Treatment of Cloud Radiative Effects in General Circulation Models (GCMs): Cloud Overlap Effects on GCM Climate Simulations

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Summary

We participate in the Atmospheric Radiation Measurement (ARM) Program with two objectives: 1) to improve general circulation model (GCM) cloud/radiation treatment with 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 recent findings in sub-grid scale variability of cloud-radiation interaction while work on two other areas (radiative fluxes with aerosols and layer clouds) is on-going.

Introduction

Clouds are often observed to occur with distinct geometric associations in the vertical direction. For example, altostratus tend to exist exclusively with cumulus while cumulonimbus and cirrus frequently occur simultaneously in the tropics. Current GCMs, however, predict only cloud fractions in individual model layers without explicitly specifying their association. Two overlap assumptions are generally adopted. Random overlap assumes that all cloud layers are independent and, thus, tends to yield a larger total cover because it neglects geometric association. This is partially corrected by mixed overlap, where adjacent cloudy layers of specific genera are allowed to share maximum overlap.

Although several studies have indicated the importance of cloud overlap, they have neither consistently treated cloud overlap in both solar and infrared radiations, nor systematically quantified the subsequent effects on climate simulations. In this study, we use a GCM to examine the differences in radiative forcing and climate simulations between random overlap and a "mosaic" approach. For the latter, a GCM grid is divided into multiple subcells such that appropriate horizontal distributions of cloudy subcells and distinct vertical alignments are used to incorporate the cloud geometric association. By this, the cloud overlap effect is more easily and consistently incorporated into both infrared and solar radiation calculations. It is shown that, in the context of plane-parallel clouds, the infrared forcing is more important than the solar forcing, and that the combined effect can lead to substantially different, but more realistic, climate simulations.

Mosaic Cloud Treatment

A GCM grid used for climate simulations typically covers an area of 300-1000 km^2. Regions of this size are characterized by large spatial variability in climate processes, especially the cloud-radiation interaction (Dudek et al. 1996). Because of coarse resolution, it is unlikely that all of the relevant scales of variability can be resolved. Here we focus on subgrid scale cloud-radiation variability related to the geometric association of cloud genera within a GCM grid. The horizontal extents of major cloud genera (such as convective, cirriform, and stratiform) are usually predicted as the overall fractional cover in individual layers. Thus, proper consideration of cloud geometric association (usually subgrid scale) requires that horizontal distributions of different genera in each layer be mixed properly in the vertical direction. To do this, we adopt a "mosaic" approach, in which the GCM grid is aggregated into N subcells horizontally (see below for the determination of N values). Separate radiation calculations are performed for each subcell with clouds, whereas clear sky radiative fluxes are computed only once and used for all subcells. The grid mean radiative heating/cooling distributions are then the aerial averages over all subcells. This framework can treat the cloud overlap more rigorously.

The mosaic approach is further simplified by the observed statistics that binary clouds (i.e., completely overcast or clear skies) are dominant in the individual mesoscale subcells (Dudek et al. 1996). For each subcell, individual vertical layers are either completely cloudy or clear. In this treatment, however, one subcell with partial cloud fraction may be needed to conserve the grid total cloud amount at a given layer. In addition, the subcells with clouds at a given layer need to be specified to allow for cloud overlap with geometric association. To do this, in each model layer, a set of randomly ordered indices is first generated to represent N distinct subcells with equal fractional area. The overall cloud amount is then distributed consecutively over the subcells from the beginning of the set until the residual becomes zero. Note that when the random overlap treatment is used, cloud genera are not distinguished and, hence, only the total cloud cover for individual layers is needed.

Since the GCM used in this study (see below) predicts separately the fractional coverage of convective (Cc), cirriform (Ci) and stratiform (Cs) clouds, the following procedure is adopted to treat the geometric association of distinct cloud genera. First, different cloud genera (Cc, Ci, Cs) in each layer are defined to be geographically distinct and, thus, minimally overlapped. Second, Cc are assigned to a single subcell, where the area is given by the largest Cc values from the convective top to the lowest layers. Third, Ci (usually in the convection top layer) then fill consecutively the subcells that are equally divided over the remaining grid area. Finally, Cs are distributed to subcells in a manner identical to that of the random overlap treatment. In this case, however, one special consideration is taken: adjacent layers that contain Cs are vertically aligned by an identical set of random-order subcells to acquire a maximum overlap, whereas discrete Cs layers use independent sets to obtain a random overlap.

The main difference between the mosaic treatment and random overlap in affecting the radiative flux is that, given identical grid mean cloud vertical distribution, the former treatment yields less tropospheric mean total cloud cover. This will result in less solar albedo and greenhouse effect for the troposphere-surface climate system (Wang et al. 1981). As will be shown below, changes in the distributions of solar and infrared fluxes are particularly large when low- and high-level clouds are encountered. These characteristics lead to significantly different radiative heating/cooling distributions with subsequent large effects on climate simulations.

Climate Model

The GCM used here was described in Liang and Wang (1995). In this model, four cloud genera are diagnosed: convective cloud (Cc), anvil cirrus (Ci), inversion stratus, and stratiform cloud. Note that stratiform cloud, which depends on local relative humidity, is allowed in all model layers. The Cc form as a vertical tower of all continuous convective layers, while Ci occupy the top layer of deep convection and inversion stratus occur in one near-surface layer. For the radiation calculation, inversion stratus and stratiform clouds are combined into a single genus (Cs).

Note that the number of subcells, N, depends on GCM resolution. In a coarser resolution model, a larger N is needed to represent mesoscale variability. In this study, the atmosphere is represented by 18 vertical layers (11 in the troposphere) with the top at 5 hPa. The horizontal resolution is R15 (4.5° latitude by 7.5° longitude). Here we choose N = 15, which corresponds to a subcell horizontal area of approximately $(170\ \text{km})^2$ in mid-latitudes and $(200\ \text{km})^2$ in the tropics. An increase of N to 30 produces small differences in the initial radiative forcing.

Initial Radiative Forcing

Figure 1 shows the altitude-latitude variation of the initial radiative forcing difference, with the cloud distribution plotted for reference. This difference is defined here as the difference in radiative cooling/heating distributions between two instantaneous GCM calculations where only the cloud geometric treatment is changed from the random (RAN) to the mosaic MOS) overlap. To ascertain forcing signal robustness, monthly ensembles of diagnostic radiative calculations are conducted using half-hourly GCM fields (including cloud distributions) simulated from RAN. The January case is discussed here while the characteristics for other months are similar.

Note that the radiative heating at a given tropospheric layer is determined by four components: absorption of solar and infrared radiation from both upward and downward directions. Note also that, given an identical cloud vertical distribution, MOS yields smaller effective cloud in both directions. For solar radiation, there exist two competing effects: a warming effect due to increased absorption of more downward (transmitted) flux and a cooling effect due to decreased absorption of upward (reflected) flux by clouds (the change in surface reflection is small). These two solar effects nearly cancel each other, and result in a small near-surface cooling in the summer hemisphere.

The infrared forcing is much more complicated and depends strongly on the cloud and temperature distributions because clouds (versus clear sky) dominate the local emissions. At a given atmospheric level, a smaller effective cloud in MOS yields a smaller downward and an enhanced upwelling flux because of less blocking of the surface emission below that level. Therefore, the reduction in flux associated with decrease in effective cloud is maximized above the low clouds for downward flux and below the high clouds for upwelling

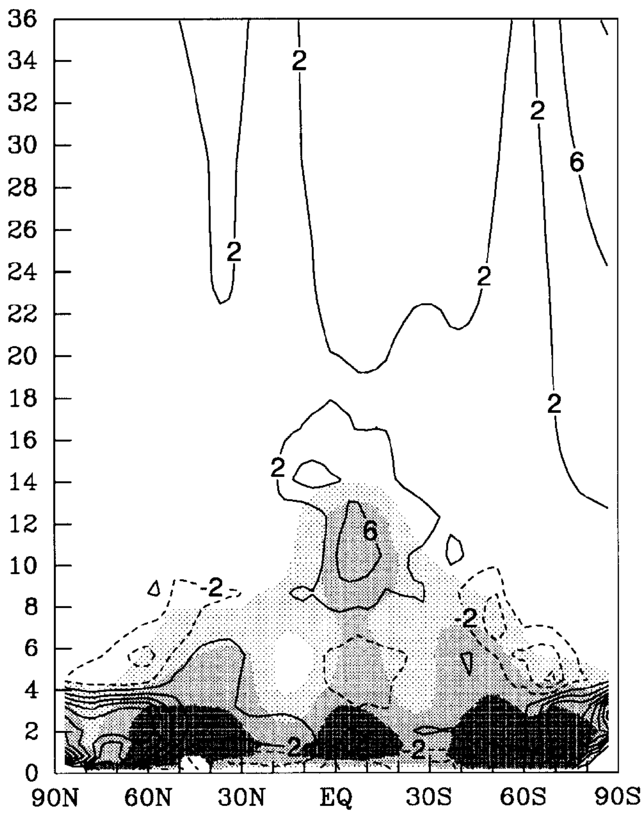

Figure 1. January altitude-latitude distribution of the heating rate (10^{-2}°C/day) that is attributed to the net radiative forcing. Contours are every 4 units, where negative values are dashed. Shadings differentiate cloud amounts between 3, 7, 15, and 50% from light to dark.

flux. Thus, the largest downward flux reduction occurs at approximately 3 km in the tropics and 1 km over the high latitudes. Therefore, these flux changes results in warming above and cooling below these levels. On the other hand, the largest upwelling flux increases are identified at 14 and 6 km for low and high latitudes, respectively. This produces warming above and cooling below these levels.

Over the tropics, convective towers cover a relatively small area and are usually associated with broad outflow anvil cirrus. Consequently, in the upper troposphere, the reduction of the effective cloud for the upwelling radiation is modest because the column cloud amount below is small, whereas it is more pronounced in the downward direction. As a consequence, the warming that results from the downward direction overwhelms the upwelling cooling and produces a net infrared heating. For the lower layers, both the downward and upwelling effects cause cooling, especially near the surface. At higher latitudes, however, middle and low clouds are much more extensive. Warming in the lower layers is dominated by downward forcing, while the cooling above is produced by the upwelling effect. An additional contribution to the forcing contrast between the tropics and extratropics is the trapping by larger water vapor amounts in the former region.

Climate Simulations

To study the climatic effects of cloud overlap, two GCM simulations with MOS and RAN for the period 1979 to 1990 were conducted, where observed monthly distributions of sea surface temperature and sea ice cover are prescribed. Figure 2 shows the January and July mean altitude-latitude temperature changes together with changes in cloud cover. Two major features are noted:

- First, in the high latitudes (60-90°N), the stratosphere experiences substantial warming (3-13°C) in January. This warming, starting in December and going through March, is caused mainly by radiation-dynamics interaction. Our analyses indicate that, in this region, much stronger upward motions prevail in the MOS simulation. This enables the heating in the lower troposphere, which results from radiative forcing, to be transported into the stratosphere.

- Second, in low latitudes, the middle to upper troposphere is identified with more than 3°C warming throughout the year. This is related to the initial radiative forcing shown in Figure 1 and the subsequent feedback associated with the elevated (i.e., higher altitude) Hadley circulation. Initially, the dipole forcing structure, with the upper tropospheric warming and near-surface cooling, diminishes tropical thermal instability. In lower layers where convection originates, the stabilization suppresses convection and, accordingly, cloud amount and precipitation.

We have examined the July altitude-latitude distribution of specific humidity change averaged over 2-20°N, where the intertropical convergence zone (ITCZ) exists. Two vertical maxima of humidity increases are noted: one near the surface and the other located between 3 to 5 km. The former reduces surface-air humidity contrast and, thus, surface evaporation, while the latter provides more available potential energy for convection to emanate from the higher altitudes. This is clearly reflected in the changes in cloud cover, especially in July. In fact, over ITCZ, cloud amount increases in the 3 to 14 km region but decreases below. This cloud distribution further augments the initial radiative forcing to produce a positive feedback in the tropics (Wang et al. 1981).

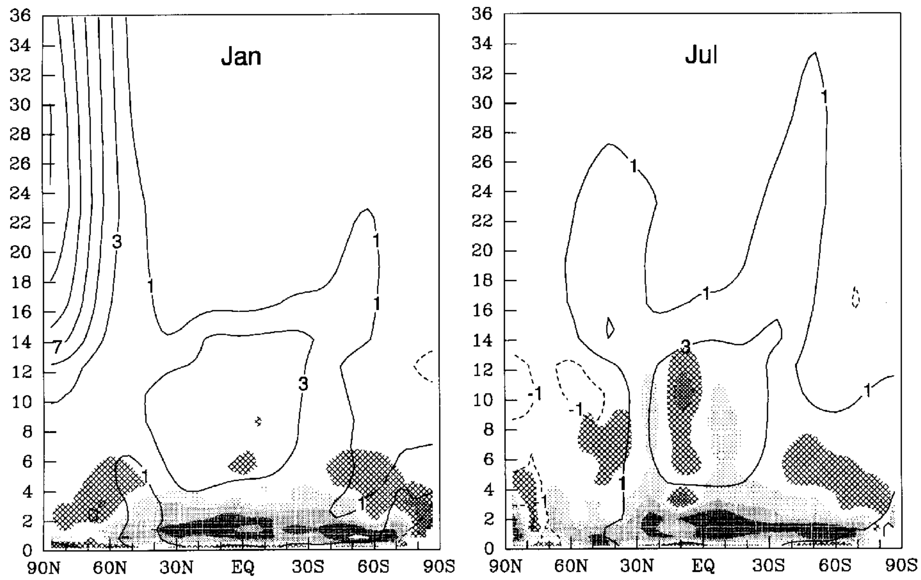

Figure 2. Altitude-latitude distributions for January and July climate responses. The contours depict temperature changes at a 2 °C interval, where negative values are dashed. Coarse and dense hatches represent 1 to 3% and 3 to 7% cloud amount increases respectively, while shadings light to dark indicate 1 to 3%, 3 to 7% and >7% cloud amount decreases.

Meanwhile, stronger subsidence (less cloud) in the subtropics compensates the intensified ITCZ updraft through the Hadley circulation and, thus, the local air warms via adiabatic heating.

Note that the standard model used in this study systematically generates cold biases in the middle-upper troposphere and polar stratosphere, which is a common feature in most GCMs. This model is also known to overpredict surface evaporation and precipitation but underestimate atmospheric moisture content, especially over the tropical oceans. The use of MOS fundamentally corrects these biases.

Conclusions

The mosaic treatment that incorporates subgrid scale cloud vertical geometric association calculates a significantly different atmospheric radiative heating/cooling distribution, which is caused mainly by the changes in infrared radiation. In the tropics, it yields a heating in the upper troposphere and a cooling in the lower troposphere especially near the surface; opposite changes are calculated in the middle-to-high latitudes. Because of a smaller effective cloudiness, the mosaic treatment calculates less infrared downward radiation reaching the surface, which is partially compensated by increased incident solar radiation. Differences in the climate responses are substantial, with several major model biases corrected by the mosaic treatment. For example, the middle-to-upper troposphere of the tropics and subtropics are warmed by more than 3°C throughout the year, and the polar night northern stratosphere becomes much warmer, up to 15°C.

The study results clearly suggest that the subgrid scale cloud-radiation variability associated with cloud geometric association is important for climate simulations. In this regard, similar sensitivity investigations using different GCMs are warranted.

References

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