Investigation of the Dynamical and Thermodynamical Ingredients for Mid-Latitude Winter Season Precipitation

by

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A thesis submitted in partial fulfillment of the
requirements for the degree of

Master of Science

at the
University of Wisconsin-Madison
Department of Atmospheric and Oceanic Sciences

2000

Abstract

Five fundamental physical ingredients – forcing for ascent, moisture, instability, precipitation efficiency, and temperature – are incorporated into an ingredients-based methodology (IBM) for use as an operational tool in the analysis and prediction of mid-latitude winter season precipitation. The forcing ingredient is combined with the instability ingredient to form a new parameter, QPV, which serves as an indicator of heavy precipitation potential by identifying regions where these two ingredients co-exist. The ingredient diagnostics and QPV are incorporated into ingredients maps which facilitate a systematic approach to forecasting the duration, intensity, and type of precipitation. Examples of the application of the IBM to forecasting winter precipitation events are presented, including a case study of a heavy snow event which occurred on March 13-14, 1997 in the upper Midwest.

A detailed investigation of the instability ingredient is also performed. The evolution of conditional (potential) instability in winter cyclones is examined by considering the local rate of change of PV_{es} (PV_e). Although horizontal advection is the dominant mechanism by which PV_e is changed, adiabatic generation, controlled by thermal wind advection of θ_e, also contributes to the reduction of PV_e, primarily upshear of the thermal ridge at the northern end of the cold front in a mature or decaying cyclone. No analogous adiabatic generation term exists for PV_{es}, however, the evolution of PV_{es} is shown to be influenced by what is termed the *saturation deficit term.* The contribution to the Eulerian decrease in PV_{es} made by the saturation deficit term is most significant where the relative humidity is low and horizontal temperature gradients are large. The saturation deficit term is generally of secondary importance to the advection of PV_{es}, though it may contribute significantly in the dry regions behind a strong cold front and upshear of a thermal ridge in mature and decaying cyclones.

Acknowledgements

This thesis was only possible through the help and support of many people. First, I would like to thank my advisor, Jonathan Martin, for providing valuable technical advice and encouragement, for giving me the flexibility to pursue independent ideas, and for carefully reading through the drafts. Also, I wish to thank my thesis readers, Michael Morgan and David Houghton, for their useful suggestions on the final draft.

I would like to express my gratitude to John Eise and Kenneth Rizzo of the National Weather Service (NWS) office in Dousman, Wisconsin, for welcoming me into the office and coordinating the NWS components of my work. They generously provided the opportunity for real-time testing of the IBM diagnostics in an operational environment. Many of the NWS forecasters in Dousman also provided support and expertise to this work, including Cris Garcia whose knowledge of winter forecasting and assistance in introducing the new diagnostic tools into daily operations has been valuable, and John Haase who provided a detailed list of convective snow events in Wisconsin. I also wish to thank Gene Brusky of the NWS office in Green Bay, Wisconsin, and Ed Fenelon of the NWS office in Marquette, Michigan, for their interest in the IBM and eagerness to incorporate it into their winter weather forecasting procedures.

A number of people were instrumental in providing computer assistance and advice. The patience and computer expertise of Pete Pokrandt have been essential to many aspects of this work, and are gratefully acknowledged. Sebastian Korner was my original UNIX, GEMPAK, and UW-NMS model mentor and I thank him for all the nuggets of knowledge he passed on to me. Michael Morgan has been continuously generous with his time in addressing computer questions throughout my studies. Shane Mayor kindly assisted me in viewing the WSR-88D data.

Finally, this thesis experience would not have been the same without the company of friends and family who enriched my days through their comraderie. I extend my appreciation to those with whom I have enjoyed my free time, whether in a coffee shop, over a home-cooked dinner, walking in the woods, or on the tennis courts. In particular, I wish to thank Hank for his selfless commitment to helping me through the final months of the thesis. I am very grateful for his compassion and patience, his flexibility in accomodating thesis weekends, and his keen perception of subtle ways to help.

This work was funded by a COMET/NWS Graduate Fellowship.

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Chapter 1

Introduction

Significant technological advances have occurred over the past decade in the National Weather Service Forecast Offices (NWSFOs) which have improved the quality of numerical weather prediction model forecasts and facilitated the analysis of gridded model data and observations. However, developments in forecasting winter season precipitation have not paralleled these technological advances, and there remains considerable reliance on empirically-derived rules of thumb. Many of the techniques for predicting snowfall accumulations currently used at NWSFOs were developed prior to the availability of sophisticated gridded data analysis programs, and generate 12- or 24-hour 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, never very satisfactory beyond the 3- to 6-hour range, is now unnecessary given the analysis tools currently available to forecasters. Instead, the fundamental elements, or ingredients, involved in a winter precipitation event can be analyzed. An ingredients-based analysis allows forecasters to base their predictions more directly on the physical processes involved, thus enabling them to tailor a forecast to the unique conditions characteristic of each event. In contrast, empirically-derived rules of thumb are generally based on canonical scenarios that assume set conditions, and the reliability of the techniques diminishes as conditions vary from these scenarios.

The first objective of this thesis is to develop an ingredients-based methodology (IBM) as an operational tool to help forecasters analyze and predict winter precipitation events. The IBM provides a systematic approach to forecasting winter weather by establishing a framework for interpreting numerical forecast model output and observations. The IBM presented here diagnoses five key ingredients for a winter precipitation event: quasi-geostrophic forcing for ascent, moisture, instability (i. e., gravitational, inertial, or slantwise instability), precipitation efficiency (specifically cloud microphysical properties), and temperature.

The second objective of this thesis is to investigate the instantaneous distribution and temporal evolution of instability in cold-season mid-latitude cyclones. Instability is arguably the least understood and most often overlooked ingredient in winter storm events. Though neither a necessary nor sufficient condition for precipitation to occur, instability modulates the response of an air column to forcing for vertical motion. A given forcing will produce considerably more vertical motion if it coincides with a region of instability. As a result, forecasts tend to underpredict snow amounts when convection, the release of instability, enhances the precipitation rate. Thus, this investigation focuses on evaluating the relative importance of the processes that govern the evolution of equivalent potential vorticity (PV_e) and saturated equivalent potential vorticity (PV_{es}), two diagnostic tools employed in the identification of regions of instability.

Chapter 1 provides a general introduction to the IBM for winter weather forecasting, discusses some of the advantages of this approach, and presents the ingredients that are implicitly included in a few of the traditional winter weather forecasting techniques. Chapter 2 presents a detailed evaluation of the instability ingredient, including an analysis of the mechanisms that influence the evolution of regions of instability in a mid-latitude cyclone. Chapter 3 presents the parameters developed for diagnosing each of the five winter weather forecasting ingredients, and discusses the application of the IBM. This application is illustrated with a case study of a winter season precipitation event that occurred on March 13-14, 1997.

1.1 Background

The ingredients-based forecast methodology has been employed operationally for more than two decades in the context of warm-season severe 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

$$R = E\,w\,q$$

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 $P = R\ t_{duration}$.

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 as $R = Ewq$, where q includes the mixing ratio anticipated by moisture advection. The ascent rate w is diagnosed by considering the synoptic and sub-synoptic scale mechanisms for lift, and 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.

The IBM presented in this thesis is based on a stricter definition of ingredient than that employed in previous studies. Here, an ingredient is defined as a fundamental physical component or process that contributes to the development of a meteorological event. This definition excludes intermediate parameters such as precipitation rate and duration which are important in the diagnosis of a precipitation event, but are dependent on the more elementary physical ingredients. Because precipitation rate and duration are derived from fundamental ingredients, they do not lend themselves for 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 rainfall rate will remain constant throughout the duration of the event. Instead, using the definition of an ingredient employed here, the storm duration can be assessed through an evaluation of the selected ingredients through all forecast hours of a numerical model. If the necessary ingredients are expected to be present at a given forecast hour, then forecasters can predict a high precipitation potential. If an important ingredient is not expected to be present, the precipitation potential will be low.

This thesis also makes a clear distinction between ingredient and diagnostic. Ingredients represent the physical components or processes directly involved in a meteorological event, while diagnostics are the observable or computed quantities which 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 “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 IBM for forecasting winter season precipitation presented here, parameters will be introduced to diagnose each ingredient; however, the IBM is not dependent on these specific diagnostics. Because this IBM is grounded on the physical components and processes involved, it has the flexibility to incorporate new diagnostics for these ingredients as theoretical and technological advances make them available.

The following five ingredients are employed in the IBM for forecasting winter season precipitation in this thesis:

1. Forcing for ascent: Where and how strong is the forcing?
2. Moisture: Where and how much moisture is available?
3. Atmospheric instability: How strong will the response be to the forcing?
4. Precipitation efficiency: How will cloud microphysical characteristics affect the precipitation rate?
5. Temperature: What form will the precipitation take?

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 previously considered as an ingredient for winter season precipitation. This omission has likely occurred because instability is not a *necessary* ingredient for precipitation, and because until recently convenient diagnostics for identifying winter season instability were not readily available nor well understood by forecasters. As previously mentioned, reduced stability is not a necessary condition for winter season precipitation, but can significantly amplify the response of an air column to forcing for vertical motion. Thus, in this thesis, the instability ingredient is included in the IBM using convenient diagnostics which are readily available to operational forecasters.

In summary, the IBM presented in this thesis follows directly from the following physical processes involved in a winter season precipitation event. To generate any amount and type of precipitation, some mechanism to force ascent (ingredient 1) in a region with sufficient moisture availability (ingredient 2) is required. The intensity of the ensuing precipitation can be modulated by the presence of instability (ingredient 3) and the cloud microphysical properties (ingredient 4). Finally, the precipitation type is related to the temperature profile (ingredient 5). A forecast using this IBM 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 application of the IBM to forecasting winter season precipitation is discussed in more depth in Chapter 3.

1.2 Traditional Forecast Techniques from an Ingredients Perspective

The traditional techniques used for forecasting winter precipitation events are largely empirical relationships established from observations of consistent patterns in the development of weather systems. Because of the abundance of observational evidence on which these techniques are based, there is good reason to trust their prognostic accuracy in similarly configured synoptic situations. However, there are many circumstances in which these techniques have failed to provide accurate forecasts. An investigation of each technique from an ingredients perspective can assist in determining the reason for the failure and help to identify the conditions under which it should or should not be applied. For example, a technique that does not consider variations in the strength of the forcing for ascent should only be applied under conditions characterized by "normal" forcing. Here, normal is defined as the strength of forcing present in the cases from which the empirical technique was derived, or for those cases where the technique's reliability has been demonstrated in operational situations. This section presents a discussion of the ingredients considered by some of the popular traditional techniques in operation at NWSFOs. Section 3.2.3 presents an investigation of the normal conditions implied by one technique, the Garcia Method (Garcia, 1994).

Forecasts for snowfall accumulation are frequently prepared in NWSFOs with the use of the synoptic climatology method (Goree and Younkin, 1966; Browne and Younkin, 1970), the Cook method (Cook, 1984), the Garcia Method (Garcia, 1994), the Magic Chart (Sangster and Jagler, 1985; Chaston, 1989), and the LEMO technique (Gordon, 1998). In the synoptic climatology method (Goree and Younkin, 1966; Browne and Younkin, 1970), the most favorable location for the occurrence of heavy snow is predicted to be 2.5^o latitude to the left of the track of the 500 hPa vorticity maximum, or 90 nautical miles to the left of the track of the 850 hPa pressure minimum. The Cook method (Cook, 1984) predicts that the average 24-hour snowfall in inches is half of the maximum “indicated warm advection” in ^{o}C at 200 hPa. Here, warm advection is defined as the difference between the warmest temperature at 200 hPa and the coldest temperature within a distance of 15^o latitude upstream of the forecast area along the height contours. The Garcia Method (Garcia, 1994) predicts the maximum 12-hour snowfall in inches will be twice the average mixing ratio (in g kg^{-1}) on an isentropic surface which intersects the forecast area between 700-750 hPa. Average mixing ratio is defined as the average between the mixing ratio at the initial time and the maximum mixing ratio which could be advected in during the subsequent 12 hours. Construction of the Magic Chart (Sangster and Jagler, 1985; Chaston, 1989) involves overlaying the 24-hour net vertical displacement (NVD) of air that will arrive at the 700 hPa layer with the 12-hour forecasted 850 hPa temperature. The location of the snowfall is determined by identifying the regions where the greatest 700 hPa NVD coincides with an 850 hPa between -3 ^{o}C and -5 ^{o}C. Furthermore, the Magic Chart predicts that the 12-hour snowfall accumulation in inches (for the period between the 12- and 24-hour forecasts) is equal to the NVD (in mb) divided by 10. Finally, the LEMO technique (Gordon, 1998) predicts that the maximum snowfall in inches is a function of the magnitude and speed of the 500 hPa vorticity maximum.

Table 1.1 identifies the ingredients addressed 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 1.1 as “LtF,” for Left to Forecaster). As shown in Table 1.1, no technique considers more than two

	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

Table 1.1: Ingredients included in traditional snow amount forecast techniques. See text for explanation.

ingredients, and the most commonly overlooked element in forecasting winter precipitation events is the instability ingredient. Although it is not a necessary ingredient for snowfall, reduced stability can strongly influence precipitation rates. Instability is investigated further in Chapter 2 before discussing the other ingredients used in the IBM and presenting case examples of the ingredients approach in Chapter 3.

There is some room for interpretation in identifying the ingredients used in the traditional forecast techniques presented in Table 1.1. Because these techniques were derived empirically, certain ingredients may be included implicitly. For example, the Magic Chart, which predicts snowfall based on the NVD of air parcels reaching the 700 hPa surface, may implicitly consider stability because air parcels in an unstable environment will experience greater vertical displacement in a given time interval than those in a stable environment. Additionally, any empirical technique may include efficiency mechanisms implicitly because the synoptic patterns identified by an empirical technique may have specific characteristic microphysical properties which are not directly accounted for but nonetheless exist in a majority of similar cases.

If modern dynamical theory is applied to interpret the physical basis underlying the empirical relationships, the implicit presence of some ingredients may be revealed, although they remain concealed from the forecaster. For example, the LEMO technique relates the strength of the 500 hPa vorticity maximum to snowfall accumulations. If this technique is put in the context of the dynamical relationship between vorticity advection and vertical motion (Sutcliffe, 1947; Trenberth, 1978), one could maintain that the forcing ingredient is included in the LEMO technique. The Cook method, which bases its forecast of snowfall accumulation on the magnitude and location of an upper level temperature anomaly, provides another example. In the context of potential vorticity (PV) thinking, an upper level temperature maximum is associated with a tropopause-level potential vorticity maximum. The synoptic-scale features of vertical motion and thermal structure could be inferred from the typical characteristics of a PV anomaly. In both cases, however, the snowfall predictions rely on the assumption that the storm behaves according to some pre-defined and technique-specific empirical model of precipitation systems. Without directly including the ingredients, these techniques do not give forecasters the capability to tailor a forecast to case-specific conditions.

1.3 Advantages of an Ingredients-Based Methodology

Empirical snowfall prediction techniques which base their forecasts on observations of consistent patterns can be thought of as conceptual models developed from the average behavior of many events. Because of the natural variability in the development of weather systems, there will always be synoptic or thermodynamic conditions which do not fit the empirical model and thus will not be properly forecasted. In contrast, one of the primary advantages of the IBM for winter season precipitation is that its validity is not restricted to specific synoptic or thermodynamic conditions. Because the IBM is based on a physical understanding of the processes involved in a precipitation event instead of empirically-derived formulae, it provides forecasters with the flexibility to accommodate a variety of conditions.

Other advantages of the IBM are associated with its utility in the interpretation of quantitative precipitation forecasts (QPFs) generated by numerical models. Instead of relying on a "black box" utilization of QPF estimates, forecasters can use the IBM to improve upon these predictions by diagnosing the mechanisms responsible for an event. This is especially important in situations modulated by instability. Under these conditions, if forecasters are aware of the potential for convective precipitation, higher accumulations can be anticipated and included in a forecast. Additionally, the IBM provides a means of comparing the forecasts of different model runs. By identifying the roles played by each ingredient, one can evaluate the differences in the QPFs generated from different models. For example, forecasters can evaluate whether there are differences in forcing patterns or moisture, or whether any forecasts are modulated by instability. As conditions begin to evolve, the modeled ingredients can be compared with observed values of the ingredients and actual precipitation patterns upstream of the forecast area to assist in deciding which model to choose.

The IBM can also be used to identify regional differences in precipitation. In contrast, many traditional forecast techniques focus on one station or a single cross-section and predict the snowfall for that small area; thus, they do not provide information about neighboring areas or the overall distribution of precipitation without tedious repetition of the technique. Using the IBM, forecasters can examine ingredients on isobaric surfaces and identify localized regions of stronger forcing for ascent, isolated areas of instability, or boundaries of moisture, and thus anticipate spatial variations in precipitation accumulation. This is particularly important when a forecast area is near the boundary of a region of high precipitation potential. In this situation, if the synoptic features evolve slightly differently from the predictions of the numerical forecast models, there may be considerably more or less snowfall over the forecast area.

Finally, the IBM can be used to improve upon empirical techniques for estimating snowfall accumulation. Although the IBM does not independently provide a quantitative estimate of snowfall accumulation, it can be coupled with an existing empirical snowfall prediction technique to provide an estimate of the accumulation. The Garcia Method (Garcia, 1994) is employed for this purpose in section 3.2.3. 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 may 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.

The ingredients approach is slightly more cumbersome than many of the traditional techniques. However, as will be shown in Chapter 3, diagnostic tools have been developed to facilitate the application of the IBM and minimize the extra effort required. The benefits of improved forecast quality undoubtedly justify this effort.