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PREDICTION OF SNOW PARTICLE HABIT TYPES WITHIN A SINGLE-MOMENT BULK MICROPHYSICAL SCHEME

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1. INTRODUCTION

Regional mesoscale models have become the central tools for operational forecasting of local weather systems for periods of 0-72 h, including quantitative precipitation forecasts (QPF). These models have increasingly relied on bulk microphysical schemes (e.g., Cotton 1982; Lin et al. 1983; Rutledge and Hobbs 1983, 1984) for the representation of clouds and precipitation. Although bulk schemes carry a set of prognostic equations for typically three to six different water species (e.g., water vapor, cloud water, rain water, cloud ice, snow, and graupel), snow is often the most active participant in the simulated microphysics of an overall storm. Colle et al. (2005) performed a microphysical budget of all 23 interaction terms in the MM5 model's bulk scheme during a simulation of a winter orographic precipitation event that occurred during the IMPROVE field project (Stoelinga et al. 2003), and their results showed that the interactions of snow with water vapor, cloud water, rain, and graupel were among the most active production terms in the scheme, when averaged over the entire lifetime and volume of the storm system.

Snow particles take on highly varied crystal habits, shapes, densities, fall speeds, collection properties, capacitances for growth from the vapor phase, and size distributions. Other precipitation species (rain, graupel) take on much less variable characteristics. Despite the complexity of snow in nature, the representation of snow in bulk schemes has generally been highly simplified, utilizing static parameters in the mass-diameter relationship (often assuming spheres of constant density), fallspeed-diameter relationship, and capacitance formula. All the production terms for snow involve several or all of these parameters, and are sensitive to them. Also, the specification of the size distribution of snow has always been a challenge in the widely used single-moment class of bulk schemes. Results from analysis of IMPROVE data (Woods et al. 2006) indicate, not surprisingly, that size distributions of snow are also dependent on the particle habit.

It follows that, considering the importance of snow in the process of precipitation production, and the complexity of snow in nature, proper representation of this complexity in bulk schemes is essential to accurate representation of microphysical processes in the atmosphere, and ultimately, to accurate QPF. Therefore, to address the currently oversimplified representation of snow in bulk schemes, we have developed an enhanced bulk scheme in which the habits of snow particles are explicitly predicted with a set of new prognostic equations, and important parameters that affect the production terms for snow are allowed to take on habit-dependent values determined from theory and observations.

2. THE MODEL

As a starting point, we used the Thompson single-moment bulk microphysical scheme within the MM5 mesoscale model (Thompson 2004). Significant upgrades have been recently made to the Thompson scheme which have not yet been reported in the literature, including a unique size distribution for snow following Field et al. (2005), gamma distributions for the other species, and look-up tables to more accurately account for size-dependent relative fall speeds of particles in collection terms involving rain (Thompson 2006, personal communication). We have tested our habit-prediction capability with both the original and upgraded Thompson schemes, and it functions properly in both.

Like most other bulk microphysical schemes, the Thompson scheme uses a single hydrometeor category for snow, and does not employ variable snow habit types and habit-dependent parameters. All snow particles are assumed to follow the same power laws for the mass-diameter and fall speed-diameter relationships, the same collection efficiencies, the same shape-dependent capacitance for depositional growth, etc.

Our approach to habit prediction is to replace the single prognostic equation for snow mixing ratio with a limited number of prognostic equations (currently seven), each of which predicts the mixing ratio of snow of a particular habit. We chose a limited number of snow habits that can be thought to comprise the majority of snow mass observed in the atmosphere and at the ground, and for which properties such as conditions for depositional growth, fall speed, shape, etc. are relatively distinct. The sum of these seven mixing ratios is the total snow mixing ratio, and the sum of the seven prognostic equations is equal (in both a continuous and discretized form) to the standard single prognostic equation for the total snow mixing ratio. The production term arising from depositional growth is added entirely to the habit whose depositional growth is expected to occur under the local conditions of temperature and humidity [as

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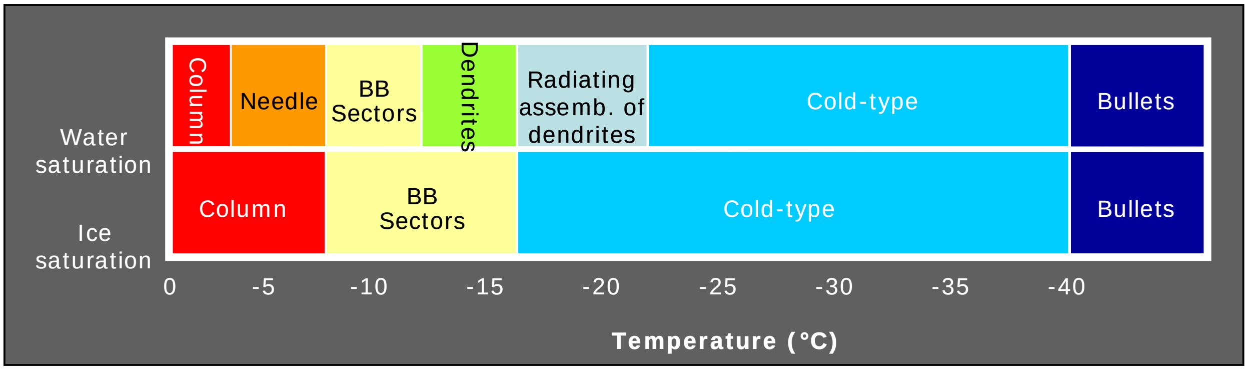

Figure 1. Snow habit growth regimes used in the habit-prediction method. "Cold-type" crystals refers to radiating assemblages of plates, sideplanes, bullets, and columns. "BB Sectors" refers to broad-branch and sector-like crystals.

indicated by studies such as Magono and Lee (1966) and Bailey and Hallett (2002), and shown in Fig. 1], and then each habit is separately transported by advection and fallout. Other production terms (such as collection of cloud water) are applied to the various habits in proportion to their local mass fraction, although more sophisticated ways of apportioning the other terms will be considered in the future. The predicted habit composition of the snow field can then be used to assign appropriate habit-specific parameters for the properties of snow at each grid point, the most important of which are the mass-diameter and fall speed-diameter relationships.

With a single snow mixing ratio predicted, aggregation is essentially a self collection mechanism, and so is not explicitly dealt with in most single-moment bulk schemes. It is implicitly represented by the fact that the empirically derived relationships for size distribution, fall speed, etc., are based on observations of snow populations that were comprised largely of aggregates. In our approach, particles of different habits obviously interact. We simplify the interactions by defining the habit mixing ratios in a general way, such that they do not refer to particles of a pure habit, but instead, they refer to the portion of the total snow mass that is in a particular habit, without regard to how the mass in each habit is distributed among single crystals, single-habit aggregates, or multi-habit aggregates. In this framework, the many collection terms (collection of habit A by habit B) can be ignored. Thus, while the habit mixing ratios are separately predicted, the bulk approach to handling the snow field is retained for some properties and processes, to keep the complexity and computational cost manageable. For example, all snow at a grid point is still assumed to follow a single mass-diameter, fallspeed-diameter, and capacitance relationship. The key difference with the habit-prediction approach is that, rather than using static snow parameters that are the same throughout the model simulation, we use habit-dependent parameters at each grid point that are consistent with the local habit composition, in a mass-weighted average sense.

3. RESULTS

The habit-prediction scheme has been applied in simulations of two different storm systems observed during the IMPROVE field studies. The first case is a wide-spread, deep stratiform precipitation band associated with an occluding frontal system that was observed on 1-2 February 2001 as it traversed the northeast Pacific Ocean offshore of the Pacific Northwest coast. The second case is also an occluding frontal precipitation band, but in this case it was observed as it approached and crossed the Oregon Cascade Mountains on 5-6 December 2001.

1-2 Feburary 2001 case: This storm served as an ideal test case for the habit prediction scheme proposed here, since detailed 2-D particle imagery from a CPI probe (Lawson et al. 2001) was obtained as the University of Washington Convair-580 research aircraft flew a vertical stack of horizontal legs through the band (described by Evans et al. 2005). The simulation of the precipitation band using habit prediction was quite similar to the control run using the standard Thompson scheme, in terms of position and intensity of the band while it was over the ocean. This lack of sensitivity is attributed to the wide-spread and relatively steady nature of the band, such that the changes in the microphysical time scales of growth and fallout did not significantly alter the overall precipitation efficiency of the band.

Predicted particle habits in the model simulation compared remarkably well to those observed in situ (as described in Evans et al. 2005) both in terms of the snow habits present and their relative fractions. Figure 2 shows the contribution to the total precipitation rate of each of the habits represented in the new scheme. Regions of precipitation growth can be ascertained from regions of negative vertical gradient of precipitation rate.

Growth of bullets can be seen at temperatures colder than -40 °C (Fig. 2a), specified according to observations of Bailey and Hallett (2002). However, the precipitation rate of bullets is low compared to other habits that grew lower down, consistent with the observations of a small number of bullet-type particles. The strongest growth of precipitation

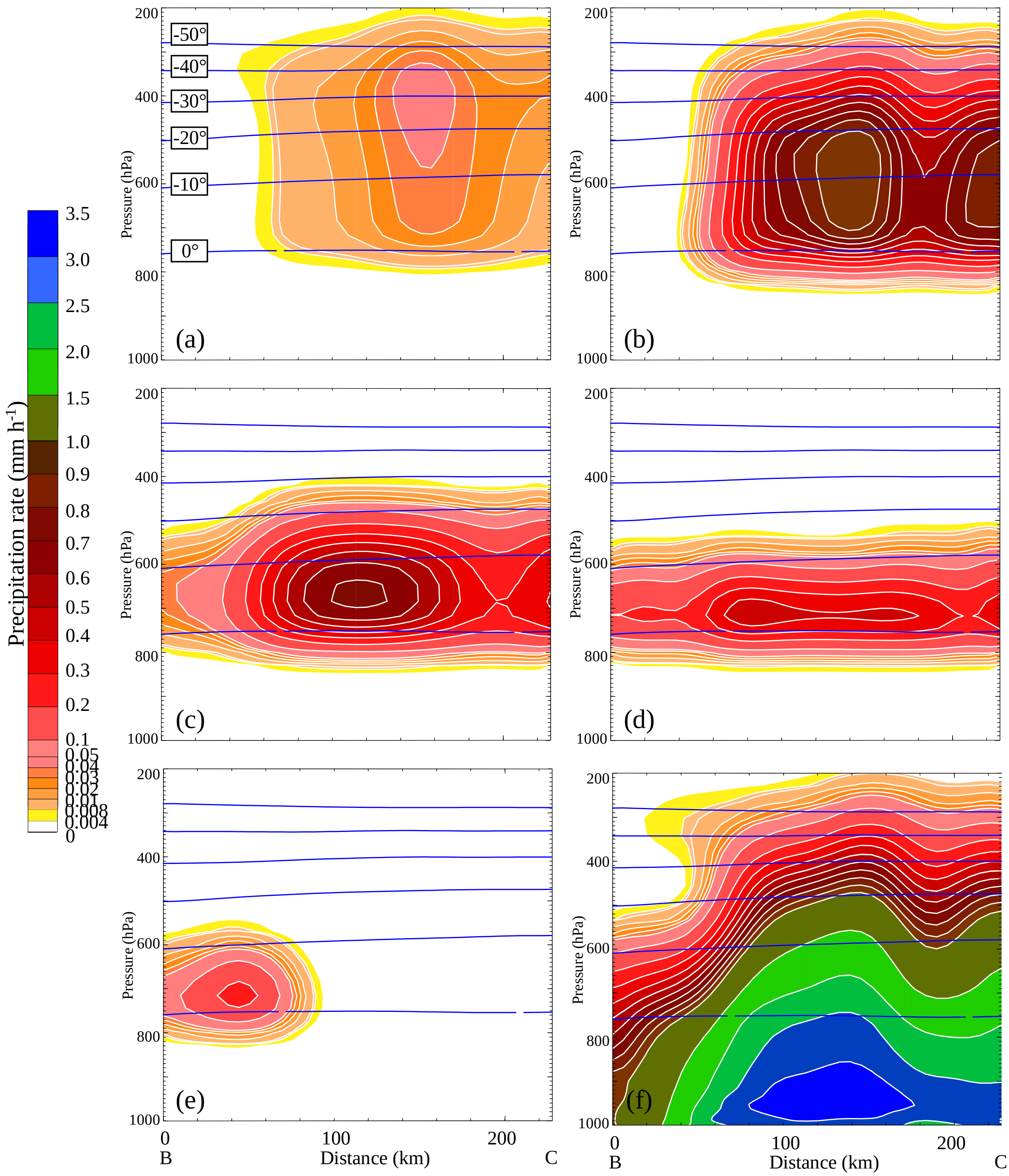

Figure 2. Precipitation rate (mm h^{-1}) within an approximately east-west vertical cross section, perpendicular to the simulated rainband, valid at 0100 UTC 2 February 2001. Blue contours are isotherms every 10 °C. (a) bullet crystal habit; (b) cold-type crystal habit; (c) broad-branch crystal habit; (d) columnar crystal habit; (e) needle crystal habit; and (f) total of all habits.

crystals, from -20 to -40 °C, making them the dominant particle predicted (Fig. 2b) and observed in the precipitation band, even below their preferred region of growth at warmer temperatures. Dendrites, which require water saturated conditions and temperatures near –15 °C for growth, were not observed within the band from the aircraft data. The new scheme performed well in this region by producing no precipitation mass in the categories of dendrites or radiating assemblages of dendrites (not shown in Fig. 16 due to low values), a direct result of the simulated lifting region not reaching water saturation at these levels. Instead, the simulation grew broadbranch crystals from -16 to -8 °C (Fig. 2c), which can grow both at and below water saturation at these temperatures (Fig. 1). Similarly, columns were produced between -8 and 0 °C (Fig. 2d), which can grow at or below water saturation.

Needles were observed in the lowest regions of the precipitation band where water saturated regions existed. It was in this region of the simulated storm that needle habits were predicted (Fig. 2e), although in minimal concentrations, in the simulation. The contribution of the needle habit particles to the overall precipitation rate was limited to regions behind the deepest portion of the precipitation band. The in situ analyses shown in Evans et al. (2005) also suggest that the primary region conducive to the formation of needle–type habits was also limited to the western portions of the precipitation band. This suggests that the simulation produced reduced water saturation levels in the lowest portions of the band, particularly immediately beneath the strongest regions of snowfall where water vapor was readily taken up by particles falling from above.

5-6 December 2001 case: During the IMPROVE-2 field studies over the Oregon Cascade Mountains, ground observers near Santiam Pass (at the crest of the Cascade Range) recorded habit types of falling particles viewed under a microscope, allowing for comparisons between the habits of particles that the model simulation with habit prediction produced at the ground, and those that actually fell. Shown in Fig. 3 are results of the habit prediction scheme for this case, in a vertical cross section that cuts through the warm-type occluded frontal structure. The frontal structure is consistent with the fact that the region with the largest variety of predicted snow crystal habits coincided with a region of deep lifting ahead of the upper cold front. The intrusion of dry air behind the upper cold front limited the solid precipitation types to needles and columns that formed at lower levels and warmer temperatures. Due to a layer of dry air between the warm front and the mountains, snow crystals produced by frontal lifting sublimated before reaching Santiam Pass, but as the storm advanced, these falling snow crystals reached the ground by the next hour. A separate, low-level region of orographically generated needles and columns is seen windward (left) of and over Santiam Pass.

A comparison of the model results to the snow crystal observations that were taken near Santiam Pass during the storm shows that: 1) the model captured the transition in snow crystal type associated with the passage of the upper cold front, from cold type crystals to needles and columns; 2) the model produced pre-frontal low-level orographic needles and columns that were *not* seen in the observations; 3) the model produced snow crystals that grew at sub-water saturated conditions in the dendritic growth region (broad branched crystals) that also were not seen in the observations; and 4) the model produced very little graupel, contrary to what was seen in the observations. This analysis illustrates that the habit-prediction method can serve as an effective tool for diagnosing problems with the model simulation when detailed snow crystal observations are available. While the model simulated the broad features of the storm as it passed over the Oregon Cascades, the snow habit analysis gives added information about differences from observations that can impact the model's QPF, as well as properties of snow fall at the ground. Further study with other IMPROVE-2 cases, should help separate case-specific errors caused primarily by initial conditions from actual model problems and biases.

4. FUTURE WORK

While the above results are encouraging, we need to improve and upgrade aspects of the habit prediction scheme that has been developed.

Although the Thompson scheme is essentially a single-moment scheme (i.e., it predicts number concentration of cloud ice but not of precipitation species), the approach we have used would work equally well in a multi-moment scheme (e.g., Meyers et al. 1997; Milbrandt and Yau 2005), since such schemes generally use the same simple representations of snow particles. NCAR plans within the next year to add a double-moment capability to the new Thompson scheme (G. Thompson, personal communication), and we plan to upgrade our habit prediction scheme in parallel with those developments. Such an upgrade will allow us to test the relative importance of multi-habit versus multi-moment snow microphysics.

Within the scheme itself, one issue that needs improvement is the treatment of riming. Most bulk schemes simulate the riming process, but do not change the characteristics of rimed snow until a point where riming growth exceeds a certain threshold, after which additional rimed cloud water (and some snow) is added to the graupel category. The difference between behaviors of unrimed snow and graupel are substantial (e.g., ~3 m s^{-1} fallspeed for lump-type graupel vs. ~1 m s^{-1} for unrimed dendrites). We propose to carry one additional prognostic equation for degree of riming, which represents a sliding scale for particle density between that of an unrimed particle of the local habit composition, and that of a graupel particle of the same size. This would

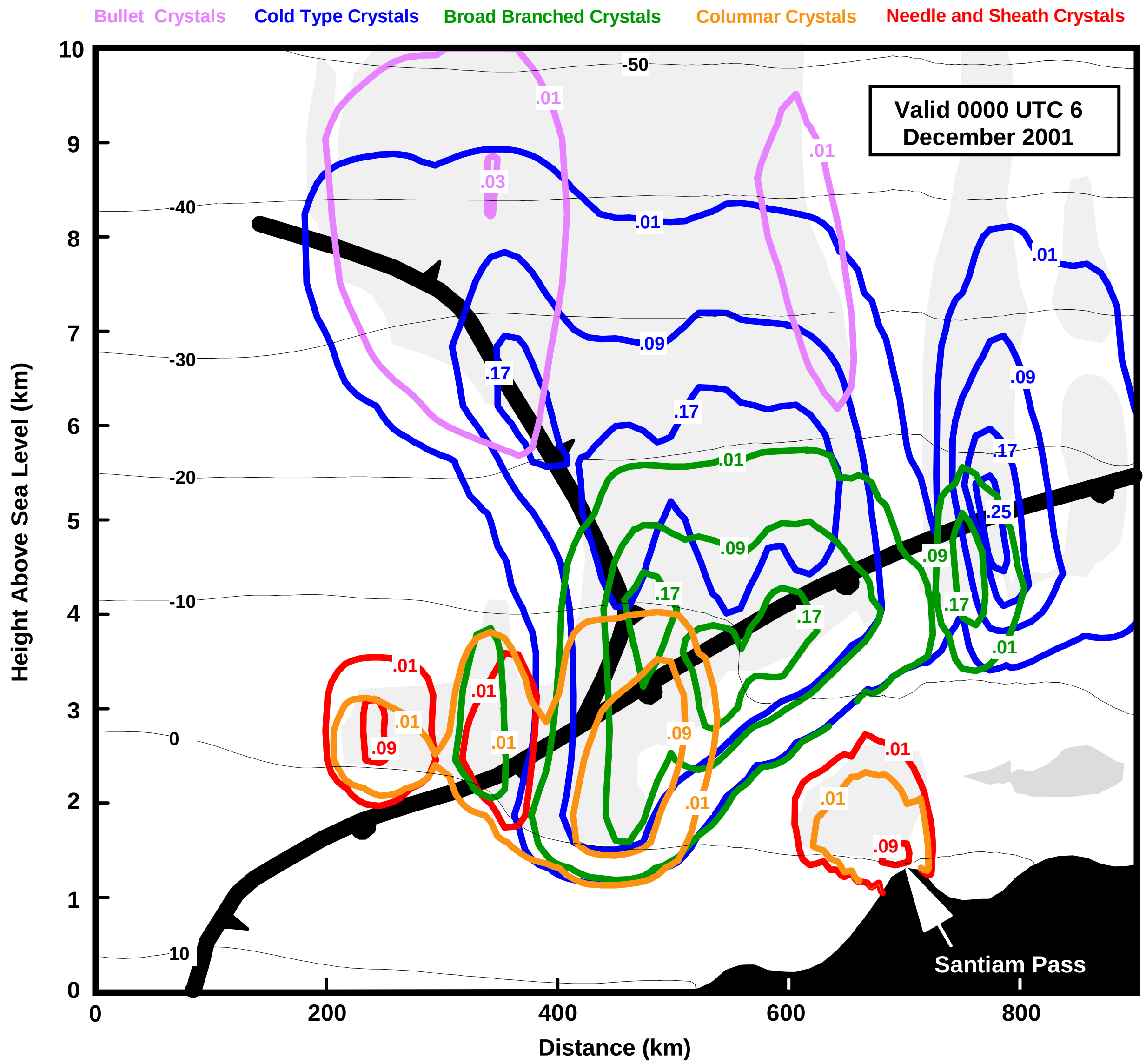

Figure 3. Cross section from an MM5 model simulation with habit prediction, valid at 0000 UTC 6 December 2001, showing temperature contours (dashed black lines every 10 °C), mixing ratios of snow crystal habit types (colored contours labeled in g m^{-3}, see color-coded habit types at top), ice saturation > 100% (gray shaded region), and frontal features (standard symbols).

allow for a transitional range of particle behaviors (like fallspeed) between that of snow and graupel, instead of the more drastic transition that is typically used in bulk schemes.

5. CONCLUSIONS

This paper describes the development and implementation of an enhancement to a standard bulk microphysical scheme that allows for prediction of snow particle habits. Results of the habit prediction were shown for two case studies. Although the distributions of habit types looked reasonable in both cases, they agreed well with observations in one case study, but not in the other. In either case, however, the results of the habit prediction scheme could be compared with available observations of particle habit types during the actual storm to evaluate the time evolution and temperature zones of the model simulation's precipitation growth.

Although it was not addressed here, the potential for feedbacks from the habit prediction into the microphysical scheme are significant, because the predicted habit types are used to adjust the fall speed and mass-diameter relationships for snow particles, to which all production terms for snow are sensitive.

Experimentation with the scheme has indicated significant quantitative precipitation forecast differences in situations where the microphysical time scales of particle fallout and growth are important, such as in orographic precipitation situations.

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