J4.4 RADIATIVE EFFECTS OF CLOUD INHOMOGENEITY AND GEOMETRIC ASSOCIATION IDENTIFIED FROM A MONTH-LONG CLOUD-RESOLVING MODEL SIMULATION

Xiaoqing Wu*, Mitchell W. Moncrieff
National Center for Atmospheric Research†
Boulder, Colorado

and Xin-Zhong Liang
Illinois State Water Survey
Champaign, IL 61820

1. INTRODUCTION

The representation of cloud systems and cloud-radiation interaction is considered to be one of major uncertainties in general circulation models (GCMs). Most GCMs are unable to get the tropical energy budgets at the top of the atmosphere and the surface to simultaneously agree with observations. For example, a good agreement of radiative fluxes at the top of the atmosphere between observations and large-scale models can be obtained by tuning the model cloud fraction and aerosol optical depth, but a large bias in the surface energy budget typically remains (e.g., Kiehl 1998). This is a crucial issue in coupled atmosphere-ocean models.

While GCMs require convection and cloud parameterizations, cloud-resolving models (CRMs) explicitly resolve convection and mesoscale organization, where cloud microphysical processes and cloud-radiation interactions directly respond to the cloud-scale dynamics. Wu and Moncrieff (2001) demonstrated that the CRM produces vertical and horizontal distributions of cloud liquid and ice that interact much more realistically with radiation than the single-column model (SCM) of the NCAR Community Climate Model (CCM3), where the radiative effect is calculated from a single volume of "effective" cloud. In most GCM parameterizations of cloud-radiation interactions, clouds are assumed horizontally homogeneous and the vertical cloud geometric association is treated by the cloud-overlap assumptions (Liang and Wang 1997). Consequently, the CRM simulation can get the top-of-the-atmosphere (TOA) and surface net shortwave fluxes to agree simultaneously with observations from the Tropical Ocean Global Atmosphere (TOGA) Coupled Ocean Atmosphere Response Experiment (COARE), whereas GCMs and SCMs generally fail to do so.

Using the CRM simualtion as a benchmark, the radiative effect of subgrid cloud horizontal and vertical variability is estimated by an offline calculation of the radiative transfer model in Wu and Moncrieff (2001). In the present study, we further conduct an offline radiation calculation to quantify separately the effects of the overlap assumption and the subgrid cloud horizontal variability on the radiative fluxes using the CRM-produced month-long cloud-scale temperature, moisture, and condensate fields.

2. CLOUD-RESOLVING MODEL SIMULATION

The NCAR CRM is based on the Clark-Hall finite-difference formulation of the anelastic, nonhydrostatic equations. A Kessler bulk warm rain parameterization and a Koenig and Murray bulk ice parameterization are used. The cloud-radiation interaction is parameterized as in the NCAR CCM. Effective radii of liquid and ice particles are assumed to be 10 μm and 30 μm, respectively. Radiation calculations are performed every 150 s, with the most recent tendencies applied between consecutive calculations. The surface fluxes of sensible and latent heat are calculated using the observed sea surface temperature (SST) and a simplified version of the TOGA COARE surface flux algorithm.

The CRM domain is 900 km wide (300 columns with a horizontal grid spacing of 3 km) and 40 km deep (52 levels with a stretched grid, a 100 m increment at the surface and increasing to 1500 m at the model top). The lateral boundary conditions are periodic. Rigid, free-slip bottom and top boundary conditions are applied together with a gravity wave absorber in uppermost 14-km of the domain.

The CRM is forced by the evolving large-scale ad-

* *Corresponding author address*: Dr. Xiaoqing Wu, NCAR, P.O. Box 3000, Boulder, CO 80307-3000. E-mail: xiaoqing@ucar.edu

†The National Center for Atmospheric Research is sponsored by the National Science Foundation.

vection of temperature and moisture during a 30-day period (5 December 1992 – 3 January 1993) of TOGA COARE. The analysis of the CRM simulation and the comparison with observations can be found in Wu et al. (1998, 1999).

3. RESULTS

In the full CRM (M0), the so-called binary clouds (i.e., completely overcast or clear skies) are used for 300 columns. We define a grid box at a given level to be completely overcast if the sum of liquid and ice water path exceeds threshold 0.2 g m^{-2}. The radiative flux is calculated for each column using the radiative transfer model, and the 300 columns are then averaged to get the mean radiative flux. The radiative effect of subgrid cloud horizontal (inhomogeneity) and vertical (geometric association) distribution is thereby explicitly included in the CRM-produced radiative flux.

The offline calculation M2 is designed to estimate the impact of cloud inhomogeneity on the radiative flux. For each completely overcast column at a given level, the cloud radiative properties (including cloud amount, emissivity, extinction optical depth, single scattering albedo, asymmetry parameter, and forward scattered fraction) are replaced by the domain-averaged value. As in M0, the radiative transfer is calculated for each column and the mean radiative flux is obtained by averaging all 300 columns. For M2, only the horizontal inhomogeneity is removed, while all others (including temperature and water vapor profiles) are kept identical to M0. Thus the differences between M0 and M2 represent the effect of cloud horizontal inhomogeneity.

As shown in Table 1, the difference between M0 and M2 is more than 30 W m^{-2} for the shortwave flux and more than 10 W m^{-2} for the TOA longwave flux. The removal of the cloud inhomogeneity is to reduce the domain-averaged shortwave and longwave fluxes. This result indicates that the CCM3 radiation scheme like many GCM parameterizations of cloud-radiation interactions which assume that clouds are horizontally homogeneous can substantially underestimate the radiative flux especially the shortwave flux.

Table 1. 30-day mean TOA and surface (SRF) radiative fluxes (W m^{-2}) from the CRM (M0) and offline radiation calculations (M1 and M2).

Fluxes	M0	M2 (M0-M2)	M1 (M2-M1)
Q_{LW}(TOA)	-195.8	-182.6 (-13.2)	-171.2 (-11.4)
Q_{LW}(SRF)	-48.2	-46.4 (-1.8)	-39.3 (-7.1)
Q_{SW}(TOA)	274.8	243.6 (31.2)	238.4 (5.2)
Q_{SW}(SRF)	179.3	145.9 (33.4)	141.1 (4.8)

In the offline calculation M1, the mean cloud radiative properties and cloud fraction profiles are obtained from the 300 columns of the CRM domain, and then the radiative flux is calculated using the mean profile. In this case, the cloud vertical distribution has to be treated by the cloud-overlap assumptions because there is only one column for each time step. So M1 is the same as what the SCM is doing except the cloud amount and cloud fraction profiles are from the CRM. Because the mean cloud radiative properties are the same for M1 and M2, the difference between M2 and M1 is due to the effect of the cloud-overlap assumption (a random overlap assumption currently used in the CCM3 radiation scheme). The random overlap assumption tends to overestimate the total cloud cover, which results in smaller shortwave and longwave fluxes in M1 than in M2 (e.g., Tian and Curry 1989; Liang and Wang 1997).

In summary, for the shortwave flux, the cloud horizontal inhomogeneity has a much larger impact on the flux than the vertical cloud-overlap assumption. However, for the longwave flux, both the cloud horizontal inhomogeneity and vertical overlapping are equally important. Incorporation of both horizontal and vertical variability using the mosaic treatment (Liang and Wang 1997) will provide a cost-effective solution to reduce the GCM biases in the estimation of radiative flux.

Acknowledgements: This research was supported by the Biological and Environmental Research Program (BER), U.S. Department of Energy, Grant No. DE-FG03-02ER63354. This work is part of the NCAR Clouds in Climate Program.

REFERENCES

Kiehl, J. T., 1998: Simulation of the Tropical Pacific warm pool with the NCAR climate system model. *J. Climate*, **11**, 1342-1355.

Liang, X.-Z., and W. C. Wang, 1997: Cloud overlap effects on general circulation model climate simulations. *J. Geophys. Res.*, **102**, 11039-11047.

Tian, L., and J. A. Curry, 1989: Cloud overlap statistics. *J. Geophys. Res.*, **94**, 9925-9935.

Wu, X., W. W. Grabowski, and M. W. Moncrieff, 1998: Long–term behavior of cloud systems in TOGA COARE and their interactions with radiative and surface processes. Part I: Two–dimensional Modeling Study. *J. Atmos. Sci.*, **55**, 2693–2714.

Wu, X., W. D. Hall, W. W. Grabowski, M. W. Moncrieff, W. D. Collins, and J. T. Kiehl, 1999: Long–term behavior of cloud systems in TOGA COARE and their interactions with radiative and surface processes. Part II: Effects of ice microphysics on cloud-radiation interaction. *J. Atmos. Sci.*, **56**, 3177-3195.

Wu, X., and M. W. Moncrieff, 2001: Long–term behavior of cloud systems in TOGA COARE and their interactions with radiative and surface processes. Part III: Effects on the energy budget and SST. *J. Atmos. Sci.*, **58**, 1155-1168.