(1999) update provides a convenient framework for quantifying the ingredients-based adjustments to the original GM predictions.

For the example of convective precipitation presented in section 3.2.2 (Fig. 3.14), the 700 hPa mixing ratio at 18Z on January 23, 1999 was 1-2 g kg\(^{-1}\) in the region of the snow band. The mixing ratio remained fairly constant at 700 hPa through the next 12 hours, so the average mixing ratio was also 1-2 g kg\(^{-1}\). This corresponds to a traditional GM maximum snowfall forecast of 2-4 inches. However, because the IBM indicates the potential for convective snowfall, the GM predicted accumulations should be increased. If the 4:1 ratio of snowfall to mixing ratio is applied instead of the original 2:1 ratio, 4-8 inches is predicted. This prediction is in good agreement with the observed snowfall.

### 3.3 Case Study – March 13-14, 1997

On March 13, 1999, a late winter snowstorm surprised forecasters in Wisconsin by producing a narrow band of up to 13 inches of snow between 4Z and 12Z, several hours before a more significant event was predicted to begin. In the next 24 hours, moderate and occasionally heavy snow with isolated convection was observed, contributing to storm total accumulations of 15 to 30 inches over a large portion of the state. Figures 3.18 a-c show the observed snowfall accumulations in Wisconsin over 3 periods: before 12Z on March 13, between 12Z on March 13 and 12Z on March 14, and for the whole 32-hour event, respectively. The snowfall amounts shown in Fig. 3.18 are considerably
Figure 3.18: Wisconsin snowfall total (in inches) for a) the 8-hour period ending at 12Z on March 13, 1997, b) the 24-hour period between 12Z on March 13 to 12Z on March 14, and c) the full 32-hour event from 4Z on March 13 to 12Z on March 14. Snowfall contoured at 4-inch intervals in (a) and 6-inch intervals in (b) and (c).
higher than predicted\textsuperscript{7}, and the NWSFO storm report for this event noted that “forecasters seem to have a difficult time with these [convective] situations, as history has shown, and snowfall amounts were well under-forecasted” (Haase, 1997).

The remainder of this section uses the March 13-14, 1997 snowstorm (hereafter, the March 1997 storm) to illustrate the application of the IBM to forecasting winter season precipitation. Following a short synoptic overview, the early onset of precipitation that led to the initial unpredicted band of snow is investigated from an ingredients perspective. The IBM will then be used to deduce a time series of precipitation type and intensity for this case. Finally, the transition from snow to freezing rain for a station in northeastern Wisconsin will be investigated.

\subsection{3.3.1 Synoptic Overview}

Surface cyclones that originate over the Oklahoma panhandle and track through Missouri, Indiana, and Michigan are called “panhandle-hook” type storms. The surface cyclone associated with the March 1997 storm followed such a path, as shown in Fig. 3.19. A standard rule of thumb used at the NWSFO located in Dousman, Wisconsin, for panhandle-hook type storms predicts that snow will begin falling in southern Wisconsin when the sea level pressure minimum reaches central Missouri. However, in this case the main surface low was still developing over the Oklahoma panhandle by the time Wisconsin had received up to 13 inches of snow (12Z on March 13). An analysis

\textsuperscript{7} The winter storm warning issued at 22Z on March 12 by the NWSFO located in Dousman, Wisconsin, called for a storm total of 6-12 inches of snow for the northern half of the state, to begin in the morning of March 13.
Figure 3.19: Observed track and minimum central pressure of the cyclone from 0Z on March 13 to 0Z on March 15, 1997.

of the mid- and upper-level dynamics along with an application of the IBM provides insight into the processes involved in this atypical storm evolution. Output from the operational NCEP-ETA model initialized at 0Z on March 13 was used throughout this investigation. The synoptic features in this model run (Figs. 3.20-3.23) verified well with observations (not shown) of a number of variables including sea level pressure, 850 hPa geopotential height and temperature, and 300 hPa geopotential height and wind speed. By using only NCEP-ETA model output, our analysis is constructed using information that was available to forecasters at the time of the snow event.

At 6Z on March 13, there were two distinct synoptic features: (1) a southern disturbance reflected as a weak surface low pressure minimum over Texas and Oklahoma, and (2) a northern system with a less obvious signature at the surface—only a weak
depression in the mean sea level pressure over Wyoming (Fig. 3.20c). However, there was a 300 hPa wind speed maximum (Fig. 3.20a), and a 500 hPa vorticity maximum (Fig. 3.20b) associated with this northern feature. The southern system was associated with a separate, but weak and poorly organized 500 hPa absolute vorticity maximum. The 300 hPa geopotential height field at 6Z 13 March reflected the presence of this southern disturbance through the trough in the height field, however it is clearly a separate feature from the more northern trough and its wind speed maximum.

By 0Z on March 14, the 300 hPa northern trough and wind speed maximum had intensified (Fig. 3.21a), and the associated 500 hPa vorticity maximum over North and South Dakota had similarly intensified (Fig. 3.21b). The sea-level pressure trough associated with these features had become slightly more pronounced as well, with an axis extending from Minnesota to northern Missouri. The Oklahoma cyclone had deepened slightly but remained more or less in the same location, a behavior that is consistent with the slow propagation of its associated weak upper level short wave trough.

Six hours later, at 6Z on March 14, the two systems had begun to interact. The 300 hPa trough over Nebraska continued to sharpen (Fig. 3.22a), and the northern and southern 500 hPa vorticity maxima remained relatively independent (Fig. 3.22b). However, by this time, the primary low pressure system was in a favorable region for development as it was located downstream of the intensifying upper trough (Fig. 3.22c). The minimum sea level pressure had fallen to 998 hPa, and the storm was centered over southern Illinois.

Finally, by 12Z on March 14, there was a well-organized mid latitude cyclone centered
Figure 3.20: 6-hour NCEP-ETA model forecast, valid at 06Z March 13, 1997 of a) 300 hPa wind speed (shaded in m s⁻¹ according to legend at left) and geopotential height (solid lines, contoured every 120 m). b) 500 hPa absolute vorticity (labeled in units of 10⁻¹⁵ s⁻¹ and shaded according to legend at left), and geopotential height (solid lines, contoured every 60 m), and c) 1000 hPa temperature (shaded every 4 °C) and mean sea level pressure (solid lines contoured every 4 hPa).
Figure 3.21: As in Fig. 3.20 except for the 24-hour NCEP-ETA model forecast valid at 0Z on March 14, 1997.
Figure 3.22: As in Fig. 3.20 except for the 30-hour NCEP-ETA model forecast valid at 6Z on March 14, 1997.
over northeastern Indiana with a sea-level pressure minimum of 996 hPa (Fig. 3.23c). This feature was located downstream of the sharp 300 hPa and 500 hPa upper trough axes (Figs. 3.23 a and b). The 1000 hPa thermal structure also reflected the structure of this system, with the cold and warm frontal regions clearly visible (Fig. 3.23c).

### 3.3.2 Investigation of the Early Onset of Precipitation

The narrow band of snow which fell unexpectedly in southern Wisconsin before 12Z on March 12 covered a region 30 miles wide, from just south of LaCrosse to just south of Sheboygan (see Fig. 3.18). As mentioned earlier, the timing of this period of snow was not consistent with the traditional rules of thumb used to predict the onset of precipitation in panhandle-hook type storms. Application of these traditional rules assumes that the snowfall will be associated exclusively with the dominant low pressure system. In this case, the initial 12-18 hours of snowfall were largely associated with an upper level feature that was independent of the sea level pressure minimum.

The NCEP-ETA model relative humidity fields valid at 6Z on March 13, 1997 provide an excellent illustration of the existence of two distinct systems in the early stages of the storm (Fig. 3.24 a and b). In both the 700-750 hPa and 600-650 hPa layers, the relative humidity fields clearly indicate two separate features. One area of nearly saturated conditions in southern Missouri and Arkansas was associated with the developing surface low over the Oklahoma panhandle and its 500 hPa vorticity maximum over eastern Texas (see Fig. 3.20). This moisture likely originated in the Gulf of Mexico. In contrast, the high relative humidity air over Wisconsin, Minnesota, and North Dakota was associated
Figure 3.23: As in Fig. 3.20, except for the 36-hour NCEP-ETA model forecast valid at 12Z on March 14, 1997.
Figure 3.24: (a) As in Fig. 3.6d except without mixing ratio lines and for the 700-750 hPa layer from the 6-hour NCEP-ETA model forecast valid at 06Z March 13, 1997. The thick solid line in (a) represents the location of the cross-section shown in Fig. 3.25. (b) As for (a) but for the 600-650 hPa layer. (c) As in Fig. 3.6b except for the 700-750 hPa layer from the 6-hour NCEP-ETA model forecast valid at 06Z March 13, 1997. (d) As for (c) but for the 600-650 hPa layer.
with the northern system and was presumably of Pacific origin.

The relative humidity fields indicate that there was ample moisture at 700-750 hPa and 600-650 hPa in southern Wisconsin for precipitation (Figs. 3.24 a and b). However, the QG forcing and instability ingredients on the standard isobaric levels at this same time (Figs. 3.24 c and d) do not indicate a significant potential for heavy snow before 12Z on March 13. The mainly weak to moderate QG forcing (\(\nabla \cdot Q = -1\) to \(-5 \times 10^{-15} K m^{-2} s^{-1}\)) over Wisconsin and the absence of instability (\(PV_{es} > 0\)) suggested that any precipitation would probably be of light intensity.

A more complete picture of the ingredient distributions at 6Z on March 13 was obtained through a cross-sectional analysis. The cross-section, drawn from south of LaCrosse to south of Sheboygan in Wisconsin (location shown in Fig. 3.24a), reveals features that were not apparent on the isobaric ingredients maps and provide significant clues to the potential for high snowfall rates. Figure 3.25a shows that a layer of conditional instability (\(PV_{es} < -0.15\) PVU) existed in the cross-section between 600-500 hPa at 6Z on March 13. With sufficient moisture at these levels (RH = 90-100% at 600 hPa) and weak to moderate forcing between 500-700 hPa, this instability could be realized and heavy precipitation is possible. Furthermore, a consideration of the efficiency ingredient shows that the temperature in the 600-550 hPa layer (-12 °C to -18 °C) enabled the maximum depositional growth and condensation rates of ice crystals to occur, providing more support for a possible heavy snowfall event.

For this case, much of the information indicating the potential for heavy snow could have also been obtained by analyzing an isobaric ingredients map in the non-standard
Figure 3.25: As in Fig. 3.13 except from Lacrosse to south of Sheboygan, Wisconsin, (location shown in Fig. 3.24a) from the 6-hour forecast of the NCEP-ETA model data valid at 6Z March 13 1997.
layer, 550-600 hPa. Such an analysis reveals a QPV maximum over western Wisconsin at 6Z on March 13 (Fig. 3.26a), corresponding to a region of weak forcing and negative $PV_{cs}$ (Fig. 3.26b). The 550-600 hPa QPV maximum coincided with ample moisture in west-central Wisconsin, indicating the potential for a high precipitation rate and convection at this time. Although much of the state was characterized by conditional instability in the 550-600 hPa layer, the heaviest snow occurred in a narrow band in southern Wisconsin where the relative humidity was greater than 80% throughout the 850-550 hPa layer.

The preceding application of the IBM to the diagnosis of the initial snow band in the March 1997 storm revealed clues for the potential for moderate to heavy snow in Wisconsin prior to 12Z on March 13. This analysis indicates that the NCEP-ETA model data available to forecasters prior to the storm contained information that could have alerted them to the possibility of the early snow event. Furthermore, the analysis provided another example of the importance of inspecting ingredients cross-sections in conjunction with the standard pressure level ingredients maps.

### 3.3.3 Ingredients-Based Forecast

The exercise of preparing a forecast for an event that has already occurred is invariably influenced by the hindsight knowledge of the actual verified conditions. However, there is value in discussing such a forecast because it illustrates techniques that could be used to anticipate the development of future storms. In this section, we discuss how an accurate forecast for precipitation duration, intensity, accumulation, and type could
Figure 3.26: (a) As in Fig. 3.24a except for the 550-600 hPa layer. (b) As for Fig. 3.24c except for the 550-600 hPa layer.
have been prepared prior to the March 1997 storm by applying the IBM. The forecast will focus on a region of central Wisconsin located 40 miles southwest of Green Bay, including the city of Appleton which received 21.7 inches of snow. Appleton is located just outside of the area affected by the early snow event, and 21 inches of its storm total accumulation fell in the 24 hours between 12Z on March 13 and 12Z on March 14.

**Forecast for Precipitation Duration and Intensity**

In order to prepare a forecast for the March 1997 storm, an evaluation of ingredient parameters from the NCEP-ETA model run initialized at 0Z on March 13, 1997 is performed. A complete application of the IBM would involve inspecting the ingredients maps at all forecast hours in the 800-850 hPa, 700-750 hPa, and 600-650 hPa layers. However, in this thesis, only a few ingredients maps are presented, and the remaining information is summarized in an ingredients table for the Appleton forecast area (Fig. 3.27).

The ingredients table in Fig. 3.27 shows that ample moisture (RH ≥ 80%) was predicted throughout the entire 850-600 hPa column for the 24-hour period between 12Z on March 13 and 12Z on March 14. Mid-level relative humidity was also forecasted to be 90-100% as early as 6Z on March 13. Some QG forcing in the Appleton area was predicted at 6Z on March 13 and continued through 6Z on March 14, with only scattered weak forcing after that time. Based on this information alone, one would expect snow to start between 6Z and 12Z on March 13 and end between 6Z and 12Z on March 14. However, because the moisture at 6Z on March 13 was limited to levels above
Figure 3.27: Completed ingredients table for the 0Z March 13, 1997 ETA model run. See text for explanation.
700 hPa, precipitation generated above 700 hPa may have sublimated or evaporated before it reached the ground.

An investigation of the strength of forcing, atmospheric stability, and precipitation efficiency will facilitate a forecast for precipitation intensity. The ingredients table in Fig. 3.27 indicates that by 18Z on March 13 and through 0Z on March 14, moderate to strong QG forcing was predicted throughout the lower- to mid-troposphere. The 700-750 hPa ingredients map shows $\nabla \cdot Q = -5 \times 10^{-15} Km^{-2}s^{-1}$ close to Appleton at 0Z on March 14 (Fig. 3.28b). Also at 0Z on March 14, an area of negative $PV_{es}$ in the 700-750 hPa layer over the forecast area is noted in the ingredients table and shown in Fig. 3.28b. The combination of forcing for ascent and conditional instability corresponds to a positive QPV value (Fig. 3.28d) for the 700-750 hPa layer in an area with 80-90% relative humidity (Fig. 3.28d). Finally, the layer-average temperature over Appleton at 0Z on March 14 was -4 to -6°C (Fig. 3.28c) at 700-750 hPa and -10 to -12°C at 600-650 hPa, indicating that the atmosphere was not cold enough to expect maximum depositional ice crystal growth.

Because of the strong forcing, ample moisture, and isolated areas of instability, snowfall intensity during the 6-hour period between 18Z on March 13 and 0Z on March 14 is expected to be higher due to possible convection. Surface observations at Appleton indicate that light snow began at 9Z on March 13, and moderate snow fell during the 14 hours between 15Z on March 13 and 5Z on March 14. WSR-88D radar from Green Bay, Wisconsin, shows embedded regions of high reflectivities (30-40 dBz) characteristic of

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8 Although the 700 hPa relative humidity over Appleton is 80%, this area was close to the dry edge of a strong moisture gradient, and below 800 hPa the relative humidity was less than 70%
Figure 3.28: As in Fig. 3.6 except for 700-750 hPa from the 24-hour forecast of the NCEP-ETA model valid at 0Z on March 14, 1997.
convection from 20Z on March 13 to 3Z on March 14. A convective cell just south of Appleton at 23:13Z on 13 March (Fig. 3.29) corresponds very well with the location of the QPV maximum in Fig. 3.28d.

![WSR-88D radar reflectivity](image)

Figure 3.29: WSR-88D radar reflectivity from Green Bay, Wisconsin 23:13Z at March 13, 1997. Echo intensity (in dBZ) is shaded according to the legend at the bottom.

By 12Z on March 14, no QG forcing is indicated in the ingredients table at 850 hPa or 700 hPa for the Appleton forecast area, and only weak QG forcing is predicted at 600 hPa (see Fig. 3.30b). Coincident with the scattered weak forcing at 600 hPa, there is
negative $PV_{es}$ (Fig. 3.30b) throughout much of the state at this level. The co-location of negative $PV_{es}$ and negative $\nabla \cdot Q$ is reflected in a few 600-650 hPa QPV maxima in central Wisconsin (Fig. 3.30d). The combination of some forcing and instability indicates the potential for convection at this time. However, because the QPV maxima were located near a boundary of sufficient moisture (RH < 70% is only about 50 miles west of Appleton at 700-750 hPa and 600-650 hPa), isolated snow showers of short duration would be more likely than heavy thundersnow.

Precipitation Type Forecast

Although the observed surface temperatures in Appleton, Wisconsin, never rose above -4°C, the forecasted 850 hPa temperature rose from -6°C at 18Z on March 13 to approximately -2°C at 0Z on March 14 before falling sharply to -8°C by 12Z (see the ingredients table in Fig. 3.27). Because of the proximity of the 850 hPa 0°C isotherm to the Appleton forecast area at 0Z 14 March (Fig. 3.28a), a forecast for precipitation type at this time requires the examination of temperature and dew point profiles. Prior to 0Z and after 12Z on March 14, the “rain-snow line” was sufficiently south of the forecast area so that all precipitation could be expected to fall as snow. The model-predicted sounding for Appleton valid at 0Z on March 14 (Fig. 3.31) revealed an elevated warm layer with a maximum temperature of -2°C at about 800 hPa. Below this warm layer, the temperature dropped below -8°C between 900-950 hPa and warmed slightly to -6 °C near the surface. The dew point followed the temperature profile throughout the 1000-700 hPa layer, although it was typically 1-3°C less. Because the maximum
Figure 3.30: As in Fig. 3.6 except for the 600-650 hPa layer from the 36-hour forecast of the NCEP-ETA model valid at 12Z on March 14, 1997.
Figure 3.31: Model-predicted skew-T profiles for Appleton, Wisconsin, from the 24 hour forecast of the NCEP-ETA model valid at 0Z March 14, 1997. Temperature is the thick solid line and dew point is the dashed line. Isopleths of $\theta$ (light dashed) and $\theta_e$ (dotted), and wind barbs (m/s) are shown. Abscissa is temperature in °C and isotherms slope upward to the right. Ordinate is pressure in hPa.

Warm layer wet bulb temperature remained everywhere below freezing, this sounding indicates that the precipitation at 0Z on March 14 would be all snow at Appleton. Surface observations throughout the storm indicate that Appleton did in fact receive snow throughout the event. Between 2Z and 4Z on March 14 (Figs. 3.32b-d), however, a station 15 miles south of Appleton reported a brief changeover to rain. Because of the surface temperature between -3°C and -4°C at this station, Oshkosh, we suspect that the precipitation was not rain as reported by the Automated Surface Observing
Figure 3.32: Central Wisconsin surface observations at a) 1Z, b) 2Z, c) 3Z, and d) 4Z on March 14, 1997. Observations are plotted as in Fig. 3.9. The cities referred to in the text, Green Bay, Appleton, and Oshkosh, are labeled in (a).
System (ASOS) at Oshkosh, but was actually freezing rain\textsuperscript{9}. The transition from snow to freezing rain at Oshkosh is investigated further in section 3.3.4.

Based on the application of the IBM presented so far in this section, a forecast for precipitation duration, intensity, and type for the Appleton area predicts light snow to begin before 12Z on March 13, with little accumulation before daybreak. Precipitation should continue throughout the day, with moderate to heavy snow falling by 18Z. Thundersnow is a possibility in the afternoon and evening, primarily between 18Z on March 13 to 0Z on March 14. Some areas may experience a period of rain after 0Z on March 14 before changing back to all snow by 12Z. The precipitation will decrease in intensity by 6Z on March 14 with only light snow or rain continuing through 12Z on March 14, and scattered snow showers between 12Z and 18Z.

**Snowfall Accumulation Estimate**

The Garcia Method, in conjunction with an analysis of the ingredients, was used to estimate the snowfall accumulation in the Appleton forecast area between 12Z on March 13 and 12Z on March 14. Because this event was predicted to last 24 hours, two independent 12-hour Garcia forecasts were formulated: (1) 12Z on March 13 to 0Z on March 14 and (2) 0Z to 12Z on March 14. The average forecasted mixing ratio ($l$) at 700 hPa for the first period was 2.75-3 g kg$^{-1}$ (initial $l = 2.5 - 3$ g kg$^{-1}$ and 6-hour maximum $l = 3$ g kg$^{-1}$). During the second period, the average forecasted mixing ratio

\textsuperscript{9} Most ASOS stations had freezing rain sensors by 1997, however a test in 1994-1995, prior to installation of these sensors on ASOS units, revealed that the freezing rain sensors agreed with observations only 66% of the time, as discussed in http://www.nws.noaa.gov/asos/frezrain.htm (accessed 12/99).
at 700 hPa was 3.3 kg m⁻¹. A conventional Garcia Method forecast would double the sum of these average mixing ratios, giving a prediction of 12-13 inches of snow for the full 24-hour period. This is considerably less than the actual amount of snow that fell in the Appleton area. However, as described in Chapter 3.2.3, the conventional Garcia Method forecast must be modified based on a comparison of the ingredients in this storm with the “normal conditions” of the Garcia Method. In the latter half of the first 12 hours and early portions of the second 12 hours, heavy snow was expected due to the presence of strong forcing, high relative humidities, and some instability. Since the Garcia Method generally applies to snowfall of moderate intensity, the heavy snow forecasted in this case necessitates the use of a 4:1 ratio between snowfall and mixing ratio. This amounts to a 24-hour forecast for 24-25 inches of snow. This is in reasonable agreement with the maximum observed snowfall of 23.5 inches in Wautoma (see Fig. 3.18b).

This example illustrates the variety of issues involved in integrating the IBM with the Garcia Method for estimating snowfall accumulations. By accounting for the forecasted strong forcing and possible instability, an obtained. Note, however, that this forecast focused only on the final 24-hour portion of this event. Total storm accumulations for the 32-hour event were even greater for areas southwest of Appleton that received snowfall in the 8-hour period prior to 12Z on March 13 (including Wautoma, whose 32-hour accumulation was 28 inches).
3.3.4 Diagnosis of a Transition from Snow to Freezing Rain

Only 11 inches of snow were observed in Oshkosh, Wisconsin, located 15 miles south of Appleton, in the 24-hour period between 12Z on March 13 and 12Z on March 14. This accumulation is nearly half of the 21 inches reported in Appleton over the same time period (see Fig. 3.18b). The reduction in snowfall at Oshkosh can be largely attributed to a transition from snow to freezing rain that occurred between 2Z and 4Z in Oshkosh but not in Appleton (see Fig. 3.32). It is conceivable that this short period of freezing rain led to the observed variation in snowfall accumulation because while moderate freezing rain was falling in Oshkosh, moderate snow was rapidly adding to the existing snow cover in Appleton.

During the period of freezing rain, Oshkosh reported a surface temperature of -3 to -4°C, indicating that warmer air must have existed above the surface. The model-predicted temperature profile for Oshkosh valid at 0Z on March 14, 2 hours prior to the transition from snow to freezing rain, shows an elevated warm layer with a maximum warm layer temperature of -1°C at 800 hPa (Fig. 3.33). Hence, the atmosphere was everywhere below freezing at 0Z on March 14 when the precipitation was still snow.

As a first step toward diagnosing the transition to rain which occurred by 2Z on March 14, an assessment of how well the model-predicted sounding agreed with observations was performed. The forecasted temperature and dew point profiles valid at 0Z on March 14 for Green Bay, Wisconsin, the closest station to Oshkosh that launches radiosondes (Fig. 3.34a), were compared with the observed soundings at Green Bay
Figure 3.33: As in Fig. 3.31 except for Oshkosh, Wisconsin.

from the same time (Fig. 3.34b). The forecasted and observed soundings both show an elevated warm layer. The maximum warm layer temperature of the model-predicted temperature profile was -3.5°C at 800 hPa, and a cold layer was positioned close to the surface with a minimum temperature of -9°C. The dew point was 1-3 °C lower than the temperature through 700 hPa, and the air dries out slightly above that level. In contrast, the observed temperature and dew point profiles (Fig. 3.34b) were nearly coincident with each other, implying a more saturated atmosphere and a wet bulb temperature profile nearly equal to the air temperature profile. Furthermore, the observed maximum warm layer temperature was -2°C, 1.5°C warmer than predicted. The maxi-
Figure 3.34: a) As in Fig. 3.31 except for Green Bay, Wisconsin. b) Observed temperature and dew point soundings for Green Bay, Wisconsin. Data plotted and portrayed as in Fig. 3.31.
mum temperature occurred around the same level as in the forecast sounding.

Because of the similarity between the structure of the model-predicted Green Bay and Oshkosh soundings, and the proximity of the stations to each other (approximately 50 miles), an adjustment can reasonably be applied to the maximum warm layer temperature of the forecasted Oshkosh sounding, based on the difference between the Green Bay forecasted and observed maximum warm layer temperatures at the same time (+1.5°C). After this adjustment, the 0Z Oshkosh maximum warm layer temperature would be above freezing at 800 hPa, though only by +0.5°C. Based on the Czys et al. (1996) and Stewart and King (1987) techniques (see section 3.1.5) for determining the degree of melting in an above-freezing elevated warm layer, a maximum temperature of 0.5°C and warm layer depth of only 50-100 hPa corresponds to very little melting. Furthermore, the cold layer at 0Z beneath 800 hPa would have refrozen any precipitation that only melted partially. Thus, the 0Z Oshkosh model-predicted sounding after adjustment was still consistent with the surface observations of snow at Oshkosh at 0Z on March 14.

In order to extrapolate the subsequent evolution of the Oshkosh temperature profile, the thermal advection in the elevated warm layer was examined. Figure 3.35 shows a strong 800 hPa temperature gradient oriented nearly parallel to the 15 m s⁻¹ winds from the south, and warm advection of +2 °C hour⁻¹ in the Oshkosh area. Although this warming may have been partially offset by adiabatic cooling of the rising air, it is still likely that the 800 hPa temperature could have risen at least 3°C during the subsequent two hours. A 3°C rise in 800 hPa temperature above the adjusted model-predicted
warm layer temperature of +0.5°C would have led to a maximum elevated warm layer temperature of 3.5°C, warm enough for complete melting (Stewart and King, 1987). Although there was a deep cool layer near the surface, the temperature in this layer was not cold enough to initiate ice crystal formation, thus freezing rain would reach the ground.