Application of the Shortwave Radiative Transfer Model, RRTMG_SW, to the National Center for Atmospheric Research and National Centers for Environmental Prediction General Circulation Models

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

J.-J. Morcrette
European Centre for Medium-Range Weather Forecasts
Reading, United Kingdom

Y.-T. Hou
National Centers for Environmental Prediction
Camp Springs, Maryland

Introduction

The k-distribution, shortwave, rapid radiative transfer model (RRTM_SW_V2.4) (Clough et al. 2005) developed for the Atmospheric Radiation Measurement (ARM) Program, uses the discrete ordinates radiative transfer model (DISORT) for scattering calculations and 16 g-points in each of its 16 spectral bands. DISORT provides agreement with line-by-line flux calculations to within 1 Wm^{-2} for direct irradiance and 2 Wm^{-2} for diffuse irradiance, but it makes RRTM_SW too computationally expensive for direct use in general circulation models. The development of RRTMG, an accelerated version of the standard RRTM radiative transfer model, supports the objective of transferring radiation model improvements realized by the ARM Program to general circulation models. RRTMG_SW (Iacono et al. 2004) uses a two-stream method and a reduced set of 112 g-points to attain enhanced computational performance while retaining an accuracy of 2 Wm^{-2} in clear sky relative to the standard RRTM_SW_V2.4 and to high-resolution radiative transfer models (Clough et al. 2005). More information on these models can be found at "rtweb.aer.com," and versions of both the longwave and shortwave RRTM that have been accelerated for general circulation model applications will be made available on that website.

The impact of RRTMG_SW is currently being tested in the National Center for Atmospheric Research (NCAR) Community Atmosphere Model (CAM3) the European Centre for Medium-range Weather Forecasts (ECMWF) weather forecast model (Morcrette et al. 2005), and the National Centers for Environmental Prediction (NCEP) Global Forecast System (GFS) model, along with RRTMG_LW. Results are presented between simulations with the NCAR and NCEP models that use the currently operational shortwave codes in these general circulation models and simulations that use RRTMG_SW. These comparisons will emphasize the impact of the improved shortwave radiative transfer on modeled fluxes, heating rates, temperature, and water vapor fields.

Clear-Sky Validations

For clear sky, the accuracy of RRTMG_SW is established by comparison to RRTM_SW. The latter has been shown to calculate irradiance to within 2 Wm^{-2} of the data-validated, code for high-resolution accelerated radiative transfer with scattering (CHARTS) model (Moncet and Clough 1997). Figure 1 shows scatter plots of clear-sky flux and heating rate differences between RRTMG_SW using a 2-stream algorithm with a reduced set of 112 g-points and RRTM_SW using DISORT with 16-streams and 224 g-points. All calculations include the effect of aerosols with a total optical depth of 0.23 in the lowest layers from 0 to 1.4 km. Calculations were made over 42 layers using the diverse set of 42 atmospheric profiles of Garand et al. (2001), and differences are plotted as a function of the RRTM_SW calculation with DISORT. Data are plotted with a number that represents the sequential index of the Garand profile. Top-of-the-atmosphere upward flux differences are within 2 Wm^{-2} (about 1%), downward flux differences at the surface are within 3 Wm^{-2} (about 0.3%), and the maximum net flux differences are within 4 Wm^{-2} (about 0.4%) for all cases. Maximum heating rate errors in the troposphere (0.1 Kd-1) and the stratosphere (0.3 Kd-1) differ by about 1% between the models.

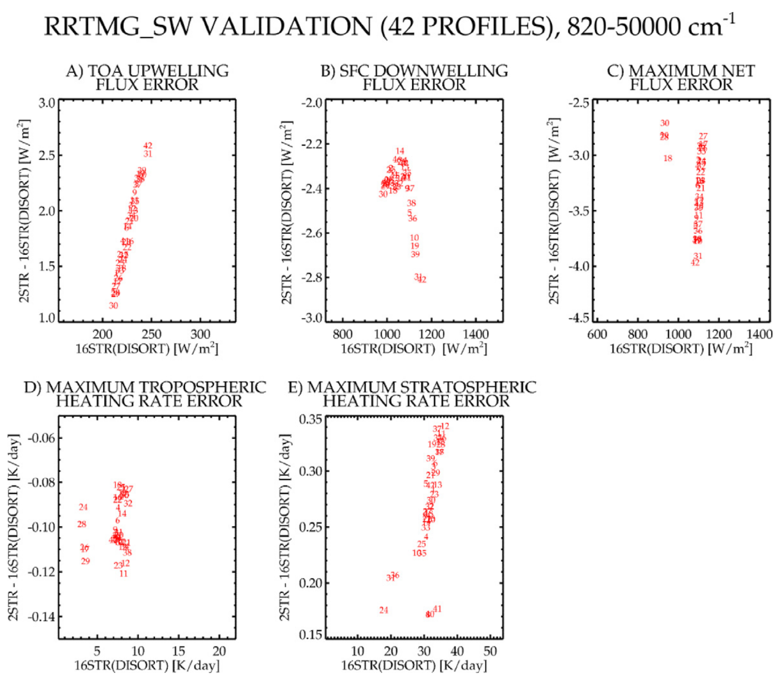

Figure 1. Scatter plots of flux and heating rate differences between RRTMG_SW (using 112 g-points and a two-stream radiative transfer method) and RRTM_SW (using 224 g-points and DISORT for radiative transfer) plotted relative to the RRTM_SW calculation for the diverse set of 42 profiles defined by Garand et al. (2001). All calculations include the effect of aerosols with a total optical depth of 0.23 in the layers from 0-1.4 km. Flux units are in Wm^{-2} and heating rate units are in Kd-1.

In the longwave, a feature has been added to RRTMG_LW that reduces downward flux errors at the surface (relative to the line-by-line radiative transfer model LBLRTM) in profiles with very high amounts of water vapor. This error is associated with the use of the standard diffusivity angle approximation for the flux integration (commonly used in general circulation models), and therefore this error is likely present in other radiation models that use this approximation. Figure 2 shows scatter plots of clear-sky longwave flux and heating rate differences between RRTMG_LW and LBLRTM, with the difference plotted versus the LBLRTM result. Differences for RRTMG_LW using the standard diffusivity angle are plotted in red. The correction involves a slight adjustment to the diffusivity angle that is proportional to the precipitable water in the column. Longwave flux and heating rate differences between RRTMG_LW using this variable diffusivity angle and LBLRTM are plotted in blue in Figure 2. The only significant impact of this adjustment is to reduce the downward surface flux difference from about 3-3.5 Wm^{-2} to 1.5-2 Wm^{-2} in the wettest profiles, which correspond to those producing the largest downward surface flux.

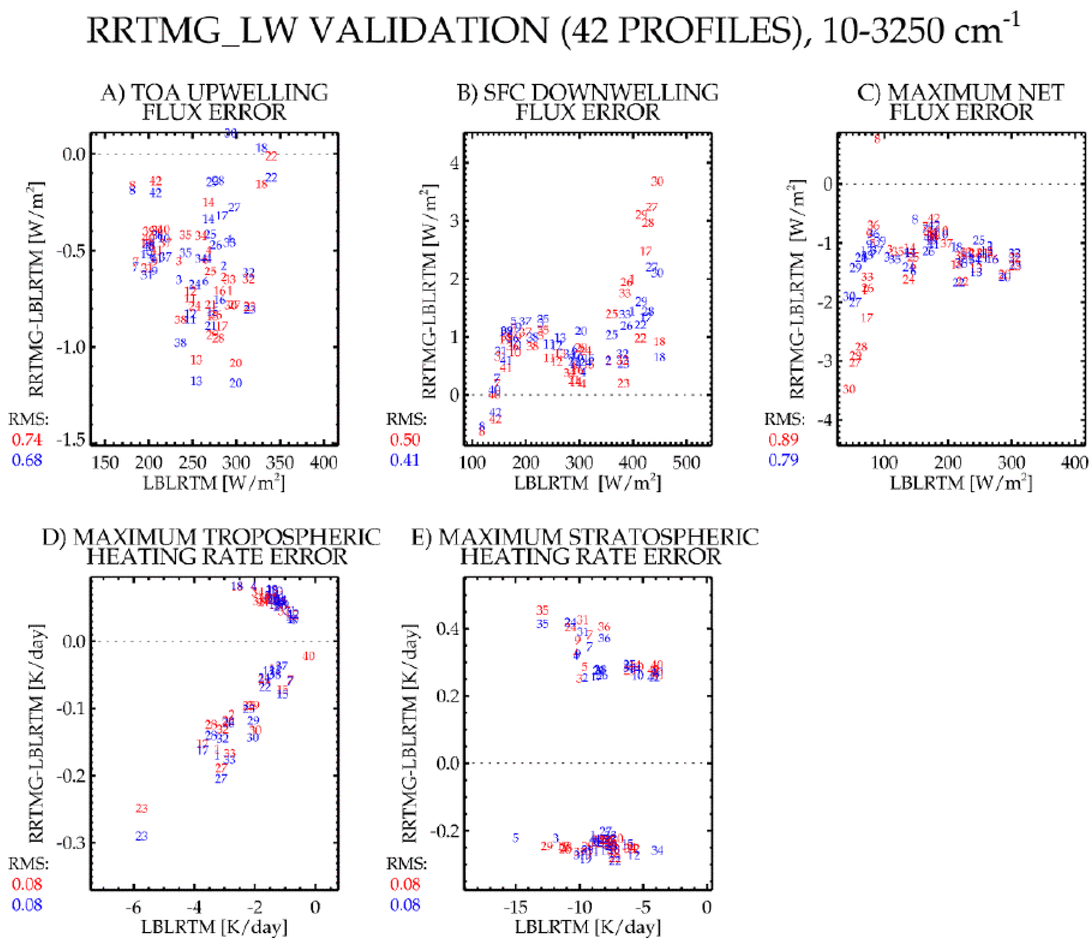

Figure 2. Scatter plots of flux and heating rate differences between RRTMG_LW (using 140 g-points) and LBLRTM plotted relative to the LBLRTM calculation for the diverse set of 42 profiles defined by Garand et al. (2001). RRTMG_LW calculations were performed with both the standard diffusivity angle (red) and with a diffusivity angle that varies in proportion to the total precipitable water in each column (blue). Flux units are in Wm^{-2} and heating rate units are in Kd-1.

Application of RRTMG to the National Center for Atmospheric Research CAM3

Both RRTMG_LW and RRTMG_SW have been implemented into the NCAR CAM3 (Collins et al. 2005) for the purpose of evaluating the radiation codes in the climate model. Simulations for the years 1980-1983 were performed with a version of CAM3 that was modified to run with RRTMG and to run the standard CAM3 radiation codes in parallel for diagnostic output. These preliminary simulations used monthly varying, prescribed sea surface temperatures and excluded aerosols. This approach allows a direct comparison of the radiative transfer models in which fluxes and heating rates are calculated by each model for identical atmospheric profiles over globally varying conditions.

A comparison of calculated surface and top of the atmosphere fluxes between RRTMG and the CAM3 radiation codes indicates that noticeable differences are present. Longwave flux differences between the two radiation models for June-August 1982 are shown in Figure 3 for both clear sky and for total sky including the effects of clouds. In clear sky (left panels of Figure 3), CAM3 upward flux at the top of the atmosphere is slightly too high relative to RRTMG_LW and downward surface flux is too low in dry regions. This suggests that longwave water vapor absorption due to the foreign continuum is slightly low in CAM3 relative to RRTMG, though both models apparently use version 2.4 of the CKD water vapor continuum. In total sky (right panels of Figure 3) the flux discrepancies are generally smaller because the models use the same cloud optical properties and similar treatments of maximum-random cloud overlap. Global flux differences (CAM3 shortwave minus RRTMG_SW) for June-August 1982 are shown in Figure 4. In clear sky (left panels), CAM3 downward surface flux is too low relative to RRTMG_SW, especially at high latitude. The cause of this discrepancy has not yet been determined. Upward top-of-the-atmosphere fluxes are influenced partly by the surface bias and partly by the slightly differing spectral treatment of the surface albedo in each shortwave model. These discrepancies show a strong seasonal dependence in that the largest clear sky surface flux differences switch to the southern polar latitudes during the summer season in the southern hemisphere. Total sky fluxes are impacted by the clear sky downward flux bias and possibly also by differences in the shortwave cloud overlap treatment. The appearance of the clear sky, northern high-latitude surface differences in the total sky result in Figure 4 might indicate that the additional downward shortwave flux and related heating that results from applying RRTMG decreases the occurrence of cloud cover, which is known to exceed observations in the standard CAM3 in polar latitudes (James Hack, personal communication, 2005).

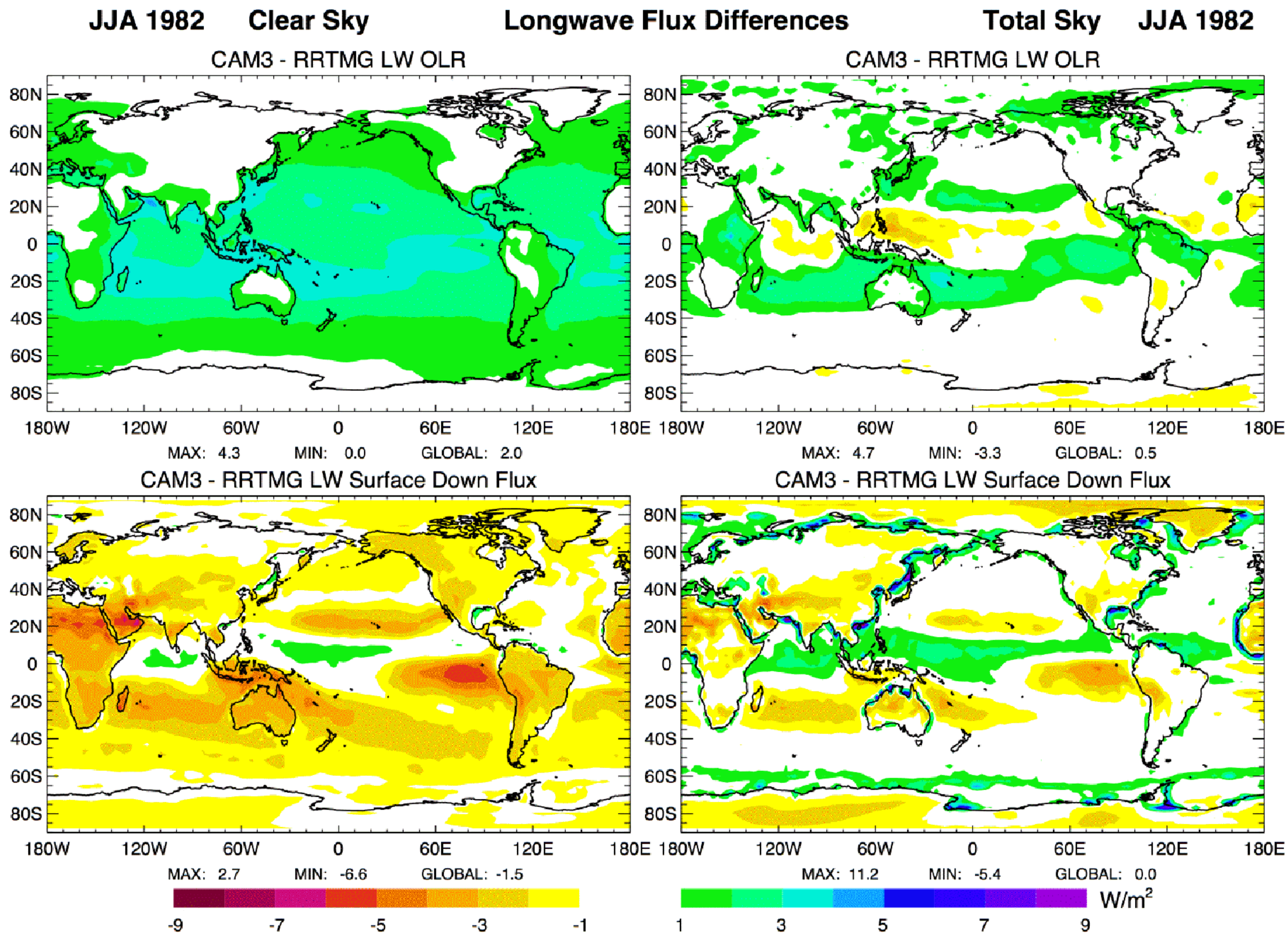

Figure 3. Differences in top-of-the-atmosphere longwave upward flux (top panels) and downward surface flux (bottom panels) between the CAM3 longwave model and RRTMG_LW from a CAM3 simulation of June-August 1982 for both clear sky (left) and total sky (right). Units are in Wm^{-2}.

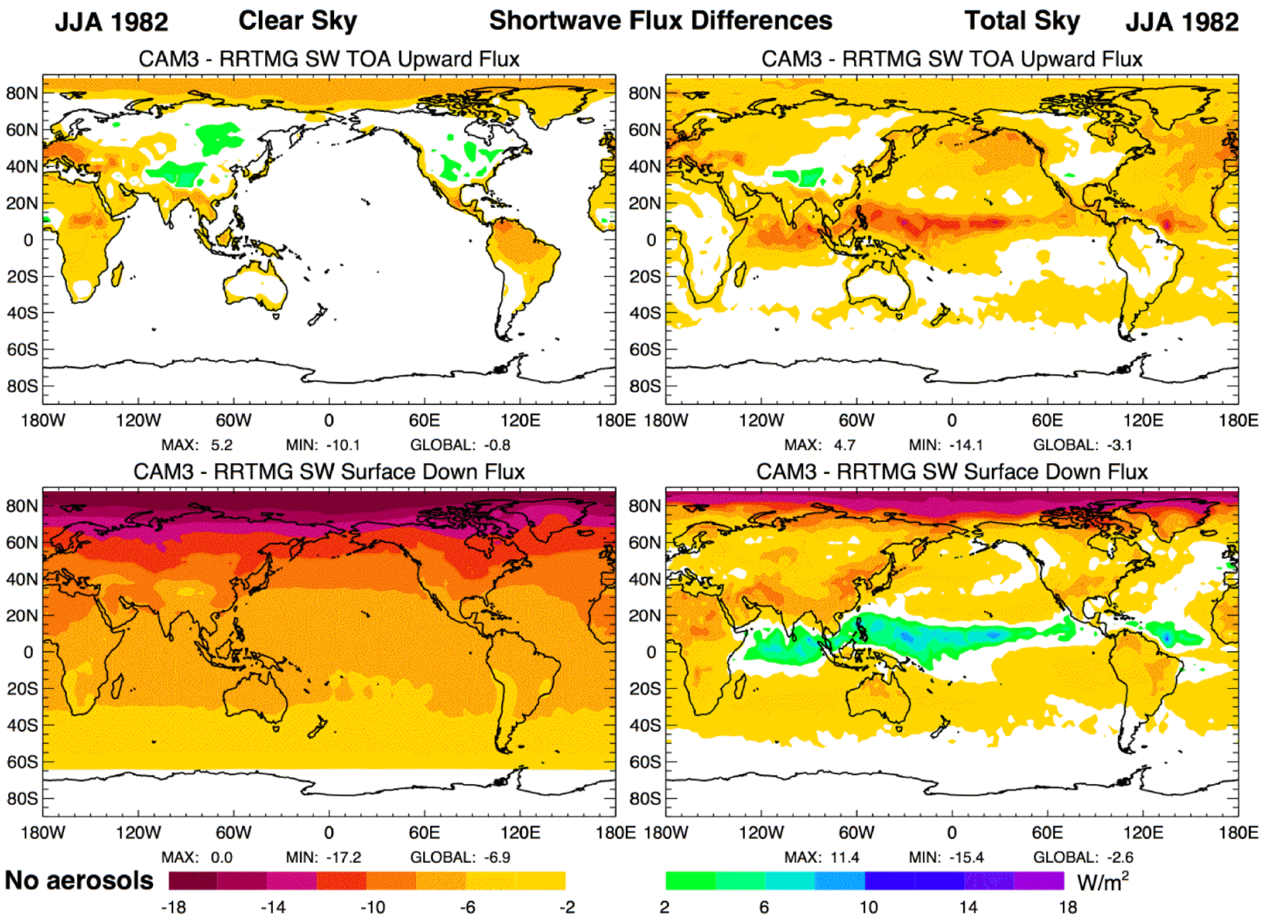

Figure 4. Differences in top-of-the-atmosphere shortwave upward flux (top panels) and downward surface flux (bottom panels) between the CAM3 shortwave model and RRTMG_SW from a CAM3 simulation of June-August 1982 for both clear sky (left) and total sky (right). Units are in Wm^{-2}.

Application of RRTMG_SW to the National Centers for Environmental Prediction Global Model

For testing purposes, NCEP has implemented RRTMG_SW into the GFS forecast model, and a pair of simulations has been performed using this modified forecast model and the operational GFS, which used the NCEP shortwave code, for several periods during 2004. The experiment with RRTMG_SW also used RRTMG_LW, which has been running operationally in the GFS since August 2003. Aerosols were excluded from these simulations. A primary objective of this experiment was to determine the impact of the improved shortwave radiative transfer on the significant upper stratospheric cold bias in the operational GFS.

The changes in zonal mean temperature between these simulations for January and July 2004 are shown in Figure 5. Temperature differences are also plotted in separate panels to highlight the troposphere (lower panels) and stratosphere (upper panels). The shortwave radiative transfer change provides a significant increase in shortwave heating above 20 mb, and this results in a substantially warmer upper stratosphere in both months.

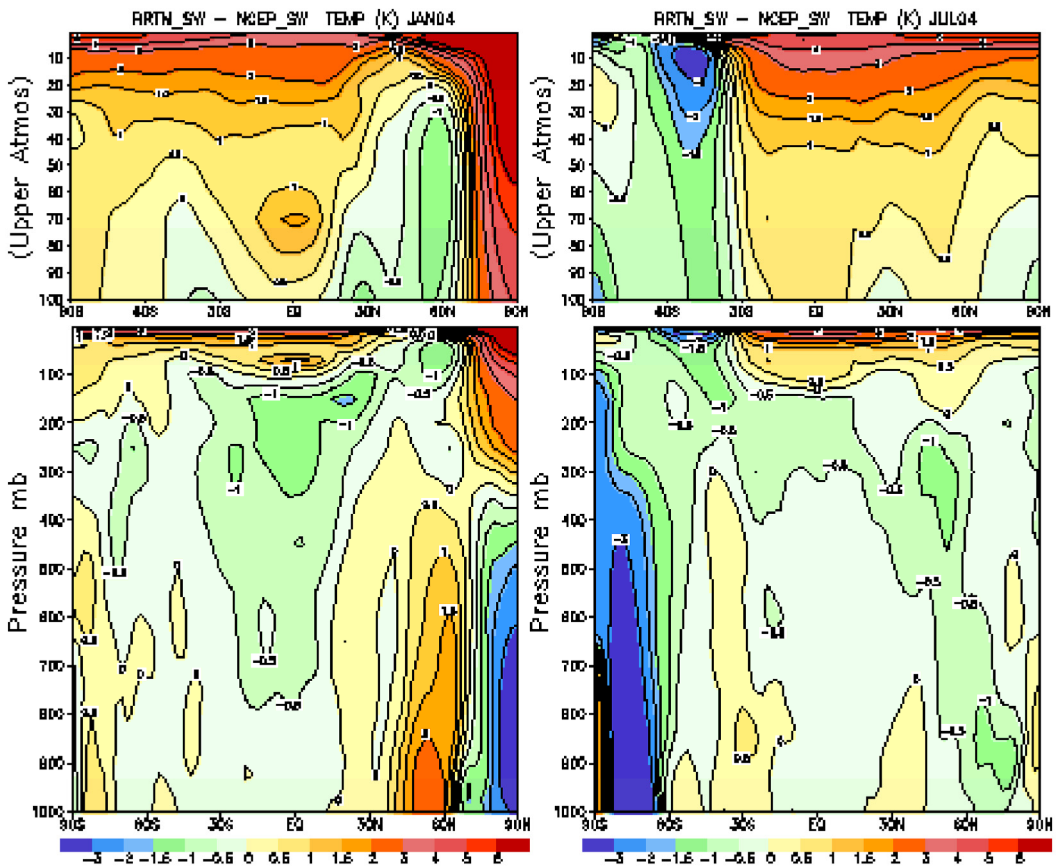

Figure 5. Zonal mean temperature differences between two simulations of the NCEP GFS model running with the NCEP operational shortwave model and with RRTMG_SW for January 2004 (left panels) and July 2004 (right panels). Data are plotted on two vertical scales to highlight the stratosphere (top) and troposphere (bottom). Units are in K.

Summary

Accelerated versions of the longwave and shortwave k-distribution model, RRTM, developed for the ARM Program, have been prepared for application to general circulation models. These GCM-ready radiation codes retain high accuracy relative to high-resolution radiative transfer models that have been extensively validated with ARM measurements. RRTMG_SW is currently being tested at several dynamical modeling centers.

RRTMG_LW and RRTMG_SW have been implemented into the NCAR CAM3 climate model for the purpose of performing a side-by-side comparison with the CAM3 radiation codes. Small flux and heating rate differences are seen in the longwave that are likely related to water vapor absorption. A large discrepancy has been shown in the CAM3 clear sky, downward shortwave surface flux, which is most apparent in the summer hemisphere at polar latitudes. Preliminary tests of RRTMG_SW in the NCEP GFS show that the improved shortwave radiative transfer reduces the upper stratospheric cold bias in the GFS by providing substantially more shortwave heating and warmer temperatures at these levels.

Corresponding Author

Michael J. Iacono, mike@aer.com, (781) 761-2208.

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