Treatment of Cloud Radiative Effects in General Circulation Models

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We participate in the Atmospheric Radiation Measurement (ARM) program with two objectives: 1) to improve the general circulation model (GCM) cloud/radiation treatment with a focus on cloud vertical overlapping and layer cloud optical properties, and 2) to study the effects of cloud/ radiation-climate interaction on GCM climate simulations. This report summarizes the project progress since the Fourth ARM Science Team meeting February 28-March 4, 1994, in Charleston, South Carolina. During this period, four graduate students continue to participate in the research.

Longwave and Solar Parameterization

We evaluate the longwave and solar radiative parameterization of the National Center for Atmospheric Research (NCAR)-Global Environmental and Ecological Simulation of Interactive Systems (GENESIS) (Wang et al. 1995) using concurrent satellite and ground measurements at the Southern Great Plains (SGP) site during the April 1994 Intensive Observation Period (IOP). The comparison results are shown in Figure 1. Note that no aerosols are used for longwave radiation while it is included in solar radiation with visible optical thickness 0.07 and surface albedo 0.16 derived from observations. For longwave radiation, the model calculates larger outgoing flux at the top of the atmosphere (TOA) but smaller downward flux reaching the surface, both suggesting smaller model atmospheric opacity. For solar radiation, the model systematically overestimates the downward flux, again an indication of the smaller model atmospheric opacity, while the agreements for reflected radiation are much better mainly because it is dominated by the surface albedo. We are currently evaluating the causes for such differences, including the instrumental errors.

High-Level Cloud Parameterization with Interactive Microphysics

A parameterization for solar radiative effect of high-level clouds with interactive microphysics, developed for use in GENESIS, is employed to study the absorption of solar radiation by high clouds. In the parameterization, the cloud particles are assumed to be composed of randomly oriented hexagonal crystals, and the broad band transmittance, reflectance, and absorptance are expressed as a function of single scattering albedo, asymmetry factor, and optical depth which depends on cloud ice water content and effective radius (Ebert and Curry 1992).

The ratio of solar cloud radiative forcing on the surface to that at the top of the atmosphere is used as an indicator for high-cloud absorption. Note that Cess et al. (1995) used observations to derive a value of 1.5 for the ratio, while we calculated 1.3 using the SGP April 1994 IOP data. In the model calculations, the existing GENESIS cloud radiative scheme gives 1.2; this smaller value can be attributed to high-cloud treatment. Indeed, the newly developed high-cloud radiative scheme calculates a value of 1.5, which however, is very sensitive to the effective radius used; for example, the calculated value is 1.2, 1.4, 1.8, and 2.1, respectively, for effective radius 10, 30, 40, and 50 µm.

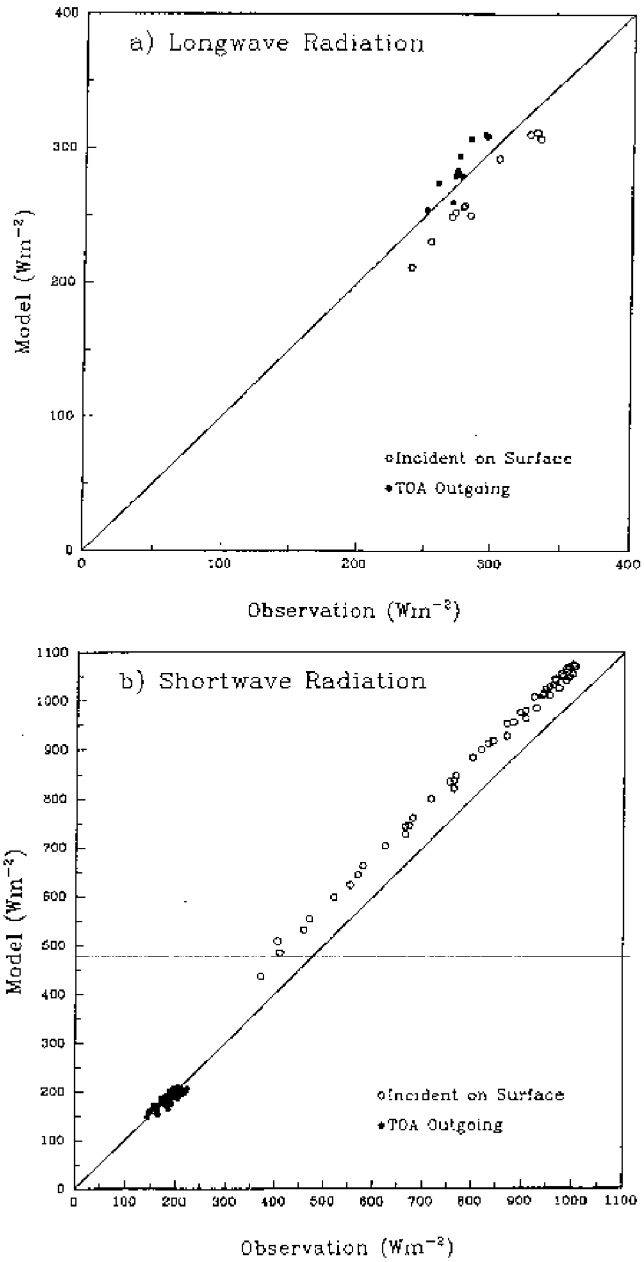

Figure 1. Comparisons between model calculated and observed clear sky of (a) longwave and (b) solar radiative flux (Wm^{-2}) at the SGP central facility during April 1994 IOP (see Figure 2). Open circles are for the downward fluxes reaching the surface while solid circles correspond to values at the top of the atmosphere. The aerosols are only included in the solar radiation calculations with τ = 0.07 and surface albedo 0.16.

Scale-Dependence of GCM Parameterizations for Cloudiness and Radiation

The scale-dependence of cloud-radiation interaction associated with the parameterizations for fractional cloudiness and radiation used in GENESIS is studied by examining the averages, for different spatial scales, of detailed structure of cloudiness and radiation simulated from a regional climate model (ReCM, based on MM5) which incorporates these parameterizations. The regional model simulation is conducted over an area about (360 km)^2 located on the SGP for the period April 10-17, 1994, during which both satellite and surface measurements of radiation fluxes and clouds are available (Figure 2).

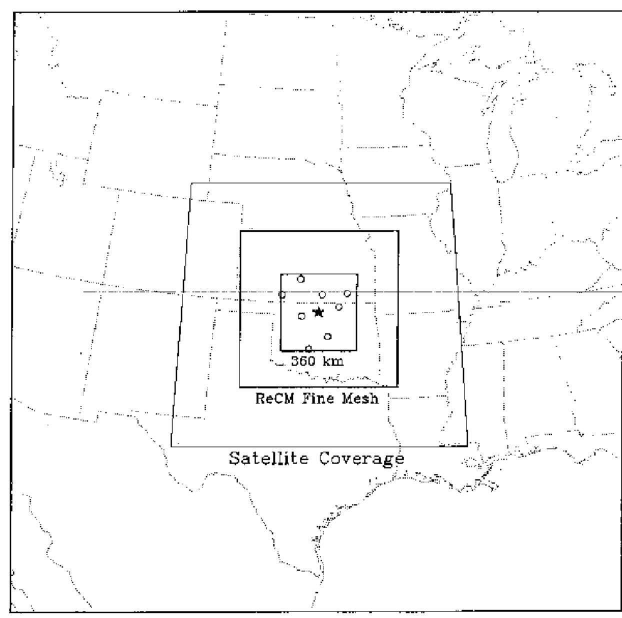

Figure 2. The physical domains for the regional climate model (ReCM) simulations over the SGP ARM site. The ReCM domain has two levels of nesting: a coarse mesh of 45 km and an inner fine mesh of 15 km. The smaller inner square covering part of Oklahoma and Kansas with an area of (360 km)^2 is used for the calculations. The ARM central facility is indicated by a star, while the open circles indicate other locations of the energy balance Bowen ratio (EBBR) measuring stations. The outer box encircles the region where the satellite data are available.

The ReCM simulates well the overall cloud and radiation temporal features when averaged over the entire region. However, specific biases exist in the spatial patterns such as the high clouds, the TOA upwelling solar radiation under cloudy conditions, and the net longwave surface flux under clear conditions at night. The cloud and radiation parameterizations are found to be sensitive to the spatial scale of the computation. The diagnosed total cloudiness shows a strong horizontal resolution dependence which leads to large changes in the surface and TOA radiation budgets. An additional experiment, in which the diagnosed cloud at each level is held constant while the radiation parameterization is recalculated, still produces a substantial sensitivity to spatial scale in the calculated radiation quantities. This is because the nature of the cloud vertical overlapping assumption changes as the horizontal scale of the computation varies.

Small-scale horizontal inhomogeneities have been found to greatly influence the interaction between the cloud and radiation parameterizations used in GCMs and make the results very sensitive to horizontal scale of the computation. This indicates that when the horizontal resolution of a model is changed, particular attention should be paid to the nature of the interaction between clouds and radiation, both in total cloud amount and in the nature of the vertical overlap assumption used by the radiation scheme. When developing and testing physical parameterizations for GCMs, it is important to compare consistent horizontal scales between the observations and the model. High resolution measurements must be averaged to a scale comparable to the model in order to successfully use measurements to develop physically based parameterizations. Details of this study are documented in Dudek et al. (1995).

Stochastic Cloud-Radiation Treatment

As found in Dudek et al (1995), within a typical GCM grid (~5°C resolution), there exits substantial sub-grid scale variability in cloud radiative forcing (CRF). To incorporate this variability into the cloud-radiation parameterization of a global climate model, we adopt a stochastic approach based on cloud probability distribution function (PDF) which describes the statistical characteristics of cloud variability.

We have examined the observations to define the characteristics of cloud variability. The individual high and total cloud cover PDFs estimated from 0.5°C (sub-cell) satellite measurements at the SGP during the April 1994 IOP (Figure 2) indicate that more than 50% of sub-cells in this domain are either total clear sky or overcast, while partial cloudy conditions occur randomly and much less frequently. We also find that the PDFs are symmetric around 50% cloud cover; for example, the PDF at 70% is quite the same as that for 30% cloud cover. These results suggest that the total and high cloud PDFs change gradually with grid mean cloud cover. These features exist for observed low- and middle-level clouds and are also reproduced (except for high clouds) by the ReCM simulations (Dudek et al. 1995). Consequently, the horizontal variation of vertical cloud distribution, the cloud cover PDF, can be used to parameterize the CRF sub-grid variability.

Given these characteristics, we have designed a new treatment for cloud vertical overlapping, which divides a GCM grid into N sub-cells where column radiation calculations are performed. It can accurately and easily handle the layer cloud optical properties and vertical cloud overlapping because the individual layers within given sub-cells are more likely to be either total clear or overcast condition (binary clouds). The sub-cell cloud covers, determined randomly using observed PDFs, can be treated either as random overlapping or constrained between non-adjacent cloud layers to produce a mixed overlapping. The treatment incorporates the observed sub-grid scale cloud cover variability, and therefore the CRF spatial variability.

Figure 3 gives an example of the effect of cloud overlapping treatment on CRFs. For all calculations, the same vertical profiles of temperature, moisture, ozone corresponding to mid-latitude summer conditions are used; the surface albedo is set at 0.16, a value representative of the SGP, while the solar insolation is fixed at July 15, 1:30 pm SGP local time. These results suggest that given an identical GCM grid mean cloud vertical distribution, surface or TOA CRF can differ by ± 30 Wm^{-2}, and the cloud vertical overlapping can affect the cloud absorption by ± 10 Wm^{-2}.

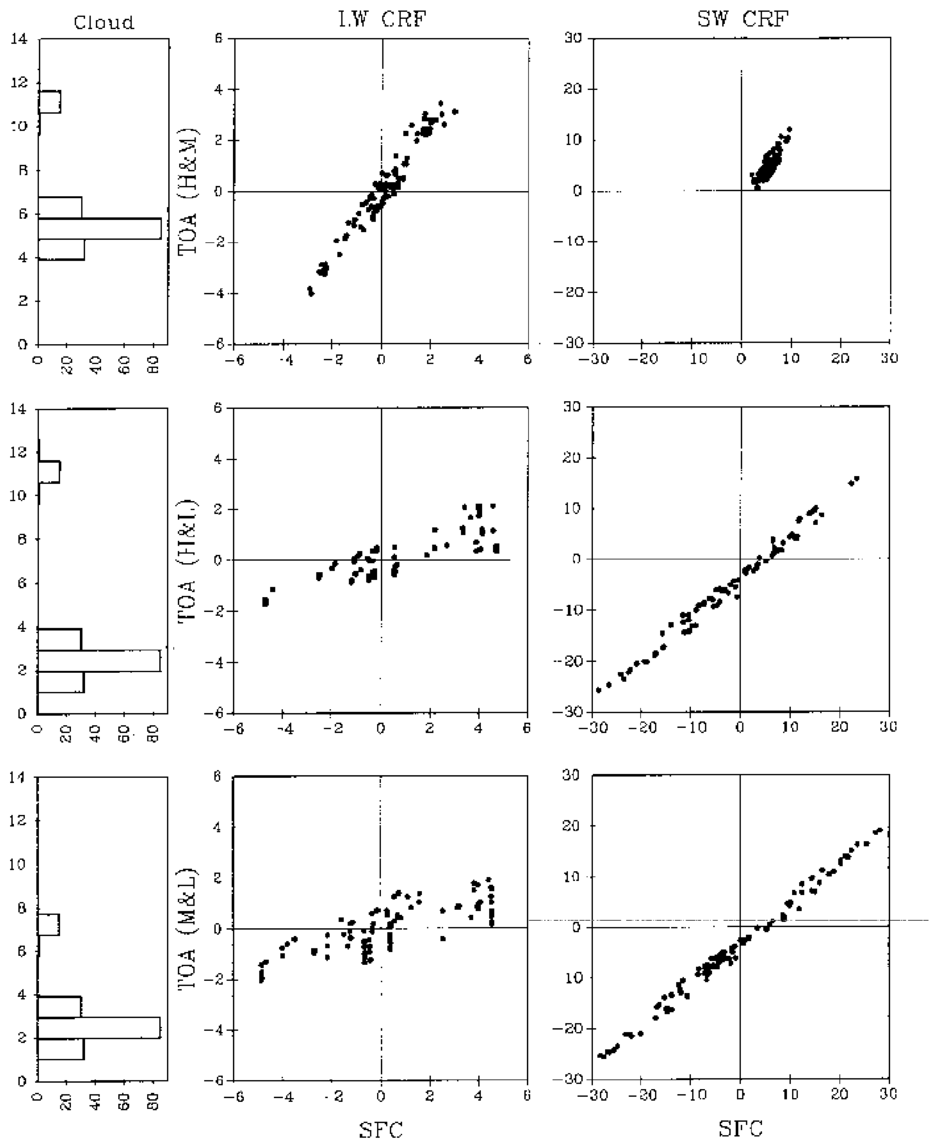

Figure 3. The effect of stochastic treatment of cloud vertical overlapping on the cloud radiative forcing at the top of the atmosphere (TOA) and on the surface (SFC). For each of three idealized cloud vertical distributions (high+middle, high+low, middle+low), 100 sets of full radiation calculations are performed on 12 sub-cells where binary cloud covers occur randomly at individual layers. Each scatter point represents the difference between the mean over the 12 sub-cells and a single grid calculation of the TOA versus surface CRF.

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