Final Technical Report

For the Project:

Application of Improved Radiation Modeling to General Circulation Models

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1. Executive Summary

This research has accomplished its primary objectives of developing accurate and efficient radiation codes, validating them with measurements and higher resolution models, and providing these advancements to the global modeling community to enhance the treatment of cloud and radiative processes in weather and climate prediction models. A critical component of this research has been the development of the longwave and shortwave broadband radiative transfer code for general circulation model (GCM) applications, RRTMG, which is based on the single-column reference code, RRTM, also developed at AER. RRTMG is a rigorously tested radiation model that retains a considerable level of accuracy relative to higher resolution models and measurements despite the performance enhancements that have made it possible to apply this radiation code successfully to global dynamical models. This model includes the radiative effects of all significant atmospheric gases, and it treats the absorption and scattering from liquid and ice clouds and aerosols. RRTMG also includes a statistical technique for representing small-scale cloud variability, such as cloud fraction and the vertical overlap of clouds, which has been shown to improve cloud radiative forcing in global models. This development approach has provided a direct link from observations to the enhanced radiative transfer provided by RRTMG for application to GCMs. Recent comparison of existing climate model radiation codes with high resolution models has documented the improved radiative forcing capability provided by RRTMG, especially at the surface, relative to other GCM radiation codes. Due to its high accuracy, its connection to observations, and its computational efficiency, RRTMG has been implemented operationally in many national and international dynamical models to provide validated radiative transfer for improving weather forecasts and enhancing the prediction of global climate change.

2. Introduction

The primary objectives of this research effort have been to develop accurate and efficient longwave and shortwave radiation codes, validate them with measurements and higher resolution radiative transfer, and provide these advancements to the global modeling community to enhance the treatment of cloud and radiative processes in general circulation models (GCMs). These goals were accomplished by applying a consistent approach over many years that emphasized the importance of designing and building radiative transfer codes from a spectral perspective, maintaining a direct connection to radiation measurements, and interacting extensively with the dynamical modeling community. A critical component of this research has been the development of the longwave and shortwave broadband radiative transfer model for GCM applications, RRTMG (*Iacono et al.*, 2008), that is based on the single-column correlated k-distribution reference model, RRTM (*Mlawer et al.*, 1997). RRTMG is a rigorously tested model that retains a considerable level of accuracy relative to RRTM, the line-by-line radiative transfer model, LBLRTM (*Clough et al.*, 2005, *Clough and Iacono*, 1995), and the high-resolution multiple scattering model CHARTS (*Moncet and Clough*, 1997) despite the performance enhancements that have made it possible to apply this radiation code successfully to dynamical models. RRTMG includes the Monte-Carlo Independent Column Approximation (McICA) technique (*Barker et al.*, 2007; *Pincus et al.*, 2003) for representing sub-grid cloud variability, which has been shown to improve cloud forcing in the ECMWF forecast model (*Morcrette et al.*, 2008). Participation in the DOE-supported Continual Intercomparison of Radiation Codes (CIRC) Program has provided an additional context for evaluating RRTMG with measurements. This development approach has provided a direct link from observations to the enhanced radiative transfer provided by RRTMG for improving weather and climate simulations.

Additional radiation model comparisons were completed during this research to demonstrate the accuracy of RRTMG relative to present climate model radiation codes. The Radiative Transfer Model Intercomparison Project (RTMIP; *Collins et al.*, 2006) calculated top of the atmosphere (TOA) and surface radiative forcing with high-resolution line-by-line models and compared this to similar calculations with current GCMs for several changes in long-lived greenhouse gases. The RTMIP cases have been reproduced with the AER broadband and line-by-line radiation models (*Iacono et al.*, 2008) to document the improved radiative forcing capability provided by RRTMG, especially at the surface, relative to GCM radiation models. In addition, the broadband model was shown to be in excellent agreement with high-resolution calculations when simulating the impact on radiative heating due to greenhouse gas increases.

Due to its competitive computational speed and high accuracy, RRTMG has been implemented in numerous national and international weather and climate models including 1) the National Center for Atmospheric Research (NCAR) Community Atmosphere Model (CAM5), Community Earth System Model (CESM1, formerly CCSM), and Weather Research and Forecasting Model (WRF-ARW), 2) the European Centre for Medium-Range Weather Forecasts (ECMWF) Integrated Forecast System (IFS) and ERA40 Reanalysis, 3) the Max Planck Institute ECHAM climate model, 4) the National Centers for Environmental Prediction (NCEP) Global Forecast System (GFS), Climate Forecast System (CFS), CFS Reanalysis (CFSR), and Rapid Update Cycle Forecast Model (RUC), 5) the Laboratory for Dynamical Meteorology (LMD) LMDZ climate model, and 6) the National Aeronautics and Space Administration (NASA) Goddard Earth Observing System (GEOS-5) Data Assimilation System. More information about RRTMG, RRTM, and LBLRTM and the source codes for each model are provided to the scientific community through the AER radiative transfer web site (rtweb.aer.com).

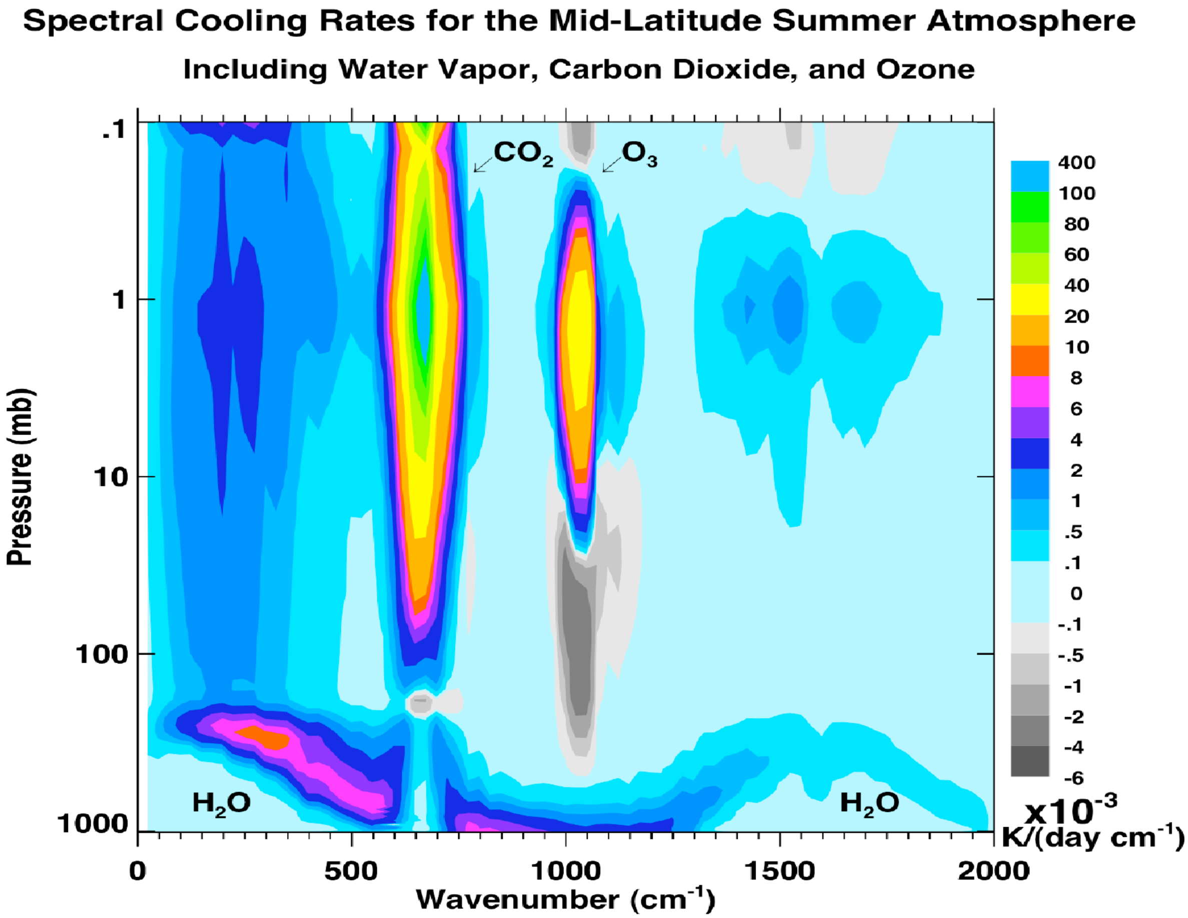

Figure 1. Spectral cooling rate profile for H_2O, CO_2 (355 ppm) and O_3 as a logarithmic function of pressure for the mid-latitude summer atmosphere (*Clough and Iacono*, 1995). The data are spectrally averaged over 25 cm^{-1} intervals. Color scale ($x10^{-3}$) is in units of Kd^{-1} $(cm^{-1})^{-1}$.

3. RRTMG Radiation Model Development

A critical aspect of the broadband radiative transfer development completed for this research is the essential requirement to retain a high level of flux and heating rate accuracy in each spectral region in addition to fully integrated quantities. This is especially significant in the context of accurately simulating the potential radiative impact of future increases in individual greenhouse gases such as methane, which are radiatively active in limited spectral intervals. For this reason, the broadband models were designed and their spectral intervals were selected based on the details of radiative processes provided by high-resolution calculations (*Mlawer et al.*, 1997). Figure 1 illustrates the spectral detail of longwave cooling rate for a LBLRTM calculation across the infrared spectrum as a function of pressure for the mid-latitude summer atmosphere (*Clough and Iacono*, 1995). The calculation included water vapor, carbon dioxide and ozone, and the resulting cooling rates are spectrally averaged over 25 cm^{-1} intervals. In Figure 1, cooling rates are shown in color, and heating rates are shown in black and white shades. As the dominant greenhouse gas in the troposphere, water vapor produces cooling across much of the longwave with its peak impact occurring in the upper troposphere in the far infrared region (200-400 cm^{-1}). Water vapor produces additional cooling in the far infrared throughout the stratosphere. Carbon dioxide and ozone are the largest contributors to radiative cooling in the stratosphere, though they are radiatively active over much narrower sections of the longwave spectrum. Finally, the overlap between carbon dioxide and water vapor in the 600-700 cm-1 spectral band, in which carbon dioxide partially offsets the impact of water vapor in the troposphere, is a critical interval for accurately simulating the radiative impact of increased concentrations of carbon dioxide.

3.1 Longwave

The RRTM and RRTMG broadband longwave models were developed based on the correlated k-distribution technique, which provides substantial increases in computational speed relative to line-by-line calculations while retaining much of the accuracy (*Mlawer et al.*, 1997). With the objective of providing a radiative transfer model for this research that can be directly applied to GCMs [*Iacono et al.,* 2003; *Iacono et al.,* 2000] with an accuracy that is traceable to ARM and other measurements, RRTM was modified to produce RRTMG. The former model retains the highest accuracy relative to line-by-line results for single-column calculations, and the latter provides better efficiency with minimal loss of accuracy for GCM applications. While RRTMG shares the same basic physics and absorption coefficients as RRTM, it incorporates several modifications to improve computational efficiency, to update the code formatting for easier application to GCMs, and to represent sub-grid scale cloud variability. In particular, the total number of quadrature points (or g-points) used to calculate radiances in the longwave has been reduced from the standard 256 in RRTM_LW (with 16 g-points in each of the 16 spectral bands) to 140 in RRTMG_LW (with the number of g-points in each spectral band varying from 2 to 16 depending on the absorption in each band). Also, RRTMG has been fully reformatted for consistency between the longwave and shortwave and to incorporate modern FORTRAN90 functionality. Clear sky RRTMG_LW accuracy relative to LBLRTM for flux is 1.5 Wm^{-2} at all levels, and heating rates agree to within 0.2 Kd^{-1} in the troposphere and generally 0.4 Kd^{-1} in the stratosphere. RRTMG_LW utilizes the single standard diffusivity angle (two streams) for flux integration, though it also incorporates a small modification of the diffusivity angle in some spectral bands that varies as a function of total column water vapor to improve fluxes and heating rates in profiles with high water vapor amounts. Additional modifications made to RRTMG during this effort include a complete source code reformatting to utilize modern FORTRAN90 features to enhance the model's modularity for GCM applications, and the conversion of the large input absorption coefficient data tables from executable statements to netCDF input data files, which was accomplished by Dr. Robert Pincus and colleagues at NOAA.

The treatment of cloud overlap and cloud optical properties are potentially very large sources of error in GCM radiative transfer partly due to the unresolved sub-grid scale of these processes. This has been addressed by implementing the Monte-Carlo Independent Column Approximation (McICA) technique (*Barker et al.*, 2007; *Pincus et al.*, 2003) into RRTMG (*Iacono et al.*, 2006) in collaboration with Dr. Robert Pincus (NOAA). For McICA, cloud state and spectral interval (or intervals in cumulative probability space in the case of a correlated k-distribution model such as RRTMG) are sampled simultaneously. In this mode, individual RT calculations across the spectral intervals are either clear or overcast in proportion to the cloud fraction. Sub-grid cloud state information is generated stochastically at each GCM grid box, model layer, and spectral interval based on the cloud state provided by the GCM. The advantage of this technique is that it allows considerable flexibility in representing the sub-grid cloud variability within RRTMG in an efficient manner. However, this statistical approach introduces random errors in the radiative transfer that depend on how the cloud properties are distributed spectrally and on the number of spectral intervals. It was shown by *Pincus et al.* (2003) that these errors are unbiased relative to reference calculations and have been shown to have little detrimental impact in the context of the large number of calculations performed during a GCM simulation or forecast (*Morcrette et al.,* 2008; *Raisanen et al.*, 2005). RRTMG is especially well suited to utilize McICA effectively, since the relatively high number of g-point intervals (140 in the longwave) used by the model limits the standard deviation of the unbiased errors associated with this technique. The input cloud state arrays (dimensioned on g-point) are provided by a stochastic sub-column cloud generator, which follows the method of *Raisanen et al.* (2004).

The McICA implementation was evaluated by comparing a standard, single-column random cloud overlap calculation with RRTMG_LW to a series of 200 calculations performed with RRTMG/McICA. For the standard (non-McICA) longwave calculation, the mid-latitude summer profile was used with two liquid cloud layers and two ice cloud layers, each with cloud fraction of 0.5 and typical values for the input cloud physical properties. A four-layer cloud configuration was used consisting of a pair of two-layer thick clouds with a cloud fraction of 0.5 and a total optical depth of 10. The calculations with McICA used the same input profile, though the cloud state variables were defined in a statistically random manner similar to the stochastic cloud generator. Figure 2 shows the distribution of longwave flux differences between the 200 RRTMG/McICA calculations and the single, non-McICA, RRTMG reference calculation (STD) for downward surface flux, upward flux at the cloud top and net flux at the cloud base. Mean differences are each less than 0.4 Wm^{-2} with standard deviations around 5 Wm^{-2}. The mean differences are less than the uncertainty of the McICA estimate, defined by *Pincus et al.* (2003) as $\sigma / \sqrt{N}$, where σ is the standard deviation of the N (200) samples.

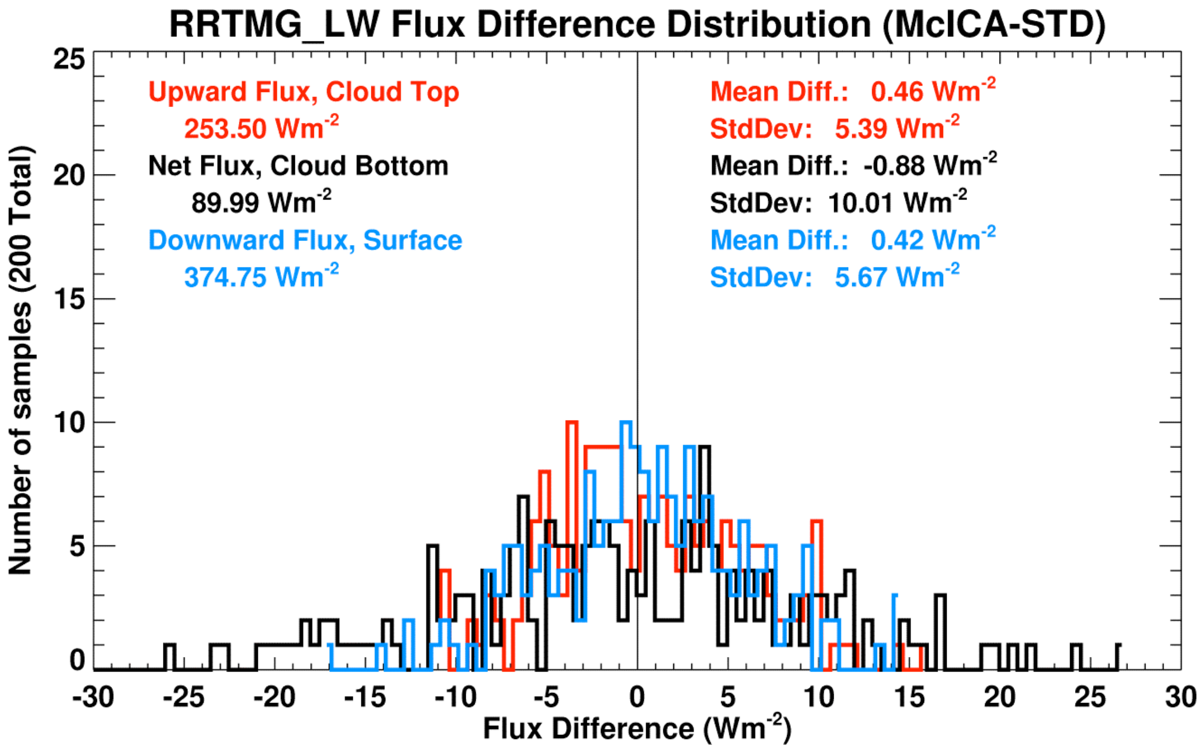

Figure 2. Distribution of longwave flux differences between 200 calculations with RRTMG_LW/McICA and a single calculation with the standard RRTMG_LW for the mid-latitude summer profile with a pair of two-layer thick clouds, each with cloud fraction 0.5, a total cloud optical depth of 10, and assuming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

3.2 Shortwave

Another major initiative of this research was the development of RRTMG_SW (*Iacono et al.*, 2008; *Iacono et al.*, 2004), a version of the single-column reference model RRTM_SW (*Clough et al.*, 2005) that is suitable for application to GCMs. As in RRTMG_LW, the critical feature justifying the utilization of RRTMG_SW in GCMs is its traceability to DOE/ARM measurements through comparisons to the high resolution, data-validated models LBLRTM and CHARTS (*Moncet and Clough*, 1997). Several features of RRTMG_SW provide potential for improvement relative to the accuracy of existing GCM and 1-D shortwave models (*Barker et al.,* 2003). These features include: (1) a correlated-k approach consistent with that for the longwave, including the method for handling overlapping molecular bands; (2) modified HITRAN2000 line parameters and CKD continuum model; and (3) the utilization of a validated (Kurucz) solar source function, incorporated in each band of the model accounting for its spectral correlation with the optical depths in the band. In addition, RRTMG_SW includes the absorption and emission from water vapor, carbon dioxide, ozone, oxygen, methane, nitrous oxide, carbon monoxide, clouds and aerosols. These absorbers with the addition of the common halocarbons are also considered in RRTMG _LW.

RRTMG_SW was adapted from RRTM_SW by improving its computational efficiency, while minimizing impacts on accuracy, and by adding flexibility in treating cloudy radiative transfer. Model efficiency was improved in two ways. First, RRTM_SW utilizes 224 g-points (i.e. the intervals in cumulative probability space over which the radiative transfer is performed in the correlated-k technique). Performance has been improved for RRTMG_SW by reducing the total number of g-points to 112 while retaining most of the original accuracy with a procedure that combines adjacent g-points with appropriate weighting in a manner that minimizes the impact on the fluxes and heating rates. This optimization of the g-point intervals into a more efficient configuration reduced the computational expense by approximately a factor of two. Second, the DISORT discrete ordinates model for multiple scattering radiative transfer in RRTM_SW is highly accurate but too computationally expensive for use in a GCM. The DISORT algorithm was replaced with a 2-stream radiative transfer solver (*Oreopoulos and Barker*, 1999), which provides an additional timing improvement of roughly a factor of 50.

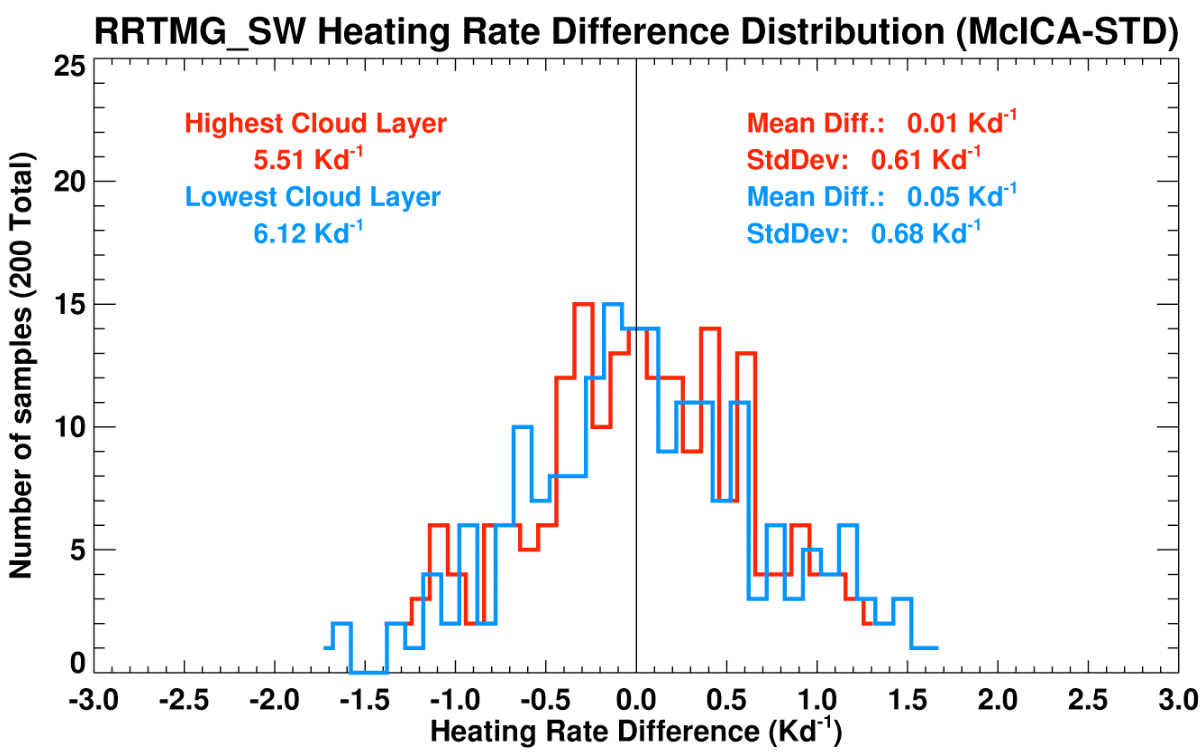

Figure 3. Distribution of shortwave heating rate differences between 200 calculations with RRTMG_SW/McICA and a reference calculation with RRTMG_SW for the mid-latitude summer profile with a pair of single-layer thick clouds, each with cloud fraction 0.5, a total cloud optical depth of 10, and assuming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

Since RRTM_SW with DISORT is restricted to fully overcast cloudy radiative transfer, a means of treating partial cloudiness and a method of representing cloud overlap, or the vertical correlation of clouds, was also required for RRTMG_SW for it to be applicable to GCMs. This requirement was achieved by incorporating the statistical McICA technique into RRTMG_SW, and this capability was verified with a similar approach to that used in the longwave. Figure 3 shows the distribution of shortwave heating rate differences between 200 calculations with RRTMG_SW/McICA and a single, non-McICA, RRTMG reference calculation (STD). A two-layer cloud configuration was used in the shortwave test with cloud fractions of 0.5 and a total cloud optical depth of 10. Mean differences are both less than 0.05 Kd^{-1}, which are close to or less than the uncertainty estimates, and the standard deviations of the heating difference in each cloud layer are about 0.65 Kd^{-1}. Mean differences of both longwave heating rates and shortwave fluxes from these tests also pass the expected uncertainty of the McICA technique. This demonstrates that the calculations with McICA are unbiased over a large sample of cases.

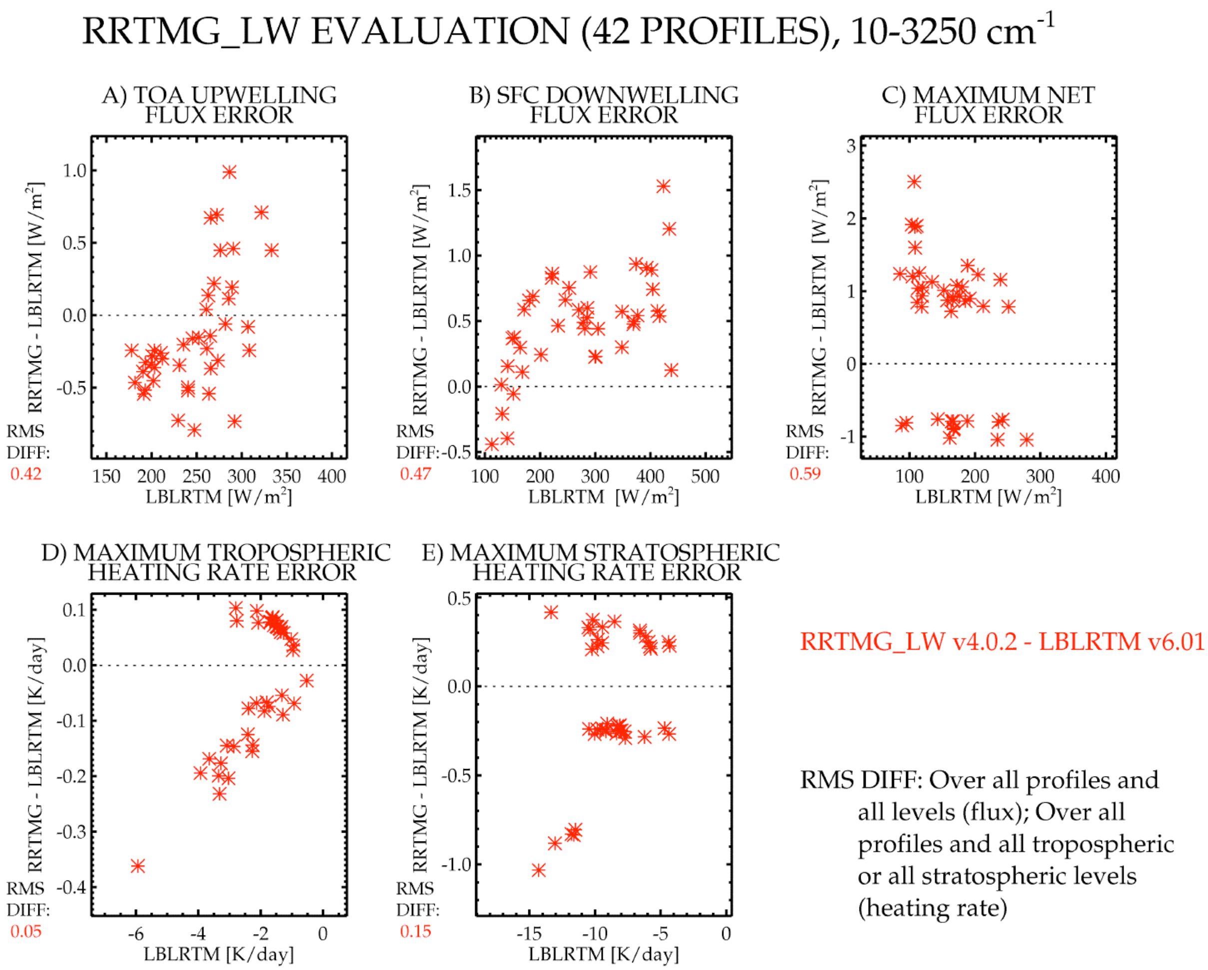

Figure 4. Scatter plots of clear sky differences between RRTMG_LW and the line-by-line model LBLRTM plotted as a function of the LBLRTM calculation over the 10-3250 cm^{-1} spectral range for top of the atmosphere upwelling flux (top left), surface downwelling flux (top middle), maximum net flux difference (top right), maximum tropospheric heating rate difference (bottom left), and maximum stratospheric heating rate difference (bottom right). Calculations are for the 42 diverse profiles of *Garand et al.*, (2001).

4. RRTMG Validation

4.1 Comparison to Line-by-line Calculations

Effectively validating the accuracy of RRTMG is an essential step before applying it to global dynamical models. Comparison to higher resolution models that are extensively validated with measurements provides the most direct way to validate RRTMG. The level of accuracy provided by RRTMG_LW relative to LBLRTM in clear sky is illustrated in Figure 4 for the diverse set of 42 atmospheric profiles defined by *Garand et al.* (2001). The five panels in Figure 4 show the difference for each of the 42 profiles between RRTMG_LW and LBLRTM calculations plotted as a function of the LBLRTM result for top of the atmosphere (TOA) upward flux (top left), downward flux at the surface (top center), maximum net flux difference at

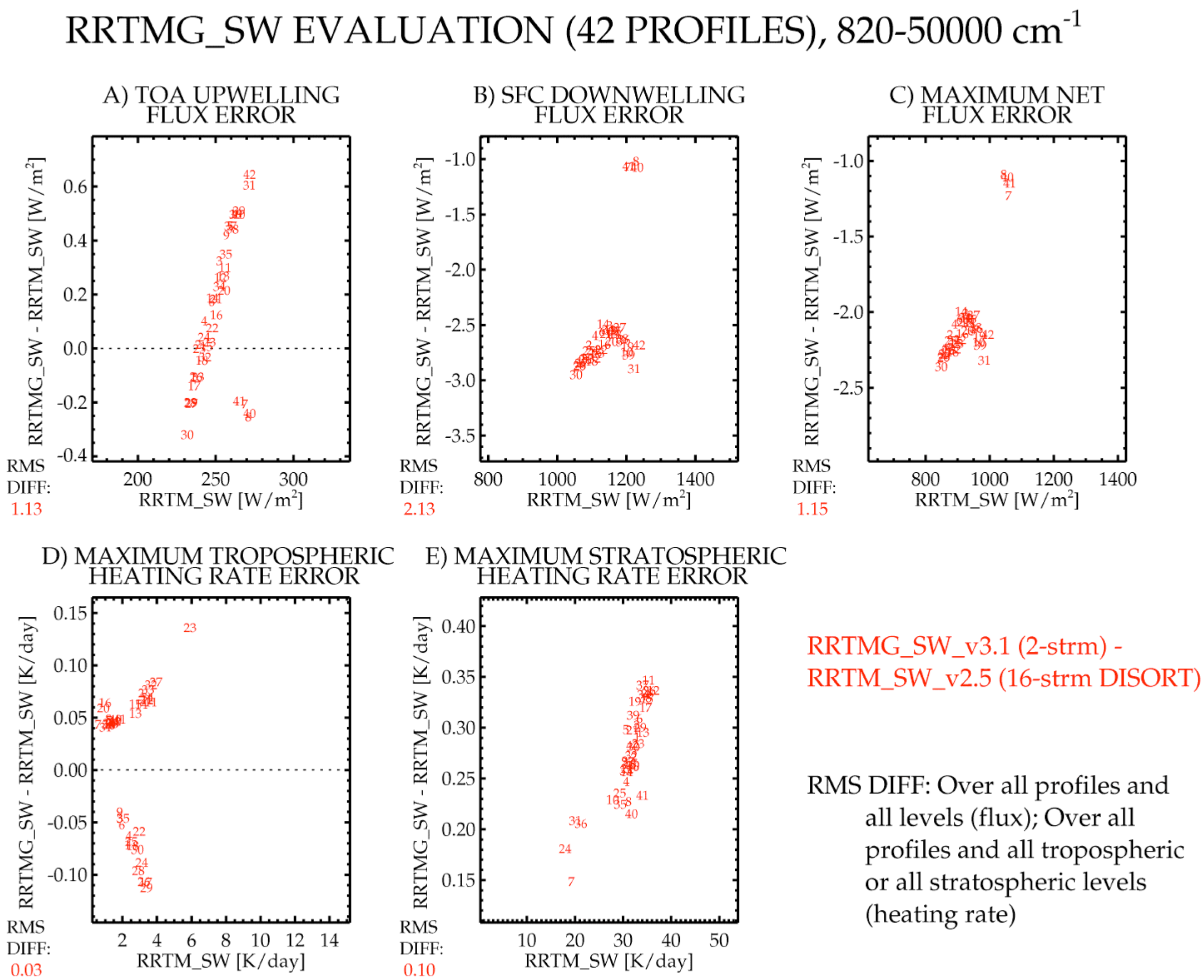

Figure 5. Scatter plots of clear sky differences between RRTMG_SW (using a 2-stream model) and RRTM_SW (using DISORT with 16 streams) plotted as a function of the RRTM_SW calculation for 820-50000 cm^{-1} top of the atmosphere upwelling flux (top left), surface downwelling flux (top middle), maximum net flux difference (top right), maximum tropospheric heating rate difference (bottom left), and maximum stratospheric heating rate difference (bottom right). Calculations are for the 42 diverse profiles of *Garand et al.*, (2001), and values are plotted with a sequential number that identifies the profile.

any level (top right), maximum heating rate difference in the troposphere (bottom left) and maximum heating rate difference in the stratosphere (bottom center). Root mean square (RMS) errors are also shown for each panel, and these are generally 0.5 Wm^{-2}. Most of the individual errors are about 1.0 Wm^{-2} or less. RRTMG_LW heating rate errors are generally 0.1 Kd^{-1} or less in the troposphere and 0.5 Kd^{-1} or less in the stratosphere relative to LBLRTM.

In clear sky, the accuracy of RRTMG_SW using the two-stream method was established by comparison to RRTM_SW. The latter has been shown (*Iacono et al.,* 2001) to calculate irradiance to within 2 Wm^{-2} of the data-validated, high-resolution model for multiple scattering, CHARTS (*Moncet and Clough*, 1997). 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 are shown in Figure 5 for the diverse set of 42 atmospheric profiles of *Garand et al.* (2001). Upwelling flux differences at TOA vary from 0.1 to 0.6 Wm^{-2} depending on total outgoing flux, while surface downwelling flux differences and maximum net flux differences cluster near 3 Wm^{-2} (about 0.3 percent). Maximum solar heating rate differences are within 0.1 Kd^{-1} in the troposphere and 0.35 Kd^{-1} (about 1 percent) in the stratosphere. This demonstrates that carefully and selectively reducing the total number of g-points used by RRTMG_SW to 112, which enhanced the model's computational performance by about a factor of two, had only small impacts on its accuracy.

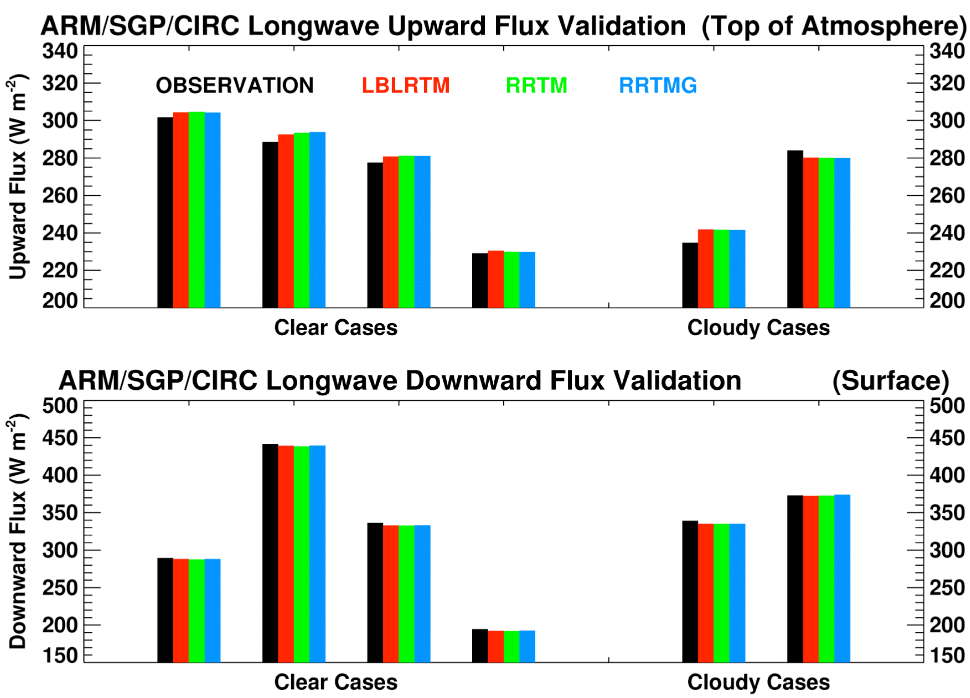

Figure 6. Comparison of longwave top of atmosphere upward flux (top) and surface downward flux (bottom) between observations (black) and calculations with the line-by-line longwave model LBLRTM (red) and the broadband models RRTM (green) and RRTMG (blue) for four diverse CIRC clear sky cases and two cloudy cases.

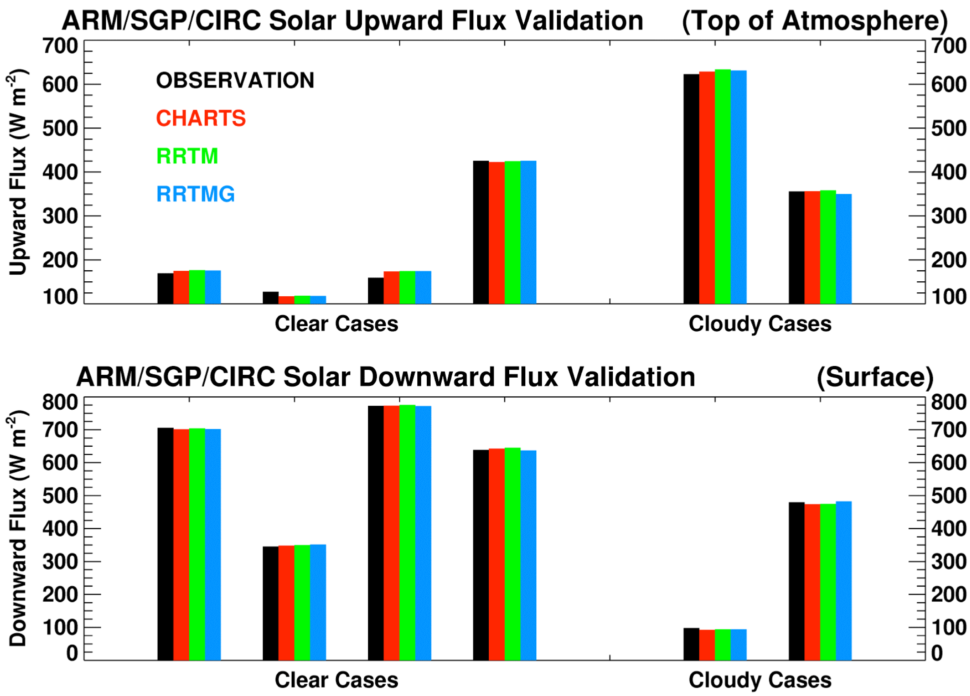

Figure 7. Comparison of shortwave top of atmosphere upward flux (top) and surface downward flux (bottom) between observations (black) and calculations with the multiple scattering model CHARTS (red), and the broadband models RRTM (green) and RRTMG (blue) for four widely varying CIRC clear sky cases and two cloudy cases.

4.2 Continual Intercomparison of Radiation Codes (CIRC)

Further model validation was accomplished through participation in the DOE-supported Atmospheric Radiation Measurement (ARM) Continual Intercomparison of Radiation Codes (CIRC; *Oreopoulos and Mlawer*, 2010) in collaboration with Dr. Lazaros Oreopoulos. This program has the objective of providing a continuously updated framework for evaluating radiation models with an emphasis on using observations to define the cases examined. The AER broadband models were run for the Phase I profiles, which include five clear sky cases and two cloudy sky cases, most with aerosols. An additional set of cases was defined, with the intent of clarifying the interpretation of the original set of profiles. All cases were completed with the AER models, and the results submitted to the CIRC program. Figure 6 shows a comparison of TOA upward longwave flux and surface downward longwave flux among the AER models and ARM measurements for four clear sky cases and two cloudy cases. In all cases, RRTMG longwave fluxes at the surface and the top of the atmosphere are accurate to well within one percent of the LBLRTM line-by-line calculations and within two percent of the measurements. Figure 7 shows a similar comparison for the shortwave of TOA upward flux and surface downward flux among the AER broadband codes, the multiple scattering model CHARTS and ARM measurements for the same cases in Figure 6. Shortwave fluxes modeled by RRTMG for these cases are also very close to the high-resolution model results, and they are within about two percent of the observations in the cloudy cases.

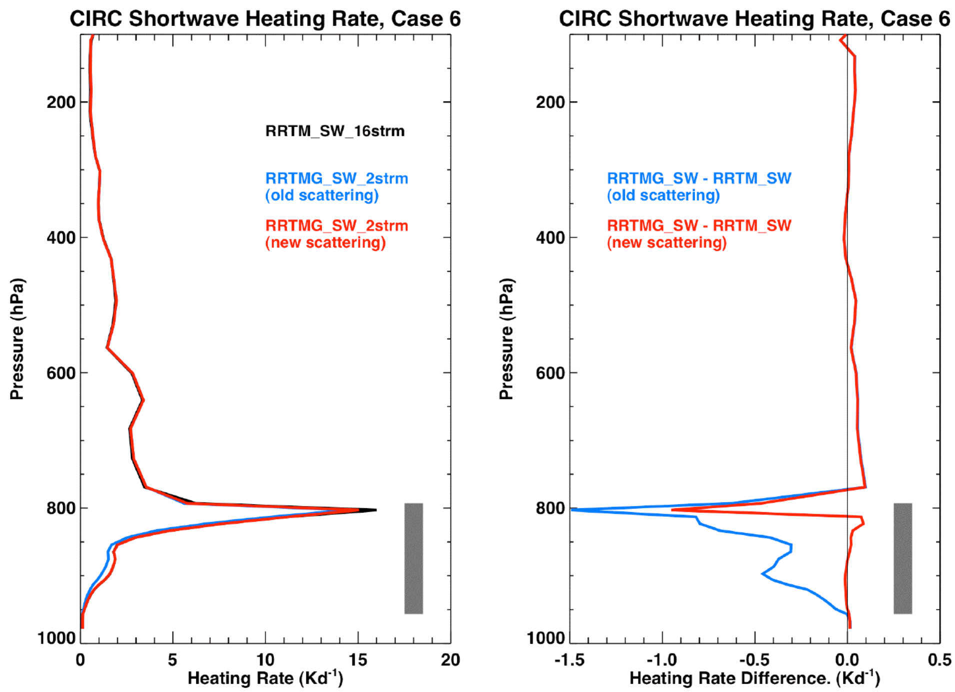

Figure 8. Shortwave heating rate for CIRC case 6 as calculated by RRTM_SW (black), RRTMG_SW (with original scattering, blue) and RRTMG_SW (with fixed scattering, red). Differences between each RRTMG result and RRTM are plotted at right. The gray bar at lower right in each plot marks the continuous block of cloudy layers in this case.

While RRTMG is now a rigorously tested and evaluated model, minor sources of inaccuracy remain that relate to cloud scattering and radiative heating that will be addressed in future research. One issue was identified during analysis of single-column CIRC calculations. Shortwave heating rate within the multi-layer, highly scattering cloud in case 6 as calculated by RRTMG_SW was originally significantly in error relative to RRTM_SW. Figure 8 illustrates the calculated heating rate profiles and model-to-model differences for this case. The result for the unmodified scattering in the RRTMG_SW 2-stream algorithm is shown in blue in Figure 8. This figure also illustrates the effect of a relatively minor adjustment to the original scattering method that ultimately eliminated much of this discrepancy (red). However, for this highly scattering cloud case, a large, unexplained heating rate difference (of 5-7 percent) remains within the top layer of the cloud after this change (Figure 8, right panel, red curve). It is very probable that this cloud radiative heating error is symptomatic of the limitation of 2-stream approximations in general, and it is likely present to some degree in all shortwave radiation codes used in dynamical models that employ a 2-stream radiative transfer solver. Resolution of this error will be of particular importance to cloud heating near the top of deep tropical convection. One possible resolution of this issue is the application of a 4-stream solver, which has been shown to reduce this bias significantly, though the additional computational expense of this solution may be impractical in GCM applications.

4.3 Radiative Transfer Model Intercomparison Project (RTMIP)

AER's long collaboration with NCAR to implement RRTMG into the CAM climate model prompted an extension of the original RTMIP model intercomparison (*Collins et al.*, 2006) to include the AER radiative transfer models and to establish the accuracy of RRTMG (*Iacono et al.*, 2008). These single-column, clear sky calculations of radiative forcing for various changes in the long-lived greenhouse gases demonstrated that in both the longwave and shortwave this radiation model retains a higher level of accuracy relative to line-by-line radiation models in most situations than the GCM radiative transfer codes examined by *Collins et al.* (2006). This is especially true at the surface, which *Collins et al.* (2006) identified as the level at which the largest discrepancies occur between the GCM radiative transfer codes and line-by-line models. Table 1 lists the surface longwave net flux radiative forcing for four of the RTMIP cases as calculated by the AER line-by-line reference model LBLRTM (v11.1) and the broadband models RRTM_LW (v3.2) and RRTMG_LW (v4.4). The mean forcing and standard deviation in each case for all of the IPCC GCM radiation models analyzed by *Collins et al.* (2006) are also shown to illustrate the improved result provided by the AER broadband models. Table 1 also lists the details of the greenhouse gas changes associated with each of the four cases. In general, the AER models are in good agreement, and notable differences are apparent from the mean IPCC GCM calculation. A similar comparison of surface shortwave net flux radiative forcing among the AER multiple scattering model CHARTS (v4.03), the broadband models RRTM_SW (v2.7) and RRTMG_SW (v3.5) and the IPCC GCM radiation models from *Collins et al.* (2006)

		Surface Longwave Radiative Forcing (Wm^{-2})			
Models	Field	2 x CO_2	GHGs 1860→2000	CH_4 & CFCs 1860→2000	1.2 x H_2O
AER*	F_{LBLRTM}	1.68	1.10	0.48	11.55
AER*	F_{RRTM_LW}	1.73	1.00	0.39	11.55
AER*	F_{RRTMG_LW}	1.79	1.05	0.42	11.92
IPCC+	$\langle F_{GCM} \rangle$	1.12	1.21	0.74	11.95
IPCC+	$\sigma (F_{GCM})$	0.39	0.38	0.28	0.75

Case	CO_2 (ppmv)	CH_4 (ppbv)	N_2O (ppbv)	CFC-11 (pptv)	CFC-12 (pptv)	H_2O
2 x CO_2	287 → 574	---	---	---	---	---
GHGs 1860→2000	287 → 369	806 → 1760	275 → 316	0 → 267	0 → 535	---
CH_4 & CFCs 1860→2000	---	806 → 1760	---	0 → 267	0 → 535	---
1.2 x H_2O	---	---	---	---	---	1.0 → 1.2

Table 1. Surface longwave radiative forcing (top) for four RTMIP cases as calculated with the AER models LBLRTM, RRTM_LW and RRTMG_LW by *Iacono et al.* (2008) and the mean forcing and standard deviation of the IPCC GCM longwave models analyzed by *Collins et al.* (2006). The details of the greenhouse gases changes associated with each case are shown at bottom.

		Surface Shortwave Radiative Forcing (Wm^{-2})			
Models	Field	2 x CO_2	GHGs 1860→2000	CH_4 & CFCs 1860→2000	1.2 x H_2O
AER*	F_{CHARTS}	-0.95	-0.87	-0.54	-6.24
AER*	F_{RRTM_SW}	-0.59	-0.54	-0.33	-6.19
AER*	F_{RRTMG_SW}	-0.57	-0.53	-0.32	-6.14
IPCC⁺	$\langle F_{GCM} \rangle$	-1.47	-0.49	0.00	-4.89
IPCC⁺	$\sigma (F_{GCM})$	1.40	0.46	0.00	0.98

Table 2. Surface shortwave radiative forcing (top) for four RTMIP cases as calculated with the AER models CHARTS, RRTM_SW and RRTMG_SW by Iacono et al. (2008) and the mean forcing and standard deviation of the IPCC GCM shortwave models analyzed by Collins et al. (2006). The details of the greenhouse gases changes associated with each case are shown in Table 1.

for four RTMIP cases is shown in Table 2. There are larger differences among the AER models than in the longwave, through these are generally smaller than differences between the CHARTS result and the mean IPCC model forcing. It should be noted that the IPCC GCM radiation models examined by *Collins et al.* (2006) do not include the effects of methane in the shortwave, while this gas is included in the AER models. This omission accounts for a roughly 0.5 Wm^{-2} error in surface radiative forcing in the IPCC climate models.

Comparisons have also been completed in collaboration with NCAR between RRTMG and the CAM4 radiation model for the RTMIP cases. Figure 9 shows the 200 hPa and surface longwave radiative forcing difference (relative to LBLRTM) for each of the cases defined by *Collins et al.* (2006) for calculations using these two radiation codes. In most of cases, the RRTMG error is substantially smaller than the CAM4 radiation. A notable exception occurs at 200 hPa in the cases for which methane is increased in which the RRTMG error is similar to or larger than the CAM result. This is due to a known algorithmic deficiency in RRTM_LW and RRTMG_LW that affects methane, and a correction for this bias is being investigated. A similar comparison of CAM and RRTMG in the shortwave (relative to CHARTS) is shown in Figure 10. As seen in the longwave, RRTMG_SW provides a smaller radiative forcing error in most cases than CAM, with significant improvement seen at the surface.

Heating rate profiles are also affected by changes in long-lived greenhouse gases through the impact on the net flux divergence. For example, doubling the concentration of carbon dioxide increases absorption of upwelling longwave radiation and reduces the upward longwave flux at the tropopause by about 4 Wm^{-2}. Emission of downward longwave radiation increases by as much as 4 Wm^{-2} in the middle troposphere and by about 2 Wm^{-2} at the tropopause and surface.

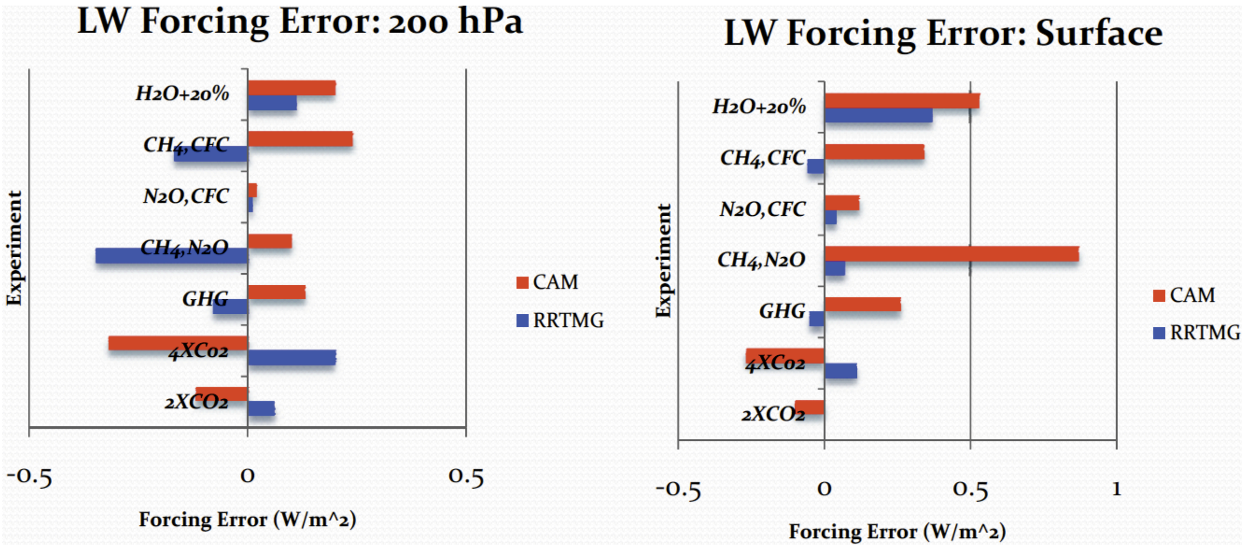

Figure 9. Bar chart of clear sky longwave radiative forcing errors for the CAM radiation (red) and RRTMG_LW (blue) relative to LBLRTM at 200 hPa (left) and the surface (right) for the seven RTMIP cases of *Collins et al.* (2006) and *Iacono et al.* (2008). Plot courtesy of A. Conley (NCAR).

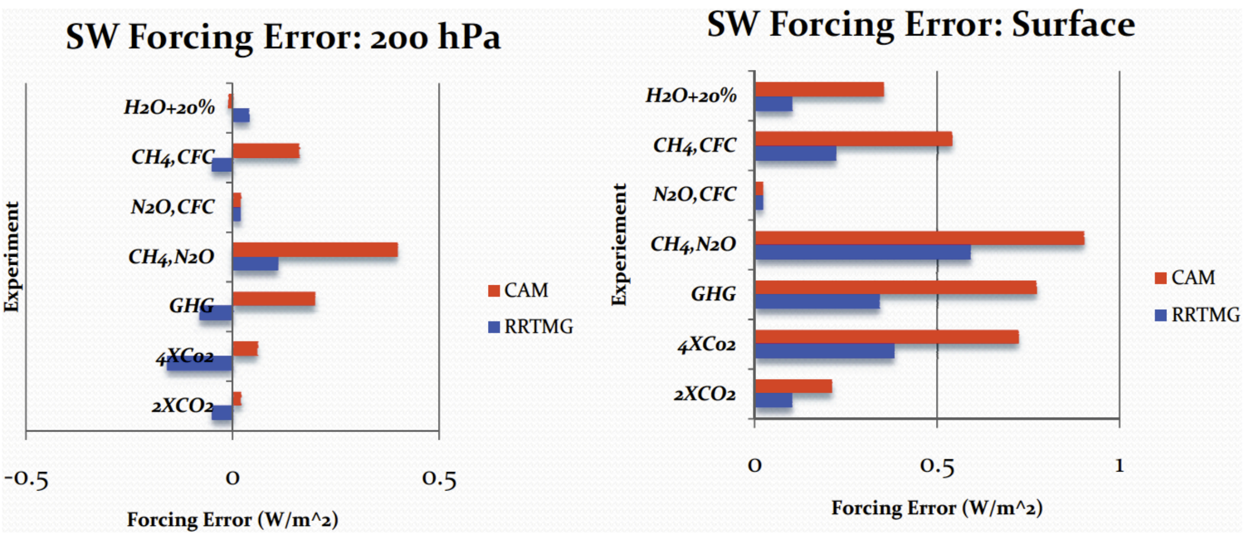

Figure 10. Bar chart of clear sky shortwave radiative forcing errors for the CAM radiation (red) and RRTMG_SW (blue) relative to CHARTS at 200 hPa (left) and the surface (right) for the seven RTMIP cases of Collins et al. (2006) and Iacono et al. (2008). Plot courtesy of A. Conley (NCAR).

This results in a decrease in net flux divergence in the lower troposphere and an increase in longwave radiative heating of up to 0.1 Kd^{-1} at these levels. The change in the longwave heating rate profile from doubling the CO_2 concentration from its 1860 amount is shown in the left panels of Figure 11 for the AER line-by-line and broadband radiation models. Results are shown from the surface to 0.1 hPa in the upper panels and from the troposphere up to 100 hPa in the lower panels. In the stratosphere, the net flux divergence is increased, which results in a substantial reduction in longwave heating (enhancement in longwave cooling) at the 1 hPa level.

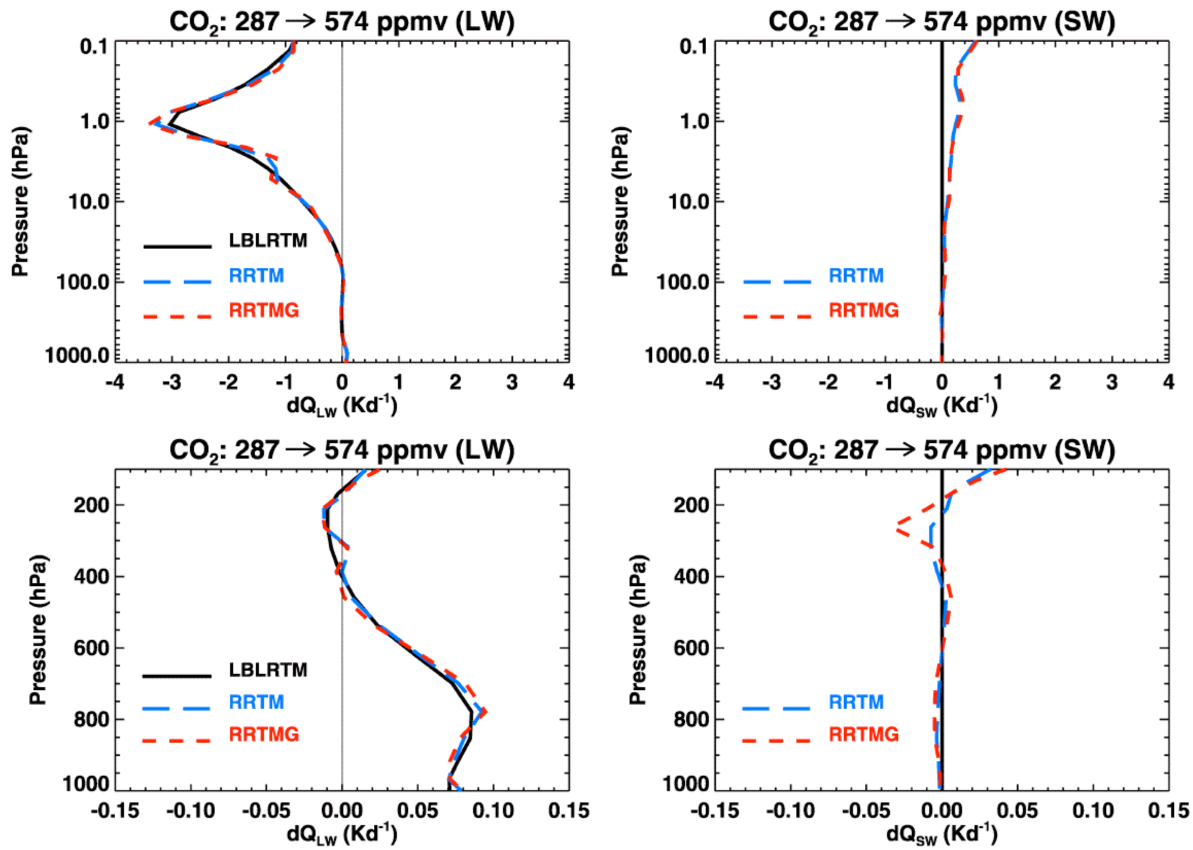

Figure 11. Heating rate profile differences from doubling the CO_2 concentration from 287 to 574 ppmv using the standard mid-latitude summer profile for the longwave (left) and shortwave (right) as calculated by the AER radiation models.

In general, the AER broadband models very closely reproduce the changes in heating rate calculated by LBLRTM throughout the column. The largest departures of about 10 percent occur at and just below the stratospheric peak in longwave cooling. Changes in the shortwave heating profile for the doubled CO_2 forcing case are shown in the right panels of Figure 11 for the two AER broadband models only. Shortwave heating rate calculations with CHARTS for the full profile were not performed due to the excessive computational effort required. RRTMG and RRTM generate very similar results with the exception of differences of a few hundredths Kd^{-1} just below the tropopause and near the 1 hPa peak in stratospheric heating. The ability of the AER broadband models to reproduce the line-by-line forcing in radiative heating throughout most of the column is noticeably better than the C06 GCM radiation models. As shown in Figure 10 of *Collins et al.* (2006), the GCM models studied in RTMIP generate results that vary considerably with some closely reproducing the line-by-line profile of heating rate perturbations while others oscillate around it by as much as 0.1 Kd^{-1}. Similar conclusions can be drawn from the other RTMIP cases.

Perturbations in the heating rate profiles from increasing each of the long-lived greenhouse gas concentrations from their 1860 to 2000 values as calculated by the AER models are shown in Figure 12. Once again, the broadband models closely reproduce the change in heating calculated by LBLRTM in the longwave (left panels) through most of the vertical regime. Notable deviations include a roughly 10 percent overestimate of the increase in longwave cooling at the 1 hPa level by the broadband models and small differences of 0.01 Kd^{-1} or less in the troposphere. In the shortwave (right panels of Figure 12), the broadband models produce nearly identical changes in heating throughout the profile with the largest difference of 0.01 Kd^{-1} occurring just below the tropopause. Accurately simulating the radiative forcing due to changes in greenhouse gases is a critical test of the ability of a radiative transfer model to perform effectively within a global climate model. The RTMIP comparisons clearly illustrate the consistency of the AER radiation codes, their accuracy relative to other widely used models, and their suitability for an extensive range of research and climate change applications.

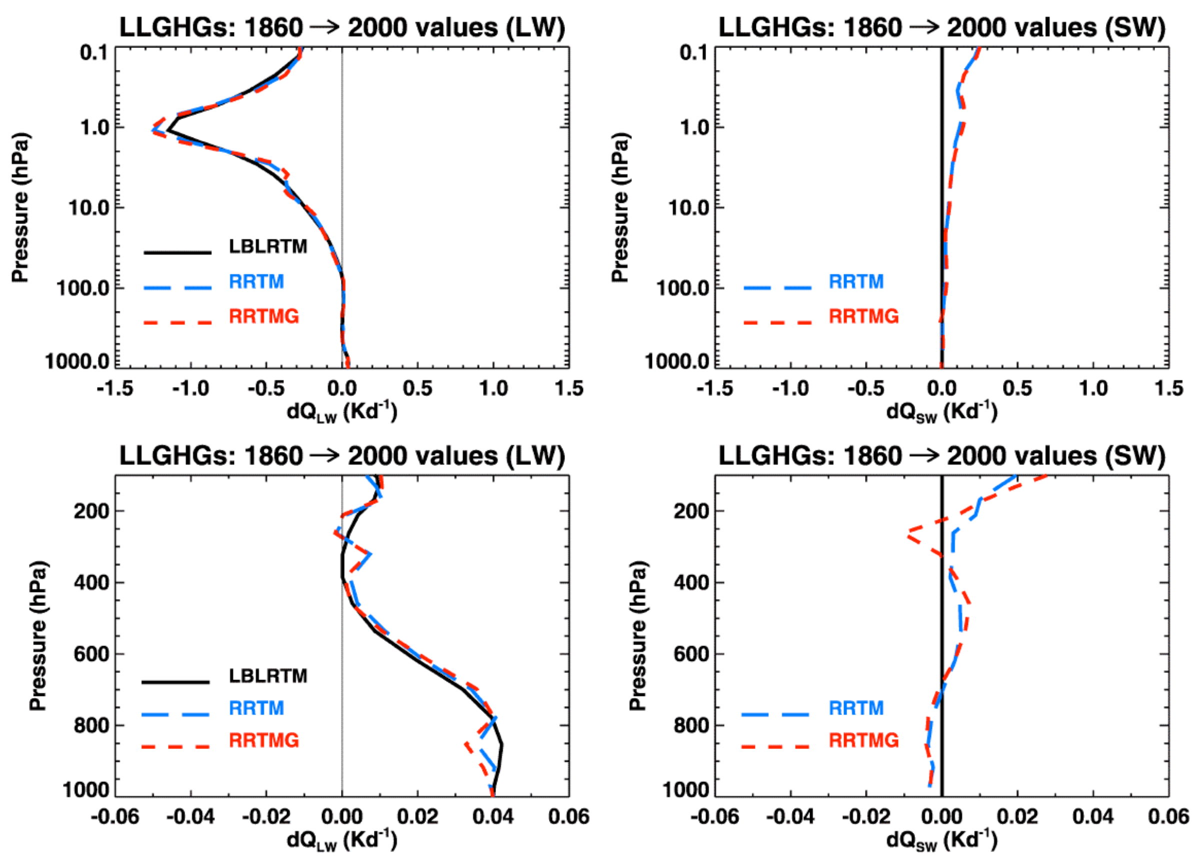

Figure 12. Heating rate profile differences from increasing the concentrations of CO_2, CH_4, N_2O, CFC-11 and CFC-12 from 1860 to 2000 values using the standard mid-latitude summer profile for the longwave (left) and shortwave (right) as calculated by the AER radiation models.

5. RRTMG Global Model Applications

This section summarizes some of the numerous collaborations between AER and dynamical modeling centers around the world that have resulted from the radiation model development activities during this project and from our efforts with these groups to implement improved radiative transfer in global models. These interactions have been mutually beneficial in that they have provided essential feedback for further improving the radiation code, and an important consequence of this research has been the gradual increase in recognition by the GCM community of the value and impact of data-validated radiative transfer. Table 3 lists the major operational and experimental RRTMG global and regional model applications as of Spring 2011.

DOE-supported Radiation for Global Models: RRTMG Applications

Global General Circulation Models	**Operational Status**
ECMWF Integrated Forecasting System (IFS, ERA)	Using LW and SW
NCEP Global and Climate Forecast System (GFS, CFS, CFSR)	Using LW and SW
NCAR Community Earth System Model (CAM5, CESM1)	Using LW and SW
Max Plank Institute climate model (ECHAM)	Using LW and testing SW
NASA GSFC/GMAO global model (GEOS-5)	Testing LW and SW
NOAA GFDL climate model (AM2)	Testing LW and SW
CMA Global/Regional Assimilation and Prediction System	Testing LW and SW
LMD CNRS climate model (LMDZ)	Using LW
JAMSTEC atmospheric GCM for Earth Simulator (AFES)	Testing LW and SW
Mesoscale/Regional Models	
NCAR Weather Research and Forecasting model (WRF/ARW)	Using LW and SW
NCEP Rapid Update Cycle forecast model (RUC)	Using LW
Penn State/NCAR Mesoscale Model (MM5)	Using LW
Meteo-France mesoscale atmospheric model	Using LW
University of Athens Limited Area Forecast Model	Using LW and SW

Table 3. List of operational and experimental RRTMG applications in global and regional models.

5.1 ECMWF

Our collaboration with ECMWF concerning radiation improvement has continued for nearly twenty years, and operational use of RRTMG_LW at ECMWF, the first dynamical modeling center to take this step, began more than a decade ago (*Morcrette et al.*, 2001). Their application of the shortwave RRTMG began in 2007 with its inclusion in their operational TL799/L91 Integrated Forecast System (IFS) weather forecast model. This forecast system was also utilized to generate the ERA-40 reanalysis (*Uppala et al.*, 2005) as well as the ongoing ERA-Interim reanalysis. The radiation code has been extensively modified by Dr. Jean-Jacques Morcrette to optimize its performance on the ECMWF computer systems, but the basic physics remain the same. In addition, ECMWF has independently implemented the McICA technique within RRTMG. Simulations with this new configuration show remarkable improvement in a number of radiative and dynamical fields due to the application of RRTMG/McICA (*Morcrette et al.,* 2008; *Morcrette,* 2007). Specifically, significant improvement is seen in surface and top of the atmosphere fluxes and cloud forcing in both the longwave and shortwave regions with the new configuration. Figure 13 shows the modeled top of the atmosphere longwave cloud forcing for the operational ECMWF model prior to the adoption of RRTMG_SW and McICA (top left panel), the revised model with the new radiation (top right panel), the CERES measurement

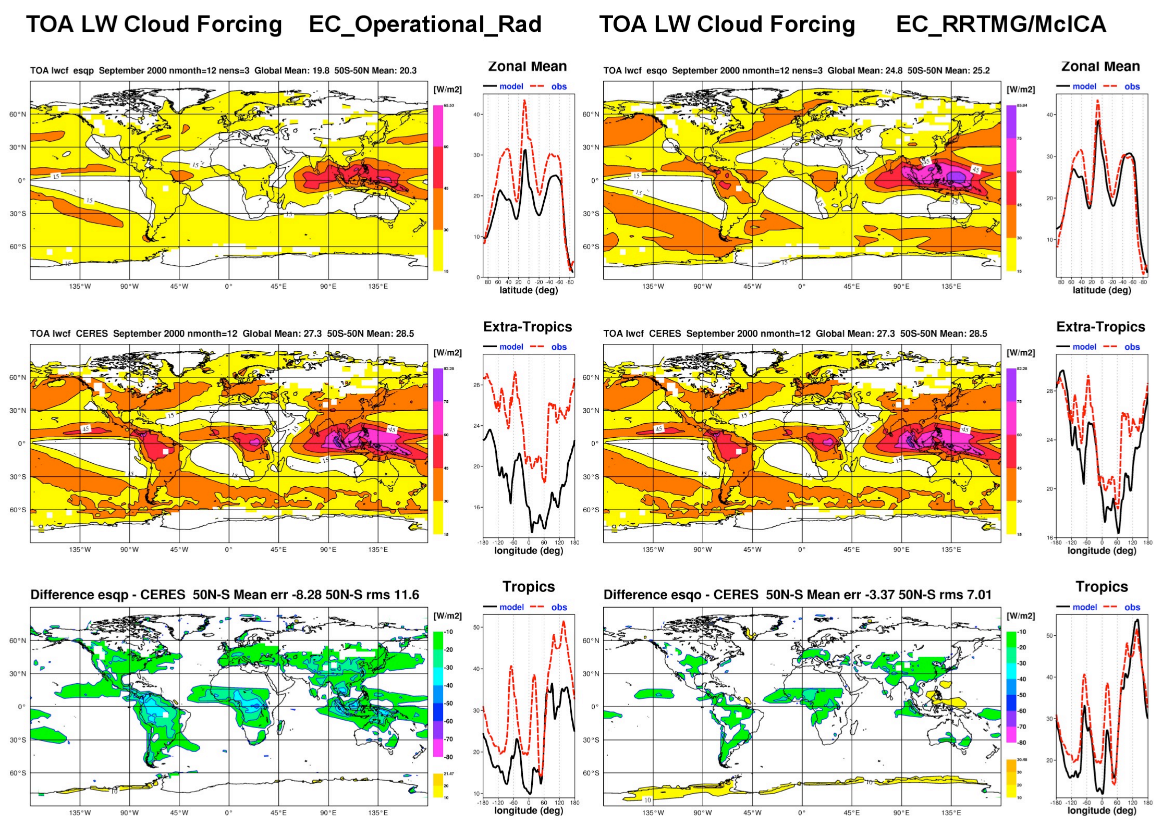

Figure 13. Comparison of longwave cloud forcing modeled by two versions of the ECMWF forecast model and CERES measurements averaged for one year ending in September 2000. LW cloud forcing is shown for the operational EC model (top left contour panel) the EC model with RRTMG/McICA (top right contour panel), the CERES measurement (center contour panels) and the model to observed differences (bottom panels). Also shown are zonal mean and longitudinal line plots averaged over the tropics and extra-tropics for each model and the observed values (*Morcrette et al.,* 2008). All units are Wm^{-2}.

(center panels), and the model to measurement differences (bottom panels) averaged over a full year starting in September 2000. Zonal means and longitudinal values averaged over the tropics and extra-tropics also show improvement as illustrated by the line plots in Figure 13.

Timing comparisons show that the entire ECMWF forecast model runs about 14% slower with the new radiation, mostly due to RRTMG_SW. Although ECMWF considers this to be within the limit of acceptable additional expense in the context of future improvements in hardware performance, further reductions in the timing of RRTMG_SW would be clearly advantageous in this regard, especially in the context of the experimental multi-year simulations currently being performed with the ECMWF model. This is one of several factors motivating future plans to investigate ways to improve the computational efficiency of RRTMG further, either by introducing new methods to optimize and reduce the selection of integration points or by utilizing new hardware technologies (i.e. GPUs) to enhance parallel processing.

5.2 NCEP GFS/CFS

Interaction between AER the National Centers for Environmental Prediction (NCEP) to improve radiative transfer in the major national weather forecast models run by NCEP began in the late 1990s. Since that time, significant progress has been made to integrate RRTMG into several NCEP forecast models. The Global Forecast System (GFS) first began using RRTMG_LW for operational forecasts on 28 August 2003, and use of RRTMG_SW began within GFS on 27 July 2010. The Climate Forecast System (CFS), which is based on GFS but adapted for longer simulations (*Saha et al.*, 2006), first began using RRTMG_LW in 2004 and the shortwave model during 2010. The recently generated Climate Forecast System Reanalysis (CFSR; *Saha et al.*, 2010) is a new, coupled global reanalysis covering the last three decades that also utilizes the RRTMG radiation within the atmospheric model. Radiation is called at one-hour intervals and a maximum-random cloud overlap approach is used for cloudy radiative transfer. At present McICA is not being used with RRTMG in any of these NCEP models, though application of this feature is planned in the future. In addition, the Rapid Update Cycle (RUC) forecast model used for short-range (18-hour) forecasts began operational use of RRTMG_LW in November 2008 after tests showed that this change provided a significant improvement in the warm surface temperature bias in this model (G. Manikin, personal communication, 2008).

Simulations completed at NCEP with the GFS and CFS models have shown benefits from the new radiation code. Particular improvement was found in the significant upper stratospheric cold bias in the operational GFS, which was shown in single column tests to be reduced by RRTMG_SW (*Iacono et al.*, 2004). In addition, results from a 60-year simulation with RRTMG in the CFS model show a noticeable reduction in sea surface temperature anomalies relative to the operational CFS. Figure 14 shows 56-year (1951-2006) mean sea surface temperatures from the Coupled Data Assimilation System (CDAS), which is close to the observed surface temperature field, and SST differences between the two versions of CFS and CDAS. The lower panel in Figure 14 shows the reduced surface temperature anomalies, especially in the lower latitudes, that are apparent in the simulation that utilized RRTMG. Improvement was also found in the variability of tropical ocean temperatures in the eastern Pacific Ocean.

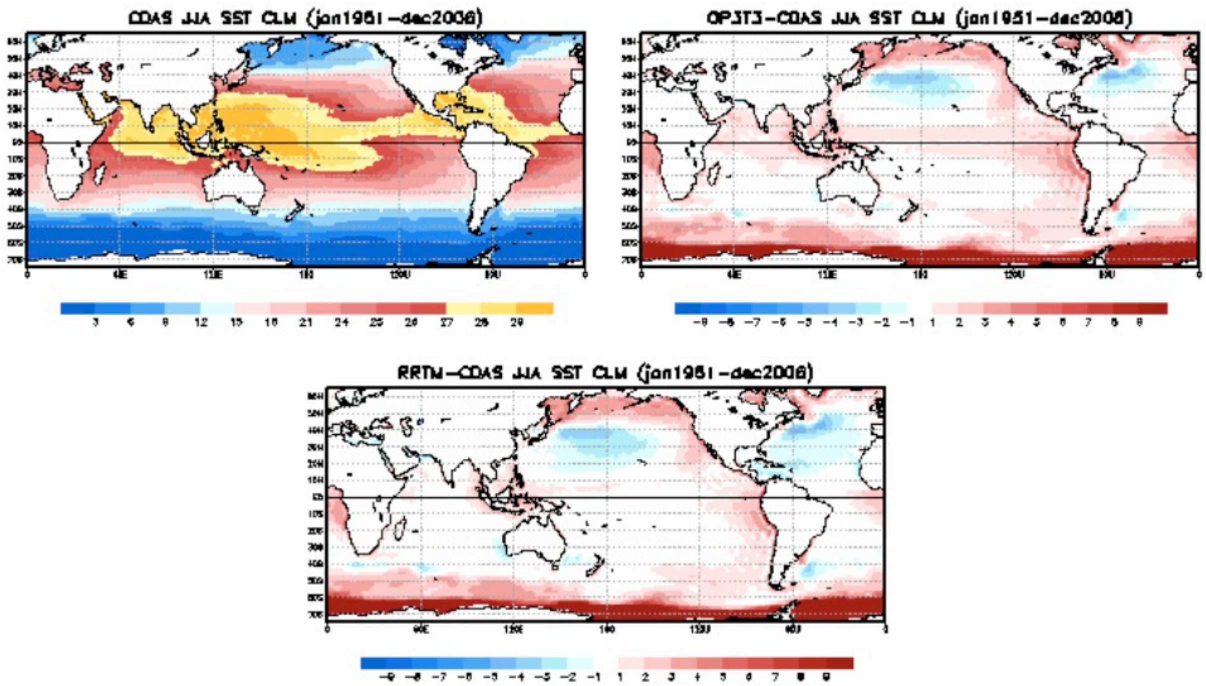

Figure 14. Fifty-six year (1951-2006) mean sea surface temperature for June-July-August (top left) from the NCEP coupled data analysis system (CDAS) and differences between two NCEP/CFS simulations of SST and CDAS for the operational CFS model (top right panel) and for the CFS model running with RRTMG_SW. Units are in K. Plot courtesy of Y.-T. Hou (NCEP).

5.3 NCAR CAM/CESM

Our more than 15-year collaboration with the NCAR Atmospheric Model Working Group to transfer DOE-supported radiation improvements (*Iacono et al.,* 2008; *Iacono et al.*, 2003; *Iacono et al.*, 2000) into the CAM climate model has successfully accomplished this objective. Both CAM5 (*Neale et al.*, 2010) and the CESM1 (Community Earth System Model, formerly CCSM) coupled climate model, which include the RRTMG radiation code, were publically released in June 2010. This achievement was made possible by the dedicated work and close interaction of many scientists at AER and NCAR over the years to address all concerns related to the development and testing of the radiation code in the NCAR models. Journal articles are in preparation for a future special issue of the *Journal of Climate* on CESM1 that will describe both the climate of the new atmospheric model (*Rasch et al.*, 2011) and the impact of the new radiation (*Conley et al.*, 2011). A related research activity has resulted in the recent publication of a collaborative paper describing climate model calculations for the AERONET program (*Quaas et al.*, 2009). One of the many experiments for this project was performed with a developmental version of CAM that included RRTMG. An additional collaborative publication is in progress with Dr. Steve Ghan and others who have developed the new modal aerosol model that has also been adopted as a component of CAM5 to provide improved treatment of the indirect effects of aerosols (*Liu et al.*, 2011).

RRTMG has been integrated into CAM5 and CESM1 along with numerous other physics changes that all affect the climate to some degree. However, simulations performed for this research with CAM3.5 and the new radiation have demonstrated its independent impact on climate simulations. Figure 15 shows vertical cross sections of zonal mean temperature difference between the CAM3.5 climate model and observations using the original CAM radiation (left panel) and RRTMG (right panel) averaged over a multi-year climatological sea-surface temperature simulation. Immediately apparent in Figure 15 is the improvement in temperature relative to observations in the lower layers in the northern high latitudes and in the stratosphere at low and middle latitudes. The upper tropospheric cold bias at high latitude is not improved by RRTMG, and the cause of this feature is apparently unrelated to radiative transfer.

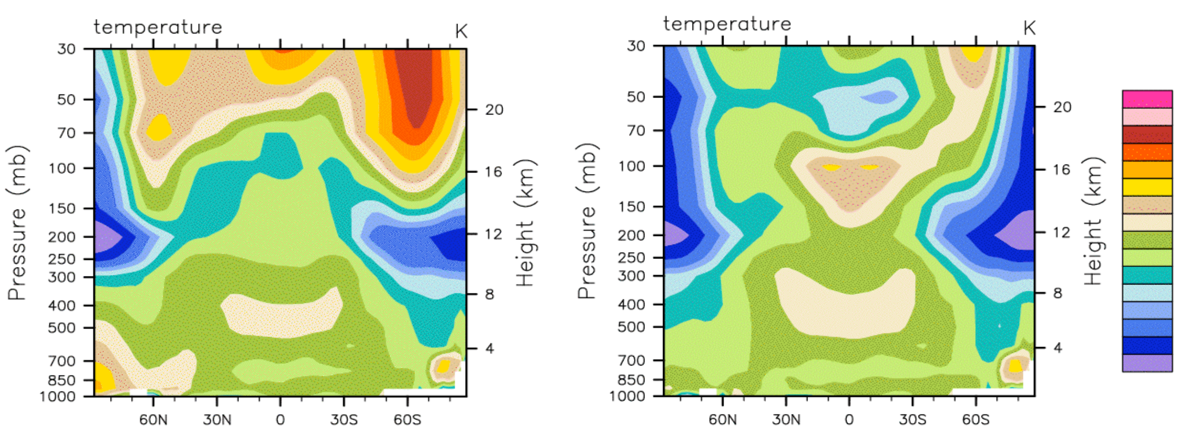

Figure 15. Vertical cross sections of zonal mean temperature difference between the CAM3.5 climate model and observations using the CAM radiation (left) and RRTMG (right). Units are in K.

5.4 NCAR WRF

Another major accomplishment of this project was realized in April 2009 with the public release of v3.1 of the Advanced Research WRF (ARW) model (*Skamarock et al.*, 2008) with RRTMG included as new longwave and shortwave radiation options. WRF, which is maintained at NCAR, is one of the premier national weather forecast models and is in extensive use for research and forecasting around the country. The integration of the new radiation model into WRF was completed at AER for this project during 2008. During the course of this activity the WRF subroutine that calculates cloud fraction for input to the radiation model was also modified to fix an existing condition in which the cloud fraction was being computed incorrectly for several microphysics options. We continue to work closely with Dr. Jimy Dudhia and others at NCAR to implement new features or fixes to the radiation model as they become available. This has recently included an effort to improve the atmospheric specification above the WRF top model layer by adding additional layers up to the top of the atmosphere for the radiative transfer calculations. This has been shown to have a positive effect on the simulation of heating rates in the stratosphere (J. Dudhia, personal communication, 2011).

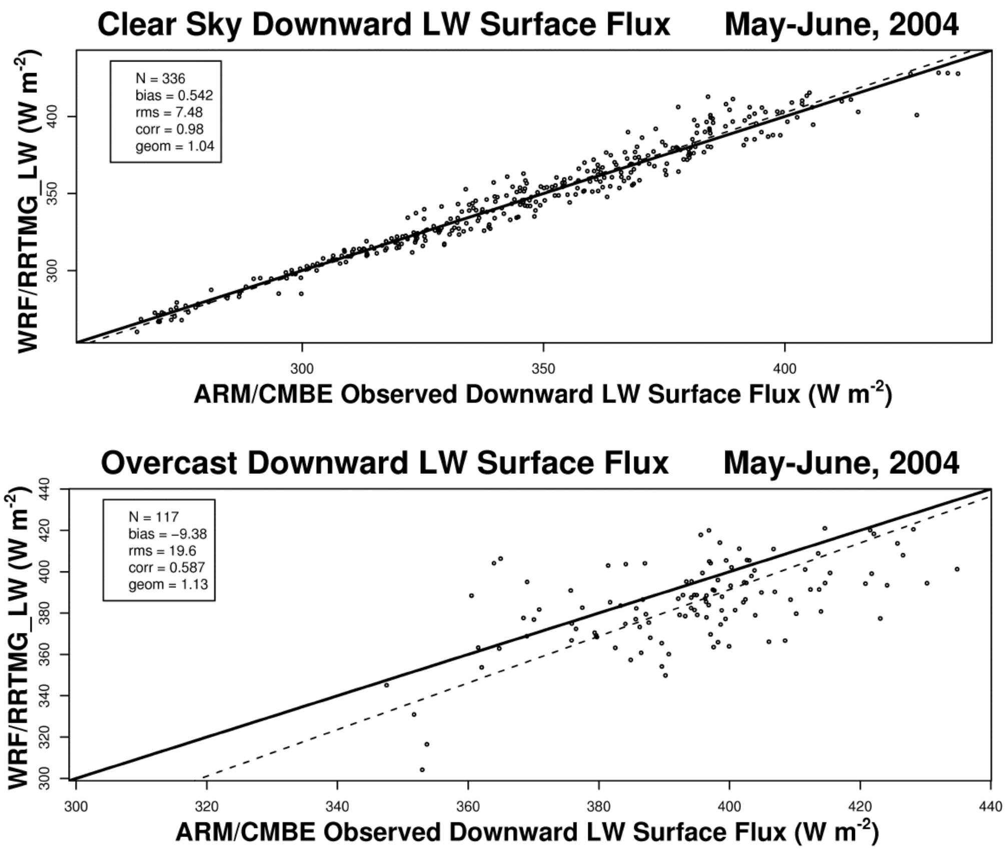

Figure 16. Scatter plots of downward longwave surface flux at the ARM/SGP site for May-June 2004 as modeled by WRF with RRTMG_LW plotted as a function of the ARM/CMBE measurement when both had clear sky (top) and when both had overcast sky (bottom).

For this research, experiments were performed with WRF which suggest that cloud fraction in the model is significantly deficient relative to measurements in some circumstances whether examined regionally or locally (*Iacono et al.*, 2009). Figure 16 shows a scatter plot of hourly downward longwave surface flux at the DOE ARM Sothern Great Plains (SGP) site over the period from May to June 2004 as simulated by WRF with RRTMG_LW. Data are plotted as a function of the ARM Climate Modeling Best Estimate (CMBE; *Xie et al.,* 2010) measurements for intervals when both model and observation were clear (top panel). The excellent agreement in clear sky is immediately apparent with a bias of about 0.5 Wm^{-2} between model and measurement. The bottom panel in Figure 16 shows the comparable scatter plot when both model and observation were overcast. For overcast conditions a much larger negative bias of about 10 Wm^{-2} is present with the modeled downward fluxes generally being smaller than observed, which suggests that clouds either have different vertical structure or are less strongly emitting in the model. Deficiencies in WRF cloud cover are also apparent from a regional perspective. Figure 17 shows a snapshot of the maximum cloud fraction in any layer modeled by WRF for a grid area (marked with the black box) over the eastern United States at 00 UTC on 25 January 2000 (left panel) and the observed mean cloud fraction from ISCCP (International Satellite Cloud Climatology Project) for the same time (right panel).

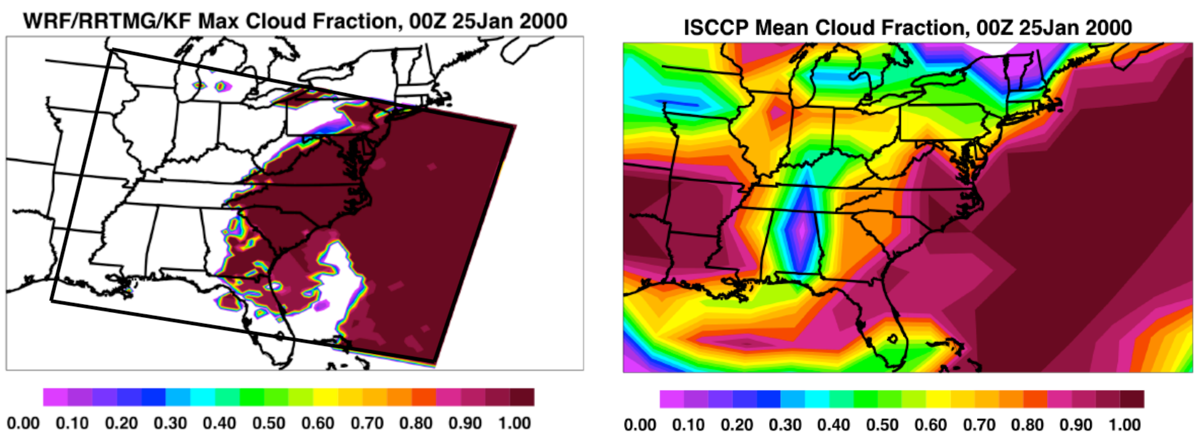

Figure 17. Maximum cloud fraction in any layer as simulated by WRF (left) and mean cloud fraction as measured by ISCCP (right) at 00 UTC 25 Jan 2000. Note that the model grid area (black box, left panel) is smaller than the geographic area shown in each plot.

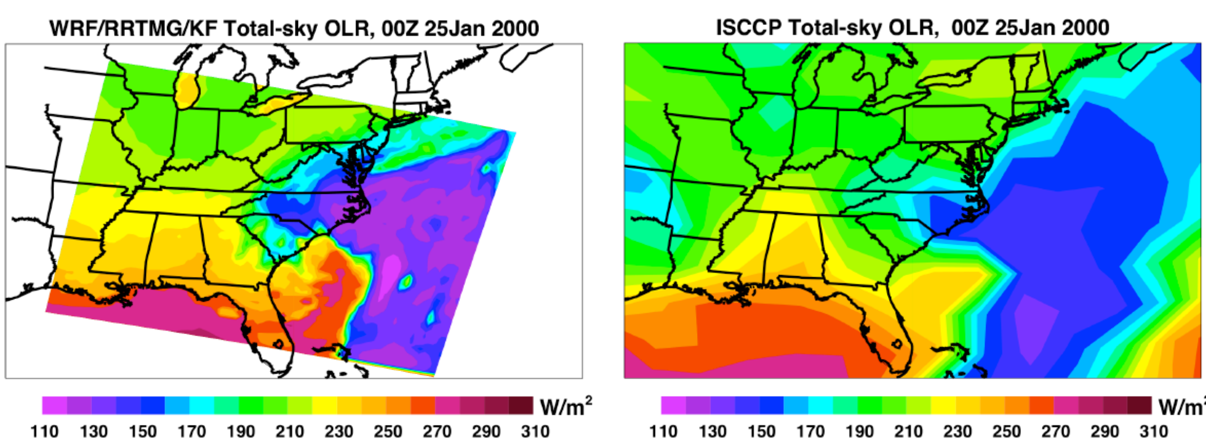

Figure 18. Total sky outgoing longwave radiation as simulated by WRF (left) and as measured by ISCCP (right) at 00 UTC 25 Jan 2000. The model grid area (LEFT) is smaller than the geographic area shown in each plot.

While the model simulates fairly well the maximum cloud cover associated with a storm off the coast of the southeastern United States, it reproduces essentially none of the cloudiness that appears in the ISCCP data from the Appalachians westward to the Mississippi River valley. The absence of cloud cover in the model over this area has a significant impact on the outgoing longwave radiation (OLR) for this time period as shown in Figure 18. Due to the deficient cloud cover, the WRF OLR is too high (by roughly 10-20 W m^{-2}) relative to ISCCP OLR west of the Appalachians. However, over the mid-Atlantic coast of the United States and over the western Atlantic the modeled OLR is too low relative to ISCCP, which suggests that the model is generating too much cloud absorption in this area. The southern Great Lakes also appear warm (higher OLR) in WRF relative to the surrounding land areas and ISCCP due to the absence of modeled clouds. A notable area of OLR agreement in Figure 18 occurs over Alabama and central Tennessee, where ISCCP shows the lowest cloud cover (10-20%) over the WRF model grid area and the OLR is essentially unaffected by clouds.

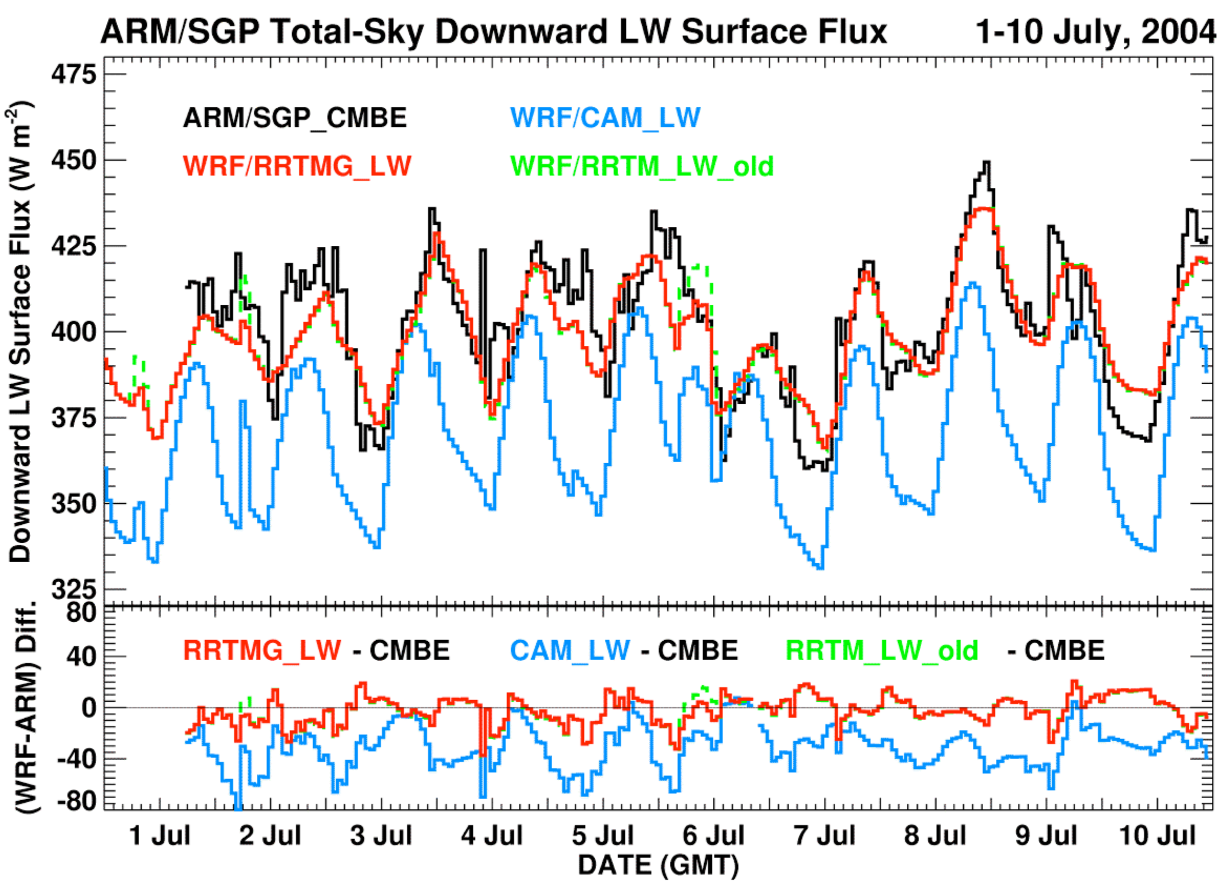

Figure 19. Ten-day WRF forecasts using different longwave radiation options and ARM/CMBE observations of hourly total-sky downward longwave surface flux (top) and difference between model and measurement (bottom) for 1-10 July 2004 at the ARM Southern Great Plains (SGP) site.

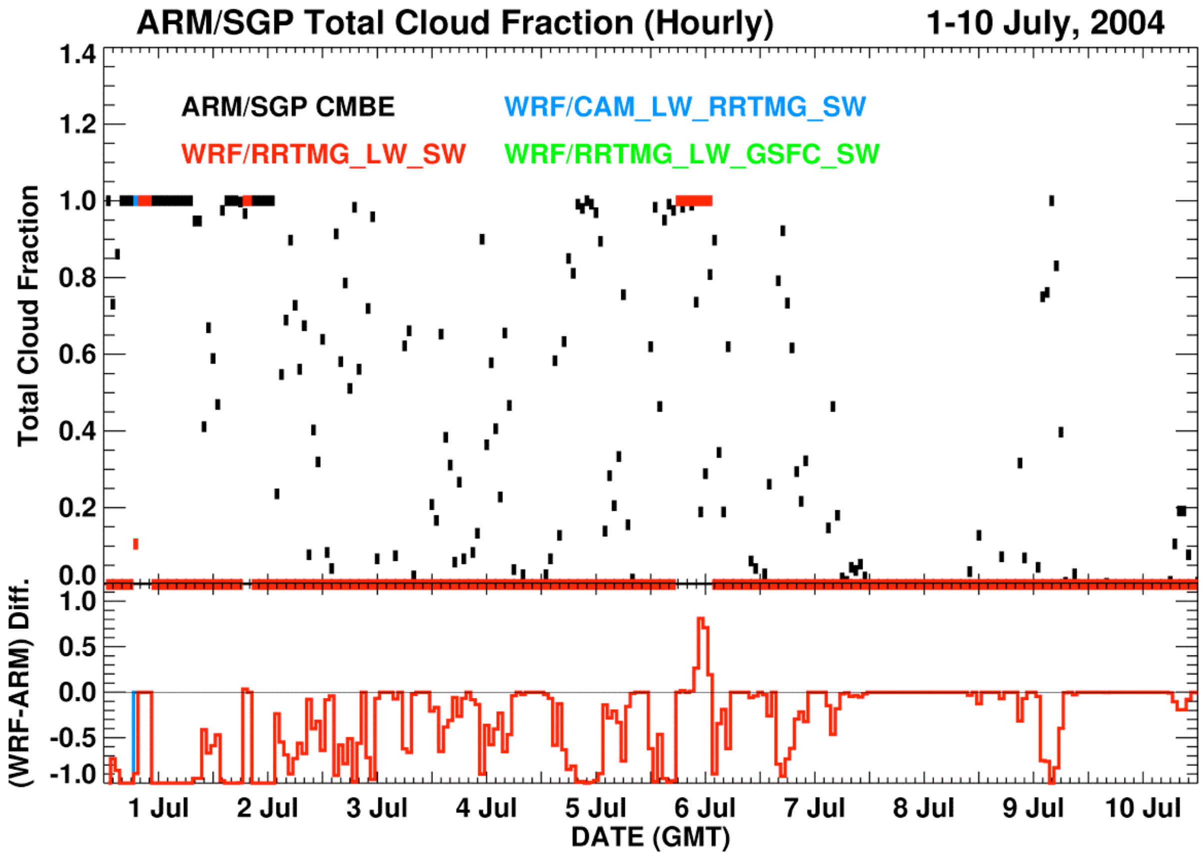

Figure 20. Ten-day WRF forecasts using different radiation options and ARM/CMBE observations of hourly total cloud fraction (top) and difference between model and measurement (bottom) for 1-10 July 2004 at the ARM Southern Great Plains (SGP) site.

This research has also examined the impact of the improved radiation in WRF simulations (*Iacono and Nehrkorn*, 2010; *Iacono et al.*, 2009). Multi-day forecast experiments utilized the ARM CMBE measurements to evaluate model output over the SGP site. Initial sensitivity tests related to the temporal frequency of the radiation in multi-day weather forecasts have shown only small flux differences for intervals between 10 minutes and one hour, with some degradation in surface flux apparent for intervals of two hours or longer. Additional experiments were performed to intercompare the radiation options in WRF. Figure 19 shows total sky, hourly downward longwave surface flux at SGP from CMBE measurements (in black) and as modeled by WRF using three longwave models, RRTMG_LW (in red), CAM_LW (in blue) and an older version of RRTM_LW (in green) for a ten-day period from 1-10 July 2004. Model to measurement differences are shown in the bottom panel in Figure 19. While at first glance the AER models provide a better result, the accuracy of the atmospheric specification that is input into the radiation must also be established. For example, Figure 20 compares the observed, hourly total cloud fraction for the same time period in Figure 19 with the hourly maximum cloud fraction calculated by WRF with various combinations of radiation models. Over this location and time period, all of the modeled cloud fractions are substantially deficient relative the observations regardless of the radiation option, and this will impact to some degree the comparison of downward longwave fluxes in Figure 19. In light of these results, a comprehensive assessment of the simulation of cloudiness in WRF is an essential task of critical interest for future research, since these experiments have demonstrated deficiencies in WRF cloudiness that will certainly have a substantial impact on the accuracy of cloudy radiative fluxes and heating rates and on the effectiveness of regional weather and climate simulations.

5.5 NASA/GSFC

An important collaboration was initiated during 2009 with Dr. Max Suarez and Dr. Lazaros Oreopoulus of the NASA Goddard Space Flight Center, which has the objective of incorporating and testing RRTMG within the GSFC Goddard Earth Observing System (GEOS-5) global model and data assimilation system. With support from AER, NASA has successfully integrated the new radiation, including the McICA feature, into the GEOS-5 model. In support of this activity, an optional new feature was added to RRTMG_LW that was requested by GSFC to maintain one aspect of their present radiation capability. This feature provides the vertical profile of the change in upward flux with respect to surface temperature. Controlled by a new input flag, this feature will output dF/dT for total sky and clear sky as a pair of new output arrays. These can be utilized to approximate the change in upward flux for a change in surface temperature only and to derive approximate changes in layer heating rate at time intervals between full radiation calls. It is suggested that this feature be used in a GCM with some caution, since large changes to only the surface temperature and emission while leaving the atmosphere unchanged will alter the flux divergence and heating in the near surface layers to a degree that may disrupt a GCM simulation. However, under conditions of small surface temperature changes over the period between full radiation calls, this feature can efficiently provide a reasonable approximation to longwave fluxes and heating rates at intervening intervals. Finally, the PI presented an invited seminar at GSFC in May 2010 on the improvement of radiative transfer in weather and climate models in support of our continuing interaction with NASA. As of Spring 2011, GSFC continues to evaluate RRTMG with the objective of applying it operationally in GEOS-5 in the near future.

5.6 Other Applications

The Max Planck Institute (MPI) has recently initiated an effort to upgrade both the longwave and shortwave radiative transfer in the ECHAM climate model to the latest versions of RRTMG (Bjorn Stevens, personal communication, 2010). The MPI climate model has used a version of the AER broadband longwave radiation for nearly a decade that was acquired from ECMWF (*Wild and Roeckner*, 2006). Since the version at ECMWF does not contain some of the latest enhancements, MPI will integrate and adapt as necessary (with AER support) the latest release versions of the AER radiation. This effort is being made with the intention of completing the changes in time to apply the new radiation in the pending ECHAM climate simulations for the next Intergovernmental Panel on Climate Change (IPCC) assessment report.

An ongoing activity at NASA GSFC has utilized RRTMG_LW to generate outgoing longwave radiation (OLR) from retrieved Atmospheric Infrared Sounder (AIRS) atmospheric properties (J. Susskind, personal communication, 2010). Preliminary calculations have shown that RRTMG_LW eliminates much of the 9 Wm^{-2} global, annual mean bias in all-sky OLR between the AIRS Version 5 product and outgoing longwave radiation observed by the Clouds and Earth's Radiant Energy System (CERES) instrument produced by the previous radiative transfer algorithm (*Susskind et al.*, 2010). As a result of this improvement, NASA will process the AIRS Version 6 global OLR product using the RRTMG longwave radiation model. This provides a new context in which the DOE-supported radiative transfer advancements developed for this research will continue to benefit the simulation and analysis of Earth's climate.

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