The Community Multiscale Air Quality (CMAQ) Model: An Interdisciplinary Approach for Multipollutant Modeling Analysis

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Model Development and Diagnostic Testing

Environmental Issue

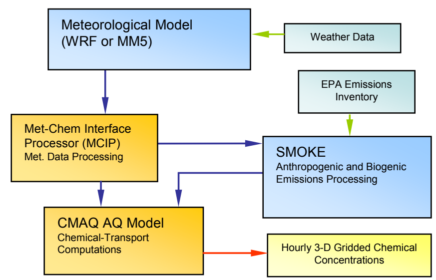
EPA and the states are responsible for implementing the National Ambient Air Quality Standards (NAAQS) for ozone and PM. New standards for 8-h average ozone and daily average $PM_{2.5}$ concentrations have recently been implemented. State Implementation Plans (SIPs) for the NAAQS rely on air quality modeling analyses to demonstrate that planned emissions control measures will help bring violating areas into attainment of the air quality standards. In addition to the SIP analyses, air quality models are used in helping formulate national rules for controlling emissions from motor vehicles, electrical generating units, and other large sector-based emissions sources of criteria and toxic air pollutants and their precursors. Therefore, air quality simulation models, such as the Community Multiscale Air Quality (CMAQ) model, are vital to air quality management at the national, state, and local levels. The CMAQ model must reflect the state-of-science to insure scientific credibility in the regulatory decision-making process. Periodic refinements to the CMAQ modeling system are provided to EPA's client office (OAQPS) as well as to the general public through the Community Modeling and Analysis System (CMAS) Center.

Research Objectives

- Develop, evaluate, and refine scientifically-credible and computationally-efficient process simulation and numerical methods for the CMAQ air quality modeling system
- Develop the CMAQ model for a variety of spatial (urban through continental) and temporal (hours to years) scales and for a **multi-pollutant** regime (ozone, PM, air toxics, visibility, acid deposition)
- Adapt and apply the CMAQ modeling system to particular air quality/deposition/climate-related problems of interest to EPA, and use the modeling system as a **numerical laboratory** to study the major science process or data sensitivities and uncertainties related to air pollution problems
- Critically evaluate the CMAQ model to characterize the accuracy of model predictions, and to identify needed improvements in modeled processes within the air quality model or model inputs
- Use CMAQ to study the interactions among different chemical species and processes as well as the influence of uncertainties in meteorological predictions and emission estimates on air quality predictions
- Collaborate with the scientific community to maintain the CMAQ model system at the cutting edge of science
- Pursue computational efficiencies (e.g., parallel processing techniques) in the CMAQ modeling system for the broader user community

Modeling Approach / Results

The CMAQ model system is composed of several major components, shown in the figure below:



The air quality (chemical transport) portion of the system, the CMAQ model, is based on a numerical solution to the atmospheric transport/diffusion equation, including reactive chemistry and aerosols (in generalized coordinates):

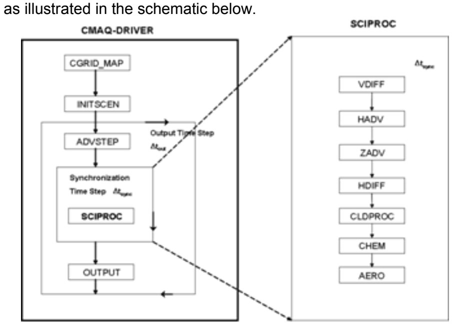
$$\frac{\partial \varphi_i^*}{\partial t} + \hat{\nabla}_\xi \bullet \left[\varphi_i^* \hat{\mathbf{V}}_\xi\right] + \frac{\partial(\varphi_i^* \hat{v}^3)}{\partial \hat{x}^3} + \hat{\nabla}_\xi \bullet \left[\bar{\rho}\sqrt{\hat{\gamma}}\,\hat{\mathbf{F}}_{q_i}\right] + \frac{\partial(\bar{\rho}\sqrt{\hat{\gamma}}\,\hat{F}^3_{q_i})}{\partial \hat{x}^3}$$

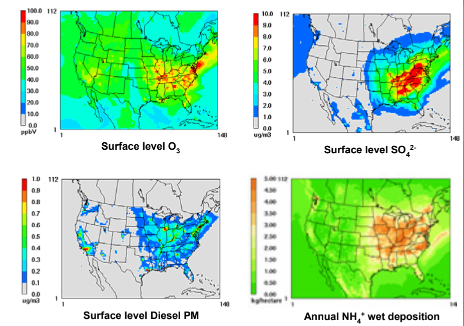
horizontal advection, vertical advection, horizontal diffusion, vertical diffusion

$$= \sqrt{\hat{\gamma}}\,R_{\varphi_i}(\bar{\varphi}_1,\ldots,\bar{\varphi}_N) + \sqrt{\hat{\gamma}}\,S_{\varphi_i} + \left.\frac{\partial(\varphi_i^*)}{\partial t}\right|_{cld} + \left.\frac{\partial(\varphi_i^*)}{\partial t}\right|_{aero}$$

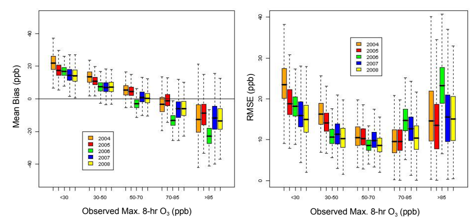
chemistry, emissions, clouds, aerosols

where $\varphi_i^* = \sqrt{\hat{\gamma}}\,\bar{\varphi}_i = (J_\xi / m^2)\bar{\varphi}_i$. $\sqrt{\hat{\gamma}}$ encapsulates coordinate transformation from physical to computational space. The numerical solution of the above equation is solved in the model, according to the fractional step method in CMAQ, as illustrated in the schematic below.





The CMAQ model produces hourly 3-D gridded output for major trace gas species involved in tropospheric photochemistry (O_3, NO_y species, VOC species, HO_x, NH_x), particulate matter (chemical composition and size distribution), visibility, Hg, and over 40 hazardous air pollutants (HAPS or air toxics). In addition, the model also outputs hourly 2-D gridded dry and wet deposition fields. Examples of model outputs are shown in the figures above. Posters 5.1 and 5.3 provide additional details on the treatment and analysis of atmospheric deposition.

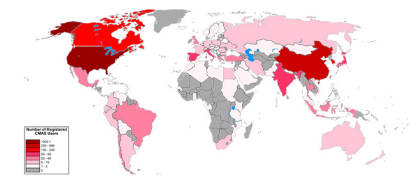


In collaboration with the National Weather Service, CMAQ has been deployed to provide operational daily air quality forecast guidance. This application of the model has assisted in the identification of systematic biases in the model and contributing processes, thereby providing guidance for model development and improvement (see Poster 2.2). Synergistic development of the community and forecast models in conjunction with detailed operational and diagnostic evaluations have resulted in continuous improvement in model performance across all mixing ratio ranges (reduced over-prediction at the low range and reduced under-prediction at the high range). Note: the performance degradation in 2006 is related to the transitioning of the operational weather forecast model from the Eta model to the Weather Research and Forecasting non-hydrostatic mesoscale model (WRF-NMM).

Conclusions

The CMAQ model has been built upon AMAD's extensive experience in developing and evaluating air quality models since the 1970's. The CMAQ model system is a numerical laboratory to understand the relevant physical and chemical processes influencing the levels of ambient air pollution and atmospheric deposition on urban to continental scales. Evaluated versions of the model are being used for multipollutant research and regulatory analyses.

The CMAQ model was initially released to the public by EPA in 1998. Periodic refinements are provided to the user community through the Community Modeling and Analysis System (CMAS) Center. This has helped create a dynamic and diverse CMAQ user community throughout the world.



Future Directions

- Extend spatial scales of applicability of CMAQ system to hemispheric on the large scale and to fine scale (~1-km cells) on the small scale, for future applications relating to climate-air quality linkage, and to air quality-human exposure linkage
- Continue development of integrated WRF-CMAQ model for two-way feedbacks between meteorological and chemical processes and models
- Apply CMAQ in a variety of applications and evaluate model performance from operational, diagnostic, dynamic, and probabilistic perspectives (see Poster 2.1), and use results to further improve the CMAQ system

Impact

CMAQ has been and continues to be extensively used by EPA and the states for air quality management analyses (SIPs; CAIR, CAMR, RFS-2 rulemakings), by the research community for studying relevant atmospheric processes, and by the international community in a diverse set of model applications.

Contributors/Collaborators

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