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Improved Cloud-Radiation Parameterization for GCMs through the ARM Program

Final Progress Report

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The final focus of our proposed cloud climate interactions work has focused on three important climate questions:

- What is the climate sensitivity of the CCSM2?
- What is the role of absorbing aerosols on the climate system?
- How do the CAM cloud parameterizations depend on model resolution?

Climate sensitivity is an important determinant of climate change. In terms of global climate response, climate sensitivity determines the magnitude of climate change due to radiative forcings by greenhouse gases. The IPCC reports have pointed out that much of the uncertainty in climate projections can be attributed to the disparity in modeled climate sensitivity. Thus, it is imperative to understand the magnitude of climate sensitivity for a given model, and an understanding of what role physical processes play in determining the models particular climate sensitivity.

We have carried out a number of simulations with the latest version of the Community Climate System Model to investigate these issues in the CCSM2. The canonical method used to evaluate model climate sensitivity is to calculate the equilibrium response of a coupled model to an instantaneous doubling of atmospheric CO_2 . Since, coupled models with full depth ocean models would require many thousands of years to reach equilibrium, the ocean model is replaced with a simpler slab ocean with prescribed mixed layer depths and geographically specified ocean heat transport. A version of the CCSM has been constructed that employs a slab ocean model and the identical thermodynamic sea ice model used in the full CCSM2. We have also carried out sensitivity simulations with the fully coupled versions of the CCSM where CO_2 is increased at the rate of 1% per year. Figure 1 shows the change in globally annual averaged surface temperature as a function of time for various versions of the CCSM.

Figure 1. Change in global annual mean surface temperature for versions of the Community Climate System Model. The change is due to a 1% per year increase in CO₂ concentration.

The key point of this figure is that these various versions show a diverse range in climate sensitivity. Analysis of these various versions indicate the low cloud fraction feedback plays a major role in determining the magnitude of the overall climate sensitivity.

Figure 2 shows the change in shortwave cloud forcing as CO₂ is increased at a rate of 1% per year in the fully coupled versions of CCSM. Note that CCSM2 has a greater rate of increase in shortwave cloud forcing than the newer model.

Figure 2. Change in shortwave cloud forcing due to a 1% increase in CO₂ per year from the CCSM2 (blue) and the CCSM3 (red).

Comparisons with the GFDL climate model indicates that low cloud feedback in GCMs is a major factor in inter-model differences in climate sensitivity. This is a major conclusion of our ARM funded research.

Field experiments over the past 5 years have shown the prevalence of absorbing aerosols in the atmosphere (e.g. INDOEX, TARFOX, ACE-ASIA). We have carried out GCM experiments to study the climate effects of absorbing aerosols. We find that these have aerosols have a significantly different role in the climate system compared to scattering aerosols. Absorption of shortwave radiation by these aerosols alters the diabatic heating of the atmosphere and, in turn, alters the hydrologic cycle. To first order the reduction of sunlight at Earth's surface is compensated by a reduction in latent heat. The implications of this are that aerosol effects go beyond directly effecting surface temperatures and a significant effect on regional patterns of the hydrological cycle. These initial studies have

led to carrying out realistic simulations of effects of absorbing aerosols on the climate of the Indian and Asian region.

Single Column Modeling

An important goal of our Single-Column Model (SCM) work has been the development of parameterizations that are physically consistent with each other, an objective strongly linked to the improvement of the representation of clouds and their radiative processes in the NCAR CAM. One component of this work was to examine the statistical properties of the diurnal variations of parameterized processes compared with observations taken over the Southern Great Plains ARM sites. This strategy complements ongoing studies of convection that attempt to deterministically reproduce the time series of observed precipitation over the ARM SGP CART site. Our studies have been aimed at understanding cloud and other large-scale processes that serve to limit the spontaneous release of convective instabilities.

Our efforts focused on the examination and improvement of the diurnal representation of warm season convection over the southern central great plains. A substantial investment in infrastructure was made to allow for routine high-temporal regional sampling of state and process behavior in the global model. This data can also be used to force the single-column version of the respective CAM physics package in order to allow more detailed investigations of process behavior. Initial work documenting the processes involved in regulating moist convection showed that deep convection persists throughout the day with a local maximum occurring at the time of maximum solar forcing, in sharp contrast with observations. One can see middle tropospheric heating by deep convection throughout the day, with two maxima occurring at local noon, and slightly later in the day at 1600 local time. It is worth noting that the second peak in convective heating is not as obviously correlated with the convective precipitation rate. This suggests that either lower tropospheric re-evaporation of rainfall is playing a larger role in the thermodynamic budget at this point in the diurnal cycle, or convective-scale transports of heat are largely responsible for the secondary heating maximum. Surface forcing occurs primarily from large sensible heat fluxes exceeding 400 W/m² near local noon. One of the important features of these simulations is that lower-tropospheric liquid water clouds are virtually non-existent throughout the diurnal cycle and are highly suppressed during the periods of most intense convection. High cloud dominates the total cloud distribution. The initial analysis of a high-resolution version of the CAM2 suggested that many of these features were robust, and not functions of resolution, although the diurnal amplitude of deep convection was much weaker.

Figure 3: The four panels show a composite (six week sample for the spring period) diurnal cycle simulation from a single CAM2 grid point over the Southern Great Plains of surface sensible and latent heat fluxes (upper left), convective precipitation rate (lower left), low, high, and total cloud amount (upper right), and the diabatic heating from convection (lower right).

Two deficiencies in the forcing of deep convection were hypothesized on the basis of the CAM2 analysis. First, the predominance of high-level ice cloud, especially during periods of deep convection is inconsistent with observations. Lower tropospheric liquid water clouds play a large role in regulating the surface solar radiation budget, where their absence could play an important role in the initiation of convection via forcing by the surface turbulent heat flux. The CAM2 cloud formulation was modified to better diagnose the presence of convective cloud. A second factor that appeared to be associated with premature initiation of deep convection is the evaluation of surface turbulent heat fluxes over sparsely vegetated land surfaces. These two improvements were folded into the CAM cloud formulation, where an analysis of convection using a revised physics package shows a striking difference in the phase and properties of the diurnal cycle. Note that convection is much more vigorous, is much less persistent throughout the day, and the maximum in convective precipitation rate occurs later in the day. The cloud field is also quite different, with a nighttime maximum in total cloud cover and considerably more low tropospheric liquid water cloud throughout the day. We also note that the surface forcing is quite different in the revised model, where the latent heat flux plays a much greater role in the total surface turbulent heat flux. We have conducted several experiments to isolate and understand the role of two aforementioned improvements to the model in altering the behavior of the diurnal cycle. The changes to the surface exchange formulation appear to contribute to a delay in the onset of convection, where our first round of experiments suggest that the primary mechanism is a shift in the surface turbulent heat flux from the sensible to latent component. A large component of this shift arises from re-evaporation of rainwater from the plant canopy, explaining nearly 50% of the total surface latent heat flux. At the moment it's not clear what role the initial condition (3 months prior to the simulation period) may be playing in the role of latent heat flux, which will require ensemble integrations to definitively address this issue. SCM simulations make it very clear, however, that the improvement to

the cloud scheme is playing a role in delaying the onset of convection by limiting surface solar insolation as the convective layer grows.

Figure 4: The four panels show a composite (six week sample during spring) diurnal cycle simulation from a single CAM grid point with a revised physics package over the Southern Great Plains. The include surface sensible and latent heat fluxes (upper left), convective precipitation rate (lower left), low, high, and total cloud amount (upper right), and the diabatic heating from convection (lower right).

Figure 5 shows the evolution of the composite cloud field in the two parameterized physics packages. As suggested earlier, the CAM2 cloud field is dominated by upper tropospheric ice water clouds, with a very weak diurnal cycle and a maximum in cloud at 10 km and 1600 hrs. The modified CAM physics package exhibits a much stronger diurnal cycle in all types of tropospheric cloud. Low and mid-level cloud begins to increase with the onset of convective motions, and limits the surface insolation by as much as 40 W/m² at local noon. The upper tropospheric cloud field also exhibits a delayed maximum (with respect to the peak convective activity) between 2200 and 2400 local time. It also produces a clear minimum in outgoing longwave radiation at this time, in sharp contrast with CAM2.

Figure 5: Time evolution of the simulated cloud field (six week springtime period) for a diurnal cycle composite from a single grid point over the Southern Great Plains for CAM2 (left panel) and the revised physics package.

Products:

The work described in this final report has led to substantial contributions to the Community Climate System Model project. The CCSM is one of the major global climate modeling efforts in the world and involves a large community of climate scientists. The work described contributed to the development of the CCSM2, which is described in the following publications:

Kiehl, J.T. and P.R. Gent, 2003: The Community Climate System Model, Version Two. *Submitted to the J. Climate.*

The SCM efforts will be submitted for publication and will cite the support of the ARM program.

As a final report, we would like to thank ARM for its many years of support of our cloud climate research efforts.

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