Chapter 4

Conclusions and Future Work

This thesis presented an ingredients-based alternative to traditional rule-of-thumb techniques for forecasting mid-latitude winter season precipitation. The ingredients-based methodology (IBM) provides an effective framework for assessing the importance of five key ingredients in a winter precipitation event: quasi-geostrophic forcing for ascent, moisture, instability, precipitation efficiency, and temperature.

A comprehensive investigation of instability, the most often overlooked ingredient in winter season mid-latitude cyclones, was performed. Saturated equivalent potential vorticity (PV_{es}) and equivalent potential vorticity (PV_e) were employed as diagnostics for identifying regions of conditional instabilities (CI or CSI) and potential instabilities (PI or PSI), respectively. Through the analysis of numerical model data from actual midwestern snow events, the mechanisms that influence the evolution of PV_{es} and PV_e with time were explored. This analysis revealed that the evolution of PV_{es} and PV_e in a mid-latitude cyclone is dominated by horizontal advection, although there are some regions where the saturation deficit term (SD), and the adiabatic generation term (AG) may contribute significantly to changes in PV_{es} and PV_e, respectively. A comparison of the horizontal advection of PV_e with the Eulerian change in PV_e (ΔPV_e) revealed substantial agreement in structure and location of these features. With a time interval of six hours, the magnitude of the PV_e advection was two to three times the magnitude of ΔPV_e. However, the magnitude of the advection terms approached that of the Eulerian PV_e change as the time interval was reduced to one hour, indicating that the overestimation was related to storm motion.

A secondary, but potentially significant, contribution to the total Eulerian change in PV_{es} was identified and called the saturation deficit term (SD). This term was shown to contribute to ΔPV_{es} where $l_s - l$ and horizontal derivatives of $l_s - l$ were large. This most commonly occurred behind a strong cold front in mature or decaying cyclones, where SD values of -0.4 to -0.8 PVU/day were typical, and a minimum SD of -1.6 was observed.

The adiabatic generation term (AG) in the PV_e time tendency equation also made only a small contribution to the Eulerian change of PV_e. The most negative AG occurred primarily upshear of the occluded thermal ridge and along the cold front of mature or decaying cyclones, where isopleths of layer-averaged θ_e were rotated counter-clockwise with respect to contours of the isobaric thickness. Typical values of AG ranged from -1 to -2 PVU/day, and a maximum reduction of -3.8 PVU/day was observed near the triple point in the mature phase of a strong cyclone. In most situations, however, the location of the Eulerian change in PV_e was not co-located with the time average adiabatic generation of PV_e.

These preliminary findings about the time tendencies of PV_e and PV_{es} were not incorporated into the IBM; however, further investigation of the evolution of PV_e and PV_{es} may have utility for the IBM. An understanding of the mechanisms that transport and generate regions of instability in mid-latitude weather systems would enable forecasters to anticipate the evolution of regions of instability given initial conditions including the PV_e or PV_{es} field. For example, when numerical forecast model simulations are not verifying with observations, current analyses of winds, temperature and moisture parameters, and PV_e or PV_{es} could be used to infer the short term evolution of regions of instability. Additionally, one could predict the location or intensity of areas of instability at times between the standard 6-hour numerical forecast model time interval by anticipating the behavior of PV_e or PV_{es}.

Following the investigation of the instability ingredient, the application of the IBM to forecasting winter season precipitation was detailed. Diagnostics for assessing each ingredient were presented. Q-vector convergence was employed to qualitatively assess QG forcing for ascent. PV_{es} was used to identify regions of CI or CSI. Relative humidity and mixing ratio quantified moisture availability, and atmospheric temperature was used for both a determination of precipitation type and as a means to assess the efficiency ingredient. Isobaric ingredients maps were introduced to assist in the visualization of the ingredient parameters, and an ingredients table was used to organize the ingredients information from numerical model data for all forecast hours and in three isobaric layers (800-850 hPa, 700-750 hPa, 600-650 hPa). In some situations, the isobaric ingredients maps and ingredients table analysis at the three standard pressure layers do not fully capture the relevant distribution of the ingredients. In these cases, a cross-sectional analysis provides a more complete picture of the vertical distribution of the ingredients. Two examples of isolated layers of instability which were not resolved in the standard isobaric layer ingredients maps but contributed to enhanced precipitation rates were presented.

The IBM can be used by itself to forecast precipitation duration, intensity, and type. It does not, however, independently provide an estimate of snowfall accumulation. This thesis presented an approach that combines the physical basis and flexibility of the IBM with the quantitative nature of a traditional forecast technique to make a preliminary prediction for snowfall accumulation. In this approach, the Garcia Method (Garcia, 1994) forecast for snowfall accumulation is considered the “normal conditions” prediction. Normal conditions for the Garcia Method correspond to moderate forcing for vertical motion, no instability, a 10:1 snow to liquid water ratio, and snow as the sole precipitation type. Thus, if the IBM indicates “abnormal conditions” (i. e., the potential for strong forcing, instability, or very cold surface temperatures), the GM-predicted snowfall accumulation should be increased. Garcia (1999) recommends a doubling of the inches of snowfall predicted by his original technique for heavy or convective snow events.

The utility of the IBM was illustrated for a case study of a poorly forecasted strong snow storm that affected Wisconsin on March 13-14, 1997. Together, the early onset of precipitation and the locally enhanced precipitation rates (as a result of convective snow) led to storm total accumulations of up to 30 inches. When applied to this case, the IBM provided an accurate description of precipitation duration, intensity, and type. The IBM identified a mid-level instability coincident with ample moisture, QG forcing, and an air temperature that could support maximum depositional growth of ice crystals. These processes were likely involved in an unanticipated snow swath that fell prior to the predicted onset of precipitation. Later in the storm, significant clues to the potential for additional convective precipitation were identified using the IBM. Using the 4:1 ratio of snowfall to mixing ratio suggested by Garcia (1999) for convective snowfall events, an accurate estimate of the snowfall accumulations was obtained.

Because the ingredients diagnostics are tied closely to gridded numerical forecast model data, it is important to relate each ingredient to an observable quantity that can be monitored throughout the storm's development. For example, regions of conditional instability could be identified in observed soundings and compared to forecasted values of the instability ingredient parameter, PV_{es}, and upper air analyses of relative humidity could be used to verify the moisture ingredient. When compared with model-predicted ingredient parameters, observations of the actual magnitude and location of an ingredient enables the forecaster to anticipate modifications in the precipitation patterns if conditions do not evolve as forecasted by the model. Additionally, such observations may facilitate the decision to choose between different model scenarios as an event is unfolding. For example, if one model predicts less precipitation because of moisture limitations, observations of moisture parameters upstream of the forecast area could be compared with forecasted relative humidity to assist in determining the preferred scenario.

Furthermore, regular monitoring of IBM diagnostics and routine verification of winter precipitation forecasts prepared with this technique may prove useful in identifying weaknesses in the computation of the quantitative precipitation forecast by numerical forecast models. If events for which the instability or efficiency ingredient is important are consistently under-forecasted by a given numerical forecast model, this information would indicate that the convective parameterization scheme (for instability) or the microphysical parameterization (for efficiency) need further work.

The $\nabla \cdot Q$ diagnostic used to evaluate the forcing ingredient in the IBM presented in this thesis is arguably the weakest element. 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). For this reason, it may prove useful to quantify the degree to which a given flow is well described by the QG assumptions. This could be accomplished by 1) computing the Rossby Number for the case, 2) comparing the model-predicted vertical velocity with that diagnosed for the QG-ω equation(equation 3.1), or 3) identifying synoptic patterns that are commonly associated with strong ageostrophic circulations.