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Forecasting Snowfall Amounts
An Ingredients-Based Methodology Supporting the Garcia Method

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ABSTRACT

The often difficult process of predicting accurate snowfall amounts is investigated in this paper by examining those physical ingredients which cause snowfall. Three commonly used operational snow amount forecasting techniques are evaluated: the Cook Method, the Magic Chart Method, and the Garcia Method. A verification study of these three techniques was performed, in which a case study approach was used to evaluate 40 snowstorm events which occurred in Kansas during three consecutive winters (1994 through 1997). The maximum snowfall totals for these events ranged from one to twelve inches. Each case was closely examined using observed data and NCEP model output to determine if the maximum snowfall amount could have been accurately forecasted 12 to 24 hours in advance using each of the three methods listed above. From this study, it was determined that the forecasting of snowfall amounts is largely a function of forecasting the ingredients which cause the snowfall, namely upward vertical motion in a given system, and the amount of water vapor available to that system to condense out. It will be shown that the success of using a snow amount forecasting technique is directly related to that technique's ability to account for the specific ingredients involved in a system. The results from this research indicate that the Garcia Method, which attempts to utilize the more important physical ingredients, can be a highly accurate and consistently reliable method of forecasting snowfall for many different types of snowstorms in the Great Plains. This paper also attempts to give some operational guidelines for analyzing and forecasting the necessary ingredients accurately. The ultimate goal of this paper is to improve the operational forecaster's skill in predicting snowfall amounts.

INTRODUCTION

Accurate predictions of snowfall amounts have long been a significant challenge to forecasting winter weather, and snow is one of the most frequent winter weather hazards. Although recent advancements in technology such as improved satellites and radar capabilities have helped forecasters decide how much snow will fall in the short term time frame of a few hours, there is still much room for improvement in our ability to accurately forecast snowfall in the 12 to 24 hour time frame and beyond. This study examines some of the more important physical processes responsible for the generation of snowfall accumulation, and discusses the prediction of snowfall based upon the forecasting of these processes. It will be shown that because the Garcia Method of forecasting snowfall amounts (Garcia 1994) incorporates many of these processes, it can be an excellent tool in aiding the forecaster in his or her snowfall forecast. To substantiate this claim, verification results of the Garcia Method will be compared to results from the Magic Chart Method (Sangster et al. 1985), and the Cook Method (Cook 1980), for 40 snowstorms which occurred in Kansas during three winters from 1994 to 1997. Hereafter, the Garcia Method, Magic Chart Method, and the Cook Method will be referred to as GM, MCM, and CM, respectively.

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Brief Review of Techniques

The CM was developed in 1980, and relates the magnitude of 200 hPa warm air advection to snowfall amounts. Approximately one-half of the value of the indicated warm air advection (°C) at 200 hPa is equal to the amount in inches of snowfall. This assumes warm air advection is also occurring at the 700 hPa level. If cold air advection is occurring at 700 hPa, one-quarter of the value is used. This technique carries limitations with it, the most restrictive being: should not use in spring and fall, a well-developed system is needed to generate the upper level warm and cold pockets, a surface low should be present, and northwest flow aloft may result in errors.

The MCM was developed in the middle to late 1980s. It uses the forecast of 850 hPa critical temperatures combined with the 12-hour net vertical displacement (NVD) of parcels arriving at 700 hPa (Reap 1992) to predict a snowfall amount. The NVD is derived from the NCEP trajectory model. Where the greatest NVD overlays the region between -3 °C and -5 °C at 850 hPa is where the heaviest snowfall is likely to occur. This method's assumptions are similar to the assumptions of the CM, in that developing upper and surface systems are necessary, and at least 90 percent mean relative humidity (RH) in the layer from 1000-500 hPa is required. An inherent limitation of this method is the temperature range between -3 °C and -5 °C, which makes this technique inappropriate in events involving an arctic air mass.

The GM is the newest of the techniques, having been developed in the late 1980s into the early 1990s, and formally published in 1994. The GM uses an empirical relationship between mixing ratios on isentropic surfaces and snowfall amount (note that values of specific humidity may also be used because the difference between values of mixing ratio and specific humidity are typically negligible). The technique examines the isentropic environment over the area of concern within the layer between 700 hPa and 750 hPa. The value of the mixing ratio (in gKg^{-1}) found on an isentropic surface over the area of concern that is within this critical layer at the onset of the event is added to the highest mixing ratio value that could be advected into the area of concern in the next 12 hours. The only assumption is that there must be some type of forcing mechanism to provide sufficient upward vertical motion. What makes this technique unique is that it is the only method that attempts to account for the quantity of moisture available to the system, not just the relative humidity. It is based on the simple principle that the amount of snow produced by a snowstorm is a function of the magnitude of water vapor which went into that snowstorm. Also, it is much less limiting in terms of the source of the forcing mechanism for upward vertical motion.

Please see the associated references for more detail on these methods.

Note on Model QPF

Although quantitative precipitation forecasts (QPF) from operational numerical weather prediction models are certainly an important part of a snow forecast, they are often unreliable. There are currently from six to eight operational models available to forecasters, each quite unique from the others. Thus they all have different QPF solutions, and too often no model accurately depicts the snow storm. Determining which model is best handling the atmosphere during the time of interest can itself be a difficult challenge. For a model to accurately forecast snowfall amounts, it must represent many atmospheric parameters including: thermal fields, moisture fields, horizontal advections, and vertical motions, just to name a few. Although the models are showing optimistic trends, there is still much room for improvement, especially in handling mesoscale features. Most models are undergoing frequent change and revision. Describing the processes involved, and the verification of, model QPF would be a monumental task. Therefore a more thorough discussion on model QPF is beyond the scope of this paper.

EXAMINATION OF THE NECESSARY INGREDIENTS FOR SNOWFALL ACCUMULATION

Doswell et al. (1996) thoroughly discuss the concept of how precipitation occurs using the simple equation

$$P=RD$$

where P is precipitation, R is precipitation rate, and D is the duration of the precipitation. The instantaneous precipitation rate at a particular point, R, is assumed to be proportional to the magnitude of the vertical moisture flux, wq, where w is the ascent rate and q is the mixing ratio of the rising air. However, not all the water vapor flowing into a cloud falls out as precipitation. Precipitation efficiency, E, is the coefficient of proportionality relating precipitation rate to input water flux, so that

$R = Ewq.$

Precipitation efficiency is defined as the ratio of the mass of water falling as precipitation, to the influx of water vapor mass into the cloud. See Doswell et al. (1996) for a more detailed discussion on this topic.

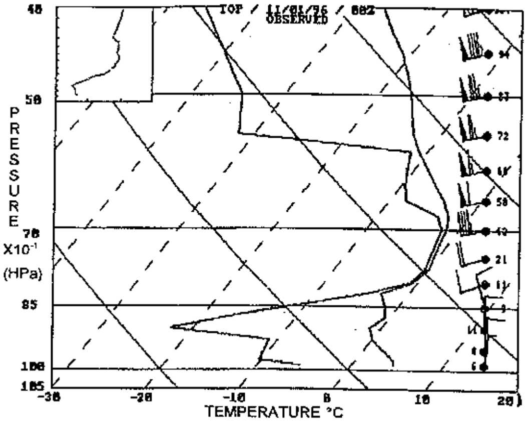

Figure 1. Skew-T thermodynamic diagram from 01, November, 1996, Topeka, Kansas. Temperature and dewpoint soundings. Note the dry layer from the surface up to 800 hPa.

Factors which might affect the precipitation efficiency of a snowstorm need to be taken into consideration by forecasters, especially when the low layers, say below 800 hPa, are very dry. Figure 1 shows a skew-T thermodynamic diagram from Topeka, Kansas observed 01 November 1996. This diagram shows the trace of temperature and dewpoint of the column of air above Topeka. Note the rather dry layer from the surface up to about 800 hPa. The forecast called for heavy snow in the 12 hours following this observation, however virga was reported for the first 4 hours, which resulted in a total snowfall of about one-half the expected amount. Had the airmass been saturated when the snow began to fall, several more inches may have accumulated.

When deriving a quantitative precipitation forecast, it has been suggested by Doswell et al. (1996) that the forecaster take an approach in which he or she considers those ingredients which are necessary for the production of heavy precipitation. This "ingredients-based methodology" can appropriately be applied to the challenge of forecasting snowfall amounts. A brief outline of some of the more important ingredients follows:

I. Column of air must be sufficiently cold
  A. Thickness parameters
    1. Ambient vertical profile
    2. Potential thermal advections
  B. Evaporative cooling
  C. Dynamical cooling
  D. Cooling due to melting
II. Snowfall Rate (R = Ewq)
  A. Moisture - q (mixing ratio)
    1. Ambient value
    2. Moisture advection
  B. Ascent Rate - w (lift)
    -numerous sources
    1. Synoptic scale
    2. Sub-synoptic scale
  C. Precipitation Efficiency - E
    1. Unsaturated low-mid layers
    2. Saturated low-mid layers
    3. Cloud physics - crystal formation
    4. Ratio of snow to liquid water
III. Snowfall Duration
  A. Speed of features
  B. Continuous redevelopment conditions
  C. Moisture availability
  D. Surface melting

Incorporating the Ingredients into the Forecast

Concerning the temperature of the column of air in which the precipitation is to fall through (I. above), no snowfall amount forecasting technique known to the authors makes a direct attempt to determine the possibility of a precipitation phase change. However, when examining 40 cases of snowfall, 61 percent of all heavy snow events involved some form of a precipitation phase change (see Fig. 2), emphasizing the point that forecasters must seriously consider this factor, or forecasted snowfall amounts may end up only being rainfall amounts.

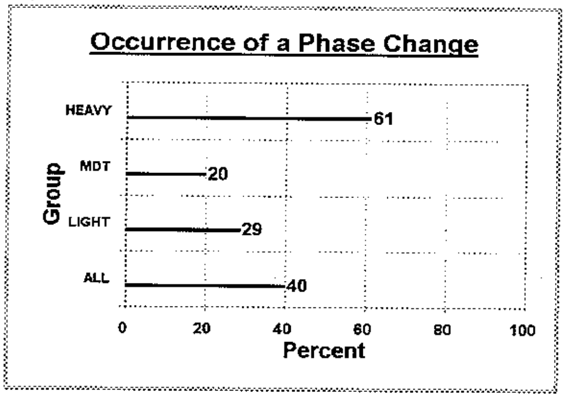

Figure 2. Occurrence of a phase change of 40 case studies sampled.

It is essential to analyze the "critical thickness" values in the 1000-850 hPa layer, the 1000-700 hPa layer, and the 850-700 hPa layer. An established rule of thumb says that for heavy snowfall to occur, the 1000-850 hPa thickness should normally be less than 1300 m. A thickness greater than this would allow too much melting of the crystals through the layer, which would normally create either rain at the surface, a mixture of rain and snow, or freezing rain if the surface was below 0 °C. According to a study by Hanks (1967), a 1000-700 hPa thickness value of around 2840 meters has been shown to effectively separate liquid precipitation from snow about 85 percent of the time. The preferred thickness values for the 850-700 hPa layer ranges from 1520 to 1540 meters. This, in addition to viewing the nearest observed upper air temperature sounding taken from balloon measurements, will give good approximations of the ambient vertical thermal profile. Forecast soundings from models can aid in determining the future temperature of the column over the area of concern.

Forecasters must also consider less obvious factors, such as evaporative cooling, dynamical cooling, and cooling due to melting. Evaporative cooling needs close attention especially when very dry air is near the surface with wet-bulb temperatures at or below freezing. Dynamical cooling is common with shortwaves involving high vorticity or strong isentropic lift, or in any situation which values of omega are high. The air is adiabatically cooled as it rises, thus cooling the column. In areas of heavier precipitation, cooling due to melting may be observed. Heat is being taken from the air because the air is warmer than the ice.

One factor which makes the GM a superior technique for predicting snowfall is that it is the only method which directly incorporates the quantitative amount of moisture a system has to work with (related to II. A. above). In an idealized hypothetical example, it is logical to conclude that the amount of moisture falling out of a system (ie, snowfall) is directly proportional to the amount of moisture going into that system (ie, water vapor). This unique function of the GM ties it to a closer approximation of the output of any snowstorm. When applying the technique, both the value of the mixing ratio over the area of concern and the value of the mixing ratio which could be advected into the area of concern are used to derive an empirical value of snowfall amount.

The technique is appropriately vague in regard to the ascent rate, because in many cases this is a function of an extremely complex variety of mechanisms and processes, especially those which are sub-synoptic in scale. Our study specifically examined ten atmospheric features which can act as "lifting mechanisms" to help the air ascend (see Table 1). An interesting find was the importance of frontogenetical forcing, (Keyser et al. 1992), which was active in 90 percent of all cases (see Fig. 3). In 60 percent of the heavy snow cases, conditional symmetric instability (Snook 1992) was indicated (see Fig. 4). Garcia (1994) points out the importance of isentropic lift, which was active in 95 percent of the heavy snow cases (see Fig. 4).

The prediction of these features is left to the judgment of the forecaster, which is much more consistent with quality operational forecasting than that of relying on model-produced empirical values or indices (Doswell et al. 1996). This points to the importance of being able to recognize and forecast the potential for such sub-synoptic scale features and processes, as well as the available water vapor, in order to achieve a high percentage of accurate snow amount forecasts. Thus an important consideration of the GM is estimating those features contributing to the magnitude of the ascent rate (II. B. above).

Concerning II. C. above, precipitation efficiency (*E*), many factors can contribute to the precipitation efficiency of a snowstorm. As illustrated earlier, if the temperature of the air at the level of maximum vertical motion is such that dendritic crystal formation takes place, the snowflakes will be larger and more efficient in increasing the rate of accumulation (Auer 1987). If the column is very cold, the snow to liquid water ratio will be higher, thus resulting in a greater snow depth. However if the surface is warmer than 1 °C (33 °F), the accumulating snow will be wet and slushy, thus limiting the accumulation. These are all important factors to consider when forecasting snowfall, and should be determined before attempting to predict a snowfall amount, regardless of the technique used.

Unlike the CM and MCM, the GM is sensitive to the fact that the life of a snowstorm can span from just a few hours to a few days (III. above). Although the average duration for all 40 events was 13.4 hours, a wide variation of durations was noted, ranging from 5 to 45 hours (see Fig. 5). The GM was designed around a 12 hour snow event, thus the 13.4 hours is convenient. The GM includes a simple adjustment which can be made when the snowfall is expected to last more or less than 12 hours. If the event is expected to last more than 12 hours, the cycle can be recomputed to account for the longer period. If the event is to last less than 12 hours, the amounts can be cut back accordingly.

Table 1. Description of Each Lifting Mechanism

Mechanism	Description
A	convective instability (can lead to thundersnow)
B	conditional symmetric instability (narrow bands of heavy snow)
C	up-slope flow (orographic induced motions)
D	warm air advection at 700 hPa (typically "over-running" lift
E	upper level divergence (typically near jet stream)
F	isentropic lift
G	low pressure system at the surface
H	frontogenetical forcing as seen through converging Q_n vectors
I	differential positive vorticity advection
J	500 hPa trof of low pressure (short-wave)

METHODOLOGY OF VERIFICATION STUDY

To test the validity of the ingredients-based methodology forecasting approach of the GM, its performance was compared to the performance of the MCM and the CM for 40 snowstorms which occurred in Kansas during the three winters from 1994 through 1997. The maximum snowfall amounts from these storms ranged from 2.6 cm to 30.8 cm (1 to 12 inches). The events were separated into three categories: light (5.1 cm or less, or 2 inches or less), moderate (5.4 to 15.1 cm, or 2.1 to 5.9 inches), and heavy (15.4 cm or greater, or 6 inches or greater). The maximum observed snowfall for each event was compared to the 24-hour forecasted snowfall from each of the methods. While each event was verified by using the methodology of the three techniques, several events did not meet the ideal criteria of the MCM or CM, as stated in the respective papers (Chaston 1989 and Cook 1980). The maximum snowfall for each storm was obtained from Kansas snow summaries containing official observations and cooperative observer reports. As with most verification studies, some difficulty was encountered in determining the maximum amount due to the inconsistency in measuring techniques and reporting guidelines

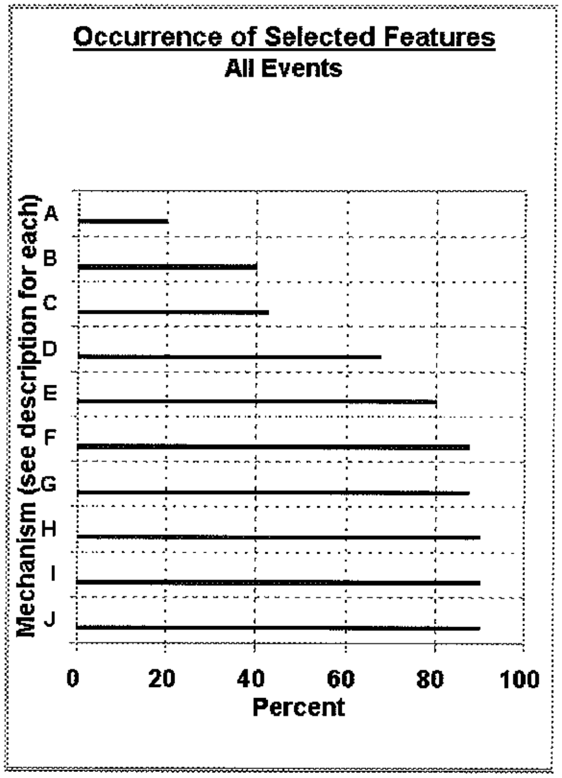

Figure 3. The percentage of occurrence of ten lifting mechanisms for all 40 events. See Table 1 for description of each mechanism.

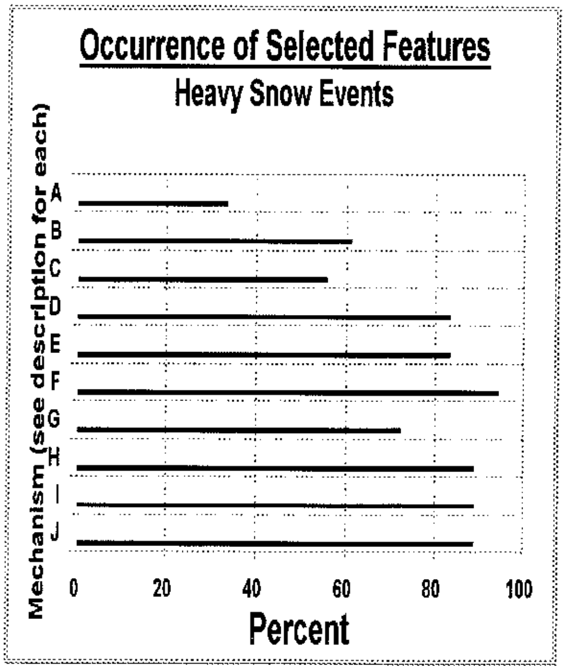

Figure 4. Same as figure 3 except for heavy snow events.

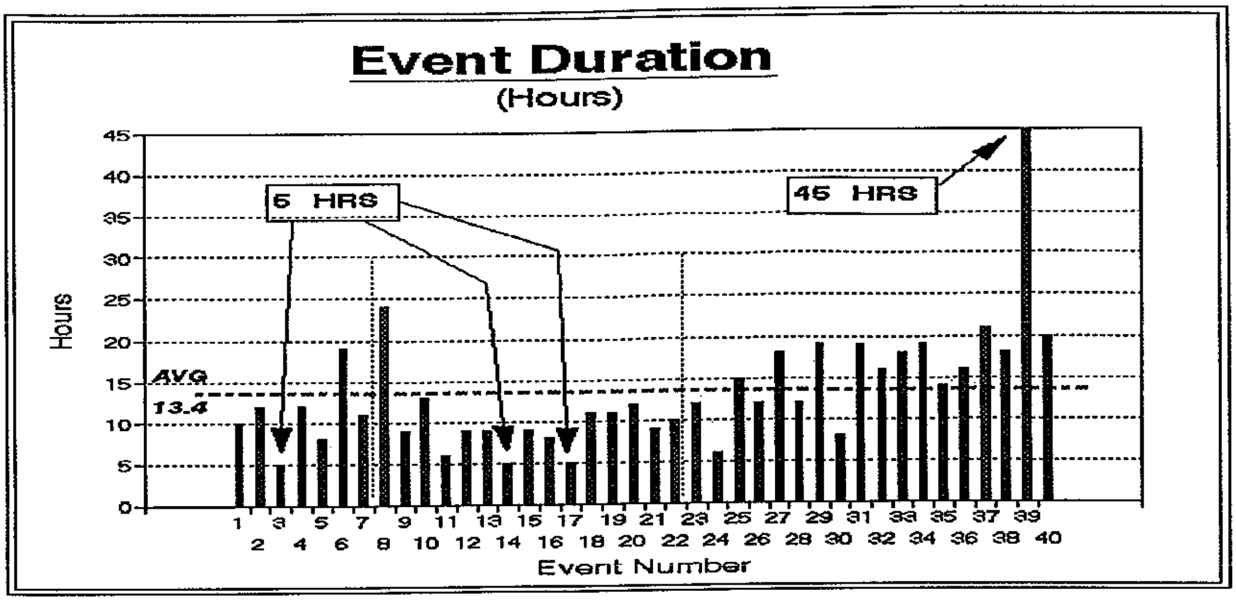

Figure 5. Duration of each event in hours.

between cooperative observers and official observation locations.

Physical characteristics and precipitation producing mechanisms of each storm were thoroughly analyzed using gridded model output, primarily from the Eta and NGM, as well as AFOS trajectory model charts and observed surface and upper air data. To simulate real forecast conditions, an effort was made to recreate an operational setting as much as possible.

Verification Results of the Methods

It can be seen in Figure 6 that the mean absolute error for all 40 events was the lowest for the GM, followed by the MCM and the CM, respectively. This was especially true for the heavy snowfall events where the GM, MCM, and CM produced mean absolute errors of 3.6 cm (1.4 inches), 9.2 cm (3.6 inches), and 14.4 cm (5.6 inches) respectively. The performance was similar for the moderate snow events, and throughout the heavy and moderate snow events the CM and MCM showed a strong bias to underforecast the snowfall amount. For the light events the mean absolute error was the largest for the GM, with a value of 5.1 cm (2.0 inches), followed by the CM and MCM with 3.3 cm (1.3 inches) and 2.3 cm (0.9 inches) respectively.

Caution must be used however with these values in regard to light snow events. For example, any snowfall method which always predicted no snowfall compared to a maximum observed amount of one inch would have a small average error. For six out of the seven light snow events, the assumptions of the MCM were not met, and as a result, in four of the seven cases it indicated either no snowfall or a negative value of snowfall. To a lesser extent, this was also the case with the CM. Because the GM has very few restrictions or assumptions to its application, it was appropriate to use in all cases.

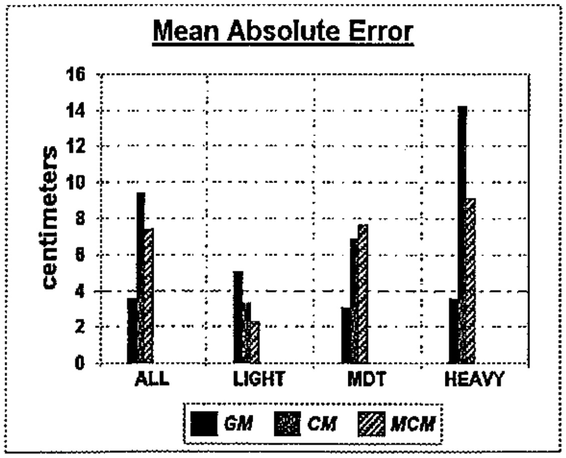

Figure 6. Mean absolute error (in cm) for the GM, CM, and MCM.

It is significant that the GM was off by an average of 5.1 cm (2.0 inches) for the light snow events, and always over forecasted the snowfall. When comparing the maximum observed snowfall amount to the GM's forecasted snowfall amount for each case, on average the GM predicted 2.3 times the observed snowfall amount. This statistic highlights the need for an adjustment to the technique in cases of weak vertical forcing, as noted in Garcia (1994). It appears that when the forcing is too weak to efficiently condense out all of the water vapor available to the system, only about half of the potential snowfall is realized. Garcia (1994) suggests that in these cases it is best to only use the ambient mixing ratio value over the area of concern, and do not advect in additional moisture. This will typically result in more accurate snowfall amount forecasts for light snowfall events.

SUMMARY

In an effort to improve the forecaster's ability to predict snowfall amounts, it was suggested that the forecaster approach the challenge using an ingredients-based methodology. This approach should result in a more thorough understanding of the significant atmospheric processes at work, which would allow the forecaster to consider synoptic and sub-synoptic scale features, and the quantitative amount of water vapor available to these features. This methodology can yield a good approximation of the expected snowfall rate, which is one of the main ingredients involved in the accumulation of snowfall.

The GM directly considers this snowfall rate ingredient, as well as another important ingredient which is the duration of the snowfall. Because of this, it has a better physical representation of the atmosphere of a snowstorm than either the CM or the MCM. Review the outline presented earlier showing the physical ingredients necessary for snow accumulation, and note the items in bold italics which the GM, at least indirectly, takes into account:

I. Column of air must be sufficiently cold
    A. Thickness parameters
        1. Ambient vertical profile
        2. Potential thermal advections
    B. Evaporative cooling
    C. Dynamical cooling
    D. Cooling due to melting
II. Snowfall Rate (R = Ewq)
    A. Moisture - q (mixing ratio)
        1. Ambient value
        2. Moisture advection
    B. Ascent Rate - w (lift)
    -numerous sources
        1. Synoptic scale
        2. Sub-synoptic scale
    C. Precipitation Efficiency - E
        1. Unsaturated low-mid layers
        2. Saturated low-mid layers
        3. Cloud physics - crystal formation
        4. Ratio of snow to liquid water
III. Snowfall Duration
    A. Speed of features
    B. Continuous redevelopment conditions
    C. Moisture availability
    D. Surface melting

Both the CM and the MCM were designed with the assumption that a developed extra-tropical cyclone is responsible for generating the snow, and thus these two methods were not appropriate to use with many of the atypical snowstorm scenarios in this study. The GM was designed with few assumptions or limitations, thus it can be appropriately applied to nearly any snowstorm scenario which could effect the Kansas region. This explains the more accurate verification of the GM over the CM and MCM for a sample of 40 snowstorm events examined in Kansas. In the case of a low ascent rate, or weak vertical forcing, it is important to follow Garcia's recommendation (Garcia 1994), of only using the amount of water vapor over the area of concern at the beginning of the snowfall, and not advect any additional moisture into the area.

A much more comprehensive and thorough paper describing the results of this study and the ingredients-based methodology is planned for the future, in which the authors will also discuss correlations between various forcing mechanisms and resultant snowfalls.

ACKNOWLEDGMENTS

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