Effect of Cloud Overlap and Inhomogeneity on Climate Simulations

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Introduction

Atmospheric radiation budgets are strongly affected by the horizontal and vertical distributions of cloud systems. With the horizontal resolution of several hundred kilometers in general circulation models (GCMs), parameterization of cloud vertical overlap and horizontal inhomogeneity in radiation schemes has long been a major challenge for climate simulations (Stephens 1984; Stephens et al. 2004). Numerous studies have focused on developing methods to approximate the effects of subgrid interactions into the GCM radiation schemes (Geleyn and Hollingsworth 1979; Stephens 1984; Liang and Wang 1997; Barker et al. 1999; Morcrette and Jakob 2000; Li 2000; Fu et al. 2000; Collins 2001; Li and Barker 2002; Stephens et al. 2004). However, the evaluation and implementation of these methods are limited due to the lack of consistent, fine-resolution observations of cloud-radiation interactions. The radiation parameterization is further complicated by the uncertainties associated with the parameterization of convection and clouds in GCMs. The development of cloud-resolving models (CRMs) and Atmospheric Radiation Measurement (ARM) observations provides an opportunity to make progress on this problem. Our research objective is to generate long-term comprehensive and physically consistent data that will facilitate quantifying the effects of subgrid cloud-radiation interactions and, ultimately, develop a physically based treatment of cloud vertical overlap and horizontal inhomogeneity for the radiation scheme in GCMs. This will contribute to the fundamental goal of the ARM Program, i.e., “to improve the treatment of radiation and clouds in the models used to predict future climate, particularly the general circulation models.”

Month-long simulations of ARM cloud systems were successfully conducted using the Iowa State University (ISU) CRM and extensively validated against various ARM measurements (Wu and Liang 2003, 2005). Further improvements to model physical processes, especially microphysics, can be made as more ARM-analyzed observational data become available. However, the current CRM simulations provide a unique cloud dataset to evaluate the existing parameterization of subgrid cloud-radiation interactions, such as the mosaic treatment for incorporating into GCMs. It was demonstrated that the mosaic approach with the CRM cloud statistics (Figure 1) can faithfully simulate the CRM domain-averaged radiative fluxes at the surface and top of the atmosphere (TOA) (having mean errors less than

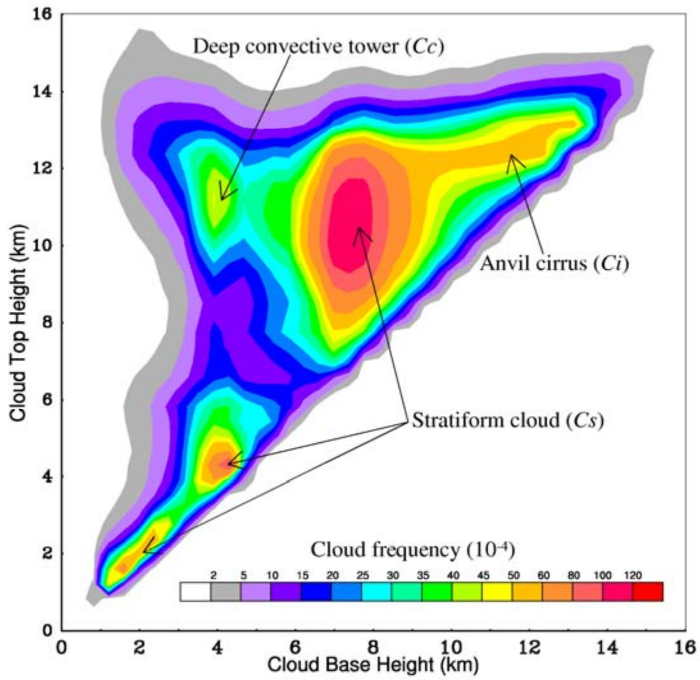

Figure 1. CRM simulated cloud frequency (10-4) distribution as a function of the base and top heights. Three major cloud clusters are identified in the centers as convective (Cc), anvil cirrus (Ci) and stratiform (Cs) that are distinguished by the mosaic approach.

5 Wm^{-2}), as well as theradiative heating rates, except in the upper troposphere (Wu and Liang 2004; Liang and Wu 2005). It represents a significant improvement over the conventional GCM approach and thus provides a cost-effective solution to incorporate the subgrid cloud overlap and inhomogeneity effects into a GCM radiation scheme. The result indicates that the parameterization of cloud overlap based on characteristic structure differences between three primary cloud genera (convective, anvil, and stratiform) and the approximation of the optical inhomogeneity by the cloud fraction scaling capture the dominant effects of the cloud geometric association and optical property variability within a GCM grid, respectively.

The radiation scheme with the mosaic treatment of cloud overlap and inhomogeneity is now implemented in the National Center for Atmospheric Research (NCAR) Community Climate Model, Version 3 (CCM3). In this paper, 5-year CCM3 simulations with the Atmospheric Model Intercomparison Project (AMIP) sea surface temperature (SST) will be presented and compared with the standard CCM3 runs to study the impact of subgrid cloud-radiation interaction on climate simulations.

Mosaic Treatment of Subgrid Cloud-Radiation Interaction

The mosaic approach of incorporating subgrid cloud-radiation interactions into a GCM was developed by Liang and Wang (1997) and evaluated using the CRM cloud statistics by Liang and Wu (2005). A brief description is given here, and references to two papers with a more detailed discussion are provided. The approach divides the GCM grid column into subcells so that an individual layer within a subcell is either completely overcast or cloud free. Each overcast subcell layer contains a specific cloud genus with distinct optical properties. The most important consideration is to distinguish, within individual cloudy subcells, two cloud fractions: one with and one without inherent geometric association. In particular, convective (Cc), anvil cirrus (Ci), and stratiform (Cs) clouds in each layer are defined as geographically distinct and minimally overlapped. Cc are assigned to a single subcell column, while Ci consecutively fill the subcells that are equally divided over the remaining grid area. Cs is distributed into random-ordered subcells with an identical sequence for adjacent layers (maximal overlap) and otherwise independent sets for random overlap. At a given layer, one subcell may contain the residual partial cloud fraction to conserve the grid total cloud amount. Separate independent column approximation (ICA) radiation calculations are then performed for each subcell with clouds; whereas, clear-sky radiative fluxes are computed only once and used for all subcells when needed. Grid mean radiative heating rates and fluxes are then the area averages over all subcells. Consequently, this mosaic approach can adequately address the cloud macrogrouping (geometric association) and inhomogeneity (within-cloud optical property variance) effects on radiation.

Experimental design of Community Climate Model Version 3 Climate Simulations

The CCM3 is the earlier version of atmospheric component in the fully coupled NCAR Community Climate System Model (CCSM). Both CCSM and CCM3 have been used worldwide for climate modeling and climate change studies. They incorporate highly comprehensive physical parameterizations for subgrid-scale processes such as boundary layer turbulence, radiation, clouds, and convection. Most relevant to this study are the parameterizations for cloud cover, optical property, and radiation transfer, for which a brief discussion follows.

In the CCM3, the radiative effect of vertically varying partial cloudiness is represented in approximation to the random overlap assumption (Kiehl et al. 1996). In the shortwave radiation, this is approximated by modifying the cloud extinction optical depth as $\tau'_c = \tau_c A_c^{3/2}$, where A_c is the fractional cloud cover in the layer. The scaling was found to produce a result that is very close to the random overlap assumption, without the computational burden of doing the radiative transfer for the spectrum of all cloudy layer combinations. In the longwave radiation, the cloud emissivity ε_c is first accounted for by defining an effective cloud amount $A'_c = \varepsilon_c A_c$ in each layer; the probability of a cloud A'_c existing in a given layer concurrent with clear sky above or below this layer is then calculated following the random overlap assumption; and finally, the radiation transfer is done once in the entire column by using the vertical profile of such probability.

In general, most GCMs have to tune the cloud fields, such as cloud liquid/ice water paths and cloud fractions, to match the observed radiation budgets at the surface and TOA. For the CCM3, which calculates the cloud liquid water using a diagnostic liquid water scale height from total precipitable water, this tuning procedure is accomplished using very unrealistic representation for cloud amount and cloud water path to constrain the model radiation budgets close to observations. The reference water concentration is set to an unrealistically low value, and the vertical distribution is prescribed as an exponential decay function of the scaled altitude. The setting compensates for the large overestimation of total cloud amount due to the random overlap assumption, which is physically inconsistent. In the newly released Community Atmospheric Model (CAM), cloud liquid and ice condensates are predicted by the bulk microphysics parameterization (Rasch and Kristjànsson 1998; Zhang et al. 2003). However, a similar inconsistency problem between cloud properties remains unsolved.

Two 5-year (1979-1983) CCM3 simulations are performed using the AMIP SST, including the control run with the standard CCM3 physics (hereafter referred to as CTL), the simulation with the mosaic treatment of overlap assumption but the modified cloud property and fraction parameterizations to match the observed radiation budget (MOS). Two additional 5-year runs are conducted to understand the difference between the MOS and CTL runs, i.e., the control run with the scaled cloud amount and total cloud water path as in MOS (CTL_MC) and the MOS run with the original cloud representation as in CTL (MOS_OC).

Effects of Subgrid Cloud-Radiation Interaction On Atmospheric Model Intercomparison Project Simulations

The 5-year (1979-1983) AMIP simulations prescribed with the observed SST showed encouraging results. Figure 2 compares net longwave and shortwave radiative fluxes at the TOA and the surface from the CTL and MOS runs and observations. The radiative fluxes from the MOS are in general agreement with the observations in the CTL. The mosaic treatment produces smaller radiation-effective clouds than the random overlap assumption. This provides an opportunity to adjust the cloud amount and cloud water path toward available observations. As an initial attempt, the CCM3 diagnosed high-level cloud amount and total cloud water path in the MOS run was scaled to match the global annual means of International Satellite Cloud Climatology Project (ISCCP) and Special Sensor Microwave/Imager (SSM/I) data, respectively. This scaling is estimated based on the initial 1-year integration and kept constant in time and space. Figure 3 shows the comparison of high-level cloud amount and total cloud water path from the CTL and MOS and observations. It is interesting to find out that the global distribution of both high cloud amount and cloud water path from the MOS are much more realistic than those from the CTL when compared with the observations. The seasonal variation of cloud amount and cloud water path from the MOS is also closer to observations than the CTL (not shown). It has been a long standing problem in many GCMs including the CCM3 that unrealistic high-level cloud amount and cloud water path have to be used to maintain the global radiation budget closer to satellite observations.

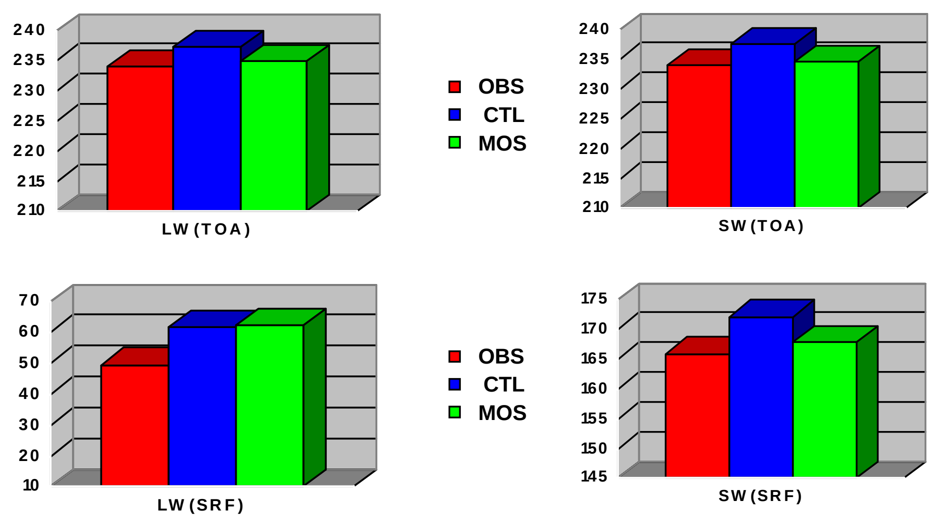

Figure 2. 5-year global averages of radiative fluxes (Wm^{-2}) from observations (OBS), CCM3 (CTL), and mosaic run (MOS).

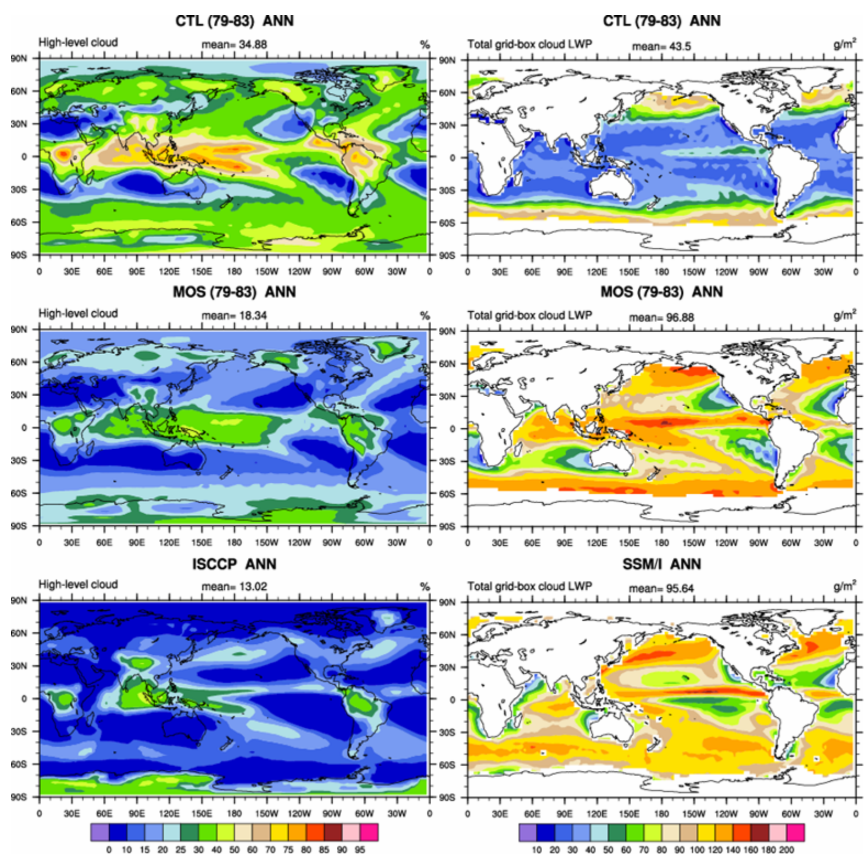

Figure 3. Left: 5-year (79-83) averages of high-level cloud fraction (percent) from CCM3 (CTL, top), mosaic run (MOS, middle), and ISCCP (bottom). Right: 5-year averages of total cloud liquid water path (gm^{-2}) from CTL (top), MOS (middle), and SSM/I (bottom).

The improved cloud and radiation fields in the MOS lead to a significantly different radiative heating rate than in the CTL (Figure 4). Consequently, the representation of cloud-radiation interaction is more physically consistent and accurate, and mean climate variables, such as the temperature field, are better simulated over the tropical upper troposphere and, overall, are closer to reanalysis and observational data (Figure 4). The global annual mean precipitation rates from the mosaic and the standard CCM3 simulations are 2.97 and 3.10 mm day-1, as compared to 2.69 mm day-1 in observations.

To isolate the impacts of the mosaic treatment of subgrid cloud distribution and the modified cloud amount and cloud water content on the climate simulations, the MOS_OC and the CTL_MC runs were conducted for 5 years using the AMIP SST. It is found that the increase of net radiative heating in the upper troposphere over the tropics (Figure 4) is due to the modification of cloud water content. The mosaic treatment of subgrid cloud distribution actually reduces the radiative heating in the upper troposphere because the radiative-effective clouds is smaller than those from the random overlap assumption, which leads to a cooling effect on temperature field. The CTL_MC run with the modified cloud parameterization shows that the net shortwave fluxes at the TOA and surface are reduced by more than 15 Wm^{-2} from the CTL run.

In short, the mosaic treatment of subgrid cloud-radiation interactions implemented in the CCM3 facilitates the use of coherent cloud amounts and cloud water paths to produce realistic radiative fluxes. Consequently, not only the representation of cloud-radiation interactions is more physically consistent and accurate, but the CCM3 climate simulations are significantly improved.

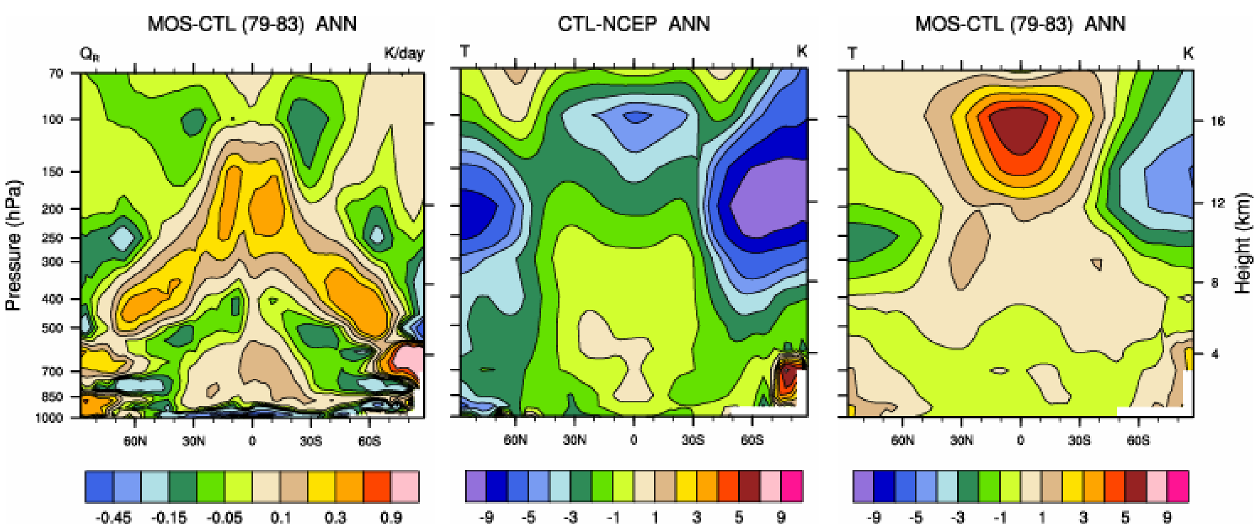

Figure 4. 5-year zonal average of the difference of radiative heating rate ($Kday^{-1}$) between mosaic run (MOS) and CCM3 (CTL) (left), the differences of temperature (K) between CTL and NCEP (middle) and between MOS and CTL (right).

Concluding Remarks

The CCM3 study was our first attempt to explore the impact of subgrid cloud-radiation interactions on climate simulations. We made adjustments to the diagnostic scheme of cloud cover and the prescribed scale factor of cloud water path to obtain global mean values close to the observed ISCCP cloud amounts and SSM/I liquid water paths. The main purpose of the experiments was to demonstrate that the mosaic treatment enables the incorporation of cloud amounts and water paths that are consistent with observations while maintaining the global radiation budget close to observations. As such, questions were raised regarding the feedback processes that may explain the resulting large climate responses when the mosaic approach is compared with the standard CCM3. Further analysis and sensitivity experiments are required to understand the physical processes involved in the climate responses to the improved radiation scheme. We are planning to implement the mosaic approach into the CAM and study its global impacts on mean climate and climate variability. We will incorporate a more realistic and consistent representation of both cloud amounts and water contents derived from comprehensive diagnostic studies using the CRM simulations in combination with ARM observations.

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