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ADDING OR DEGRADING A MODEL FORECAST: ANATOMY OF A POORLY FORECAST WINTER STORM

Richard H. Grumm
NOAA/National Weather Service
State College, PA
and
Robert E. Hart
The Pennsylvania State University

1. INTRODUCTION

On 13 November 1997 a winter storm moved through the mid-Atlantic and northeastern United States. This early season event produced rain, mixed precipitation, and heavy snow. Forecasts for the evolution of precipitation type focused on the potential for a winter storm, with heavy snow over much of central Pennsylvania and central New York State and a mix of ice pellets, snow and freezing rain across most of south central Pennsylvania. High-resolution profile data from the 29 and 48 km Eta models (Hart et al. 1998) suggested that the precipitation would fall primarily in the form of ice pellets over central and northern Pennsylvania. Hence, the manually produced forecasts diverged from model forecasts. This case may be an example where the reliance on more traditional forecast techniques allowed the model to outperform the human forecaster.

Traditional methods for forecasting winter weather place a high emphasis on examining plan view maps. During the 1950's, studies of snow and ice storms lead to the evolution of critical thickness values (Penn 1957; Pondofolo 1957; Wagner 1957) to determine precipitation type. These concepts were developed and modeled after earlier studies conducted in the United Kingdom (Murray 1952). In the study by Pondofolo (1957) emphasis was placed on an analysis of the thermal structure from the surface to 700 mb. Due to the lack of a dense sounding network, techniques involving plan view maps that depicted critical thickness values were developed. During the 1950's, critical thickness values for various levels were determined to assess the potential intrusion of warm air from the surface to 700 mb.

A summary of these thickness ranges and the critical thickness values are summarized in Table 1. The critical thickness is often used as a rain/snow delineator but was shown to have geographic and seasonal variability due to terrain and proximity to water bodies. Comparison of a critical lower layer thickness value to a mid-layer thickness value is used to determine precipitation type. Ice pellets and freezing rain are typically forecast where 1000-500 mb thickness values are above the critical value (540 dm) and the 1000-850 mb thickness values are below the critical value (130 dm). In effect, the higher value aloft represents warmer air aloft and the lower value below represents the colder air.

Regionalized studies, such as Keeter and Cline (1991), have shown that the critical thickness value is a function of location. Therefore, the values in Table 1 are very general and may work well over most of the eastern United States, but would tend to underforecast the potential for snow over elevated terrain. Model Output Statistics (MOS; Glahn and Lowry 1972) equations incorporated these concepts along with statistics from atmospheric soundings to determine precipitation type (Boccherri 1980; Boccherri and Maglaras 1983).

The availability of numerical output data in gridded form in the 1990's encouraged the use of plan view maps and critical thickness values (Evans 1994; Wichrowski 1997) to forecast precipitation type. Gridded data allowed the user to rapidly compute thickness values and overlay critical thickness from different layers. In addition to the ability to examine critical thickness values, the gridded data facilitated the examination of plan view maps of temperatures, dew points, and wet bulb temperatures to assess the precipitation type. Emphasis was placed on the 850 mb temperatures (dry and wet bulb); however, the earlier Pondofolo (1957) study recommended examining the thermal character from the surface to 700 mb.

Gridded data sets allow the forecaster to examine plan view maps of many thermal fields. These gridded data sets also allow forecasters to assess interpolated thermal profiles at select points. However, these values were often of limited vertical resolution (Hart et al. 1998). In addition to the large amounts of gridded forecast data, the availability of full resolution hourly profiles has increased the ability of forecasters to assess the thermal profile of the atmosphere. In addition to providing full-model resolution thermal profiles, the profile data includes significant forecast parameters such as derived precipitation type (Baldwin 1995) and diagnosed 2-meter temperature, which can be used as input for the forecast process to determine precipitation type.

The purpose of this paper is to evaluate how the traditional forecast methods and the high resolution profile data forecast the precipitation performed during the 14 November 1997 winter storm. Forecasts of precipitation type and amounts will be presented only to show how the guidance was used. The goal is to assess the forecast methods, and not to critique the decision process in place at the time.

2. METHODOLOGY

The gridded model data in this study included data from the operationally available NCEP stepped terrain 48 km Eta (Black 1994) and the 29 km version of the Eta (Meso; Rogers et al. 1995). The 48 km version of the Eta was replaced with a 32 km version in February of 1998. All model data were examined by using the objective analysis package

GEMPAK5.2 (desJardines et al. 1991). For ease of interpretation, all the GEMPAK5.2 graphics show the valid time and forecast length of each product. Gridded forecast products from the Eta and Meso from the 1200 and 1500 UTC forecast cycle will be examined. The emphasis is on how the 29 and 48 km Eta models forecast the thermal structure of the atmosphere during the period of significant ice accumulation (0600 through 1200 UTC 14 November).

Observed precipitation and snowfall data were retrieved in real-time from the National Weather Service (NWS) cooperative network. These data were displayed using GEMPAK5.2. At most locations, accumulations of ice pellets were recorded as snow. Therefore, displays of "snowfall" include accumulations of "ice pellets."

The model profile data were acquired and plotted as described by Hart et al. (1998). Similar to the gridded data, forecasts will be limited to those produced during the 1200 and 1500 UTC forecast cycles. Additional forecast products are available at http://bookend.met.psu.edu/~rgrumm/cases/14novice/.

3. RESULTS

a) Observations

The verifying snowfall and precipitation maps for the 24 hour period ending at 1200 UTC 14 November 1997 are shown in Fig. 1. These data reveal that no location in the State of Pennsylvania received heavy snow (greater than 150 mm) during the forecast period. Heavy snow was observed in central New York State where many locations received excess of 150 mm of snowfall. Precipitation amounts (Fig. 1a) indicate that most locations in central Pennsylvania had snowfall to rainfall ratios on the order of 2:1. An examination of meteograms (not shown) from Altoona (KAOO), Williamsport (KIPT), and State College (KUNV), Pennsylvania revealed that most of the precipitation fell as ice pellets and freezing rain. Closer to the New York border, at locations such as Elmira, (KELM) New York the precipitation fell primarily as snow and ice pellets. In southeastern Pennsylvania, all surface stations reported rain (not shown). However, ice accumulations of 6-12 mm along the ridges was observed in this area.

b) Model-forecast synoptic pattern

The 18 and 24 h forecasts of the surface cyclone evolution, 1000 mb heights, and ageostrophic wind valid at 0600 and 1200 UTC 14 November 1997 are shown in Fig. 2. The forecasts are all from 1200 UTC 13 November 1997 Eta. These data indicated a surface cyclone would move across the Ohio valley with a secondary low developing over the North Carolina coast. The 1000 mb heights and ageostrophic winds forecast northerly low-level winds over Pennsylvania as the Ohio valley low approached from the west. This pattern often indicates cold air damming (Forbes et al. 1987), and is a common feature in many East Coast winter storms. With the exception of a slightly stronger cyclone along the North Carolina coast and stronger low-level ageostrophic winds, the Meso forecasts were similar to those produced by the Eta (not shown).

c) Model-forecast traditional precipitation-type fields

The 48-km Eta thickness forecasts for the four most widely used critical thickness layers, valid at 0600 UTC 14 November 1997 are shown in Fig. 3. With the exception of the 850-1000 mb critical thickness value (Fig. 3c), all the critical thickness values over Pennsylvania indicated less than a 50% probability of snow.

The 48-km Eta forecasts of 850 and 700 mb temperatures and wetbulb temperatures valid at 0600 UTC and 1200 UTC 14 November 1997 are shown in Figs. 4 & 5, respectively. These data show that the 48 km Eta forecast both the 850 mb temperature and wet bulb temperature to remain at or below 0^{o}C over most of Pennsylvania. However, at 700 mb both the temperature and the wet-bulb temperature were forecast to be equal to or greater than 0^{o}C over most of the southern two thirds of Pennsylvania. There was very little difference between the dry and wet bulb temperatures at these times because the model was producing precipitation and the lower 3 km of the atmosphere were nearly saturated

A comparable forecast from the Meso is shown in Fig. 6. These data are for the 18-h forecast valid at 0900 UTC 14 November, the mid-point of the time of the data in Figs. 4 and 5. These data show that the Meso forecast a more northward progression of the warm air at 850 mb than the Eta. By 0900 UTC the Meso forecast the 850 mb temperatures to be at or above freezing over virtually all of Pennsylvania. The 0^{o}C isotherm was aligned nearly east-west along the New York border. The 700 mb zero isotherm was slightly south of the 48 km Eta's position of this feature and was more closely aligned with the 850 mb zero isotherm. The pattern over Pennsylvania suggested a nearly isothermal in the layer from 850 to 700 mb. A model sounding from the gridded data revealed that this nearly isothermal profile was from near the surface to 700 mb over central Pennsylvania (Fig. 7).

d) Model-profile-derived precipitation type forecasts

Forecasts of precipitation amounts and types based on the 1200 UTC Eta and 1500 UTC Meso from 13 November hourly profiles are shown in Figs. 8 and 9. These profiles plot the precipitation (inches) and derived precipitation type (Baldwin 1995) versus time (hour). Additional data include a summary of the precipitation forecast including total precipitation; and the amount forecast to fall as rain, snow, ice pellets and freezing rain. Initially, the Eta suggested light snow at all four locations. The precipitation was forecast to rapidly change to ice pellets and freezing rain at Capitol Cities airport (KCXY) in southeastern Pennsylvania; and ice pellets ending as snow in central Pennsylvania (KUNV and KIPT). The Eta forecast mainly ice pellets in Bradford, Pennsylvania (KBFD) close to the New York border. The Eta forecast a major ice storm at all of these locations with 28-38 mm (1.2 to 1.7 inches) of ice pellets.

The Meso forecasts were slightly different than the Eta forecasts (Fig. 9). At KCXY, the precipitation was forecast to turn to rain before 1200 UTC 14 November. The Meso also forecast a period of freezing rain at the other locations. The Meso generally forecast less precipitation at most locations, except at

KBFD. The Meso also forecast the potential for 6-18 mm (0.25 to 0.70 inches) of freezing rain across Pennsylvania, a worse travel hazard than snow or ice pellets.

These precipitation type forecasts are well explained by examining a cross section of the thermal structure at KUNV from the Eta (Fig. 10). The Eta forecast a layer of above freezing air from near 840 mb upward to around 680 mb. The warmest air (5^{o}C) was forecast around 1200 UTC near 780 mb. The elevated warm layer was forecast to remain over UNV from 0400 through 2200 UTC 14 November. In addition to this elevated warm layer, the Eta forecast a deep (+100 mb) layer of sub-freezing air from 850 mb to the surface. The Eta forecast the entire column to remain sub-freezing until around 0100 UTC, leading to the forecast of snow at KUNV (Fig.9) prior to 0100 UTC. The Meso forecasts revealed a similar thermal structure as the 48 km Eta and are not shown. The Meso forecast a shallower cold layer beneath the warm layer and slightly higher temperatures near 840 mb. The slightly warmer air in the sub-freezing layer combined with a slightly shallower sub-freezing layer beneath the warm air may have produced the period of freezing rain at KUNV (Fig. 9) between 0600 and 1200 UTC 14 November 1997. The vertical profile taken from the 1500 UTC 13 November 1997 Meso valid at 1000 UTC 14 November (Fig. 11) confirmed the earlier runs, forecasting a deep warm layer near 840 mb extending to around 670 mb.

4. DISCUSSION/CONCLUSION

This analysis suggests that both traditional plan view maps and detailed model profiles pointed toward a significant winter storm over Pennsylvania. However, the 48 km Eta maintained 850 mb temperatures and wet bulb temperatures (Fig. 4a) at or below 0^{o}C over most of central and northern Pennsylvania throughout the event. These plan view maps may have played a role in operational forecasts of heavy snow across Pennsylvania. The use of critical thickness values suggested a lower probability of snow and higher probability of rain or a wintry mix across most of central and northern Pennsylvania. Forecasts of sleet and freezing rain would have been more widespread had the 700 mb temperatures (Figs. 4c and Fig. 6c) and wet bulb temperatures (Figs. 4d and 6d) been examined. Vertical profiles, such as the one for State College (Fig. 10) revealed a warm layer between 850 and 700 mb and a trapped cold layer near the surface, which would have precluded forecasts for heavy snow over most of Pennsylvania and southern New York State.

Meso plan view maps of the thermal patterns over Pennsylvania further pointed toward rain, sleet, and freezing rain. The Meso produced significantly warmer temperatures at 850 mb than the Eta. Unlike the Eta, the Meso did not forecast warmer air at 700 mb over the colder air at 850. In fact, the Meso forecast similar temperatures at both 700 and 850 mb. An examination of a Meso sounding valid at 0900 UTC 14 November over UNV (Fig. 11) revealed a deep layer of warm air from around 870 to 670 mb. The sounding also showed that both the 850 and 700 mb temperatures were around 0^{o}C. The saturated profile from the surface to 640 mb indicates that the model was producing precipitation at this time. The nearly isothermal above-freezing profile between 870 and 700 mb suggests that any precipitation falling through this deep warm layer would melt.

An examination of some of the significant tools used to forecast precipitation type suggest that 850 mb temperature forecasts may have played a significant role in the forecasts of heavy snow. An examination of 700 mb temperatures would have revealed the likelihood of a mixed event rather than a snow event. The Meso continually produced overall warmer 850 mb temperature forecasts than the Eta. Forecasts from 0000/0300 UTC 13 November through 0000 UTC on 14 November from the Eta/Meso showed that the Eta was slightly colder than the Meso. It would appear that either the Meso forecasts were not examined closely or the Eta 850 mb temperature forecasts played a more significant role in the forecast process. Operational forecasts for heavy snow across Pennsylvania suggest that forecasters relied on plan view maps of temperatures, but not thicknesses. With the exception of the 850-1000 mb thickness chart (Fig. 3c), the thickness forecasts suggested a low probability of snow (Figs 3a, 3b and 3d). The thickness values, which included the warm layer between 850 and 700 mb, offered valuable forecast guidance.

Despite the subtle forecast differences between the Eta and the Meso as examined on plan view maps, the vertical profiles from the hourly soundings (Fig. 11) and six-hourly sounding from the gridded data (Fig. 7) for both models clearly showed an intrusion of warm air in a layer between 850 and 650 mb. Neither of these soundings supported snow. The hourly sounding data provided better timing of when the warm air would arrive and the change of precipitation type. The hourly model precipitation trace and type plots revealed timing of the precipitation changes and forecasts of the amount and type of precipitation. In this case, these data provided useful forecast information. Furthermore, the vertical profiles should be easier to interpret than the older thickness charts and do not require a table of "statistically significant" values. The use of the precipitation trace and type plots also would have emphasized ice pellets and freezing rain rather than snow.

A significant problem in the forecast process is the limited amount of time available to examine various types of data and the various fields within each dataset. A potential solution is to improve the way data are examined. visualization software, with the ability to examine both the vertical and horizontal thermal structure, could improve forecasts of precipitation types. Until more robust operational visualization software becomes available, plan view maps can be used to identify areas of concern and vertical cross and temporal sections should then be used to refine the forecast of precipitation type.

This case was chosen because it represented an example of how the hourly model profiles could have been used to improve the forecast. Other cases have been collected and examined. Preliminary results suggest that these profiles offer important information during mixed precipitation events. The forecasts of implied precipitation type of either ice pellets or freezing rain are generally reliable when an elevated warm layer is present. However, the current algorithm (Baldwin 1995) shows little skill discerning between ice pellet or freezing rain events.

The biggest forecast problem for the scheme is forecasting snow in marginal events where no above-freezing layer is present between the surface and 700-mb. Several marginal snow events from the winter of 1997-98, where the surface temperatures remained close to freezing have been collected and examined. During the winter storm of 24 February 1998, the 23 February 0000 and 0300 UTC model forecasts from the 32 km Eta (Fig. 12) and the 28 km Eta (Fig 13) respectively, forecast rain and snow across central Pennsylvania. At KUNV, the precipitation briefly began as rain and snow mixed. As the precipitation rates increased it changed to all snow. The cooling effect of melting snow has been observed in the past (Wexler et al. 1954). The 1200 UTC 32 km Eta (not shown) forecast only 20% of the precipitation to fall as snow. The official observing point in State College reported in excess of 32 cm of snow. Snowfall and liquid equivalents in the 30 cm and 3.7 cm range, respectively, were observed in the area around KUNV and at KIPT. The surface temperature at KUNV remained at or slightly above freezing during the period of snowfall. A similar snowfall to liquid ratio was observed at KAOO and KIPT. These results and data from several other cases suggest a bias toward forecasting rain and freezing rain during warm snow events.

These warm-snow events have revealed a fundamental bias associated with the Baldwin (1995) precipitation type scheme. As shown in Baldwin (1995), a forecast of snow vs freezing precipitation is determined by calculating the area of the sounding with a wetbulb above -4°C. Since the criteria used is sub-freezing (rather than the more physically consistent criteria of 0°C), it is possible for a completely subfreezing sounding to give forecasts for types other than snow. This is most likely to occur when a deep saturated layer of -0.5° to -3.5°C exists. In these cases, a snow sounding is clearly present; yet, the Baldwin scheme will indicate a precipitation type other than snow since the wetbulb area of the sounding above -4°C is large. The typical model profile precipitation type forecast by the Baldwin scheme in these cases is for ice pellets or freezing rain. Forecasters are urged in these situations to examine the full-resolution vertical profile to determine if the scheme is producing precipitation type forecasts that are physically inconsistent with the forecast thermal profile.

Ultimately, the use of robust 3-dimensional applications software should mitigate the problems associated with interpreting large amounts of data. As mesoscale numerical models improve over the course of the next decade, the use of visualization techniques will increase. Visualization software will likely play an increasingly more important role in the modern forecaster’s diagnosis of meteorological situations. The effective use of visualization software would have revealed the warm layer between 850 and 700 mb during the 14 November 1998 winter storm, emphasizing ice pellets and freezing rain rather than heavy snow. The concept of examining the thermal profile from the surface to 700 mb to forecast precipitation type (Pondofolo 1957) is still valid. However, unlike forecasters of the 1950s, forecasters today have the tools to apply this steadfast forecast technique on observational and detailed model forecasts.

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Table 1. Critical thickness values for specified layers used to forecast precipitation type. The critical value is typically associated with the 50% rain/snow probability. The ranges were derived from studies mentioned in the text and reflect the geographical variability ascribed to the use of thickness values.

Critical Thickness Values			
Layer (mb)	***Critical Value (m)***	***Significance***	***Ranges***
1000-500	5400	50% rain/snow	5340-5552
1000-850	1300	50% rain/snow	1280-1330
1000-700	2840	50% rain/snow	2825-2860
850-700	1520	50% rain/snow	1520-1560

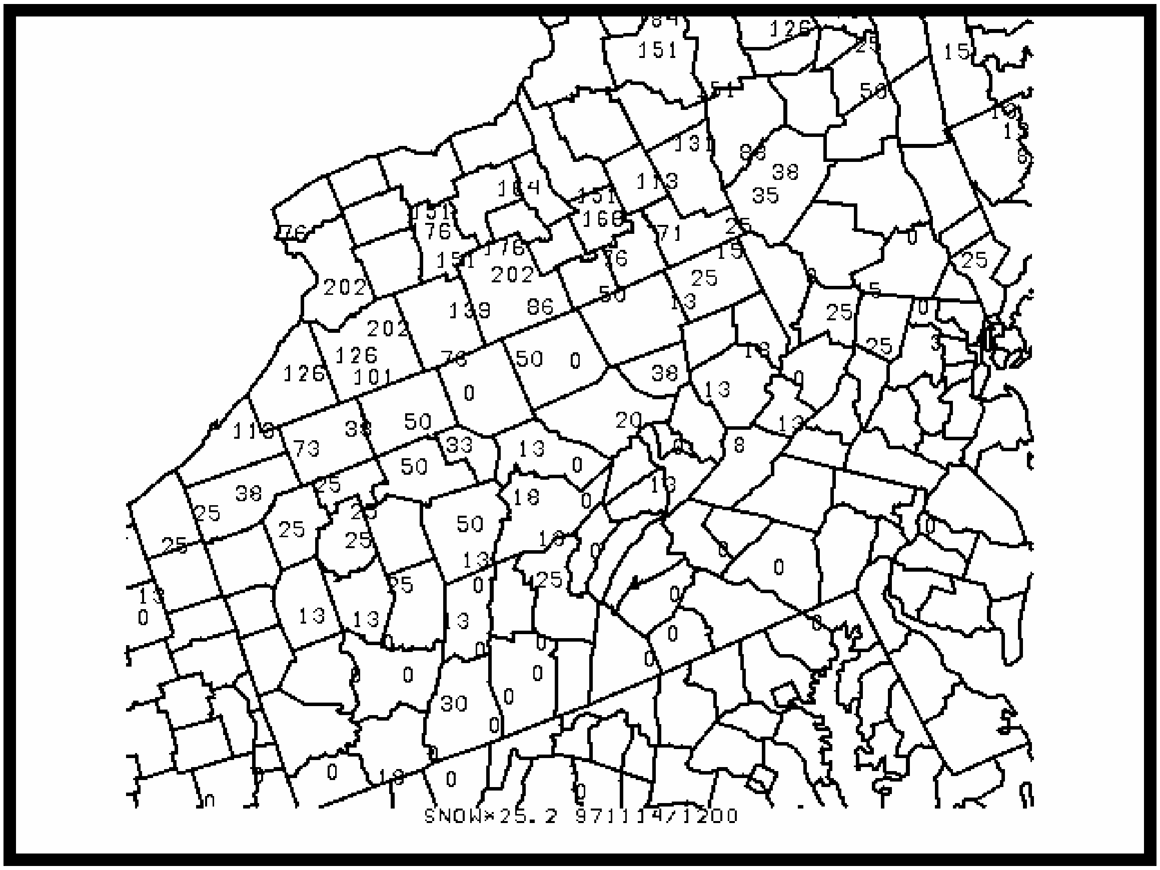

Figure 1a. The 24 hour accumulated snowfall (mm) across Pennsylvania and New York State valid at 1200 UTC 14 November 1997.

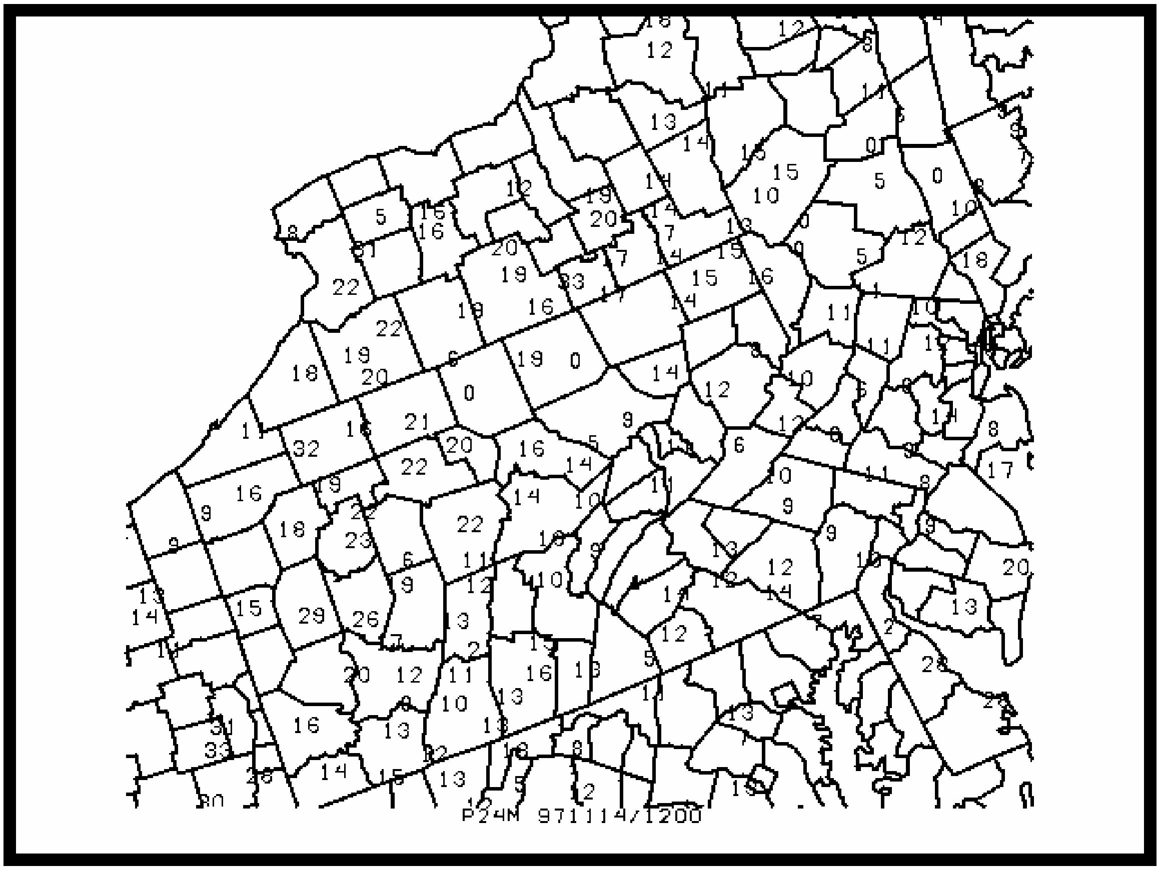

Figure 1b. The 24 hour liquid equivalent precipitation (mm) across Pennsylvania and New York State valid at 1200 UTC 14 November 1997.

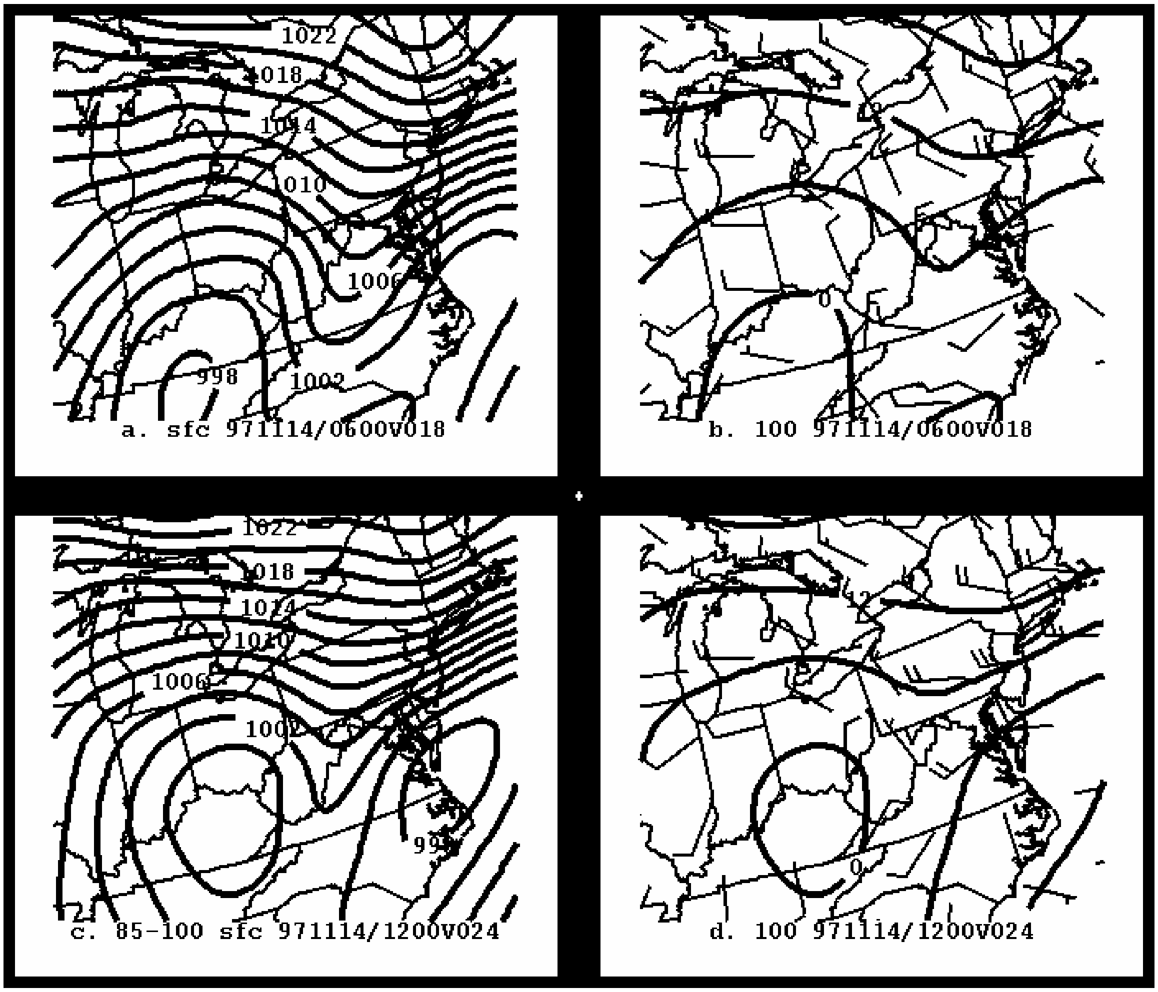

Figure 2. 48 km Eta model forecasts from the 1200 UTC 13 November 1997 forecast cycle of a) mean sea-level pressure (hPa) and b) 1000 hPa heights and ageostrophic winds valid at 0600 UTC 14 November 1997 and c) mean sea-level pressure and d) 1000 hPa heights and ageostrophic winds valid at 1200 UTC 14 November 1997. The titles in each panel show the valid time and forecast length. Mean sea-level pressure contours are every 2 hPa and 1000 hPa heights are contoured every 6 dm.

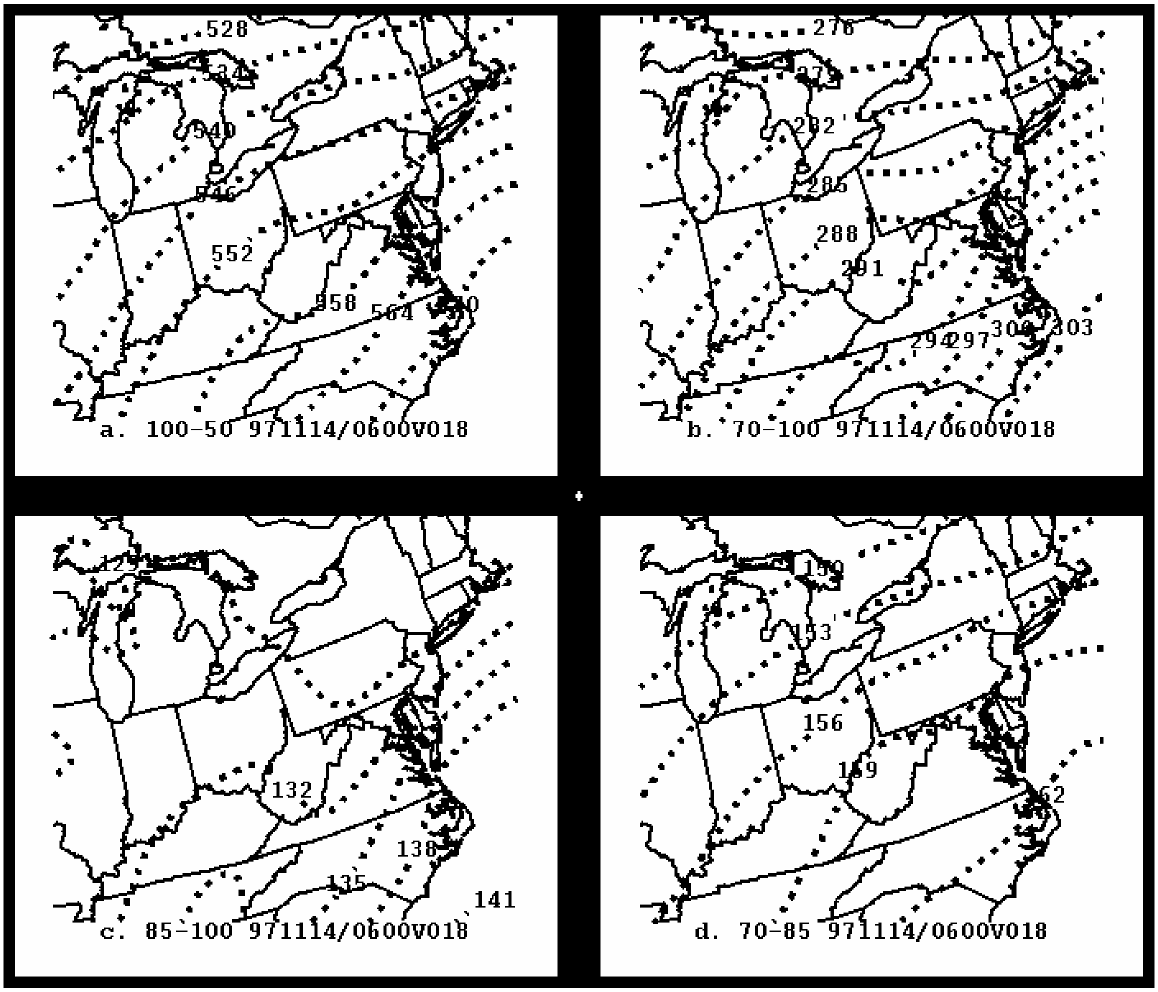

Figure 3. Thickness forecasts (dm) from 1200 UTC of the 48 km Eta model valid at 0600 UTC on 14 November 1997of a) 1000-500 hPa, b) 1000-700 hPa, c) 1000-850 hPa, and d) 850-700 hPa. Values are contoured every 3 dm with the exception of panel a where the increment is 6 dm.

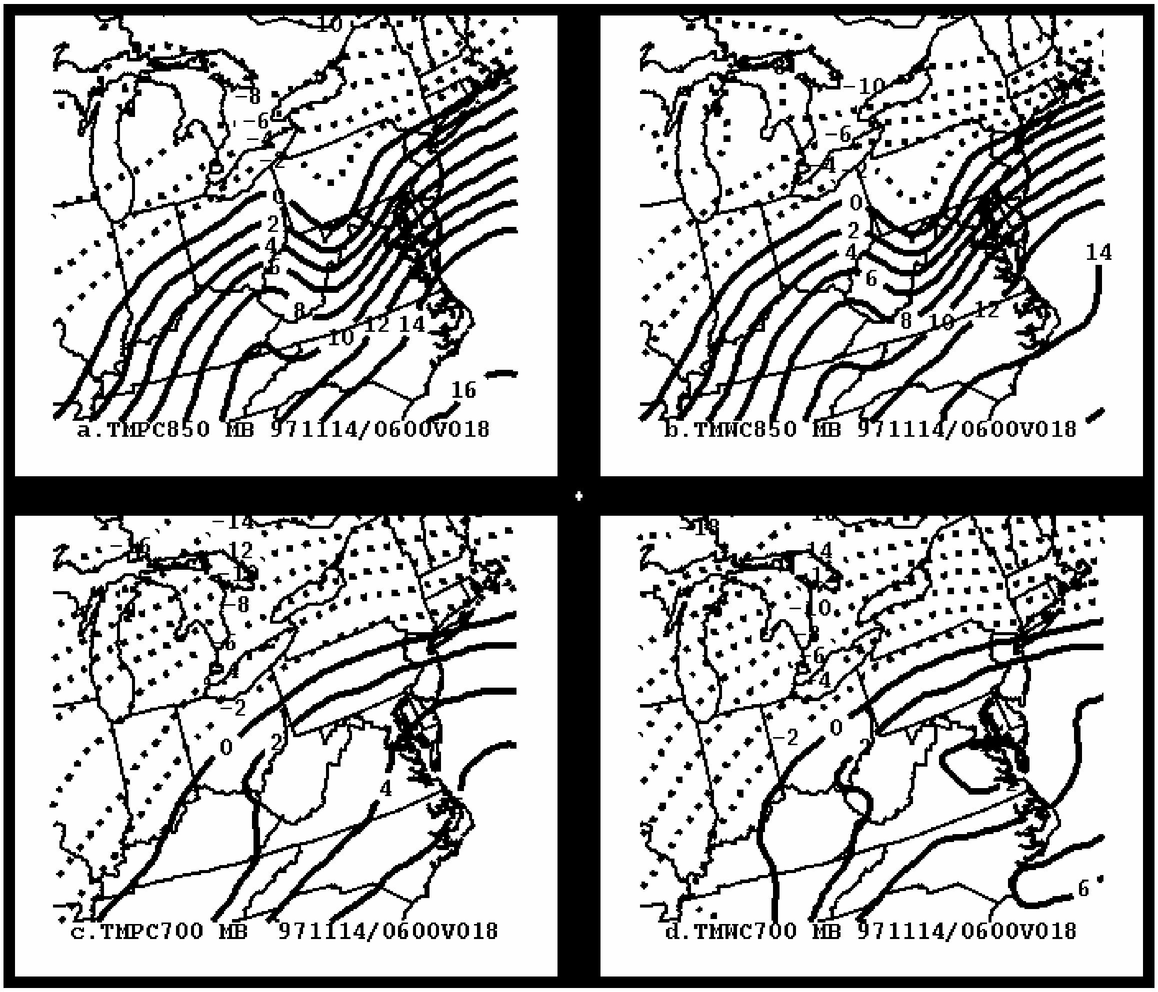

Figure 4. As in Figure 2 except valid at 0600 UTC 14 November 1997 showing a) 850 hPA temperatures (^{o}C), b) 850 hPa wet-bulb temperatures (^{o}C), c) 700 hPa temperatures, and d) 700 hPa wet-bulb temperatures. Contours are every 2^{o}C.

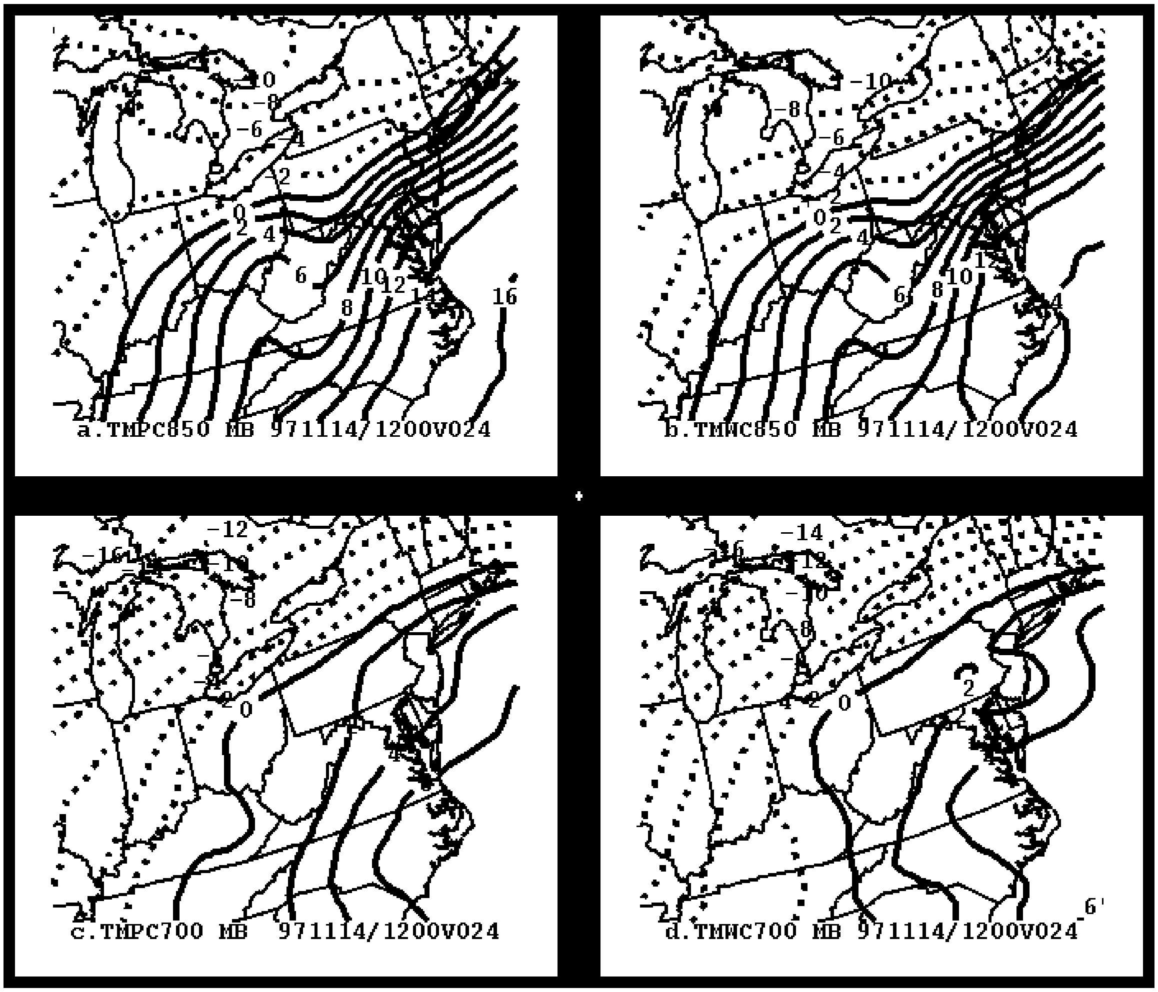

Figure 5. As in Figure 4 except showing 24 hour forecasts valid at 1200 UTC 14 November 1997.

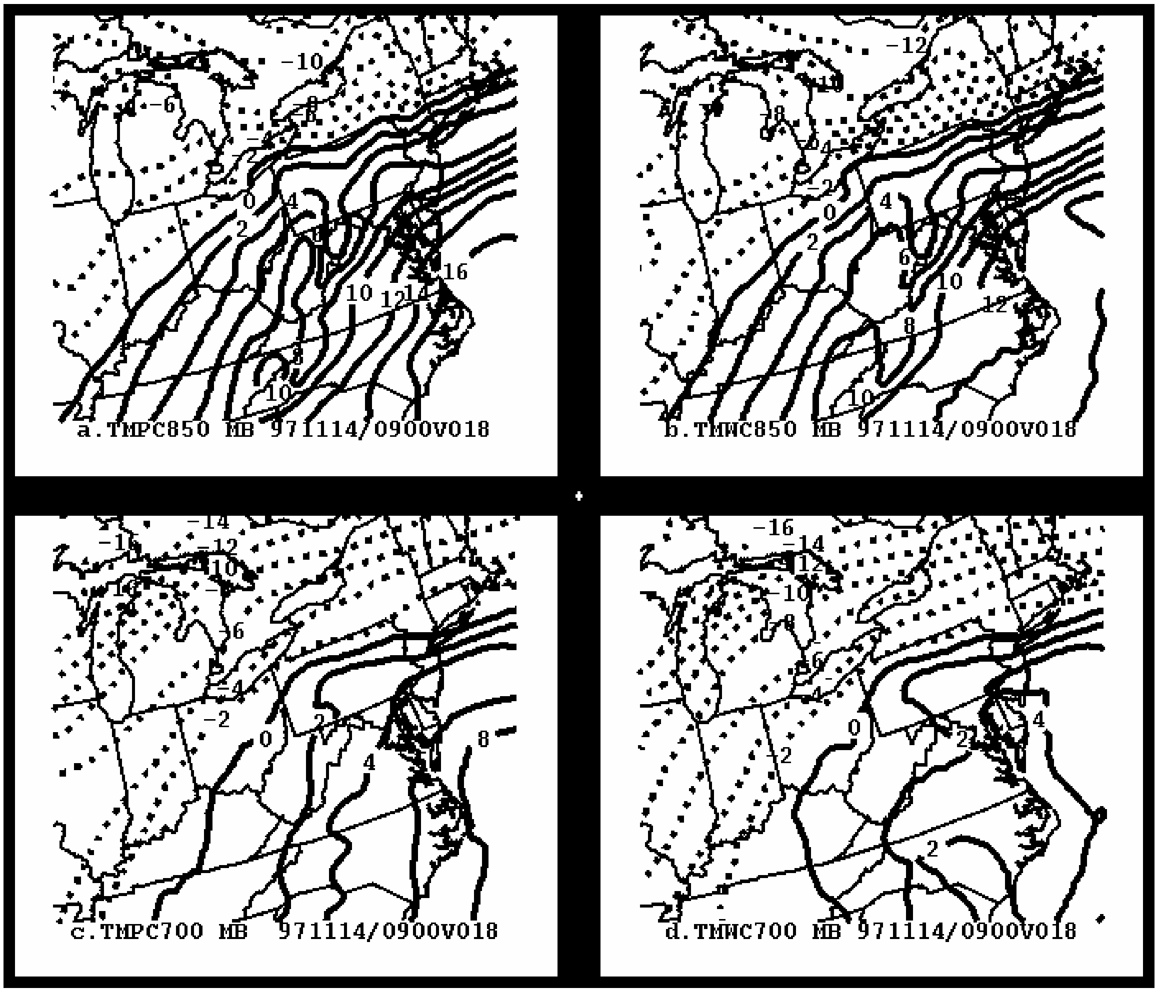

Figure 6. As in Figure 4 except forecast from the 1500 UTC 29 km Eta valid at 0900 UTC 14 November.

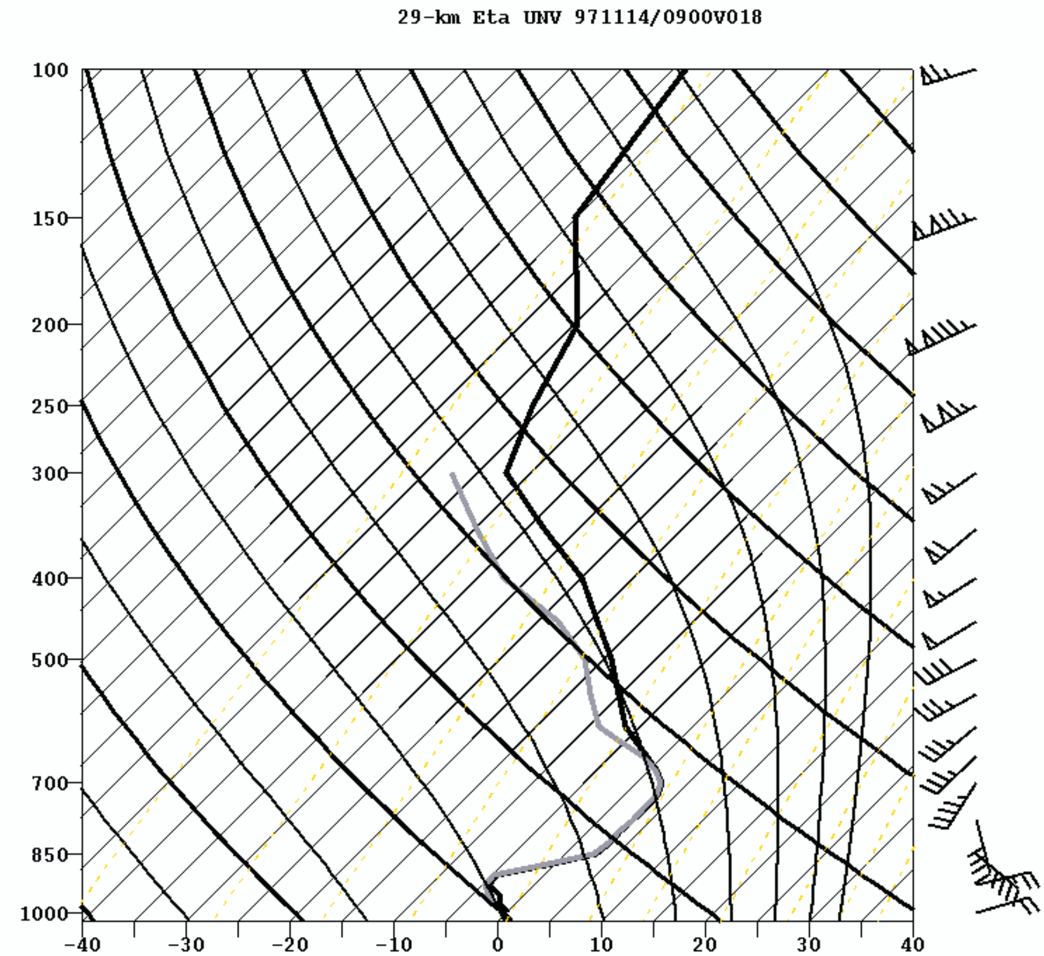

Figure 7. Model sounding taken from the 1500 UTC 29 km Eta grids valid at 0900 UTC 14 November. Data are interpolated for the location of University Park (UNV) airport. Data plotted include temperature (^{o}C) dew point (^{o}C), and winds (kts).

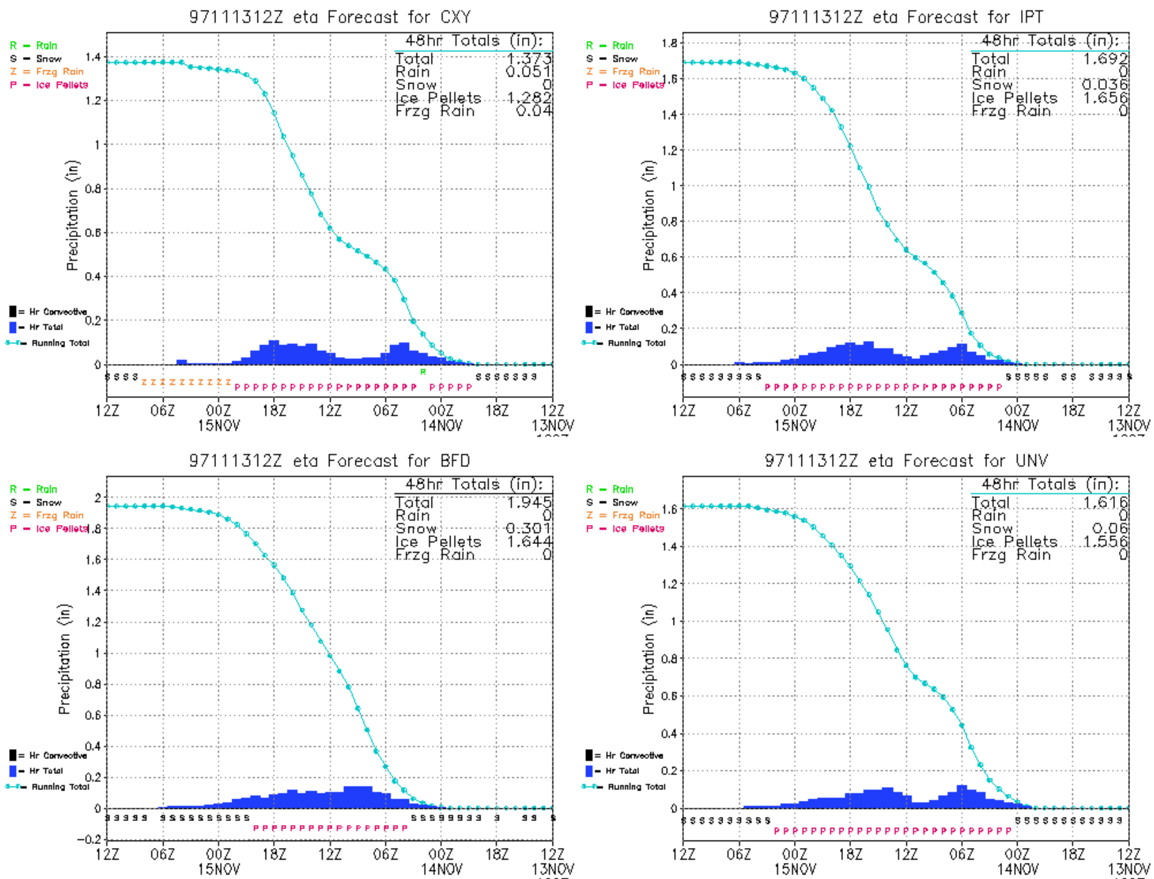

Figure 8. Meteograms of hourly data from the 1200 UTC 48 km Eta profile data base for a) Capitol Cities airport (CXY), b) Williamsport (IPT), c) Bradford (BFD), and d) University Park airport (UNV. Data include plot both the total and hourly accumulated precipitation (inches); and precipitation type (see key in upper left) verse time (hour). Additional data include a summary of the precipitation forecast including total precipitation; and the amount forecast to fall as rain, snow, ice pellets and freezing rain.

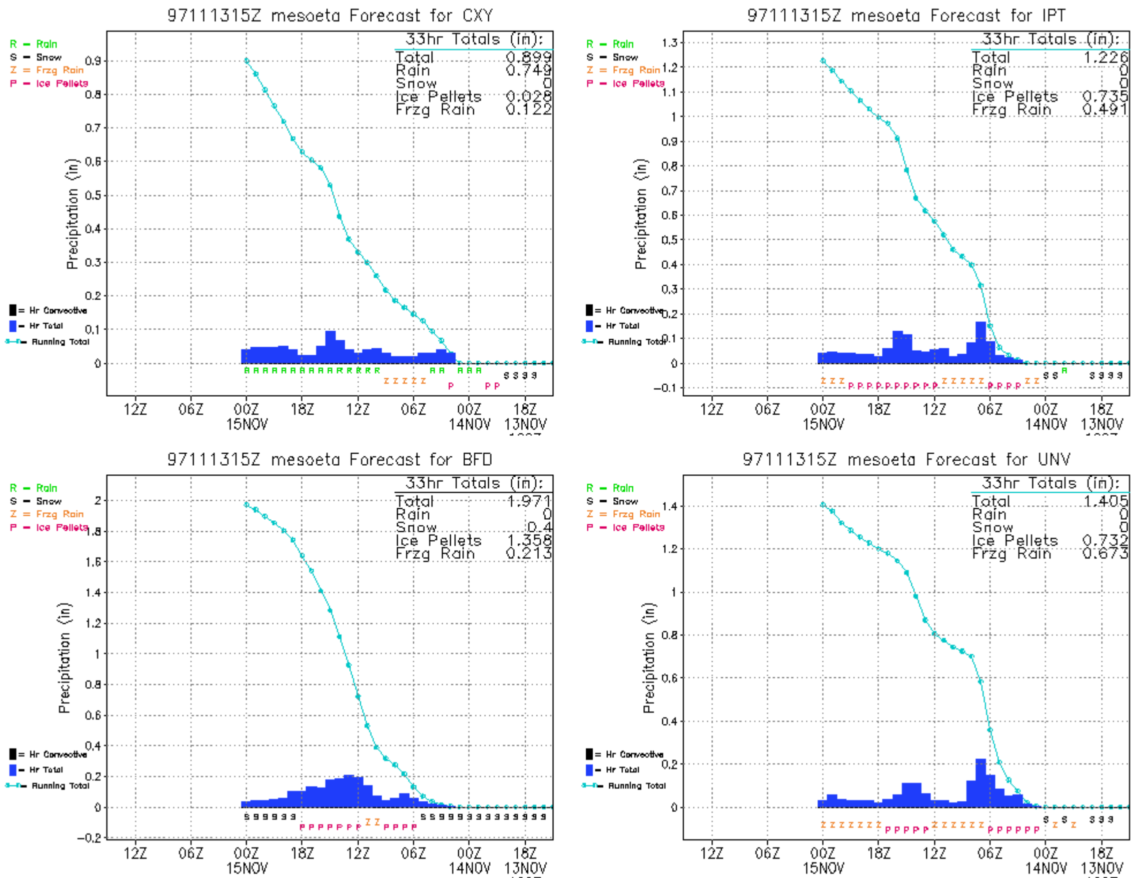

Figure 9. As in Figure 8 but data from the 1500 UTC 29km Eta.

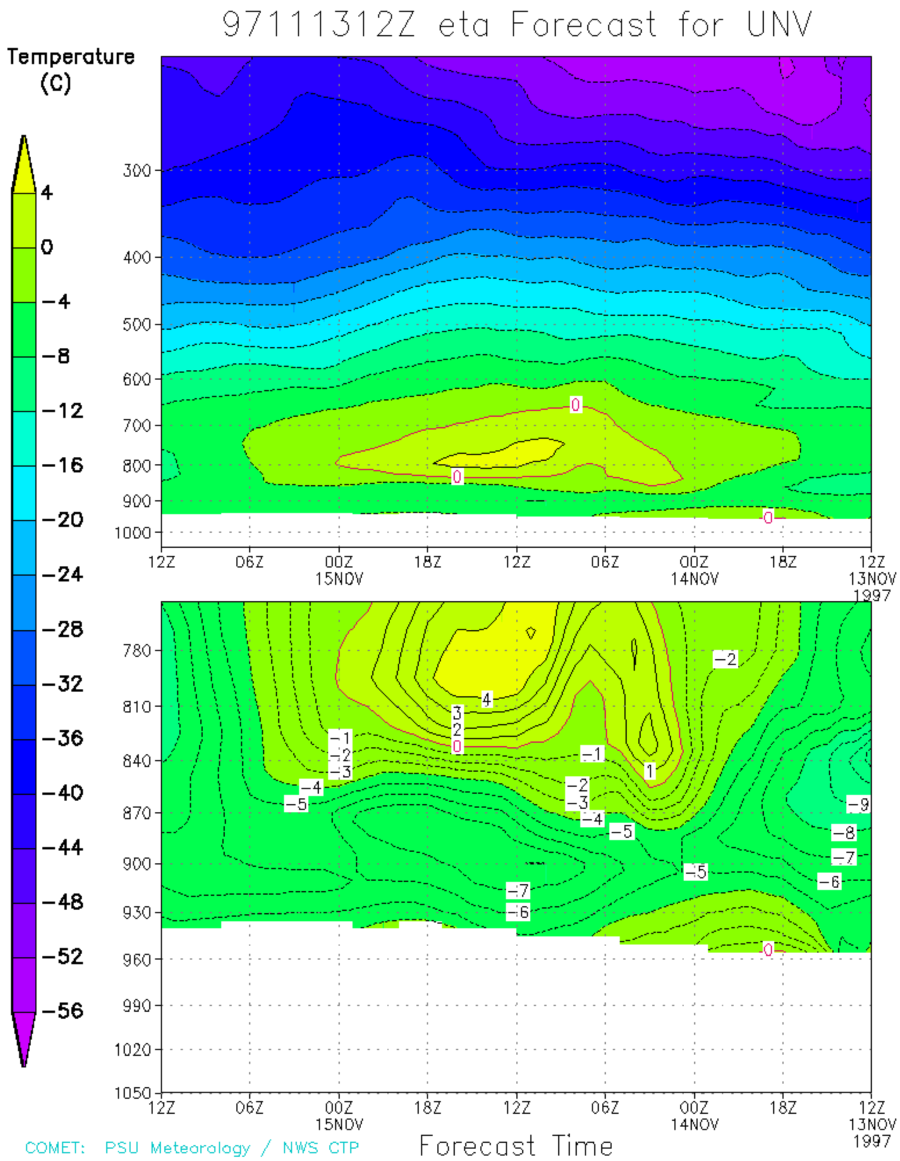

Figure 10. Time-height section of temperature forecasts at State College (KUNV) from the 0000 UTC 14 November 1997 48 km Eta. The upper panel shows the temperature profile through the approximate depth of the troposphere and the lower panel shows a zoomed in view of the thermal structure from the surface to 750 hPa. Temperature contours are every 1 ^{o}C. Dashed lines denote values less than 0 ^{o}C while solid contours denote values greater than 0 ^{o}C. The 0 ^{o}C is shown in red.

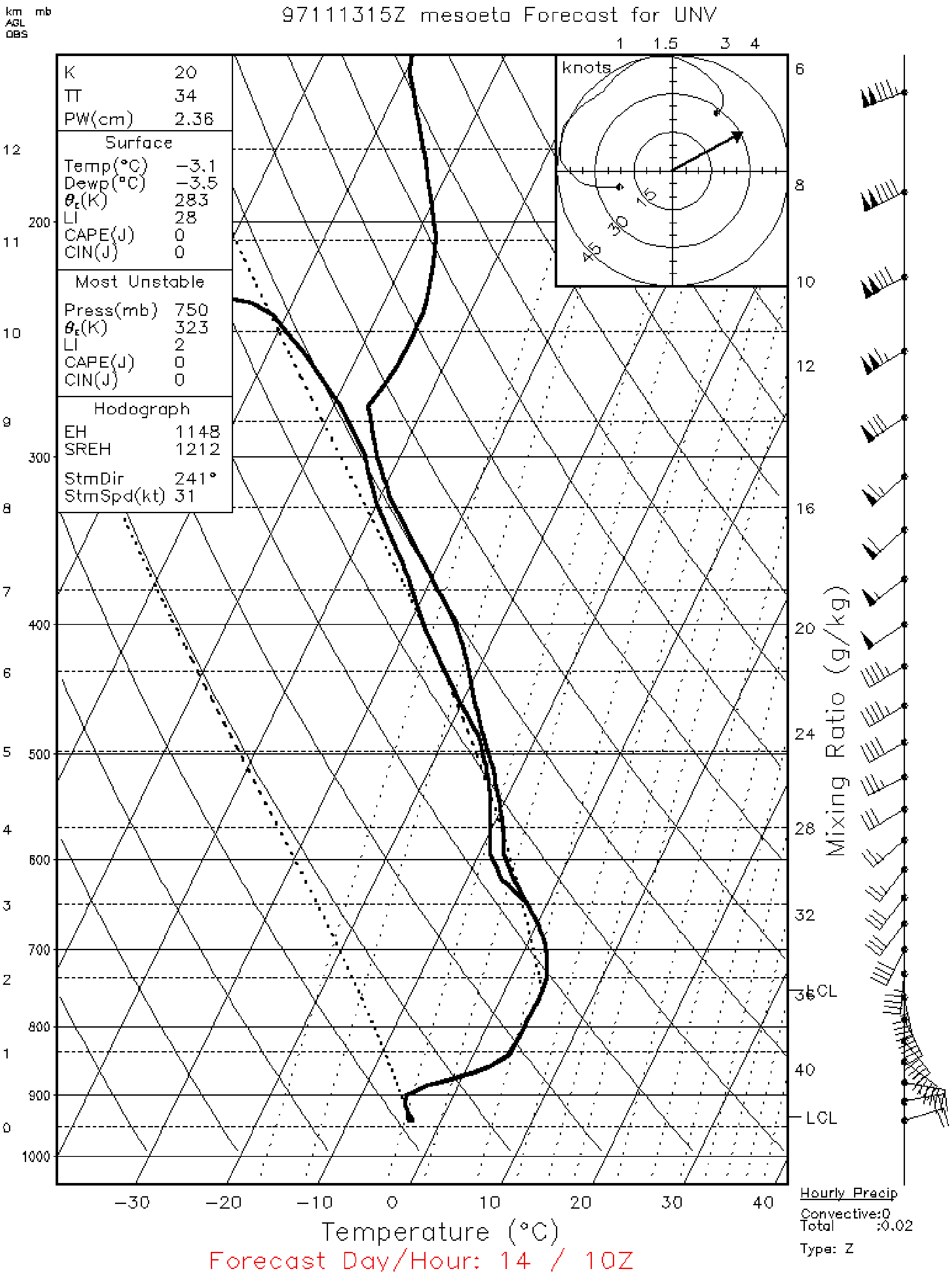

Figure 11. Vertical profile or sounding taken at UNV valid at 1000 UTC 14 November 1997. Data are from the 1500 UTC 29 km Eta profile data base.

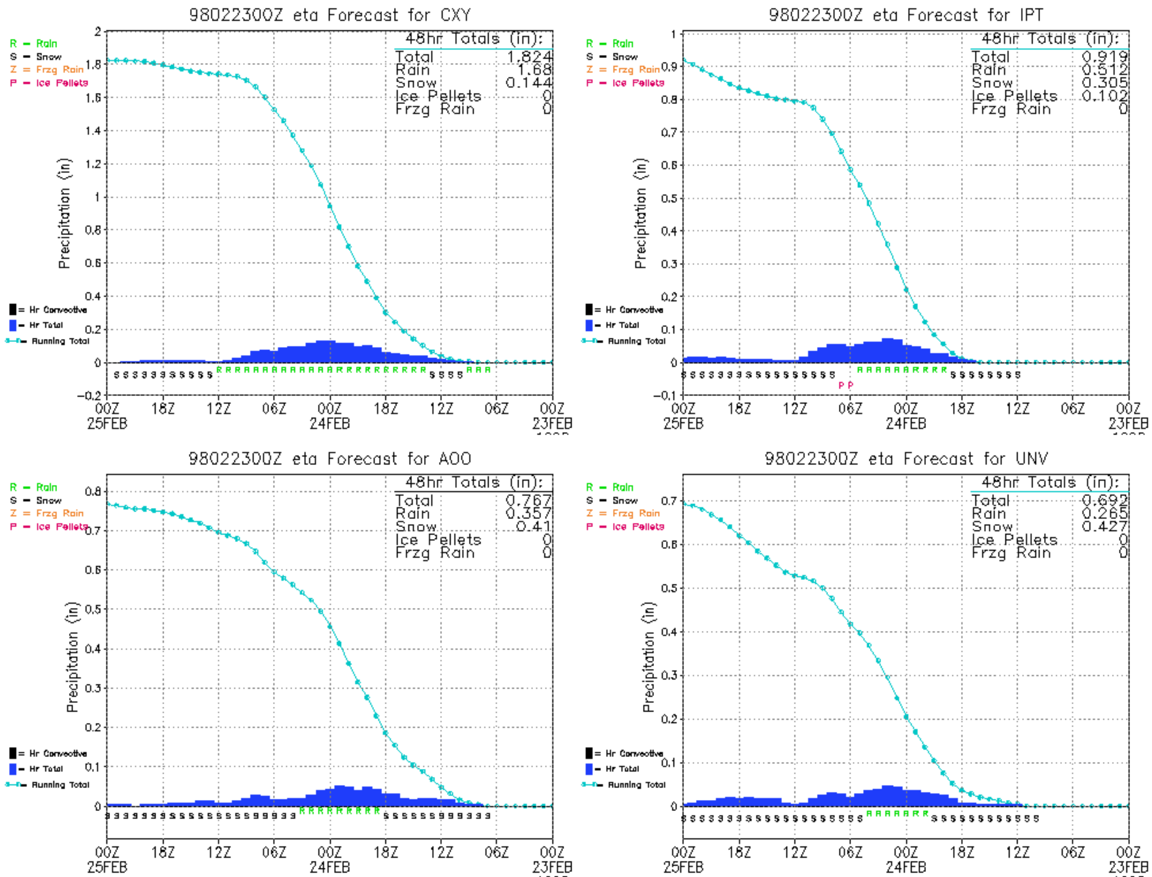

Figure 12. As in Fig. 8 except data is from the 0000 UTC 23 Feb 1998 run of the 32 km Eta.

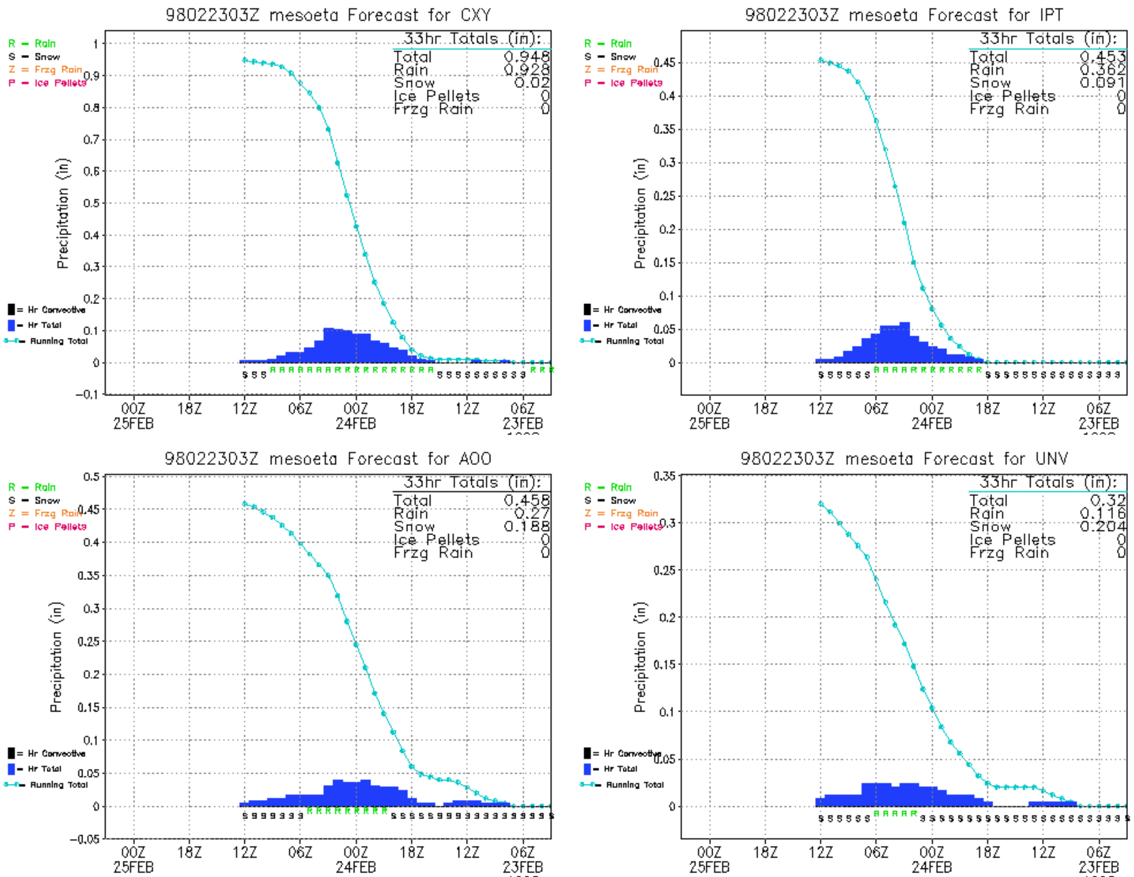

Figure 13. As in Fig. 8 except data is from the 0300 UTC 23 Feb 1998 run of the 29 km Eta.