Examining the sensitivity of MM5–CMAQ predictions to explicit microphysics schemes and horizontal grid resolutions, Part III—The impact of horizontal grid resolution

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Abstract

Examination of model sensitivity to horizontal grid resolutions can help identify optimal compromise in accuracy and computational efficiency for regulatory and research-grade applications of 3-D atmospheric models. In this Part III paper, the performance and sensitivity of simulated precipitation and wet deposition amounts by the MM5/CMAQ model to three horizontal grid resolutions (4-, 12-, and 36-km) are evaluated over North Carolina (NC).

In contrast with simulated O₃, PM₂.₅, and some PM₂.₅ species such as NH₄₊, simulated precipitation and wet deposition amounts are quite sensitive to grid resolutions. Compared with results at coarser resolutions, simulated precipitation amounts are lower in both August and December at 4-km, with the largest sensitivities to grid resolutions occurring in mountain and coastal regions of NC. For wet deposition predictions, the model performs the best for NO₃⁻ at 4-km and for NH₄₊ and SO₄²⁻ at 12-km in August, but the best for NH₄₊ and NO₃⁻ at 36-km and for SO₄²⁻ at 4-km in December. Such sensitivities and lack of clear trends in model performance at various resolutions can be attributed to seasonality in meteorology and differences in characteristics of land use, emissions and concentrations of PM precursors, as well as nonlinear responses of chemistry and meteorology to grid resolutions. The overall performance trends demonstrate a high sensitivity in precipitation and wet deposition predictions over complex terrain and the fact that higher grid resolution does not always lead to improved model performance.

Keywords: MM5; CMAQ; Sensitivity; Horizontal grid resolutions; Precipitation; Wet deposition

1. Introduction

Rapid computational technology advancements in the past two decades have enabled three-dimensional (3-D) numerical modeling applications at increasingly fine spatial resolutions. With reduced grid cell size and increased computational costs, improved air quality model (AQM) performance is generally expected due to a more detailed representation of emissions, land use, and meteorological and chemical processes. The US EPA has therefore suggested that the AQM modeling in support of state implementation plan (SIP) may benefit from increased grid resolution (US EPA, 2007). However, it continues to be a challenge to represent complexity of the atmosphere within the computational...
constraints. An examination of sensitivity of model predictions to horizontal grid resolutions can help to determine the degree of differences and/or improvements resulting from the use of finer resolutions and therefore identify optimal compromise in accuracy and computational efficiency for regulatory and scientific applications of 3-D models.

Research has shown that finer resolution atmospheric modeling is particularly important for reproducing the actual structure of the atmosphere. For example, the accurate modeling of the structure and evolution of convective systems has shown improvements with smaller grid-spacing, with slower convective evolution (Weisman et al., 1997; Mass et al., 2002), larger errors in heavy precipitation events (Weisman et al., 1997; Grabowski et al., 1998; Mass et al., 2002), and much weaker developed updrafts (Weisman et al., 1997) at coarser resolutions. All these factors associated with the simulation of precipitation will affect the amounts and location of pollutant scavenging by convective precipitation. Several meteorological parameters such as wind fields, planetary boundary layer (PBL) height, and turbulent kinetic energy (TKE), known to have direct implications on air quality via dispersion and transport, also show sensitivity to horizontal resolution (Salvador et al., 1999; Baklanov et al., 2002; Jimenez et al., 2005). An increased grid resolution also provides a more detailed and accurate representation of key factors (e.g., complex terrain features, emission sources, urban characteristics) that influence air pollutants (Jang et al., 1995a; Baklanov et al., 2002; Jimenez et al., 2005). While the average transport of non-reactive pollutants does not show sensitivity to grid resolution, reactive species are sensitive (Jang et al., 1995a, b), illustrating the nonlinear relationship between chemistry and horizontal grid resolution. The horizontal resolution affects the representation of chemical processes and characteristics, such as O3 formation efficiency and nighttime O3 titration, with an improved performance at finer resolution (Mathur et al., 2005). The inability of the models at a coarser resolution to accurately represent different air masses and their blending has also been suggested as a possible source of errors causing reduced model performance for O3 predictions (Liang and Jacobson, 2000). Studies have also shown that finer grid resolutions do not always give better performance, due to the complexity in chemistry and meteorology and their nonlinear interactions and responses to grid resolution (Zhang et al., 2006a, b; Wu et al., 2008).

In this Part III paper, the sensitivity of meteorological (e.g., precipitation amounts and cloud coverage) and chemical predictions (e.g., particulate matter (PM) concentrations and wet deposition amounts) to horizontal grid resolution (4-, 12-, and 36-km) for August and December is examined. The 4-km simulations are based on Wu et al. (2008), and the 12- and 36-km simulations are taken from the Visibility Improvement State and Tribal Association of the Southeast (VISTAS) Phase II modeling efforts (Morris and Koo, 2004). The domains of all three simulations are shown in Fig. 1 in the Part I paper (Queen et al., 2008). A complete description of the 4-km simulation results for August and December and observational datasets for model evaluation can be found in Wu et al. (2008), Queen et al. (2008) (Part I), and Queen and Zhang (2008).

![Fig. 1](image-url) Observed (diamond) and simulated monthly average hourly precipitation in August ((a)–(c)) and December ((d)–(f)) 2002 at horizontal resolutions of 4-km (left), 12-km (middle), and 36-km (right).
(Part II). The observational datasets included in this study include precipitation from the Automated Surface Observing System/Automated Weather Observation System (ASOS/AWOS), precipitation and wet deposition from the National Acid Deposition Program (NADP), O₃ and PM NH₄⁺, NO₃⁻, and SO₄²⁻ from the Clean Air Status and Trends Network (CASTNET), O₃ and PM₂.₅ from the Air Quality System (AQS), and PM₂.₅ and its composition from the Interagency Monitoring of Protected Visual Environments (IMPROVE) and the Speciated Trends Network (STN). All model configurations, except for horizontal grid resolution and the cumulus parameterization, which is turned off in the 4-km simulation, remain unchanged for the simulations with different grid resolutions.

Several studies have evaluated the sensitivity of model predictions over NC to horizontal grid resolutions. Mathur et al. (2005) and Arunachalam et al. (2006) evaluated the impact of grid resolution on O₃ simulated by the Multiscale Air Quality Simulation Platform (MAQSIP) for 19–25 June 1996 and a few days in summers 1995–1997, respectively. Neither work assesses the impacts of grid resolutions on meteorology and PM₂.₅ concentrations and wet deposition amounts. Our earlier assessment of such impacts (Wu et al., 2008) was conducted in terms of only statistical performance for the model predictions of meteorological (i.e., daily mean values of temperature, specific humidity, wind speed, wind direction, and precipitation) at 4- and 12-km and chemical variables (i.e., maximum 1- and 8-h average O₃ mixing ratios, 24-h average PM₂.₅ and its composition, and weekly wet deposition of NH₄⁺, NO₃⁻, and SO₄²⁻) at 4-, 12-, and 36-km for both August and December 2002. Evaluation of such impacts has not been done for spatial variability and temporal variation, as well as the correlation of responses between meteorological and chemical variables, which is the focus of this Part III paper.

### 2. Evaluation of cloud and precipitation amounts

#### 2.1. Statistical performance

Using observed hourly temperature (T), specific humidity (SH), and surface wind speed (WS) and direction (WD) from the University Corporation for Atmospheric Research’s (UCAR) ds472.0 (TDL) archive and weekly precipitation from the NADP network, Wu et al. (2008) have shown that the results at 4- and 12-km are quite similar, with slightly better results at 4-km for daily and hourly mean T, SH, and WS in August 2002 and for WD in December 2002. However, larger differences exist for monthly average hourly precipitation predictions, particularly at the ASOS/AWOS network sites. Table 1 shows performance statistics for August precipitation amounts at both the NADP and ASOS/AWOS network sites. The simulated domain-wide monthly average hourly precipitation amounts show increasing values with increased grid size for both networks. The performance becomes worse with increased grid size, with overall larger overpredictions of summer precipitation amounts at NADP sites (NMBs of 40.9%, 57.1%, and 121.5% at 4-, 12-, and 36-km, respectively). Statistics at ASOS sites show opposite trends, with better domain-wide performance for simulations with coarser resolutions (NMBs of −35.7%, −25.1%, and −7.1% for 4-, 12-, and 36-km simulations,

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<tr>
<th>Network</th>
<th>ASOS/AWOS</th>
<th>NADP</th>
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<td>12-km</td>
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<td>0.15</td>
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<td>36-km</td>
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<tr>
<td>Mean simulated</td>
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<tr>
<td>0.11</td>
<td>0.14</td>
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<td>NMB (%)</td>
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<td>36-km</td>
<td>121.5</td>
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<td>NME (%)</td>
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<td>103.8</td>
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aNMB: normalized mean bias.
bNME: normalized mean error.

Table 1
Performance statistics of monthly average hourly precipitation (mm) for August and December (values in italic) 2002
respectively). Statistics for December also show increased simulated precipitation amounts with larger resolutions. These differences result in less underpredictions at 12-km (NMB of −4.1%) as compared with the 4-km results (NMB of −22.8%) and moderate overpredictions at 36-km (NMB of 16.8%) at NADP sites. Increased precipitation amounts with coarser resolutions also occur at the ASOS/AWOS sites, with NMBs of −8.7%, 12.5%, and 20.6% at 4-, 12-, and 36-km, respectively.

2.2. Spatial distribution

Fig. 1 compares spatial distributions of simulated and observed monthly average hourly precipitation amounts at three grid resolutions in August and December. The degree of detail is lost with increased grid size. The localized precipitation maximums at 4-km are not as evident as those at the coarser resolutions throughout the domain. This difference is especially evident in the NC coastal plain region where the areas of maximum precipitation cover much larger areas and the sporadic convective nature of summer precipitation is not well characterized. The precipitation patterns in the western domain also show significant differences, with little or no precipitation amounts in the northwest corner at 4-km but >0.1 mm at coarser resolutions. The high spatial variation trend of precipitation in the complex terrain area of the Appalachian Mountains becomes smooth at the coarser resolutions, especially at 36-km. The increased sensitivity in the western domain indicates the greater impact of the grid resolution on precipitation in regions of complex terrain. As with the August results, noticeable differences in simulated precipitation in December occur in the western domain, especially upwind of the Appalachian Mountains where higher precipitation amounts occur at coarser resolutions. Because enhanced precipitation trends with coarser resolutions in this region occur in both August and December, the differences in the treatment of orographically induced precipitation processes at different grid-scale may dominate differences in the simulated precipitation amounts in this region. The southeastern NC is another area showing differences where simulations at 12- and 36-km produce increased precipitation amounts, including an area of maximum precipitation off the southeastern NC coast.

The large differences in the spatial distribution of precipitation between 4-km and coarser resolutions can be attributed to several factors. For example, the Kain-Fritsch 2 cumulus parameterization is used at 12- and 36-km and is turned off at 4-km. Such a difference affects model predictions, particularly in August, when the convection has a larger contribution to total cloud fractions and precipitation because of the more convective nature of summer weather conditions. The impact of different cumulus treatments can be clearly seen in simulated cloud fractions in Fig. 2. While simulated cloud fractions are somewhat different at various resolutions in both months, substantial differences exist between 4-km and coarser resolutions in August. While the precipitation is higher at coarser resolutions, the cloud fractions are lower at coarser resolutions, because controlling processes

![August Cloud Fraction](image1)

![December Cloud Fraction](image2)

Fig. 2. Observed (diamond) and simulated monthly average hourly cloud fraction in August ((a)–(c)) and December ((d)–(f)) 2002 at horizontal resolutions of 4-km (left), 12-km (middle), and 36-km (right).
for precipitation and cloud fractions are somewhat different and their sensitivities to grid resolutions are different. Differences in land surface characteristics (e.g., terrain heights and land use categories) at different grid resolutions also contribute to differences in model predictions, because they can influence the development and structure of local circulations. The largest difference in terrain is along the Appalachian Mountains (the highest elevation in the domain), with maximum heights of 1616, 1279, and 1105 m at 4-, 12-, and 36-km, respectively. In the eastern domain, a large portion of the mesoscale circulations likely result from differential surface heating (i.e., sea-breeze and sandhills initiated convection). At coarser resolutions, the differences in surface heating could be smoothed over the larger grid-scale leading to reductions in impacts of differential surface heating. Since orographically induced precipitation dominates in December, the differences in terrain characteristics are expected to influence model results at different resolutions. Reduction in spatial detail at coarser resolutions is also apparent in land use information (not shown here), particularly in the mountain and coastal regions. Those factors explain the differences in simulated precipitation

Fig. 3. 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.
amounts at various resolutions over such regions of complex terrain, in particular at 12- and 36-km with similar model configurations.

2.3. Site-specific analyses

Fig. 3 compares the observed and simulated monthly average hourly precipitation at individual sites for both August and December. The largest increases in simulated summer precipitation at coarser resolutions occur at a number of ASOS/AWOS (e.g., KAVL, KEWN, KINT, KLBT, KMEB, KNKT, KRDU, KRWI, and KRZZ) and NADP (e.g., KY22, NC03, NC25, NC34, NC35, NC36, TN04, and VA13) sites. Since the precipitation amounts simulated at 4-km are overall underpredicted at ASOS/AWOS sites but overpredicted at NADP sites, such increases at coarser resolutions improve the model performance at ASOS/AWOS sites but worsen that at NADP sites. Further examination of the observed and simulated weekly total precipitation amounts at the western NADP

![Figures](https://example.com/figures)

Fig. 4. Observed and simulated weekly total precipitation amounts in August and December 2002 at the NADP sites in the western (left) and eastern (right) domains.
sites in August shows different trends at specific sites (see Fig. 4). The largest sensitivity to horizontal grid resolution is found at those sites closest to the Appalachian Mountains (e.g., NC25 and NC45). Increased precipitation amounts with increased grid size occur at NC25, which are located further west. However, such increases do not occur with the same magnitude at 12- and 36-km. For example, at NC25, the 36-km simulation predicts significantly higher precipitation amounts, the 12-km simulation gives slightly higher precipitation during 20–27 August but much lower during 13–20 August. At TN11, the 12-km simulation shows the highest precipitation amounts, whereas the 36-km simulation gives the lowest. Decreasing precipitation amounts occur with increased grid resolutions at NC45. At most sites in both the western and eastern domains, non-zero precipitation amounts are predicted at 12- or 36-km or both where little precipitation is predicted at 4-km. In the eastern domain, the 36-km simulation predicts the highest overall precipitation amounts only at NC03, with diverse variations at other sites.

Compared with August, simulated precipitation amounts in December are less variable among the three simulations at both ASOS/AWOS and NADP sites (Fig. 3). The largest differences in simulated monthly average hourly precipitation amounts in December, occur at the western-most NADP sites such as KY22, NC25, TN00, TN04, and TN11 (Fig. 4). The site showing the largest sensitivity to the grid resolution is NC25, located in the southern mountains, where higher amounts are predicted at 12- and 36-km. NC34, located furthest away from the Appalachian Mountains, shows the least variability. These results illustrate that the largest differences in precipitation amounts simulated at various resolutions occur in the more complex terrain regions. By contrast, little variability is found at the eastern NADP sites indicating a reduced influence of the grid resolutions in December in regions with less complex terrain.

3. Evaluation of PM concentrations and wet deposition amounts

3.1. Statistical performance

While Mathur et al. (2005) reported improved O3 performance with increased grid resolution over NC, Arunachalam et al. (2006) showed similar O3 performance at 4- and 12-km, with slightly more apparent differences between 4/12- and 36-km. Our evaluation of O3 performance at 4-, 12-, and 36-km is consistent with Arunachalam et al. (2006) (see Wu et al., 2008). As described in Wu et al. (2008), the model performance in terms of simulated maximum 1- and 8-h O3 mixing ratios is slightly better at 12- and 36-km in August but the same or slightly worse in December. PM2.5 predictions at 4-km are generally better at AQS and STN sites, nitrate (NO3\textsuperscript{-}) at all sites, and sulfate (SO4\textsubscript{2}\textsuperscript{-}) at IMPROVE sites in August. They are generally better or similar for PM2.5, ammonium (NH4\textsuperscript{+}), NO3\textsuperscript{-}, black carbon (BC), and organic matter (OM) at IMPROVE and CASTNET sites and for SO4\textsubscript{2}\textsuperscript{-} at STN and CASTNET sites in December. Overall, the results between 4- and 12 km are not significantly different for PM2.5, NH4\textsuperscript{+}, BC, and OM in August and BC and OM in December, due to the lesser sensitivity of emissions to grid resolution for this episode. However, relatively more pronounced differences are found in PM2.5 in December and SO4\textsubscript{2}\textsuperscript{-} and NO3\textsuperscript{-} concentrations in both months, indicating higher sensitivity to nonlinearity in chemistry and meteorology (e.g., via cloud fractions and precipitation which affect aqueous-phase formation of SO4\textsuperscript{2}\textsuperscript{-}) due to different grid resolutions as compared with that of emissions.

In addition to different details in terrain and land use at different grid resolutions, the influence of different distribution and magnitudes in emissions of precursors to PM NH4\textsuperscript{+}, NO3\textsuperscript{-}, and SO4\textsubscript{2}\textsuperscript{-} formation may also impact model performance. As shown in Supplementary Figs. A-1 and A-2 online, the coarser simulations do not provide as much detail regarding NH3, NOx, and SO2 emissions. This difference is especially true in larger urban areas for NOx and SO2 emissions, where the larger grid sizes do not show the strong contrast of elevated emissions as compared with surrounding areas. Overall the spatial trends in emissions are captured throughout the domain by all three simulations, including the seasonal differences for these species. However, some areas including the urban areas, as well as, directly to the west of the Appalachian Mountains do show more visible differences in emission magnitudes. Such differences can lead to differences in simulated PM precursors, concentrations of NH4\textsuperscript{+}, NO3\textsuperscript{-}, and SO4\textsubscript{2}\textsuperscript{-} and their subsequent wet deposition at different grid resolutions. As shown in Supplementary Figs. A-3 and A-4 online, the predicted concentrations of gas-phase precursors (i.e., NH3, NOx, HNO3, and SO2) show the most
noticeable differences between the 4-, 12-, and 36-km simulations in local maximum concentration areas. For NH₃ these areas are the northwest and southwest of NC, where the emissions of NH₃ are also maxima. All other gas-phase species show localized maxima in urban areas generally located in central NC. Higher concentrations are found for NH₃, NOₓ, and SO₂ at 4-km but for HNO₃ at coarser resolutions. For NOₓ and HNO₃, differences in the oxidation of NOₓ to form HNO₃ may explain opposite trends within the three simulations, illustrating the nonlinearity of chemistry at different resolutions. The differences in spatial distributions and magnitudes of simulated gas-phase and PM concentrations can be attributable to differences in characteristics of emissions, transport, and chemical transformation at various resolutions, as well as the impact of averaging over grid cells of different dimensions.

A more detailed analysis of the seasonalities and sensitivity of emissions of PM₂.₅ gaseous precursors such as NH₃, NOₓ, and SO₂ and simulated concentrations of PM₂.₅ and its gaseous precursors such as HNO₃, NH₃, NOₓ, and SO₂ to grid resolutions is provided in Appendix I online.

Table 2 shows performance statistics of wet deposition predictions for August and December. The 4- and 36-km simulations have very similar performance for NH₄⁺ (with NMBs of 35.9% and 35.6%, respectively) in August. The 12-km simulation has better performance with less overpredictions (NMB of 4.3%). For SO₄²⁻, the 12-km simulation performs the best (with an NMB of 20.4%) and the 4-km simulation performs the worst (with an NMB of 85.1%). In contrast, the 12-km simulation has the worst performance for NO₃⁻ (NMB of −60.2%), while the 4-km simulation shows the least underpredictions (NMB of −37.3%). The largest difference in performance statistics of wet deposition amounts of NO₃⁻ and SO₄²⁻ occurs between 4- and 12-km, consistent with large spatial variations between the two resolutions as shown in Fig. 5. The lower simulated wet deposition amounts at 12-km lead to larger underpredictions in NO₃⁻ wet deposition, but less overpredictions for NH₄⁺ and SO₄²⁻ wet deposition. In this case, the coarser grid resolution may not always deteriorate model performance.

The simulated wet deposition amounts at 4- and 12-km in December do not show significant differences in terms of statistics. For NH₄⁺ and NO₃⁻ wet deposition, the finer resolution simulations perform the worst, with larger overpredictions at 12-km (NMBs of 33.9% and 39.5%, respectively) and 4-km (NMBs of 32.9% and 42.3%, respectively). For SO₄²⁻ wet deposition, the 36-km simulation has the largest underpredictions, with an NMB of −39.4%. However, the variation in statistics is smaller in December than that in August. These results indicate that seasonal conditions influence the degree of sensitivity of wet deposition predictions to grid resolution.

### 3.2. Spatial distribution

Figs. 5 and 6 compare the spatial distributions of wet deposition of NH₄⁺, NO₃⁻, and SO₄²⁻ in August and December. The 4- and 12-km in December do not show significant differences in terms of statistics. For NH₄⁺ and NO₃⁻ wet deposition, the finer resolution simulations perform the worst, with larger overpredictions at 12-km (NMBs of 33.9% and 39.5%, respectively) and 4-km (NMBs of 32.9% and 42.3%, respectively). For SO₄²⁻ wet deposition, the 36-km simulation has the largest underpredictions, with an NMB of −39.4%. However, the variation in statistics is smaller in December than that in August. These results indicate that seasonal conditions influence the degree of sensitivity of wet deposition predictions to grid resolution.

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<td><strong>Performance statistics of monthly average hourly wet deposition amounts (g ha⁻¹) of NH₄⁺, NO₃⁻, and SO₄²⁻ for August and December (values in italic) 2002</strong></td>
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<td><strong>NMB (%)</strong></td>
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<td><strong>NME (%)</strong></td>
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aNMB: normalized mean bias.
bNME: normalized mean error.
and December, respectively. For August simulations, the area with elevated ($>1.0 \text{ g ha}^{-1}$) $\text{NH}_4^+$ wet deposition amounts extends into central NC and along the lee-side of the Appalachian Mountains at 4-km but only occurs in southeastern NC at coarser resolutions. The wet deposition of $\text{NO}_3^-$ shows local maxima in western and central NC at 4-km, which have been smoothed out at 12- and 36-km. For wet
deposition of SO$_4^{2-}$, the coarser simulations also show overall lower simulated values throughout most of NC, except at the grid cell northeast of the Clinton Crops Research Station (NC35) (see Fig. 5(i)) and near the eastern portion of the NC/VA border where the simulated wet deposition amounts are lower at 12-km but higher at 36-km. Additionally, increased amounts of SO$_4^{2-}$ wet deposition are found at 12- and 36-km along the western side of the Appalachian Mountains in August.

For December simulations, decreased NH$_4^+$ wet deposition amounts are found at both 12- and 36-km in central NC and along the NC/TN border at 36-km. The wet deposition amounts of NH$_4^+$ have only one area of maximum values at 36-km compared with localized heavy amounts evident throughout the domain at 4-km. Similar to NH$_4^+$, the wet deposition amounts of NO$_3^-$ decrease throughout the domain with increased grid size in December. Elevated amounts are found along the NC/TN and NC/SC borders at 4-km, which are not evident at 36-km. In addition, areas of local minimum NO$_3^-$ wet deposition occur in the extreme northwest corner of NC at 12-km, which occur in a much smaller area at 4-km. For SO$_4^{2-}$ wet deposition, enlarged areas of localized minima occur at 12- and 36-km in northwest NC into southwest VA, as well as, in the central and eastern portions of NC, especially at 36-km.

3.3. Site-specific analyses

Fig. 7 shows temporal trends in predicted wet deposition amounts in August and December at selected western and eastern NADP sites. In August (Fig. 7(a)–(f)), simulated wet deposition amounts of SO$_4^{2-}$ are higher than those of NH$_4^+$ and NO$_3^-$. The largest variations among the three grid resolutions typically occur during 20–27 August. Both NC45 and NC34 show higher amounts at 4-km during this week. However, higher wet deposition occurs at 36-km at NC25. Similar to precipitation predictions, the results vary among sites owing to the variability in mesoscale meteorological conditions. The variations in wet deposition amounts of SO$_4^{2-}$, along with NH$_4^+$ and NO$_3^-$, may be attributable to their dependence on precipitation, which is highly variable during the summer in this region (see Fig. 4). Similar variations occur throughout August at the eastern sites, with the largest wet deposition of SO$_4^{2-}$. The sensitivity to grid resolution is most apparent for SO$_4^{2-}$ at those eastern sites located in more southern parts of central and eastern NC, where the 4-km simulation tends to give higher values. This is also true for NO$_3^-$ wet deposition. Additionally, at NC03, the 12- and 36-km simulations predict higher amounts of wet deposition of all three species as compared with 4-km predictions during 6–13 August, when neither precipitation nor wet deposition was observed. The model bias with non-zero predicted precipitation amounts at 12- and 36-km in August is apparently responsible for biases in wet deposition predictions.

For December simulations (Fig. 7(g)–(l)), both NC45 and NC34 show increasing wet deposition amounts with finer horizontal resolutions during most periods, especially for NO$_3^-$ and SO$_4^{2-}$ wet deposition totals, whereas no clear pattern in magnitudes is found at NC25. This is similar to the simulated variations at those sites in August. The locations of the three NADP sites relative to the Appalachian Mountains may contribute to different trends at those sites. The impact of the horizontal resolutions on wet deposition processes shows dependence on the actual location relative to the mountain range in August and December. Overall the variability among the three simulations at the eastern sites is not as large as that at the western sites, illustrating the higher sensitivity to horizontal resolution in complex terrains.

4. Summary

The sensitivity of MM5/CMAQ predictions, in particular, precipitation and wet deposition amounts to different horizontal grid resolutions is examined in this Part III paper. While Arunachalam et al. (2006) have shown limited benefit with higher grid resolutions in O$_3$ modeling for NC due to little sensitivity in simulated O$_3$ mixing ratios to horizontal grid resolutions, our work has demonstrated moderate sensitivity of PM$_{2.5}$ predictions and high sensitivity of precipitation and wet deposition amounts to grid resolution, indicating a need for further sensitivity and benefit studies with finer grid resolutions for specific applications. The impact of horizontal resolution on meteorological and chemical predictions varies with particular regions and seasons having increased sensitivity. Geographically, the largest variations among the three different resolutions occur in the areas of complex terrain such as the eastern domain in summer.
and along the Appalachian Mountains in winter. The differences in simulated concentrations and wet deposition amounts can be attributed to differences in characteristics in emissions, precipitation, transport, and chemical reactions at different grid resolutions.
While Mathur et al. (2005) found that the 4-km grid resolution provides the most realistic O\textsubscript{3} simulation due to better representation of the downwind lateral dispersion of emissions and their chemical evolution, we found in this study that this conclusion is not always true for all meteorological and chemical predictions and in particular for predictions of precipitation, PM\textsubscript{2.5} concentrations, and wet deposition amounts. We also found that the 4-km simulation does not always enhance model performance. For example, as shown in our earlier work in Wu et al. (2008), SO\textsubscript{4}\textsuperscript{2-} predictions at 4- or 12-km resolutions are not always better than those at a 36-km resolution, indicating high nonlinearity in secondary PM\textsubscript{2.5} simulation. In August, the 4-km simulation shows the best results for precipitation, because the finer resolution can simulate mesoscale precipitation processes more accurately. The 4-km simulation also has the best performance for NH\textsubscript{4}\textsuperscript{+}, and NO\textsubscript{3}\textsuperscript{-} wet deposition amounts, showing the impact of improved meteorological representation on wet deposition predictions. However, SO\textsubscript{4}\textsubscript{2-} wet deposition is poorly simulated by the 4-km simulation, resulting from its poor concentration predictions. In December, the 12-km simulation actually has better results for precipitation but worse for PM concentrations. The appropriateness of finer grid resolutions should be therefore evaluated for specific applications. Observational datasets that provide increased temporal and spatial details along with co-located meteorological and chemical data will be valuable and lend further insight on the sensitivity and appropriateness of different horizontal grid resolutions for 3-D AQM applications.

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Appendix A. Supplementary Materials

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.atmosenv.2008.02.035.

References


