High-resolution simulations of winter precipitation over the Colorado Rockies

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Abstract: The Weather Research and Forecasting (WRF) model simulated the weather for eight consecutive years at high resolution (grid spacing of 4 km) over a limited domain covering most of the central Rocky Mountains. Shorter duration simulations were performed to test sensitivity to grid spacing and numerous physical parameterizations including radiation, planetary boundary layer, and microphysics schemes. Of seven microphysics schemes tested for a 3-month period, two matched the observations of surface precipitation extremely well while the others over-predicted the amount. Details of one of the microphysics schemes, how it is tested during development, and a few of its applications are discussed in this paper.

1. Introduction

When developing the Thompson et al (2008) bulk microphysical parameterization, the primary objective was to create a scheme that was efficient and based on recent observations from intensive field campaigns. Additional motivations were to improve forecasts of quantitative precipitation as compared with other, legacy schemes and to improve the prediction of water phase, particularly, supercooled liquid water, which is responsible for icing of aircraft and ground surfaces. During development as well as subsequent modifications, the scheme is heavily tested using a variety of idealized simulations of specific weather regimes such as orographic-induced clouds and precipitation, convective squall lines, and isolated supercell thunderstorms. This brief paper discusses some of the characteristics of the scheme, especially compared to legacy microphysics schemes as well as some of the developmental testing and applications.

2. Characteristics of the bulk microphysical scheme

2.1. Cloud water

Various numerical weather prediction models utilize a microphysics scheme that traces back to Lin et al (1983; hereafter referred to as “L83”). An inherent assumption in many of these schemes is a monodisperse cloud droplet distribution in which a constant number of cloud droplets all have the same size. One difference in the Thompson et al (2008; hereafter referred to as “T08”) scheme is the use of a generalized gamma distribution with a variable shape parameter following the observations in Martin et al (1994) in which the distribution variance is related to the droplet number concentration. Changing the distribution shape based on the number concentration of droplets produces a more dramatic shift in the mean size of water drops (see Fig. 1) as compared to a constant spectra as most other schemes assume.

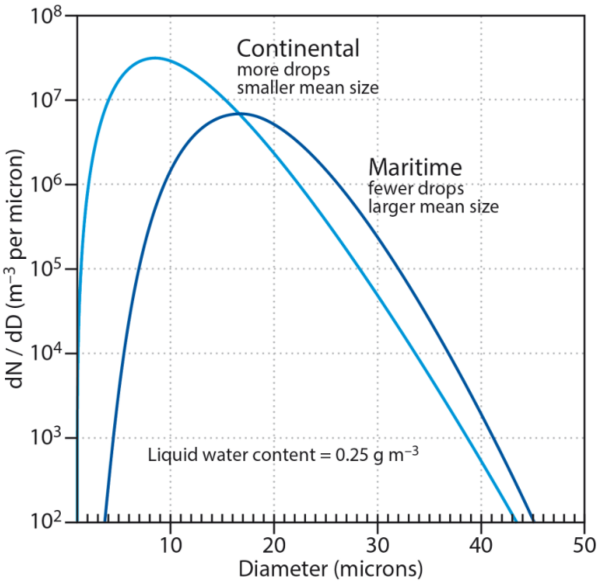

Figure 1: Assumed cloud water distribution with a typical "Maritime" value of cloud droplet concentration (75 cm^{-3}) versus "Continental" (750 cm^{-3}) due to the variable shape parameter following Martin et al (1994) in a generalized gamma distribution. Alternatively, a constant shape parameter as found in some other schemes would have a less significant shift in mean size of droplets.

Related to the cloud water spectra, an artificial physical process termed "autoconversion" is responsible for representing the collision and coalescence process that grows water droplets large enough to gain appreciable fall speed and become drizzle or rain. The number of different autoconversion schemes is staggering including those that were intended to be based on the same starting point. An excellent review of the myriad ways in which various investigators have implemented the Berry and Reinhardt (1974; hereafter referred to as "BR74") autoconversion scheme is found in Gilmore and Straka (2008). The T08 scheme implements a direct version of BR74 with proper replication of three characteristic diameters but extended it beyond the original range of variance of cloud droplet spectra. Various other microphysics schemes employ an explicit autoconversion threshold, or minimum cloud water content, before creating some rain (e.g., Berry, 1968) or potentially create rain almost as quickly as they create tiny cloud droplets (i.e., Seifert and Beheng, 2006). Due to the manner in which the BR74 characteristics diameters are used to form rain, the T08 scheme results in an implicit threshold of cloud water content that varies with droplet concentration, which is a result of the variable shape parameter since this greatly affects the assumed droplet sizes in the spectra. As an approximate guideline, nearly 0.1 g/m^{-3} water content is needed to make rain when only 25 cm^{-3} droplets exist ranging to nearly 0.8 g/m^{-3} when 750 cm^{-3} droplets exist. In the overall sense, this is believed to be a sufficient representation of most realistic clouds in a maritime versus continental setting. More sophisticated treatments such as explicit "bin" or size-resolved representations of droplet spectra are cost-prohibitive by comparison and the implementation in T08 performs well when compared with such a sophisticated bin scheme (Geresdi, 1998).

2.2. Rain

The T08 scheme assumes that rain follows a generalized gamma distribution with a pre-determined value for the shape parameter. Model users may choose this value at the start of a simulation and it does not change with time or in space. Besides the mass mixing ratio of rain, the number concentration of drops is also explicitly predicted in the updated T08 scheme. This more recent addition (undocumented) is believed to improve the representation of two primary generation mechanisms of rain: melting of ice particles consisting of relatively large water drops, and collisions/coalescence of tiny cloud droplets to form drizzle, which are generally smaller than the melted ice.

Compared to many other legacy microphysics schemes, the T08 scheme uses an accurate fall speed relation for falling rain from Ferrier (1994) and adjusts the shape parameter differently for sedimenting the number of rain compared with the mass in order to mitigate the inherent numerical problem of excessive size sorting. Idealized testing of this alteration shows improved vertical profiles of radar reflectivity as compared to standard numerics used by essentially all other two-moment rain schemes.

2.3. Cloud ice

The T08 scheme assumes a generalized gamma distribution of cloud ice with a pre-determined value for the shape parameter. Similar to rain, model users can easily change this constant, but it does not vary in space and time during the simulation. The most unique characteristic about the cloud ice is the manner in which it grows and transfers to the larger size category of snow. Whereas many other schemes use a saturation adjustment to ice (or ice/liquid mix; e.g., Braun and Tau, 2000), the T08 scheme computes the explicit vapor deposition rate and allows high ice supersaturations to remain in the upper atmosphere, which is far more consistent with observations (Molthan and Colle, 2012). Furthermore, the ice transfers to the snow category using an explicit size bin approach and all mass/number of cloud ice larger than 200 microns is transferred to snow. As a result and compared with many other bulk schemes, the T08 scheme tends to have an order of magnitude lower cloud ice because the explicit size bin approach is very efficient at transferring cloud ice into snow while keeping the cloud ice mean size much smaller than most other schemes.

2.4. Snow

The largest difference between the T08 scheme and nearly all other bulk microphysics schemes is found in the snow category. One distinguishing feature of the T08 scheme is the assumption of a general two-dimensional snow crystal whose density varies with size that is consistent with observations in contrast to assuming a constant density spherical shape. Another feature is the assumed size distribution following observations by Field et al (2005) instead of typical exponential distribution found in most schemes. The Field et al (2005) distributions and empirical relations between moments of the snow distribution were derived from 9000 aircraft observations whereas most of the legacy bulk microphysiscs schemes use snow distribution and mass-size and velocity-size relations that derived from far fewer observations (e.g., Locatelli and Hobbs, 1973). The T08 scheme's sum of two gamma distributions evolve as a function of snow amount and temperature. Previous bulk microphysics schemes such as Reisner et al (1998) and Thompson et al (2004) have altered the y-intercept parameter of the snow distribution based on mass or temperature, respectively, but none has included both variables at the same time.

2.5. Graupel/Hail

The T08 graupel/hail category is a hybrid between more typical graupel schemes that are pre-determined to show characteristics more like graupel from heavily rimed snow or large, high-density, and fast-falling hail from large water drops freezing and subsequent wet growth into hailstones. The T08 scheme uses a variable y-intercept parameter of an exponential size distribution to become a hybrid of the two categories. Although density remains constant, it is set to an intermediate value while its observed range of values could be a factor of two higher or lower. However, the y-intercept parameter has far greater variability of over two orders of magnitude and so a compromise of constant density but variable intercept gives this category a computationally efficient means to mimic characteristics of both species. A recent modification to the diagnosis of graupel y-intercept parameter since Thompson et al (2008) is the combination of supercooled liquid water (potential for rapid wet growth) and mixing ratio of graupel (a surrogate for strong vertical velocity) to diagnose the y-intercept value at each time step (see Fig. 2).

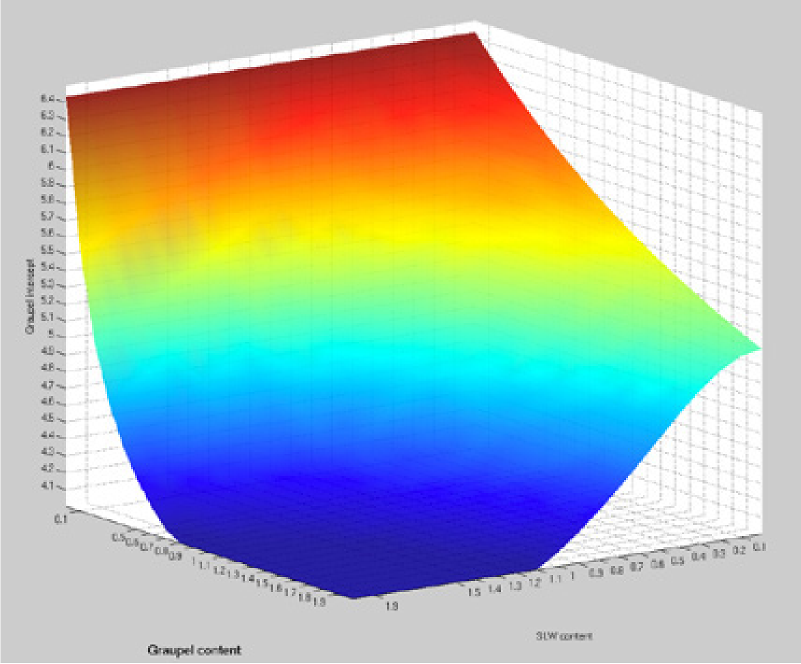

Figure 2: Three-dimensional surface showing the diagnostic behaviour of the graupel y-intercept parameter as it depends on its mass mixing ratio (a proxy for the vertical velocity) and supercooled liquid water from both cloud and rain water, which relates to the potential for wet growth.

Another unique aspect of this category is how rimed snow transfers to graupel. Whereas most schemes use threshold amounts of snow and cloud water content to produce graupel, the T08 scheme uses a linear function based on the ratio of riming to depositional growth rates of snow and transfers only a partial amount of the rimed snow to graupel. Minimizing the use of thresholds throughout the scheme lessens the occurrences of strange “jumps” seen in the model output as compared with some legacy schemes.

3. Development testing

Since its inception in 2006, the T08 scheme is frequently tested within a series of two- and three-dimensional idealized simulations to evaluate new additions or modifications. Repeated running of a large number of two-dimensional tests of flow over prescribed terrain (e.g., Thompson et al, 2004) allows for direct comparisons against a much more sophisticated bin/explicit scheme of Geresdi (1998) and Rasmussen et al (2004). Furthermore, comparisons with other bulk microphysics schemes by Morrison et al (2009), Milbrandt and Yau (2005), and Hong et al (2004) provide additional insights. While the T08 scheme was initially developed in the MM5 and WRF models, it has since been ported to the Navy's COAMPS model where it is used for tropical cyclone investigations (Jin et al, 2012) and it was also ported to the KiD model (Shipway and Hill, 2012) for idealized tests and comparing with other bulk schemes and one bin scheme.

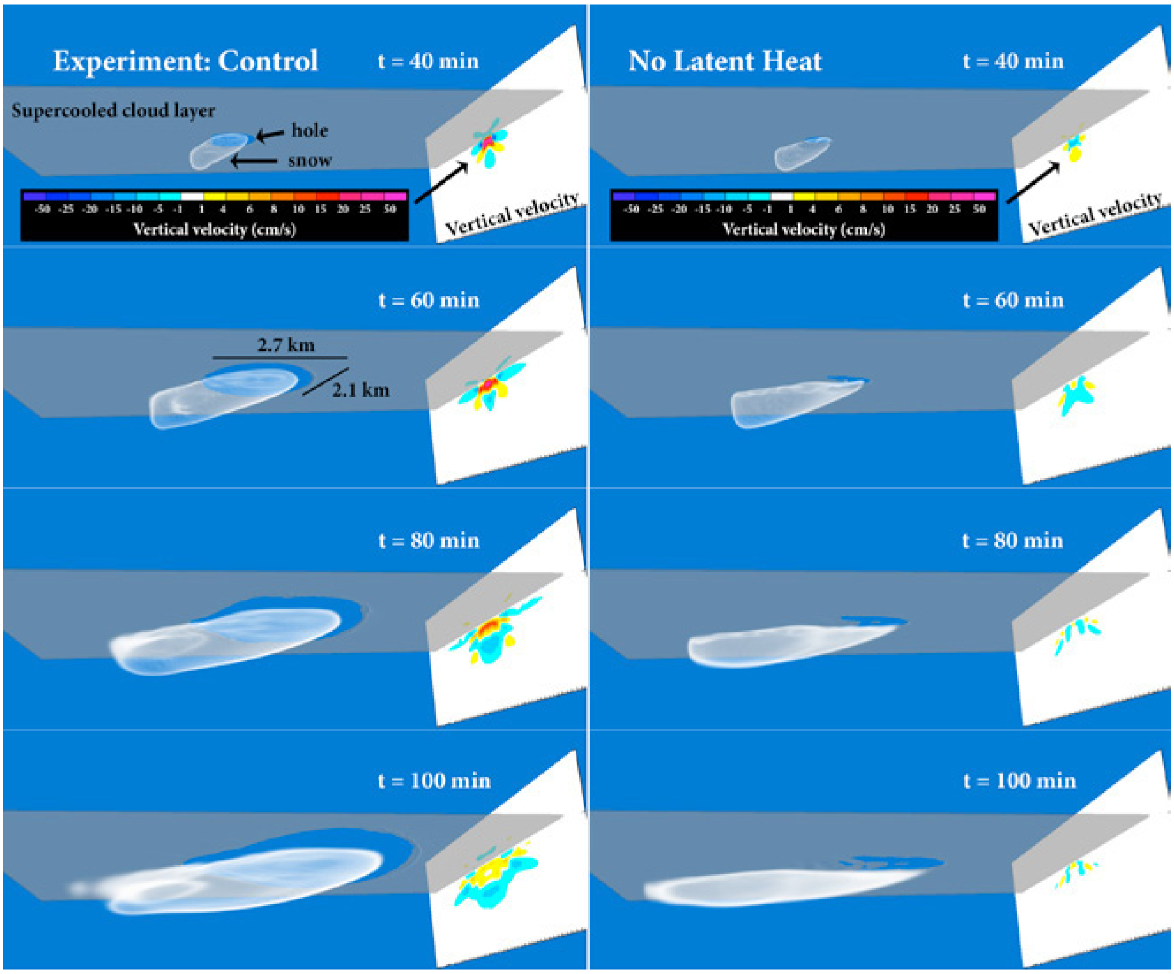

Figure 3: Three-dimensional view of a "sheet" of supercooled cloud water (gray horizontal surface) and ice crystals (semi-transparent white) simulating an observed "cloud hole" scenario as described in Heymsfield et al (2011). A perpendicular cross-section of vertical velocity through the center of the hole as viewed into the page is projected to the right side of each frame. The simulation on the left used full physics whereas the simulation on the right disabled the latent heat due to vapour depositing onto ice crystals. The simulation with full physics shows an evolving (40 to 100 minutes at 20-min interval) and expanding hole whereas the simulation disabling latent heat shows a short-lived cloud hole that deteriorates as the ice crystals fall below the supercooled water cloud. The conclusion is that the latent heat release causes sufficient upward motion to create new ice crystals that continue to grow and produces a positive feedback mechanism and sustain the Bergeron-Findeisen process.

A good example of idealized testing of specific processes can be found in Heymsfield et al (2011) in which the T08 scheme re-created "cloud holes" and confirmed that the Bergeron-Findeisen process was properly replicated. It also tested the direct role that latent heat plays to sustain these phenomena (see Fig. 3). Other idealized tests include two and three-dimensional convective squall lines, idealized supercell thunderstorms, and various winter storm features such as a detailed study of melting snow (Minder et al, 2010).

4. Applications

The Thompson et al (2008) microphysics scheme has been running as part of the NOAA/NWS Rapid Refresh (RAP) model operationally at the National Centers for Environmental Prediction (NCEP) since May of 2012. Prior to this model implementation, the Rapid Update Cycle (RUC) model utilized the older Thompson et al (2004) scheme, which was rooted in the same legacy Lin et al (1983) scheme as many other models continue to use.

As part of a study (Rasmussen et al, 2010; Ikeda et al, 2010) at the National Center for Atmospheric Research regarding the headwaters of the Colorado River, the WRF model was used to simulate eight continuous years of precipitation using the Thompson et al (2008) microphysics scheme. The results comparing model-simulated versus observed precipitation at snow telemetry (SNOTEL) sites is presented in Fig. 4 and show excellent agreement, with a relatively minor amount (5-10%) higher in the model than in the observations, which is well within the observational error.

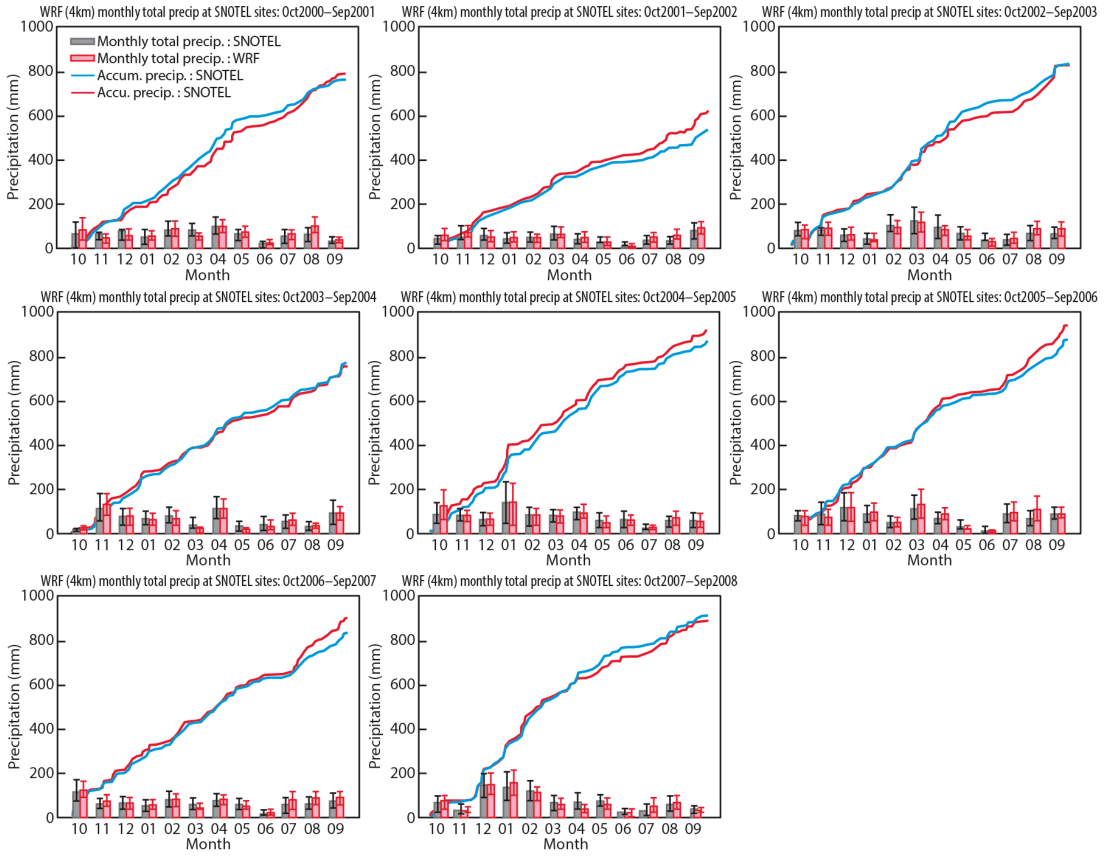

Figure 4: Monthly accumulated precipitation from the WRF model (red lines) and from SNOTEL observations (blue lines) for a continuous eight-year simulation over the headwaters region of the Colorado River (figure courtesy of K. Ikeda).

In a related study by Liu et al (2011), the WRF model was used to repeat a three month period within the full eight years and test a variety of model options for various physical parameterizations, including radiation, planetary boundary layer, and microphysics. The three-month period primarily simulated snow in the middle of winter as compared to summer or convective precipitation so the majority of sensitivity was found with different microphysics as compared to the other physical parameterizations. Of seven different microphysics schemes used, the Thompson et al (2008) and Morrison et al (2009) schemes showed nearly the same precipitation amounts that agreed very well with the observations whereas all other schemes predicted far greater amounts (see Fig. 5).

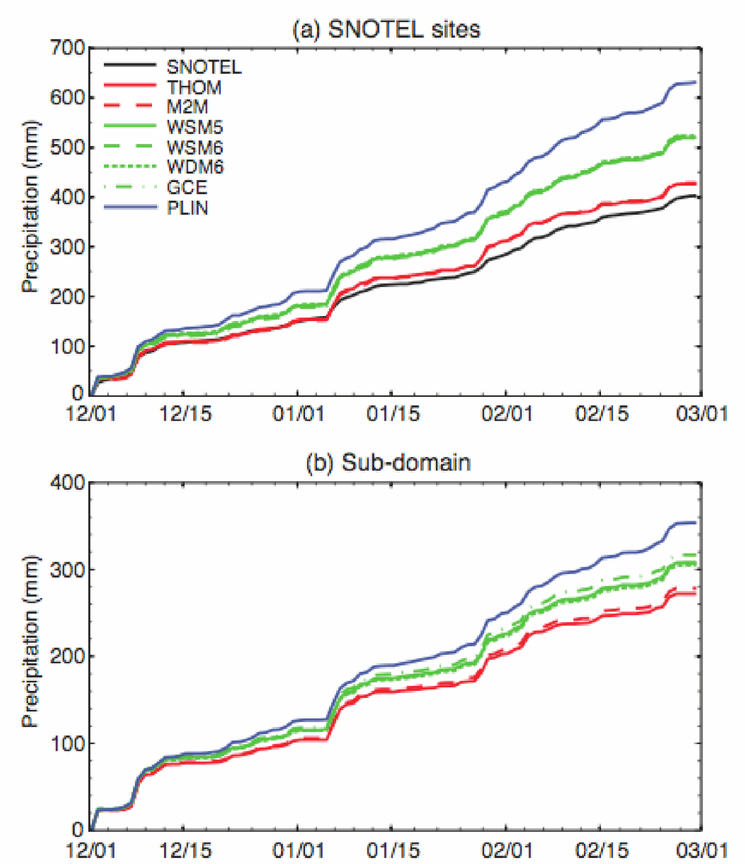

Figure 5: Comparison of 3-month duration precipitation from WRF model simulations using seven different microphysical parameterizations versus SNOTEL observations (black line in top panel). The red solid and dashed lines show results using the Thompson et al (2008) and Morrison et al (2009) schemes, respectively. The solid, dashed, dotted, and dash-dotted green lines show results using WSM5, WSM6, WDM6, and Goddard schemes, respectively and reveal approximately 20% higher precipitation amounts than observations while the Purdue-Lin (blue line) scheme over-predicts amounts by nearly 50%. See more details in Liu et al, 2011

For summer weather conditions, researchers at NOAA's National Severe Storms Laboratory, together with Oklahoma University's Center for Analysis and Prediction of Storms (CAPS), have been running high resolution, convection-permitting ensemble simulations with various microphysics schemes for the past few years. Details can be found in Clark et al (2012). Included in Fig. 6 are images of radar reflectivity and synthetic satellite imagery from a convective event and give a subjective comparison between four microphysics schemes: Thompson, Morrison, Milbrandt, WDM6, which are described in Thompson et al (2008), Morrison et al (2009), Milbrandt and Yau (2005), and Hong et al (2004) respectively. From viewing images like these in real-time during the experiment (lasting several months each year), NOAA forecasters and collaborating scientists have noted some consistent behaviors characteristic of the various microphysics schemes. In many circumstances, the differences between the various microphysics are less than the differences between any model run and the observed convection, however, some apparent biases have been noted. The T08 and Morrison et al (2009) simulations are most similar and often represent the observed convection more realistically than other schemes, but there is often too much high-level cloud ice seen in the latter. The Milbrandt and Yau (2005) scheme has the highest maximum reflectivity too often but also the most extensive upper-level cloud anvils, typically much more widespread than satellite observations would indicate. The WDM6 scheme has nearly the direct opposite with far too low reflectivity in most circumstances with far too little upper level cloud anvil. More comprehensive objective analyses are ongoing.

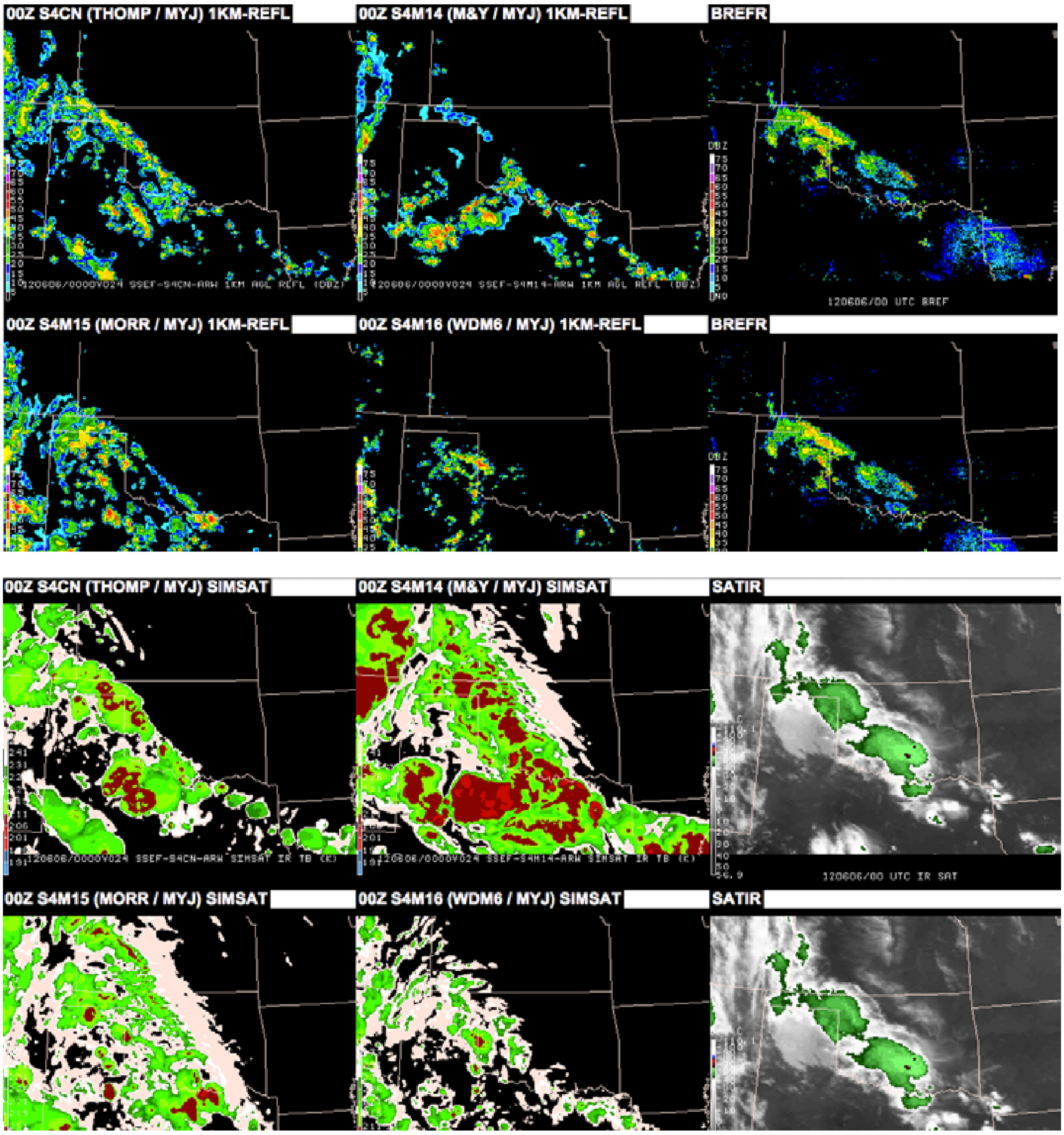

Figure 6: WRF model convection-permitting simulations from OU-CAPS Spring Experiment showing model-predicted and observed radar reflectivity as well as an observed and synthetic infrared satellite image using four different microphysics schemes: Thompson et al (2008; "THOMP"), Milbrandt and Yau (200x; "M&Y"), Morrison et al (2009; "MORR"), and Hong et al (2011; "WDM6").

In conjunction with the eight-year duration WRF simulations mentioned earlier, the data were further mined for evaluation as an explicit forecast of aircraft icing. At each location of a positive report of aircraft icing, the WRF model data were probed to see if the model predicted the presence of supercooled liquid water. Overall, 54% of the icing reports were properly captured by the direct numerical model prediction of icing as compared with only about 20% found in a prior study using a coarser grid spacing RUC and RAP model (Wolff and McDonough, 2010). Two causes are speculated for the dramatic increase in direct capture of icing conditions: increased liquid water content due to higher resolution and stronger vertical velocity as well as greater tendency in the newer physics to limit the production of ice crystals and, therefore, glaciated clouds.

Another analysis of these data helped determine if the model predicts the observed relationships between median volume diameter (MVD), liquid water content (LWC), and temperature. Shown in Fig. 7 is a scatter diagram of all of the values of these three variables from the icing pilot report study. Here we see that the majority of relatively high LWC and largest MVD occur at the highest temperatures, which is very consistent with observations. Lower temperatures are more likely to contain ice crystals so this will help to limit the LWC. The curve on the left represents the data from the cloud water category and has the expected relation of water content is directly proportional to diameter cubed since there is only a single value of cloud droplet concentration (100 cm^{-3}) used in this model run. In contrast, the scheme independently predicts the rain number concentration and

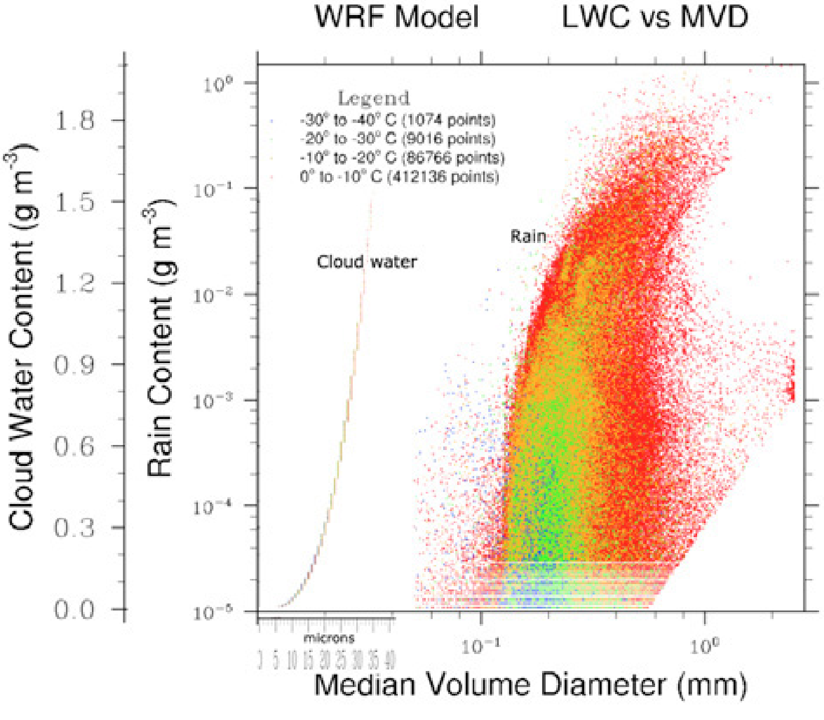

Figure 7: Scatter diagram of WRF model-predicted liquid water content (LWC) versus median volume diameter (MVD) for cloud water and rain, color-coded by temperature from the eight-year simulation over the Colorado Rockies and corresponding to locations where aircraft observed active in cloud icing. The points for cloud water align and show direct LWC proportionality to size cubed since a constant droplet concentration was used for this simulation, whereas the droplet concentration of rain is a predicted variable and shows a much greater scatter. The correlation with temperature is physically reasonable since, at lower temperatures, we expect to find lower LWC and smaller MVD since lower temperatures is expected to produce more glaciated clouds.

shows the expected scatter of related but independent values of LWC and MVD. A newer version of code with a predicted second moment (number concentration) in the T08 scheme will be employed and a larger scatter in the data is expected with this addition. Subjectively, the sizes of both cloud water and rain appear physically correct.

In another recent study by Podolskiy et al (2012), the Thompson et al (2008) scheme was compared with other microphysics schemes in its prediction of ground icing conditions in Japan. Consistent with similar studies by others (Nygaard, personal communication), the T08 scheme typically had the more frequent occurence of supercooled liquid clouds rather than glaciated clouds, which usually matched the observed conditions better than other model schemes.

5. Conclusions

The Thompson et al (2008) scheme is very widely used in both operational models and research. The code is generally flexible, documented, efficient, and well-tested in a variety of applications. Early indications are that it is performing well to predict quantitative precipitation amounts, especially compared with similar bulk microphysics schemes. The scheme has been developed primarily with a focus on prediction of supercooled liquid water (and aircraft/ground icing) and so it is the most likely of comparable schemes to predict mixed phase and liquid water clouds rather than fully glaciated clouds. Initial indications are that this feature is a positive step forward based on numerous case studies and intensive field campaign data. The general improvement in QPF is believed to be a result of better water phase prediction aloft and the details of ice initiation and growth, since these factors will, in general, deplete the liquid water and more rapidly increase precipitation efficiency.

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