Chapter 15

Contributions of the ARM Program to Radiative Transfer Modeling for Climate and Weather Applications

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1. Introduction

Accurate climate and weather simulations must account for all relevant physical processes and their complex interactions. Each of these atmospheric, ocean, and land processes must be considered on an appropriate spatial and temporal scale, which leads these simulations to require a substantial computational burden. One especially critical physical process is the flow of solar and thermal radiant energy through the atmosphere, which controls planetary heating and cooling and drives the large-scale dynamics that moves energy from the tropics toward the poles. Radiation calculations are therefore essential for climate and weather simulations, but are themselves quite complex even without considering the effects of variable and inhomogeneous clouds. Clear-sky radiative transfer calculations have to account for thousands of absorption lines due to water vapor, carbon dioxide, and other gases, which are irregularly distributed across the spectrum and have shapes dependent on pressure and temperature. The line-by-line (LBL) codes that treat these details have a far greater computational cost than can be afforded by global models. Therefore, the crucial requirement for accurate radiation calculations in climate and weather prediction models must be satisfied by fast solar and thermal radiation parameterizations with a high level of accuracy that has been demonstrated through extensive comparisons with LBL codes.

The calculation of a vertical profile of radiative fluxes and heating rates for each spatial grid cell and time step in a global model involves computations of

- absorption and scattering properties of the gases, clouds, and aerosols present in the cell at that time, but in a parameterized form that circumvents the consideration of the full complexity of the physics;
- values related to sources of solar and thermal radiation;
- solution of the radiative transfer equation for each subelement of the parameterization;

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- and finally integrating the solutions for these subelements to obtain spectrally broadband fluxes and heating rates.

Numerous simplifications and approximations are typically made in these parameterizations, such as assuming that each grid cell is homogeneous and plane parallel (i.e., not dependent on clouds in neighboring cells and ignoring planetary curvature). This complexity makes it difficult to build a parameterization that is both fast and accurate enough to be useful.

The challenge of improving radiative transfer calculations in climate simulations was a central motivation for the establishment of the Atmospheric Radiation Measurement (ARM) Program and, consequently, one of the most critical objectives of the program's first decade. In Stokes and Schwartz (1994, p. 1203), the primary objectives of the ARM Program are 1) "to relate observed radiative fluxes in the atmosphere, spectrally resolved … to the atmospheric temperature, composition … and surface radiative properties" and 2) "to develop and test parameterizations that describe atmospheric water vapor, clouds, and the surface properties governing atmospheric radiation … with the objective of incorporating these parameterizations into general circulation and related models." The second of these objectives depends on the first. Confidence that a computationally fast radiative transfer parameterization used for climate simulations accounts accurately for the radiative effects associated with all relevant atmospheric conditions must spring from confidence that we have a detailed understanding of these radiative processes. This, in turn, necessitates a rigorous evaluation of our ability to compute spectrally resolved radiative fluxes for this range of conditions. Accomplishments in the ARM Program led to substantial advances with respect to both objectives. Mlawer and Turner (2016, chapter 14) address the program's accomplishments with regard to the observation and modeling of spectrally resolved radiation, while this chapter details achievements related to the modeling of radiative processes for climate and weather applications.

The results of the Intercomparison of Radiation Codes in Climate Models (ICRCCM) effort (Ellingson and Fouquart 1991) provided important motivation for the objectives of the ARM Program (Ellingson et al. 2016, chapter 1). ICRCCM was directed at understanding and evaluating the differences between radiative transfer models, both spectrally resolved (i.e., LBL) and fast parameterizations for climate applications. The longwave (LW) intercomparisons (Ellingson et al. 1991) determined that the uncertainties in spectroscopic parameters prevented any LBL model from being considered a reference, but progress was noted
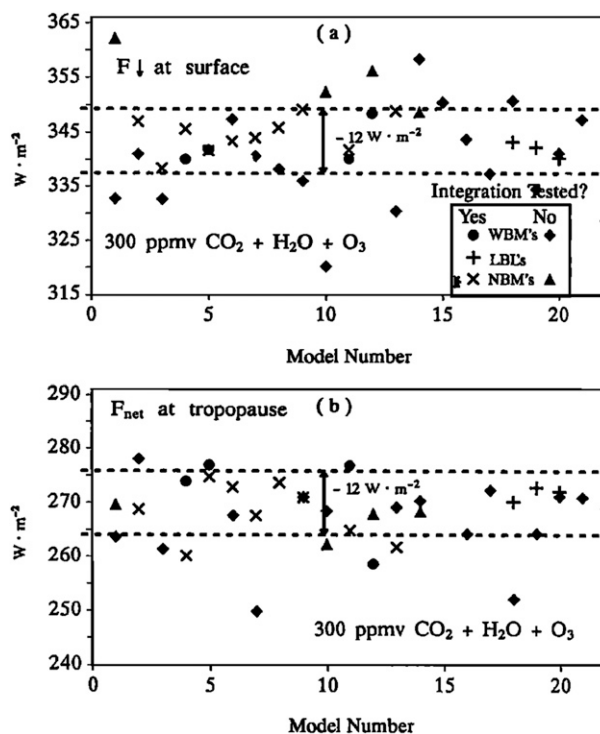

FIG. 15-1. For longwave radiation codes participating in ICRCCM, calculations of (top) downwelling surface flux and (bottom) net flux at the tropopause for the midlatitude summer atmosphere (H_2O and O_3 abundances only) and 300 ppmv of CO_2. For further explanation, see caption of Fig. 15 and related discussion in Ellingson et al. (1991).

relative to previous comparisons. The conclusions from ICRCCM with respect to longwave radiation codes suitable for climate applications were sobering, with a 5%–10% rms differences from LBL results and "poorer agreement" for the sensitivity to changes in abundances of absorbing gases. Figure 15-1 (Fig. 15 from Ellingson et al. 1991) provides evidence that supports this conclusion. For an atmosphere with reasonable profiles of H_2O, CO_2, and O_3, the best-performing "band models" have their respective computed downward surface fluxes (Fig. 15-1a) and net fluxes at the tropopause (Fig. 15-1b) fall within $12 \, W \, m^{-2}$ (3.5%) of each other, and within approximately $\pm 6 \, W \, m^{-2}$ (1.7%) of reference LBL calculations. Band models that perform more poorly also can be seen in this figure. For comparison, doubling the abundance of CO_2 in the atmosphere causes a radiative forcing of $\sim 4 \, W \, m^{-2}$, while the radiative forcing by individual long-lived greenhouse gases over the last two centuries is less than $1 \, W \, m^{-2}$. Shortwave (SW) results from ICRCCM were not any better, with "a considerable spread in the responses of different codes to a set of well-defined atmospheric profiles" (Fouquart et al. 1991, p. 8955). The SW ICRCCM study concluded

that errors in the solar radiation calculations of these band models were greater than those required for accurate climate simulations.

The dual issues of LBL model uncertainties and broadband model errors led to major ARM initiatives in the early years of the program. Shepard (Tony) Clough of Atmospheric and Environmental Research (AER) was a key figure in many of the program's accomplishments that helped resolve these issues. His 1990 research proposal to ARM resolved to attack on both fronts, proposing "to provide a highly accurate RT model for scattering and nonscattering atmospheres, to use calculations from this model for the parameterization required for GCM RT codes ... and to validate this code against measurements and calculations from the high accuracy model for a wide range of atmospheric regimes." This research program led to the establishment of AER's Line-By-Line Radiative Transfer Model (LBLRTM; Clough et al. 1992) as "a highly accurate RT model" through extensive validation with high-quality measurements of spectrally resolved radiation, which is detailed in Mlawer and Turner (2016, chapter 14). With this result, Clough was able to confidently undertake the crucial goal of developing a new, fast radiation code that effectively reproduced the flux and cooling rate calculations of LBLRTM, thereby ensuring that the calculations of this parameterized code would be directly traceable to ARM spectral radiation measurements. Developed from ARM funding and using ARM measurements, this fast radiation code, RRTM for GCM applications (RRTMG; Mlawer et al. 1997; Iacono et al. 2000), which was subsequently incorporated in numerous climate and weather prediction models throughout the world, represents a major triumph for the program.

Section 2 of this chapter discusses the development of RRTMG and its implementation in various general circulation models (GCMs), most notably the Integrated Forecast System of the European Centre for Medium-Range Weather Forecasts and the Community Earth System Model (CESM1) of the National Center for Atmospheric Research. Although the core of RRTMG is its stored tables of gaseous absorption coefficients and algorithms that operate on these coefficients, the application of this code (and other fast RT codes) to climate or weather problems also must consider cloudy conditions. As a result, the ARM Program also has given rise to major accomplishments in cloudy-sky radiative transfer within GCMs. This includes a development of the ice optical property parameterization (Mitchell 2002) integrated in RRTMG for use in CESM1. ARM support also led to the Monte Carlo Independent Column Approximation (McICA; Pincus et al. 2003; Barker et al. 2008), a method to treat subgrid-scale variability in cloud

properties, including the variability introduced by cloud vertical correlations (overlap). Both these accomplishments relevant to cloudy-sky RT in GCMs are discussed in section 3 of this chapter. In addition, sections 3 and 4 detail initiatives supported by ARM that extended and updated previous RT code intercomparisons, the ICRCCM-III effort (Barker et al. 2003), and the Continual Intercomparison of Radiation Codes (Oreopoulos and Mlawer 2010; Oreopoulos et al. 2012).

2. Development of RRTMG

The development of RRTMG progressed in two steps. First, a fast radiation code was built with the general goal of achieving accuracy effectively equivalent to state-of-the-art LBL models with respect to the impact on climate simulations. Ad hoc but ambitious accuracy targets of $1 \, \text{W m}^{-2}$ for net flux at all altitudes and $0.1 \, \text{K day}^{-1}$ for tropospheric hearting rate were adopted; there were no known studies that established that this level of accuracy would have an undetectable effect on simulations. The name of the code that was developed was motivated by the phrase Rapid Radiative Transfer Model (its formal name is simply RRTM). This code serves as a reference fast radiation code for scientific applications and further development, but it is not fast enough for use in GCMs. The second step was to increase the computational efficiency of RRTM without significantly degrading its accuracy, thereby enabling the use of this accelerated version, RRTMG, in GCMs (both codes are available at http://rtweb.aer.com).

a. Development of RRTM

In the years immediately preceding the development of RRTM, a number of compelling papers (e.g., Goody et al. 1989; Lacis and Oinas 1991; Fu and Liou 1992) established the capability of the correlated-k method (Ambartzumian 1936) for fast and accurate calculations of radiative fluxes and heating rates in the atmosphere, including the effects of multiple scattering. In the correlated-k method, absorption coefficients as a function of wavenumber are reordered monotonically (creating a k distribution), thereby allowing spectral elements with similar opacities to be grouped together and treated as a single monochromatic element. This technique reduces the number of needed individual radiation calculations by $\sim 10^5$ relative to LBL calculations, thereby allowing a dramatic increase in computational speed while maintaining a level of accuracy believed to be acceptable for climate and weather simulations. This combination of speed and accuracy motivated the choice of the correlated-k method for RRTM instead of other band model approaches available at the time.

One aspect of the correlated-k method that limits its accuracy is that the mapping from spectral space to a space where absorption coefficients are monotonically ordered (g space, where the ordering variable g ranges from 0 to 1) is not fixed for a given spectral region, but depends on pressure, temperature, and, importantly, atmospheric composition. Therefore, a range of g values in a k distribution at one vertical level generally does not correspond to the same spectral elements as the same g values at a different level. The k distributions stored in RRTM were computed for a range of values of pressure, temperature, and ratio of key absorbing gases and then averaged for chosen subintervals in g space. Radiative transfer calculations, with each subinterval being treated in the same manner as a single monochromatic element in an LBL calculation, are performed using these stored values despite the possible absence of correlation. This potential lack of spectral correlation is an important contributor to RRTM errors, as is the fact that the approach used to combine spectral elements with similar opacities does not necessarily preserve the average transmittance of those elements. Extensive validation (see below) has shown that this approach provides impressive accuracy. Details about RRTM's bands and their respective absorbing gases, grid of stored absorption coefficients, subintervals in g space, etc. can be found in Mlawer et al. (1997) and Mlawer and Clough (1998).

RRTM relies on a number of innovative algorithmic features to obtain this high level of accuracy. Spectral regions in which two gases have spectrally overlapping absorption bands pose an issue for correlated-k models since varying abundances of gases involved in such an overlap (e.g., H_2O) allow a wide variety of mappings from spectral space to g space. This overlapping makes it difficult for the code to store a reasonable number of absorption coefficients from which to accurately compute optical depths for all abundance combinations that might be encountered. Also, overlapping absorption bands can cause a lack of spectral correlation in g space between different levels in a vertical profile, leading to the accuracy issue discussed above. RRTM handles overlapping absorbing bands through the use of a "binary species parameter" in affected spectral regions, which varies from 0 (second species is dominant) to 1 (first species is dominant) in such a way that most abundances encountered have values of this parameter between 1/8 and 7/8, allowing accurate linear interpolation of stored coefficients. A more detailed interpolation method is performed near the extreme values of this parameter. Another feature of RRTM is that spectrally dependent values, such as the optical depths due to minor absorbing gases in a band, the Planck function in the thermal infrared spectral region, and the extraterrestrial solar
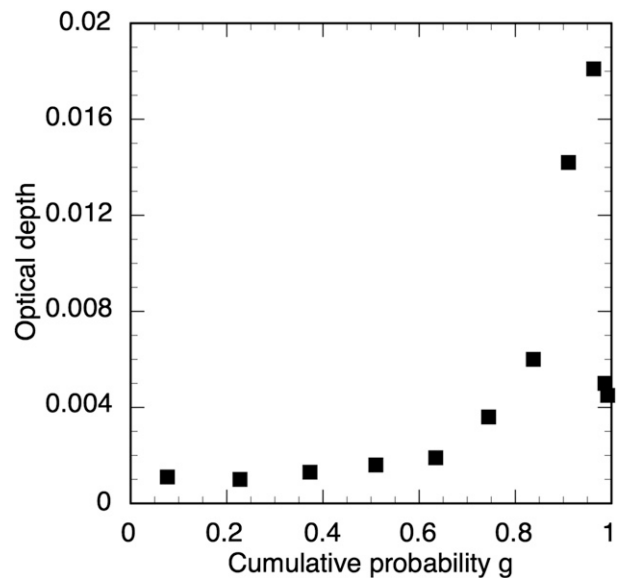

FIG. 15-2. For a layer in the midlatitude summer atmosphere profile and the spectral range 980–1080 cm^{-1}, optical depths were obtained by applying the mapping from spectral space to g space that defines the layer's k distribution (for all absorbing gases) to the optical depths for this layer due to the minor absorbing gas CO_2. The results shown were then averaged over the subintervals in g space used in RRTM. The optical depths are not monotonic with respect to g. The use of this approach in the code ensures a reasonable spectral correspondence between the optical depths from major and minor absorbing species in a band, while allowing an accurate calculation when the abundance of each species is independently varied (from Mlawer et al. 1997).

irradiance in the shortwave, are handled in a manner that respects their respective correlations with the major absorbing gases. This approach, which is implemented by applying the mapping from spectral space to g space that defines the k distribution to other spectrally dependent quantities (for a subset of the parameters for which the main absorption coefficients are stored), allows greater consistency with monochromatic radiative transfer. Figure 15-2 provides an example of this approach.

Liquid cloud optical properties derived from the Hu and Stamnes (1993) parameterization were implemented in RRTM, as were several parameterizations of ice cloud optical properties, most notably Fu (1996) and Fu et al. (1998). A user can also specify band-by-band cloud optical properties directly. For RRTM_LW a fast maximum-random overlap algorithm (called two-layer memory) is available while the shortwave code assumes that each cloudy layer is completely overcast. Spectral variability of aerosol optical depths is handled in RRTM_SW by a generalized Ångström relation (Molineaux et al. 1998), with aerosol scattering properties allowed to vary with spectral band. Great care was taken to validate the radiative effect of aerosols computed by the code with respect

to LBL calculations for a range of aerosol properties, water vapor loadings, and solar zenith angles.

Not only does RRTM obtain its stored absorption coefficients from LBLRTM, but it also has been extensively validated with respect to flux and heating rate calculations performed with LBLRTM. Therefore, the performance of RRTM is traceable directly to the numerous validations of LBLRTM that have been performed with high-quality spectrally resolved measurements, including those detailed in Mlawer and Turner (2016, chapter 14). Mlawer et al. (1997) presented validations with respect to LBLRTM for six standard atmospheres, but this set proved to not be sufficiently broad to establish the code's accuracy for the full range of conditions encountered in global simulations. In subsequent evaluations, a suite of 42 atmospheres (Garand et al. 2001) was utilized successfully. Detailed validation statistics for RRTMG are provided in section 2b(2) below.

b. RRTMG and its application to GCMs

1) RRTM TO RRTMG

To provide a radiative transfer model that can be applied directly to GCMs with an accuracy that remains traceable to measurements, RRTM was modified to produce RRTMG (Iacono et al. 2003; Morcrette et al. 2008). The former model retains the highest accuracy relative to LBL results for single-column calculations, while the latter provides improved computational efficiency with minimal loss of accuracy for GCM applications. RRTMG shares the same basic physics and absorption coefficients as RRTM, but it incorporates several modifications that improve computational efficiency and represent subgrid-scale cloud variability. In particular, the total number of quadrature points (g points) used to calculate radiances in the longwave was reduced from the standard 256 in RRTM_LW to 140 in RRTMG_LW. For each spectral band, the particular reduction implemented was based on minimizing the impact on flux and heating rate accuracy, resulting in 2–16 g points per band. In the shortwave, the number of g points was reduced from the 224 in RRTM_SW to 112 in RRTMG_SW. In addition, the multiple-scattering code Discrete Ordinates Radiative Transfer Program for a Multi-Layered Plane-Parallel Medium (DISORT; Stamnes et al. 1988) employed by RRTM_SW was replaced with a much faster two-stream radiative transfer solver (Oreopoulos and Barker 1999) in RRTMG_SW. (RRTMG does not include the effects of scattering in the LW.) The complexity of representing fractional cloudiness in the presence of multiple scattering was eventually addressed in RRTMG_LW and SW with the addition of McICA (Barker et al. 2002;

Pincus et al. 2003), which is a statistical technique for representing subgrid-scale cloud variability including cloud overlap. This method is described in detail in section 3b(2).

2) RRTMG VALIDATION

A critical component of applying RRTMG to atmospheric models is the validation of its accuracy. Figure 15-3 presents an analysis of RRTMG_LW accuracy relative to LBLRTM (as of 2007) for a set of 42 clear atmospheric profiles spanning a wide range of temperature and moisture values. For most cases, the accuracy of RRTMG_LW for clear-sky net flux is better than $1.5\,W\,m^{-2}$ at all levels, and heating rates agree to within $0.2\,K\,day^{-1}$ in the troposphere and $0.4\,K\,day^{-1}$ in the stratosphere. RRTMG_SW accuracy in clear sky relative to RRTM_SW is within $3\,W\,m^{-2}$ for flux at all levels, and heating rates agree to within $0.1\,K\,day^{-1}$ in the troposphere and $0.35\,K\,day^{-1}$ in the stratosphere. Motivated by interactions with the GCM community, Iacono et al. (2008) evaluated RRTMG using the methodology of the Radiative Transfer Model Intercomparison Project (RTMIP; Collins et al. 2006), which involved model calculations "forced" by increased abundances of greenhouse gases for a set of scenarios relevant to climate change. This study reasserted the overall excellent performance of RRTMG, most notably at the surface, where Collins et al. (2006) found the largest discrepancies between GCM and LBL radiative transfer codes. In all RTMIP cases except one, RRTMG longwave forcings were within a range of -0.20 to $0.23\,W\,m^{-2}$ of those calculated by LBLRTM, with more than half of the results within $0.10\,W\,m^{-2}$. In the shortwave, for all RTMIP cases except one, RRTMG shortwave forcings were within a range of -0.16 to $0.38\,W\,m^{-2}$ of the spectral multiple-scattering model Code for High-Resolution Atmospheric Radiative Transfer with Scattering (CHARTS). Since radiative forcing by individual long-lived greenhouse gases over the last two centuries is on the order of $1\,W\,m^{-2}$ or less, the results in Iacono et al. (2008) were key to establishing that RRTMG has sufficient accuracy to be used by GCMs to properly model the radiative contribution of these gases to global climate change.

It is important to view these validation results, later confirmed by the Continual Intercomparison of Radiation Codes (CIRC) intercomparison (see section 4), in the context of the overall unsatisfying results of ICRCCM that led to the birth of the ARM Program. In less than a decade, efforts performed under the program's auspices had led to the development of a fast radiation code with impressive clear-sky accuracy that was traceable to ARM high-quality spectral radiation measurements. The next

RRTMG_LW EVALUATION (42 PROFILES), 10-3250 cm⁻¹

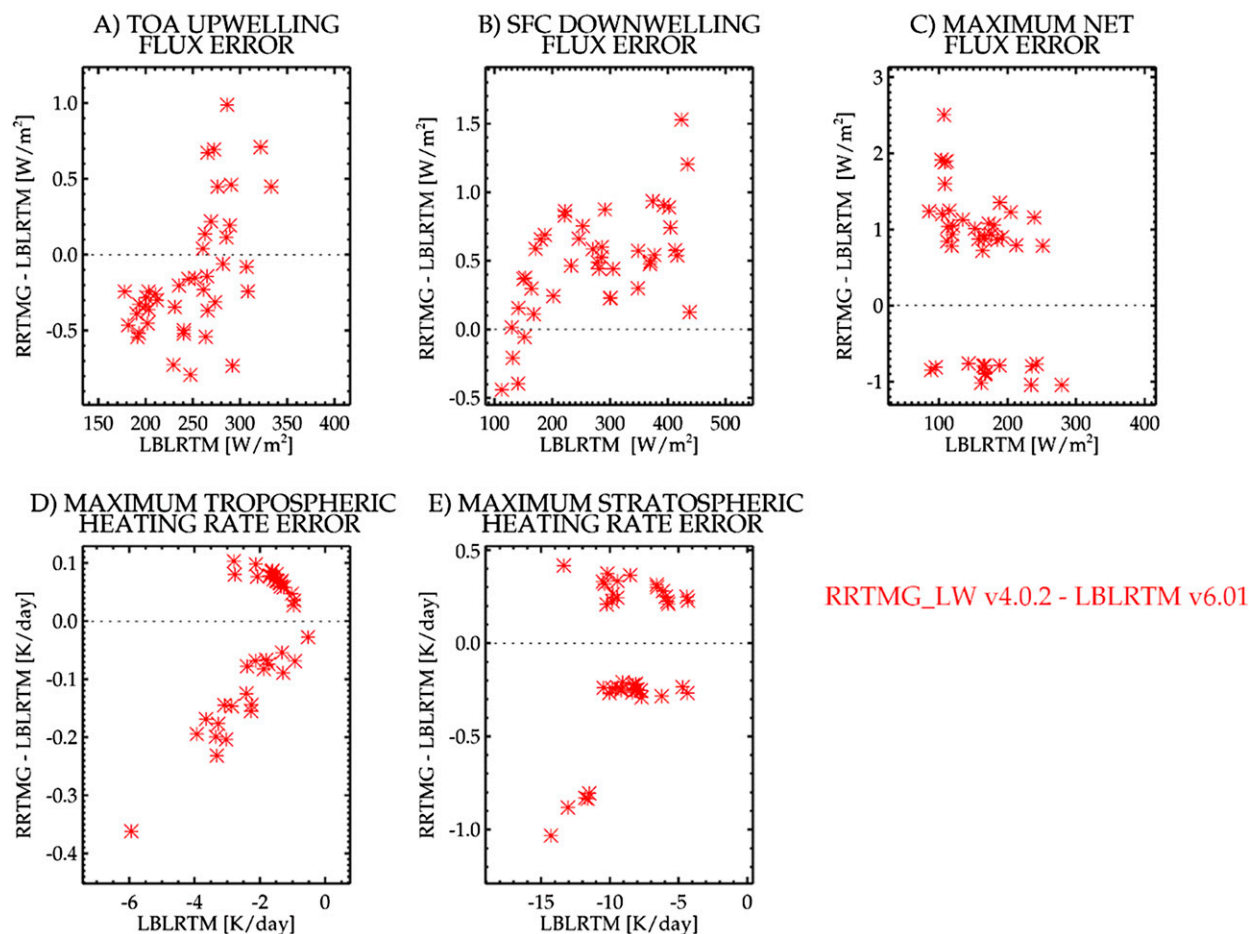

FIG. 15-3. Scatterplots of clear-sky differences between RRTMG_LW and the LBL model LBLRTM plotted as a function of the LBLRTM calculation over the 10–3250 cm⁻¹ spectral range for (a) TOA upwelling flux, (b) surface downwelling flux, (c) maximum net flux difference, (d) maximum tropospheric heating rate difference, and (e) maximum stratospheric heating rate difference. Calculations are for the 42 diverse profiles of Garand et al. (2001). Since RRTMG_LW calculations are intended to reproduce those of LBLRTM as closely as possible, the differences between the two models are referred to as "errors" in this figure.

chapter in this success story was the use of this code to advance climate and weather simulations.

3) IMPLEMENTATION IN ATMOSPHERIC MODELS

Because of its high accuracy and computational efficiency, RRTMG has been implemented in numerous national and international atmospheric models to provide validated radiative transfer for improved weather forecasts and climate change predictions. The European Centre for Medium-Range Weather Forecasts (ECMWF) became the first modeling center to make operational use of RRTMG_LW in 2000 to improve radiative processes within the Integrated Forecast System (IFS) weather forecast model (Morcrette et al. 2001). This forecast system was used to generate the ERA-40 reanalysis (Uppala

et al. 2005) as well as the ERA-Interim reanalysis. Further reduction in shortwave and cloudy-sky radiation biases was realized with the application of both RRTMG_SW and McICA in the IFS in 2007 (Morcrette et al. 2008). Simulations with this configuration showed remarkable improvement in a number of radiative and dynamical fields due to the application of RRTMG and McICA (Morcrette et al. 2008; Ahlgrimm et al. 2016, chapter 28). Particular improvement was seen in the simulation of longwave (see Fig. 15-4) and shortwave cloud radiative forcing (now usually referred to as "cloud radiative effect").

The National Centers for Environmental Prediction (NCEP) first began using RRTMG_LW in the Global Forecast System (GFS) for operational forecasts in 2003, and RRTMG_SW in 2010, though the GFS does not
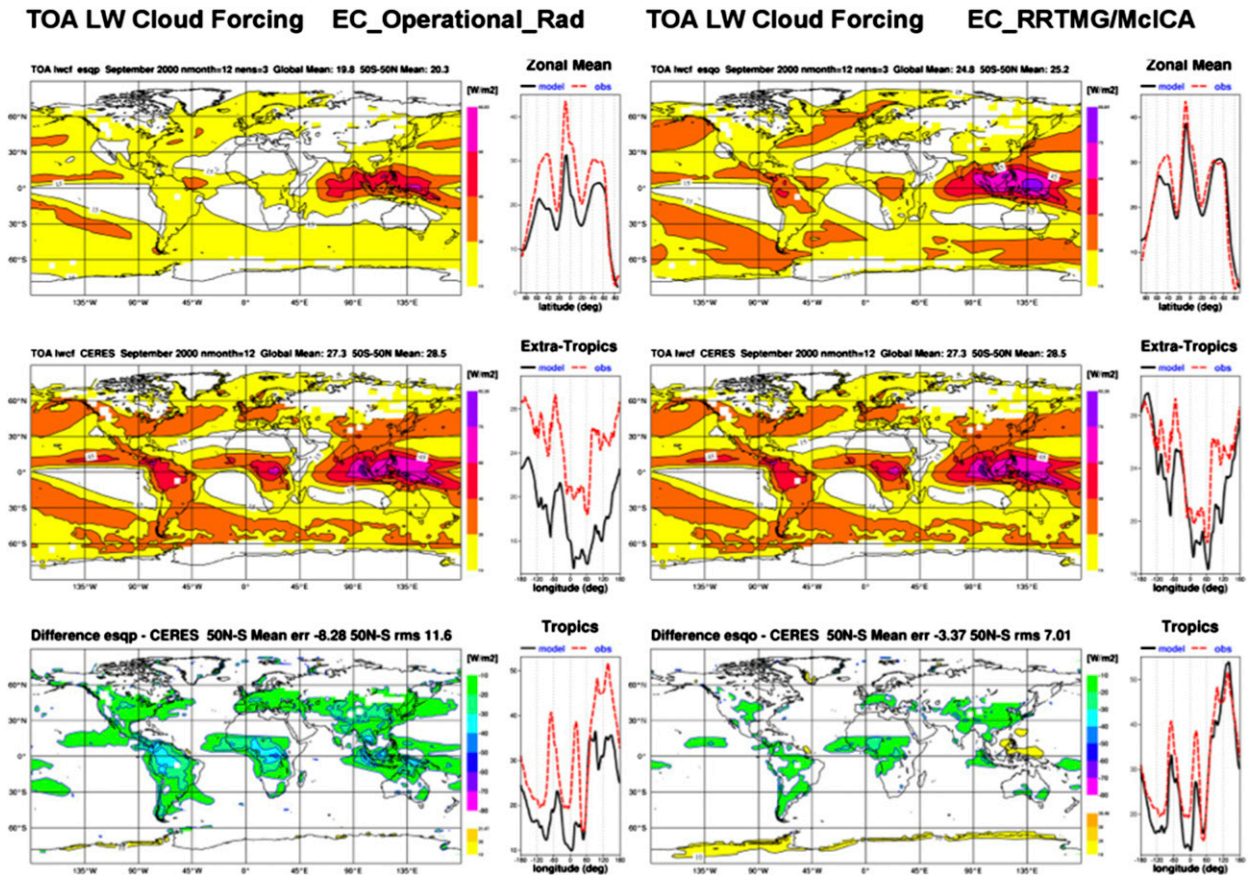
FIG. 15-4. Comparison of longwave cloud forcing modeled by two versions of the ECMWF forecast model and Clouds and the Earth's Radiant Energy System (CERES) measurements averaged for 1 year ending in September 2000. Longwave cloud forcing is shown for the (top left) operational ECMWF model, (top right) the ECMWF model with RRTMG/McICA, (center) the CERES measurement, and (bottom) the model minus observed differences. Also shown are zonal mean and longitudinal line plots averaged over the tropics and extratropics for each model (black) and the CERES observed values (red) (Morcrette et al. 2008). All units are W m^{-2}.

currently utilize McICA. The Climate Forecast System (CFS), which is based on GFS but adapted for longer simulations (Saha et al. 2006), first began using the longwave code in 2004 and the shortwave code in 2010. The recently updated CFS version 2 has implemented McICA with the latest versions of RRTMG (Saha et al. 2014). Application of the new radiation code showed particular improvement in the significant upper stratospheric cold bias in the operational GFS and a notable reduction in sea surface temperature anomalies in the CFS. NCEP's coupled global reanalysis covering the last three decades, the Climate Forecast System Reanalysis (CFSR; Saha et al. 2010) also uses RRTMG within its atmospheric component.

Experiments with the original National Center for Atmospheric Research (NCAR) Community Climate Model (CCM) suggested that this global model would benefit from improvements in radiative transfer (Iacono et al. 2000, 2003). Application of RRTMG and McICA into the NCAR Community Atmosphere Model (CAM) was realized with the public release of CAM5 in 2010

(Neale et al. 2010), now the atmospheric component of the coupled Community Earth System Model (CESM1). The radiation enhancement was accompanied by several additional major changes to the physics parameterizations in the NCAR climate model, including the treatment of cloud microphysics (see next section) and aerosols. Both the longwave and shortwave RRTMG codes are also radiation options in the NCAR-supported Advanced Research version of the Weather Research and Forecasting (WRF) Model (Skamarock et al. 2008), one of the most widely used regional weather forecast models.

Global and regional models currently utilizing RRTMG are listed in Table 15-1.

3. Advances in cloudy-sky radiative transfer

The development of RRTMG, built on the foundation of extensive validations of LBLRTM with spectral radiation measurements, resolved the major clear-sky radiative transfer issues in GCMs that were a key

TABLE 15-1. Global and regional model applications of RRTMG.

European Centre for Medium-Range Weather Forecasts (ECMWF)	Integrated Forecast System (IFS)
	ERA-40 reanalysis
Max Planck Institute (MPI)	ECHAM (ECMWF-Hamburg)
National Centers for Environmental Research (NCEP)	Global Forecast System (GFS)
	Climate Forecast System (CFS)
	Climate Forecast System Reanalysis (CFSR)
	Rapid Update Cycle (RUC)
NCAR (National Center for Atmospheric Research)	Community Atmosphere Model (CAM)
	Community Earth System Model (CESM)
	Advanced Research version of Weather Research and Forecasting Model (ARW)
National Aeronautics and Space Administration/Goddard Space Flight Center (NASA/GSFC)	Goddard Earth Observing System (GEOS)
Laboratory for Dynamical Meteorology (LMD)	LMDZ
China Meteorological Administration (CMA)	Global/Regional Assimilation and Prediction System (GRAPES)
French National Meteorological Service (Météo-France)	Nonhydrostatic Mesoscale Model (Meso-NH)

motivation for the ARM Program. This assessment rests, in part, on the representativeness of the validations to which LBLRTM and RRTMG have been subjected. In large part, the assessment also is based on a solid theoretical understanding of the propagation of radiation in a clear atmosphere, including the underlying molecular spectroscopy and observations of the homogeneity of absorbing gas abundances at GCM scales. This combination of systematic validation and theoretical understanding is conclusive in establishing the accuracy of the radiation model for all clear-sky conditions that occur in the atmosphere.

Establishing a similar level of confidence in radiative calculations in cloudy atmospheres is not nearly as straightforward. ARM-supported research has had impacts at both the scale of individual cloud particles and on the scales of cloud systems. Both scales exhibit variability that hinders radiation parameterization development and its systematic validation with radiometric observations. One focus in the program has been on methods to represent the optical properties of ice clouds, which are difficult because ice crystal shapes and sizes can vary widely. The material properties of ice (i.e., refractive indices) are well-known, but shape and habit have profound impacts on the spectral absorption and scattering of radiation that have historically been hard to generalize.

Though the single-scattering properties of spherical drops are much more certain, both liquid and ice clouds exhibit substantial horizontal and vertical variability across a wide range of scales, which undermines the use of plane-parallel, homogenous RT methods. One consequence is that it is extremely challenging to construct cloudy-sky comparisons between LBL models and spectral observations since the models cannot account for the impacts of inhomogeneity. This inability also is present in the radiation calculations in GCMs and introduced

first-order biases quantified by the ICRCCM-III project described below. ARM-funded research both highlighted this problem and eventually found a solution.

a. Development of a parameterization of ice optical properties for CAM

The optical properties of spherical liquid cloud droplets are predicted accurately by Mie theory. Prior to 1990 there was hope that Mie theory could treat the optical properties of ice clouds adequately using an equivalent area sphere approach. However, aircraft observations of the microphysical and radiative properties of cirrus clouds showed that, for a given observed downward thermal emittance from a cirrus cloud, a Mie calculation predicting this emittance also produced an albedo value that was at least a factor of 2 smaller than that was observed (Stackhouse and Stephens 1991). This discrepancy could not be explained microphysically [e.g., by adding unmeasured small ice crystals to the ice particle size distribution (PSD)], and it became apparent that new approaches were needed to treat the scattering and absorption properties of nonspherical ice particles. The ARM-funded research described in this section advanced the understanding of ice optical properties, eventually leading to a new parameterization incorporated in CAM5's implementation of RRTMG.

Ice optical properties depend strongly on ice particle shape (e.g., Mitchell and Arnott 1994), but an important question is how they can be formulated for any particle shape. Using ARM funding, Mitchell et al. (1996) proposed a solution by representing ice particle mass and projected area (on which optical properties depend) as area- and mass-dimensional power laws (henceforth A–D and m–D relationships). By combining a form of van de Hulst's (1981) anomalous diffraction approximation (ADA) as described by Bryant and
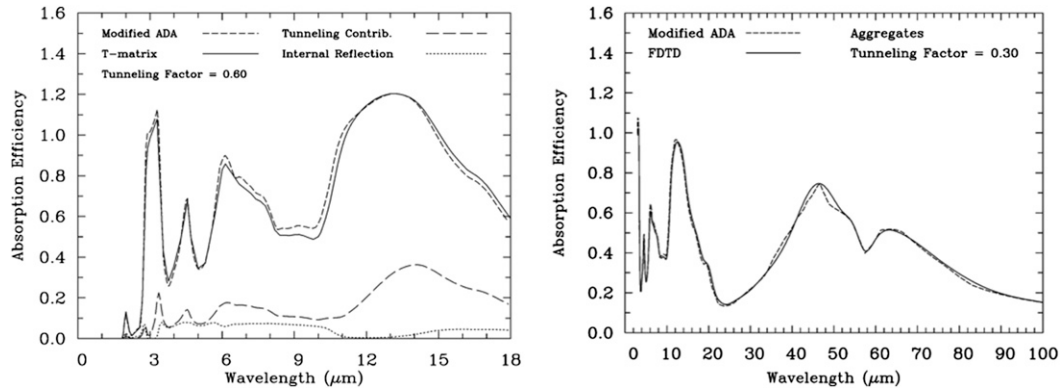
FIG. 15-5. (left) Comparison of MADA with T matrix for Q_{abs} based on a measured PSD of hexagonal columns. Absorption contributions predicted by MADA for photon tunneling and internal reflection/refraction are indicated. (right) Comparison of MADA with the FDTD method at terrestrial wavelengths for a cirrus PSD at −55°C. Ice particles are aggregates of hexagonal columns and plates.

Latimer (1969) with m–D and A–D relationships, analytical solutions for the extinction and absorption coefficients, β_{ext} and β_{abs}, were obtained as a function of the ice PSD parameters, ice particle shape, and wavelength. The asymmetry parameter for the PSD was estimated from ray-tracing calculations and parameterized in terms of ice particle shape, size, and wavelength (Mitchell et al. 1996). While the effects of internal reflection and refraction were accounted for in the solutions for β_{ext} and β_{abs}, wave resonance effects (also referred to as photon tunneling) were not. Subsequent ARM-funded research (Mitchell 2000) then parameterized wave resonance effects into a modified ADA (MADA) by relating resonance to the index of refraction and size parameter x (where $x = \pi d_e/\lambda$, d_e = effective photon path diameter of particle and λ = wavelength). Two types of wave resonance were parameterized: one increasing the ray path within a particle through internal "resonating" reflections (affecting both β_{ext} and β_{abs}) and another responsible for surface waves (depending solely on x and affecting only β_{ext}). The latter are sometimes referred to as edge effects. Although first tested against Mie theory and applied to liquid water clouds, MADA was applied subsequently to ice clouds as described in Mitchell (2002).

The left panel of Fig. 15-5 shows the PSD absorption efficiency Q_{abs} calculated by T matrix and MADA for a laboratory-grown ice cloud having a narrow PSD, with contributions from internal reflection/refraction and tunneling shown as predicted by MADA. MADA is compared against the finite difference time domain (FDTD) method over a greater wavelength range in the right panel of Fig. 15-5 for ice crystal aggregates and a PSD typical of cirrus clouds. The difference between MADA and these other methods is never more than 15% for any PSD size parameter ≥1 (based on

PSD effective diameter) for any ice particle shape assumed. MADA also has been tested successfully against laboratory extinction efficiency (Q_{ext}) measurements (Mitchell et al. 2001, 2006), and an earlier version of MADA (Mitchell et al. 1996) used observed cirrus microphysical measurements to successfully predict the radiometric measurements mentioned above (Stackhouse and Stephens 1991).

MADA formed the basis of the cloud (both liquid water and ice) optics scheme of Harrington and Olsson (2001), and it is used in the Regional Atmospheric Modeling System (RAMS; Cotton et al. 2003) and in cloud-process models (e.g., Liu et al. 2003). More recently, this scheme was implemented in RRTMG to provide the ice optics in CAM5 (Gettelman et al. 2010). This allows the microphysical and radiative processes in CAM5 to be based on common assumptions about ice particle mass and projected area (i.e., m–D and A–D expressions) and a common ice PSD. The latter is important since, for a given effective diameter D_e and ice water content, β_{ext} and β_{abs} may vary up to 42% and 33%, respectively, for different PSD shapes (e.g., degree of bimodality) at thermal infrared wavelengths (Mitchell et al. 2011).

Prior to CAM5, the ice optical properties in CAM were treated using the projected area equivalent spheres approach of Ebert and Curry (1992, hereinafter EC). In Fig. 13 of Mitchell et al. (2006), the flux weighted mass absorption coefficient predicted in the IR window region (8.0–12.5 μm) by EC for cirrus clouds ($D_e <$ 150 μm; hexagonal columns assumed) is ~50% greater than that predicted by MADA and the ice optics schemes of Fu et al. (1998) and Yang et al. (2001). These three other schemes produce almost identical results. In the SW for a given D_e, both the mass normalized β_{ext} and g are greater in the EC scheme than in MADA.

Evaluation of the radiative effect of the MADA-based parameterization in RRTMG used in CAM5 determined that the globally averaged shortwave cloud radiative effect changed by $\sim 4.5\,W\,m^{-2}$ compared to RRTMG with the EC ice optics parameterization.

b. The role of cloud variability and the development of McICA

By the late 1990s, it was widely recognized that fluxes computed by 1D multilayer, plane-parallel, homogeneous (PPH) radiative transfer models used in large-scale atmospheric models (LSAMs) contained significant (local values $> 10\,W\,m^{-2}$) biases that depend strongly on cloud regime. Such models typically relied on basic two-stream approximations to compute fluxes in the clear and cloudy portions of a layer, each assumed to be homogeneous, and weighted the fluxes transported between layers using some analytic representation of an idealized vertical overlap assumption. Both sources of error, horizontal variability and the handling of vertical overlap, were originally considered as separate problems, although they are both fundamentally issues of small-scale heterogeneity.

The neglect of horizontal variability of cloud extinction attracted interest because it was known to introduce biases in both shortwave (Stephens 1988; Cahalan et al. 1994) and longwave (Fu et al. 2000) calculations. A variety of methods were used to address the impact of variability, all of which attempted to fold descriptions of cloud structure, or cloud-radiation interactions, directly into the 1D radiative transfer model. The simplest approach, applicable to shortwave radiation, was to continue to use the two-stream approximation but with a reduction in cloud optical depth that depended on cloud fraction (Tiedtke 1996). Others sought to analytically rescale the cloud optical properties based on assumptions about isotropic variability (e.g., Stephens 1988; Cairns et al. 2000). Barker (1996) introduced an elegant solution to a very specific problem by weighting single-layer two-stream solutions with lognormal density functions of optical depth (this choice of distribution being inspired by satellite retrievals and cloud-scale models). Oreopoulos and Barker (1999) extended this approach to multiple layers, though the handling of cloud overlap was simplistic. Each of these methods had inherent drawbacks or limiting assumptions, ranging from physical implausibility (in the case of tuned values of parameters) to inflexibility with respect to assumptions made in other parts of the model.

The small-scale heterogeneity caused by cloud overlap was treated almost uniformly by analytically mixing clear- and cloudy-sky fluxes within radiation codes. Collins (2001) introduced the idea of enumerating all possible combinations of cloudy layers and their relative frequencies and weighting the fluxes computed for the columns that most strongly affected radiation by that frequency. This approach was computationally expensive because it required many individual cloudy-column calculations and could not be extended to internally inhomogeneous clouds because the number of possible combinations quickly became enormous.

1) IDENTIFYING THE PROBLEMS: ICRCCM-III

With no approach giving satisfactory results, the feeling among modelers was that the existing paradigm of searching for closed-form solutions had hit an impasse. It seemed that the most productive way forward was to corral those models that were, or could be, used in atmospheric models and perform an intercomparison resembling that of Fouquart et al. (1991), but focusing on their handling of cloudy rather than clear-sky spectral fluxes. This intercomparison, designated ICRCCM-III (Barker et al. 2003) and supported using ARM funding, had as its primary motivations to 1) assess 1D solar radiative transfer models suitable for use in atmospheric models for complicated cloudy atmospheres and 2) demonstrate the relative importance to those models of addressing unresolved vertical and horizontal cloud fluctuations.

Participating codes were assessed first for clear-sky and single-layer, plane-parallel, homogeneous cloudy atmospheres in order to establish baseline differences in broadband fluxes before moving to complicated cloud cases. Benchmark fluxes were produced by a range of 3D Monte Carlo algorithms operating on cloud fields produced by cloud-resolving models (CRMs), which established the results that all 1D codes strived for. A single 3D model was used to establish "conditional" benchmarks for simplified versions of the CRM fields, such as precise overlap of horizontally homogenized plane-parallel clouds. The conditional benchmarks allowed a modeler to verify that their code, which they knew was incomplete, was at least addressing properly what it intended to address. An example of the methodology used in this intercomparison is shown in Fig. 15-6.

The main result of the study involved the range of conditional benchmarks, for they demonstrated clearly that overlap and horizontal fluctuations of cloud have to be dealt with together. The secondary result was that classes of 1D models had wide ranges of performance relative to their appropriate conditional benchmark—often they were not doing what was expected of them. Finally, no single 1D model, or 1D modeling strategy, stood out as the clear choice for use in atmospheric models, confirming what many had suspected at the outset of ICRCCM-III.
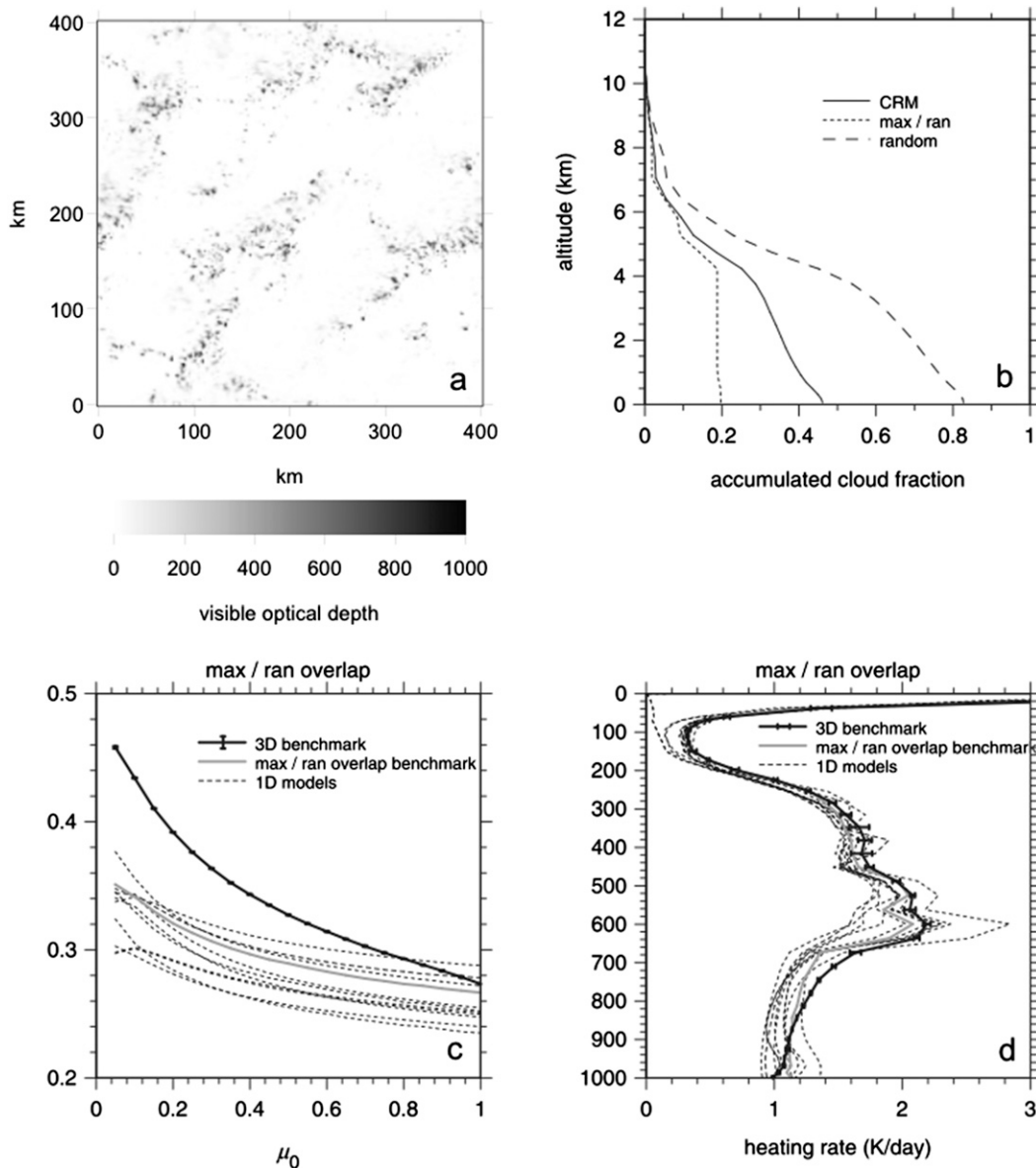
FIG. 15-6. (a) Model-generated cloud field that could be inside a GCM cell (Grabowski et al. 1998). (b) Downward accumulated cloud fractions for the cloud field shown in (a). CRM represents the actual function, while max/ran and random are corresponding functions assuming that layer cloud fractions follow the maximum-random and random overlap assumptions, respectively. (c) TOA albedo as a function of cos(SZA) for the field shown in (a). The 3D benchmark is the mean of four Monte Carlo models with error bars representing standard deviations. Gray line is from a Monte Carlo model acting on this field's correct maximum-random overlap rendition with horizontally homogeneous clouds. Dashed lines are from several 1D codes that all claimed to be doing max/ran overlap with horizontally homogeneous clouds. (d) Domain-averaged heating rates for the calculations described in (c) (from Barker et al. 2003).

ICRCCM-III highlighted a significant challenge for climate model radiation codes, namely, the treatment of variability in cloudy atmospheres. The study demonstrated that both horizontal variability and vertical structure are important in determining domain-mean fluxes, and also that methods existing at that time to describe overlap did not reproduce benchmark Independent Column Approximation (ICA) calculations (whose utility ICRCCM-III demonstrated), particularly for solar radiation calculations in which multiple scattering is important. Climate modelers understood that representing this variability was important for radiation [among other processes (Pincus and Klein 2000)], so these results were timely, as they arrived soon
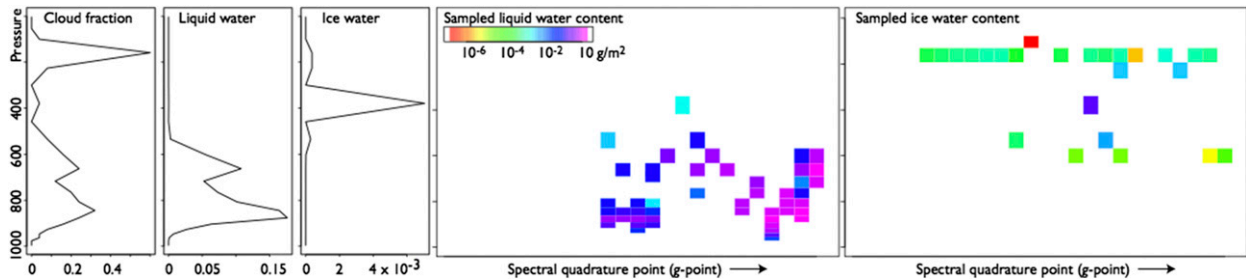
FIG. 15-7. An example of generating cloud samples (subcolumns) from atmospheric states for use with McICA. In this example, clouds are represented within the model with values for cloud fraction and liquid and ice water contents; profiles for an example column are shown. These values are used to infer distributions of total water at each level (see Pincus et al. 2005). An overlap assumption describes the probability of cloudiness and cloud condensate amount at each level depending on the value in the level above. Samples, shown in the two panels on the right, are constructed randomly using probabilities consistent with the statistics within each layer and the overlap assumption, so that large ensembles of columns reproduce the input properties.

after initial efforts to predict small-scale cloud variability in climate models (Tompkins 2002; Golaz et al. 2002) and new formulations of overlap from ground-based ARM-like instruments (Hogan and Illingworth 2000).

A subsequent ARM-funded analysis in the longwave spectral region supported the conclusion of the shortwave-based ICRCCM-III study that 1D approaches faced great challenges in modeling inherently inhomogeneous clouds. For several complex cloud fields, Kablick et al. (2011) evaluated the ability of various approximate methods to compute radiative fluxes and heating rates with respect to benchmark calculations by a 3D Monte Carlo algorithm. Results of the study indicated that overlap schemes used in GCMs such as maximum/random resulted in large errors in domain-averaged fluxes and heating rates, while ICA calculations were consistently more accurate. The authors concluded that "there is an inherent deficiency in the ability of 1D models to accurately calculate radiative quantities" in inhomogeneous cloud fields.

2) A FLEXIBLE SOLUTION: McICA

At the 2002 ARM Science Team Meeting, just two days after the ICRCCM-III manuscript was submitted for publication, an entirely new method for treating variability of all kinds was conceived. McICA weaves together two threads of prior experience with a new insight. The first thread was the idea that arbitrarily complicated cloud structures, no matter how they arose, could be represented as a set of discrete, internally homogeneous samples (or subcolumns). This idea, which came from the synthetic pixels used by the "ISCCP simulator" (Yu et al. 1996; Klein and Jakob 1999), greatly simplifies the radiative transfer. Simply expanding the number of radiation calculations by the number of samples would incur far too much computational cost. Experiences in numerical weather prediction, however, had already demonstrated

that model forecasts are remarkably resilient to grid-scale noise (Buizza et al. 1999). It was therefore suggested that the new method could exploit this resilience by drawing as many samples of cloud states as there are spectral integration points in the host radiation scheme. As schematically represented in Fig. 15-7, each cloud sample is associated with a different, randomly chosen spectral point (further randomized at each time step and grid column) and the spectral fluxes are summed as in a normal ICA calculation. This means that any variability in cloud properties is sampled incompletely for any given radiative flux calculation, but that this limited sampling introduces random noise, not bias, with respect to the reference calculation (i.e., the ICA on an infinitely large set of samples). Initial experiments with the European Centre for Medium-Range Weather Forecasts model (Pincus et al. 2003) suggested that the amount of noise introduced by McICA would not affect model forecasts.

McICA has conceptual appeal because it offers a method for treating cloud variability in an unbiased way regardless of the cause or form of the variability. It thus fits naturally with interest in predicting in-cloud variability through a time-evolving probability distribution (Shupe et al. 2016, chapter 19), and with formulations for cloud overlap that account for in-cloud variability (Räisänen et al. 2004; Pincus et al. 2005) and aim for insensitivity to vertical resolution. It has structural appeal because the radiative transfer routines are separated perfectly from the description of cloud variability and may be simplified by removing overlap and other complex treatments; the routines can then track the governing equation sets closely. Had McICA been available at the time of ICRCCM-III, it would have replicated the ICA benchmarks (subject to statistical noise), which for domain averages agree very well with full 3D solutions, and been an obvious path forward.

As a practical matter, McICA is also relatively easy to implement and effective. Experiments were first tried with the climate models developed by NCAR (Räisänen et al. 2005) and GFDL (Pincus et al. 2006); this number soon expanded to half a dozen (Barker et al. 2008), none of which seemed to be affected by the noisy sampling of small-scale cloud variability introduced by McICA. Medium-range weather forecasts were improved (Morcrette et al. 2008), and McICA became operational at ECMWF on 5 June 2007. McICA was introduced along with RRTMG for shortwave calculations; longwave calculations had used RRTMG since June 2000. The ECMWF implementation was built in-house along with vectorized versions of RRTMG.

McICA also was adopted as the only means of treating overlap in the versions of RRTMG supported by AER starting in August 2007 (with version 4.1 of the longwave and 3.1 of the shortwave). The AER implementation generates samples following Räisänen et al. (2004), although facilities also are available for using externally generated samples. Compared to other fast codes with fewer monochromatic points, RRTMG is especially well-suited to utilize McICA since its relatively high number of g points allows for good sampling of the distribution of cloud properties within each column.

At the same time, it became clear that it was too easy to introduce errors into radiation parameterizations, especially for the treatment of absorption by gases (Collins et al. 2006; Oreopoulos et al. 2012), so modeling centers were strongly motivated to adopt parameterizations like RRTMG that are routinely tested against spectrally detailed observations and reference LBL calculations. Over time RRTMG has replaced custom radiative transfer packages in many models (the NCAR CESM1, for example) and McICA has been adopted even more widely. (It is used by the Met Office HadGEM series with a completely different radiation package; see Hill et al. 2011.) The increasing uniformity of radiative transfer treatments across models does not reduce the value of multimodel ensembles, however. Model diversity in an ensemble is used to represent uncertainty, and the relatively small uncertainty in radiative transfer permits a single parameterization to be used for this physical process for all ensemble members.

4. Evaluation of GCM RT codes

While the findings and lessons of ICRCCM were major motivations for developing the concept of the ARM Program, no organized effort to establish a new radiative transfer code intercomparison that would take advantage of ARM radiative and other observations emerged for many years. This may at first seem surprising given that the Spectral Radiance Experiment (SPECTRE), an experimental field program considered in some ways a predecessor of ARM (Ellingson et al. 2016, chapter 1), was designed specifically to establish reference standards against which to compare radiative transfer models (Ellingson and Wiscombe 1996). Undoubtedly, part of the reluctance to embark on an intercomparison using ARM data was the desire for a certain level of maturity to be reached with regard to understanding instrument capabilities and the limitations of retrieval algorithms. By the time of the GEWEX Radiation Panel meeting in 2003, participants with close involvement in ARM deemed that such maturity had been reached. An additional reason that using ARM data for an RT intercomparison gained momentum was the existence and success of the Broadband Heating Rate Profile (BBHRP) effort (Mlawer et al. 2002; McFarlane et al. 2016, chapter 20) which required assembling and synthesizing multiple ARM data streams to enable production of an RRTM-based radiative flux and heating rate product. The birth of the Continual Intercomparison of Radiation Codes (CIRC; Oreopoulos and Mlawer 2010) can be traced back to those discussions. As the name implies, one of the central ideas was that the project would become the source of an evolving and regularly updated permanent reference database for evaluation of radiative transfer codes used in a variety of Earth system models.

During the initial stages of CIRC planning, it became apparent that choosing only cases with homogeneous atmospheric conditions best supported the need for CIRC cases to be well characterized and easily understood by participants. This condition also allowed the intercomparison to be inclusive of all approaches to handling the radiative effects of clouds. In addition, for ideal CIC cases, radiative closure had to be achieved for the measured radiative flux at two physical and two spectral domain boundaries, that is, the SW and LW upward irradiances at the top of the atmosphere and the downward fluxes at the surface. Another major criterion was that the set of cases would have to span a wide variety of conditions, not only with regard to the presence or absence of clouds, but also with respect to atmospheric moisture and aerosol content, surface properties, and illumination conditions. Because the single-scattering properties of ice crystals are not defined uniquely for a given effective size, cloudy cases containing ice (including those of mixed thermodynamic phase) were not considered for the first phase of CIRC.

The BBHRP data stream contained sufficient information to identify the candidate cases and further test their suitability by matching (per SPECTRE rationale) LW spectral measurements at the surface from the
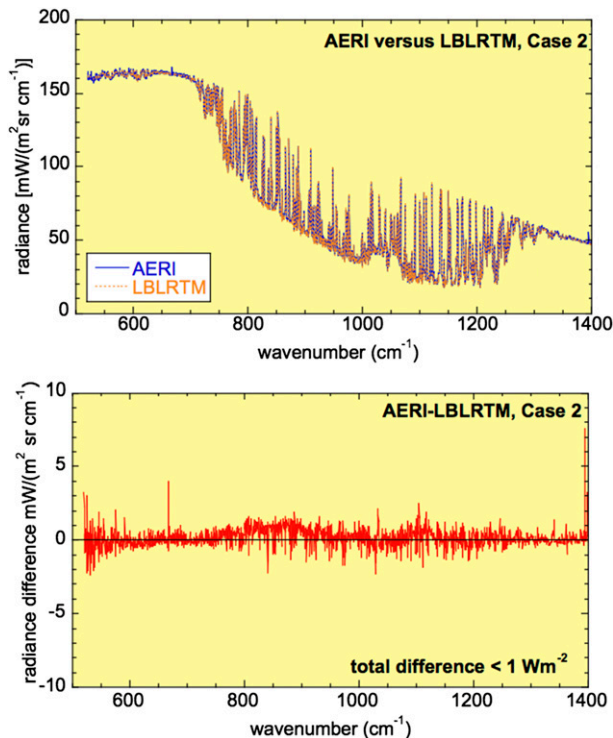
FIG. 15-8. (top) Spectral radiances for an extensive range of the radiatively important thermal spectrum as measured by AERI and calculated with LBLRTM and (bottom) their differences for CIRC baseline case 2. When converted to fluxes the differences correspond to less than 1 W m^{-2}. Such comparisons were essential for assuring the quality of atmospheric input and of the reference LBL thermal calculations of CIRC cases (from Oreopoulos and Mlawer 2010).

atmospheric emitted radiance interferometer (AERI) instrument with LBLRTM calculations (Fig. 15-8). These LBL calculations and their SW counterparts were then used as the reference calculations to evaluate the approximate models (see CIRC website http://circ.gsfc.nasa. gov), and thus the cases for the initial phase of CIRC were born almost 5 years after the idea for such a project was put forth. Six of the seven "baseline" cases were based purely on observations and supported by flux closure, while the remaining case was a 2xCO$_2$ extension of the driest and coldest observed case. Additional cases were generated by simplifying these baseline cases with successive removals of aerosol, cloud, and the spectral dependence of surface albedo (details can be found in Oreopoulos et al. 2012). These extra cases not only enabled testing model performance for simpler atmospheres, but also allowed assessments of cloud and aerosol forcing, and the impact of spectral surface albedo variations.

Figures 15-9 and 15-10 summarize the performance of the radiative transfer codes that participated in CIRC phase I in terms of percentage errors. Blue shades (negative values) indicate underestimates by the approximate

codes. RRTM and RRTMG—models 1 and 2 in these figures, respectively—demonstrated notable accuracy in this intercomparison. An overall finding of CIRC was that approximate codes match LW reference calculations (Fig. 15-9) better than those in the SW (Fig. 15-10), echoing one of the main ICRCCM findings. Diffuse and absorbed SW fluxes are particular areas of concern. Obtaining the correct breakdown of total downward flux into direct and diffuse may be important for the simulation of surface processes such as vegetation growth and the carbon cycle in advanced Earth system models with interactive land components and should receive more attention in the future. The underestimate of SW absorption by less spectrally detailed models was recognized previously (e.g., Ackerman et al. 2003) and seems to have persisted for most approximate codes. This is consistent with a general tendency to overestimate the total downward SW flux reaching the surface, which makes obtaining a global balance between net radiative warming at the surface and cooling by turbulent fluxes problematic when modeling the surface radiation imbalance. The details of how surface albedo was averaged in very wide bands were found to be relevant for the SW TOA fluxes of the CIRC experiments, suggesting that more care should be given to proper representations of spectral albedo variations. While performance with regard to LW CO$_2$ forcing calculations was good overall with a couple of exceptions, estimation of SW CO$_2$ forcing was found to be a capability that some codes either did not have at all or was restricted to downwelling surface fluxes. For codes with full SW CO$_2$ forcing capabilities, performance was often quite poor, consistent with Collins et al. (2006). These and additional findings are described in greater detail in Oreopoulos et al. (2012).

So, how much progress have approximate radiation codes made since the ICRCCM era? ICRCCM had many more participating codes and its cases were conceived differently; for example, some experiments were based on synthetic atmospheres of a single absorber. ICRCCM's results therefore likely exposed different model deficiencies than CIRC did. Despite these difficulties in quantifying improvement, Oreopoulos et al. (2012) attempted a simple comparison with Ellingson et al. (1991) and Fouquart et al. (1991) and provided measures that indicated the CIRC generation of models is indeed better than those of the ICRCCM era.

Obviously, many aspects of approximate radiative transfer model performance were not addressed by CIRC. The cloudy cases, for instance, were as simple as possible since it is still challenging to produce reference LBL fluxes for complex cloud microphysics and structures. CIRC also did not explore whether the accuracy of the participating models with respect to the reference LBL calculations
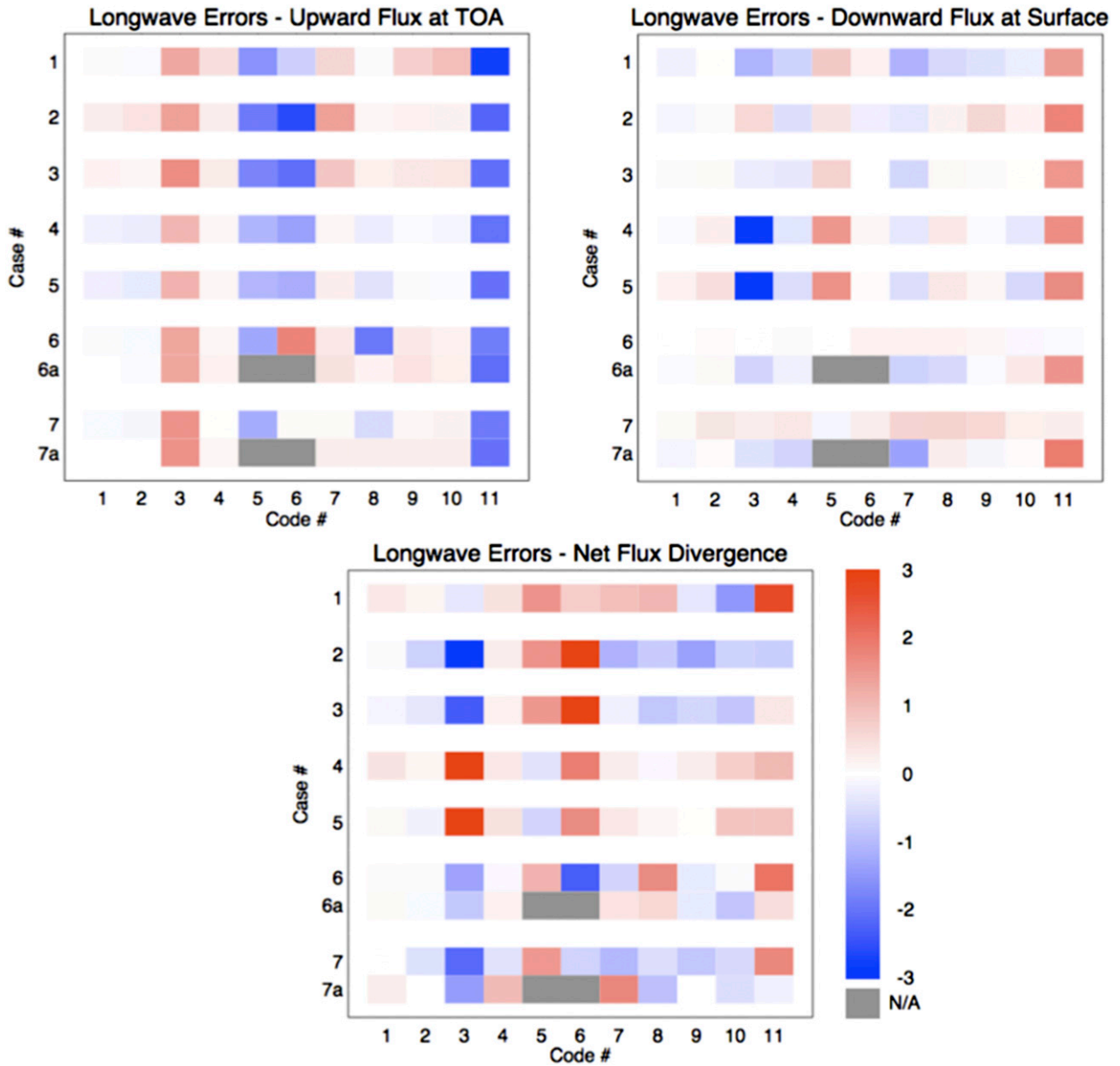
FIG. 15-9. Percentage errors for each participating model and CIRC phase I case for thermal infrared fluxes (upward flux at TOA, downward flux at the surface and atmospheric flux divergence). Gray indicates unavailable submissions (from Oreopoulos et al. 2012).

correlates (inversely) with their computational efficiency. A proper assessment of computational efficiency is feasible as a future endeavor as long as a common computational platform can be made available for performing all calculations. Undertakings such as the CIRC-tested Cloud–Aerosol–Radiation (CAR) Ensemble Modeling System (http://car.umd.edu) that assemble different radiation codes under a unified modeling infrastructure potentially can facilitate such computational speed assessments.

Regardless of what exact direction future radiative transfer code intercomparisons will take, CIRC has paved the way on how to use a variety of observations and the concepts of broadband and spectral closure to build cases, accentuate the reliability of LBL calculations, and create reference datasets that can be maintained, updated, and expanded periodically. These accomplishments would not be possible without the infrastructure and seed datasets available because of ARM. As ARM radiation measurements continue to be analyzed and their accuracy becomes better characterized, a consensus may be reached on the fundamental problem of determining acceptable levels of performance for the approximate radiation codes used in either earth model or operational flux product generation environments.
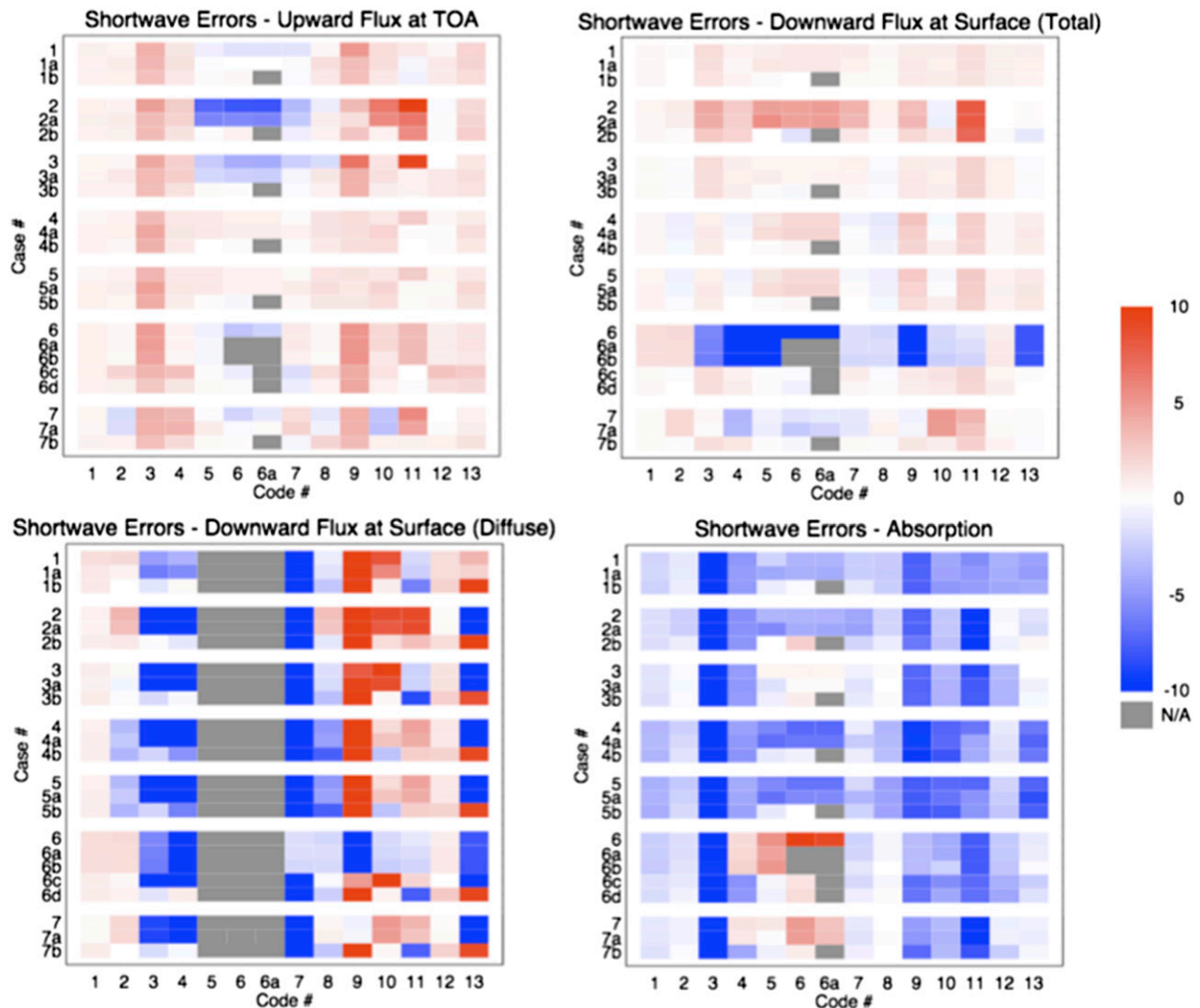
FIG. 15-10. As in Fig. 15-9, but for solar radiation. In addition, the downward diffuse flux at the surface (difference between downward total and direct solar flux) is shown (from Oreopoulos et al. 2012).

5. Conclusions

The accomplishments precipitated by the ARM Program with respect to improved radiative transfer in atmospheric models have been profound, leading the program to significantly lower its priority on radiation-related research. Ultimately, the mission of ARM was redefined in tandem with the creation of a new science-focused program (Atmospheric Systems Research; Ackerman et al. 2016, chapter 3) without "radiation" in its title. Despite this reordering of priorities, ARM's history of radiative transfer research is viewed rightfully as one of the program's greatest successes.

This reordering of the program's priorities should be seen, however, as a temporary, and perhaps premature, declaration of victory. Prior to ICRCCM, the atmospheric modeling community thought that there was a solid understanding of atmospheric radiative fluxes and heating rates, only to be proven wrong. Progress during the past decades, including the substantial accomplishments detailed in this chapter and Mlawer and Turner (2016, chapter 14), has placed our understanding on a more solid foundation, but future global models are likely to have a much higher level of sophistication. In particular, consideration of 3D radiative effects in climate and weather simulations is likely to gain prominence, especially as the spatial scale of models continues to decrease. More ambitious objectives for radiation calculations in climate and weather prediction models perhaps will reinvigorate the need for improvements to radiation parameterizations, leading to a new cycle of investment, investigation, and accomplishment.

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