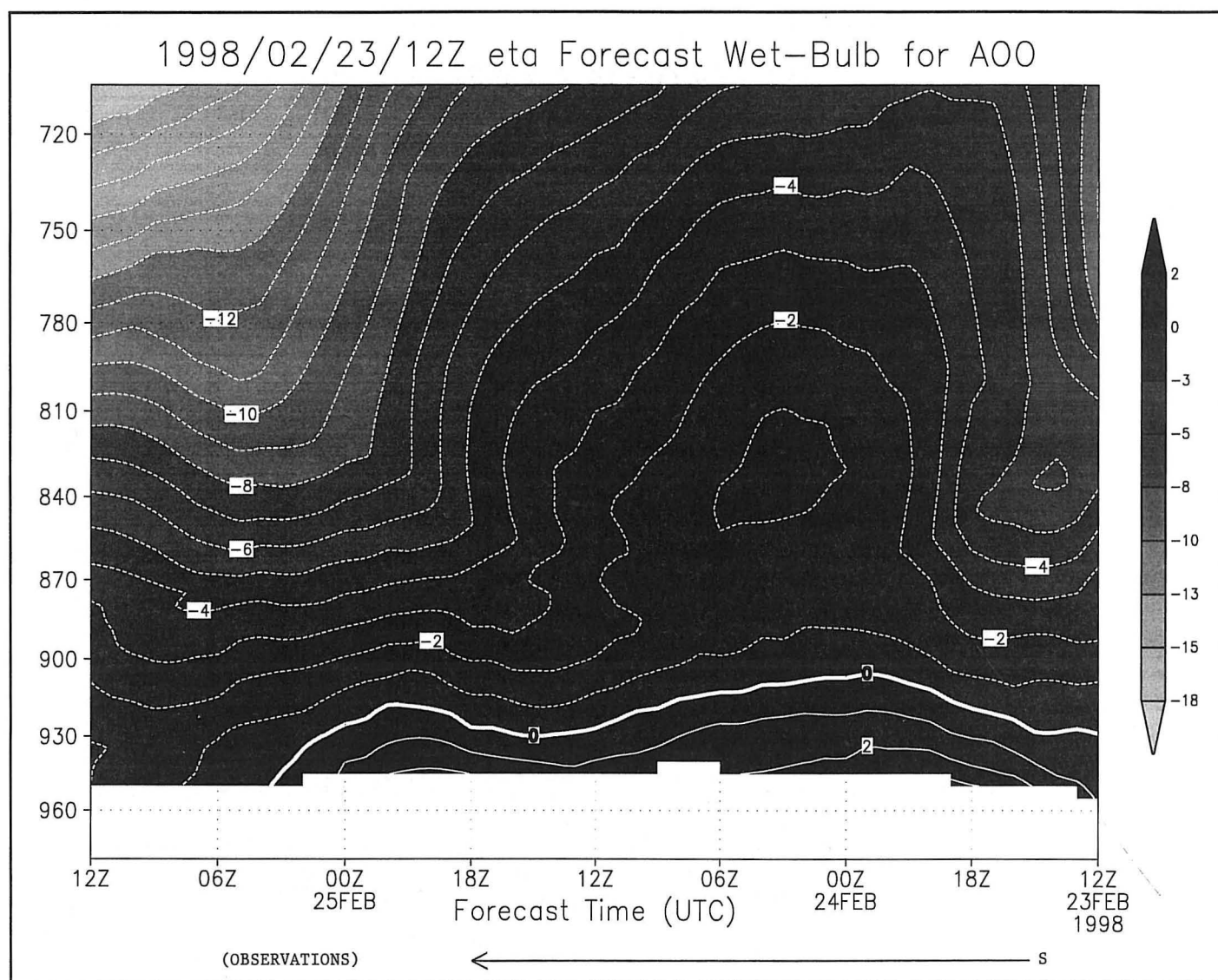


Fig. 10a. An Eta forecast time-height diagram of temperature using the hourly profile data at Altoona, Pennsylvania valid from 1200 UTC 23 February 1998 through 1200 UTC 25 February 1998. Note time axis increases from right to left.

a warm layer aloft, sleet occurred with cold layer depths ranging from 90 to 150 mb, and warm layer depths ranging mostly from 80 to 140 mb (or 800 to 1400 m, based on a standard atmosphere centered at 850 mb). One outlier occurred with a warm layer depth of 190 mb. Maximum wet-bulb temperature within the warm layers ranged from 1 to 5°C. Czys et al. (1996) developed a method for predicting the occurrence of sleet based on the depth of the warm layer aloft, the temperature within the warm layer, and the radius of the falling ice particle. Their results indicated that when the maximum temperature within the warm layer exceeds 1°C, the depth of the warm layer should typically not exceed 1500 m, for sleet to occur. When the mean temperature exceeds 5°C, the warm layer should not exceed 500 m in depth. It was hypothesized that warm layer depths exceeding those critical values would completely melt falling ice particles, resulting in freezing rain at the surface, instead of sleet. The fact that the results from our study match well with results from the observational work of Czys et al. indi-

cates that the Eta forecasts were reasonably accurate. This fact also lends credence to the results in this study, despite the limited number of sleet cases. These results suggest that combining the Eta forecast model soundings with the technique described by Czys et al. could have been used effectively to forecast sleet for most of the cases in this study.

The data from the event on 14-15 January 1999 (section 4a) shows that snow changed to sleet at KAVP around the time when the Eta hourly profile data indicated the development of an elevated warm intrusion. Sleet continued as the forecast warm intrusion gradually increased in depth to about 130 mb by 1200 UTC on the 15th (Fig. 5a). Clearly, the hourly profile data would have been an excellent tool for forecasting precipitation type at KAVP for this event, as the forecaster would have been alerted to the potential for sleet by the presence of the warm intrusion. As was discussed in section 4a, the use of high resolution profile data in this case would have been critical, since 850 mb plan view maps would not

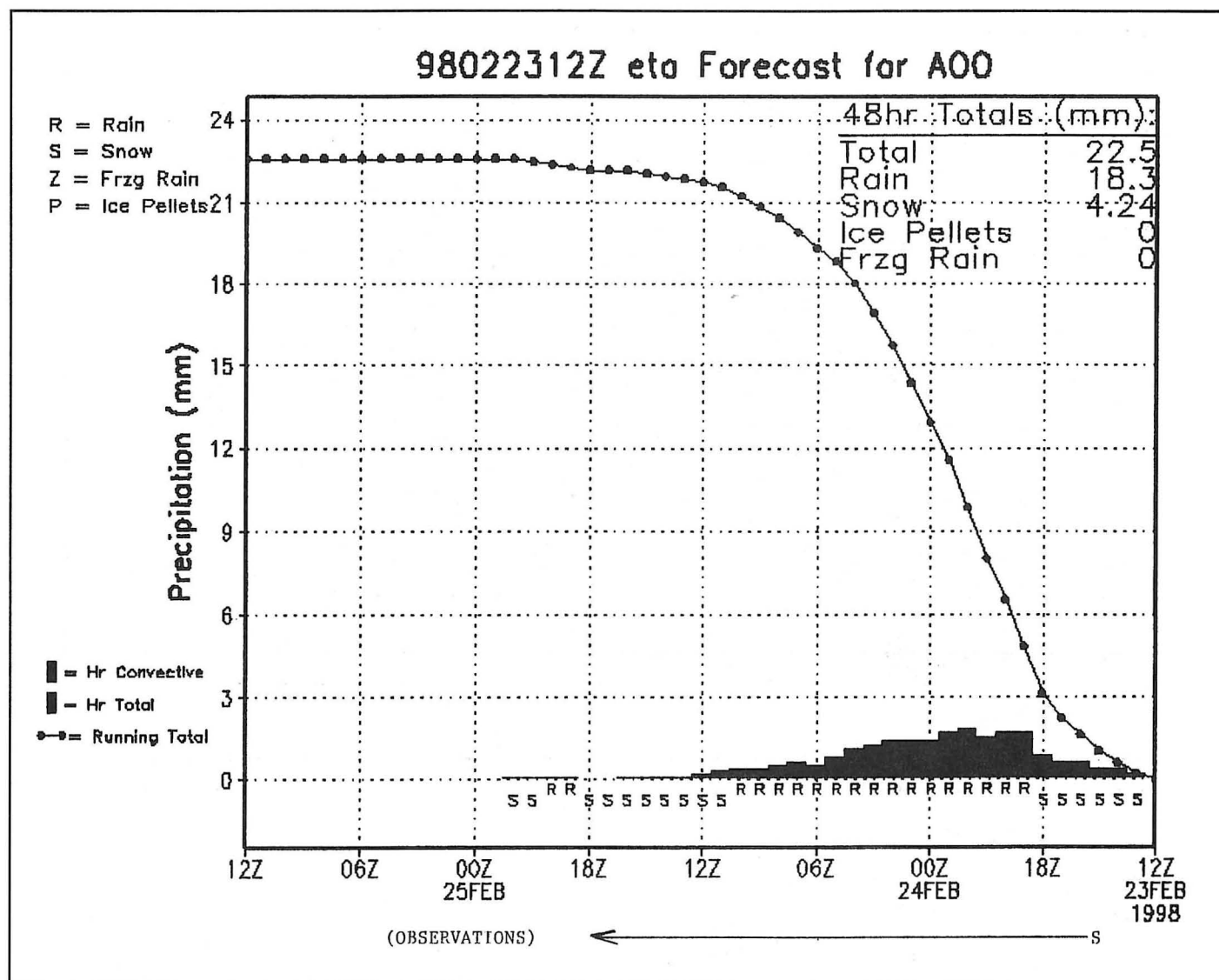


Fig. 10b. Eta model forecast quantitative precipitation and precipitation type (using the Baldwin method) at Altoona, Pennsylvania, from 1200 UTC 23 February 1998 through 1200 UTC 25 February 1998. Note time axis increases from right to left.

have indicated a warm intrusion until around 15/0000 UTC. At KPOU, the precipitation remained primarily snow until 15/0900 UTC, despite the fact that the Eta forecast the development of a shallow warm intrusion shortly after 14/1800 UTC, with the warm intrusion growing in depth to around 120 mb by 15/0600 UTC (Fig. 6a). The Baldwin technique forecast a change from snow to sleet at 14/1800 UTC. In this case, the Baldwin technique changed the snow over to sleet too quickly, at first due partially to the presence of a deep saturated layer from 0 to -4°C after 14/1800 UTC. Grumm and Hart (1998) discussed the potential for the Baldwin method to change frozen precipitation to freezing or liquid too quickly when deep saturated layers from 0°C and -4°C are forecast. Eventually, the model forecast simply became too warm, probably due to an underestimation of the amount of cold air associated with a large anticyclone over the northeast U.S., and the resultant cold air damming in the Hudson Valley. As evidence of the model's underestimation of this cold air, recall from sec-

tion 4a that the Eta model's forecast surface temperature verifying at 15/0000 UTC at KPOU was 8°C too warm. The 12-h forecast of 1000-850-mb thickness verifying at KPOU at 15/0000 UTC was close to the corresponding 00-h thickness from the 15/0000 UTC Eta model run. However, the 18-h 1000-850-mb thickness forecast at KPOU verifying at 15/0600 UTC (not shown), was about 10 m warmer than the corresponding 6-h forecast from the 15/0000 UTC Eta forecast. That finding suggests that a lower-tropospheric warm bias developed in the 14/1200 UTC Eta run forecast by 15/0600 UTC.

It is interesting to note that the precipitation on 14-15 January 1999 changed from snow to sleet at KAVP, while at KPOU the precipitation changed from snow to freezing rain. A close look at the hourly wet-bulb temperature profiles at the two location may provide some insight as to why this occurred. Note that at KAVP, Fig. 5a indicates isotherms slanted at about a 45° angle near and just below the freezing level between 14/1800 UTC and 15/1200 UTC. By contrast, the isotherms on the KPOU

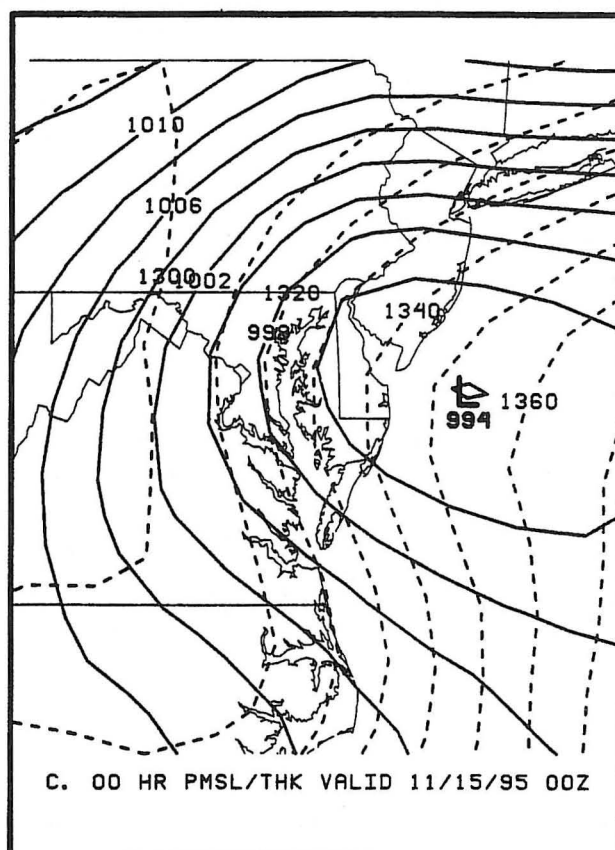
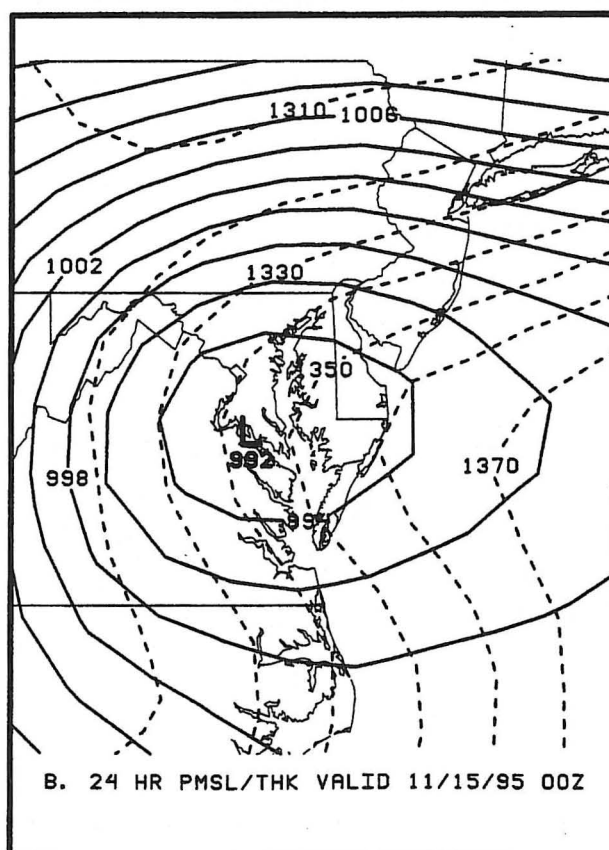
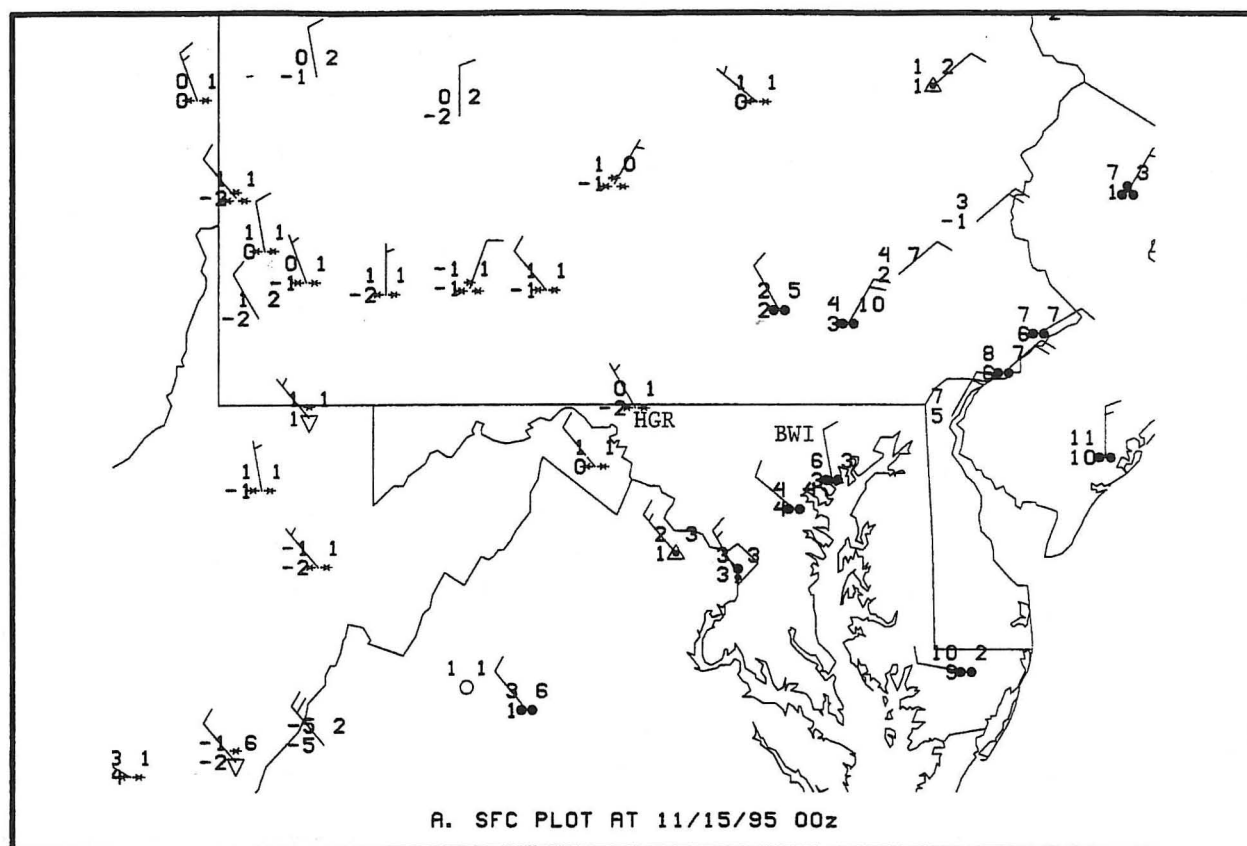


Fig. 11. a) A surface plot in standard notation valid at 0000 UTC 15 November 1995. Eta forecast mean sea-level pressure and 1000-850-mb thickness valid 0000 UTC 15 November 1995 from: b) 24-h and c) 00-h.

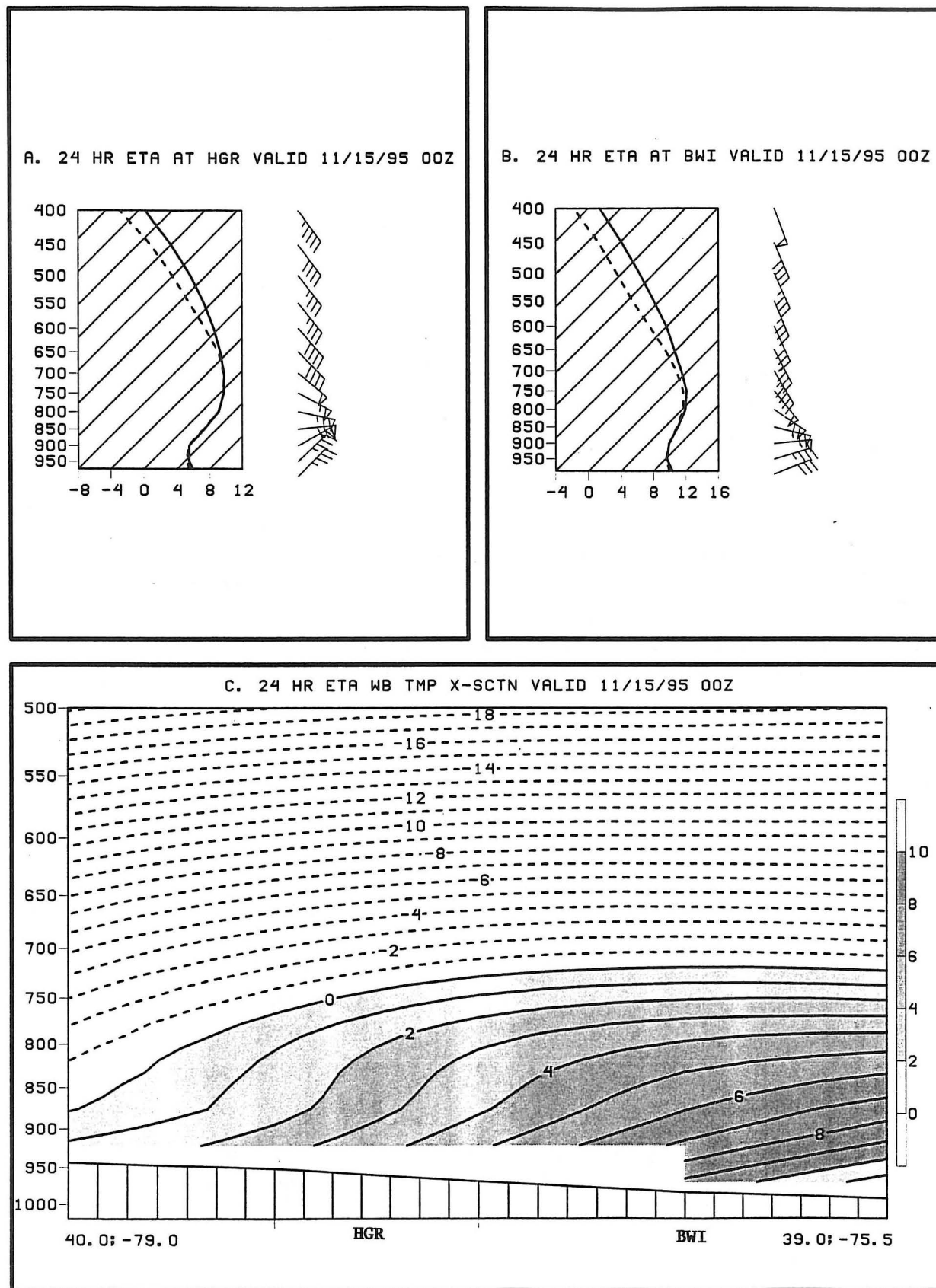


Fig. 12. The 24-h Eta forecast soundings at a) Hagerstown, Maryland, and b) Baltimore, Maryland valid 0000 UTC 15 November 1995. Plotting conventions as in Fig. 3. c) A 24-h Eta forecast cross section of wet-bulb temperature from western Maryland to central Delaware valid 0000 UTC 15 November 1995.

time-height diagram (Fig. 6a) are more tightly packed and nearly vertical. The tightly packed more vertical orientation of the isotherms at KPOU suggests a more rapid warming through a deeper layer of the lower troposphere than at KAVP. The more rapid growth of the warm layer through a deeper layer at KPOU could have resulted in more freezing rain than sleet at that location, given that the surface temperatures remained below freezing.

Data from the second case study (24 February 1998 (section 4b)), showed that the Baldwin method forecast mostly rain at KAOO during the event, when in fact the precipitation in that case fell as all snow. This incorrect forecast was likely related to the fact that the Baldwin method forecasts a precipitation type other than snow when deep layers of the sounding are characterized by wet-bulb temperatures above -4°C (Baldwin et al. 1995; Grumm and Hart 1998). In this case, the Eta forecast sounding at KAOO (Fig. 8a) indicated a wet-bulb temperature between -4°C and 0°C through a deep layer. This case illustrates an important point about using model output. Precipitation type forecasts from algorithms like the Baldwin method are usually quite reliable and can be utilized effectively as a first guess when making a forecast. However, all algorithms have weaknesses. Therefore, it is the author's contention that the best way to forecast precipitation type is to view the model profiles, from which the algorithms are derived. This should produce a better forecast in the few cases where the model forecast is good, yet the algorithm produces a bad forecast. In addition, when model forecast errors are anticipated, the profiles can be manually adjusted if they are viewed directly. Adjusting output from an algorithm based on an unseen profile would be more difficult.

In this study, a warm bias was frequently noted in the Eta model forecast lower tropospheric wet-bulb temperatures. Recall, for example, that the critical warm layer depth for melting snow indicated by the Eta sounding data in this study was slightly higher than critical layer depths indicated by observational studies. Figure 1f shows a scatter diagram plotting the difference between the forecast and observed surface temperatures (the temperature error) vs. the forecast temperature difference from the surface to 850 mb. The data indicate that positive (forecast too warm) errors occurred at 34 points, no error occurred at 9 points, and negative (forecast too cold) errors occurred at 8 points. The mean error was 1.4°C , with a standard deviation of 2.0°C . A Student's *t* test revealed that error to be significant at the 0.01 level. The data also indicate that the warm bias was most pronounced when positive wet-bulb temperature differences were forecast from the surface to 850 mb (temperature decreasing with height). In those cases, 22 of 24 forecasts were too warm. The mean error was 2.2°C , with a standard deviation of 1.5°C . Meanwhile, when the forecast wet-bulb temperature difference was zero or negative (temperature unchanged or increasing with height), the mean error was only 0.6°C , with a standard deviation of 2.3°C ; not significant at the 0.01 level.

These results in no way indicate that an overall warm bias exists with the Eta boundary layer wet-bulb temperatures, since these data represent unique cases where wet-bulb temperature forecasts would be particularly

susceptible to a variety of factors including storm track errors. Hart et al. (1998) studied the performance of Eta two-meter temperature forecasts prior to 1997 and found a warm bias in temperatures during the day, and a corresponding cold bias at night. These problems were apparently related to errors with the models lower-tropospheric radiation scheme. Since these schemes have been corrected, Hart found a slight to moderate cool daytime bias, and a slight warm bias at night.

An examination of several of the too-warm forecast soundings from this study reveals that more accurate forecasts could have been made if isothermal wet-bulb temperature profiles had been forecast in the lower troposphere. Instead, the Eta forecast relatively steep lapse rates in the lower troposphere at those locations; hence the relationship between temperature error and the forecast surface-to-850 mb temperature differences indicated in Fig. 1f. These kinds of events are frequently referred to as "warm snows", and often present difficult forecast challenges. The second and third case studies from section 4 are excellent examples of this kind of storm.

Findeisen (1940) and Stewart (1984) found that once snow begins to fall through a warm layer, a deep (up to 1 km), lower-tropospheric 0°C isothermal layer typically develops by cooling due to melting, as the surface-based layer becomes saturated. In the cases mentioned above, the Eta apparently failed to generate this lower-tropospheric saturated isothermal layer. Possible factors that could have led to a failure to saturate the boundary layer in these cases range from an inadequacy in the microphysics scheme that governs the Eta's melting and saturation processes, to problems simulating the intense mesoscale upward vertical motion in proximity to the rain-snow line. An under-forecast of quantitative precipitation amounts in the vicinity of the rain-snow line would be an indication of either of these problems. It can be noted that the Eta did in fact under-forecast quantitative precipitation amounts at KAOO in the case shown in section 4b (by about 40 percent). Meanwhile, no such tendency to under-forecast precipitation amounts was observed in the other "warm boundary layer" case from section 4 (15 November 1995). In that case, serious model forecast errors with the track of the storm were likely the main reason why the lower-tropospheric wet-bulb temperature forecast was too warm. As a result, the only way to make an accurate forecast of precipitation type in that case would have been to anticipate the storm track error, and manually adjust the model forecast soundings accordingly.

b. Visualizing the data

The results shown here clearly demonstrate that viewing data on plan view maps to determine precipitation type is not optimal. Forecasters need to visualize the data both temporally and spatially. National Weather Service (NWS) forecasters can now view forecast model soundings and time-height diagrams using the Advanced Weather Interactive Processing System (AWIPS). Depending on the NWP model used, AWIPS generates 3-to-6 hourly model soundings. Interpolating from the surrounding grid points generates the soundings and time-height diagrams from the surrounding grid points.

In addition to AWIPS, many NWS offices and Universities use programs such as GARP to display model data. GARP allows the user to view soundings and time-height diagrams from the model grid points. The temporal resolution depends on the frequency of the model output files. These data are often available on more spatially dense grids than those currently used in AWIPS.

Additional model sounding data sets, with 1-h temporal resolution are available for the Eta, NGM, and RUC (Hart et al. 1998). These soundings are derived data from the grid point nearest the select forecast location. The user must be aware of the displacement difference between a model sounding grid point and its station name. The primary method for visualization of the higher resolution sounding data in the operational community for the past few years has been through BUFKIT, a software package developed at the National Weather Service Forecast Office in Buffalo, New York (Niziol and Mahoney 1997). These high temporal resolution data can also be viewed using several freeware packages. Figures 5, 6, 9, and 10 from the case studies section show examples of the kind of visualization graphics available from the GRADS (Grid Analysis and Display) software package (Web site: www.ems.psu.edu/wx/etats.html).

6. Summary and Conclusion

In this study, 12 to 24-hour Eta model forecast soundings were examined at locations near the rain-snow boundary for 15 mixed-precipitation events over the northeast United States. Data were taken from heavy snow producing systems, at locations near where peak precipitation rates were occurring.

The results indicate that Eta model forecast soundings are usually accurate enough to be used to effectively forecast precipitation type. In the study, when the only warm layer (defined by wet-bulb temperature) was surface-based, snow typically fell when the warm layer depth was less than or equal to 100 mb, and the maximum wet bulb temperature within the warm layer was 3°C or less. Rain fell with a deeper warm layer or with higher wet-bulb temperatures within the warm layer. When the only warm layer was located above a surface-based cold layer, sleet typically fell when warm layer depths within the forecast soundings ranged from 80 to 140 mb, surface-based cold layer depths ranged from 90 to 150 mb, and maximum wet-bulb temperatures within the warm layer ranged from 1 to 5°C. Shallower warm layers were associated with snow. Finally, when warm layers were forecast aloft and at the surface, rain occurred when the depth of any warm layer exceeded 100 mb.

Three case studies were shown to illustrate some of the findings of the study. The first case involved a mixed-precipitation event where a warm layer was located above a surface-based cold layer. In that case, sleet over northeast Pennsylvania was associated with an Eta forecast of a deepening mid-tropospheric warm intrusion. Meanwhile, snow fell farther east over the mid-Hudson Valley, with a shallower mid-tropospheric warm intrusion. The change from snow to sleet appeared to be well forecast by the Eta model over

Pennsylvania, however the Eta forecast appeared to be too warm farther east, over the Hudson Valley, where the effect of cold air damming may have been underestimated. In the second case, the warmest air was surface-based. In that case, the Eta forecast unrealistically unstable temperature profiles between the surface and 850 mb when moderate to heavy precipitation should have produced a more isothermal lower-tropospheric profile. As a result, adjusting the lower-tropospheric temperature forecast to a more realistic profile was required in order to make an accurate wet-bulb temperature forecast. In the third case, the Eta model forecast soundings were much too warm, due probably to a poor forecast cyclone track. In that case, the forecaster would have needed to recognize that the forecast storm track was in error, and adjust the entire forecast temperature profile downward by several degrees.

From these results, some basic guidelines can be derived for using Eta model forecast soundings to predict precipitation type. **These guidelines should only be used in conjunction with major cyclones, when intense upward vertical motion and significant precipitation amounts are expected.** Lighter precipitation rates would likely be associated with smaller warm layer critical depths.

- When a single surface-based warm layer is forecast, predict snow when the depth of the warm layer is 100 mb or less, with a wet-bulb temperature of 3°C or less. Predict rain when the warm layer depth exceeds 100 mb, or when the maximum wet-bulb temperature is greater than 3°C. It should be emphasized that this applies only when moderate or heavy precipitation is expected. Lower critical warm layer depths and wet-bulb temperatures would be associated with light precipitation.
- When a single warm layer is forecast aloft, forecast sleet when the depth of the warm layer ranges from 80 to 140 mb, the depth of the surface-based cold layer ranges from 90 to 150 mb, and the forecast maximum wet-bulb temperature ranges from 1 to 5°C. Deeper warm layers increase the chance for freezing rain, while shallower warm layers increase the chance for snow. The Eta will frequently make good predictions of the location and depth of warm layers aloft, which are crucial for accurate precipitation type forecasting. Warm layers aloft often develop first between 850 mb and 700 mb; therefore they will be identified most easily using model profiles, instead of plan-view maps of temperature at mandatory levels.
- When warm layers are forecast at the surface and aloft, forecast rain whenever the depth of any warm layer exceeds 100 mb. Otherwise, forecast snow.
- Expect that the Eta forecast surface temperatures to be 1 to 4 °C too warm in the vicinity of the rain-snow line when the forecast temperature difference from the surface to 850 mb is greater than 0°C, and moderate to heavy precipitation is expected.

- The Eta model forecast soundings are only as accurate as the rest of the model forecast. Adjustments must be made to the forecast soundings if an error is expected in the forecast storm track, or timing of the storm. Also, the forecaster should consider the effects of terrain, and mesoscale processes on the temperature forecast.

In conclusion, Eta model forecast soundings are clearly useful tools for forecasting precipitation type. One strategy for forecasting precipitation type would be to first use plan-view maps of thickness or temperature to "zero" in on areas to be examined more closely, then to look at the model forecast soundings. The results from this study indicate that subjective adjustments to the soundings will occasionally be required in order to account for model errors associated with the track of the surface cyclone. The results also indicate that the temperature profiles will often need manual adjustment in the boundary layer, in order to account for physical processes that may not be well handled by the model. Forecasters who understand the effects of terrain, mesoscale processes, and diabatic processes on the local temperature profile, can best make adjustments in that area.

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