THE USE OF CLIMATOLOGY TO CONSTRUCT A PHYSICALLY BASED METHOD FOR DIAGNOSING SNOW TO LIQUID RATIO

Martin A. Baxter*, Charles E. Graves, and James T. Moore

Department of Earth and Atmospheric Sciences
Saint Louis University
St. Louis, Missouri

Abstract

A 30-year climatology of snow to liquid equivalent ratio (SLR) using National Weather Service Cooperative Summary of the Day data has been compiled. This climatology is useful to operational forecasters by allowing knowledge of statistical characteristics of SLR, stratified by geographical regions and time of season, to be incorporated into the prediction and diagnosis of ratio values for a given snowfall event. When correlated to meteorological parameters, such as 850 mb temperatures, the resulting anomalies can then be used by forecasters to provide a rough expectation of SLR, relative to the seasonal and geographical SLR means. However, such an approach has limited diagnostic and predictive value for a given snowfall even. Indeed, previous research has shown that the type of ice crystal initially formed, the subsequent modification of the ice crystal as it descends through the cloud and sub-cloud layers, and various surface processes combine to determine SLR. In turn the formation and evolution of ice crystals, so important to the resulting SLR, is largely dependent upon the vertical profiles of temperature and moisture. Three SLR case studies are presented. These cases examine the vertical temperature and moisture profiles and the resulting SLR values. These cases illustrate the potential for forecasters to diagnose and predict (via numerical model data) SLR values by employing a physically based method involving an analysis of ice crystal structural changes along with an analysis of 850 mb temperature anomalies, accompanied by the use of seasonal means of SLR. The case studies also demonstrate the potential for higher SLR values whenever a strong frontal inversion is present.

1. Introduction

In order to forecast snowfall amounts for a winter extratropical cyclone, the forecaster employs a two-step process, as discussed in Baxter et al. (2005). First, current dynamic and thermodynamic fields must be analyzed in conjunction with numerical model forecasts to determine a quantitative precipitation forecast (QPF). This QPF represents the liquid equivalent expected to precipitate from the system. To convert this liquid equivalent to a snowfall amount, a snow to liquid equivalent ratio (SLR) must be applied.

As early as 1875, the United States Weather Bureau provided a typical SLR value of 10 to 1 inches (10:1) to its observers, later instructing observers in 1894 that the 10:1 ratio was only a rough approximation (Henry 1917). In 1878 a 10:1 mean SLR value was determined for Toronto, Canada when an observer came to this conclusion after a long series of experiments (Potter 1965). A number of studies have shown that there is considerable variation from this estimate depending on location and various environmental parameters (e.g., Henry 1917; LaChapelle 1962; Grant and Rhea 1974; Doesken and Judson 1996; Super and Holroyd 1997; Judson and Doesken 2000; Roebber et al. 2003). Many National Weather Service (NWS) forecast offices are aware of the variation in ratios and use either a climatological value or an empirical method based upon surface or in-cloud temperatures (Roebber et al. 2003). The NWS "New Snowfall to Estimated Meltwater Conversion Table" utilizes surface temperatures to estimate snowfall from liquid equivalent (U.S. Department of Commerce 1996). It is only marginally effective, as it does not account for geographic location or in-cloud microphysical processes. Although this table was not intended for operational use (Roebber et al. 2003), anecdotal evidence from NWS forecasters reveals that the table has been used operationally in at least some forecast offices.

The goal of this paper is to discuss how a forecaster might use knowledge of the climatological mean of SLR in conjunction with an understanding of microphysical processes in order to diagnose and predict SLR. Section two will describe the major factors affecting SLR as documented in the relevant literature. Section three addresses the possible effects of a temperature inversion on SLR. Section four describes the datasets and methodology used to perform this research. Section five briefly presents the seasonal means of SLR for the contiguous United States. Section six details three case studies that provide insight as to how climatology in conjunction with a knowledge and evaluation of microphysical processes might be used to estimate SLR. Finally, section seven summarizes the results and presents suggestions for future research.

*Current affiliation: Department of Geography, Central Michigan University, Mt. Pleasant, MI

2. Factors Affecting SLR

Much of the research done on SLR is from the middle part of the twentieth century (e.g., Diamond and Lowry 1954; Bossolasco 1954; LaChapelle 1962), with the subject enjoying a recent revival (e.g., Judson and Doesken 2000; Roebber et al. 2003; Ware et al. 2005). In contrast to previous studies that attempted to correlate SLR to various parameters, recent attempts focus on a more physically based method involving the analysis of microphysical processes that determine SLR. Much of the literature review in this section has been discussed in Baxter et al. (2005), but is provided here for completeness. The literature review is designed to provide the operational forecaster with a concise overview of how SLR is determined using the principles of cloud physics.

The primary factor that determines SLR is the amount of air space trapped in the interstices between ice crystals within the newly fallen snow. Thus, to diagnose SLR the evolution of the ice crystals from their origin to the surface must be analyzed. As Roebber et al. (2003) discuss, not only must the in-cloud structure of the crystal be considered, but also sub-cloud processes and the degree of compaction at ground level. The initial ice crystal habit is dependent upon the temperature and degree of supersaturation with respect to ice and liquid water aloft (Magono and Lee 1966). Temperature will differentiate the basic habit of the crystal, while the extent of supersaturation delineates the specific crystal type (Pruppacher and Klett 1997). It is likely due to this fact that Roebber et al. (2003) found the impacts of moisture on SLR to be of secondary importance compared to the effects of temperature.

The air space between the individual crystals is correlated with the air space that results from the crystals in a new snowfall. Dendrites and needles exhibit the lowest density for single crystals (Fukuta and Takahashi 1999). Needles produce a lower density (higher SLR) snow, as the crystals form at a warmer temperature (-3° to –8°C, leading to increased potential for aggregation) and tend to form snowflakes with a more open structure (Power et al. 1964). Dendrite crystals also produce a lower density (higher SLR) snow, as their fernlike branches are conducive to aggregation despite the fact that dendrites form at temperatures much less than 0°C, in the –12° to –17°C range (Pruppacher and Klett 1997). Differences in crystal size also produce different inter-crystal space differences. Stashko (1976) was able to achieve correlations as high as 0.97 between SLR and surface temperature when snowfall data were stratified by crystal size. The larger crystals exhibited higher SLR values due to the larger spaces within each crystal, while small crystals packed together at the surface to create lower SLR values.

After the crystal forms, the surrounding environment will determine the type of growth. The process of crystal growth is very complex; as the crystal falls through the atmosphere it may encounter many different temperatures and degrees of saturation. This causes snowfall to consist not of one uniform habit, but of many different individual habits and superimposed habits known as polycrystals (Pruppacher and Klett 1997). As the crystal falls, the extent to which it undergoes either depositional growth (vapor to solid phase change) or growth by riming (liquid to solid phase change) will impact the amount of air space entrapped within each crystal, and thus the subsequent SLR. Riming reduces interstice space and causes higher density (lower SLR) snow. Riming has different effects on density for different crystal types (Power et al. 1964). The differences in riming effects are due to the greater number of cloud droplets collected in the case of plates and dendrites than in the case of needles. This results from the greater cross-sectional areas of dendrites and plates as compared to needles. Even if needles have a greater terminal velocity, the larger surface area of the dendrites and plates more than offsets this effect (Fletcher 1962). Thus it can be speculated that when riming is present, lower SLRs will result when the dominant crystal types are dendrites and plates as compared to the SLRs that result when the dominant crystal type is needles.

Compounding the process of crystal growth is the fact that different crystal types and crystals that grow larger relative to their neighbors will exhibit varying terminal velocities. This effect can cause fragmentation of ice crystals as well as a sweep-out of smaller particles (Roebber et al. 2003). Strong winds may also cause breakup of ice crystals, particularly those with fragile structures such as dendrites (Griggs and Choularton 1986; Rauber 1987). The seeder-feeder relationship plays a key role in diagnosing crystal growth regimes (Jiusto and Weickmann 1973). In the seeder-feeder relationship, ice crystals are generated from aloft in the seeder cloud and fall into a lower-level feeder cloud containing supercooled water. When both a seeder and a feeder cloud are present (although they need not be separate entities), precipitation efficiency is increased as the potential for growth via deposition and/or riming is increased. Precipitation efficiency would also be increased via aggregation as the additional sweep-out of snow particles in the feeder clouds results from larger particles falling from above. The precipitation intensity is always light when the seeder cloud alone is present, but this is not the case when only the feeder cloud is available since the rate of condensation in the feeder cloud system (which may or may not be convective) can be very high (Jiusto and Weickmann 1973).

As Roebber et al. (2003) presented, lower-level temperatures (and to a lesser extent, relative humidities) play a strong role in determining SLR. After falling from the cloud, ice crystals and snowflakes are further modified through sublimation (solid to vapor phase change) and melting. Sublimation occurs when ice crystals or snowflakes fall through an environment subsaturated with respect to ice. Crystals that are denser and have a habit with a large surface area will take longer to fully sublimate. Theoretical studies show that column type crystals of low density may survive less than 1 km before they are fully sublimated (Hall and Pruppacher 1976). Snowflake or ice crystal melting is a function of air temperature near the hydrometeor surface, relative humidity, the size of the crystal or snowflake, and the amount of liquid water present. Even the densest snowflakes will melt completely within 1 km (or much less than 1 km) if the relative humidity is less than 100% and temperatures are greater than 0°C (no sublimation present; Matsuo and Sasyo 1981).

Once crystals have reached the ground, snow densification begins and considerable increase in snow density can take place within a 24-h period as metamorphosis and crystal structural changes (known as destructive metamorphism) take place within a new snow layer. The weight of the snow itself does not appear to be a controlling factor (LaChapelle 1962; Meister 1986). Gunn (1965) reached the same conclusion even when applying external weights to the snow. Temperature and vapor variations that cause crystal structural changes, as well as the presence of strong wind compaction, exert a greater control on densification. Judson and Doesken (2000) present some evidence that for a heavy snowfall with higher water equivalent, a much higher density may occur due to possible pressure effects, but they also state that the relationship between new snow depth and new snow density is not rigorous. Compaction due to wind does play a strong role (Roebber et al. 2003), but no correlations between wind speed and SLR were found by Meister (1986).

While the previously discussed microphysical processes cannot be measured operationally, knowledge of their effects on SLR can assist the forecaster in the diagnosis of SLR. As Roebber et al. (2003) and other studies (e.g., Potter 1965; Judson and Doesken 2000) suggest, since the formation and growth of ice crystals is largely determined by the vertical profile of temperature and moisture, it may be possible to extract out the bulk effects of the microphysical processes using a thermodynamic sounding that measures the mesoscale environment. Therefore, a challenge exists to determine the extent of interaction between the dynamical forcing that acts to create the vertical profile of temperature and moisture and the microphysical processes that determine SLR (A. R. Lupo 2003, personal communication). While the dynamical forcing largely determines the initial structure and evolution of the ice crystals, the crystals themselves cause the vertical profile of temperature and moisture to change, creating a feedback. The determination of SLR is in essence a determination of cold-season precipitation efficiency where the depth of the snow for a given amount of liquid will be determined by the accumulated effects of the complex interaction between the microphysical processes and the vertical profile of temperature and moisture.

3. SLR Values in the Presence of a Frontal Inversion

The maximum growth rate of crystals is expected to occur near the level of maximum upward motion within the cloud, corresponding to the greatest water vapor delivery (Auer Jr. and White 1980). Typically such an area would not reside below an inversion. Power et al. (1964) document cases where the environment was such that the conditions necessary for dendritic growth were below a frontal inversion rather than above it in the overrunning warm air. Power et al. (1964) stated that the vertical mixing process beneath an inversion in this temperature range can produce an ice supersaturation of 14 to 18% necessary for dendrite growth. According to their findings, rapid snow growth is often found well below frontal zones, and frequently rather close to the ground; contradictory to the expectation that maximum crystal growth always occurs above the inversion. Kyle and

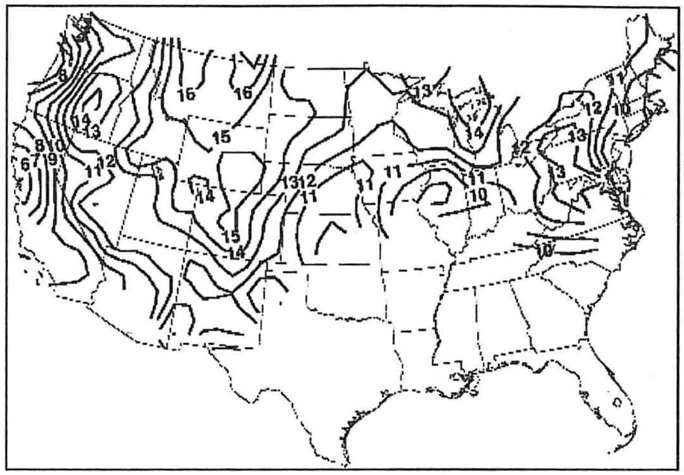

Fig. 1. Mean SLR (1971-2000) values for October and November. Mean SLR values are shown as single numbers (e.g., 10 represents a 10 inch to 1 inch ratio of snow to liquid equivalent precipitation).

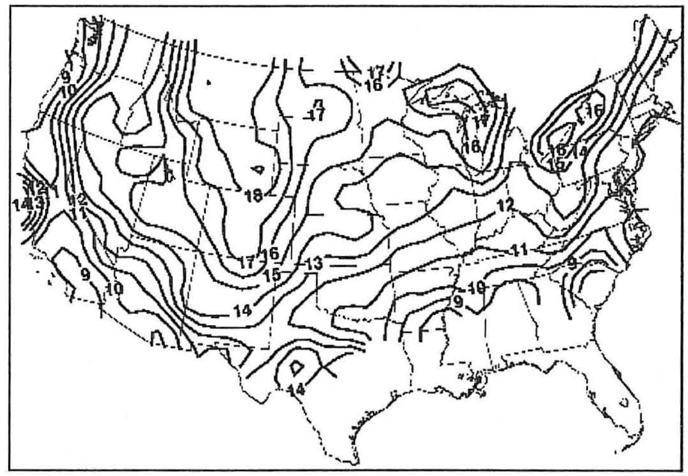

Fig. 2. Mean SLR (1971-2000) values for December, January, and February.

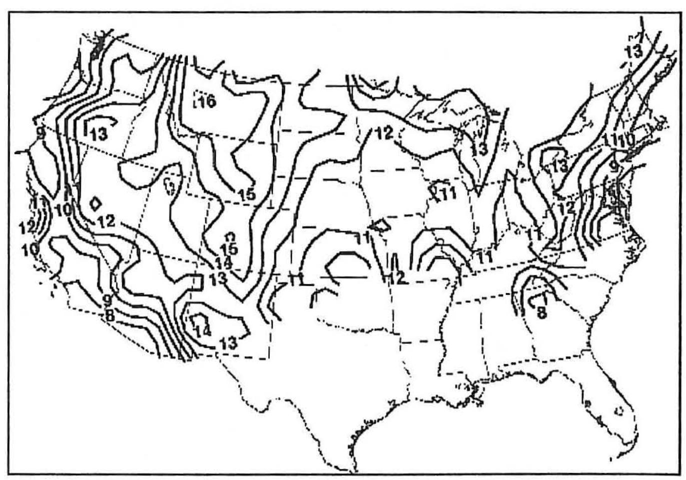

Fig. 3. Mean SLR (1971-2000) values for March and April.

Wesley (1996) studied a High Plains snowstorm in which the snow crystals formed and grew aloft in the warmer air, and then fell through the cold air in the lowest levels. They state that storms in the High Plains can occasionally contain significant amounts of liquid, as mid-level temperatures can be warmer than surface temperatures. Yet in this instance the SLR value was 18.5 to 1, not a value normally associated with a riming environment. The relatively high SLR value could be due to the presence of a secondary dendritic growth zone in the cold air in the lower levels.

Magono and Lee (1966) presented research on ice crystal habit in the presence of an inversion. Snow crystals that pass through a cold layer around –20°C develop spatial extensions on their basal plane, for reasons unknown. This phenomenon usually occurs when snow crystals that only exhibit growth in the horizontal planes fall through an inversion layer. Growth results in the c-plane (vertical) of the crystal, forming a chandelier crystal (Pruppacher and Klett 1997). Jiusto and Kaplan (1972) stated that snow stacking can act to increase SLR values for intertwining spatial dendrites (three-dimensional structures formed from polycrystals). The three-dimensional structure of the spatial dendrite is very similar to the chandelier crystal. As the crystals falling through the inversion stack at the surface, space for air is increased due to the three-dimensional character of the crystals, creating higher SLR values.

4. Dataset and Methodology

Surface data were obtained from the National Climatic Data Center (NCDC) Cooperative Summary of the Day (COOP) collection to create 30-year (1971-2000) climatology of SLR. These data represent daily observations taken by trained weather observers. Values for both liquid precipitation and snowfall were used in this study. SLR is simply the value for snow divided by the value for precipitation. Only snowfalls greater than two inches and liquid equivalents greater than 0.11 inches were included, following the standard set by Roebber et al. (2003). Reports that were estimated by NCDC were not included. Only stations that had a minimum of 15 observations over the 30-year period were included. For more information on the methods used to create the climatology as well as possible biases in the climatology, see Baxter et al. (2005).

For the case studies, standard surface and upper-air rawinsonde data from the NWS observational network were collected via Unidata's Internet Data Distribution network. Eta initialized numerical model data were obtained from the Data Support Section of the Scientific Computing Division at the National Center for Atmospheric Research[1] and analyzed using the Grid Analysis and Display System (GrADS)[2]. Surface plots, upper-air plots, meteograms, and other diagnostic fields were displayed using the General Meteorological Package (GEMPAK) software[3].

A hand analysis of SLR for an individual event proved to contain too much variability to be of significant value. So a mean SLR value over a 40,000 km^2 (200 km by 200 km) box was used. While significant variability may still be present within each box, measurement errors are substantial enough to cause difficulty in discriminating between the variation due to measurement error and actual variations in SLR, hence the need to examine SLR on a larger scale. The size of the box is comparable to an average NWS County Warning Area (CWA). As a result, the case studies presented in this study will attempt to discern SLR values on this scale only. Also, variations in SLR on time scales shorter than one day will not be examined, as necessitated by the data.

As previous studies have shown, SLR is determined largely by the vertical temperature profile. Thus the 30-year mean SLR is likely associated with a mean vertical temperature profile. An SLR value that is higher or lower than the 30-year mean is presumably associated with an anomalous vertical temperature profile that is colder or warmer, respectively. Anomalies of observed temperatures at selected pressure levels were computed using Saint Louis University's SLUbrew diagnostic software. The climatological dataset used for upper-air temperatures is a 30-year monthly mean taken over the period 1970-1999. Only 850 mb temperature anomalies were investigated in this study in order to devise a method that would be expedient enough for an operational environment. Although a more rigorous algorithm may be created in the future, it is important that forecasters still use fundamental methods that allow them to employ a process-oriented approach to forecasting. A lower pressure level may prove more useful in high-elevation areas. In this study, it is assumed that SLR values lower than the mean result from a negative (i.e., colder) 850 mb temperature anomaly. This assumption may be valid in only a general sense as the temperature anomalies were calculated based upon ALL dates, not just those on which snowfall occurred. It is possible that 850 mb temperature anomalies are often negative on days with snow. However, it is proposed that the anomalies as calculated here still have utility, especially in cases with significant temperature anomalies. Some research states that SLR values begin to increase as temperatures throughout the column decrease to very cold temperatures (< -20°C) where the predominant crystals will be small irregularly shaped structures, bullets, and columns (Grant and Rhea 1974; D. Moore 2005, personal communication regarding observed crystals). More research is needed to substantiate the details of this phenomenon, thus no cases of this type are included in the study.

To determine the in-cloud layer with the strongest upward motion, plots of the vertical profile of vertical motion using the Bellamy triangle method (Bellamy 1949) were generated. The Bellamy triangle method is used because the model dataset did not include vertical velocities. Only the times of maximum vertical motion for each case are discussed. Time-height sections of temperature for each station were labeled with the most likely crystal habit that formed in the layer based upon Magono

[1] Available online at http://dss.ucar.edu
[2] Available online at http://grads.iges.org/grads/grads.html
[3] Available online at http://my.unidata.ucar.edu/content/software/gempak

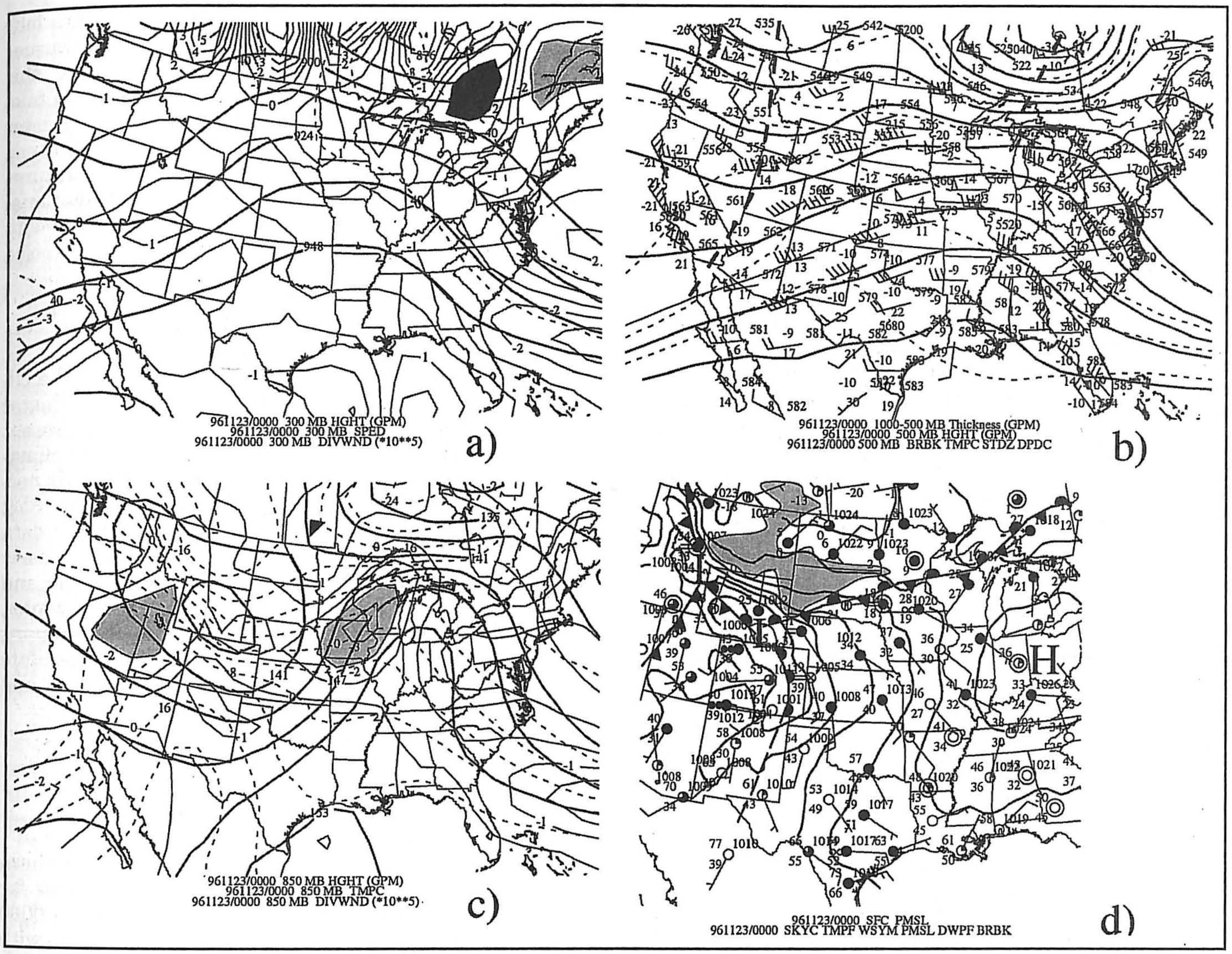

Fig. 4. Synoptic analysis valid at 0000 UTC 23 Nov 1996. (a) Objective analysis of observed 300 hPa heights (120 gpm; solid), wind speed greater than 40 m s^{-1} (10 m s^{-1}; dashed), and divergence (10^{-5} s^{-1}; thin solid; shaded gray < -2 and black > 2). (b) Standard station models of observed 500 hPa data with objectively analyzed heights (60 gpm; solid), and 1000-500 hPa thickness (60 gpm; dashed). (c) Objective analysis of observed 850 hPa heights (30 gpm; solid), divergence (10^{-5} s^{-1}; thin solid; shaded gray < -2 and black > 2), and temperature (4°C; dashed). (d) Standard station models of observed surface data with objectively analyzed mean sea level pressure, which is contoured every 4 hPa. Areas of frozen precipitation are shaded. Subjective analysis of fronts, highs and lows, and troughs is based upon more station data than indicated on plot.

and Lee's (1966) classification of observed snowflakes and the temperature of the environments in which they form. Values for the temperature contours that partition the ice crystal habits in the time-height sections of temperature were determined from Magono and Lee (1966; his Fig. 2). The contour values should not be taken as exact boundaries for delineating ice crystal habit, but rather as guidelines, as many studies have estimated the temperatures at which differing ice crystal habits grow (e.g., the summary paper by Magono 1962). Time-height sections of relative humidity (with respect to water) for each station are included, as saturated conditions are required for snow crystal growth. The degree of supersaturation (with respect to ice or water) was not taken into account in identifying the crystal types, as withholding relative humidity information from the prediction of SLR by Roebber et al. (2003) resulted in only a 5% loss of performance in their prediction model. Including the degree of supersaturation could make the diagnosis of crystal type much more difficult to perform in an operational environment. By identifying the layer of maximum upward motion and examining the type of crystal that forms in the layer, one can anticipate the initial crystal habit and speculate as to how the crystal habit will be modified upon its descent through the cloud. This method, known by some as the "top down" method for forecasting winter precipitation (Baumgardt 1999), is not designed for the purpose of creating a rigorous prediction algorithm, but rather to enable the forecaster to establish a more physically based methodology for the diagnosis and prediction of SLR. For instance, the presence of riming is very difficult to ascertain in the atmosphere, as many field studies

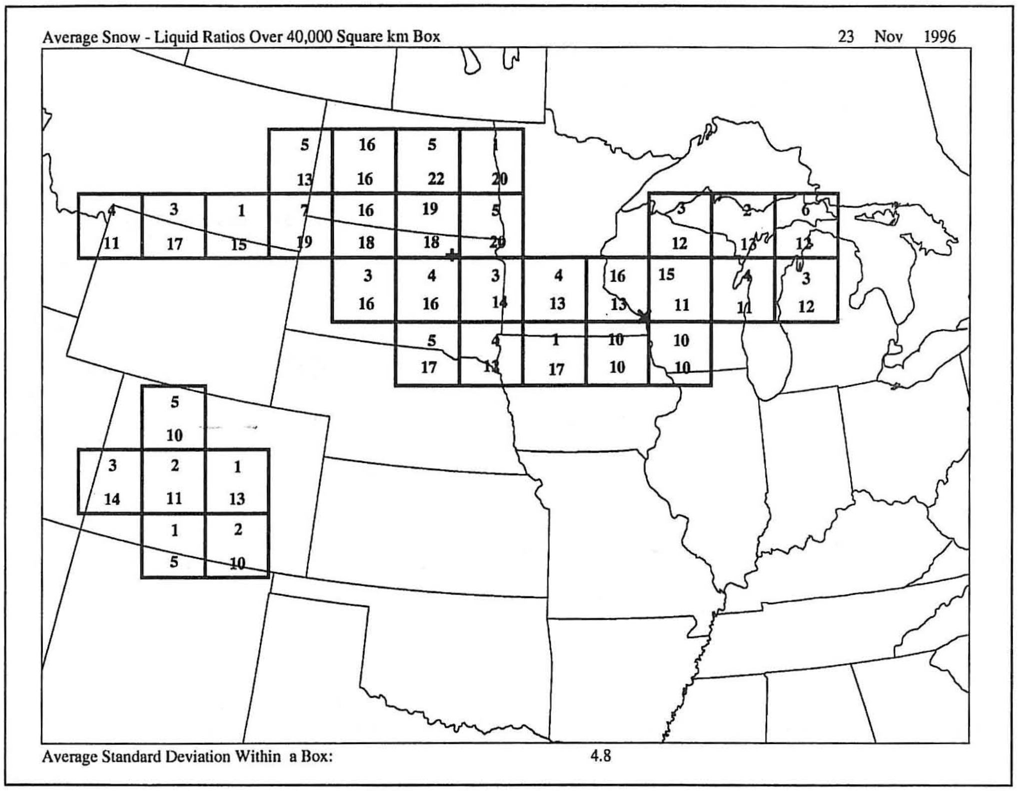

Fig. 5. Mean SLR over 40,000 km² boxes for the period 1200 UTC 22 Nov 1996 – 1200 UTC 23 Nov 1996 indicated as the bottom number. Top number indicates the number of reports included in the box. Average standard deviation within the boxes is included in the lower right corner of the figure. Aberdeen, SD (ABR) is indicated by +, Lacrosse, WI (LSE) is indicated by x.

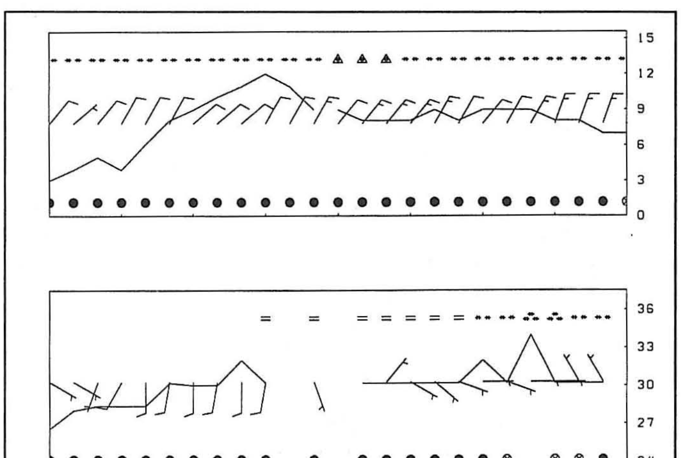

Fig. 6. Surface meteogram displaying weather symbol, wind speed in knots, temperature in °F (solid line), and sky condition for 1200 UTC 22 Nov 1996 – 1200 UTC 23 Nov 1996. Breaks in the temperature line indicate missing data. Figure reads left to right. Stations included are Aberdeen, SD (top) and Lacrosse, WI (bottom).

have been performed to investigate this quantity (e.g., Stoelinga et al. 2003). It is certain, however, that the amount of supercooled water increases as cloud temperatures increase due to the lack of ice nuclei present at warmer temperatures. Therefore, this study assumes riming to take place at temperatures greater than –4°C, even though it can occur at lower temperatures when crystal depositional growth does not keep pace with the production of supercooled water.

5. Climatology[4]

A full description of the climatology is included in Baxter et al. (2005). In the present paper, only the seasonal climatology is provided, as it is necessary for evaluating the SLR in the case studies. The data sample was divided into early winter, containing October and November (Fig. 1), mid-winter, containing December, January, and February (Fig. 2), and late winter, containing March and April (Fig. 3).

6. Case Studies

a. 23 November 1996

This case features a snowfall swath from northern Wyoming eastward into Michigan, with snowfall as far south as Iowa. The synoptic pattern at 300 mb on 0000 UTC 23 Nov 1996 appears relatively inactive with respect to jet streaks and centers of divergence (Fig. 4a). A trough is present west of the Rockies, with a smaller trough located in Canada north of the Great Lakes. The 500 mb height pattern also features troughs in approximately the same positions (Fig. 4b). The low height center at 850 mb is located in central Wyoming, east of the main upper level trough, indicating the potential for further strengthening of the system. Of particular interest on the 850 mb chart is the strong convergence located in Iowa and northeastward into Wisconsin, indicative of moisture flowing into the area from the south (Fig. 4c). The surface pattern features two low pressure centers located in southeastern Wyoming and eastern Idaho (Fig. 4d). A stationary front stretches between the two lows and to the east into Canada. Through the 12-h period ending at 1200 UTC 23 Nov 1996, the low height center at 850 mb moved southeastward into northwestern Kansas. The stationary front became a cold front in the Southern Plains, while remaining stationary near the Great Lakes (not shown).

[4] Color figures and an interactive view of the climatology using NWS CWAs is available online at http://www.eas.slu.edu/CIPS/Research/snowliquidrat.html

The mean SLR values for the 24-h period 1200 UTC 22 Nov 1996 through 1200 UTC 23 Nov 1996 exhibit noticeable stratification (Fig. 5, SLR is the bottom value and the number of reports is the top value in each box). Throughout the Dakotas, relatively high SLR values are present. A transition zone exists in northern Iowa and southern Minnesota, followed by the lowest SLR values as the Great Lakes are approached. The two stations to be further examined in this case are Aberdeen, SD (ABR) and Lacrosse, WI (LSE). The SLR at ABR was 21.0 (18 for the grid box), while the SLR at LSE was 9.5 (13 for the grid box).

The meteograms for 1200 UTC 22 Nov 1996 through 1200 UTC 23 Nov 1996 display considerable variation in the surface environments (Fig. 6). The ABR surface temperatures indicate that the station is on the cold side of the stationary front, with temperatures never exceeding 12°F. Surface temperatures at LSE range from the 27° to 33°F, indicating that LSE is located on the warm side of the stationary front or right along it. LSE exhibits light winds of 5-10 kts (2.6-5.1 m s^{-1}) from a more southerly to easterly direction, in contrast to the stronger 5-15 kt (2.6-7.7 m s^{-1}) northerlies at ABR. ABR received 4.2 in. of snowfall over the period, while LSE received 5.4 in. Surface maximum temperatures over the previous five days ranged from 12° to 25°F for ABR, and 27° to 32°F for LSE. Higher antecedent surface temperatures may lead to more extensive compaction of the snow.

For ABR, at 0300 UTC 23 Nov 1996, an adjusted omega value of –7.0 μbars s^{-1} is apparent in a layer centered around 500 mb (not shown). At this time, relative humidities in this layer are > 90%, indicating that snow growth is likely (Fig. 7). Temperatures between –20° and –13.5°C in the layer at 0300 UTC 23 Nov 1996 indicate the likely crystal type will be plates and/or dendrites (Fig. 8). As the crystals descend, they encounter a much warmer layer. Relative humidities in the riming layer are > 80%, indicating the presence of supercooled water available for riming of the plates/dendrites at temperatures > -4°C. As the crystal further descends it encounters a cold layer near the surface, indicating the presence of a very strong temperature inversion associated with the front. In the 900 to 950 mb layer, relative humidities are from 70 - 90% and temperatures between –13.5° and –16.5°C favor dendritic growth. Even in the absence of strong vertical motion, snow growth will likely continue if the layer is near saturation (relative humidity > 80%) and ice nuclei are present. In this case, the crystals falling from above will serve as nuclei for new dendritic snow growth via the seeder-feeder mechanism, or new nuclei will be activated as temperatures are low enough that 75% of the clouds will contain at least some ice crystals (Pruppacher and Klett 1997). Even with the melting and possible riming at the top of the inversion, it is likely that the secondary dendritic growth provided enough air space in the interstices of the crystals to give SLR values higher than the 30-year mean over the 24-h period. Examining the histograms of SLR for individual NWS CWAs presented in Baxter et al. (2005) or on the aforementioned website may help determine how much higher SLRs might be.

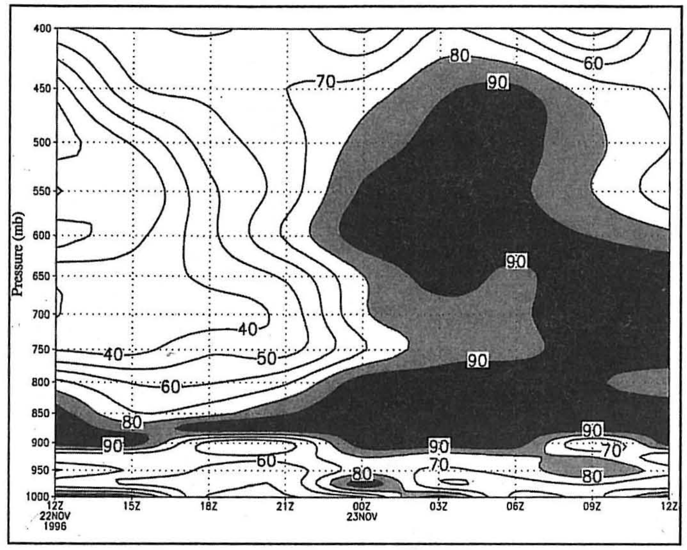

Fig. 7. Relative humidity for ABR for 1200 UTC 22 Nov 1996 – 1200 UTC 23 Nov 1996 using 3-hourly Eta initializations. Figure reads left to right. Values > 80% shaded light gray; > 90% shaded dark gray.

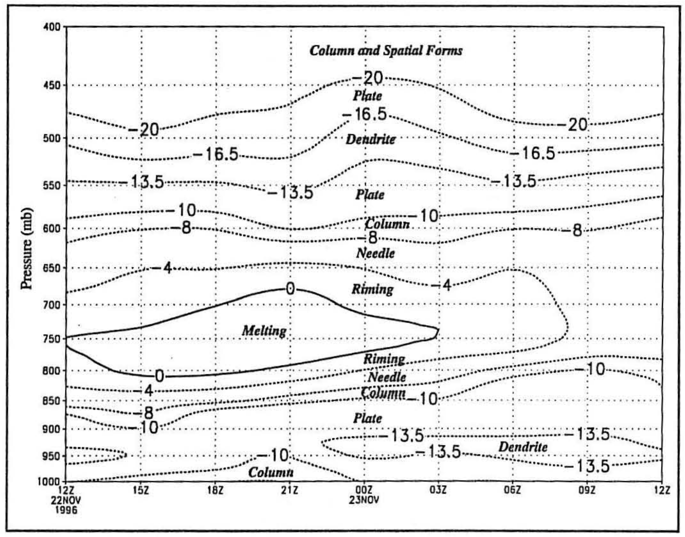

Fig. 8. Temperature in °C for ABR for 1200 UTC 22 Nov 1996 – 1200 UTC 23 Nov 1996 using 3-hourly Eta initializations. Figure reads left to right. Labels have been placed within each temperature layer to indicate the type of ice crystal that typically grows in that environment.

The previous evolution of the vertical temperature and moisture profiles over the 24-h period is provided to illustrate the complexity involved in using this "top down" method to diagnose SLR (Figs. 7 and 8). SLR values change less over the period of observation and are easier to diagnose when the vertical temperature and moisture profiles exhibit little change. In this case, the temperature profile exhibits little variation over the 24-h period, but the moisture profile is much more variable (as is often the case). During the period 1200 UTC 22 Nov 1996 to 2300 UTC 22 Nov 1996, the relative humidities are < 60% in the 650 to 750 mb layer centered at the top of the inversion where isentropic ascent due to frontal forcing would be expected. Temperatures in the layer are too

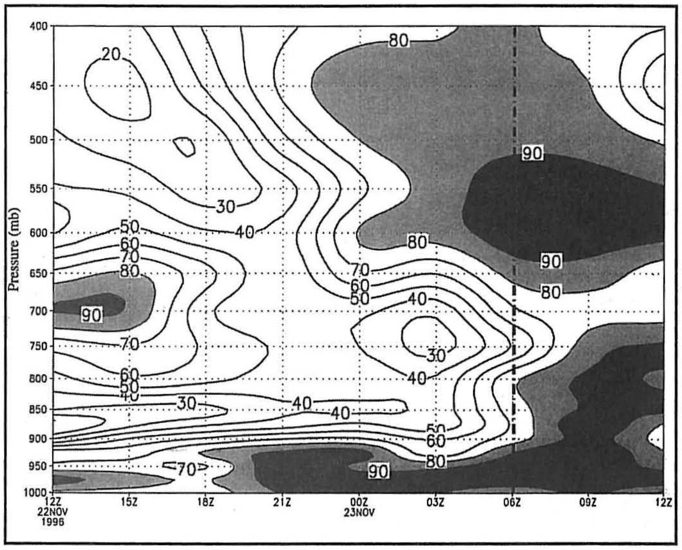

Fig. 9. Relative humidity for LSE for 1200 UTC 22 Nov 1996 – 1200 UTC 23 Nov 1996 using 3-hourly Eta initializations. Dashed line indicates the hour snowfall was first observed. Figure reads left to right. Values > 80% shaded light gray; > 90% shaded dark gray.

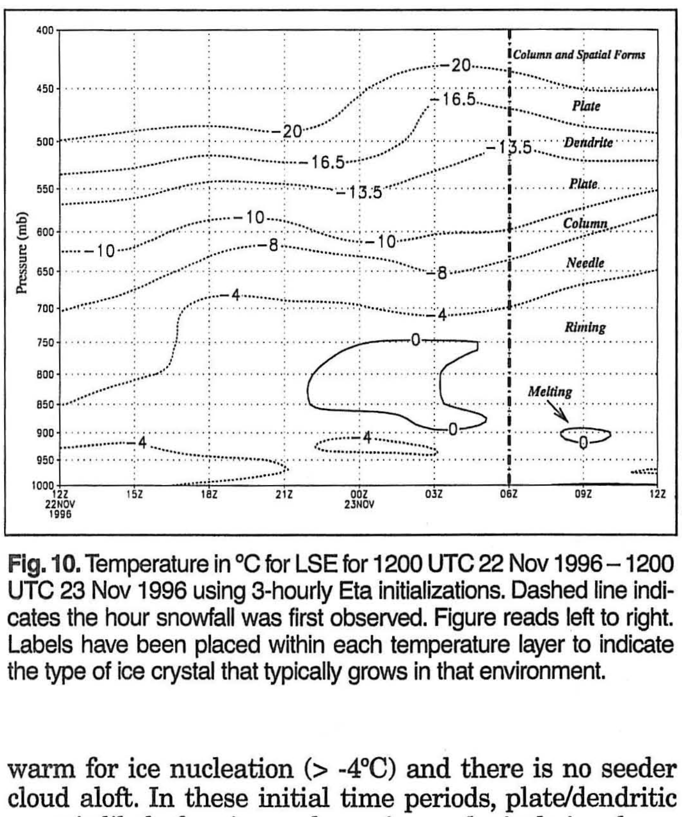

Fig. 10. Temperature in °C for LSE for 1200 UTC 22 Nov 1996 – 1200 UTC 23 Nov 1996 using 3-hourly Eta initializations. Dashed line indicates the hour snowfall was first observed. Figure reads left to right. Labels have been placed within each temperature layer to indicate the type of ice crystal that typically grows in that environment.

warm for ice nucleation (> -4°C) and there is no seeder cloud aloft. In these initial time periods, plate/dendritic snow is likely forming and growing exclusively in a layer from 950 to 1000 mb, as temperatures of –10°C are cold enough for 50% of the clouds to contain ice (Pruppacher and Klett 1997). As time progresses past 2300 UTC 22 Nov 1996, vertical motion and mid-level relative humidity both increase, producing the environment previously discussed.

For LSE, a maximum vertical motion value of –5.0 μbars s^{-1} occurred just below 600 mb at 1200 UTC 23 November 1996 (not shown). Relative humidity values in the 500-700 mb layer range from 70 to 80% (Fig. 9). In this layer, temperatures between –4 and –8°C favor the development of needles (Fig. 10). Although maximum snow growth occurs in the layer of maximum vertical motion, snow growth does occur in the colder, saturated upper layers where ice nuclei are present. These ice crystals are likely dendrites and/or plates that serve as feeder nuclei for the lower level seeder cloud, initiating needle type growth. As the needles descend, they may undergo considerable riming (possibly even melting) in the layer from 650 mb to the surface, reducing the amount of air space in the interstices of the aggregated needles and leading to lower than the 30-year mean SLR values.

The comparison of the thermodynamic environments of ABR and LSE provides insight into the potential for very different SLR values based upon the surrounding air mass. This case also suggests the varying impacts inversions can have on SLR. If the inversion approaches 0°C, one would assume SLR values would be lower due to the presence of rimed particles reducing the air space within the interstices of the crystals. This appears true in the LSE sounding, but the ABR sounding still has relatively high SLR values. The difference in SLR between LSE and ABR is likely due to the depth over which the near surface temperature is below freezing. In the case of the ABR sounding, the temperature decreases very rapidly over a shallow layer to a surface temperature of –13°C as the ice pellets are falling. It appears that the majority of the precipitation that fell exhibited characteristics that led to higher SLR values, despite the presence of ice pellets from 0000 UTC 23 Nov 1996 – 0300 UTC 23 Nov 1996 (Fig. 6). Magono and Lee (1966) stated that growth along the vertical plane of the ice crystals occurs when crystals pass through an inversion layer. This growth would lead to an increase in the pore space of the ice crystal, which would lead to higher than mean SLR values when the snow reaches the surface.

The 850 mb temperature anomalies for 0000 UTC 23 Nov 1996 (Fig. 11a; midpoint of snowfall occurring at ABR) and 1200 UTC 23 Nov 1996 (Fig 11b; closest upper-air observation time for snowfall occurring at LSE) are compared with the observed SLR values. As the event occurred in November, it is best to use the temperature anomalies in conjunction with the 30-year SLR mean for the fall season (Fig. 1). 850 mb temperature anomalies at ABR show a value 9°C less than the climatological mean. The negative temperature anomaly indicates that it is likely the SLR value will be above the mean SLR value for the fall season. The grid box SLR value for ABR was 18 (Fig. 5), higher than the fall mean of between 13 and 14 (Fig. 1). 850 mb temperature anomalies at LSE show a value 2°C colder than the climatological mean. The small negative value indicates that it is likely the SLR value will be slightly above the mean SLR value for the fall season. The grid box SLR value for LSE was 13, just above the fall mean of 12.

b. 30-31 December 1998

In contrast to the previous case that featured largely zonal flow across the Northern Plains, this case contains mid-tropospheric flow from the northwest associated with an Alberta Clipper-type system. Snowfall occurs in a northwest to southeast line from North Dakota to Illinois. The synoptic pattern at 300 mb on 0000 UTC 31 Dec 1998 depicts wind speeds exceeding 50 m s^{-1} (100 knots) in the Northern Plains and the southeast United States (Fig. 12a). An area of divergence is located along the Illinois – Indiana border, indicating the potential for strong upward motion. At 500 mb, three perturbations are seen in the flow in the form of rapidly moving shortwave troughs (Fig. 12b). At 850 mb an area of convergence is located along the Missouri – Illinois border, just to the west of the upper level divergence area (Fig. 12c). The isotherms at 850 mb exhibit a considerable north-south gradient, particularly in Iowa, Missouri, and Illinois where temperatures range from +4° to –16°C. At the surface, low pressure is present in northeast Kansas and the Oklahoma panhandle (Fig. 12d). A stationary front extends from the Kansas low northwestward through Montana, along with an inverted trough stretching northward from the Kansas low through Minnesota. Through the period 1200 UTC 30 Dec 1998 – 1200 UTC 31 Dec 1998 the synoptic pattern changes little, with the exception of the southward advancement of cold air as the surface low progressed to the southeast.

The mean SLR pattern for this case featured much higher than 30-year mean values, considering the southward extent of the system (Fig. 13). SLR values to the north are higher than those to the south. The two stations to be further examined in this case are Ames, IA (AMW) and Jackson, KY (JKL). The SLR at AMW was 25 (21 for the grid box), while the SLR at JKL was 10 (16 for the grid box).

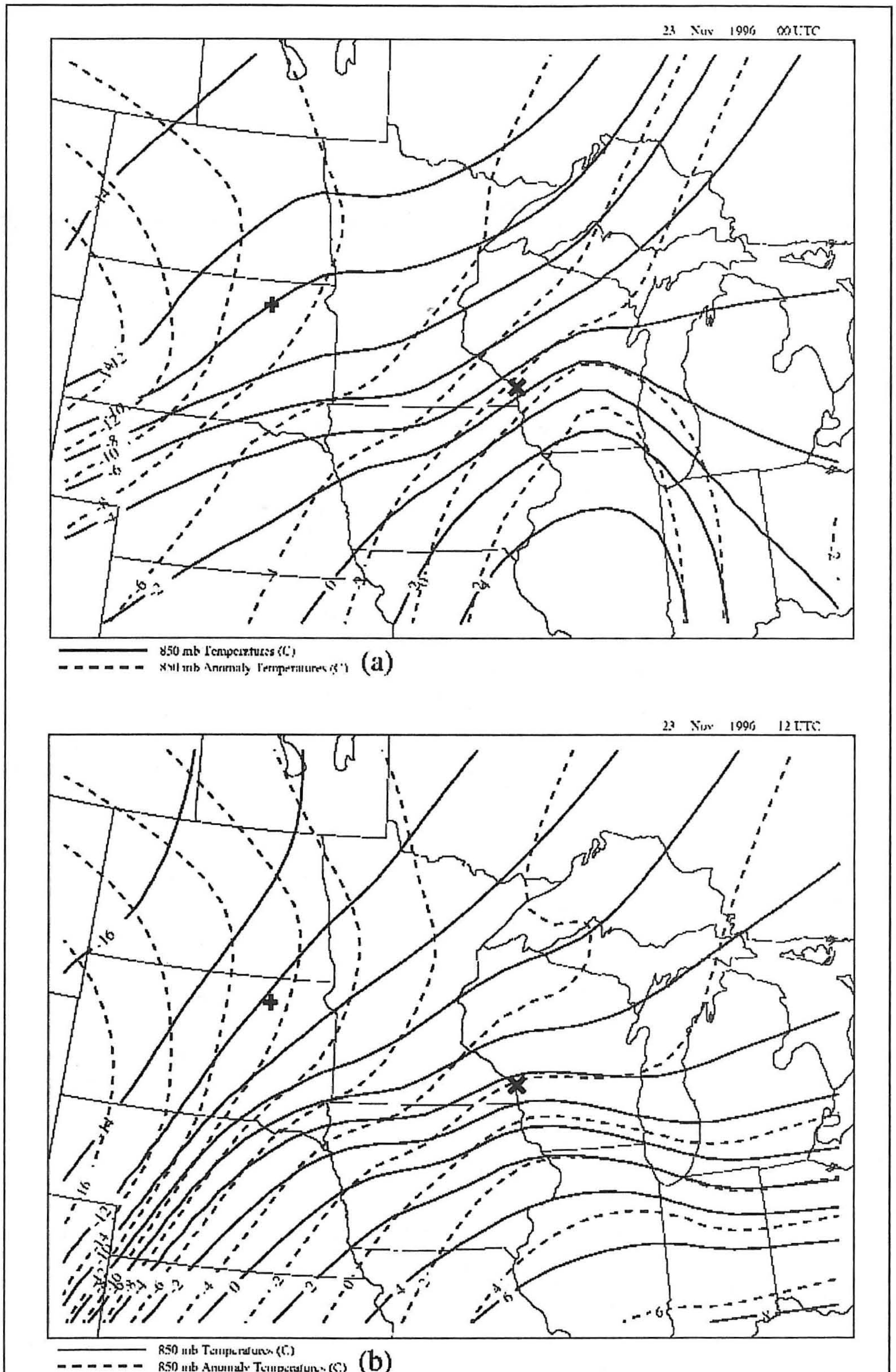

Fig. 11. 850 hPa temperatures (solid lines) and temperature anomalies (dashed lines) in °C for (a) 0000 UTC 23 Nov 1996 and (b) 1200 UTC 23 Nov 1996. ABR is indicated by +, LSE is indicated by x.

The meteograms at both locations for 1200 UTC 30 Dec 1998 through 1200 UTC 31 Dec 1998 are shown in Fig. 14. Winds at each station do not exceed 10 kts (5 m s^{-1}). During the period of snowfall, temperatures at AMW hovered around 5°F, while temperatures at JKL hovered around 21°F. AMW received 7.0 in. of snowfall over the period, while JKL received 2.5 in. Surface maximum temperatures over the previous five days ranged from 40° to 16°F for AMW, and

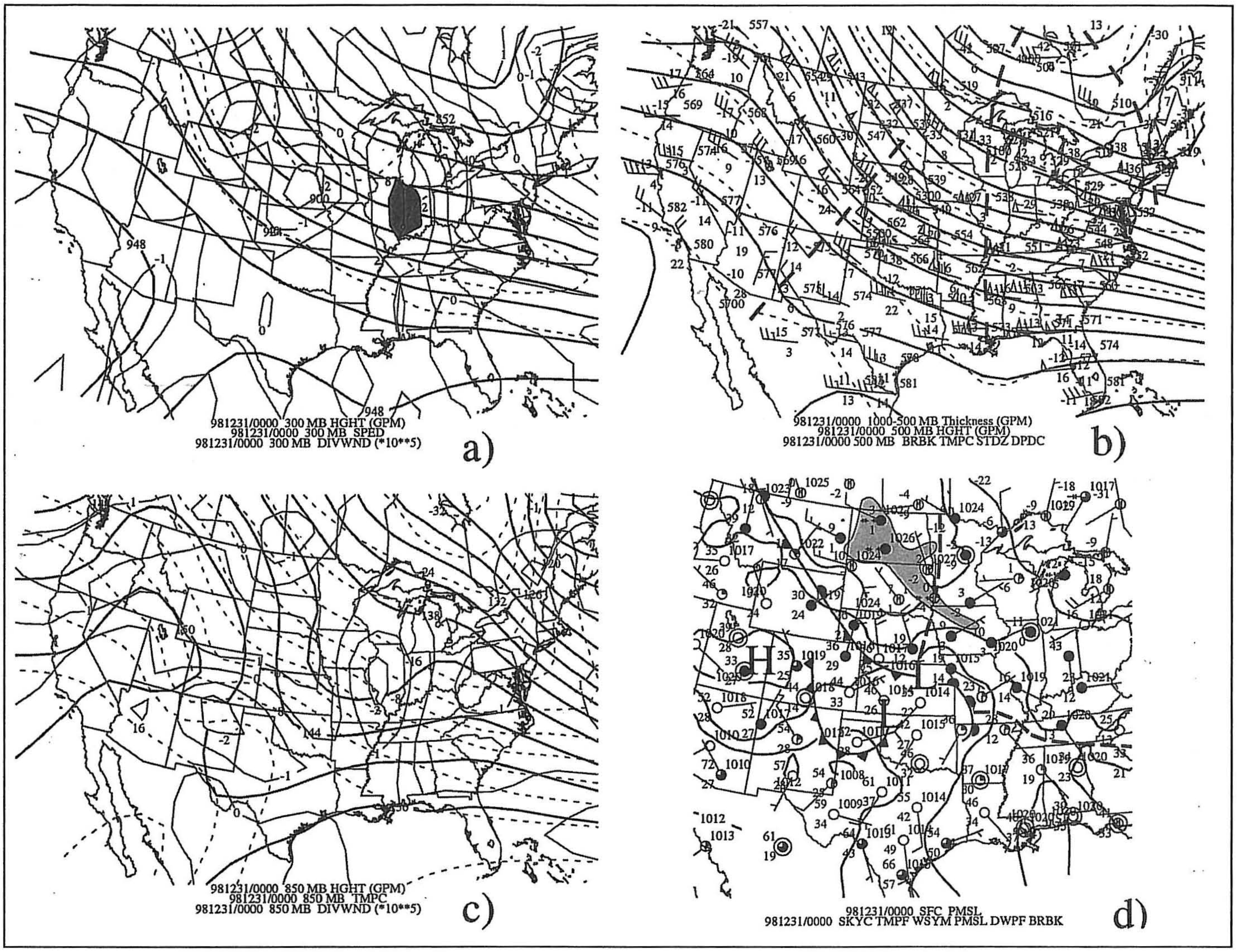

Fig. 12. As in Fig. 4, but valid at 0000 UTC 31 Dec 1998.

44° to 32°F for JKL. Surface maximum temperatures decreased as the Clipper system approached.

For AMW at 1800 UTC 30 Dec 1998, an adjusted omega value of –2.0 μbars s^{-1} is seen in a relatively low layer from 600 to 800 mb (not shown). Relative humidities in this layer are > 80%, indicating that snow growth is likely (Fig. 15). Temperatures between –20° and –10°C in the layer suggest the likely crystal type will be plates and/or dendrites (Fig. 16). As the crystals descend, it can be surmised that temperatures do not decrease enough to cause other crystal types to form or riming to occur. The lack of riming and/or formation of additional crystal types allow the open structure of the dendritic/plate crystals to be preserved, consistent with the observed relatively high SLR values. In contrast to the previous case, the temperature and moisture profiles during the snowfall period exhibit little variation, making the diagnosis of SLR less complex.

For JKL at 0600 UTC 31 Dec 1998, an adjusted omega value of –4.0 μbars s^{-1} is seen in a relatively high layer centered around 400 mb (not shown), with a secondary maximum of –3.5 bars s^{-1} in the 700 to 800 mb layer. As relative humidities above 500 mb are less than 70%, it is likely that the lift centered on 400 mb did not produce the snow crystals (Fig. 17). Instead, the crystal growth occurred in the lower levels below 500 mb where relative humidities were greater than 80% and vertical motions were still less than –3.0 μbars s^{-1}. Much like at AMW, temperatures in the snow growth region ranged from –20° to –10°C, indicating the likely crystal type will be plates and/or dendrites (Fig. 18). In contrast to the temperature profile at AMW, temperatures decrease as the crystals fall, indicating that the initial crystal type in the lower levels where vertical motion is maximized (700-800 mb) will likely be column and needle. With the dominant crystal growth type in the lower levels no longer being dendritic, SLR values in the vicinity of JKL can be expected to be less than those at AMW, where dendrites are diagnosed to be dominant.

The 850 mb temperature anomalies for 0000 UTC 31 Dec 1998 (Fig. 19a; closest upper-air observation time for snowfall occurring at AMW) and 1200 UTC 31 Dec 1998 (Fig 19b; closest upper-air observation time for snowfall occurring at JKL) are compared with the observed SLR values. As the event occurred in December, it is best to use the temperature anomalies in conjunction with the 30-year mean for the winter season (Fig. 2). 850 mb temperature anomalies at AMW and JKL are approximately –10° and –11°C, respectively. The negative temperature anomalies indicate that it is likely the SLR value will be above the mean SLR value for the winter season. The SLR value for the grid box containing AMW was 21 (Fig. 13), much higher than the winter mean between 13 and 14 (Fig. 2). The SLR value for the grid box containing JKL was 16, higher than the winter mean of approximately 12. 850 mb temperatures at AMW and JKL were –12° and –11°C, respectively. It is likely that the difference in SLR values arose due to the thermal structure in the layer below 850 mb. Surface temperatures at AMW through the period of snowfall hovered around 5°F, indicating the potential for a low-level dendritic growth zone as was seen in the previously discussed 22-23 Nov 1996 case. Surface temperatures at JKL through the period of snowfall were around 21°F, suggesting the lack of a low-level dendritic growth zone. As previously mentioned, antecedent surface temperatures were warmer at JKL than at AMW. This likely aided the extent of compaction of the snowfall at JKL, leading to relatively lower SLR values This case elucidates the fact that although 850 mb temperature anomalies can be helpful, a full examination of the evolution of the vertical temperature and moisture profile must be undertaken in order to better anticipate relative areas of high or low SLR values for a storm system.

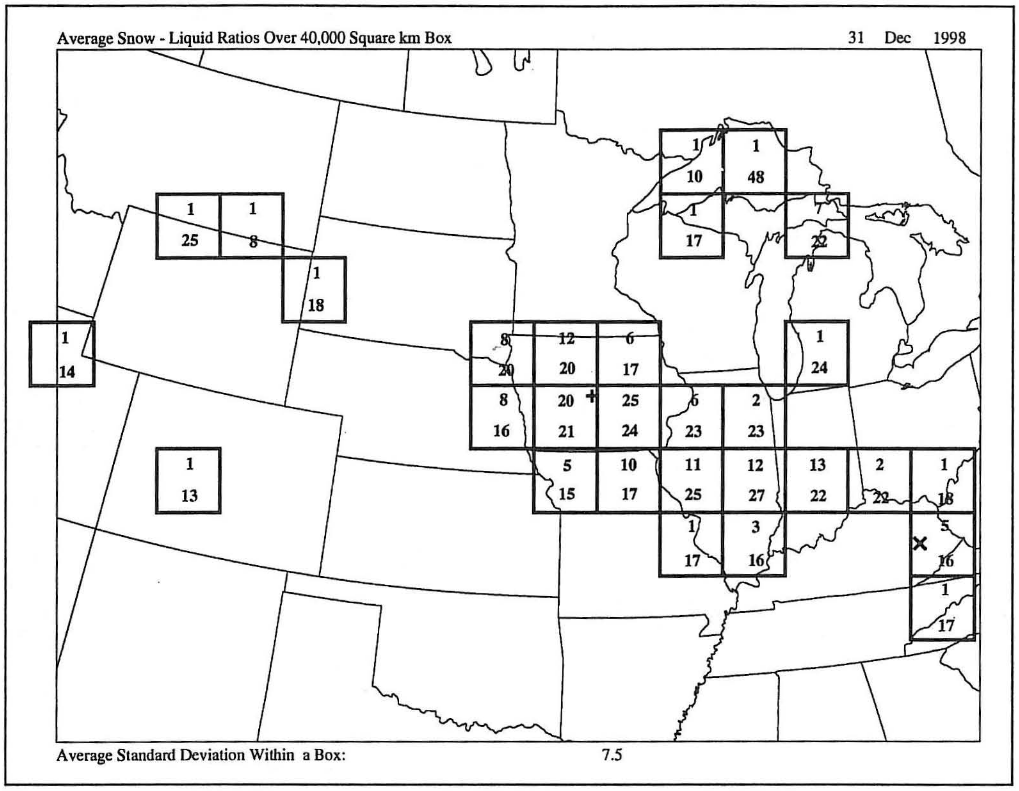

Fig. 13. As in Fig. 5, but for 1200 UTC 30 Dec 1998 – 1200 UTC 31 Dec 1998. Ames, IA (AMW) is indicated by +, Jackson, KY (JKL) is indicated by x.

c. 12-13 March 1999

This case deviates from the previous cases in that the Gulf of Mexico is a significant source of moisture. In the interest of conciseness, only a brief analysis of this case will be presented. Snowfall is present from far southern Nebraska southward to eastern Colorado and western Kansas, then eastward through southern Missouri. The mean SLR pattern for this case indicates higher SLR values in the west and lower SLR values to the south and east (Fig. 20). Much of this is due to rain and mixed precipitation occurring in the southern and eastern sections of the region. Note that the 37 SLR value in south-central Missouri is likely due to measurement error, as this value is far removed from the surrounding values. The two stations to be further examined in this case are McCook, NE (MCK) and Dodge City, KS (DDC).

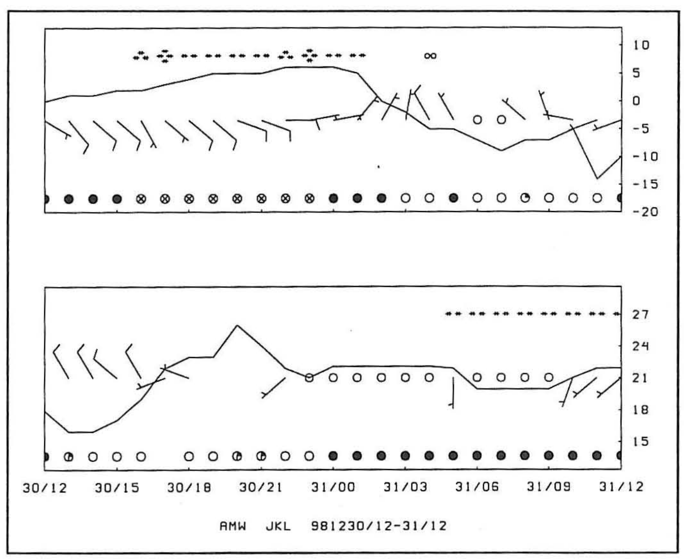

Fig. 14. Surface meteogram as in Fig. 6, but for 1200 UTC 30 Dec 1998 – 1200 UTC 31 Dec 1998. Stations included are Ames, IA (top) and Jackson, KY (bottom).

The 850 mb temperature anomalies for 0000 UTC 13 Mar 1996 (the midpoint of snowfall occurring at both MCK and DDC) are compared with the observed SLR values. As the event occurred in March, it is best to use the temperature anomalies in conjunction with the 30-year mean for the spring season (Fig. 3). 850 mb temperature anomalies at both DDC and MCK are

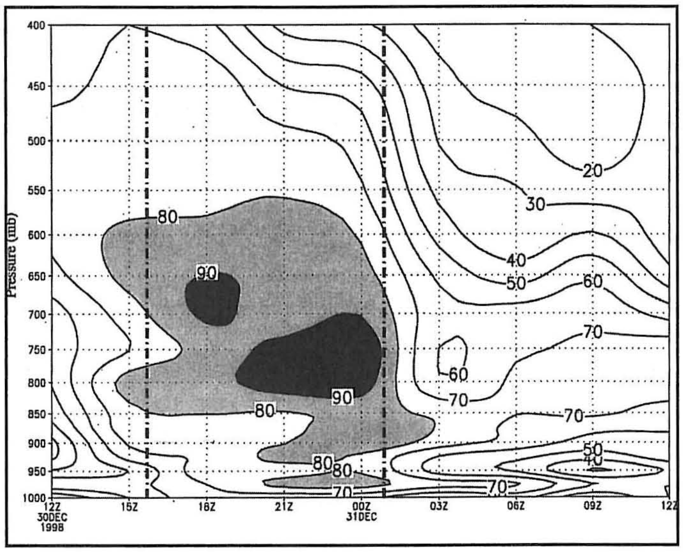

Fig. 15. As in Fig. 7, but for AMW, encompassing 1200 UTC 30 Dec 1998 – 1200 UTC 31 Dec 1998. Dashed lines delineate period when snowfall was observed.

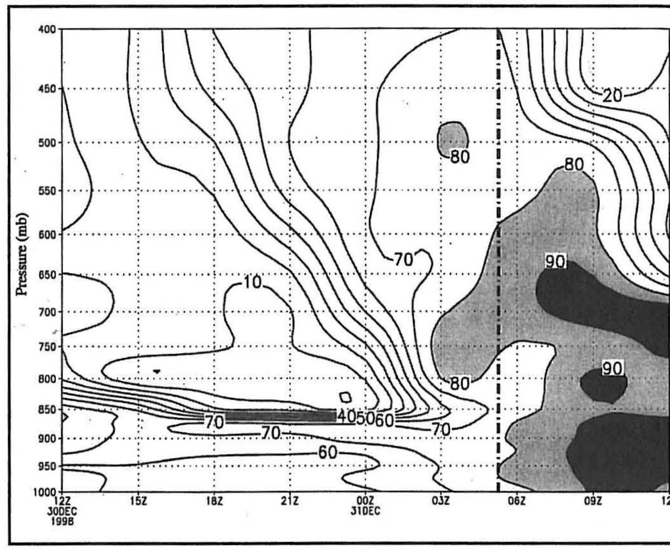

Fig. 17. As in Fig. 7, but for JKL, encompassing 1200 UTC 30 Dec 1998 – 1200 UTC 31 Dec 1998. Dashed line indicates period when snowfall was first observed.

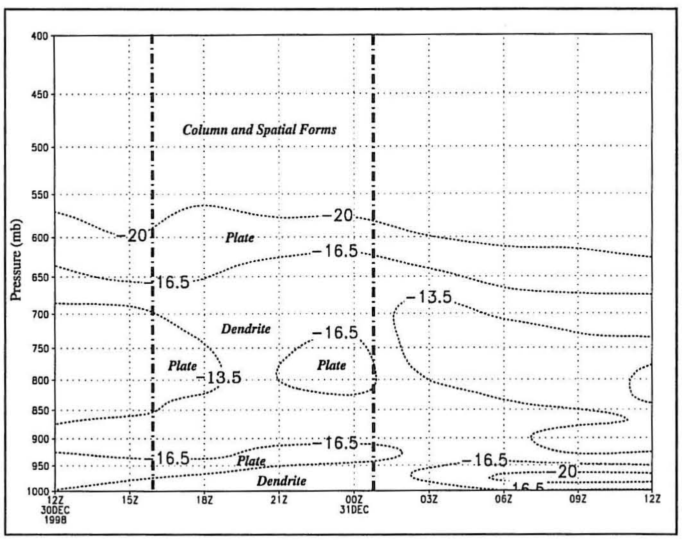

Fig. 16. As in Fig. 8, but for AMW, encompassing 1200 UTC 30 Dec 1998 – 1200 UTC 31 Dec 1998. Dashed lines delineate period when snowfall was observed.

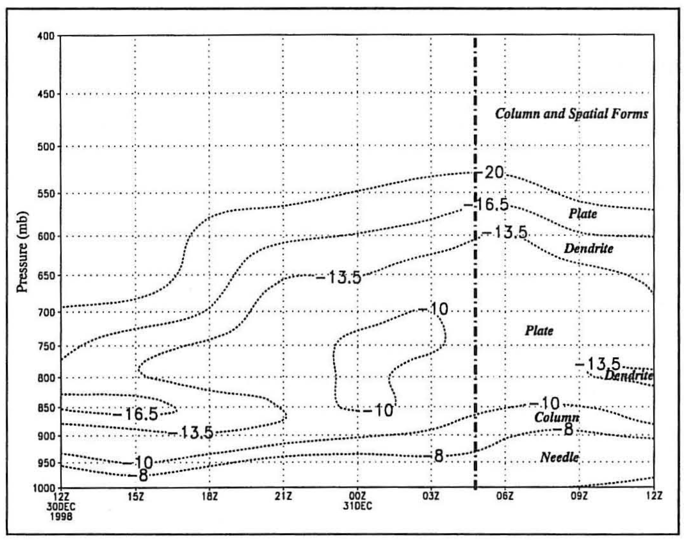

Fig. 18. As in Fig. 8, but for JKL, encompassing 1200 UTC 30 Dec 1998 – 1200 UTC 31 Dec 1998. Dashed line indicates period when snowfall was first observed.

approximately –11°C (Fig. 21). The negative temperature anomalies indicate that it is likely the SLR value will be above the mean SLR value for the spring season. The SLR value for the grid box containing MCK was 13 (Fig. 20), slightly higher than the spring mean between 11 and 12 (Fig. 3). The SLR value for the grid box containing DDC was 10, close to the spring mean that was between 10 and 11, despite the negative temperature anomaly at 850 mb. In this example ground temperatures at DDC were above freezing during part of the period, illustrating the fact that surface temperatures above freezing can override the importance of 850 mb temperatures. This difference in surface temperature between MCK and DDC likely caused the SLR values to be lower at DDC than MCK.

7. Discussion and Conclusions

This study evaluated the synoptic, thermodynamic, and moisture environments for two cases in detail and one case more briefly in order to examine the extent a SLR value at a spatial scale of 40,000 km^2 might be diagnosed using information on the above environments. The three case studies illustrate the potential for forecasters to diagnose and predict (when used with numerical model data) SLR values using a physically based method involving an analysis of ice crystal structural changes along with an analysis of 850 mb temperature anomalies, accompanied by the use of seasonal means of SLR.

In analyzing the case studies, in most instances it was possible to determine relative areas of higher and lower

SLR values within a given storm system based upon an analysis of crystal structure from the top of the clouds to the surface. By examining the thermodynamic and moisture profiles coupled with knowledge of microphysical processes, some skill is apparent in estimating a specific SLR value in comparison to the mean climatological value for a given region. 850 mb temperature anomalies proved helpful in this pursuit, particularly in cases where strong deviations from the mean were present. Examination of more cases should further aid in establishing a stronger relationship between thermodynamic and moisture environments and SLR. Further stratifying the 850 mb temperature anomalies into those days where wintry weather precipitation occurred might result in a stronger relationship between the estimated SLR for a given event to its associated anomalous 850 mb temperature. The method presented involves significant assumptions that may cause it to be inaccurate in some cases. In particular, a considerable amount of non-linearity is present among the parameters that create a given SLR value that cannot be accounted for without the use of advanced statistical techniques. Thus, for this study to be most useful, emphasis should be placed on the method used to diagnose SLR itself. Such a framework allows forecasters to use their understanding of microphysical processes to improve the diagnosis and prediction of SLR. Through experience, the forecaster will be able to delineate situations for which the method will be less accurate and a more complex (but less physically intuitive) approach must be sought out.

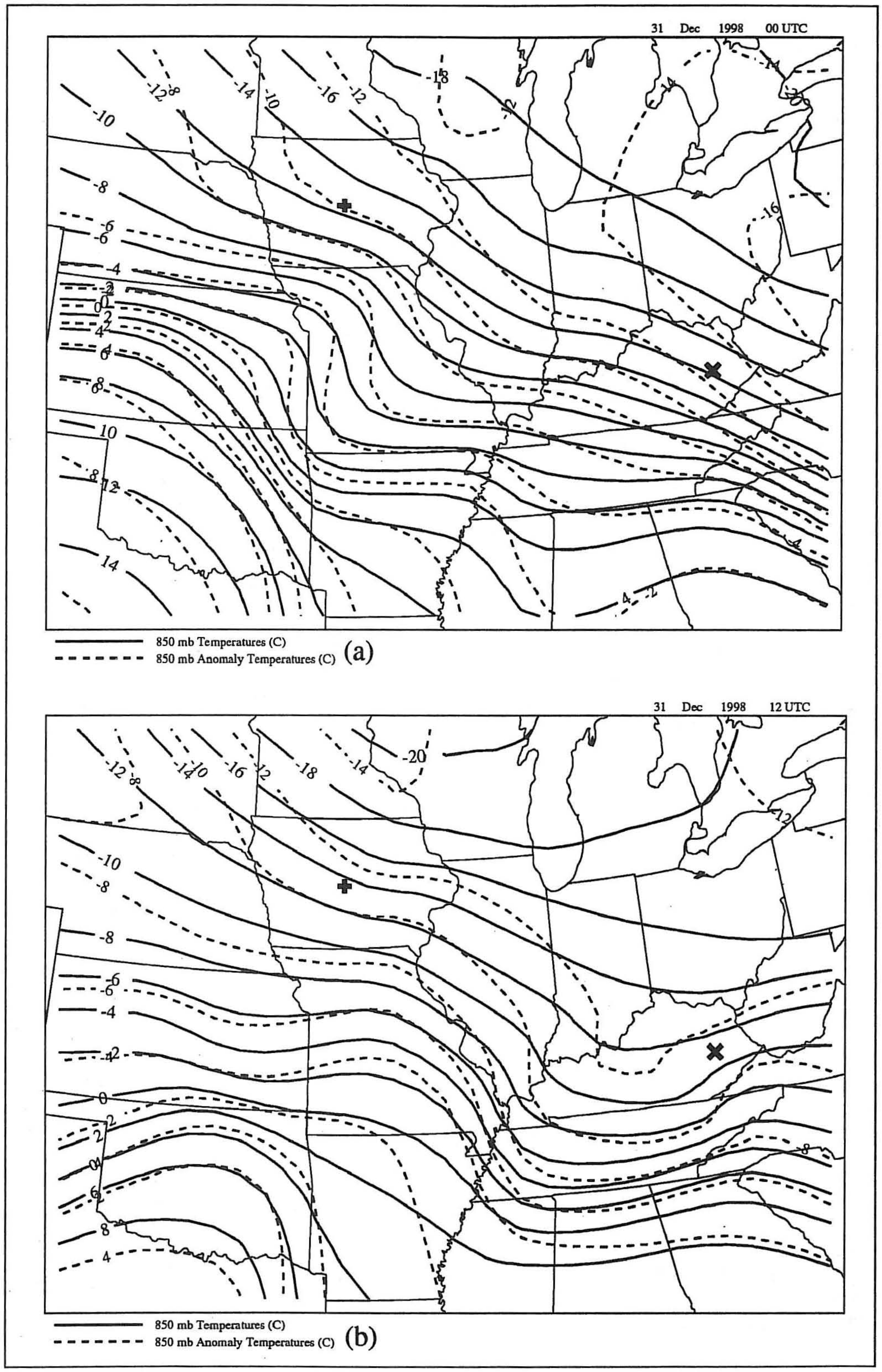

Fig. 19. 850 hPa temperatures (solid lines) and temperature anomalies (dashed lines) in °C for (a) 0000 UTC 31 Dec 1998 and (b) 1200 UTC 31 Dec 1998. AMW is indicated by +, JKL is indicated by x.

Opportunities for further research on the topic of SLR remain abundant. Of particular interest are the characteristics of snow growth in the presence of inversions. Magono and Lee (1966) describe growth in the c-plane (vertical) of the crystal as the crystal falls through a layer of cold air between –10° and –20°C. The logical extension of this fact would account for the relatively high SLR values in such areas as occurred in the 22-23 Nov 1996 case. It would be valuable to exam-

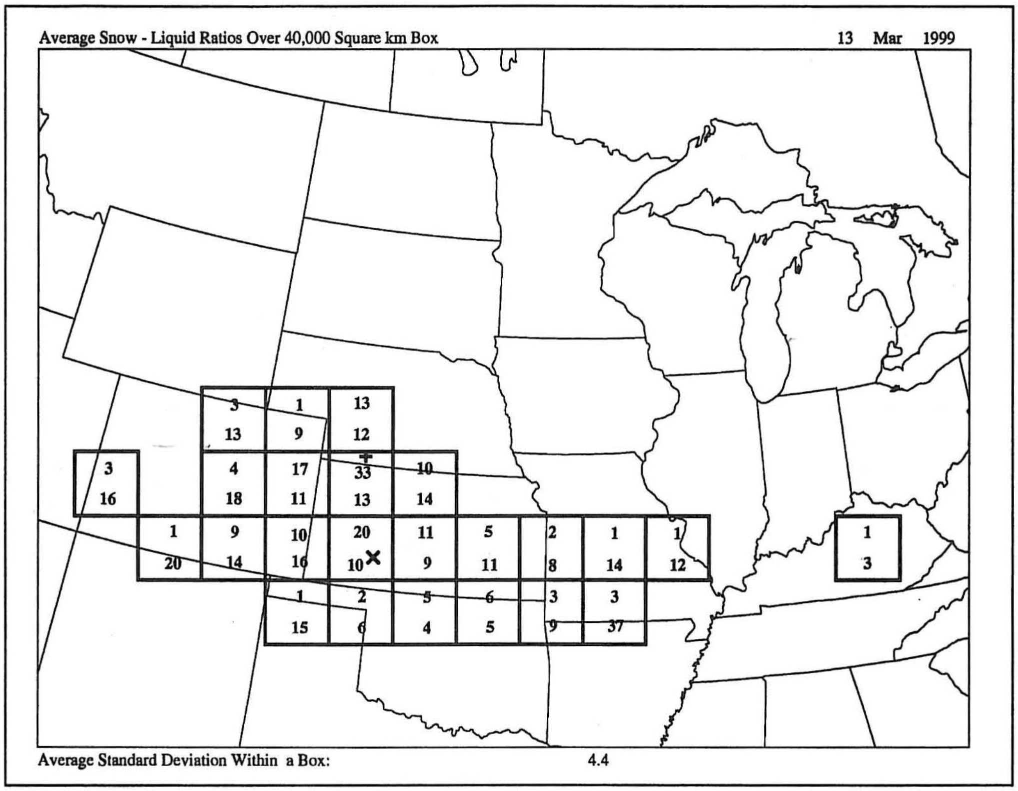

Fig. 20. As in Fig. 5, but for 1200 UTC 12 Mar 1999 – 1200 UTC 13 Mar 1999. McCook, NE (MCK) is indicated by +, Dodge City, KS (DDC) is indicated by x.

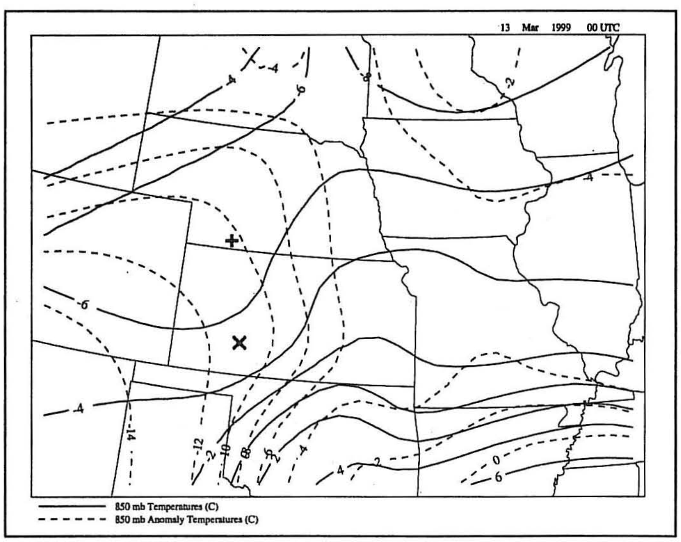

Fig. 21. 850 hPa temperatures (solid lines) and temperature anomalies (dashed lines) in °C for 0000 UTC 13 Mar 1999. MCK is indicated by +, DDC is indicated by x.

ine the habits of ice crystals that fall during these types of events. Another avenue for research lies in numerical simulations. Real-time simulations could be used to attempt to develop an algorithm for SLR using information from existing cloud parameterizations. Such an attempt would be difficult, as no solid relationships between thermodynamic and moisture variables have yet been established. Therefore, the climatological statistics derived in Baxter et al. (2005) might be of use in creating an algorithm to predict SLR, in much the same way climatological information is used in multiple linear regressions to create Model Output Statistics.

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Authors

Martin A. Baxter is an Assistant Professor of Meteorology at Central Michigan University where he teaches synoptic meteorology and introductory meteorology. This work represents a portion of his Master's thesis which was completed while working as a research assistant for the Cooperative Institute for Precipitation Systems at Saint Louis University. His research interests include the climatology of precipitation and multi-scale physical processes involved in frozen and convective precipitation. Dr. Baxter received his Ph.D. in Meteorology from Saint Louis University in 2006. Corresponding author address: Martin A. Baxter, Department of Geography, 296 Dow Science Building, Central Michigan University, Mt. Pleasant, MI 48859. E-mail: *baxte1ma@cmich.edu.*

Charles E. Graves is an Associate Professor of Meteorology at Saint Louis University and teaches instrumentation and remote sensing, principles of radiative transfer, satellite meteorology, and statistical methods in meteorology. Dr. Graves is co-Principal Investigator of the Cooperative Institute for Precipitation Systems. His research interests include the climatology of precipitation and numerical modeling of precipitation

systems. Dr. Graves received his Ph.D. in Physics from Iowa State University in 1988.

James T. Moore was a Professor of Meteorology at Saint Louis University and taught synoptic and dynamic meteorology, severe local storms, and mesoscale dynamics. Sadly, Dr. Moore passed away in July of 2006. Dr. Moore was co-Principal Investigator of the Cooperative Institute for Precipitation Systems. His recent research interests included the initiation and propagation of mesoscale convective systems, precipitation efficiency of thunderstorms, and conditions favoring heavy banded snowfall in the central United States. Dr. Moore received his Ph.D. in Meteorology from Cornell University in 1979. He will be greatly missed.

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