1. Introduction

The current understanding of how aerosols affect weather and climate contains large uncertainties that must be reduced in order to better estimate the impact of anthropogenic emissions on the atmosphere. Towards this end, cloud-aerosol modules have been added to the chemistry version of the Weather Research and Forecasting Model (WRF-chem) by researchers at the Pacific Northwest National Laboratory (PNNL). These new modules build upon the existing PNNL modules added to WRF-chem that were described at the 2005 Joint WRF/MM5 User's Workshop [Gustafson et al., 2005]: the CBM-Z gas phase chemistry mechanism [Zaveri and Peters, 1999], the MOSAIC sectional aerosol module [Zaveri et al., 2005a,b,c, 2006], the Fast-J photolysis module [Barnard et al., 2004; Wild et al., 2000], and direct aerosol-radiation feedbacks [Fast et al., 2006].

2. Aerosol-Cloud Modules

Capabilities added to WRF-chem this year by PNNL focus on cloud-aerosol interactions:

- the addition of cloud-phase aerosol with an accompanying activation mechanism,
- wet removal of aerosols,
- aqueous chemistry, and
- the first and second aerosol indirect effects.

Activation of aerosols from interstitial to cloud phase is determined based upon the supersaturation of updrafts and the critical supersaturation of each aerosol type and size. Aerosols are transferred to the cloud phase when the environmental supersaturation exceeds the critical supersaturation. Likewise, as droplets evaporate, they return to the interstitial phase. The method implemented in WRF-chem is similar to the one used in the MIRAGE general circulation model [Ghan et al., 2001]. A two-moment treatment of cloud water (cloud water and droplet number) has been added to the Lin et al. microphysics scheme and is active only when the user chooses to include cloud-aerosol interactions in the simulation. Since the Lin et al. treatment of autoconversion of droplets to rain is independent of droplet number, the Lin et al. treatment is replaced by that of Lin et al. [2005]. For simulations without chemistry, droplet number is predicted using a prescribed aerosol (or equivalently, CCN) size distribution. For simulations with chemistry, droplet number is predicted using the simulation aerosol size distribution. When the Goddard shortwave radiation scheme is used, the droplet number affects droplet mean radius and cloud optical depth. Aerosol activation and resuspension is calculated simultaneously with turbulent vertical mixing.

Once in the cloud phase, aerosols and dissolved trace gases interact via an aqueous chemistry module [Fahey and Pandis, 2001] that is currently only compatible with the CBM-Z gas-phase chemistry mechanism. The aqueous chemistry uses a bulk approach and treats oxidation of S(IV) by H₂O₂, O₃, trace metals, and radical species; and non-reactive uptake of HNO₃, HCl, NH₃, and other trace gases. The increases in cloud-borne sulfate, nitrate, and ammonium masses result in transfer of particles between size bins.

In addition to changing phase, cloud processes can now remove aerosols via wet removal in and below the clouds. In-cloud wet removal of aerosol particles involves removal of the cloud-borne aerosol particles at the same first-order rate that cloud water is converted to precipitation. For trace gases, this same removal rate is applied to the fraction of each gas that is dissolved in cloud water (this fraction is calculated in the cloud chemistry module). Below-cloud wet removal of aerosol particles is by impaction scavenging via convective Brownian diffusion and gravitational or inertial capture, calculated as in Easter et al. [2004]. Below-cloud wet removal of trace gases by rain is limited irreversible uptake of H₂SO₄, HNO₃, HCl, and NH₃, and simultaneous reactive uptake of SO₂ and H₂O₂ as in Easter et al. [2004]. Aerosols and trace gases scavenged by precipitation are assumed to be instantly removed (wet deposited), and there is no resuspension of scavenged material from evaporating precipitation.

Feedbacks between aerosols and clouds now include the first indirect effect (change in cloud albedo) and the second indirect effect (change in precipitation and cloud lifetime). Currently, these feedbacks are implemented in the Goddard shortwave radiation and the Lin et al. microphysics schemes. No interaction currently takes place with any cumulus parameterizations. The number of activated aerosols is tracked and used to determine the number of cloud drops, which is then used to determine the cloud albedo and to not affect the autoconversion process.

Improvements to the WRF software infrastructure during the past year by John Michalakes, specifically the
reduction of include file sizes, has made the new
capabilities possible. Because the interstitial and cloud-
borne aerosol species are both treated prognostically
with MOSAIC configured for eight size bins and all
capabilities enabled, the total number of gas and
aerosol variables advected by WRF-chem v2.1.2 is now
221. With WRF-chem v2.0.3, this would not have been
possible due to compiler constraints. Now, this is no
longer an issue, and successful simulations have been
done with both the Intel and Portland compilers.

3. The NEAQS 2004 Demonstration Case

A six-day period beginning 5 August 2004 has been
simulated to demonstrate the impact of the new aerosol-
cloud interactions over the northeastern U.S. This
period coincides with the New England Air Quality Study
(NEAQS) 2004, which included a suite of aerosol and
meteorological measurements from surface and aircraft
instrumentation, supported by the U.S. Department of
Energy’s (DOE) Atmospheric Sciences Program, which
can be used to validate the model. The simulation uses
a nested grid setup with the coarsest grid covering the
eastern half of the United States ($\Delta x = 18$ km), a second
grid surrounding Pennsylvania and the Ohio River
Valley ($\Delta x = 6$ km), and the finest grid over western
Pennsylvania ($\Delta x = 2$ km). This period is particularly
good for evaluating the cloud interactions because a
frontal passage occurs during the period in addition to
the occurrence of widespread boundary-layer clouds.
Sulfur dioxide emissions from power plants in the Ohio
River Valley and Pennsylvania readily interact with the
clouds and contribute to additional aerosol growth
through aqueous conversion to sulfate.

Two model runs have been performed. The first
serves as a control and consists of a WRF-chem run
configured to not include the new aerosol-cloud
interactions. The second run is the same as the first run
except the aerosol-cloud interactions are enabled. This
leads to changes in both the chemistry and the
meteorology.

An example of the effects of cloud-aerosol
interactions modules on cloud optical depth and
precipitation is shown in Figs. 1a and 2, respectively. At
18 UTC 7 August, the magnitude and spatial distribution
of the cloud optical depth predicted by the simulation
without aerosol-cloud interactions is similar to MODIS
satellite measurements (Figs. 1a and 1b). The
difference between the two simulations (Fig. 1c) show
that the inclusion of cloud-aerosol interactions alters the
cloud optical depth by more than 10. Some of the
differences can be attributed to small changes in the
predicted location of clouds. These differences also
depend on the prescribed aerosol size distribution in the
simulation with no cloud-aerosol interactions. Over the
highest-resolution nested domain that encompasses
western Pennsylvania, the simulation with cloud-aerosol
interactions had less rain than the simulation without
cloud-aerosol interactions (Fig. 2).

Additional details on the cloud-aerosol interactions
incorporated into WRF-chem and the performance of

![Fig. 1. (a) MODIS cloud optical depth re-gridded to a 20-km grid, (b) predicted cloud optical depth from simulation without cloud-aerosol interactions over domain 1 ($\Delta x = 18$ km), and (c) difference in simulated cloud optical depth (with - without cloud aerosol interactions). Simulation results at 18 UTC 7 August 2004 and MODIS measurements at 1850 UTC.](image-url)

the model when compared with the surface and aircraft
measurements will be presented at the conference.

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Fig. 2. Difference in accumulated precipitation averaged over domain 3 for the simulations with and without cloud-aerosol interactions.

4. References


