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Examining the sensitivity of MM5–CMAQ predictions to explicit microphysics schemes and horizontal grid resolutions, Part I—Database, evaluation protocol, and precipitation predictions

Ashley Queen[a], Yang Zhang[a,*], Robert Gilliam[b], Jonathan Pleim[b]

[a]*MEAS, North Carolina State University, Campus Box 8208, Raleigh, NC 27695, USA*
[b]*Atmospheric Sciences Modeling Division, NOAA, Research Triangle Park, NC, USA*[1]

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Abstract

Wet deposition of chemical species is one of the most difficult processes to simulate in three-dimensional (3-D) air quality models, due to the complex interplay among meteorology, cloud, and atmospheric chemistry. Different cloud microphysical treatments and horizontal grid resolutions in 3-D models can directly affect simulated clouds, precipitation, and wet deposition. In this study, the performance and sensitivity of the simulated precipitation, concentrations, and wet deposition to different explicit microphysics schemes and horizontal grid resolutions are evaluated for August and December 2002 for a domain centered over North Carolina (NC). Four explicit microphysics schemes in MM5 are examined: Reisner 1 (R1), Reisner 2 (R2), Dudhia (SI), and Hsie (WR).

The precipitation evaluation indicates that monthly-average precipitation amounts are underpredicted by all schemes in both August and December at all sites except for the R1 August simulation that shows overpredictions at National Acid Deposition Program (NADP) sites. An increased sensitivity to microphysics schemes is found at locations in both the coastal plain and mountain regions in August and the mountain region in December. The differences in simulation results in August and December are mainly attributed to seasonal differences in dominant meteorological forcing (mesoscale vs. synoptic, respectively). Among the schemes tested, R2 and SI give the best overall performance in predicting precipitation for both months. These findings are applicable for NC and neighboring states with similar meteorological and emission characteristics.
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Keywords: MM5; CMAQ; Explicit microphysics scheme; Wet deposition; Precipitation

1. Introduction

Clouds and precipitation play a critical role in the removal of air pollutants via wet deposition, which can proceed first with cloud formation through heterogeneous nucleation (Hallberg et al., 1997;

*Corresponding author. Tel.: +1 919 515 9688; fax: +1 919 515 7802.
E-mail address: yang_zhang@ncsu.edu (Y. Zhang).
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Andronache, 2004) and aerosol activation (Zhang et al., 2002); then with in-cloud scavenging by existing clouds (Hallberg et al., 1997; Andronache, 2004); or below-cloud scavenging by falling precipitation (Andronache, 2004) or both. All these processes influence the amount and composition of surface precipitation, which may lead to acidic precipitation and adverse environmental effects. An additional intricacy in accurately simulating wet deposition lies in the fact that it depends not only on the meteorological processes/parameters but also on the ambient concentrations of depositing species in all phases. These concentrations are, in turn, affected by numerous processes such as emissions, transport, gas and aqueous-phase chemistry, aerosol thermodynamics and dynamics, cloud processing of gases and aerosols, as well as removal by dry and wet deposition. Because of the complexity of the interactions involving formation, transport, and removal, accurate representation of these processes within numerical models is difficult. However, without proper representation of cloud and precipitation processes, skilled meteorological and chemical predictions cannot be achieved. The impact of any associated model errors in representing cloud processes cannot be well understood without assessing the appropriateness of the model configurations and associated uncertainties, as well as the likely causes of model discrepancies in meteorological and chemical predictions judged against observations.

Recent studies have shown the sensitivity of meteorological predictions to cloud microphysics schemes (Gilmore et al., 2004). In this work, an evaluation of simulated precipitation and wet deposition and their sensitivity to various model configurations (i.e., explicit microphysics scheme and horizontal grid resolution) is conducted for the Fifth Generation National Center for Atmospheric Research/Pennsylvania State University (NCAR/PSU) Mesoscale Model (MM5) (Grell et al., 1994) and the US EPA Community Multiscale Air Quality (CMAQ) modeling system (Byun and Schere, 2006). The objectives are to study major uncertainties in the simulated wet deposition of ammonium (NH_4^+), nitrate (NO_3^-), and sulfate (SO_4^{2-}) and to identify the strengths and weaknesses of various MM5 explicit cloud microphysics schemes and the model sensitivities to horizontal grid resolution. Those objectives are achieved by first examining the impacts of MM5 explicit microphysics schemes and horizontal grid resolutions on precipitation and the subsequent impacts on simulated particulate matter (PM) concentrations and wet deposition, and then the correlations among simulation biases for precipitation, concentrations, and wet deposition. The results will be presented in three parts. Part I describes the model configurations, observational databases, evaluation protocols, and the evaluation of precipitation predictions. Part II (Queen and Zhang, 2008a) evaluates chemical predictions and their correlation with meteorological predictions and provides recommendations for microphysics schemes in MM5–CMAQ. Part III (Queen and Zhang, 2008b) examines the sensitivities of model predictions to different horizontal grid resolutions.

2. Model configurations and episode selection

In this study, the MM5/CMAQ modeling system is applied over a 4-km horizontal grid domain centered on North Carolina (NC). The input files for initial and boundary conditions (ICs and BCs) and meteorology are developed based on the MM5/CMAQ model simulations at 36- and 12-km grid resolutions obtained from the Visibility Improvement State and Tribal Association of the Southeast's (VISTAS) 2002 modeling program (http://www.vista-sesarm.org.asp). Fig. 1 shows the 36- and 12-km domains of VISTAS and the nested 4-km domain used in this study. The results from the 4-km simulations will be first presented in Parts I and II, and then compared with those from coarser grid resolutions in Part III. For the 4-km domain, 34 layers are used for MM5 and 19 layers are used for CMAQ, extending from surface to the tropopause (~15 km) with ~38 m for the first layer height. The MM5 v3.7 with the four-dimensional data assimilation (FDDA) and the Meteorology-Chemistry Interface Processor (MCIP) v3.1 are used to generate meteorology for CMAQ v4.4. MM5–CMAQ is applied for two 1-month periods with distinct meteorological and chemical characteristics, August and December 2002. While December was the coldest month in 2002, emissions of major pollutants were the highest in August. The two months have different meteorological forcing mechanisms, with August precipitation driven by localized convection while that in December was forced by larger-scale synoptic systems with west-to-east movement through the domain. The differences in meteorological forcing in the 2 months result in differences in the simulated precipitation,

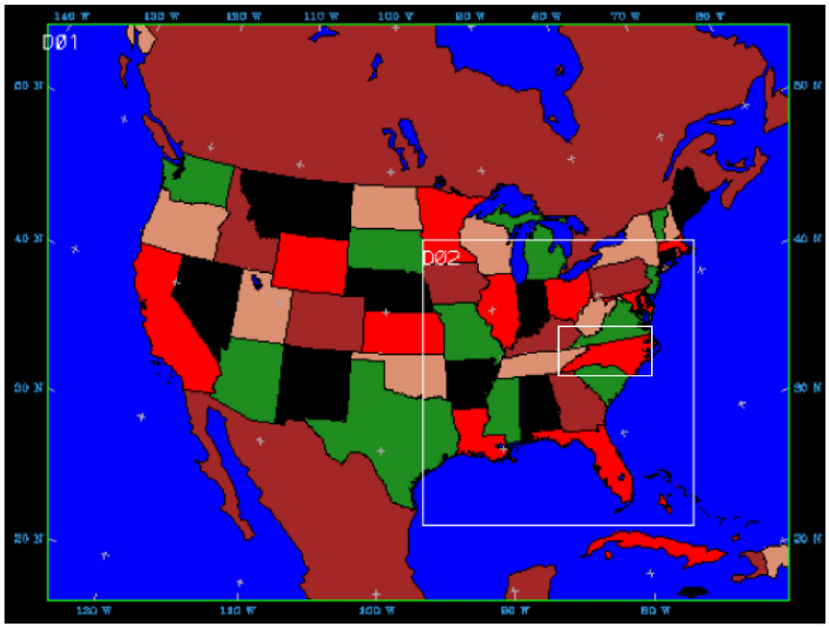

Fig. 1. The nested modeling domains at horizontal spacings of 4-km (NC), 12-km (eastern US), and 36-km (continental US) (adapted from Olerud and Sims, 2004).

chemical concentrations, and wet deposition. A more detailed analysis of meteorological conditions in the 2 months is provided in Appendix I online.

Four simulation pairs are conducted with different MM5 explicit microphysics schemes: Reisner 1 (Reisner et al., 1993), Reisner 2 (Reisner et al., 1993, 1998), Dudhia simple ice (Dudhia, 1989), and Hsie warm rain (Hsie, 1984) (hereafter referred to as R1, R2, SI, and WR, respectively). All model configurations for the R1 simulation, based on Wu et al. (2008), are the same as those used in the 12- and 36-km VISTAS simulations described in Morris et al. (2005), except for the MM5 Kain-Fritcsh 2 cumulus parameterization option, which was turned off at 4-km since all cloud and precipitation processes are assumed to be resolved by the explicit microphysics scheme (Roselle and Binkowski, 1999). One main difference among the four schemes is the treatment of ice-phase microphysics, which is summarized in Table 1. The simplest scheme is the WR scheme, which does not include any treatment of ice microphysics. The SI scheme includes the treatment of ice, but simplifies conditions for phase changes between liquid and ice. It is assumed that at the freezing point, 0 °C, a complete change between phases takes place. This assumption neglects co-existence of super-cooled liquid and ice particles. It, however, increases computational efficiency and the assumption may hold and not significantly affect simulation accuracy in certain situations (Mass and Kuo, 1998). Both the R1 and R2 schemes include treatment of ice microphysics and also have the ability to simulate super-cooled liquid droplets. Their main difference is that R2 explicitly simulates graupel formed via the riming processes, which is not included in the R1 scheme. While the R2 includes a more realistic representation, it may require larger CPU times. For one simulation hour, the CPU costs are 0.41, 0.42, 0.44, and 0.62 h for WR, SI, R1, and, R2, respectively. The tradeoff between numerical complexity and computational

Table 1
Characteristics of the Reisner 1 (R1), Reisner 2 (R2), Dudhia (SI), and Hsie (WR) explicit microphysics schemes

Scheme	Inclusion of ice microphysics	Simulated super-cooled liquid	Simulated riming process
Reisner 1 (R1)	Yes	Yes	No
Reisner 2 (R2)	Yes	Yes	Yes
Dudhia (SI)	Yes	No	No
Hsie (WR)	No	No	No

efficiency makes the assessment of the skills of each scheme necessary to determine under what situations the benefit from the increased microphysics detail will outweigh that of the increased computational demand.

3. Observational datasets and evaluation protocols

The variables evaluated include precipitation, wet deposition amounts of NH_4^+, NO_3^-, and SO_4^{2-}, and daily-average concentrations of NH_4^+, NO_3^-, and SO_4^{2-} in particulate matter with aerodiameters equal to or less than 2.5 μm ($PM_{2.5}$). Simulation results are compared with observations at sites from five monitoring networks, including the NC Automated Surface Observing System/Weather Observation System (ASOS/AWOS), the National Acid Deposition Program (NADP), the Clean Air Status and Trends Network (CASTNET), the Interagency Monitoring of Protected Visual Environments (IMPROVE), and the Speciated Trends Network (STN) (see Fig. 2). Table 2 summarizes databases used for evaluation. Simulated precipitation amounts are compared with observations at different time scales, hourly for ASOS/AWOS and weekly totals for NADP. Monthly-average hourly precipitation and wet deposition are used in comparison between ASOS/AWOS and NADP networks and also in the statistical evaluation. Simulated weekly-average (CASTNET) and daily-average (IMPROVE and STN) $PM_{2.5}$ concentrations are evaluated separately for different networks because of different measurement methods and sampling periods. For comparison at specific sites, the sites from NADP are matched to the nearest site from all other networks (defined as co-located sites), wherever appropriate. The procedures for calculating monthly-average hourly values and determining co-located sites are described in Appendix II online.

Performance evaluation and sensitivity analysis of MM5–CMAQ using the four schemes are conducted in terms of spatial, statistical, and

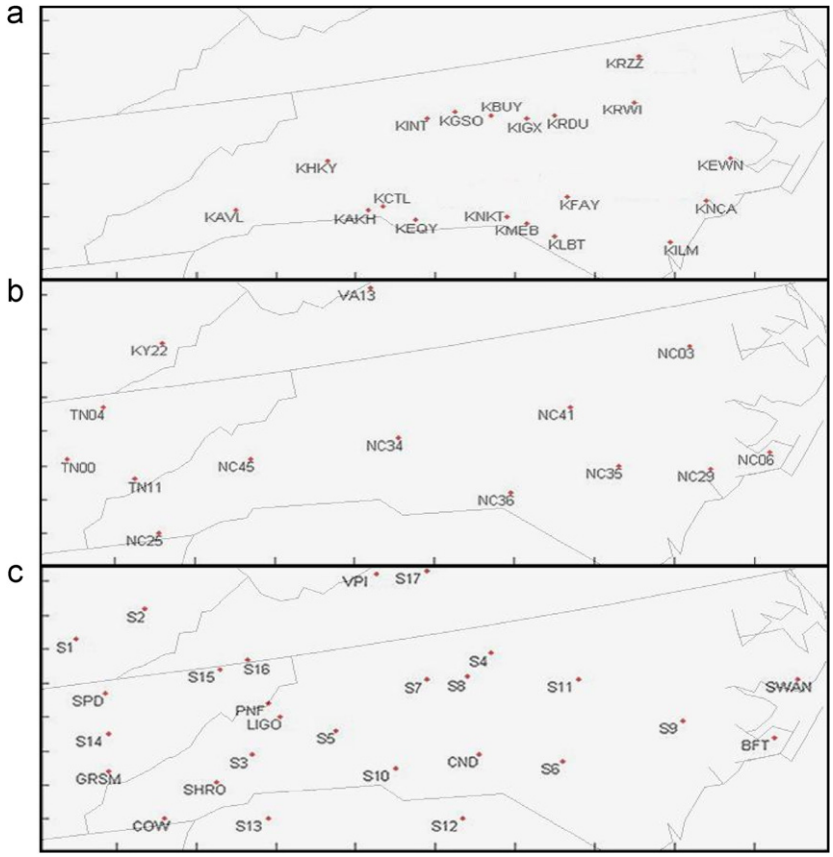

Fig. 2. The locations of measurement sites from (a) ASOS/AWOS, (b) NADP, and (c) IMPROVE, STN, and CASTNET used in the model evaluation for the 4-km MM5/CMAQ simulations.

Table 2
Observational datasets used in the model evaluation

Network	Parameter/species		Total sites evaluated	Sampling period
ASOS/AWOS[a]	MET[b]	Precipitation	19	Hourly total
NADP[c]	MET	Precipitation	14	Weekly total
	WETDEP[d]	NH_4^+, NO_3^-, SO_4^{2-}	14	Weekly total
CASTNET[e] (mostly rural sites)	$PM_{2.5}$[f]	NH_4^+, NO_3^-, SO_4^{2-}	7	Weekly average
STN[g] (urban areas and towns)	$PM_{2.5}$	NH_4^+, NO_3^-, SO_4^{2-}	17	1 in 3 days; 24-h average
IMPROVE[h] (mostly remote sites)	$PM_{2.5}$	NH_4^+, NO_3^-, SO_4^{2-}	4	1 in 3 days; 24-h average

[a]ASOS/AWOS—Automated Surface Observing System/Automated Weather Observation System.
[b]MET—meteorology.
[c]NADP—National Acid Deposition Program.
[d]WETDEP—wet deposition.
[e]CASTNET—Clean Air Status and Trends Network.
[f]PM—particulate matter.
[g]STN—Speciated Trends Network.
[h]IMPROVE—Interagency Monitoring of Protected Visual Environments.

temporal comparisons, following the evaluation protocol of Zhang et al. (2006). Statistics such as normalized mean bias (NMB) and normalized mean error (NME) are calculated. While NMBs describe the model tendency (overpredict or underpredict), NMEs assess the overall degree of model discrepancy. Site-specific analyses focus on co-located sites where correlation between meteorological and chemical variables may be possible and examine daily-total (precipitation and wet deposition) and daily-average (PM concentrations). Those sites are selected based on geographical characteristics (western vs. eastern) and availability of matching sites (see Supplementary Table 1, Appendix II online).

4. Evaluation of precipitation prediction

The simulated amounts and distributions precipitation are analyzed for 3-week long segments in August (i.e., 6–13, 13–20, and 20–27 August) and 4-week long segments in December (i.e., 3–10, 10–17, 17–24, and 24–31 December) that correspond to the NADP weekly sampling periods.

4.1. Spatial distribution

As shown in Fig. 3, spatial patterns of simulated precipitation differ between August and December, indicative of the differences in their dominant forcing mechanisms. As described in Appendix I online, summer precipitation in this region more likely results from local, free-convective initiation, whereas winter precipitation pattern is dominated by synoptic forcing. This seasonal contrast in precipitation patterns is captured by all simulations, regardless of the schemes chosen. The results in August show high sensitivity to different schemes in two regions, on the lee-side of the Appalachian Mountains (western 1/3 of NC) and in the coastal plain (eastern 1/3 of NC). Both R1 and R2 simulations show increased precipitation in the eastern mountain and western piedmont regions. The R1 simulates increased precipitation in the area aligned closer to the mountain range, while the R2 gives the increased precipitation slightly more to the east. Increased precipitation amounts predicted by R1 and R2 in both regions may result from the enhancement of convective storm systems with the presence of mixed-phases (liquid and ice), which has been shown to increase precipitation production, updrafts, and storm system length (Gilmore et al., 2004). Along the coastline, the WR also gives high precipitation, while the SI gives the least precipitation among the four schemes. The different treatments of the ice-phase processes by these schemes likely contribute to these results. Mölders et al. (1995) state that the assumption of liquid-phase only leads to higher cloud and rainwater mixing ratios above the freezing level. These higher ratios may lead to the larger precipitation amounts along the coastline. Meanwhile, the direct conversion of liquid to ice above the freezing level by the SI may explain the lower overall precipitation amounts in this region.

For December, the area with the largest variations occurs in the Appalachian Mountains region.

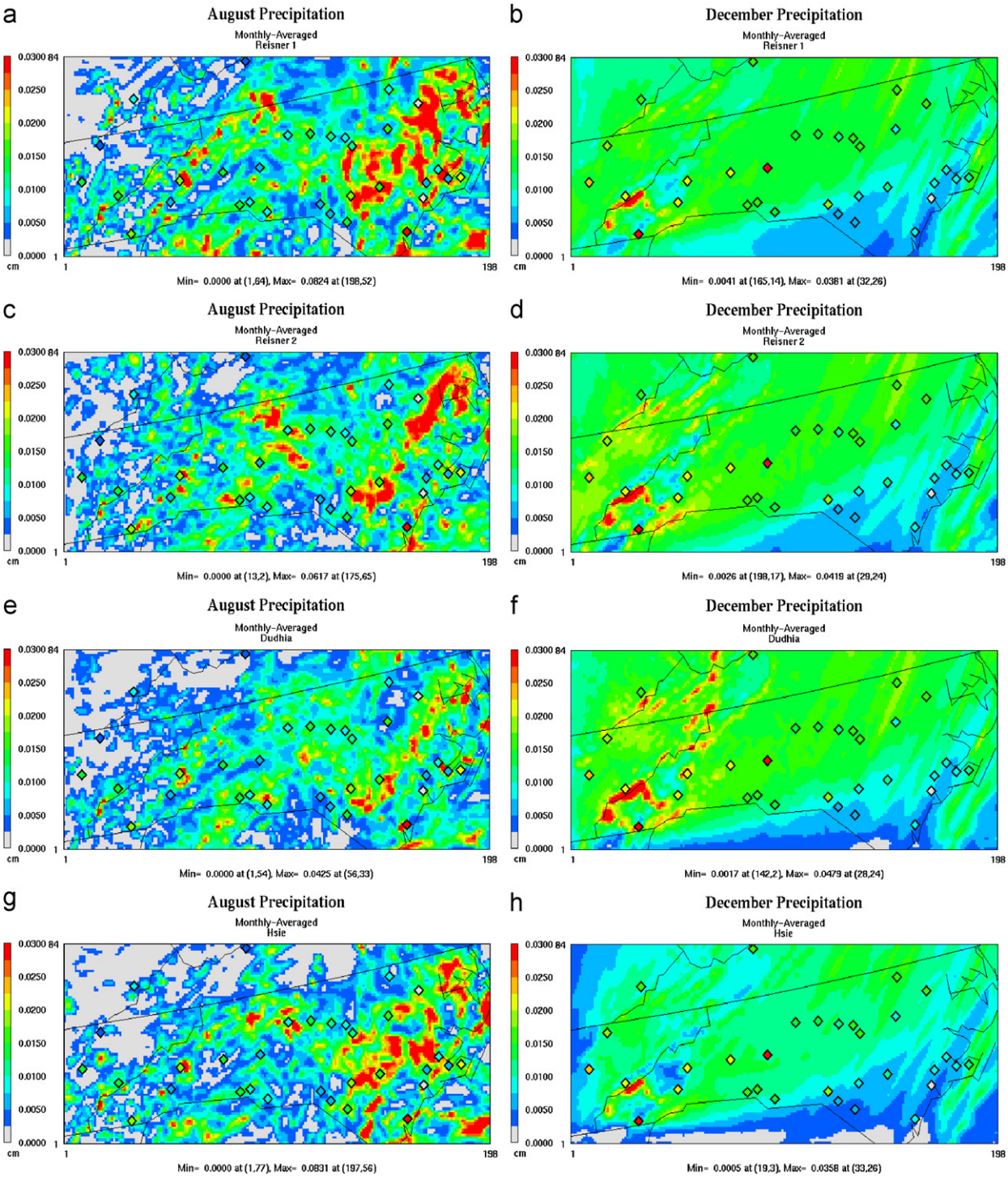

Fig. 3. Comparison between NADP and ASOS/AWOS observed (diamond) and simulated monthly-average hourly precipitation during August (left column) and December (right column) 2002 with the four explicit microphysics schemes: Reisner 1 (R1) (a and b), Reisner 2 (R2) (c and d), Dudhia (SI) (e and f), and Hsie (WR) (g and h).

The R1 and R2 give similar spatial patterns with the largest precipitation located along the southern portion of the mountain range, while the SI simulation extends the area of increased precipitation amounts throughout the Appalachians. Meteorologically, the forcing occurring in this region results from orographically enhanced precipitation developing as part of a synoptic-scale weather pattern. The higher amounts of orographic precipitation by the SI may result from its tendency to produce too much rain and snow aloft (Reisner et al., 1998; Grubisic et al., 2005). At a high grid resolution, additional precipitation aloft has been shown to advect across mountain ranges (Colle, 2004; Vellore et al., 2003), which may enhance surface precipitation amounts. The amount of precipitation simulated by the WR simulation is lower than others along the mountain range, consistent with the findings of Colle and Mass (2000) for lee-side locations. This lower precipitation may result from the scheme's simplifications that neglect the treatment of ice-phase processes.

Fig. 3 also shows the monthly-average hourly observed vs. simulated precipitation. The observed August precipitation amounts are typically below 0.02 cm throughout the domain, with slightly higher values at two sites located directly on the NC coastline. Simulated values, especially R1, R2, and WR have areas of simulated precipitation higher than 0.03 cm in the central and eastern domain where the largest overpredictions occur in August. The observed precipitation amounts in December were the highest at mountain sites and more uniform, lower in the eastern domain. Generally good agreement against the observations is found for R1, R2, and SI throughout the domain, while the WR gives larger underpredictions along the Appalachian Mountains. Overall the spatial comparisons show better agreement in December, reflective of the model's ability to better replicate the larger-scale systems than the mesoscale convection present in August.

4.2. Statistical trends

The performance statistics of the four simulation pairs are shown in Table 3. All four August simulations underpredict precipitation at the ASOS/AWOS sites, with NMBs ranging from −38.9% to −35.7%. Underpredictions also occur at NADP sites by the R2, SI, and WR, with NMBs of −14.3% to −2.8%. Only R1 overpredicts precipitation in August, with an NMB of 40.9%. As analyzed in the Part III paper (Queen and Zhang, 2008b), turning off the Kain-Fritcsh 2 cumulus parameterization at 4-km appears to be a major reason for an underprediction in precipitation by most schemes at all sites, due to the convective nature of summer precipitation. The sensitivity of monthly-average hourly precipitation to different schemes is most evident at the NADP sites. A comparison of differences in NMEs between

Table 3
Performance statistics of monthly-average hourly precipitation (mm) for August and December (values in italic) 2002

Network	Sample no.	Simulation	Mean Obs.	Mean Sim.	NMB[a] (%)	NME[a] (%)
ASOS/AWOS	19	R1	0.17	0.11	−35.7	51.0
			0.12	*0.11*	*−8.7*	*20.5*
		R2	0.17	0.11	−37.4	53.7
			0.12	*0.12*	*−0.4*	*16.9*
		SI	0.17	0.11	−36.9	47.4
			0.12	*0.12*	*−0.5*	*20.7*
		WR	0.17	0.10	−38.9	53.9
			0.12	*0.10*	*−22.9*	*28.8*
NADP	14	R1	0.11	0.15	40.9	94.1
			0.18	*0.14*	*−22.8*	*25.1*
		R2	0.11	0.10	−2.8	72.5
			0.18	*0.14*	*−17.6*	*23.8*
		SI	0.11	0.09	−14.3	75.1
			0.18	*0.16*	*−7.4*	*23.0*
		WR	0.11	0.10	−7.5	65.3
			0.18	*0.11*	*−38.7*	*38.7*

[a]NMB—normalized mean bias; NME—normalized mean error.

networks also shows increased differences among simulations at NADP sites, with NMEs ranging 65.3–94.1% compared with a narrower range of 47.4–53.9% at ASOS/AWOS sites. An examination of monthly-average hourly observed and simulated values at the sites within both networks shows the largest variations in simulated precipitation at NADP sites, in particular at NC06, NC29, NC34, NC41, and NC45 (Fig. 4). These sites are located in two distinct geographic areas, the lee-side mountain and coastal plain regions, where the largest sensitivity among simulations occur as shown in Fig. 3. The R1 gives the largest predicted precipitation at four of the five sites, NC06, NC29, NC41, and NC45, which is consistent with the large positive NMB for this simulation shown in Table 3. Meanwhile higher R2-simulated precipitation occurs at the remaining site, NC34, which is consistent with the spatial patterns in Fig. 3 that show elevated local precipitation in the western piedmont region. This localized difference in R1 and R2 simulated precipitation illustrates the differing impacts of

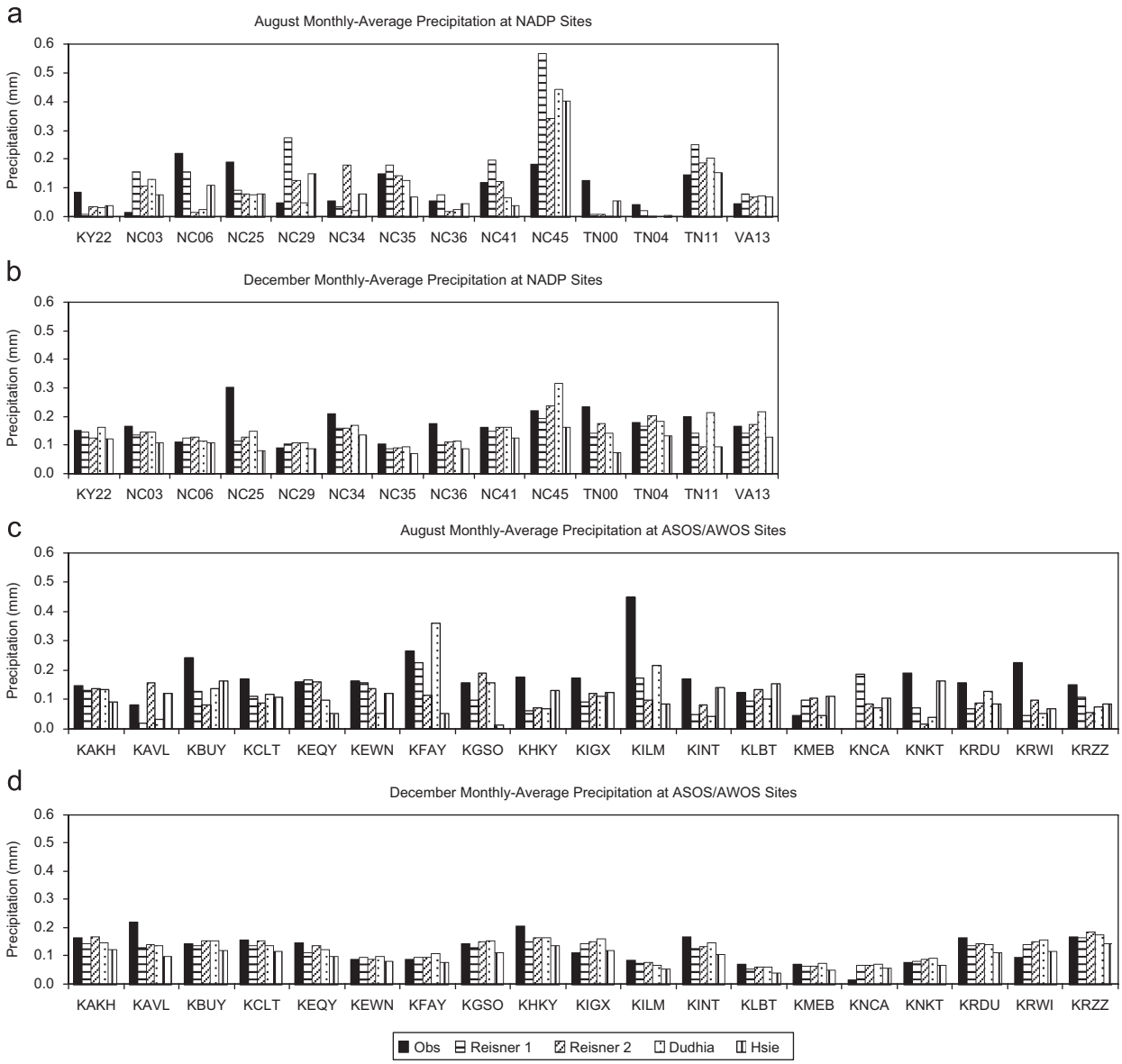

Fig. 4. Comparison between observed and simulated monthly-average hourly precipitation amounts in August and December 2002 at the NADP (a and b) and ASOS/AWOS (c and d) observational sites.

inclusion of graupel processes in precipitation predictions. This finding is consistent with Fovell and Ogura (1988), which indicates the importance of the riming processes in simulated precipitation production.

All four simulations underpredict precipitation for both networks in December. The WR gives the largest underpredictions for both ASOS/AWOS and NADP sites with NMBs of −22.9% and −38.7%, respectively. For the ASOS/AWOS network, the R2 and SI have the best performance with NMBs less than 1%. The SI performs the best at NADP sites with an NMB of −7.4%. Unlike August, the variation among different simulations is similar for both networks, showing a similar response to changes in explicit microphysics schemes throughout the domain. Similar magnitudes and variability of monthly-average observed and simulated precipitation are shown at each site for the two networks (Fig. 4), with the exception of a high observed value of 0.30 mm at NADP site NC25, which is twice the value shown at most other sites. The largest variation is found at NADP sites NC45 and TN11, which is not as significant as that in August. This seasonal difference in statistical variations is quite consistent with that in the spatial patterns shown in Fig. 3. A combination of spatial and statistical evaluation shows the best overall model performance by the R2 for August, due largely to an increased skill in the coastal plain. The R1 and SI perform similarly at ASOS/AWOS sites but have poorer performance at NADP sites. The WR performs poorly at both networks. December results show the best and the second best performance by the R2 and SI, respectively, at the ASOS sites and by the SI at NADP sites. Although the SI has shown spurious behavior in some applications causing more precipitation than R2 for complex terrains (Colle, 2004), it does not show reduced statistical performance for this episode and region. Therefore, the SI may be an optimal choice for December simulation because of its accuracy and low CPU cost.

4.3. Temporal variation

To further examine the difference in predictions in those areas showing increased sensitivity to microphysics schemes, namely, along Appalachian Mountains and eastern NC, the weekly (NADP) and daily (ASOS) total precipitation amounts are examined at specific sites in these regions, focusing on NADP sites and their site-matched ASOS sites (note that all NADP sites are matched with ASOS sites but not AWOS sites because of smaller distances between NADP sites with respect to ASOS sites). Three sites from the western (i.e., in mountain and western piedmont areas) and eastern regions are included. The western region sites are NC45 (KAVL), NC25, and NC34 (KCTL) and the eastern sites are NC03 (KRZZ), NC36 (KMEB), and NC06 (KEWN) (matching ASOS sites are given in parentheses).

Variations among weekly-simulated precipitation in August are evident at all western sites shown in Fig. 5. All sites show zero measured precipitation during 6–13 August. During the other 2 weeks, NC45 shows the largest simulated precipitation with R1 values being the largest. As noted previously, the interaction of ice and liquid phases at this mountain site may contribute to increased precipitation. Also, the differences in the R1 and R2 simulations are attributed to the inherent differences in their mixed-phase representations with respect to graupel, which influences rain production (Fovell and Ogura, 1988). The non-mountain site of NC34 shows opposite results, with R2 having higher precipitation than R1 and overall lower weekly precipitation. The influence of graupel processes with respect to the different topographic characteristics and convective nature of precipitation at NC45 and NC34 may lead to these opposing results. Daily precipitation in Fig. 6 at ASOS sites, KAVL and KCTL, show different trends in precipitation from their closely located NADP sites. For example, the KAVL site shows significantly higher R2 precipitation on 16 August (see Fig. 6), when NC45 gives the highest precipitation by R1 during this period (see Fig. 5). NC45 and KAVL are apart by 50 km but show significantly different model predictions, which may be attributed to the localized, convective precipitation taking place at both sites in August. Localized summer precipitation patterns are a feature of the NC mountains, with both the driest and one of the wettest August climates being closely located within the region (State Climate Office of NC, 2007). The week of 6–13 August was also a dry period at all three eastern NADP sites. However, at the NC36 site, a small amount of simulated weekly precipitation occurred (see Fig. 5). The site-matched ASOS sites for NC06 and NC36 also have daily-simulated precipitation on 6 August (see Fig. 6). Typically the week of 20–27 August has higher simulated precipitation at the eastern sites, with

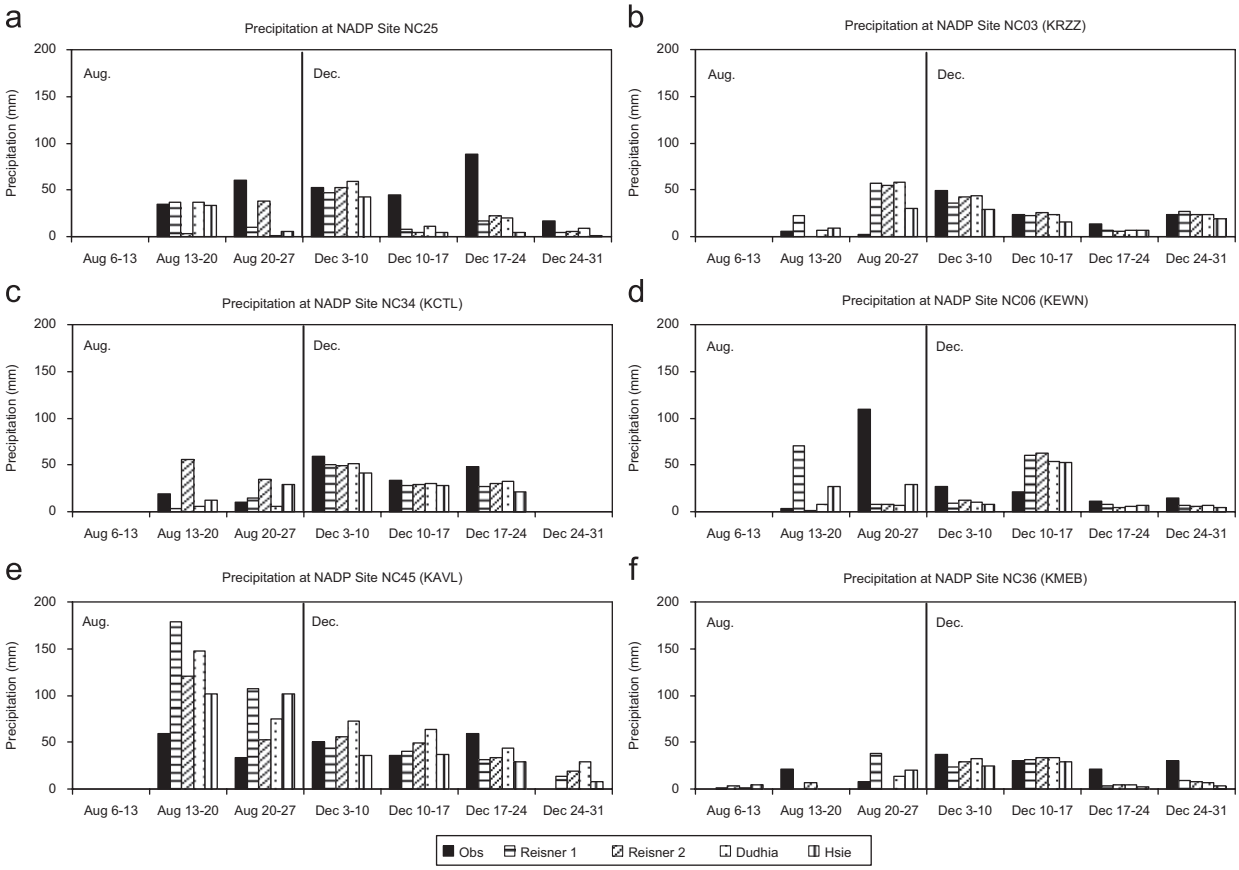

Fig. 5. Observed and simulated weekly-total hourly precipitation amounts in August and December 2002 at the NADP western (left column) and eastern (right column) region sites of North Carolina. Co-located ASOS sites are shown in parentheses.

large variations among simulations with different microphysics schemes. NC36 has higher precipitation simulated by R1 during 20–27 August, due likely to the inclusion of mixed-phases without the riming process, which can be a main sink of cloud water reducing precipitation formation in specific conditions (i.e., strong vertical forcing, convective systems) (Mölders et al., 1995). At the other two eastern sites, the simulated precipitation in 20–27 August is similar for R1, R2, and SI with larger amounts by WR at NC06 and smaller amounts at NC03. This agrees well with the monthly-average hourly precipitation spatial distribution with WR simulating higher values in the central and southern coastal plain where NC06 is located. In the northern portions of the NC coastal plain, WR has similar and slightly lower precipitation, especially when compared with the R1 and R2. Fig. 6 also shows similarity in timing but larger variations in magnitudes among simulations in 20–27 August. This similarity in timing, while magnitudes differ, suggests that typically the microphysics schemes influence the amount of rain production once a system has developed with less influence on the actual placement of the convective storms. In addition, the variations in model sensitivity between regions and particular sites reflect the random convective nature of summer precipitation.

The weekly precipitation in December at the western sites in Fig. 5 also vary from site to site, but show more consistency among simulations as compared with August. The SI gives the highest simulated precipitation at all three sites, while WR gives the lowest. One exception occurs in 17–24 December at NC25 where R2 gives a slightly higher amount than SI. The difference in magnitudes is the highest at NC45, and the lowest at NC34. NC45 is located within the mountain region, which is more susceptible to the known differences in orographic precipitation among the four simulations. NC34 is

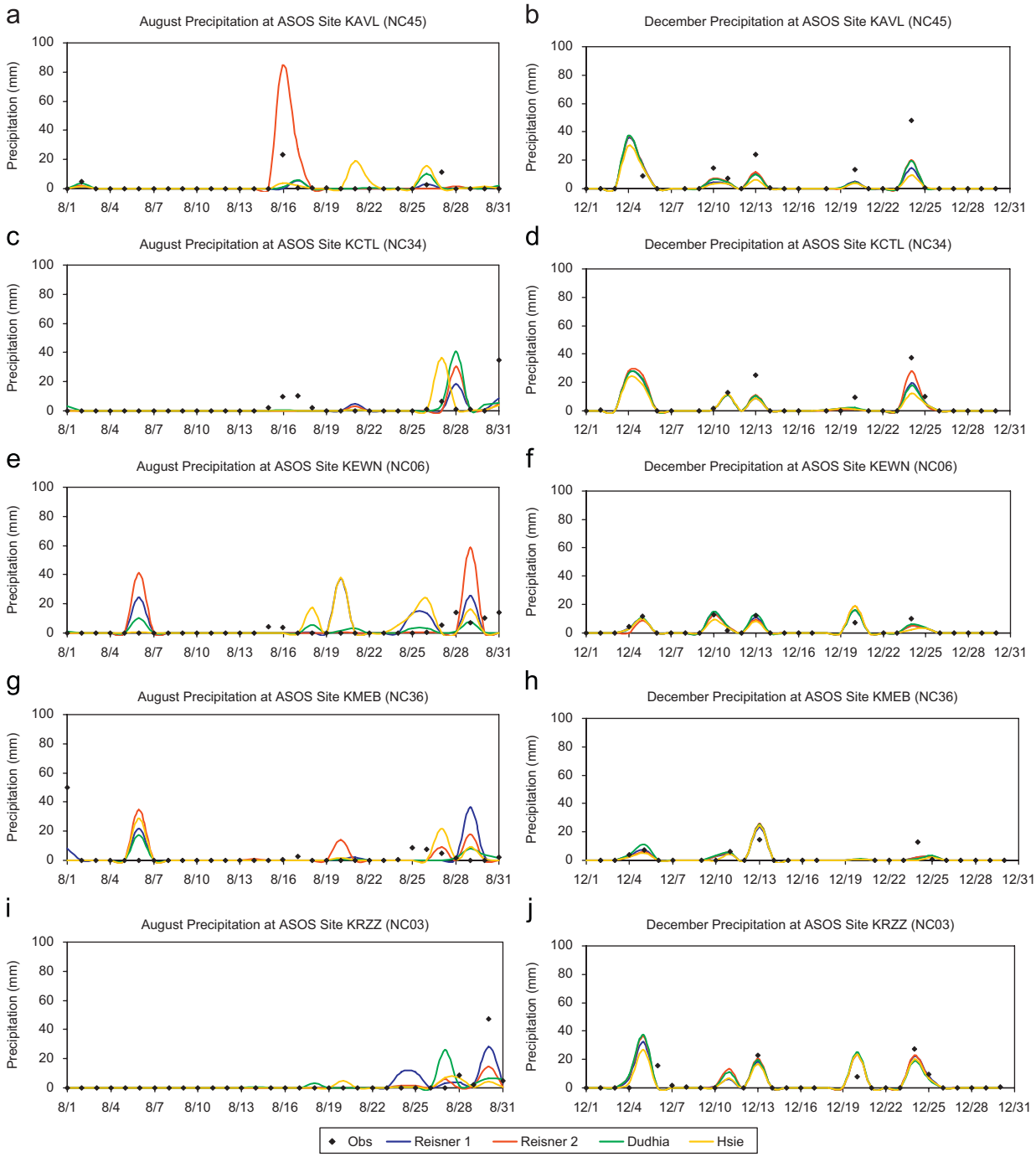

Fig. 6. Daily total precipitation amounts during August (left column) and December (right column) 2002 at ASOS sites in the western (KAVL and KCTL, a–d) and eastern (KEWN, KILM, KMEB, and KRZZ, e–j) regions of North Carolina.

further east and is less likely to have variations in simulated precipitation because of orographic influence. NC25 shows the least agreement between observed and simulated values with underpredictions occur in 10–13 December. This is consistent with the spatial results where the monthly-average hourly precipitation at NC25 is larger than 0.3 mm and the simulated values remain below 0.2 mm

(see Figs. 3 and 5). Compared with August, the magnitudes of simulated weekly precipitation are similar for the western sites, more specifically at NC45 and NC34. This similarity highlights the synoptic-scale nature of precipitation events in December. An examination of the timing and magnitudes of daily precipitation at KAVL and KCTL also shows strong similarities. In addition, the differences in magnitudes of December precipitation at these ASOS sites are significantly smaller than those in August, with the WR precipitation remaining consistently lower than the other simulated values. Weekly precipitation amounts at eastern sites do not show as much sensitivity to the microphysics scheme as the western sites in December. This is expected as the main influence for variations in simulated precipitation found at the western sites result from orographic precipitation differences. At all three eastern sites, the R1, R2, and SI results are very similar with the WR precipitation being slightly lower, except at NC06 during 17–24 December. Daily precipitation at ASOS sites is lower for the WR simulation (see Fig. 6). One exception occurs at KEWN, which shows some periods of the highest precipitation simulated by WR. The proximity of this site to the coastline compared to other sites could likely cause some differences in results. The magnitude of precipitation at the eastern sites is generally lower than those at western sites, especially during the last 2 weeks of December. This spatial pattern results from the orographic enhancement of precipitation events in the westernmost portion of the domain. Additionally, precipitation enhancement occurs for those events originating both to the west and east of the Appalachian Mountains leading to overall higher precipitation at the western sites. Compared with August, the temporal variation at the eastern sites is much smaller in winter. This is expected since the main difference at these sites in August can be attributed to the impact of the ice-phase treatment in convective storms and December precipitation does not have the same convective forcing. While an examination of both summer and winter results shows sensitivity to the microphysics schemes chosen within MM5, the dominant effect on the simulated precipitation seems to lie in the difference in amount among simulations. A trend in simulated magnitudes is more evident in December (similar results for R1, R2, and SI and noticeably lower amounts by WR), while the August results show dependence on both site location and timing of precipitation.

5. Summary

As Part I of a comprehensive evaluation and sensitivity study, this paper focuses on evaluating the model performance of MM5 with different explicit microphysics, and examining the subsequent changes in meteorological and chemical predictions associated with wet deposition processes. In August 2002, all four simulations underpredict precipitation at ASOS/AWOS sites, while all but R1 underpredict NADP precipitation amounts. The underpredictions at NADP sites are smaller than those found at ASOS/AWOS sites, which also have larger monthly-average observed values. Underpredictions by all four simulations also occur for both ASOS/AWOS and NADP sites in December. Larger differences in the precipitation totals are found between networks in August than in December, illustrating the difficulty in accurately simulating localized convective precipitation under summer conditions. Spatial patterns also indicate more variability in August precipitation and more uniform throughout the domain in December precipitation totals (with the most obvious differences occurring only along the Appalachian Mountains in December). Site-specific examination shows that both August and December precipitation amounts are sensitive to microphysics schemes with the largest differences occurring in the amount, and not timing. The timing of nearly all precipitation events is the same for all four simulations in December. August precipitation shows some sensitivity of simulated precipitation timing in the last week. Overall R1 and R2 give very similar precipitation patterns and trends, especially in December. While the SI gives more similar results to the R1 and R2 simulations, the WR shows the largest difference; this is most noticeable in December when significantly lower precipitation amounts are predicted at most locations. The trends in August are more difficult to discern for each simulation, as they vary greatly both spatially and temporally. In August, the R2 simulation shows better performance spatially and statistically while remaining consistent at sites between the two networks. The inclusion of more ice-phase processes may lead to the improved representation of convective systems in this region during the summer. Meanwhile, the simplified SI scheme shows overall better performance in this region in December, with lower underpredictions at both NADP and ASOS/AWOS sites while capturing

regional variations in precipitation, including orographic precipitation along the Appalachian Mountains. The successful application in this region, especially in the mountain region, is consistent to past research supporting the use of SI in complex terrain. Model evaluation of all four explicit microphysics schemes are also conducted for chemical variables, and the impacts of different precipitation predictions on both PM concentrations and wet deposition amounts will be presented in the Part II paper.

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Appendix A. Supporting Information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.atmosenv.2007.12.067.

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