First Steps Towards Incorporating Aerosol-Cloud Interactions in Reanalyses

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The radiative heat balance of the earth and the distribution of precipitation are two important attributes of the state of the earth to academic and commercial endeavors using reanalyses. The important influence of aerosols on cloud formation and, thus, both these attributes powerfully demonstrates the integrated nature of the earth system with clear connections between anthropogenic activity and cloud characteristics. The incorporation of improved representations of these complex processes in climate models and the maturation of global observational datasets of radiative impacts of clouds motivates the addition of aerosol influences on cloud processes into reanalyses, especially to move toward better representations of the hydrological cycle in the datasets.

Nevertheless, including physically-based aerosol-cloud interactions in complex data assimilation systems is far from trivial. Often, model simplifications are necessary due to the time and spatial scales considered for climate-relevant investigations. More recently, integration of chemistry and climate models has become feasible. Analysis of these models is an ongoing endeavor, represented, in part, by the Chemistry-Climate Model Validation Activity for Stratospheric Processes And their Role in Climate (SPARC) (CCMVal) and Aerosol Comparisons between Observations and Models (AEROCOM). As elements of these models are established as reasonable representations of important physical processes, integration of aerosol-cloud interactions ought to be included in data assimilation frameworks and, in time, reanalyses.

The engine for assimilation of observations is the adjoint of a model for three- or four-dimensional variational (3DVar or 4DVar) data assimilation, a common approach to reanalysis. Both the computational constraints of conducting data assimilation on climatic scales and the construction of the adjoint of the model pose significant challenges to increasing the complexity of models employed in reanalyses. The latter must first be overcome to even test capability of the rapidly increasing computational resources available to address these challenges. This work represents the first steps toward incorporating aerosol-cloud interactions in data assimilation systems for climate models.

Here, the recent development of adjoint models for a physically-based cloud droplet activation parameterization of Nenes and Seinfeld and an aerosol equilibrium thermodynamics model, ISORROPIA, are detailed. The integration of these adjoint models into the adjoint of the global chemical transport GEOS-Chem demonstrates the feasibility of tracing the influence of many (10^5) parameters to aerosol or droplet concentrations. Specifically, through the adjoint of the droplet activation parameterization, the sensitivities of cloud droplet concentrations with respect to aerosol number concentration, hygroscopicity of soluble aerosol species, and other determining factors in cloud droplet formation are displayed for the range of global conditions.

Furthermore, the sensitivity of droplet concentrations over selected geographical regions to emissions of aerosol precursor gases are examined to reveal the most significant contributors.

Assimilation of satellite-based observations of aerosol precursor gases to adjust the emissions rates of these species further exhibits the feasibility of future incorporation into more comprehensive 4DVar assimilation systems. Currently, the NASA Global Modeling and Assimilation Office and the Harvard Atmospheric Chemistry Modeling Group are working to integrate the Goddard Earth Observing System Data Assimilation System Version 5 (GEOS-5), recently used to conduct the Modern Era Retrospective-Analysis for Research and Applications (MERRA), with the major components of GEOS-Chem in a column-model framework. As this effort in the wider community advances, the data assimilation capabilities of the GEOS-5 system will maximize the utility of the advanced adjoint capabilities of GEOS-Chem as well as those described in this work for the purpose of accurately assessing climate-relevant sensitivities and, eventually, reanalyses.

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