Effects of Improved Radiative Transfer Modeling for Climate Simulations

M. J. Iacono, E. J. Mlawer and S. A. Clough
Atmospheric and Environmental Research, Inc.
Cambridge, Massachusetts

Introduction

The interaction of shortwave and infrared radiation in the atmosphere with clouds and greenhouse gases represents a complex process that contributes significantly to maintaining earth's climate system. For climate model simulations to become more accurate, it is essential that this process be modeled properly as verified by direct comparisons with observations and with results from a validated line-by-line model. For this purpose, a rapid radiative transfer model (RRTM) has been developed that reproduces the computational accuracy of a more complex line-by-line radiative transfer model (LBLRTM) (Clough and Iacono 1995) at the high speed necessary for its application within a general circulation model. We have compared RRTM longwave fluxes and cooling rates to those calculated by the National Center for Atmospheric Research's (NCAR) Community Climate Model (CCM3) radiation algorithm for both clear and cloudy conditions. We will introduce RRTM into CCM3 to establish the effect of the improved longwave radiative cooling rate profiles on the global simulation of temperature, moisture, precipitation, and the general circulation, in addition to surface and top of the atmosphere radiative fluxes.

Models

RRTM: Rapid Radiative Transfer Model

A significant feature of the RRTM (Mlawer et al. 1997) is its direct connection to LBLRTM, which has been extensively validated against observed spectral measurements (Clough et al. 1992; hereafter CIM). RRTM employs a correlated-k method and sixteen spectral intervals for the calculation of clear sky, longwave (LW) fluxes, and cooling rates using absorption coefficients derived from LBLRTM. All significant trace gases are included in the model, and water vapor, carbon dioxide (at 330 ppmv), ozone, methane, nitrous oxide, CFC-11, and CFC-12 are used in the present results to match the greenhouse absorbers included in CCM3. The model uses an updated version of the water vapor continuum model of Clough et al. (1989; hereafter CKD). The accuracy of RRTM based on validations with LBLRTM includes a total error in net flux at any altitude of less than 1.0 W/m^2, a total cooling rate error in the troposphere and lower stratosphere of 0.07 K/day and in the upper stratosphere of 0.75 K/day. In addition, timing tests on a Cray YMP show that RRTM's computational speed is within a factor of two of the CCM3 longwave radiation model.

CCM3: Community Climate Model

The features of CCM3 relevant to this study concern its longwave radiation code, which has been described by Kiehl et al. (1997). To summarize, the CCM3 longwave algorithm employs a broadband, nonisothermal emissivity and absorptivity parameterization over six spectral intervals. The model considers the absorption from H_2O, CO_2, O_3 and several trace gases and includes the water vapor continuum of Roberts et al. (1976). We have replaced this algorithm with RRTM for the clear-sky calculation. Cloud radiative effects are modeled within RRTM to reproduce their contribution to the cooling profiles as closely as possible to their effects in CCM3. In particular, the LW cloud emissivity is approximated as a negative exponential function of cloud liquid water path as in CCM3. All other aspects of CCM3 are unchanged, and both the single-profile comparisons below and the anticipated seasonal simulations with the revised radiation scheme will be performed with the CCM3 standard 18-layer resolution.

Flux and Cooling Rate Comparisons

Clear Sky

Comparisons between RRTM and the CCM3 column radiation model for identical, individual clear-sky profiles indicate significant differences in longwave fluxes and cooling rates for the profiles examined. Figure 1a shows the upwelling, downwelling, and net (up-down) fluxes computed with the CCM3 longwave algorithm for the mid-latitude summer (MLS) atmosphere (left panel) and the flux differences, RRTM-CCM3, between the two models (right panel). RRTM produces a net flux that is 10 W/m^2 lower at the top of the atmosphere, 12 W/m^2 lower at the tropopause, 20 W/m^2 lower in the middle troposphere, and 7 W/m^2 lower at the surface relative to the CCM3 radiation model. The MLS cooling rate comparison is shown in Figure 1b. RRTM cooling rate is as much as 0.4 K/day higher near the 300-mb peak in water vapor continuum absorption and 0.4 K/day lower in the lower troposphere.

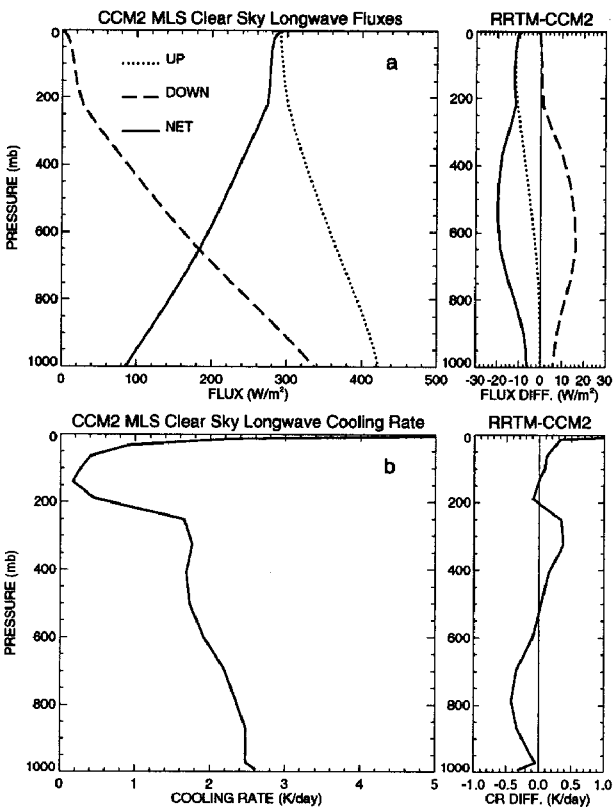

Figure 1. Calculations with the CCM3 radiation model and the difference between RRTM and CCM3 for a) upwelling, downwelling, and net LW fluxes and b) LW cooling rate for the clear sky mid-latitude summer atmosphere.

Nearly all of the difference in upwelling flux is generated in the mid to upper troposphere, and the downwelling flux difference begins just below the tropopause and extends to the surface. As a result, we attribute a portion of these differences to the handling of the water vapor continuum in the two models, with the remaining discrepancy likely resulting from the differing algorithmic approaches. Supporting this conclusion is the discussion of the CKD and Roberts continuum models in CIM, which includes a comparison plot (CIM Figure 19) of MLS cooling rate using each continuum. This figure indicates a cooling increase in the upper troposphere and a cooling decrease in the lower troposphere due to the CKD continuum, changes that are similar to the cooling rate differences in Figure 1b between RRTM and CCM3.

The CCM3 flux and cooling rate profiles and the differences from RRTM for the mid-latitude winter (MLW) atmosphere are shown in Figure 2. Here, the total atmospheric water column is about 30% of its MLS value, and the troposphere is 10-20 K colder. As a consequence, the tropospheric fluxes and cooling rate are sharply reduced. The difference in net flux between the models (Figure 2a) is reduced to about 6 W/m^2 at the top of the atmosphere, while the peak net

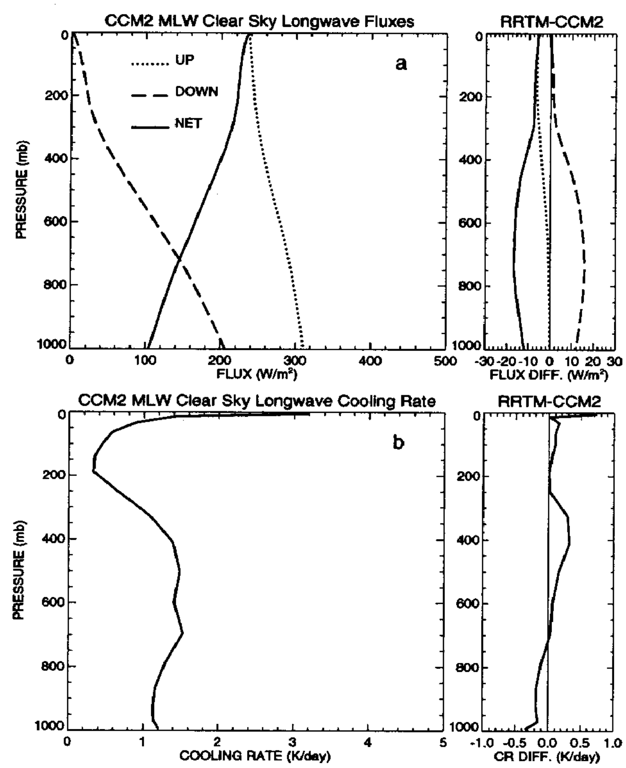

Figure 2. Calculations with the CCM3 radiation model and the difference between RRTM and CCM3 for a) upwelling, downwelling, and net LW fluxes and b) LW cooling rate for the clear-sky mid-latitude winter atmosphere.

net flux difference in the troposphere has dropped to 17 W/m^2 and occurs lower in the atmosphere. Overall, the net flux difference is diminished in the upper troposphere and increased in the lower troposphere and at the surface due to changes in the up and down fluxes brought about by the lower tropopause and water vapor column for MLW. The resulting cooling rate difference (Figure 2b) shows the same pattern as MLS, though with much less vertical contrast. The tropospheric peak of 0.3 K/day occurs at a lower level (400 mb), and the lower tropospheric difference is reduced to 0.2 K/day and is shifted closer to the surface. Comparisons for tropical (TRP), sub-arctic winter (SAW), and sub-arctic summer (SAS) profiles all display similar differences in proportion to their water column amounts.

To put the flux differences in perspective, we list in Table 1 the clear-sky outgoing LW radiation (OLR) at 3 mb for each model for five atmospheric profiles. In each case, CCM3 produces an excess of OLR, which varies from 7.1 W/m^2 in the tropics to 3.4 W/m^2 in the dry sub-arctic winter atmosphere. Also shown is a global mean clear-sky OLR for each model, which is a weighted average of the five zonal regions, where the tropics extend from 20S to 20N (total weight 0.342), the mid-latitudes extend from 20 to 60 degrees (each of weight 0.262), and the sub-arctic zones include the areas poleward of 60 degrees (each of weight 0.067). The resulting excess in OLR for CCM3 relative to RRTM on a global average basis is about 6 W/m^2 for this simple, rudimentary comparison. Kiehl et al. (1997) specify a more representative CCM3 global average clear sky OLR of 266.3 W/m^2 based on a multi-year simulation with the climate model. They compare this with the observed clear-sky OLR of 264.0 W/m^2 derived from Earth Radiation Budget Experiment (ERBE) measurements to define a CCM3 excess of 2.3 W/m^2. The values in Table 1 demonstrate that using RRTM within CCM3 to compute longwave fluxes would adjust the OLR downward, bringing it into closer agreement with the ERBE observation, though the extent of this correction requires simulations with the full climate model (see below) to be precisely quantified.

Table 1. Clear-sky top of the atmosphere (TOA) LW fluxes calculated by RRTM and the CCM3 radiation model for five atmospheric profiles and the global average as defined in the text. The RRTM-CCM3 TOA flux difference is also shown. Units are W/m^2.

Atmos.	RRTM	CCM3	RRTM-CCM3
TRP	286.3	293.4	-7.1
MLS	279.7	286.5	-6.8
MLW	229.8	234.0	-4.2
SAS	261.9	267.9	-6.0
SAW	197.1	200.5	-3.4
GLOBAL	262.2	268.1	-5.9

Cloudy Sky

To implement RRTM within the climate model, an algorithm for the absorption and emission of radiation in clouds has been included in RRTM that is consistent with the current CCM3 infrared cloud algorithm. The effect of adding a relatively thin high cloud with an optical depth of 1.0 and a cloud fraction of 1.0 on the clear sky MLS fluxes and cooling rate (see Figure 1) is shown in Figure 3. The high cloud, which fills the layer from 455 mb to 367 mb, has the effect of decreasing the upwelling flux above the cloud latitude summer atmosphere with a thin high cloud and increasing the downwelling flux

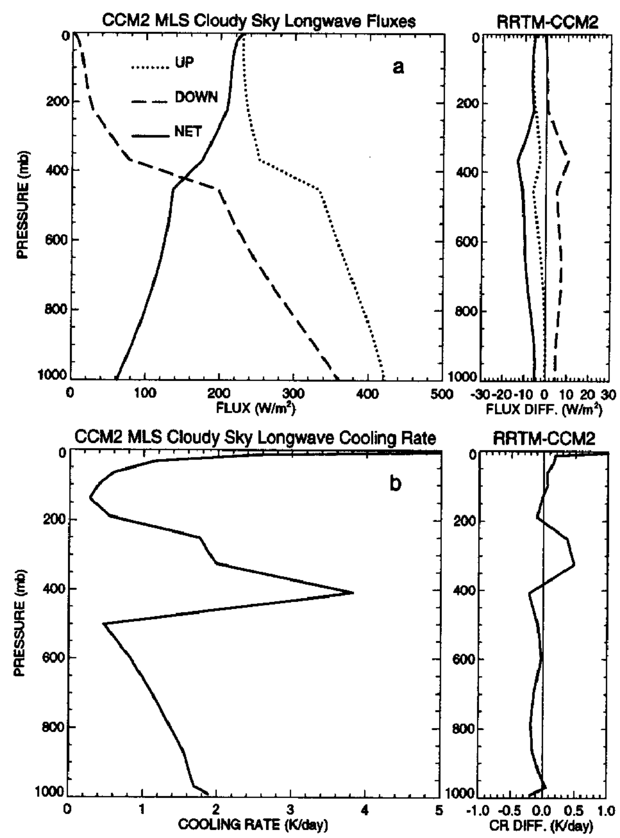

Figure 3. Calculations with the CCM3 radiation model and the difference between RRTM and CCM3 for a) up, down, and net LW fluxes and b) LW cooling rate for the mid-latitude summer atmosphere with a thin high cloud.

below the cloud (Figure 3a). The flux differences between RRTM and CCM3 are diminished as a result. In addition, the cloud increases the cooling rate at the cloud top and reduces the cooling rate at cloud bottom (Figure 3b), while the model cooling difference is generally reduced below the cloud level.

General Circulation Model Simulations

The impact of the improved radiative transfer provided by RRTM on global simulations has been examined with a version of CCM3 that uses RRTM for its longwave calculations. A preliminary two-season simulation, including a three-month adjustment period, was performed for fixed sea surface temperatures to analyze any resulting changes in the modeled radiative and dynamical fields. For the simulated season June-August 1986, OLR was lowered by RRTM, especially in regions with high water vapor content, while downward longwave surface flux was increased primarily in polar and elevated low water regions. This is largely a consequence of the CKD water vapor continuum model in RRTM. The cooling rate profile changes shown in Figures 1-3, when introduced into CCM3, have a destabilizing effect on the temperature profile especially in moist, tropical regions. The resulting effect on the simulated dynamics produces a slightly cooler and drier upper troposphere, while shifting the tropical Hadley circulation southward by about 10 degrees and reducing its magnitude by 10-20%.

Conclusions

Atmospheric fluxes and cooling rates calculated with an improved radiative transfer model, RRTM, show significant differences from those calculated by a widely used general circulation model, CCM3. Single-column calculations show that RRTM produces a lower clear-sky OLR than CCM3 for five different atmospheric profiles, in closer agreement with ERBE measurement. A preliminary seasonal simulation has shown the significant impact of the presented cooling rate profile differences on the dynamical processes in the climate model. Multi-year simulations will be done to establish the full dynamical consequences.

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