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Examples of Using WRF-Chem for Aerosol-Climate Applications

William I. Gustafson Jr., Yun Qian, Elaine G. Chapman,
Steven J. Ghan, Richard C. Easter, L. Ruby Leung, and Jerome D. Fast

Atmospheric Science and Global Change Division, Pacific Northwest National Laboratory

1. Introduction

Aerosol effects on climate are an important area of study; our lack of understanding about them introduces large uncertainty in our understanding of climate change. In fact, aerosol effects have the largest uncertainty of the identified contributions to atmospheric climate change in the IPCC AR4 report (Solomon et al. 2007). With the latest release of WRF-Chem (v2.2) a powerful tool is now available to the public for investigate the interplay between aerosols and climate from urban to continental scales, with the potential, in theory, to work up to global scales. The modeling system incorporates a fully interactive coupling between the chemistry-aerosol and meteorology (radiation and cloud-physics) portions of the model. Two examples of how this tool can be used are presented in this paper. The first investigates the impact of assuming uniform CCN distributions across model grid cells within a global climate model. The second uses black carbon deposition from a year-long WRF-Chem run to investigate the impact of carbon on the snow pack of the western United States.

Modules have been progressively added to WRF-Chem to enable its use for fully interactive aerosol-climate investigations. Specifically, WRF-Chem includes parameterizations for the shortwave portion of the direct effect (absorption and scattering of radiation by aerosols), the first indirect effect (changes to cloud albedo due to changes in the cloud condensation nuclei (CCN) count), and the second indirect effect (changes to the cloud lifetime and precipitation due to changes in CCN). Each of these effects is reproduced by linking the MOSAIC sectional aerosol model (Zaveri et al. 2007) with the appropriate physics parameterizations: the aerosol optical properties and cloud droplet number are passed to the shortwave radiation scheme, and the aerosol number, size, and hygroscopicity are used to diagnose activated CCN, which is passed to the microphysics scheme. Currently, the Goddard Space Flight Center shortwave scheme and Lin microphysics scheme (Skamarock et al. 2005) are the only parameterizations linked with the aerosols, but future plans include merging the effects into other schemes. More detailed descriptions of these parameterizations can be found in Fast et al. (2006) for the direct effect and Gustafson et al. (2006) and Gustafson et al. (2007) for the indirect effects.

Corresponding author: William.Gustafson@pnl.gov

2. Sub-grid spatial variability of CCN

As awareness of the impact of the aerosol indirect effects on climate grows, GCM developers have begun incorporating this process into their models (e.g. Ghan et al. 2001; Menon et al. 2002; Storelvmo et al. 2006). By necessity, the sub-grid scale information regarding aerosol size and composition has been disregarded due to computational constraints. However, nonlinearity in the cloud system potentially makes this assumption problematic. With WRF-Chem we have been able to do an initial test of this assumption over western Pennsylvania (Gustafson et al. 2007). This area was chosen because it has very spatially heterogeneous aerosol distributions due to many large power plants. It also is the site of the New England Air Quality Study 2004 (NEAQS2004) field experiment during the summer of 2004, which has been used to validate the model simulation.

The general approach to the problem is as follows. First, we performed a control simulation for an area the size of a GCM column over Pennsylvania using detailed aerosol physics and feedbacks, and nesting down to a grid spacing of 2 km. We labeled this the "interactive aerosol" (IA) simulation. This simulation was then used to calculate an "average" aerosol distribution representing the information available in a typical GCM grid column. This was done two different ways. The first was by making horizontal averages for each time by level, resulting in a time and height varying, yet spatially averaged aerosol distribution. The second was to

make the averages over all time, in the horizontal, and within the bottom 20 model levels (roughly the height of the daytime boundary layer) resulting in a single uniform aerosol distribution. With these two averaged aerosol distributions, two more "prescribed aerosol" simulations were performed, substituting in the prescribed aerosol distributions for the particulates available to form CCN. For the simulation using the distribution averaged only in the horizontal, the simulation was labeled PA_{XY}. The simulation using the constant distribution was labeled PA_{XYZT}. Then, by comparing the three runs, one could see how the loss of information due to averaging affects the cloud and radiation fields. Figure 1 shows the results, in terms of domain averaged time series of cloud optical depth (COD), cloud fraction (defined as the percent of columns in the domain with COD<1), downwelling shortwave radiation, and cloud water. The aerosol averaging leads to a reduction in average shortwave radiation of 11 W m^{-2} (3 W m^{-2}) and a 27% (6%) increase in cloud optical depth for PA_{XYZT} (PA_{XY}) versus IA.

The results indicate that accurately representing the CCN distribution is important for reproducing the cloud field. However, the differences between the prescribed and interactive aerosol simulations are presumably smaller than the errors generated by most cloud parameterizations. Even so, if this bias persists throughout long-term simulations used for climate change assessment, the differences could become significant. This suggests that GCMs which simulate vertical and temproal fluctuations in CCN distributions are likely to be much more accurate and better able to capture regional cloud variations.

3. Black carbon deposition on snow

The importance of black carbon (BC) content in snow is beginning to be recognized observationally (e.g. Stohl et al. 2006; Stohl et al. 2007). However, little work has been done to understand the process in a detailed manner, and minimal modelling has been done to investigate the impact over large areas (e.g. Jacobson 2004). With WRF-Chem, a detailed climatology of carbon deposition on the snow pack can be created by tracking the BC deposition over time within the model. As a first attempt to demonstrate this capability, this has been done for the western United States for a year-long simulation beginning in September 2003 using 12-km grid spacing. The mass of BC deposited via dry deposition, wet deposition concurrent

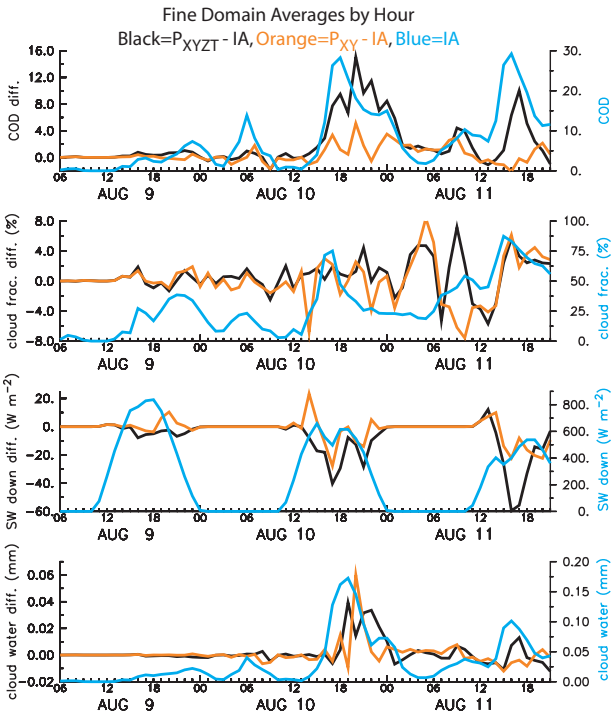

Figure 1 Time series of cloud optical depth (COD), cloud fraction (as percent of domain columns with COD>1), downwelling shortwave radiation, and cloud water content. The back line is the difference between PA_{XYZT} and IA, the orange line is the difference between PA_{XY} and IA, and the blue line is the value of the variable for IA. The blue lines correspond to the secondary y-axes on the right side.

with rain, and wet deposition concurrent with snowfall was saved on an hourly basis, along with the snow depth and surface meteorological variables. Other meteorological variables, e.g. the 3-D fields, were saved every six hours to minimize storage requirements. A simplified setup for MOSAIC was also used by reducing the number of size bins from eight to four to speed up the calculation.

With the above annual cycle of BC deposition and snow pack, an offline model was created to determine the BC concentration within the top 30 cm of snow, by hour, throughout the year. The overall approach follows that of Jacobson (2004) with some modifications. Figure 2 shows preliminary results for the BC-snow mixing ratio for the winter and spring seasons. This mixing ratio can then be used to estimate changes in the snow albedo to bound sensitivity tests for longer climate runs using WRF in a regional downscaling manner. With additional work, the snow albedo could be determined online and allow for fully interactive feedbacks between the black carbon and the snow pack. However, for most investigators, using WRF-

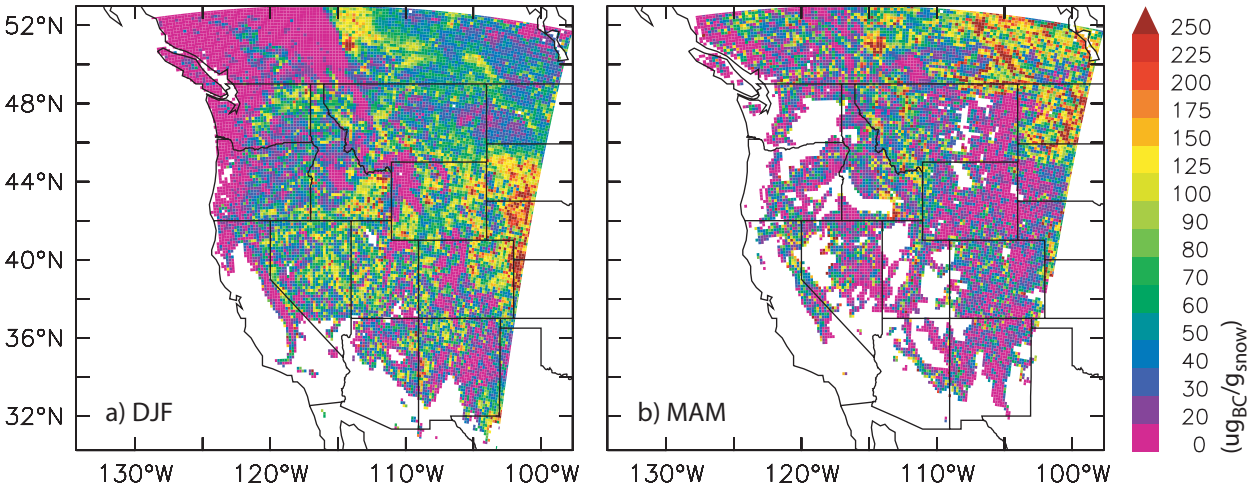

Figure 2 Simulated (a) winter (December 2003 through February 2004) and (b) spring (March 2004 through May 2004) averaged black carbon-snow mixing ratio. Units are µg of BC per g of snow. Note the non-linear color scale.

Chem with fully interactive feedbacks for a decade or longer climate simulation is still not computationally realistic. This work is preliminary, and the technique is still being developed. However, it demonstrates the broad possibilities opened up with a complete aerosol-meteorology coupled model.

4. Conclusion

As briefly demonstrated by the two examples above, WRF-Chem can be used for a broad range of aerosol-climate investigations. Examples include process studies, resolution studies, sensitivity of climate to aerosol characteristics, etc. WRF-Chem can also be used to design and test aerosol-cloud parameterizations applicable to GCM resolutions by providing an infrastructure wherein big-brother type experiments can be performed. As in the first example, a high resolution simulation verified against observations can be used as a control to compare against the simplified approach to the particular problem at hand. In the second example, the additional information gained with the aerosol model can be used to investigate a broader array of climate impacts than previously possible.

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