FINAL REPORT

1. **PI:** Joyce E. Penner, University of Michigan

2. **Title of Research Grant:** Model simulations of aerosol effects on clouds and precipitation in comparison with ARM data

3. **Scientific Goal(s) of Research Grant:**

One of the biggest uncertainties associated with climate models and climate forcing is the treatment of aerosols and their effects on clouds. The effect of aerosols on clouds can be divided into two components: The first indirect effect is the forcing associated with increases in droplet concentrations; the second indirect effect is the forcing associated with changes in liquid water path, cloud morphology, and cloud lifetime. Both are highly uncertain. The objectives of this proposal are to evaluate the capabilities of the CAM5 model to capture cloud-aerosol-precipitation interactions, to identify weaknesses, and to ascertain possible improvements. This will be carried out through a combination of cloud system resolving model (CSRM) studies, studies with CAM5, and comparison of both with ARM measurements. We will focus our efforts on liquid water clouds with small liquid water paths, since these clouds are predicted to have the largest forcing effects.

4. Progress and accomplishments of the project:

There is now a rich set of model studies linking changes in aerosols to changes in clouds and precipitation (e.g. Jiang et al., 2002; Ackerman et al., 2004; Guo et al., 2007ab; Lee and Penner, 2010; Lee and Feingold, 2010; Jiang et al., 2010). Most of the studies quoted here examined low-level stratiform, strato-cumulus, or trade-cumulus clouds, but the effects of aerosols on deeper convective clouds have also been examined (e.g. Fridland et al., 2004; Fan et al., 2009; Fan et al., 2010; Lee and Feingold, 2010; Lee et al., 2010; van den Heever et al., 2011; Morrison and Grabowski, 2011). Our work has examined both stratiform clouds and thunderstorms (Lee et al., 2009; Lee et al., 2010) with a Cloud System Resolving model (CSRM). This model allows us to use Large-Eddy Simulation (LES) grid resolutions to treat stratocumulus and stratiform clouds (50 – 100m in the horizontal and 20 – 40 m in the vertical) and higher resolutions for deep convective clouds. We have used the Goddard CSRM to isolate the factors contributing to the response of cloud systems to increased aerosols and to identify weaknesses in our version of the CAM model (called CAM3+). Here, we wish to extend our analysis to enable us to improve the representation of cloud-aerosol-precipitation in the CAM5 model.

We performed a comparison of the CAM5.3 model to the CSRM, similar to the analysis performed by Lee and Penner (2010) but focusing on a simulation of clouds measured at the ARM Southern Great Plains (SGP) site. In particular, we simulated continental shallow warm clouds with a very small precipitation rate (< 0.1 mm day^{-1}) observed on 05/27/2011 at the SGP measurement site using the single column version of a global climate model (CAM5.3) and a cloud resolving model and explored plausible causes for the differences in the response of these two models to increases in aerosols. Notably, we specifically identify that the cloud top growth and turbulence mixing parameterizations within CAM require improvement, rather than only the autoconversion rate, as hypothesized in Wang et al. (2012).

An important difference between CAM5 and the CSRM is that in the CSRM cloud droplets are divided into small and large cloud droplets. Small and large cloud droplets range 2–40 μm and 40–80 μm in diameter, respectively. The 40 μm division between the two droplet modes is natural because it is well known that collection rates for droplets smaller than this size are very small, whereas droplets greater than this size participate in vigorous collision and coalescence. The large cloud- droplet mode is allowed to interact with all other species (i.e., the small-cloud-droplet mode and rain for warm microphysics). The large-cloud-droplet mode plays a significant role in the collision-coalescence process by requiring droplets to grow at a slower rate as they pass from the small-cloud-droplet mode to rain, rather than being transferred directly from the small-cloud-droplet mode to rain. It will be interesting to understand whether the new CAM version that includes a two-moment scheme for precipitation as well as cloud drops and is under development by Morrison is able to better reproduce the results of the CSRM.

CAM has 30 vertical layers and a variable vertical resolution which depends on the surface pressure and the vertical temperature profile. In the case studied in this paper the vertical resolution is roughly 100 meters near the surface and stretches to about 300 m at 2 km decreasing to 1 km at 10 km. The time step is 20 minutes. GCE has 128 grids in the two horizontal directions and 144 vertical layers. The horizontal resolution is 50 m, so the domain size is 6.4 km × 6.4 km. GCE also uses a stretched vertical resolution that varies from about 30 m near the surface to about 90 m at 2 km and further to ~200 m at 10 km. The time step of the GCE model is 1 second. Both models use the same initial conditions (surface pressure/temperature, vertical temperature/water vapor/wind profiles), boundary conditions (surface sensible/latent heat fluxes, surface pressure/temperature). Advective tendencies of temperature and moisture (both vertically and horizontally) are specified based on an objective variational analysis approach (Xie et al. 2014) fit to the Midlatitude Continental Convective Clouds Experiment (MC3E) campaign observations which were conducted from April to June 2011 near the SGP site. The analyzed advective tendencies cover the period from April 22nd to June 21th, 2011. Middle to deep convective clouds were observed in most cloudy days. For this study, May 27th, 2011, was selected because middle and high clouds were absent during a low cloud period observed near noon. This was partly due to the fact that the CAM5.3 model greatly over predicted convective clouds.

To study the effect of aerosols on clouds, we scaled the aerosol vertical profiles in both models by increasing the surface aerosol number concentrations from 250 cm^{-3} to 4000 cm^{-3}. GCE uses a prescribed aerosol profile which decreases linearly from its surface concentration to 100 cm^{-3} at an altitude of 14 km and above. The activation of aerosols to cloud droplets is based on the grid resolved vertical updraft velocity, temperature, and aerosol number and size from a look-up table constructed from results of a Lagrangian parcel model (Saleeby and Cotton, 2004). For CAM, we extracted the averaged aerosol profile in May at this location from a 5-year run of CAM5 using the MAM3 aerosol module and scaled the aerosol profile based on the surface aerosol number concentrations. The activation of aerosols into cloud droplets in CAM is diagnosed as a function of the modeled subgrid-scale updraft velocity and aerosol compositions/sizes/numbers (Abdul-Razzak and Ghan 2000).

We compared the base case simulations with close to observed surface aerosol number concentrations to observations at the SGP site. Compared to the observations, the simulated clouds from both models begin later in the day and have a smaller vertical coverage. But the models compare relatively well to each other which suggests that differences between the models and the observations may largely be caused by the possible errors/uncertainties associated with the derived initial conditions or advective tendencies. Nevertheless, we can see that the GCE model captures the observed growth of the clouds with height while CAM does not. In addition, both models underestimate the LWP during the day, similar to their underestimation of cloud cover.

However, the response of the two models to increasing aerosols is quite different. The LWP in the GCE model slightly increases with the increasing aerosol number before ~14:00 but starts to decrease with the increasing aerosol number when the clouds start to decay after around 14:00. On the other hand, the LWP from CAM increases substantially and consistently with increasing aerosol number and matches the observed LWP better when the surface aerosol number is equal to 4000 cm^{-3}. In addition, the precipitation rate from CAM consistently decreases with increasing aerosol number and is nearly suppressed after 13:00. The change is most prominent when the aerosol number is increased from 250 to 500 cm^{-3}. This result is due to a combination of decreased autoconversion/accretion and increased evaporation of rain. When the aerosol number is increased from 250 to 500 cm^{-3}, the sum of autoconversion/accretion decreases. Meanwhile since there is less rain falling through the unsaturated sub-cloud layers, the final fraction of rain which can survive evaporation also decreases. The relatively large decrease of surface precipitation is peculiar to the aerosol numbers and environmental conditions simulated here. The precipitation rates from GCE are overall very small with maximum values less than 0.08 mm day^{-1}. The change in precipitation for GCE with increasing aerosol numbers is a little more complex. During the growing phase of the clouds, as in CAM, the precipitation rate decreases. But during the decaying phase, the precipitation rate actually increases even though the LWP decreases.

We also diagnosed the reason for the different responses of LWP and cloud fraction in the two models by examining the budgets of the LWP. In the GCE, when aerosol concentrations are increased from 250 cm^{-3} to 1000 cm^{-3}, the term representing condensation minus evaporation decreases substantially, especially in the decaying phase of the cloud, whereas it does not change much in the CAM model. In the GCE, this decrease offsets to a large extent the effect of decreasing the autoconversion/accretion rate. There is no such change in condensation minus evaporation in the CAM model. We found that the decrease in condensation minus evaporation in the GCE is associated with increased evaporation at cloud top. The increased evaporation cools the cloud top, reduces the temperature lapse rate and thus increases the entrainment of drier air above the cloud top and accelerates the decaying process of the clouds.

One unique aspect of the present paper is that the response of the LWP over the lifetime of the cloud is negative in the CRM while it is positive in the CAM model for the same forcing conditions. One critical deficiency of CAM for this case is that the effect from increased mixing of drier air from above the cloud layer through enhanced entrainment caused by increased aerosol numbers is missing. First, CAM is not able to simulate the growth of the cloud top due to its coarse vertical resolution. However, even if the CAM vertical resolution were high enough to capture the growth of the cloud top, since the moist turbulence scheme and the evaporation of cloud condensate in the cloud macrophysics parameterization at the cloud top are not related to the cloud droplet number, aerosol number will not have a direct impact on the cloud top mixing or the LWP.

Products:

Comparison of CAM5.3 and CSRM Over the Ocean, C. Zhou, J.E. Penner, D. Posselt, S.S. Lee, 2013 DOE ASR Fall Working Group Meeting, Washington DC, Nov 7th, 2013.

Do GCM's overestimate the warm cloud aerosol indirect effect?, Joyce Penner, DOE ASR Program Cloud-Aerosol-Precipitation Interaction Breakout Group, Nov 7, 2013.

Is the indirect forcing by aircraft soot positive or negative? Cheng Zhou and Joyce E. Penner, DOE ASR Program Cloud-Aerosol-Precipitation Interaction Breakout Group, Nov 7, 2013.

Simulations of Aerosol, Cloud, and Precipitation Effects in Comparison with ARM Data, C. Zhou, J. E. Penner, D. Posselt, S.-S. Lee, and G. Lin, Poster presented at 2014 DOE ASR Annual Meeting, Bolger Conference Center, MD, March 2014.

Comparison of NASA GCE-CRM and SCM-CAM5 (SCAM) with ARM data, C. Zhou and J.E. Penner, presented at the ARM annual meeting, 2015.

Comparison of GCE-CRM and SCM-CAM5 with ARM data, C. Zhou, Joyce E. Penner, Derek Posselt, G. Lin, S.S Lee, presented at the Fall 2015 AGU meeting, San Francisco.

Why do GCMs overestimate the aerosol cloud lifetime effect? A comparison of CAM5 and a CRM, J.E. Penner and C. Zhou, Kaufman Symposium, June 21-23, 2016, Goddard Space Flight Center.

Zhou, C. and J. E. Penner, 2017: Why do GCMs overestimate the aerosol cloud lifetime effect? A case study comparing CAM5 and a CRM, Atmos. Chem. Phys., 17, 21–29, doi:10.5194/acp-17-21-2017.

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