Assimilation of Satellite Derived Aerosol Products to Improve PM2.5 Predictions

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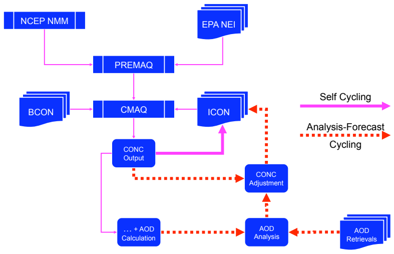
1. Introduction

PM2.5 (particulate mass for particles smaller than 2.5 μm in median diameter) concentration is one of the key indicators of air quality. High concentration of PM2.5 can cause serious human health problems (e.g. asthma). The Community Multiscale Air Quality (CMAQ) model system that provides hourly PM2.5 predictions has uncertainties due to uncertainties in initial/boundary conditions and in emissions.

Validation studies show that satellite derived column aerosol optical depth (AOD) and ground-level PM2.5 are well correlated. Thus we propose an analysis-forecast cycling scheme to assimilate satellite derived AOD in CMAQ. An industrial haze episode and a wild fire episode that occurred in the summer of 2006 were simulated and AOD retrievals from the GOES-12 satellite and from MODIS instruments on board the Terra/Aqua satellites were assimilated. Comparisons of CMAQ AODs with AERONET AODs and CMAQ surface PM2.5 with AIRNow PM2.5 observations indicate that assimilation of satellite derived AODs improves PM2.5 predictions by up to a factor of 2.

2. The CMAQ Model System

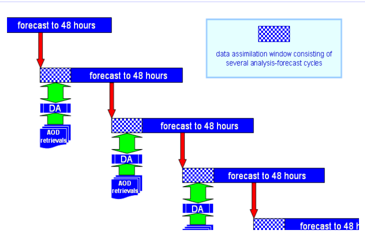
The CMAQ model system was originally developed at EPA and adopted by NOAA/NCEP as its regional air quality forecasting system (AQFS). The major inputs include emissions from the EPA National Emissions Inventory (NEI) and meteorological and surface characteristic fields from NWS/NCEP Nonhydrostatic Mesoscale Model (WRF/NMM). The aerosol version of the AQFS covers CONUS with 442x265 mesh grid at 12 km resolution. There are 22 *P-σ* layers vertically.



Above is the schematic flow chart of AQFS. PREMAQ is a pre-processor to the CMAQ model. It takes NCEP NMM forecasts and EPA NEI datasets and provides driving meteorological fields, surface characteristics and emission sources. The boundary condition (BCON) is specified with static profiles of component species. The initial condition (ICON) is specified with static clean air profiles when it is "cold" started. For a continuous runs, two options are shown on the flow chart. With the original option which is called "Self Cycling" scheme and represented by the thick solid arrow, the initial condition is taken from the previous model output of the aerosol CONCentrations. The model thus keeps running without any correction. The proposed option is called "Analysis-Forecast Cycling" scheme and displayed as thick dashed arrows. It takes satellite retrieved AOD to perform objective analysis with model output AOD, adjust model species concentrations accordingly and construct updated initial conditions.

3. Analysis-Forecast Cycling Scheme

Instead of taking model output concentration for the initial condition, we propose to use the model output AOD as the first guess and satellite AOD as input observations to generate AOD analysis, with which the model output concentrations are adjusted and fed back to the model as the initial condition. For each daily job running from 12Z for 48 hours, the data assimilation window covers up to the first 12 hours, depending on the temporal availability of the input observations. For the verification studies shown later in this poster, forecasts for the 13-36 hours, which is after the DA window, are taken as sampling data.

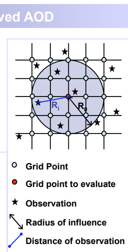


3.1 Objective Analysis of Satellite-derived AOD

$$\tau^{ana} = \tau^{guess} + \frac{\sum W_i(\tau_i^{obs} - \tau_i^{guess})}{\sum W_i}$$

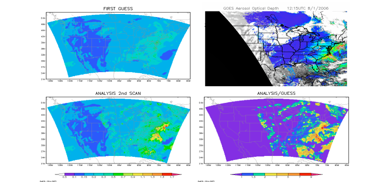
$$W_i = \frac{R_0^2 - R_i^2}{R_0^2 + R_i^2} \quad \text{for } R_i < R_0$$

$$W_i = 0 \quad \text{for } R_i \ge R_0$$



- Cressman style successive correction scheme
  - τ^{ana}, τ^{guess} and τ^{obs} are analysis, the first guess and satellite retrieved AODs, respectively
- Two passes with reducing radius of influence
  - 1st pass: R_0 = 4 grid-length (48km)
  - 2nd pass: R_0 = 2 grid-length (24 km)

3.2 An Analysis Example



The top left panel is the first guess field taken from the model output; the top right panel is GOES AOD retrievals. The analysis field after the 2nd scan is on the bottom left panel. The last map is the ratio of the final analysis to the first guess. We are going to use this ratio to adjust the concentration fields.

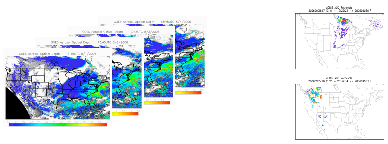
3.3 Aerosol Concentration Adjustment

$$C^{ana} = C^{guess}\frac{\tau^{ana}}{\tau^{guess}}$$

Number, surface area and mass concentrations of all aerosol species in all layers are adjusted the same way, so that the size, type and vertical distributions from the first guess are all kept.

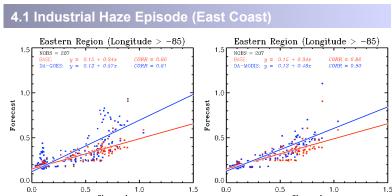
4. Simulation experiments and Results

An industrial haze episode along the east coast during the early August 2006 and a wild fire episode in the northwestern region during the early September 2006 were selected to test the proposed Analysis-Forecast Cycling scheme. The AOD retrievals derived from GOES-12 satellite and from MODIS instruments on board Terra/Aqua satellites were assimilated. Each series of experiments consists of four or five 48-hour daily simulations starting at 12Z. The initial conditions for the "BASE" experiments valid at 12Z August 1 for industrial haze episode and at 12Z September 3 for the wild fire episode were constructed from the output concentrations of the previous model simulations, which were "cold" started with static initial conditions two days earlier. The initial conditions for the data assimilation experiments were generated with the Analysis-Forecast Cycling scheme.

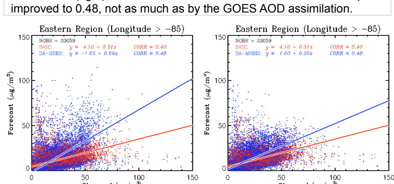


- **GOES AOD retrievals**
  - 4 km X 4 km horizontal resolution over CONUS
  - Every 30 minutes during daytime
- **MODIS AOD retrievals**
  - More accurate AOD retrievals from advanced instruments
  - Limited spatial coverage (orbital) and temporal resolution (once a day)

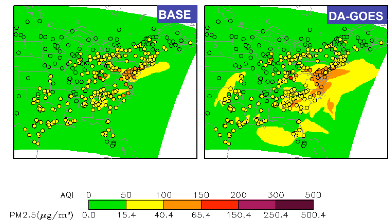
4.1 Industrial Haze Episode (East Coast)



We matched-up model output AOD with AERONET AOD. With GOES AOD assimilated (left), the correlation is slightly decreased from 0.86 to 0.81. The slope is improved from 0.34 to 0.57. With MODIS AOD assimilated (right), the correlation increases to 0.90 and the slope is improved to 0.48, not as much as by the GOES AOD assimilation.

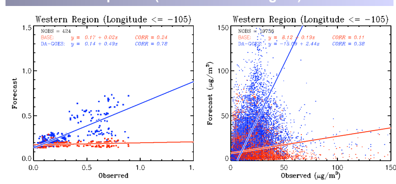


Above are the scatter plots of the match-ups of model output surface PM2.5 concentrations with the AIRNow observations. With GOES AOD assimilated (left), the correlation increases from 0.40 to 0.48 and the slope is improved from 0.31 to 0.69. With MODIS AOD assimilated (right), the correlation and slope increases to 0.48 and 0.50, respectively.



These two maps are 24-hr average surface PM2.5 concentrations simulated with CMAQ models, with AIRNow PM2.5 ground observations overlaid as small circles. The left panel was from the BASE run and the right panel was from the hourly GOES AOD assimilation experiment. The intensity over the east coast region got greatly recovered through the GOES AOD assimilation. Improvement in other regions can also be observed.

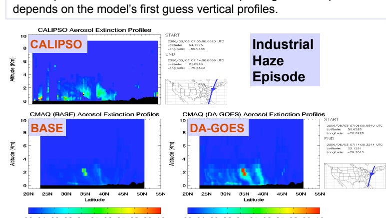
4.2 Wild Fire Episode (Northwestern Region)



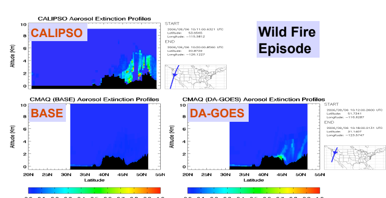
Above are the scatter plots of the match-ups of model output vs. AERONET AOD (left) and AIRNow PM2.5 concentrations (right). The results from the BASE experiment show little responses to the wild fire high aerosol event. This is mostly because the corresponding bio-mass burning emission is not included in the model. With GOES AOD assimilation runs, better correlations for both AOD and PM2.5 are obtained. Under-predicted AOD and over-predicted PM2.5 indicate that the current DA scheme distributes most of aerosol loading near the surface and too little above in this case.

4.3 Comparison with CALIPSO Aerosol Vertical Profiles

The impact of AOD assimilation on improving PM2.5 predictions depends on the model's first guess vertical profiles.



For the industrial haze episode, although the intensity of the BASE run is weak, the relatively realistic vertical structure helps the DA-GOES run to recover the aerosol vertical loading distribution quite well.



For the wild fire episode, the BASE run did not simulate the aerosol vertical structure well due to the lack of the bio-mass burning emissions. As a result, the DA-GOES run failed to correctly redistribute aerosol loading very well, holding most of aerosol loading near the surface and too little above.

5. Conclusions

- GOES AODs have a bigger impact on PM2.5 predictions than MODIS AODs. Specifically due to frequent updates of CMAQ initial conditions with GOES compared to MODIS
- Improvements depend on
  - Original CMAQ aerosol vertical profiles
  - Quality of satellite data
- An objective way to determine altitude dependent tuning of aerosol concentrations is required to correctly assimilate satellite data. But that is a challenge for all satellite data assimilation experiments.
- Aerosol assimilation studies show a big impact on CMAQ PM2.5 predictions