Application of a Maximum-Random Cloud Overlap Method for RRTM to General Circulation Models

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Introduction

An important consideration in the calculation of longwave radiation through multiple cloudy layers is the spatial relationship, or cloud overlap, among the cloud fractions in each layer. Many general circulation models (GCMs) apply random cloud overlap in which clouds in adjacent layers are assumed to be unrelated. However, this approximation is not appropriate for situations in which clouds are vertically correlated (e.g., deep convection), and recent studies have demonstrated the importance of cloud overlap treatment to GCM simulations (e.g., Jakob and Klein 1999). For this reason, a maximum-random cloud overlap approach has been developed for the longwave model rapid radiative transfer model (RRTM) for use in GCMs and other radiative transfer applications. RRTM is a rapid and accurate, correlated-k, radiative transfer model (Mlawer et al. 1997) that has been developed for the Atmospheric Radiation Measurement (ARM) Program to address the ARM objective of improving radiation models in GCMs.

Maximum-Random Algorithm

The maximum-random (MR) cloud overlap approach is designed to represent more realistically the vertical relationship of multi-level clouds by using maximum overlap within all adjacent cloudy layers, while applying random overlap for non-contiguous blocks of cloudy layers. The algorithm uses a “two-layer memory” approach in which the cloud fractions for up to two previous layers are considered in the radiative transfer in a cloudy layer.

To test the new method, a series of ARM/Tropical Western Pacific (TWP) atmospheric profiles from July 1997 were used to calculate the outgoing longwave radiation (OLR) and downward surface flux over a wide variety of cloud conditions for both random (left) and MR (right) cloud overlap. The fluxes are plotted in Figure 1 as a comparison between a normal, single-column calculation and a more accurate “20-box” calculation. The latter is accomplished by performing 20 radiative transfer calculations for each profile in which the same temperature and moisture amounts are used, but the cloud fractions in each layer are segmented into 20 even components that have a cloud fraction of either 0 or 1. The 20 computations are then equally weighted and combined to produce a single result for each profile. This result is more accurate because it simulates dividing a single grid box into 20 sub-grid boxes and more precisely accounts for the sub-grid cloud fractions in the radiative transfer. Figure 1 shows that, in many cases, random cloud overlap produces outgoing fluxes that are substantially deficient and

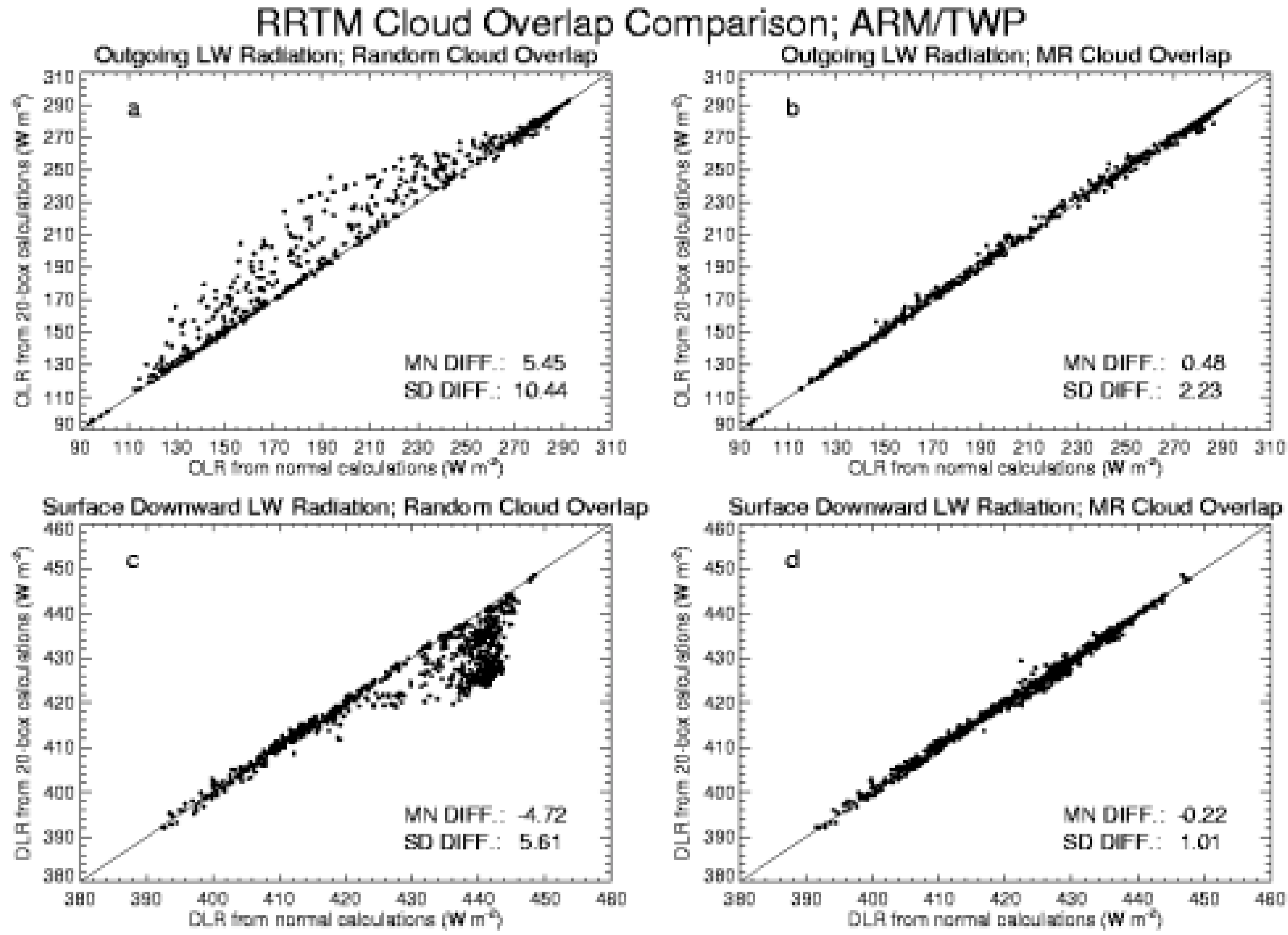

Figure 1. Scatter plot that compares RRTM longwave fluxes from a normal single-column calculation to a reference calculation using 20 sub-grid points (see text), for more than 700 ARM/TWP July 1997 profiles. Comparisons are shown for (a) OLR for random cloud overlap, (b) OLR for MR cloud overlap, (c) downward surface flux (DLR) for random overlap, and (d) DLR for MR overlap. The mean difference and standard deviation of the differences are also shown for each plot.

downward surface fluxes that are too high relative to the “reference” 20-box calculation. The application of MR overlap greatly reduces these differences.

Single-Column Comparisons

To demonstrate the significant impact of cloud overlap on atmospheric longwave fluxes and cooling rates, single-column calculations with RRTM for the mid-latitude summer profile are shown in Figure 2 as differences between MR and random cloud overlap for three cloud cases. Layers with cloud are marked with gray boxes to the right of each plot in Figure 2. All cloud layers have an optical depth of 5. For the two-layer low cloud case, shown on the left in Figure 2, MR cloud overlap reduces downward

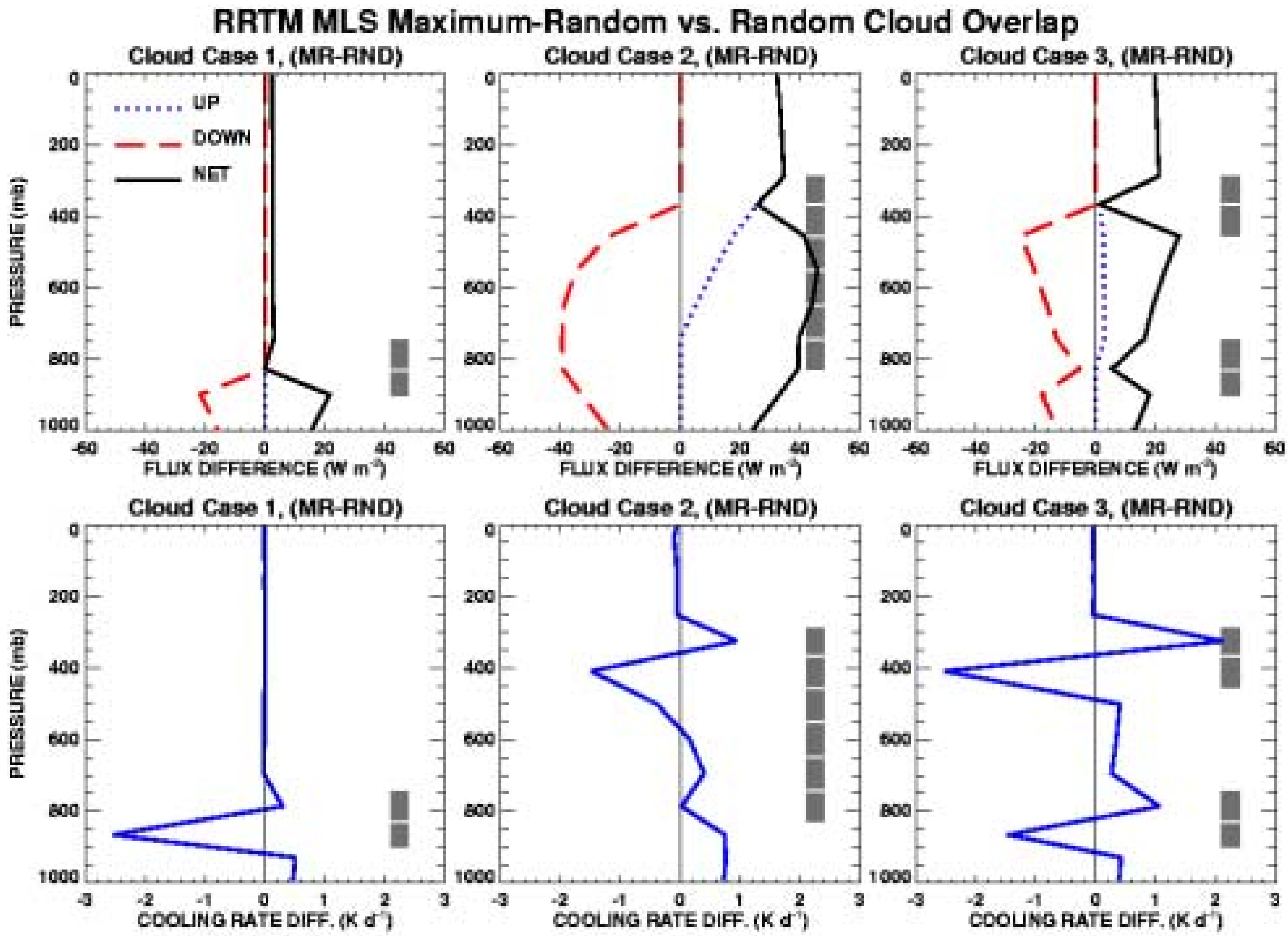

Figure 2. Differences in longwave up, down, and net fluxes (top row) and cooling rates (bottom row) between MR cloud overlap and random overlap as calculated by RRTM for three cloud cases. Layers with cloud are marked with gray boxes to the right in each plot. All clouds have an optical depth of 5 in each layer. Cloud cases 1 and 2 are for cloud fractions of 1.0 on each layer, and cloud case 3 has cloud fractions of 0.5 in each layer.

flux from the cloud base to the surface by about 20 W m^{-2}. For the multi-layer cloud case in the middle plots, downward flux is reduced within the cloud by as much as 40 W m^{-2} and by more than 20 W m^{-2} at the surface. Finally, the plots to the right in Figure 2 show the impact on two separate clouds to be somewhat less than the impact within the deep layered cloud. For all cases, cooling rates are significantly modified within the clouds.

GCM Simulations

Comparisons between RRTM and CCM3_LW have been performed for two 5-year CCM3 simulations with climatological sea surface temperatures using each LW model and assuming random cloud overlap. This experiment demonstrated the significant impact of the improved clear-sky longwave absorption on the climate model (Iacono et al. 2000).

In order to test the effect of the RRTM MR cloud overlap approach in the GCM, a single winter season from the previous experiment was simulated with the identical model except that the random cloud overlap method was replaced with MR overlap in the longwave model. Figure 3 shows that the initial forcing impact on the downward longwave surface flux for the Northern Hemisphere winter season is a global average decrease of about 4 W m^{-2}. Larger decreases of about 8 W m^{-2} to 10 W m^{-2} occur near the Northern Hemisphere storm tracks. No increases in downward flux are indicated. This result is consistent with the three single-column cloud cases shown in Figure 2. More extensive tests of the RRTM MR cloud overlap method will be performed when the RRTM shortwave model has been prepared for use in GCMs and an experiment can be devised that maintains consistency in the cloud overlap method for both the longwave and shortwave radiative transfer.

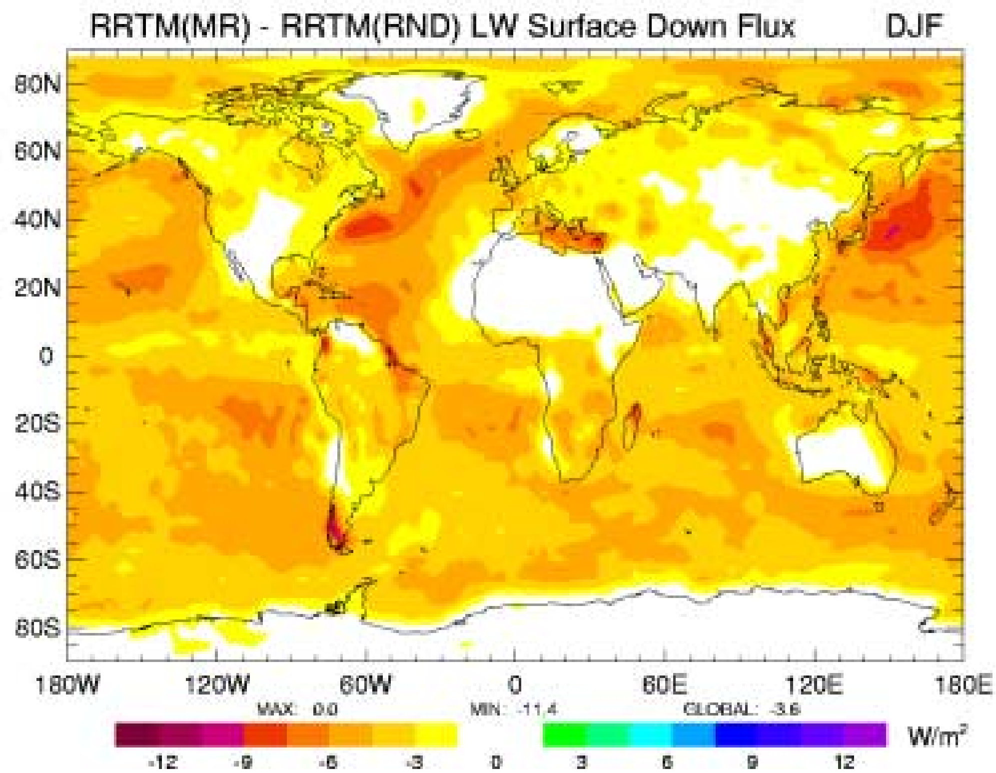

Figure 3. Initial forcing impact on downward longwave surface flux for Northern Hemisphere winter of maximum-random cloud overlap relative to random cloud overlap. Difference is between two parallel RRTM longwave calculations using each overlap method within a CCM3 simulation that used climatological sea surface temperatures.

Summary

A maximum-random cloud overlap method has been developed for RRTM and shown to have a large impact on longwave fluxes and cooling rates relative to the widely used random cloud overlap assumption. MR overlap is shown to produce more accurate surface and top of the atmosphere (TOA) fluxes than random overlap by comparing single-column calculations to a more accurate 20-box reference calculation. The MR overlap method has been tested with the longwave RRTM within the

NCAR climate model for a single season. These results are preliminary, since random cloud overlap was used in the shortwave calculation, though it has been demonstrated that atmospheric fluxes are significantly impacted and that cloud overlap is an important consideration in the accurate representation of cloudy radiative transfer.

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