Effects of a Validated Longwave Radiation Model, RRTM, on GCM Simulations

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Introduction

An improved, longwave radiation model, rapid radiative transfer model (RRTM; Mlawer et al. 1997), developed for the Atmospheric Radiation Measurement (ARM) Program, has been incorporated into two general circulation models (GCMs) to establish its impact on climate model simulations. RRTM has been shown to provide results that are consistent with those from a comprehensive line-by-line radiative transfer model (LBLRTM; Clough and Iacono 1995), which itself has been extensively validated with measurements.

The National Center for Atmospheric Research (NCAR) Community Climate Model (CCM3) and the European Centre for Medium Range Weather Forecasting (ECMWF) weather forecast model were both modified to replace their existing longwave (LW) parameterizations with RRTM. A series of ensemble weather forecasts and two seasonal simulations were performed with the modified ECMWF model, and a one-year simulation was conducted with the modified CCM3. The impact of RRTM is demonstrated by comparison of the results with output from previously conducted experiments using unaltered versions of each GCM. RRTM greatly enhances water vapor absorption relative to the LW models in these GCMs, largely due to its water vapor continuum model, CKD_2.3. As a result, outgoing longwave radiation (OLR) flux is generally reduced, especially at low latitudes, and downward surface fluxes are increased, especially at dry, high-altitude and polar areas. The temperature field in each model responds with lower values in the upper troposphere and stratosphere and with higher temperatures in the lower troposphere and at the surface. It is expected that RRTM will be formally adopted as part of the operational ECMWF model during the summer of 1998. Also, RRTM is currently under consideration for formal adoption as the longwave model in the next release of the National Center for Atmospheric Research (NCAR) climate model, CCM4, during 1999.

Rapid Radiative Transfer Model

RRTM uses the correlated-k technique and applies absorption coefficients derived from LBLRTM to produce the necessary k-distributions. Mlawer et al. (1997) describes RRTM, its connection to spectral radiance measurements through the extensive validation of LBLRTM, and comparisons to line-by-line calculations for several atmospheres. The relevant features of RRTM include the use of all major absorbers and important trace species and the CKD_2.3 water vapor continuum model (Clough et al. 1989). Each of the 16 spectral bands is computed for 16 sub-intervals, or g-points, giving a total of 256 radiative transfer operations to calculate the full LW spectrum. Cloudy radiative transfer is accomplished by combining gaseous and cloud optical depths in each cloud layer. Random cloud overlap is assumed. This standard version of RRTM has been used in the ECMWF model, with a few modifications to accommodate more advanced cloud optical properties and surface emissivity in each band. For use in the CCM3 simulations described below, the standard RRTM was used with no additional changes. For its possible future application to CCM4, RRTM has been modified to improve its computational performance. One such change was the reduction of the number of radiative transfer operations from 256 to 140. This was accomplished while producing errors in net flux of less than 0.5 W m^{-2} and in cooling rate of less than 0.1 K/day at all levels relative to the standard RRTM.

ECMWF Forecast Model

RRTM has been introduced into the ECMWF weather forecast model and its effect examined in various tests that have been documented recently (Morcrette et al. 1998). The current operational LW radiation model at ECMWF is based on the emissivity method in which the transmission functions for water vapor and carbon dioxide were fitted using Pade approximates on narrow-band transmittances obtained from statistical band models (Morcrette 1991). The ECMWF model uses the water vapor continuum of Roberts et al. (1976). The effect of RRTM on ECMWF forecasts was examined with two sets of 12 experiments starting on the 15th of each month from 15 April 1996 to 15 March 1997 for T213 resolution at 31 layers, with the LW model the only difference between the sets.

The root mean square forecast errors of geopotential at 1000 mb and 500 mb and of zonal wind at four representative levels were affected only negligibly by the use of RRTM, while the impact on the temperature field was much larger. The mean forecast errors for Northern Hemisphere temperature at 850 mb, 500 mb, 200 mb, and 50 mb, averaged over the 12 monthly experiments, are shown in Figure 1. At all levels except 500 mb, RRTM dramatically reduces forecast errors through the tenth forecast day relative to the operational ECMWF LW model. Temperatures are warmed in the lower atmosphere and cooled in the mid to upper troposphere largely due to the enhanced greenhouse effect of the RRTM water vapor continuum.

NCAR Climate Model, CCM3

RRTM has also been implemented into the NCAR CCM3 atmospheric GCM (Kiehl et al. 1998a). For use in CCM3, the standard version of RRTM was modified as described above. The CCM3 LW model also uses the Roberts water vapor continuum. Clouds are modeled with the broad-band emissivity approach used in CCM3, except for the treatment

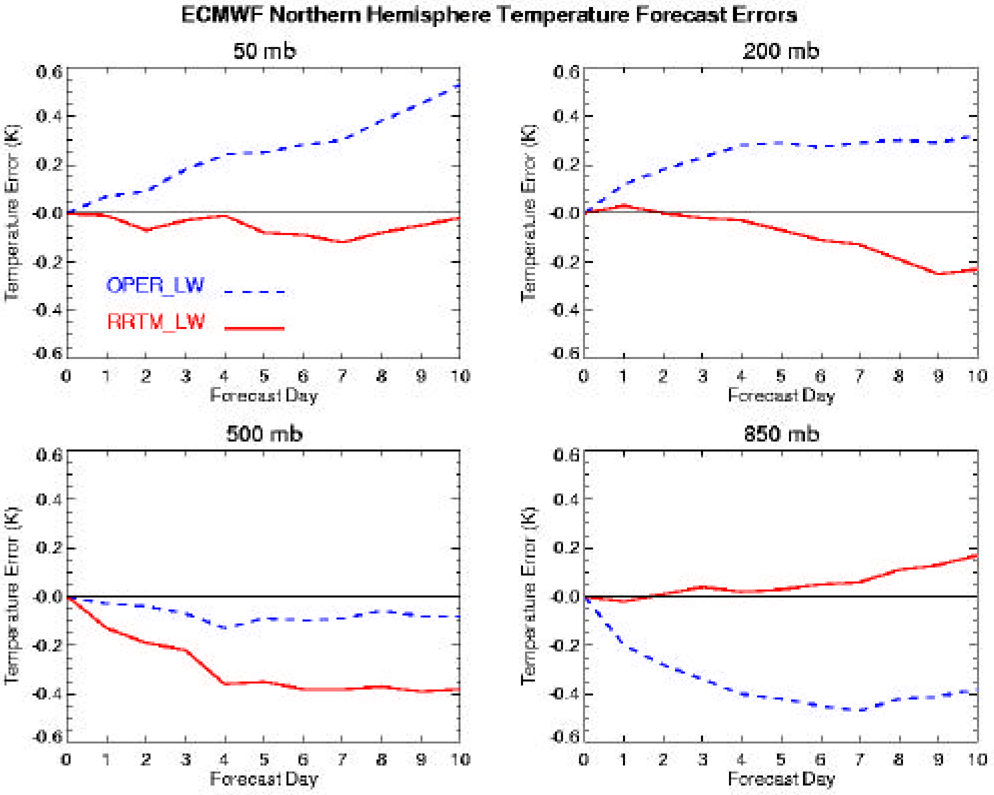

Figure 1. Ten-day forecast errors of northern hemisphere temperature for the ECMWF weather forecast model using the ECMWF operational LW model (dashed line) and RRTM (solid line) for four pressure levels. (For a color version of this figure, please see *http://www.arm.gov/docs/documents/technical/conf_9803/iacono-98.pdf*.)

of gas and cloud overlap mentioned above. A 1-year CCM3 simulation including a four-month adjustment period was performed using RRTM as the LW model and climatological sea surface temperatures (SSTs). The CCM3 LW model ran concurrently for diagnostic purposes. Differences between the radiation models from this run provide a basis for comparing the models for identical atmospheric states and represent RRTM's initial forcing impact. The RRTM effect on CCM3 dynamics was obtained by comparing this run to output from a separate CCM3 climatological simulation previously run and archived at NCAR.

Figure 2 shows the initial forcing impact on OLR for clear sky (Figure 2a) and total sky (Figure 2b) as an annual mean difference (RRTM-CCM3). RRTM reduces OLR at all latitudes, especially in the tropics, by a global average of 5.7 W m^{-2} in clear sky and 2.0 W m^{-2} in total sky. The similar cloud radiative approaches reduce the large clear-sky differences in cloudy regions. At the surface, RRTM lowers the net longwave flux in clear sky (Figure 2c) by increasing the downward flux, especially in the drier atmospheres found at high latitudes, deserts, and high elevations. Since the atmosphere near the surface is largely opaque to water vapor absorption in the pure rotation band below 500 cm^{-1} for moist atmospheres, the enhancement of absorption from the CKD_2.3 continuum is more apparent in the less opaque, low water areas. Figure 2d shows that clouds also reduce the net flux differences at the surface.

The global, annual mean top of the atmosphere (TOA) and surface fluxes for the two models are shown in Table 1. The values in Table 1 are from two separate CCM3 simulations and include the feedback effect of each LW model's

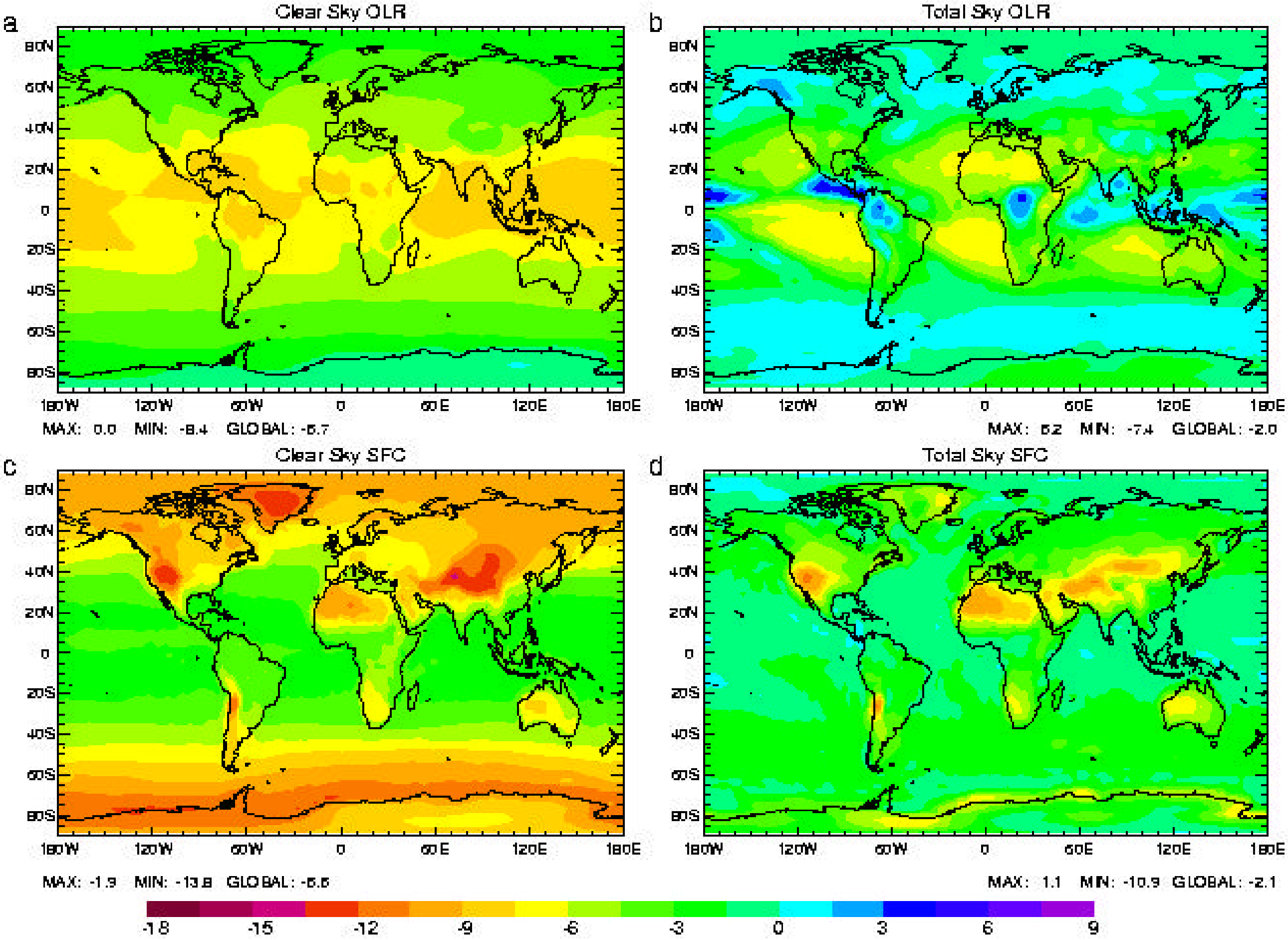

Figure 2. RRTM-CCM3 annual mean net flux differences in W m^{-2} for (a) clear-sky OLR, (b) total-sky OLR, (c) clear-sky surface, and (d) total-sky surface, for a CCM3 simulation in which both LW models were run. RRTM provided the LW fluxes and cooling rates used in the one-year simulation. (For a color version of this figure, please see *http://www.arm.gov/docs/documents/technical/conf_9803/iacono-98.pdf*.)

Table 1. Annual mean CCM3 TOA and surface fluxes in W m^{-2} for separate simulations using RRTM and the CCM3 LW models. The observed and CCM3 fluxes are from Kiehl et al. 1998b. Differences between CCM3 and observation are also shown for each field.

Field	Observation	CCM3		CCM3 w/RRTM	
Top of Atmosphere					
OLR	234.8	236.97	+2.17	233.43	-1.37
Clear Sky OLR	264.0	266.22	+2.22	260.76	-3.24
Solar Absorbed	238.1	236.88	-1.22	237.91	-0.19
Clear Solar Absorbed	286.3	286.42	+0.12	286.28	-0.02
Surface					
Net Longwave	66	60.68	-5.32	59.86	-6.14
Clear Net LW	70.7	92.39	+21.69	88.06	+17.36
Solar Absorbed	168	171.05	+3.05	172.35	+4.35
Clear Solar Absorbed	217.2	220.83	+3.63	221.15	+3.95

fluxes and cooling rates on changes in the atmospheric state. The Earth Radiation Budget Experiment (ERBE) observed quantities and CCM3 values are from Kiehl et al. (1998b). The TOA fluxes for both clear and cloudy sky are reduced by RRTM, so that the differences from ERBE fluxes change sign from about 2 W m^{-2} higher with the CCM3 LW model to 1 W m^{-2} to 3 W m^{-2} lower with RRTM. A residual effect of RRTM is to reduce the absorbed shortwave flux differences between CCM3 and ERBE.

Through its adjustment of atmospheric fluxes and the resulting cooling rate profiles, RRTM alters the CCM3 temperature field, generally producing warmer temperatures in the lower troposphere and cooler temperatures above 600 mb. The increase in downward flux contributes to warming the surface as shown in Figure 3 for the northern hemisphere winter (DJF) season. The temperature change is shown as differences from the NCAR/NCEP (National Centers for Environmental Prediction) reanalysis surface temperature for CCM3 running with RRTM (Figure 3a) and the CCM3 LW model (Figure 3b). The overall effect of RRTM is to reduce the cold bias over Antarctica, northern Africa, and North America and to warm the Arctic. In the global mean, RRTM reduces the CCM3-NCEP difference from -0.4 K to +0.1 K.

Conclusions

The introduction of an improved LW radiative transfer model, RRTM, into two GCMs has shown that a more accurate longwave algorithm significantly impacts TOA and surface fluxes in these models. Through changes in the cooling rate profile, the temperature fields are also modified. Future multi-year CCM3 experiments will establish the full impact of RRTM on the global energy budget as well as the hydrologic and thermodynamic properties of this climate model.

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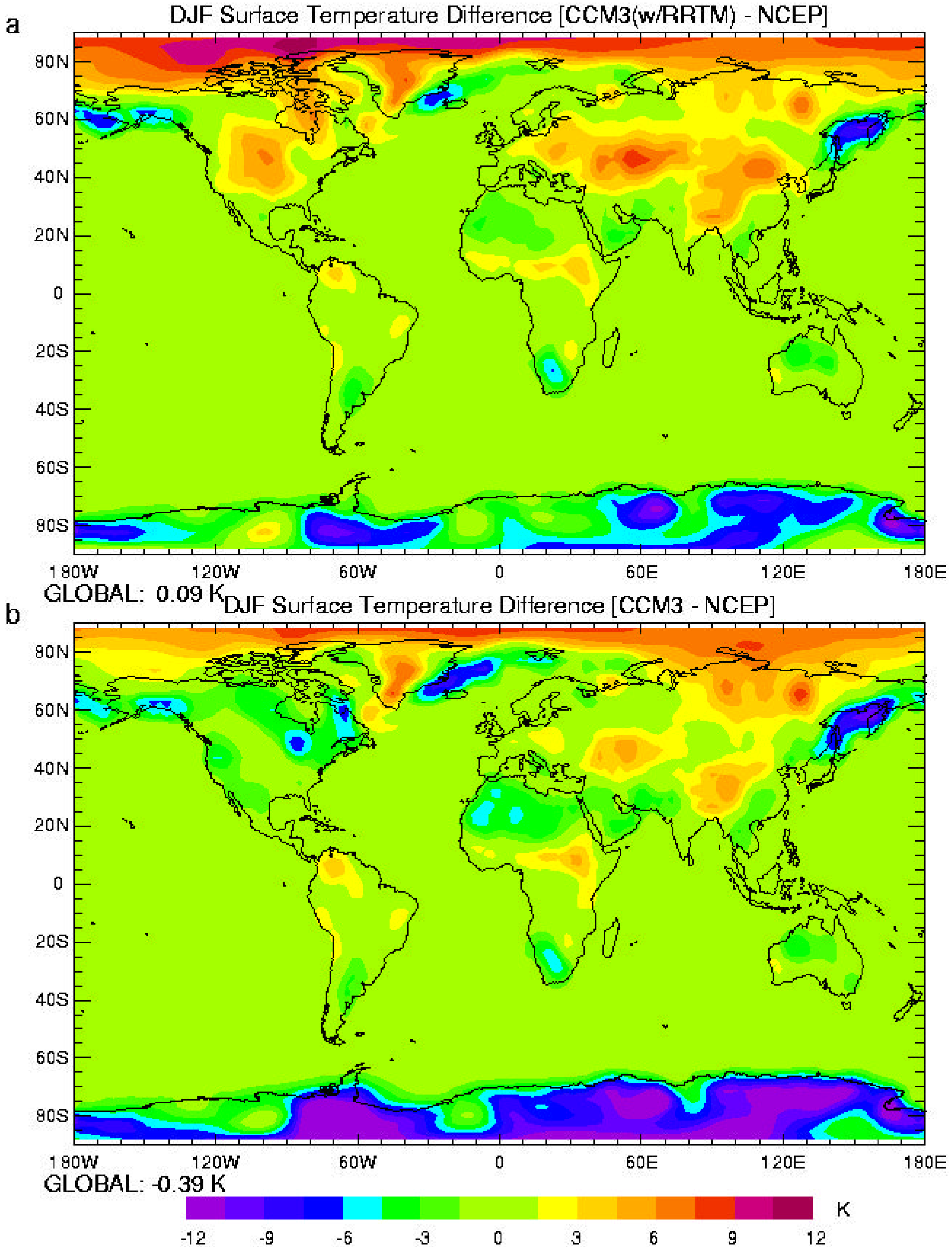

Figure 3. CCM3 surface temperature differences from the NCAR/NCEP reanalysis surface temperature for northern hemisphere winter using (a) RRTM as the LW model, and (b) the CCM3 LW model. (For a color version of this figure, please see *http://www.arm.gov/docs/documents/technical/conf_9803/iacono-98.pdf*.)

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