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M E M O R A N D U M

TO: Ashley Williamson, DOE Program Manager
RE: Project report
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PROJECT TITLE: Parameterizations of Cloud Microphysics and Indirect Aerosol Effects.

1. OVERVIEW

Aerosols and especially their effect on clouds are one of the key components of the climate system and the hydrological cycle [Ramanathan et al., 2001]. Yet, the aerosol effect on clouds remains largely unknown and the processes involved not well understood. A recent report published by the National Academy of Science states "*The greatest uncertainty about the aerosol climate forcing - indeed, the largest of all the uncertainties about global climate forcing - is probably the indirect effect of aerosols on clouds [NRC, 2001]*." The aerosol effect on clouds is often categorized into the traditional "first indirect (i.e., Twomey)" effect on the cloud droplet sizes for a constant liquid water path [Twomey, 1977] and the "semi-direct" effect on cloud coverage [e.g., Ackerman et al., 2000]. Enhanced aerosol concentrations can also suppress warm rain processes by producing a narrow droplet spectrum that inhibits collision and coalescence processes [e.g., Squires and Twomey, 1961; Warner and Twomey, 1967; Warner, 1968; Rosenfeld, 1999].

The aerosol effect on precipitation processes, also known as the second type of aerosol indirect effect [Albrecht, 1989], is even more complex, especially for mixed-phase convective clouds. Table 1 summarizes the key observational studies identifying the microphysical properties, cloud characteristics, thermodynamics and dynamics associated with cloud systems from high-aerosol continental environments. For example, atmospheric aerosol concentrations can influence cloud droplet size distributions, warm-rain process, cold-rain process, cloud-top height, the depth of the mixed phase region, and occurrence of lightning. In addition, high aerosol concentrations in urban environments could affect precipitation variability by providing an enhanced source of cloud condensation nuclei (CCN). Hypotheses have been developed to explain the effect of urban regions on convection and precipitation [*van den Heever and Cotton*, 2007 and S*hepherd*, 2005].
Recently, a detailed spectral-bin microphysical scheme was implemented into the Goddard Cumulus Ensemble (GCE) model. Atmospheric aerosols are also described using number density size-distribution functions. A spectral-bin microphysical model is very expensive from a computational point of view and has only been implemented into the 2D version of the GCE at the present time. The model is tested by studying the evolution of deep tropical clouds in the west Pacific warm pool region and summertime convection over a mid-latitude continent with

different concentrations of CCN: a low "clean" concentration and a high "dirty" concentration. The impact of atmospheric aerosol concentration on cloud and precipitation will be investigated.

2. MODEL DESCRIPTION AND CASE STUDIES

2.1 GCE MODEL

The model used in this study is the 2D version of the GCE model. Modeled flow is anelastic. Second- or higher-order advection schemes can produce negative values in the solution. Thus, a Multi-dimensional Positive Definite Advection Transport Algorithm (MPDATA) has been implemented into the model. All scalar variables (potential temperature, water vapor, turbulent coefficient and all five hydrometeor classes) use forward time differencing and the MPDATA for advection. Dynamic variables, u, v and w, use a second-order accurate advection scheme and a leapfrog time integration (kinetic energy semi-conserving method). Short-wave (solar) and long-wave radiation as well as a subgrid-scale TKE turbulence scheme are also included in the model. Details of the model can be found in Tao and Simpson (1993) and Tao *et al.* (2003).

2.2 Microphysics (Bin Model)

The formulation of the explicit spectral-bin microphysical processes is based on solving stochastic kinetic equations for the size distribution functions of water droplets (cloud droplets and raindrops), and six types of ice particles: pristine ice crystals (columnar and plate-like), snow (dendrites and aggregates), graupel and frozen drops/hail. Each type is described by a special size distribution function containing 33 categories (bins). Atmospheric aerosols are also described using number density size-distribution functions (containing 33 bins). Droplet nucleation (activation) is derived from the analytical calculation of super-saturation, which is used to determine the sizes of aerosol particles to be activated and the corresponding sizes of nucleated droplets. Primary nucleation of each type of ice crystal takes place within certain temperature ranges. A detailed description of these explicitly parameterized processes can be found in Khain and Sednev (1996) and Khain *et al.* (1999, 2001).

2.3 Case Studies

Three cases, a tropical oceanic squall system observed during TOGA COARE *(Tropical Ocean and Global Atmosphere Coupled Ocean-Atmosphere Response Experiment,* which occurred over the Pacific Ocean warm pool from November 1992 to February 1993), a midlatitude continental squall system observed during PRESTORM (*Preliminary Regional Experiment for STORM-Central,* which occurred in Kansas and Oklahoma during May-June 1985), and mid-afternoon convection observed during CRYSTAL-FACE (Cirrus Regional Study of Tropical Anvils and Cirrus Layers – Florida Area Cumulus Experiment, which occurred in Florida during July 2002), will be used to examine the impact of aerosols on deep, precipitating systems.

3. SUMMARY of RESULTS

- For all three cases, higher CCN produces smaller cloud droplets and a narrower spectrum. Dirty conditions delay rain formation, increase latent heat release above the freezing level, and enhance vertical velocities at higher altitude for all cases. Stronger updrafts, deeper mixed-phase regions, and more ice particles are simulated with higher CCN in good agreement with observations.

- In all cases, rain reaches the ground early with lower CCN. Rain suppression is also evident in all three cases with high CCN in good agreement with observations *(Rosenfeld*, 1999, 2000 and others). Rain suppression, however, only occurs during the first hour of simulation. This result suggests that microphysical processes dominate the impact of aerosols on precipitation in the early stage of precipitation development.
- During the mature stage of the simulations, the effect of increasing aerosol concentration ranges from rain suppression in the PRESTORM case to little effect on surface rainfall in the CRYSTAL-FACE case to rain enhancement in the TOGA COARE case.
- The model results suggest that evaporative cooling is a key process in determining whether higher CCN reduces or enhances precipitation. Cold pool strength can be enhanced by stronger evaporation. When cold pool interacts with the near surface wind shear, the low-level convergence can be stronger, facilitating secondary cloud formation and more vigorous precipitation processes. Evaporative cooling is more than two times stronger at low levels with higher CCN for the TOGA COARE case during the early stages of precipitation development. However, evaporative cooling is slightly stronger at lower levels with lower CCN for the PRESTORM case. The early formation of rain in the clean environment could allow for the formation of an earlier and stronger cold pool compared to a dirty environment. PRESTORM has a very dry environment and both large and small rain droplets can evaporate. Consequently, the cold pool is relatively weaker, and the system is relatively less intense with higher CCN.
- Sensitivity tests are conducted to determine the impact of ice processes on aerosol-precipitation interaction. The results suggested that ice processes are crucial for suppressing precipitation due to high CCN for the PRESTORM case. More and smaller ice particles are generated in the dirty case and transported to the trailing stratiform region. This reduces the heavy convective rain and contributes to the weakening of the cold pool. Warm rain processes dominate the TOGA COARE case. Therefore, ice processes only play a secondary role in terms of aerosol-precipitation interaction.
- Two of the three cloud systems presented in this paper formed a line structure (squall system). A 2D simulation, therefore, gives a good approximation to such a line of convective clouds. Since the real atmosphere is 3D, further 3D cloud-resolving simulations are needed to address aerosol-precipitation interactions.

4. REFERENCES

Tao, W.-K., X. Li, A. Khain, T. Matsui, S. Lang, and J. Simpson, 2007: The role of atmospheric aerosol concentration on deep convective precipitation: Cloud-resolving model simulations. *J. Geophy. Res.*, **112**, D24S18, doi:10.1029/2007JD008728.

All other references can be found in above paper.

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