Simulation of the indirect radiative forcing of climate due to aerosols by the two-way coupled WRF-CMAQ over the eastern United States

Shaocai Yu[1], Rohit Mathur[1], Jonathan Pleim[1], David Wong[1], Annmarie G. Carlton[1], Shawn Roselle[1], S.T. Rao[1], Yang Shao[2]

[1]Atmospheric Modeling and Analysis Division, National Exposure Research Laboratory, U.S. Environmental Protection Agency, Research Triangle Park, NC 27711

[2]NRC/Environmental Science Division, NERL, U.S. EPA, RTP, NC 27711

Abstract In this study, the shortwave cloud forcing (SWCF) and longwave cloud forcing (LWCF) are estimated with the newly developed two-way coupled WRF-CMAQ over the eastern United States. Preliminary indirect aerosol forcing has been successfully implemented in WRF-CMAQ. The comparisons with the observed $PM_{2.5}$ at the AIRNow sites indicates that the models captured a majority of observed daily $PM_{2.5}$ within a factor of 2, but generally underestimated the observations in the high $PM_{2.5}$ concentration range. The domain means of CERES satellite observations, WRF-CMAQ/CAM and WRF-CMAQ/RRTMg for SWCF (LWCF) are -48.1 (31.9), -31.9 (22.6), -19.8 (15.5) watts m^{-2}, respectively. This means that the WRF-CMAQ model generally underestimated the cloud field for the 12-km resolution simulations.

Keywords indirect aerosol forcing, WRF-CMAQ, two-way

1. Introduction

Aerosol particles can influence the Earth's climate both directly by scattering and absorption of incoming solar radiation and terrestrial outgoing radiation, and indirectly by affecting cloud radiative properties through their role as cloud condensation nuclei (CCN) (Yu, 2000; Yu et al., 2001). The IPCC (2007) concludes that increasing concentrations of the long-lived greenhouse gases have led to a combined radiative forcing +2.63 [±0.26] W m^{-2}, and the total direct aerosol radiative forcing is estimated to be −0.5 [±0.4] W m^{-2}, with a *medium-low* level of scientific understanding, while the radiative forcing due to the cloud albedo effect (also referred to as first indirect), is estimated to be –0.7 [–1.1, +0.4] W m^{-2}, with a *low* level of scientific understanding. Clearly, the great uncertainty in the indirect aerosol forcing for the assessment of climate forcing by anthropogenic aerosols must be reduced.

2. The modeling system and observational databases

The two-way coupled WRF-CMAQ modeling system was developed by linking the Weather Research and Forecasting (WRF) model and Community Multiscale Air Quality (CMAQ) model. In this system, radiative effects of absorbing and scattering aerosols and the cloud droplets diagnosed from the activation of CMAQ-predicted aerosol particles interact with the WRF radiation calculations, resulting in a "2-way" coupling between atmospheric dynamic and chemical modeling components (Pleim et al., 2008; Mathur et al., 2010). Figure 1a shows a schematic coupling for the WRF and CMAQ modeling system. A flow diagram for calculation of indirect aerosol forcing in the two-way coupled WRF-CMAQ model is shown in Figure 1b. Specifically, the cloud droplet number concentrations are diagnosed from the activation of CMAQ-predicted aerosol particles. The resulting cloud droplet number is used to calculate variations in droplet effective radius, which in turn allows us to estimate aerosol effects on cloud optical depth and microphysical process rates for indirect aerosol forcing by tying a two-moment treatment of cloud water (cloud water mass and cloud droplet number) to precipitation (the Lin cloud microphysics scheme) and two radiation schemes (RRTMg and CAM) in the WRF. The $PM_{2.5}$ data from the AIRNow and shortwave cloud forcing (SWCF) and longwave cloud forcing (LWCF) data from CERES satellite were used to evaluate the model performance.

3. Results and discussions

The scatterplot of $PM_{2.5}$ concentrations between model and observations in Figure 2 indicates that the model captured a majority of observed daily $PM_{2.5}$ within a factor of 2, but generally underestimated the observations in the high $PM_{2.5}$ concentration range. The domain means ± standard deviation of observations, WRF-

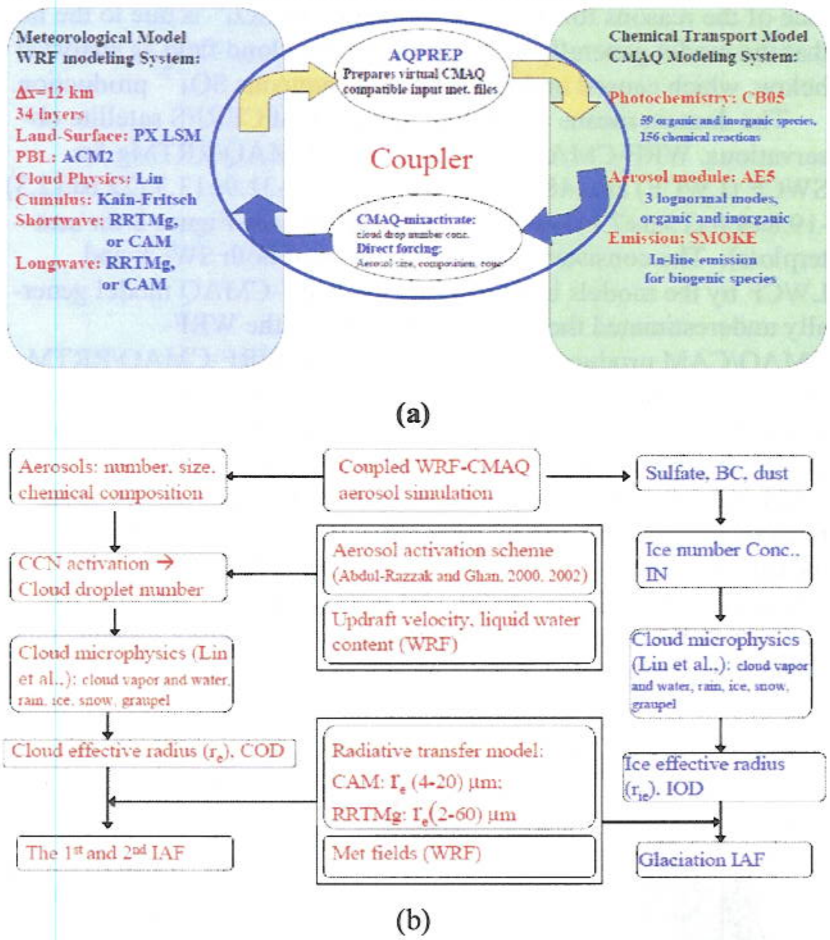

Figure 1. (a) The two-way coupled WRF-CMAQ modeling system, (b) Flow diagram for calculation of indirect aerosol forcing (IAF)

CMAQ/CAM and WRF-CMAQ/RRTMg for $PM_{2.5}$ concentrations are 13.9±7.9, 10.2±6.7, and 9.5±5.9 μg m^{-3}, respectively. The comparisons of $PM_{2.5}$ chemical composition at the IMPROVE sites (no shown here) indicate that WRF-CMAQ/CAM and WRF-CMAQ/RRTMg underestimated observed SO_4^{2-} by -26% and -23%, respectively, and underestimated observed OC by -25% and -26%, respectively, mainly leading to the general underestimation of $PM_{2.5}$. One of the reasons for the underestimation of SO_4^{2-} is due to the fact that the model generally underestimated the cloud field as analyzed below, which caused underestimation of aqueous SO_4^{2-} production.

The domain means ± standard deviation of CERES satellite observations, WRF-CMAQ/CAM and WRF-CMAQ/RRTMg for SWCF (LWCF) are -48.1±17.6 (31.9±12.4), -31.9±13.3 (22.6±12.3), -19.8±9.0 (15.5±7.1) watts m^{-2}, respectively (see Figure 2 for scatterplots). The consistent underestimations of both SWCF and LWCF by the models indicated that the WRF-CMAQ model generally underestimated the cloud field, although the WRF-CMAQ/CAM produced more cloud than the WRF-CMAQ/RRTMg. One of the reasons for the underestimation of cloud is that the subgrid convective clouds do not include aerosol effects because the model simulations were run at 12 km resolution. On the other hand, CAM and RRTMg radiation schemes used different parameterizations to calculate the optical properties of cloud, in part, leading to the different results for WRF-CMAQ/CAM and WRF-CMAQ/RRTMg. More studies and tests are needed although preliminary indirect aerosol forcing has been successfully implemented in the two-way coupled WRF-CMAQ.

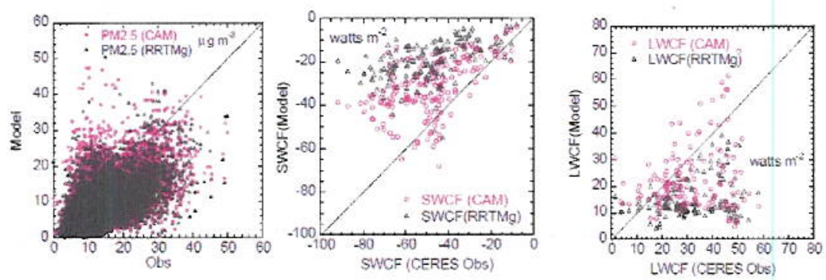

Figure 2. Comparison of modeled (two-way coupled WRF-CMAQ) and observed $PM_{2.5}$, SWCF and LWCF for two radiation schemes (RRTMg and CAM) over the eastern US for August of 2006.

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Questions and Answers

S. Hanna:

If NWP models are underpredicting the occurrence of subgrid clouds (as in a partly cloudy sky), does this not also imply a bias in prediction of radiative effects?

Answer:

Yes, this will lead a bias in prediction of radiative effects. This is one of issues we try to understand. Hopefully, we can improve this in the future.

A. Venketram:

Why do the two radiation schemes produce different water contents?

Answer:

One of the reasons is that CAM and RRTMg radiation schemes used different parameterizations to calculate the optical properties of cloud, in part, leading to the different results for WRF-CMAQ/CAM and WRF-CMAQ/RRTMg.