Representing Sub-Grid Scale Cloud Variability with Monte-Carlo Independent Column Approximation and RRTMG in the National Center for Atmospheric Research Community Atmosphere Model, CAM3

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Introduction

The impact of representing inhomogeneous cloud structure in a global climate model (GCM) using a sub-column cloud generator and the Atmospheric Environmental Research, Inc. (AER) GCM radiation model, RRTMG, which has been modified to use, the Monte-Carlo Independent Column Approximation (McICA) (Pincus et al. 2003), has been examined in the National Center for Atmospheric Research (NCAR) Community Atmosphere Model, CAM3.0. The McICA method uses stochastically generated sub-grid cloud properties (Raisanen et al. 2004) that are randomly sampled during the spectral integration of the radiative transfer model. This approach provides results that are unbiased relative to the accurate, though computationally expensive, Independent Column Approximation. Random flux errors, which depend on cloud optical properties, cloud spatial structure and spectral sampling size, are introduced by McICA, and the sensitivity of GCM simulations to this random noise is being evaluated (Barker et al. 2006; Raisanen et al. 2005).

RRTMG, the GCM-ready version of the RRTM correlated-k radiative transfer model developed for the Atmospheric Radiation Measurement Program (Clough et al. 2005), is well suited to use McICA effectively due to 140 total longwave g-intervals and 112 shortwave g-intervals that are used to integrate the cumulative probability functions in the radiative transfer calculation. A single-column version of

RRTMG/McICA has been tested with 200 realizations for each of several cloud configurations. Both RRTMG/McICA and a sub-column cloud generator, which provides the cloud fraction and other cloud properties as randomly distributed arrays, have been implemented in CAM3.0. Results of simulations using a maximum-random cloud overlap representation with CAM3, CAM3_RRTMG, and CAM3_RRTMG/McICA are described.

Single-Column Tests

The implementation of McICA has been tested in RRTMG with a series of single-column experiments. These were performed without the sub-column cloud generator, though a random number generator was utilized to mimic the cloud generator for several simple cloud configurations. In the longwave, the test performed consisted of a single calculation with the standard RRTMG and 200 calculations with RRTMG/McICA for the mid-latitude summer profile with a pair of ice cloud layers separated from a pair of liquid cloud layers, which had a total optical depth of 10 and a cloud fraction of 0.5 in each cloud layer. In the shortwave, similar sets of calculations were performed with a single ice cloud layer separated from a single liquid cloud layer with a total optical depth of 10 and cloud fraction of 0.5 in each cloud layer. The single longwave reference calculation with the standard RRTMG presumed random cloud overlap. In the shortwave, the reference calculation was performed as an weighted average of four calculations, with each representing the four possible cloud configurations for two cloud layers each with 0.5 cloud fraction (clear-clear, clear-cloud, cloud-clear, and cloud-cloud). For the 200 calculations with RRTMG/McICA, the cloud state is sampled simultaneously with the g-interval dimension of RRTMG, where the 140 total g-intervals in the longwave and 112 total g-intervals in the shortwave are used to integrate the k-distribution probability functions in RRTMG to derive the radiance in each spectral band. A random number generator was used to provide the cloud state fields on the g-interval dimension, such that the cloud properties were randomly distributed by g-interval and vertical level for each of the 200 sample calculations.

Distributions of longwave flux difference between a single reference calculation with RRTMG_LW and 200 calculations with RRTMG_LW/McICA are shown in Figure 1 for upward flux at the top of the highest cloud layer, net flux at the bottom of the lowest cloud layer, and downward flux at the surface. Each distribution is shown to be unbiased, with small mean differences of 0.4 Wm^{-2} or less as listed in Figure 1. In addition, the mean differences satisfy the statistical test of Pincus et al. (2003) in that the mean differences are all less than $\sigma / \sqrt{N}$, where σ is the standard deviation and N is the sample size (200). This indicates that the uncertainty of the McICA estimate is sufficiently small for this number of calculations. Distributions of longwave cooling rate differences in the highest cloud layer and in the lowest cloud layer are shown in Figure 2. Here, the mean differences are also small and satisfy the statistical test of Pincus et al. (2003).

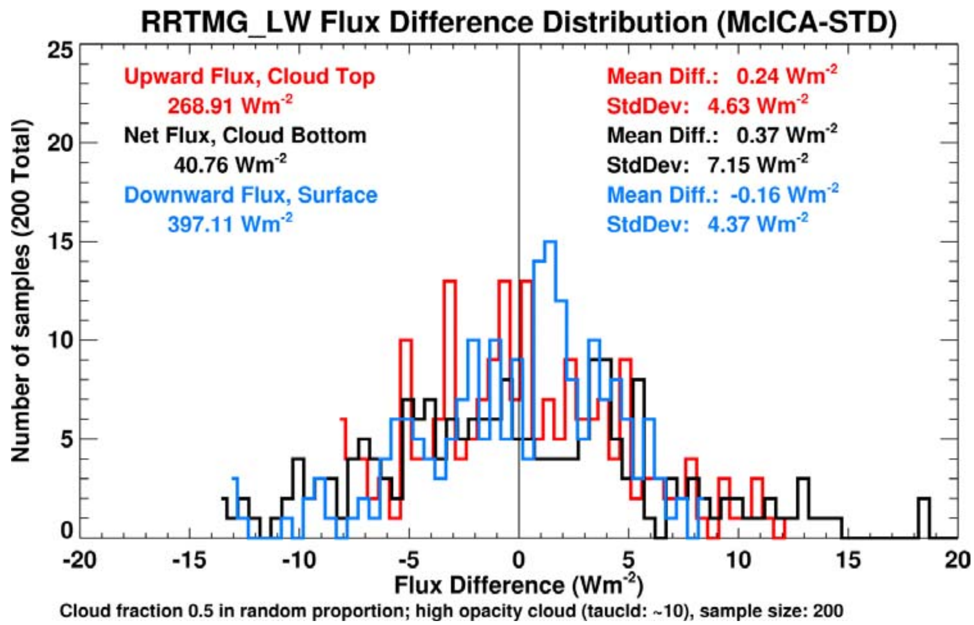

Figure 1. Distribution of longwave flux differences between 200 calculations with RRTMG_LW/McICA and a single calculation with the standard RRTMG_LW for the mid-latitude summer profile with a pair of two-layer thick clouds, each with cloud fraction 0.5, a total cloud optical depth of 10, and assuming random cloud overlap. Units are in Wm^{-2}.

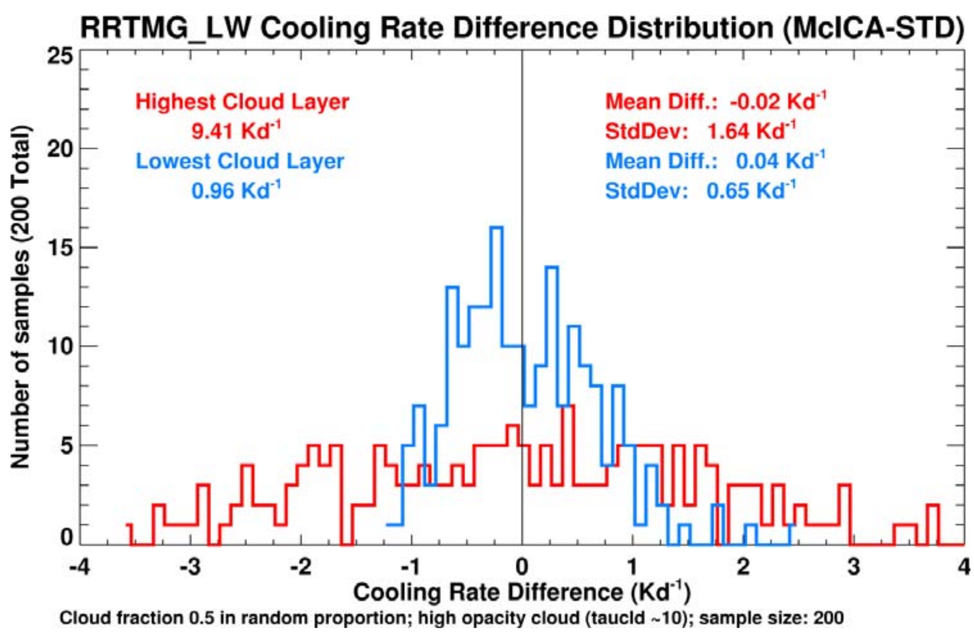

Figure 2. Distribution of longwave cooling rate differences between 200 calculations with RRTMG_LW/McICA and a single calculation with the standard RRTMG_LW for the mid-latitude summer profile with a pair of two-layer thick clouds, each with cloud fraction 0.5, a total cloud optical depth of 10, and assuming random cloud overlap. Units are in Kd^{-1}.

Shortwave flux difference distributions between the RRTMG_SW reference calculation and 200 calculations with RRTMG_SW/McICA are shown in Figure 3 for upward flux at the top of the highest cloud layer, net flux at the bottom of the lowest cloud layer, and downward flux at the surface. The distributions are also found to be unbiased, with small mean differences of 1 Wm^{-2} or less as listed in Figure 3. The mean differences for both the fluxes shown in Figure 3 and for the shortwave in-cloud heating rates (not shown) are all unbiased and satisfy the statistical test of Pincus et al. (2003). This is taken as evidence that the McICA technique for representing sub-grid cloud variability has been successfully implemented RRTMG.

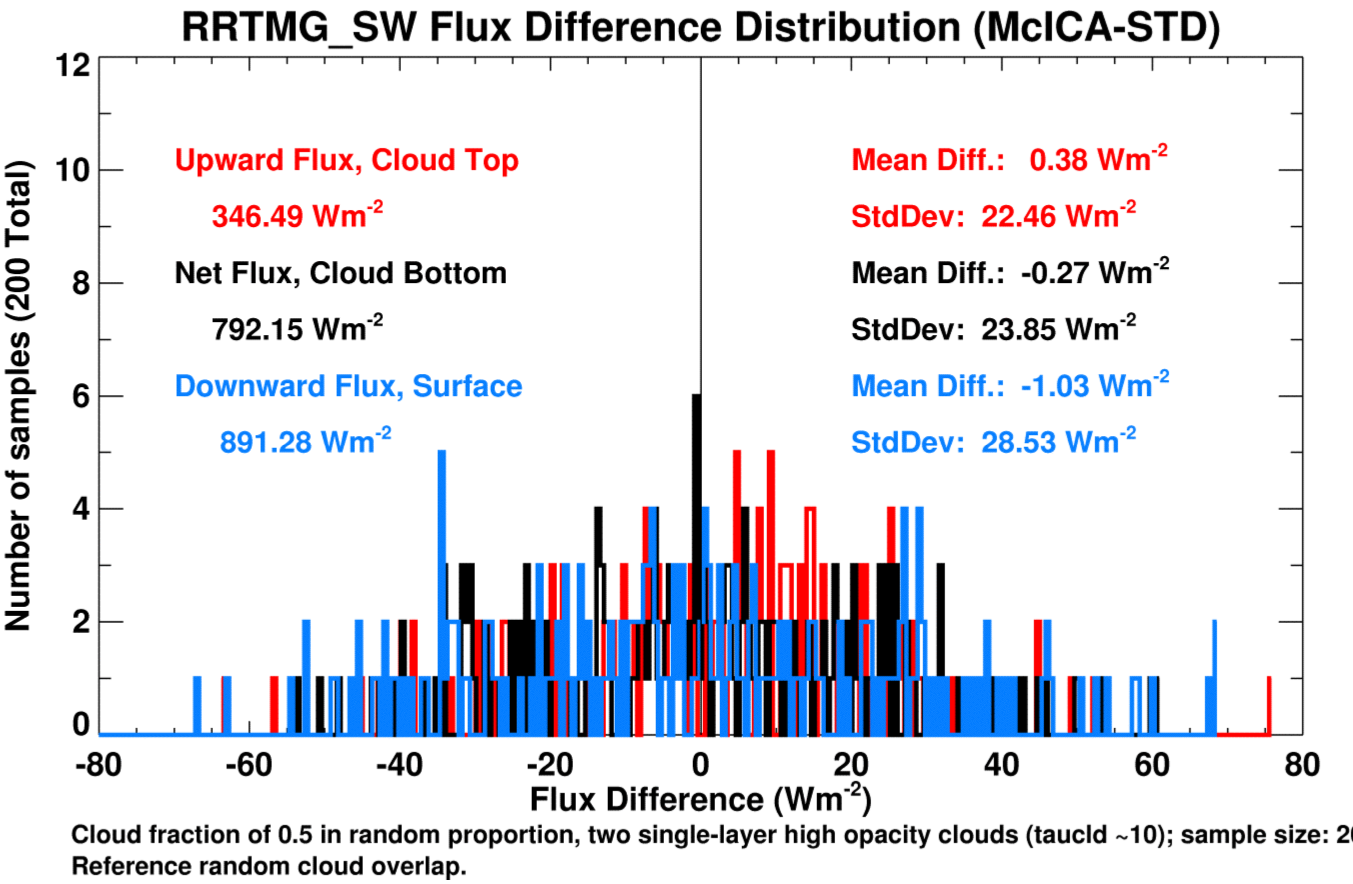

Figure 3. Distribution of shortwave heating rate differences between 200 calculations with RRTMG_SW/McICA and a reference calculation with RRTMG_SW for the mid-latitude summer profile with a pair of single-layer thick clouds, each with cloud fraction 0.5, a total cloud optical depth of 10, and assuming random cloud overlap. The reference calculation is a sum over four evenly weighted calculations as described in the text. Units are in Wm^{-2}.

Simulations with RRTMG/McICA in the NCAR CAM3

Having demonstrated the effective incorporation of the McICA method, RRTMG/McICA has been implemented into the NCAR Community Atmosphere Model, CAM3 (Collins et al. 2006), for the purpose of testing this configuration of the AER radiation model in this climate model. Simulations for the years 2002-2003 were performed with the standard CAM3, with CAM3_RRTMG (without McICA), and CAM3_RRTMG/McICA. Neither of the latter two simulations has been retuned to provide top of the atmosphere (TOA) radiation balance. Also, all simulations were performed without aerosols, since the CAM3 aerosol optical property database has not been adapted for the RRTMG spectral bands. Differences in the annual mean TOA outgoing longwave flux and downward surface flux for 2003 between the CAM3_RRTMG simulations with and without McICA are shown in Figure 4. Clear-sky flux differences are in the left panels, and total sky flux differences are in the right panels. As expected, there are only minor differences in the clear-sky fluxes (indirectly caused by McICA through changes in the simulated atmospheric state), while much larger differences are seen in total sky largely due to differences in cloud states between the simulations and partly due to differences in the treatment of maximum/random cloud overlap between the two calculations.

Differences in the mean TOA upward shortwave flux and downward surface flux for June-August 2003 between the simulations with the standard CAM3 and with CAM3_RRTMG/McICA are shown in Figure 5. The primary feature is the significant difference in clear-sky shortwave fluxes between the CAM3 shortwave model and RRTMG_SW with the former producing too little high latitude downward shortwave surface flux and upward TOA flux. In total sky, differences are small at most latitudes, except where the clear-sky discrepancy is apparent. Thus, RRTMG/McICA with maximum/random cloud overlap closely reproduces the shortwave cloudy fluxes that are produced by the standard CAM3 radiation model and cloud overlap method.

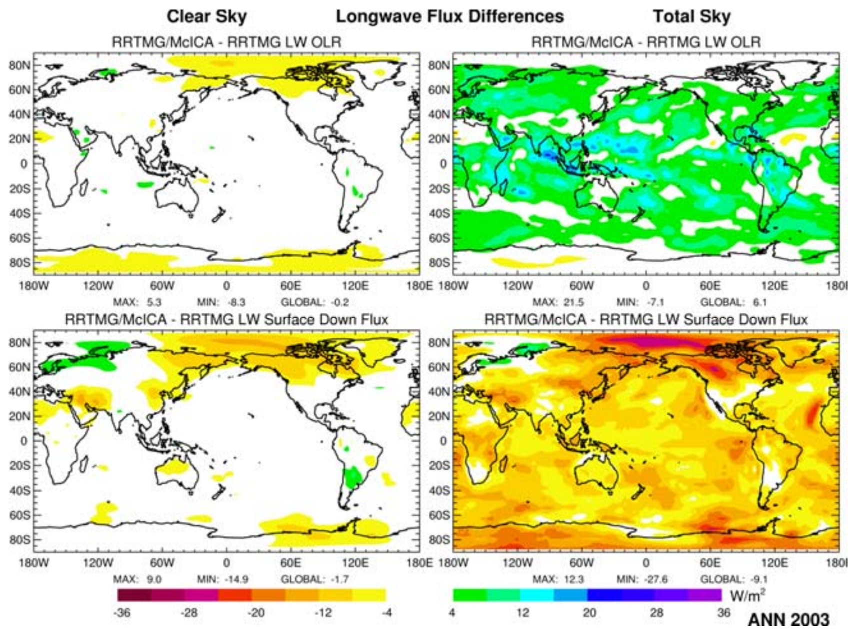

Figure 4. Differences in top of the atmosphere longwave upward flux (top panels) and downward surface flux (bottom panels) between a pair of CAM3 simulations running with the standard RRTMG and with RRTMG/McICA for the year 2003 for both clear sky (left) and total sky (right). Units are in Wm^{-2}.

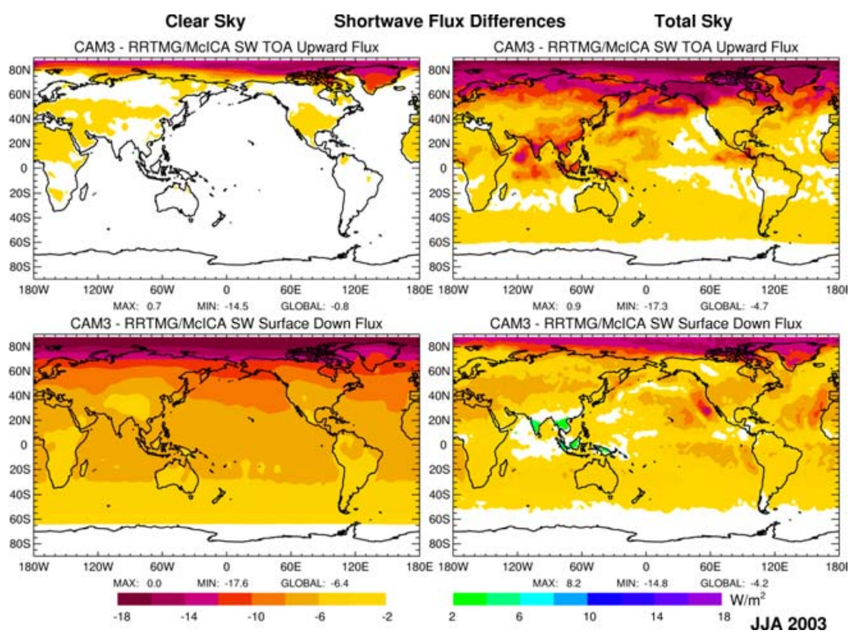

Figure 5. Differences in top of the atmosphere shortwave upward flux (top panels) and downward surface flux (bottom panels) between a pair of CAM3 simulations running with the CAM3 shortwave model and with RRTMG_SW/McICA for June-August 2003 for both clear sky (left) and total sky (right). Units are in Wm^{-2}.

The impact of RRTMG/McICA in CAM3 has also been evaluated using the NCAR Atmospheric Model Working Group CAM3 diagnostic package. This software utility processes climate model output to produce numerous tables and plots for analysis of model-to-model or model-to-measurement comparison using a large number of observational and reanalysis datasets. Figure 6 shows a preliminary comparison of modeled temperatures for the year 2003 between the NCEP/NCAR Reanalysis and both the standard CAM3 simulation (labeled 'aer122' in Figure 6) and the CAM3_RRTMG/McICA simulation (labeled 'aer126' in Figure 6). The left panels of Figure 6 show the zonal, annual mean temperature from the NCEP reanalysis (top), and the zonal, annual mean temperature difference between CAM3_RRTMG/McICA and NCEP (center) and between CAM3 and NCEP (bottom). The right panels in Figure 6 show the annual mean surface temperature from the NCEP reanalysis and the differences from each model. Both simulations of temperature are similar in the troposphere, though some differences in surface land temperatures at high latitude and in zonal mean temperatures in the stratosphere are seen compared to the NCEP Reanalysis with the application of RRTMG/McICA in CAM3 for this time period.

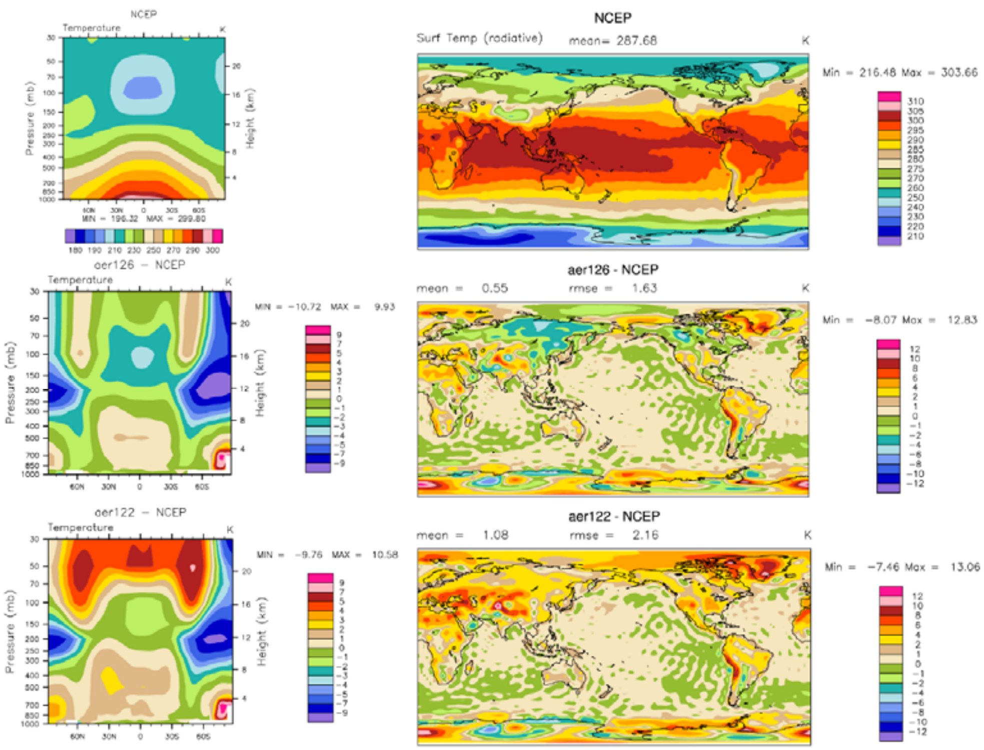

Figure 6. Zonal, annual mean 2003 temperature from the NCAR/NCEP Reanalysis (top left) and zonal mean temperature differences between CAM3_RRTMG/McICA and the reanalysis (center left) and between the standard CAM3 and reanalysis (bottom left). Annual mean 2003 surface temperature from the NCAR/NCEP Reanalysis (top right) and mean surface temperature differences between CAM3_RRTMG/McICA and the reanalysis (center right) and between the standard CAM3 and reanalysis (bottom right). Units are in K.

Summary

The statistical McICA technique for representing sub-grid cloud variability in GCMs has been implemented in both the longwave and shortwave RRTMG. Single column tests have shown that RRTMG/McICA produces unbiased fluxes and heating rates as expected for a sample of 200 calculations. RRTMG has been implemented in the CAM3 climate model both in its original form and with McICA using a sub-column cloud generator to provide the cloud state variables as randomized arrays on the g-interval dimension within RRTMG.

Separate CAM3 AMIP simulations for the year 2003 were performed with the standard CAM3 as a control and with each version of RRTMG. The later runs have not yet been retuned for TOA radiation balance. All simulations used maximum-random cloud overlap. Model to model comparisons from these experiments show a considerable discrepancy in clear-sky downward shortwave flux in CAM3. RRTMG/McICA greatly reduces biases in total sky shortwave fluxes that were due to the original RRTMG_SW cloud overlap treatment, which was known to produce large errors for some clouds. Preliminary comparison of model results to observations suggests that RRTMG/McICA has a mixed impact in CAM3 with differences noted in shortwave fluxes and both atmospheric and surface temperatures.

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