FORECASTING TECHNIQUE

An Operational Ingredients-Based Methodology for Forecasting Midlatitude Winter Season Precipitation

SUZANNE W. WETZEL* AND JONATHAN E. MARTIN

Department of Atmospheric and Oceanic Sciences, University of Wisconsin—Madison, Madison, Wisconsin

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ABSTRACT

An ingredients-based methodology (IM) for the operational analysis and prediction of midlatitude winter season precipitation is developed. Diagnostics for five fundamental physical ingredients involved in the production of precipitation—forcing for ascent, moisture, instability, precipitation efficiency, and temperature—are incorporated into the IM. The forcing ingredient is combined with the instability ingredient to form a new parameter, PVQ, that serves as an indicator of heavy precipitation potential by identifying regions where these two ingredients coexist. The diagnostics and PVQ are incorporated into ingredients maps that facilitate a systematic approach to forecasting the duration, intensity, and type of winter precipitation.

1. Introduction

Significant technological advances have occurred over the past decade in National Weather Service Weather Forecast Offices (NWS WFOs) that have facilitated the analysis of gridded fields of observations and model forecast data. Developments in forecasting winter season precipitation have not paralleled these technological advances partly because of considerable reliance on empirically derived rules of thumb. Some of the techniques for predicting snowfall accumulations were developed prior to the availability of sophisticated gridded analysis programs, and generate 12- or 24-h forecasts by simply extrapolating current observations or numerical model forecasts of synoptic variables (e.g., 200-hPa temperature, 500-hPa vorticity, or 700-hPa mixing ratio). Basing forecasts on extrapolation, rarely very satisfactory beyond the 3–6-h range, is now unnecessary given the analysis and diagnostic tools available. In the modern era, the fundamental elements, or ingredients, involved in a winter precipitation event can be identified and analyzed using numerical model or observational datasets. While the value of such analyses is limited by the quality of the objective analysis (for observational data) or the skill of the numerical forecast, such an ingredients-based analysis allows a prediction to focus on the physical processes involved, thus enabling the unique conditions characteristic of each event to be incorporated into the forecast. In contrast, empirically derived rules of thumb are generally based on specific conditions, and the reliability of the techniques diminishes as actual conditions vary from the canonical scenarios.

An ingredients-based methodology (IM) is developed here as an operational tool for the analysis and prediction of winter precipitation events. The IM provides a systematic approach to forecasting winter weather by establishing a framework for interpreting numerical forecast model output and observations. The five key ingredients for a winter precipitation event diagnosed by the technique presented here are quasigeostrophic forcing for ascent, moisture, instability (i.e., gravitational, inertial, or slantwise instability), precipitation efficiency (specifically, cloud microphysical properties), and temperature.

Section 2 provides a general introduction to the IM for winter weather forecasting, including a brief history of the ingredients-based methodology, a discussion of our definition of an ingredient, and a rationale for the chosen ingredients. Section 3 presents the parameters employed in the diagnosis of each of the five ingredients and discusses the application of the IM to forecasting winter season precipitation. The method is applied to the analysis of a case of heavy convective snow in southern Wisconsin in section 4. The results are discussed in section 5 where we offer some conclusions.

* Current affiliation: Cooperative Institute for Meteorological Satellite Studies (CIMMS), University of Wisconsin—Madison, Madison, Wisconsin.

Corresponding author address: Dr. Jonathan E. Martin, Department of Atmospheric and Oceanic Sciences, University of Wisconsin—Madison, 1225 W. Dayton Street, Madison, WI 53706.
E-mail: jon@meteor.wisc.edu

2. Background

a. History

An ingredients-based forecast methodology has been employed operationally for more than two decades in the context of warm-season convective weather. It was originally developed to forecast the initiation of deep moist convection associated with warm-season thunderstorms (McNulty 1978, 1995; Doswell 1987; Johns and Doswell 1992). This methodology included three ingredients—instability, moisture, and lift—and looked for all three to be present in order for deep moist convection to occur. More recently, Doswell et al. (1996) proposed an ingredients basis for the prediction of rainfall associated with flash floods. Starting with the premise that heavy precipitation is the result of sustained high rainfall rates, which are a direct consequence of the rapid ascent of moist air, the authors qualitatively predicted the instantaneous rainfall rate (R) by assuming that it is proportional to the vertical flux of moisture. This notion is formalized in the relationship, $R = Ewq$, where precipitation efficiency (E), ascent rate (w), and mixing ratio (q) constitute three ingredients in this approach. Precipitation efficiency serves as the constant of proportionality and is defined as the ratio of the mass of water falling as precipitation to the influx of water vapor mass into the cloud. Using a fourth ingredient, precipitation duration (t_duration) and estimates of rainfall rate R, they predicted total precipitation (P) as $P = R \cdot$ t_duration.

Nietfeld and Kennedy (1998) adjusted the approach of Doswell et al. (1996) for application in forecasting snowfall amounts. They proposed air temperature, snowfall rate, and snowfall duration as the three ingredients in a snow event. The snowfall rate (R) ingredient is further described, following Doswell et al. (1996), as $R = Ewq$, where q includes the mixing ratio anticipated by moisture advection. The ascent rate w is diagnosed by considering the synoptic- and subsynoptic-scale mechanisms for lift, and efficiency, E, describes the degree of saturation of the air mass, cloud physics pertaining to snowflake formation, and the ratio of snow to liquid water. Although Nietfeld and Kennedy (1998) use the ingredients terminology, their approach was essentially designed to serve as a conceptual model and was not developed to have operational utility.

Janish et al. (1996) developed a similar ingredients-based approach to diagnosing the areal distribution of precipitation *type* for application in an operational environment. This approach uses winter weather composite charts to combine hand analyses of three variables (moisture, temperature profile, and vertical motion) onto a single map. Their method provides useful guidance for short-term forecasts of precipitation type. Consideration of similar maps constructed using numerical forecast output of the three central variables was suggested as a means of making longer-range forecasts of precipitation type. The present study expands upon the concepts in Janish et al. (1996). The IM presented here includes more of the physically relevant elements involved in a winter precipitation event (i.e., precipitation duration and intensity) and thus provides for more comprehensive forecast guidance.

b. Definition and choice of ingredients

The IM presented in this paper is based on a stricter definition of ingredient than that employed in previous studies. Here, an ingredient is defined as a fundamental physical element or process that directly contributes to the development and intensity of a precipitation event. This definition excludes intermediate parameters such as precipitation rate and duration that, though important in the prediction of a precipitation event, are dependent on more elementary physical ingredients. Such intermediate parameters do not lend themselves to use in a physically based forecast that can be easily tailored to event-specific conditions.

Use of duration as an ingredient in the manner of Doswell et al. (1996) and Nietfeld and Kennedy (1998) implicitly assumes that the precipitation rate will remain constant throughout the duration of the event. Instead, using the definition of an ingredient employed here, the storm duration itself can be assessed through an evaluation of the selected ingredients throughout the forecast time period. If the necessary ingredients are expected to be present at a given forecast hour, then precipitation can reasonably be expected at that time. If an important ingredient is not expected to be present at the next forecast hour, precipitation is unlikely to occur at that hour. Such an evaluation can be made at successive forecast hours to render a duration forecast for a given station.

The approach presented here also makes a clear distinction between ingredient and diagnostic. Ingredients are the physical elements or processes directly involved in a meteorological event, while diagnostics are the observable or derived quantities that can be used to assess the presence and strength of an ingredient. Previous work has often blurred this distinction, as illustrated by the use of the mixing ratio as an ingredient by Doswell et al. (1996) and Nietfeld and Kennedy (1998). Mixing ratio is actually only one of a number of parameters that can be used to quantify the moisture availability and, thus, is more appropriately considered a diagnostic of the moisture ingredient. In the IM for forecasting winter season precipitation presented here, parameters will be introduced to diagnose each ingredient; however, the IM is not dependent on these specific diagnostics. Because this IM is based upon physical elements and processes, it has the flexibility to incorporate new diagnostics of the fundamental ingredients as theoretical and technological advances make them available.

Justification for our choice of ingredients follows directly from the argument that in order to produce precipitation, some mechanism to force ascent (ingredient 1) in a region with sufficient moisture availability (in-

TABLE 1. Ingredients included in traditional snow amount forecast techniques. See text for explanation.

	Synoptic climatology	Cook	Garcia	Magic chart	LEMO
Forcing for ascent	No	No	LtF	Yes	No
Moisture	No	No	Yes	LtF	No
Instability	No	No	No	No	No
Efficiency	No	No	No	No	No
Temperature	No	Yes	No	Yes	No

gredient 2) is required. The intensity of the ensuing precipitation can be modulated by the presence of instability (ingredient 3) and the precipitation efficiency (ingredient 4). Finally, the precipitation type (particularly relevant in winter) is related to the temperature profile (ingredient 5). A forecast using this methodology involves evaluating each ingredient at various levels in the atmosphere for every forecast hour for which gridded data are available, to determine which ingredients are present over the forecast area.

The first, second, and fourth ingredients are similar to ingredients used by Nietfeld and Kennedy (1998). The fifth ingredient was implicit in their study, which considered only snow events. The third ingredient, however, has not been widely or rigorously considered as an ingredient for winter season precipitation. This omission has occurred partly because instability is not a *necessary* ingredient for precipitation production, though its presence can significantly amplify the response of an air column to forcing for vertical motion. Also, until recently, convenient diagnostics for identifying instability were not readily available to operational forecasters.

c. *Traditional forecast techniques from an ingredients perspective*

Traditional techniques used for forecasting winter precipitation events are largely empirical relationships established from observations of consistent patterns in the development of weather systems. The abundance of observational evidence on which these techniques are based vests them with a degree of prognostic accuracy in similarly configured synoptic situations. However, in many cases, these techniques fail to provide accurate forecasts.

Some techniques used in operational forecasting at NWS WFOs include the synoptic climatology method (Goree and Younkin 1966; Browne and Younkin 1970), the Cook method (Cook 1980), the Garcia method (Garcia 1994), the magic chart (Sangster and Jagler 1985; Chaston 1989), and the LEMO technique (Gordon 1998). A review of these traditional techniques is given in Wetzel (2000) and will not be presented here. Table 1 identifies the fundamental ingredients that are explicitly considered in these empirical methods. Some techniques do not directly include an ingredient, but acknowledge its importance by instructing the forecaster to consider it independently (indicated in Table 1 as LtF, for left to forecaster). As shown in Table 1, no technique considers more than two ingredients. Also of note is that the important instability ingredient is a commonly overlooked element in these traditional forecasting techniques.

TABLE 2. Classification of Q-vector forcing.

$\nabla \cdot \mathbf{Q}$ (km^{-2} s^{-1} $\times$ 10^{-15})	Classification
-1 to -5	Weak forcing
-5 to -15	Moderate forcing
<-15	Strong forcing

3. Ingredient diagnostics

In this section, the diagnostic parameters used to describe the fundamental ingredients are presented and a rationale for each choice is given. We begin with a discussion of the forcing for ascent ingredient.

a. *Forcing for ascent*

Diagnosis of quasigeostrophic (QG) forcing for vertical motion can be obtained using the Q-vector form of the adiabatic and inviscid QG-omega equation (Hoskins et al. 1978):

$$\left(\sigma\nabla^2 + f^2\frac{\partial^2}{\partial p^2}\right)\omega = -2\nabla \cdot \mathbf{Q}, \qquad (1)$$

where $\mathbf{Q} = [-(\partial \mathbf{V}_g/\partial x) \cdot \nabla(-\partial\phi/\partial p)\hat{\mathbf{i}},\ -\partial \mathbf{V}_g/\partial y \cdot \nabla(-\partial\phi/\partial p)\hat{\mathbf{j}}]$, ϕ is the geopotential, and $\omega = dp/dt$.

Use of the Q vector to calculate the synoptic-scale forcing for vertical motion is now a widespread practice in operational environments. Recognizing that the forcing, $\nabla \cdot \mathbf{Q}$, and the response, ω, are related by the pseudo-Laplacian operator, (1) provides a means of making a qualitative estimate of the vertical motion. Convergence (divergence) of the Q-vector corresponds to a negative (positive) ω and thus forcing for upward (downward) vertical motion. Therefore, isobaric contours of $\nabla \cdot \mathbf{Q}$ computed at a number of levels, in conjunction with a cross-sectional analysis, provide a qualitative estimate of the direction and magnitude of the vertical motion throughout the atmosphere.

Based on an evaluation of a number of case studies, a general classification for describing the magnitude of the QG forcing has been developed and is shown in Table 2. These ranges are only intended to provide a consistent terminology for discussing the strength of QG forcing for ascent in the context of the IM and should not be interpreted as predictions of the resulting upward vertical motion. As revealed in (1), quantifying only the QG forcing for ascent neglects the modulation of omega controlled by the static stability (σ). Useful operational estimates of the upward vertical motions associated with a given Q-vector convergence must include consideration of the stability of the stratification.

It is also important to remember that use of the Q-vector diagnostic as the sole means of representing vertical motion forcing does impose limits on the analysis. No accommodation for the role of non-QG motions in modulating the observed vertical motions is made in the approach presented in this paper. Such effects may be particularly significant in the vicinity of frontal zones or jet streaks where the strength of the secondary ageostrophic circulation can be underrepresented by QG theory.

b. Instability

The stability parameter σ in (1) considers only gravitational stability and does not identify regions of symmetric instabilities. In order to allow for consideration of this important type of instability, saturated geostrophic equivalent potential vorticity, PV_{es}, is used in the IM to diagnose the instability ingredient, where PV_{es} is defined by

$$PV_{es} = -g\zeta_{geo} \cdot \nabla\theta_{es}, \tag{2}$$

where ζ_{geo} is the 3D geostrophic absolute vorticity vector and θ_{es} is the saturated equivalent potential temperature. By choosing to use PV_{es} rather than PV_e, only conditional gravitational (CI) and conditional symmetric instabilities (CSI) are considered, rather than potential gravitational and potential symmetric instabilities. Where PV_{es} is negative, CI exists if $-\partial\theta_{es}/\partial p < 0$ and CSI exists if $-\partial\theta_{es}/\partial p > 0$ and the flow is two-dimensional. Both CI and CSI are measures of the susceptibility of the atmosphere to moist gravitational and moist symmetric convection, not indicators of the existence of such convection (Schultz and Schumacher 1999). Thus, for the instability to be realized and convection to occur, saturation must be present locally and a mechanism to force an infinitesimal upward vertical motion must also exist. Operationally, it is important to distinguish between gravitational and symmetric instabilities only insofar as the atmosphere may respond differently to each type of instability with respect to the organization of precipitation bands. However, this distinction is not emphasized in the IM because both instability mechanisms have similar implications, namely increased snowfall amounts and the potential for lightning and thunder. Instead, the IM focuses on identifying regions of instability, with the understanding that only further analysis of cross sections can determine whether a vertical or slantwise response can be expected.

It would be useful to derive a relationship between $\nabla \cdot \mathbf{Q}$, PV_{es}, and ω to provide quantitative estimates of the vertical motion; however, this derivation is beyond the scope of the current paper. Instead, regions where enhanced vertical motions might be expected are identified based on the collocation of forcing for ascent and instability. Since both $\nabla \cdot \mathbf{Q} < 0$ (associated with upward vertical motion) and negative PV_{es} (associated with conditional instabilities) are indicative of a strong precipitation potential, regions with large positive values of the product $[(PV_{es})(\nabla \cdot \mathbf{Q})]$, computed where both terms are negative, have a strong likelihood for experiencing extreme precipitation events provided that sufficient moisture is available. Here, a new diagnostic parameter, PVQ, is introduced to capture this effect. PVQ is defined as

$$PVQ = \begin{cases} (PV_{es})(\nabla \cdot \mathbf{Q}) & \text{for negative } PV_{es} \text{ and negative } \nabla \cdot \mathbf{Q} \\ 0 & \text{for positive } PV_{es} \text{ and/or positive } \nabla \cdot \mathbf{Q} \end{cases} \tag{3}$$

and is computed as

$$PVQ = \left(\frac{PV_{es} - |PV_{es}|}{2}\right)\left(\frac{\nabla \cdot \mathbf{Q} - |\nabla \cdot \mathbf{Q}|}{2}\right). \tag{4}$$

Where PVQ is nonzero, there is forcing for ascent in the presence of instability, and strong upward vertical motion can reasonably be anticipated. Because the two quantities $\nabla \cdot \mathbf{Q}$ and PV_{es} span a different range of values, the absolute magnitude of the quantity PVQ may be more sensitive to one than the other. Thus, we employ PVQ only as an indicator of the potential for convective precipitation without regard to its absolute magnitude. It is important to remember that PV_{es} need not be negative for significant precipitation to fall. In fact, heavy snow often occurs when sufficient moisture and strong forcing are present in a stably stratified atmosphere. *Therefore, contours of PVQ should only be used to identify areas of potentially convective snowfall.*

c. Moisture

Precipitation will not be produced in a dry atmosphere even in the presence of strong forcing and instability. Given ample moisture,[1] however, even very weak forcing can be sufficient to generate precipitation. Thus, an evaluation of available moisture should be included in any scheme developed to forecast precipitation.

There are a variety of ways to assess the moisture availability in a system and the traditional techniques mentioned previously all consider moisture availability differently. The evaluation of moisture availability in this work first involves the inspection of relative humidity at a number of levels throughout the lower and middle troposphere to measure the degree of saturation. After determining the degree of saturation, the available moisture is quantified in terms of the mixing ratio in

[1] Relative humidity greater than 80% generally indicates sufficient moisture to generate at least some precipitation, provided a vertical motion forcing mechanism is in place.

TABLE 3. Summary of ingredients and diagnostics for forecasting winter season precipitation.

Ingredient	Diagnostic	Critical values
Forcing	$\nabla \cdot \mathbf{Q}$ (km^{-2} s^{-1} $\times$ 10^{-15})	−1 to −5 → weak forcing, −5 to −15 → moderating forcing, <−15 → strong forcing
Moisture	Relative humidity mixing ratio	>80%
Stability	PV_{es}	<0 for instability (CI or CSI)
Efficiency	Cloud-level temperature	Maximum depositional growth at −15°C; ice crystal nucleation at −10° to −15°C
Temperature	850-hPa T wet-bulb temperature cross section	0° to −4°C rain/snow transition region

order to provide information about the absolute moisture content.

d. *Efficiency*

An analysis of the efficiency ingredient is included in the IM by inspection of temperature at each isobaric level and on cross sections in order to 1) assess the likelihood of ice nucleation and 2) anticipate enhanced precipitation rates associated with rapid snowflake growth. Due to the presence of multiple types of ice nuclei (IN) in a cloud, the variation of initiation temperature with ambient relative humidity, and surface characteristics of the IN, assigning a precise value to the temperature at which ice nucleation is initiated is difficult. Instead, guidelines determined by statistical studies are used to identify a range of temperatures for which ice nucleation can be expected. Based on the results of a number of studies (e.g., Borovikov et al. 1963; Mossop 1970), D. A. Baumgardt (1999, personal communication) concluded that −12° to −14°C should be considered the minimum range for a high likelihood of ice being in a cloud, and offered −10°C as the operational cutoff point for no ice. This component of the efficiency analysis is best performed using satellite-derived cloud-top temperature data and inspection of soundings during the event. However, forecasts of temperature on isobaric surfaces and cross sections can provide a reasonable estimate of the likelihood that ice will be initiated in an event.

After initiation, the growth rate by deposition is greater at colder temperatures, with a maximum around −15°C (Rogers and Yau 1989). Growth by aggregation generally occurs when temperatures are warmer than −10°C and once snowflakes have grown large enough to begin to fall. Using model-predicted temperature, the likelihood of snowflake growth can be assessed in the IM by evaluating whether an area of strong forcing for ascent coincides with a region of maximum depositional growth (temperature approximately −15°C). In this situation, heavy precipitation is possible provided sufficient moisture is present (Auer and White 1982).

e. *Temperature*

An analysis of the temperature ingredient in a winter season midlatitude cyclone addresses the issue of whether the precipitation will fall as rain, snow, ice pellets, or freezing rain. Isobaric and cross-sectional analyses of model-predicted temperature and moisture fields can be used to forecast precipitation type well in advance of an event; however, an accurate forecast of precipitation type ultimately requires the careful monitoring of observed temperature and moisture profiles as the storm develops.

In the IM, the temperature ingredient diagnostics include isobaric maps of forecasted temperature and cross sections of wet-bulb temperature. If the cross section indicates that the wet-bulb temperature remains everywhere below zero, the precipitation will remain frozen and fall as snow. For an atmosphere with a monotonically decreasing temperature profile, the 850 hPa −4°C to 0°C isotherm band corresponds to the region of precipitation type transition as suggested by McNulty (1988). Locations corresponding to an 850-hPa temperature cooler than −4°C have a high likelihood of snow, while those with an 850-hPa temperature warmer than 0°C have a high likelihood of rain.

For conditions characterized by a layer with $T > 0$°C sitting atop a layer with $T < 0$°C (an elevated warm layer), the potential exists for freezing rain or sleet/ice pellets. A cross-sectional analysis of the forecasted maximum warm layer temperature and the depth of the warm layer facilitates a determination of the degree of melting and, thus, the precipitation type (Stewart and King 1987; Czys et al. 1996). Operational guidelines adapted from Stewart and King (1987) by D. A. Baumgardt (1999, personal communication) predict complete melting of a snowflake if it encounters a maximum warm layer temperature of 3°–4°C or greater, partial melting for $T =$ 1°–3°C, and very little melting for $T < 1$°C.[2]

f. *Ingredients maps*

Table 3 summarizes the diagnostics that are employed for evaluating each of the fundamental ingredients involved in the IM. These diagnostics are combined in this section into isobaric ingredients maps and ingre-

[2] Because the depth of the warm layer is generally proportional to the maximum warm layer temperature, this simplification has proven to be a good diagnostic for determining the degree of melting (D.A. Baumgardt 1999, personal communication).

dients cross sections. The ingredients maps facilitate the use of the IM to forecast winter season precipitation by displaying all ingredient diagnostics together in a convenient manner.

The IM was in operation during the 1999/2000 winter season at several NWS WFOs in the central United States.[3] Through an analysis of the ingredients and the derivative PVQ on a number of pressure surfaces and cross sections, the ingredients-based approach facilitates consideration of the following questions:

- When will precipitation begin? When will it end?
- What will be the intensity for each 6-h period during which precipitation occurs? Are potentially higher intensities possible or expected in the forecast area as a result of the presence of areas of instability or locally stronger forcing?
- What will be the areal extent of the precipitation?
- What form will the precipitation take?

Though the analysis of the ingredients maps requires considerable subjective judgment, certain guidelines have been found to apply in most situations. With sufficient moisture and no instability, weak, moderate, and strong forcing for ascent will generally correspond to light, moderate, and heavy precipitation, respectively. However, the intensity of precipitation will be greater in the presence of instability and weaker when small amounts of moisture are available. Instability at any level with ample moisture and at least weak forcing can result in heavy precipitation, possibly accompanied by thunder and lightning. Additionally, the depth of the moist layer may have a significant impact on the intensity of the precipitation.

4. Case example of the use of ingredients maps

Experience has shown that the application of the IM for three thin layers in the lower to midtroposphere (800–850, 700–750, and 600–650 hPa)[4] often adequately captures the relevant distribution of the ingredient parameters. However, there may be features of consequence that lie between these layers and are therefore not captured by such an analysis. Such features can often be identified by evaluation of the ingredients in a vertical cross section, what we term ingredients cross sections. In this section an example of the use of isobaric and cross-section ingredients maps in diagnosing a late January winter season precipitation event in Wisconsin is presented.[5] It should be noted that the structure and evolution of this cyclone were well forecasted by the National Centers for Environmental Prediction (NCEP) Eta Model.

a. *Isobaric ingredients maps*

Figure 1 is the 800–850-hPa layer ingredients map for the 24-h NCEP Eta Model forecast valid at 0000 UTC 27 January 1996. In Fig. 1a, a well-developed midlatitude cyclone is centered just south of the Wisconsin–Illinois border. Though the sea level pressure field does not portray one of the ingredients, it does provide a useful reference for relating synoptic-scale features to the ingredients diagnostics.

An ingredients-based forecast begins with an evaluation of the *precipitation onset and duration.* If an area of vertical motion forcing coincides with relative humidity values of 80% or greater, some precipitation is likely. The onset of precipitation occurs when this collocation of forcing and available moisture first occurs over a forecast area. In the example presented here, only one time period is considered; thus, an evaluation of the instantaneous precipitation distribution, rather than the onset and duration, is performed. The model forecast shows that QG forcing for ascent in the lower troposphere ($\nabla \cdot \mathbf{Q} < 0$) overlapped the contours of relative humidity greater than 80% over the southeastern two-thirds of Wisconsin at 0000 UTC (Figs. 1c and 1d). For this storm, a collocation of the forcing and moisture was also observed over the same portion of Wisconsin in the 700–750-hPa (not shown) and the 600–650-hPa atmospheric layers (Figs. 2c and 2d). In other cases, significant variation in the vertical distribution of moisture may require additional consideration. Based on the diagnostics of the moisture and forcing ingredients at this time period, precipitation should be expected throughout most of Wisconsin with the exception of the northwestern portion of the state. The surface observations in Fig. 3 show that at 0000 and 0100 UTC 27 January precipitation was indeed reported in this region.

Following an analysis of the precipitation onset and duration, the *intensity of the precipitation* can be evaluated. The intensity of precipitation is related to the strength of the forcing and may be limited by the availability of moisture. Additionally, if the forcing coincides with an area of weak stability, an enhanced response to the forcing with higher precipitation rates can be expected. At 800–850 hPa, mainly moderate forcing ($\nabla \cdot \mathbf{Q} = -5$ to -15) existed throughout the south-

[3] The Web page http://speedy.meteor.wisc.edu/~swetzel/winter/winter.html includes descriptions of the five ingredients, a detailed discussion of the steps required to prepare an ingredients-based forecast for winter precipitation, and case studies that illustrate application of the IM into daily operations at NWS WFO, Dousman, WI. The site also provides access to GEMPAK/UNIX, AWIPS, and NTRANS scripts to create the ingredients maps and cross sections.

[4] The **Q** vector as a diagnostic of forcing for ascent is less meaningful when applied near the surface of the earth. Thus, the 800–850-hPa layer should not be evaluated near mountainous terrain.

[5] Additional examples and case studies are available online at http://speedy.meteor.wisc.edu/~swetzel/winter/winter.html.

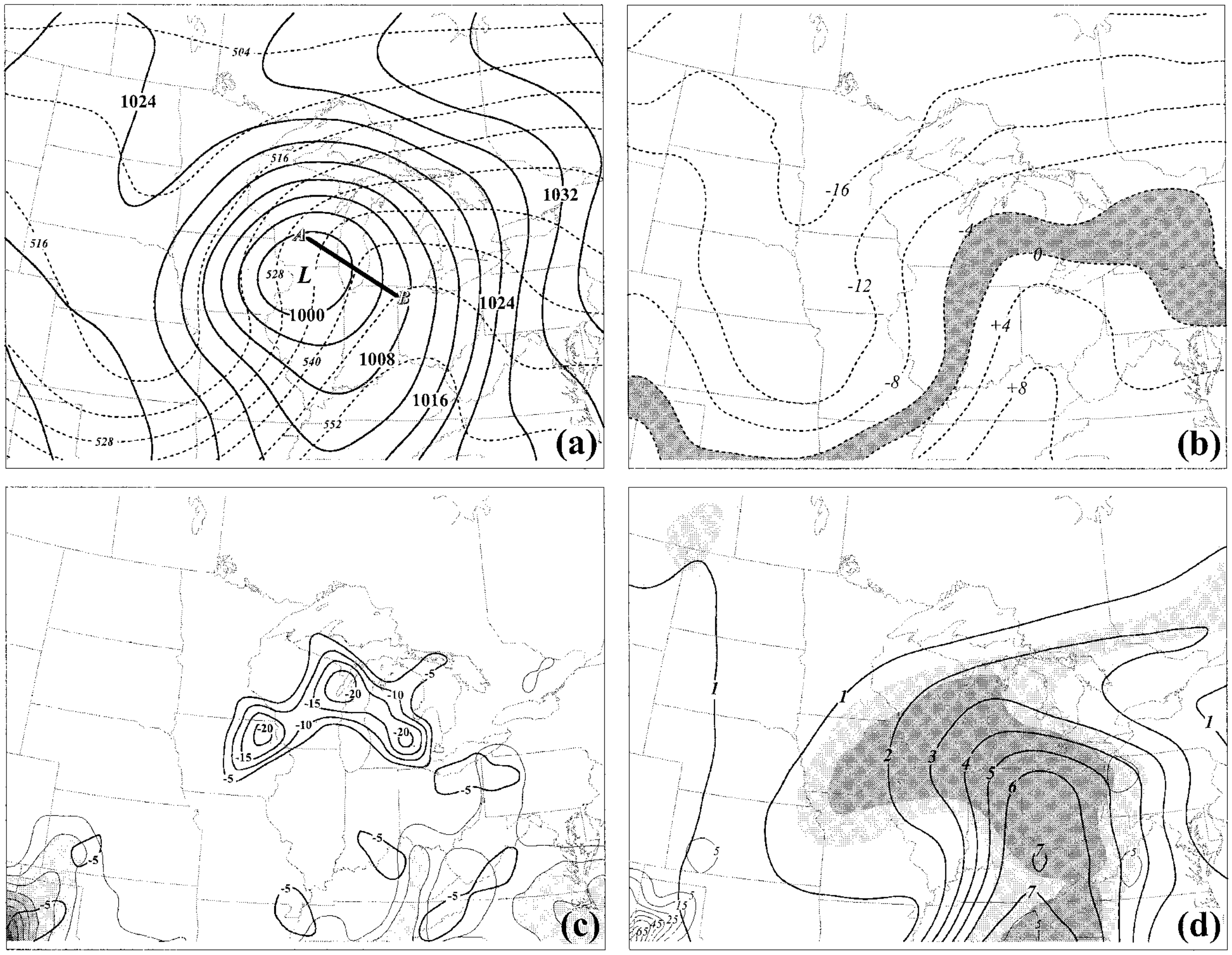

FIG. 1. An 800–850-hPa ingredients map from the 24-h forecast of the NCEP Eta Model valid at 0000 UTC 27 Jan 1996. (a) Sea level pressure (solid lines) and 1000–500-hPa thickness (dashed lines). Sea level pressure labeled in hPa and contoured every 4 hPa. The 1000–500-hPa thickness is labeled in dm and contoured every 6 dm. Capital L indicates location of the sea level pressure minimum. (b) The 850-hPa temperature is labeled in °C and contoured every 4°C. Shaded region highlights the location of the $-4°$ to 0°C isotherm band. (c) The 850-hPa Q-vector convergence (solid lines) and 800–850-hPa layer-average negative PV_{es} (shaded). The Q-vector convergence contoured every -5×10^{-15} K m^{-2} s^{-1} beginning with -5×10^{-15} K m^{-2} s^{-1}. Here, PV_{es} shaded at increments of -0.15 PVU (1 PVU $= 10^{-6}$ m^2 K s^{-1} kg^{-1}) beginning at zero. (d) The 800–850-hPa layer-average relative humidity (RH) (shaded), mixing ratio (thick solid lines), and PVQ (thin solid lines). Darkest shading represents RH $\geq$ 90% with successively lighter shadings representing thresholds of RH $\geq$ 80% and 70%, respectively. Mixing ratios labeled in g kg^{-1} and contoured every 1 g kg^{-1}. See text for explanation of PVQ.

eastern two-thirds of Wisconsin (Fig. 1c) and no instability was present, as indicated by the absence of negative PV_{es} in the region of interest in Fig. 1c. In the 700–750-hPa layer (not shown), moderate to strong forcing for ascent ($\nabla \cdot \mathbf{Q} = -10$ to -25) occurred throughout the southeastern two-thirds of Wisconsin. Finally, the 600–650-hPa ingredients map shows that moderate to strong forcing for ascent extended up to this level (Fig. 2c). Furthermore, an area of instability at 600–650 hPa in southeastern Wisconsin (Fig. 2c) coincided with moderate to strong forcing at 0000 UTC and can be seen as a PVQ maximum in Fig. 2d. Where nonzero PVQ overlaps sufficient moisture, heavy precipitation and possibly thunderstorms can occur. Although the region of positive PVQ at 600–650 hPa (Fig. 2d) was close to the boundary of sufficient moisture in the middle troposphere, with only 70%–80% relative humidity predicted at 650 hPa for Milwaukee, moisture was abundant at lower levels and the strong vertical motions at 850 and 700 hPa would have supplied the 600–650-hPa layer with ample moisture. Thus, based on these ingredients maps, heavy precipitation and possible convection would be expected in southeast Wisconsin. Observations from this time indicate that thundersnow and heavy snow were indeed reported in the Milwaukee area at 0000 and 0100 UTC (Fig. 3).

Precipitation intensity can also be modulated by the efficiency ingredient. If a region with sufficient moisture and upward vertical motion coincides with the temperature of maximum depositional ice crystal growth

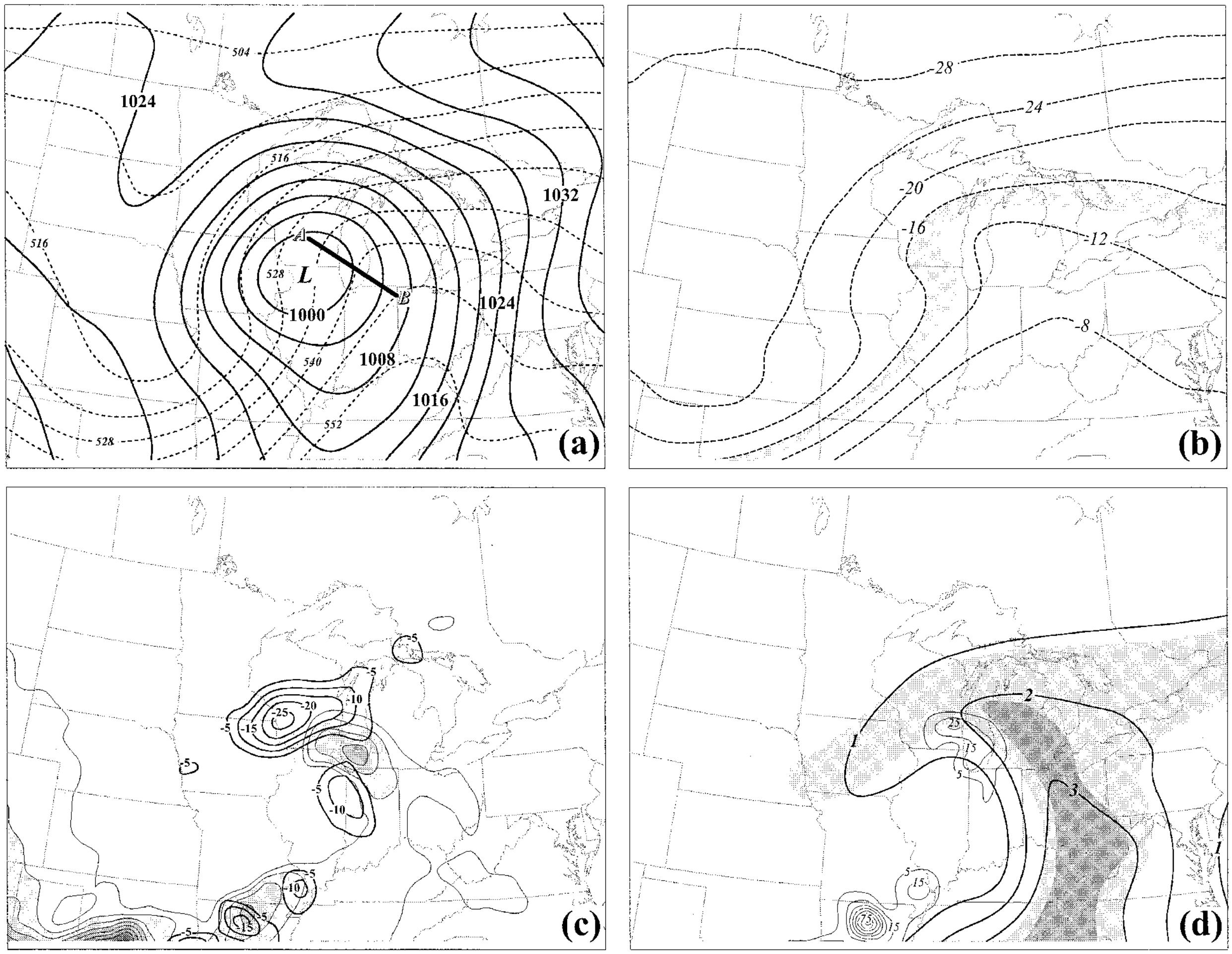

FIG. 2. The 600–650-hPa ingredients map from the 24-h forecast of the NCEP Eta Model valid at 0000 UTC 27 Jan 1996. (a) As for Fig. 1a. Ingredients cross sections along line A–B are shown in Fig. 4. (b) The 600–650-hPa column-average temperature is labeled and contoured as in Fig. 1b. Shaded region highlights the location of the −14° to −16°C isotherm band. (c) As for Fig. 1c except for the 600–650-hPa layer. (d) As for Fig. 1d except for the 600–650-hPa layer.

(−15°C) enhanced precipitation rates may result. In this case, the 600–650-hPa layer average air temperature in the vicinity of the PVQ maximum in southeast Wisconsin was −13° to −14°C, providing additional evidence of the potential for enhanced precipitation intensity.

Once the issues of when and where the precipitation will fall, and at what intensity, have been addressed, the temperature ingredient can be used to analyze the *precipitation type.* A rough characterization of the precipitation type can be inferred from the position of the 850 hPa 0° to −4°C isotherm band, although a more rigorous approach to determining precipitation type would involve an analysis of forecast and observed soundings. The 850-hPa temperature at 0000 UTC 27 January (Fig. 1b) was nearly everywhere below −4°C in Wisconsin, indicating that the precipitation at this time should have been snow throughout the state. This was indeed the case. However, Milwaukee experienced a brief changeover to light rain from 0200 to 0300 UTC. This precipitation type transition highlights the importance of evaluating ingredients cross sections, soundings, and other more numerous upper-air observations such as aircraft reports throughout the forecast period to anticipate changes in precipitation type.

By inspecting ingredients maps frequently at a variety of isobaric levels, the ingredient diagnostics can help anticipate the intensity, onset time, and end time of a winter precipitation event. Because of the amount of information contained in the ingredients maps, it may be helpful to use a table to organize the ingredient parameters and to ensure a systematic evaluation of each. Such a table is also useful as a means of documenting the storm for archival examination of the effectiveness of the IM.

b. Cross-section ingredients maps

In addition to using the IM on pressure surfaces, it is important to consider the vertical distribution of in-

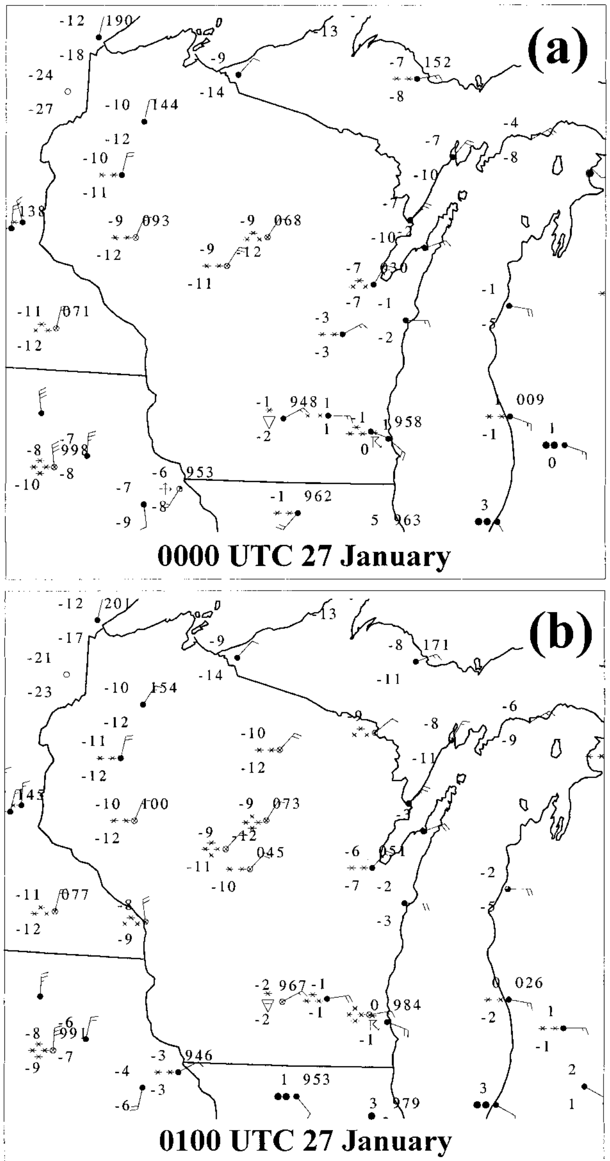

FIG. 3. (a) Surface observations in and around WI at 0000 UTC 27 Jan 1996. For each station the following data are shown: temperature (°C, to the upper left of the station symbol), dewpoint (°C, to the lower left of the station symbol), sea level pressure [labeled in tenths of hPa, dropping the hundreds digit(s)], wind direction and speed, sky cover, and present weather. Sky cover is shown using the following symbols: open circle, clear; one-quarter shaded circle, scattered clouds; one-half shaded circle, broken clouds; three-quarters shaded circle, mostly cloudy; fully shaded circle, overcast; and open circle with an ×, sky obscured. Wind speeds are indicated by a circle around a circle—calm: half barb, <2.5 m s^{-1}; short barb, 2.5 m s^{-1}; and long barb, 5 m s^{-1}. Conventional present weather symbols are used with intensity of precipitation indicated by number of precipitation symbols at a station. (b) As for Fig. 3a except for 0100 UTC 27 Jan 1996.

gredients to assist in a determination of precipitation type and to identify layers of instability or forcing that may exist at levels not captured by the regularly generated ingredients maps (i.e., 800–850, 700–750, 600–650 hPa). Perhaps most importantly, the depth of forecasted dry or moist layers can be visualized more effectively in an ingredients cross section. Additionally, provided the cross section is oriented perpendicular to the shear of the geostrophic wind and the flow is two-dimensional, cross sections can be used to distinguish between regions of CI and CSI.

Figure 4 presents an example of a cross-section ingredients map for the 27 January 1996 case. The cross section is oriented northwest to southeast, through the 600–650-hPa PV_{es} minimum in southeastern Wisconsin (location shown in Fig. 2a). Although the cross section is locally perpendicular to the thermal wind, the 1000–500-hPa geostrophic shear is not two-dimensional in this region (Fig. 2a). Thus, the necessary conditions for CSI cannot be diagnosed along this cross section. The cross section shows an elevated tongue of instability between 720 and 550 hPa coincident with moderate forcing over Milwaukee (Fig. 4a). An analysis of the θ_{es} fields (Fig. 4b) indicates that the negative PV_{es} corresponds to a region of gravitational instability ($-\partial\theta_{es}/\partial p < 0$). Thus, the fact that CSI cannot be assessed is of little consequence.

The cross section of relative humidity (Fig. 4c) reveals a layer with relative humidity greater than 90% from the surface to 700 hPa, and greater than 70% below 600 hPa over Milwaukee. Together with the forcing and instability, this moisture distribution suggests the potential for a heavy precipitation event. In the same layer as the elevated instability and forcing for ascent, the air temperature reached -15°C (Fig. 4d), the maximum temperature for depositional growth of snowflakes. Thus, as seen in the isobaric ingredients maps, the moisture, forcing, instability, and efficiency ingredients over southeastern Wisconsin all pointed toward a heavy snow event.

An analysis of the wet-bulb temperature cross section assists in the determination of precipitation type. The wet-bulb temperature over Milwaukee remained everywhere below 0°C and decreased monotonically, indicating precipitation type should be snow (Fig. 4d). However, just above the surface southeast of Milwaukee (MKE), the wet-bulb temperature warms considerably to near 0°C. Farther to the southeast a surface warm layer was forecasted to extend to 850 hPa implying the precipitation would fall as rain. When the forecast region is in a similar area of precipitation transition, conditions must be monitored carefully as these features evolve.

c. *Snowfall accumulation estimates*

The IM developed here is best suited to provide the forecaster with information concerning precipitation intensity and type at each analyzed forecast hour. However, in an operational environment, forecasts for winter season precipitation require that the snowfall accumulation be quantified. Currently, these estimates are based primarily on traditional empirical techniques such as those described in section 2c. Although the IM for forecasting winter season precipitation does not independently provide a *quantitative* prediction of snowfall ac-

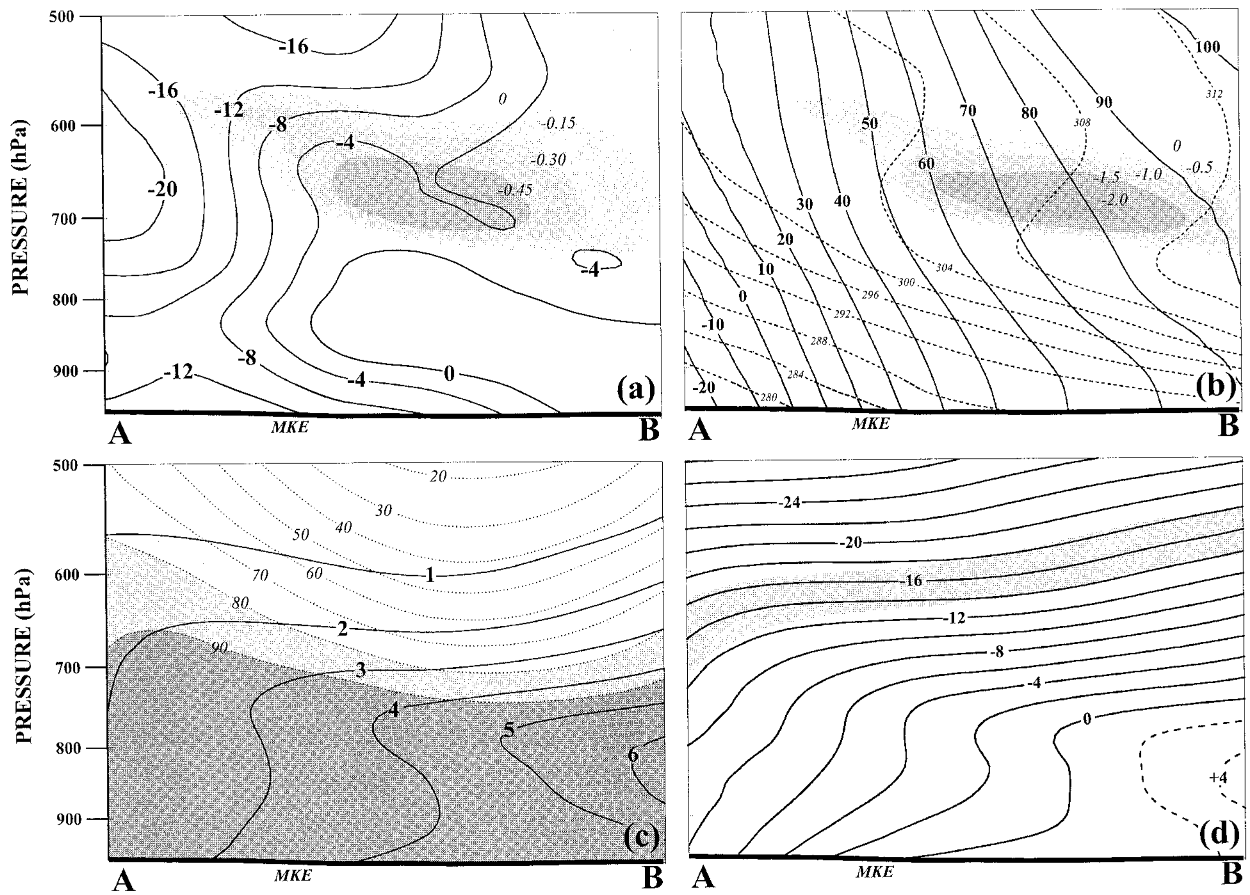

FIG. 4. Ingredients cross section (along line A–B in Fig. 2a) from the 24-h forecast of the NCEP Eta Model valid at 0000 UTC 27 Jan 1996. (a) The Q-vector convergence (solid lines) and negative PV_{es} (shaded). The Q-vector convergence is labeled as in Fig. 1c and contoured every -4×10^{-15} K m^{-2} s^{-1} beginning at 0. Here, PV_{es} is labeled in potential vorticity units (PVU) and shaded every -0.15 PVU beginning at zero. MKE indicates the position of Milwaukee along all cross sections. (b) Geostrophic momentum (solid lines), θ_{es} (dashed lines), and the conditional instability term, $\partial\theta_{es}/\partial z$ (shaded). Geostrophic momentum labeled in m s^{-1} and contoured every 10 m s^{-1}. Here θ_{es} is labeled in K and contoured every 4 K. Conditional instability term, $\partial\theta_{es}/\partial z$, labeled in K km^{-1} and shaded every -0.5 K km^{-1} beginning at zero. (c) Relative humidity (dotted) and mixing ratio (solid lines). Relative humidity is labeled in percent and contoured every 10% between 20% and 90%. Relative humidity greater than 70% is also shaded. Mixing ratio is labeled in g kg^{-1} and is contoured every 1 g kg^{-1}. (d) Wet-bulb temperature labeled in °C and contoured every 2°C. Values above 0°C are dashed. Shading indicates region where air temperatures are between $-12°$ and -16°C.

cumulation, the physical basis and flexibility of the IM can be coupled with the quantitative predictive guidelines of a traditional technique to obtain reasonable estimates of snowfall over a broad region. By examining these empirical techniques from an ingredients perspective, the conditions under which they should or should not be applied can be determined. Furthermore, use of the IM in conjunction with traditional snowfall prediction techniques may reveal a set of guidelines for modifying the empirically derived snowfall accumulation estimates. For example, a technique that does not consider the strength of the forcing for ascent should only be applied under conditions typical of those cases from which it was derived. Such a technique will underestimate (overestimate) the snowfall accumulation when stronger (weaker) forcing occurs.

An example of employing the Garcia method (Garcia 1994) in collaboration with the IM is presented in Wetzel (2000). Further analysis of case studies and real-time applications may lead to the development of a quantitative relationship between the magnitudes of the ingredients and the expected snowfall totals. However, development of such a quantitative relationship should be undertaken with care so as not to compromise the physical basis and flexibility inherent in this approach, and would be useful only when employed in conjunction with an analysis of the individual ingredients.

5. Conclusions

Empirical snowfall prediction techniques base quantitative forecasts of precipitation amount on conceptual models developed from observations of the composite structure and behavior of many events. As a result, the synoptic or thermodynamic conditions of a given event may not fit the empirical model and thus precipitation amounts for that event will not be properly predicted. This paper introduces an operational ingredients-based methodology for forecasting midlatitude winter season precipitation, which provides an effective framework for assessing the importance of five elemental physical ingredients that can conspire to produce winter precipitation events: quasigeostrophic forcing for ascent, moisture, instability, precipitation efficiency, and temperature. Because the IM is based on identification and diagnosis of these elements, instead of on empirically derived conceptual models, it is vested with the flexibility to accommodate a variety of conditions. Thus, unlike the traditional techniques, its efficacy is not restricted to specific synoptic or thermodynamic conditions.

The application of the IM to forecasting winter season precipitation was detailed and diagnostics for assessing each ingredient were presented. The Q vector convergence is employed to qualitatively assess QG forcing for ascent; PV_{es} is used to identify regions of CI or CSI. Relative humidity and mixing ratio quantify moisture availability, and atmospheric temperature is used both in determining precipitation type and as a means to qualitatively assess ice initiation and snowflake growth. Isobaric ingredients maps were introduced to assist in the visualization of the ingredient parameters within three standard isobaric layers (800–850, 700–750, and 600–650 hPa). Since there will be situations in which the isobaric ingredients maps at the three standard pressure layers will not fully capture the relevant distribution of the ingredients, a cross-sectional analysis was undertaken to demonstrate the more comprehensive picture of the vertical distribution of the ingredients thereby achieved.

The IM is also useful in the assessment and diagnosis of quantitative precipitation forecasts (QPFs) generated by numerical models. Instead of relying on a ‘‘black box’’ utilization of QPF estimates, the IM can be used to interpret these predictions through diagnoses of the mechanisms that conspire to produce an event. This is especially important in situations modulated by instability. Under these conditions, awareness of the potential for convection and the attendant increased precipitation accumulations can be anticipated and included in a forecast. Additionally, while model-generated QPF only provides an estimate of time-integrated precipitation, the ingredients-based approach to forecasting winter season precipitation provides qualitative guidelines regarding the *instantaneous* precipitation intensity and distribution. This is useful in comparison with radar observations of actual precipitation patterns for assessing how well a model forecast is verifying. The instantaneous depiction of precipitation is also helpful in forecasting the timing of periods of increased or decreased precipitation intensity.

Because the ingredients diagnostics are calculated using gridded numerical model output, it is important to relate as many ingredients as possible to observable quantities that can be monitored throughout the storm’s development. For example, regions of conditional instability could be identified in observed soundings and compared to the forecasted distribution of the instability ingredient parameter, PV_{es}. Upper-air analyses of relative humidity could be used to evaluate forecasts of the moisture ingredient. When compared with model-predicted ingredient parameters, observations of the actual magnitude and location of an ingredient (or its proxy) might compel modification of a precipitation forecast if observed conditions are not evolving as suggested by the numerical guidance. Additionally, such observations assist in the comparison between competing model solutions as an event is unfolding. For example, if one model predicts less precipitation than another because of moisture differences, observations of moisture parameters upstream of the forecast area could be compared with forecasted relative humidity in the competing solutions to help determine the preferred scenario.

The IM, as currently configured, does suffer from a trio of notable limitations. First, an implicit limitation of any forecast method that employs numerical model output is that it cannot be of much prognostic use when the model forecast is inaccurate. Second, its application does not result in a precise quantitative precipitation forecast. This deficiency may, through use of the IM in conjunction with a traditional quantitative forecasting method, gradually give way to a refined relationship between the ingredients and a quantitative forecast. Third, reliance on the Q vector as the sole diagnostic used to evaluate the forcing for ascent ingredient here is limiting. Use of this diagnostic excludes explicit consideration of the effects of ageostrophy on the redistribution of temperature and momentum and, thus, on the vertical motion forcing itself as suggested by Eliassen (1962). Future extensions of the IM outlined here might well include incorporation of the more complete semigeostrophic or full-wind frontogenetic diagnoses of forcing for ascent.

Despite these limitations, the IM retains an operational flexibility that is rooted in its systematic, physical approach to the diagnosis and prediction of winter precipitation and has proven useful in an operational setting. Finally, it is important to acknowledge that presentation of a single case example of the use of the IM does not constitute proof of its operational value in forecasting winter season precipitation. It is our hope, however, that through introducing the method here it will be put to a wider operational test. Clearly, it is only through such testing that the operational utility of the IM will finally be determined.

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