# THE CONTINUAL INTERCOMPARISON OF RADIATION CODES (CIRC)

## Assessing Anew the Quality of GCM Radiation Algorithms

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**THE PROBLEM AT HAND AND CURRENT KNOWLEDGE.** The simulation of changes in the Earth's climate due to solar and thermal radiative processes with global climate models (GCMs) is highly complex, depending on the parameterization of a multitude of nonlinearly coupled physical processes. In contrast, the germ of global climate change, the radiative forcing from enhanced abundances of greenhouse gases, is relatively well understood. The impressive agreement between detailed radiation calculations and highly resolved spectral radiation measurements in the thermal infrared under cloudless conditions (see, for example, Fig. 1) instills confidence in our knowledge of the sources of gaseous absorption. That the agreement spans a broad range of temperature and humidity regimes using instruments mounted on surface, aircraft, and satellite platforms not only attests to our capability to accurately calculate radiative fluxes under present conditions, but also provides confidence in the spectroscopic basis for computation of fluxes under conditions that might characterize future global climate (e.g., radiative forcing). Alas, the computational costs of highly resolved spectral radiation calculations cannot be afforded presently in GCMs. Such calculations have instead been used as the foundation for approximations implemented in fast—but generally less accurate—algorithms performing the needed radiative transfer (RT) calculations in GCMs.

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**GCM RADIATION ALGORITHMS AND PRIOR INTERCOMPARISONS.** Credible climate simulations by GCMs cannot be ensured without accurate solar and thermal radiative flux calculations under all types of sky conditions: pristine cloudless, aerosol-laden, and cloudy. The need for accuracy in RT calculations is not only important for greenhouse gas forcing scenarios, but is also profoundly needed for the robust simulation of many other atmospheric phenomena, such as convective processes. Despite the approximations used in GCM RT algorithms, their share of CPU resources in climate simulations is still typically the largest of all the parameterizations of physical processes. Given the importance of radiation calculations to climate simulations and the relatively settled status of spectrally detailed clear-sky radiative transfer, one would think that GCM radiation codes would by now faithfully reproduce the radiative effects of greenhouse gases computed by more detailed models at present and projected future concentrations, thereby allowing confidence in this critical aspect of the simulation when tackling nonpristine atmospheric states. Unfortunately, this has not generally been the case. For example, a 2006 study in the *Journal of Geophysical Research* (*JGR*) by Collins et al. presented forcing intercomparisons between line-by-line (LBL) radiative transfer models and their speedier, but coarser, GCM counterparts that participated in the Intergovernmental Panel for Climate Change (IPCC) 4th Assessment Report. The exercise was primarily targeted at well-mixed greenhouse gases, and in some respects updated a similar effort completed more than a decade earlier under the auspices of the Intercomparison of Radiation Codes in Climate Models (ICRCCM). Collins et al. reported that for many of the cases analyzed, GCM codes exhibited "substantial discrepancies" relative to the detailed spectral LBL standards, a finding echoing earlier conclusions by ICRCCM. While the mostly cloudless synthetic cases in both these studies provided the benefit of well-defined controlled experiments, a major deficiency was the lack of validation of the baseline reference results with measurements. Fouquart et al. had already recognized (in a 1991 *JGR* article) at the inception of ICRCCM that "the absolute tests of the validity of the radiation algorithms would be comprehensive field experiments in which the radiative and all relevant atmospheric parameters are measured to a high degree of accuracy." This sentiment was reaffirmed a few years later in a 1996 *BAMS* article by Ellingson and Wiscombe, who stressed that "what was needed [in addition to calculations] was a set of accurate atmospheric spectral radiation data measured simultaneously with the important radiative properties of the atmosphere like temperature and humidity." Such capabilities are now more readily available, especially with the advent and blossoming of the United States Department of Energy's Atmospheric Radiation Measurement (ARM; www.arm.gov) program and similar programs elsewhere in the world, and have thankfully been exploited to yield some of the encouraging spectral closure results mentioned earlier. Real-world conditions at ARM measurement sites include the effects of spatially variable cloud, aerosol, and surface reflectance, and therefore present greater challenges for achieving spectral or even broadband agreement across the full range of wavelengths important for climate applications. Evaluating GCM radiation codes under nonidealized—but still well-characterized conditions—should thus remain a high priority, while recognizing at the same time that any assessments about code performance relative to radiation measurements must be performed in the context of the uncertainties in the observationally based input to the codes. The Continual Intercomparison of Radiation Codes (CIRC), endorsed by the GEWEX Radiation Panel (GRP) and the International Radiation Commission (IRC) and supported by the ARM program, intends to fulfill this need.

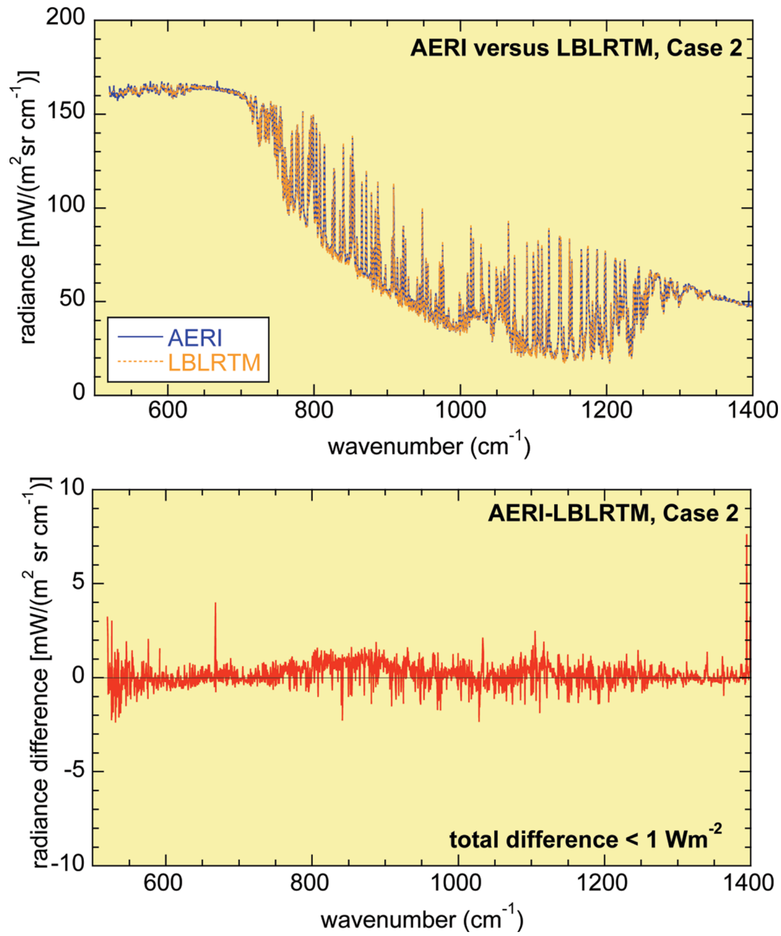


**Fig. 1. (top) Spectral radiances for an extensive range of the radiatively important thermal spectrum as measured by AERI and calculated with LBLRTM, and (bottom) their differences for CIRC Case 2. When converted to fluxes, the differences correspond to less than 1 W m$^{-2}$. Comparisons of this kind provide validation of the quality of atmospheric input and of the measured/calculated infrared radiances for this particular CIRC case.**

**A NEW PARADIGM FOR GCM RT CODE INTERCOMPARISON.** As in previous intercomparisons, CIRC uses high spectral-resolution calculations as its benchmarks. What distinguishes CIRC from previous efforts, however, is that it also uses observations for input and validation of these calculations. CIRC employs an ensemble of cases in which the atmospheric and surface inputs, as well as the radiation measurements attesting to the quality of the reference calculations, are based on ARM measurements. The data used thus far in CIRC have mostly originated from ARM Climate Research Facility (ACRF) surface measurements and satellite observations in the vicinity of these ACRFs as compiled in the Broadband Heating Rate Profile (BBHRP) evaluation product. Additional datasets from ARM field campaigns have been added to complete the set of cases released, and spectral radiances from the Atmospheric Emitted Radiance Interferometer (AERI) instrument have been used to ensure the integrity of the atmospheric input used in the radiative transfer calculations (Fig. 1). The intention is to continue using the fullest suite of ARM retrievals and observations available to understand and improve the quality of existing and future CIRC cases.

Another distinguishing feature of CIRC rests in its nature as an evolving and regularly updated permanent reference source that serves the global modeling community. As such, it makes all pertinent information publicly available and is designed as a long-lasting, continual endeavor, as explained below.

**CIRC MODUS OPERANDI AND DATA.** CIRC is releasing self-contained collections of cases in stages that will be referred to as "phases." Specification of the input fields, output from the reference radiation calculations [top-of-the-atmosphere (TOA) and surface-spectral fluxes, broadband flux profiles, and heating rates], sample code to ingest the data, and instructions on how to run the cases are openly available at the CIRC Web site (http://circ.gsfc.nasa.gov). Currently, all such information pertaining to Phase I cases are posted. In the near future, the CIRC Web site will expand with documentation on implementation details from participating codes and analysis of the submissions by registered CIRC participants. Registration with CIRC is a means by which the project provides benefits to the participants such as notifications about changes, updates, and corrections to the project database, and priority to participate in workshops and publications. To advance certain CIRC activities in a timely manner, registered users may in turn have to submit results within predetermined deadlines.

The CIRC Phase I cases, with one exception, are drawn from the BBHRP dataset, and satisfy preset criteria that make them appropriate for the objective of this phase, which is to evaluate the RT codes under presumably the least challenging conditions. The prin-

**TABLE 1. Synopsis of CIRC Phase I cases. The gray columns show observed and LBL-calculated (in bold) flux values (in W m$^{-2}$) at the surface (SFC) and the top of the atmosphere (TOA) for both the thermal/longwave (LW) and solar/shortwave (SW) part of the spectrum. Observed TOA fluxes are from GOES using narrowband to broadband conversion algorithms or from CERES (Case 4), while observed SFC fluxes come from ARM instruments. The cyan columns provide some essential input information (SZA = solar zenith angle; PWV = precipitable water vapor; LWP = liquid water path). The aerosol optical depth ($\tau_{aer}$) is for 0.55 $\mu$m. Case 5 is as Case 4, but with doubled $CO_2$. SGP indicates Southern Great Plains ACRF; NSA indicates Northern Slope of Alaska ACRF; and PYE indicates the ARM Mobile Facility in Pt. Reyes, California.**

| Date (Site) | Case | SZA | PWV (cm) | $\tau_{aer}$ | LWP (g m$^{-2}$) | $LW_{SFC}$ | $LW_{TOA}$ | $SW_{SFC}$ | $SW_{TOA}$ |
|---|---|---|---|---|---|---|---|---|---|
| 25 Sep 2000 (SGP) | 1 | 47.9° | 1.23 | 0.04 | | 289.7 **288.2** | 301.7 **304.3** | 705.9 **701.2** | 169.8 **175.0** |
| 19 Jul 2000 (SGP) | 2 | 64.6° | 4.85 | 0.18 | | 441.8 **439.3** | 288.6 **292.6** | 345.4 **348.0** | 127.8 **117.1** |
| 4 May 2000 (SGP) | 3 | 40.6° | 2.31 | 0.09 | | 336.4 **333.0** | 277.6 **280.8** | 772.5 **773.1** | 159.6 **173.6** |
| 3 May 2004 (NSA) | 4 | 55.1° | 0.32 | 0.13 | | 194.7 **192.4** | 229.1 **230.5** | 638.9 **642.8** | 425.8 **422.9** |
| 3 May 2004 (NSA, $CO_2$) | 5 | 55.1° | 0.32 | 0.13 | | **195.7** | **229.2** | **641.3** | **422.7** |
| 17 Mar 2000 (SGP) | 6 | 45.5° | 1.90 | 0.24 | 263.4 | 339.0 **335.2** | 234.8 **241.8** | 97.6 **92.1** | 623.2 **628.8** |
| 6 Jul 2005 (PYE) | 7 | 41.2° | 2.42 | | 39.1 | 373.2 **372.6** | 284.0 **280.2** | 479.8 **473.7** | 356.0 **356.4** |

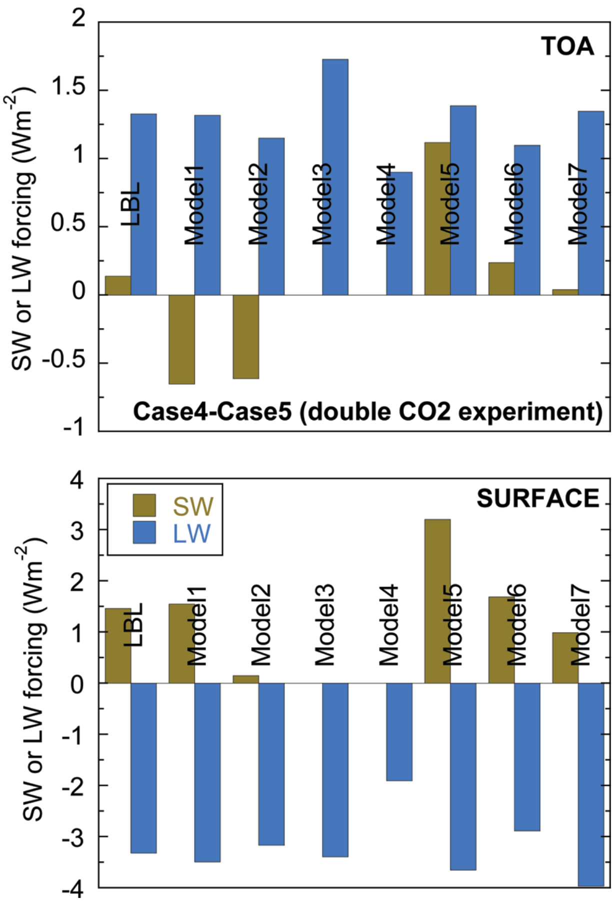


**FIG. 2. Preliminary results of SW and LW radiative forcing at the SFC (bottom) and at the TOA (top) for doubling $CO_2$ from 375 ppm for Case 4 to 750 ppm for Case 5 (Case 5 fluxes are subtracted from Case 4 fluxes) under very dry and cold conditions at the Northern Slope of Alaska. Reference line-by-line (LBL) forcings are compared to early CIRC submissions and publicly available radiation codes (not identified). The baseline LBL calculations (unperturbed $CO_2$ for Case 4) agree with the observations within ~1% (see Table 1). Note that not all radiation codes are GCM implementations, and that Model3 and Model4 are not capable of perturbed $CO_2$ experiments in the SW. A significant range of forcing values in both the SW and LW can be seen. The negative SW TOA forcings for Model1 and Model2 are a result of the limited sensitivity of the upwelling irradiance in these models to a change in $CO_2$ which makes the greater effective near-infrared band-averaged albedo in Case 5 the dominant factor in the TOA forcing. Note that besides the albedo function weighted by spectral flux incident at the surface used in this analysis, we also provide an albedo function weighted by the extraterrestrial spectral irradiance.**

cipal criterion for selecting cases was good agreement between radiation measurements and calculations (i.e., radiative closure) at both the surface and the top of the atmosphere (for both the solar and thermal part of the spectrum), including spectral closure. Other criteria for the cloudy cases were: (a) overcast conditions; (b) the presence of only one water phase (liquid); and (c) cloud homogeneity. The clear-sky cases were chosen to include: (a) a wide range of precipitable water loadings; (b) a significant range of aerosol loadings; and (c) a significant range of solar angles. The selection criteria may be different for future phases of CIRC, depending on specific aspects of the radiation codes that may become foci of attention. The Phase I criteria yielded seven cases—five cloud-free, and two with overcast liquid clouds. Three cloudless cases come from the BBHRP March 2000–February 2001 dataset from the Southern Great Plains ACRF (SGP) and one case from the BBHRP Northern Slope of Alaska (NSA) ACRF. Additionally, this NSA case is the basis of the fifth cloud-free case, which evaluates the sensitivity of radiative fluxes to a doubling of the $CO_2$ concentration from the year 2004 value. One cloudy case comes from the SGP site and the other from the deployment in Pt. Reyes, California, of the ARM Mobile Facility (AMF). A synopsis of the cases is provided in Table 1, with detailed descriptions, specific data sources, and links to the respective input and output available at the CIRC Web site.

All input information typically needed by a GCM-type radiative transfer algorithm to calculate radiative fluxes and heating rates is provided, namely profiles of atmospheric pressure, temperature, gas concentrations, aerosol single scattering properties, cloud fraction/water path/effective particle size, and spectral surface albedo. A comprehensive list of all input components and details on their derivation or specification can be found at the CIRC Web site. The high-resolution thermal reference results were obtained with the Line-By-Line Radiative Transfer Model (LBLRTM, v11.3) run on a spectral grid of ~0.001 cm$^{-1}$. The reference results at solar wavelengths were obtained by first running LBLRTM to calculate gaseous absorption optical depths at high spectral resolution, then using these as input to the adding-doubling Code for High-Resolution Accelerated Radiative Transfer with Scattering (CHARTS). For all reference calculations, the most accurate current spectroscopic parameters were used. The output from the reference calculations consists of surface and TOA fluxes provided at a spectral resolution of one wavenumber (1 cm$^{-1}$) and broadband thermal flux and heating rate profiles. The present CHARTS design does not provide multilevel radiative fluxes from a single run, so output is currently limited to fluxes at the boundaries of the atmospheric column, but additional atmospheric levels (such as the tropopause) may be added in the future. The output requested from CIRC participants consists of broadband thermal and solar flux and heating rate profiles. Some of the provided input, such as finely resolved (1 $cm^{-1}$) spectral surface albedo, is typically not available in operational GCMs, but for the purposes of CIRC a detailed description is necessary to provide flexibility for the participants to build their own coarse descriptions of spectral surface albedo. On the other hand, input information that some models require may not be provided (e.g., aerosol composition for internal calculation of their optical properties). While CIRC would ideally receive submissions from runs where the model uses as much of the information provided as possible, even if this requires small modifications to the RT algorithms from operational settings, submissions from runs where the algorithms operate with assumptions and input corresponding more closely to routine operational conditions are also encouraged.

**WHAT CIRC INTENDS TO ACCOMPLISH.** CIRC seeks to provide standards against which radiation code performance will be documented in scientific publications, in coordinated joint modeling activities such as GCM intercomparisons, or important international undertakings such as the radiative forcing calculations for the assessment reports of the IPCC. Preliminary results (see Fig. 2) indicate that a great deal may be learned about the approximations, assumptions, and overall behavior of GCM-class radiation codes from the relatively simple CIRC cases. While it is understood that the CIRC reference calculations reflect current spectroscopic knowledge and may themselves be imperfect, the intent is to update them whenever algorithmic or database improvements are available. Even though prior experience indicates that LBL codes generally agree with each other very well (e.g., the 2006 *JGR* article by Collins et al.), submission of results from other LBL implementations (e.g., including scattering in the infrared) is welcomed and may prove useful for further validation of the reference results.

The first-order goal of CIRC is to document the performance of the participating models relative to the reference calculations, emphasizing foremost absolute rather than perturbative (i.e., forcing) accuracy. This stems from CIRC's design to rely on observations to establish the credibility of the reference results. While forcing is also important and will be addressed to the extent possible, RT model performance cannot be critically evaluated without first directing attention to operational GCM requirements for current climate simulations and comparisons with observations. As implementation details provided by the participants are better understood, performance targets will be established for evaluating model performance. Such targets will essentially be communal standards for the evaluation of RT algorithms, and may be further used for assessments of the reliability of radiative forcings and feedbacks generated by GCMs using these algorithms. Suggestions from participants, users of the dataset, and atmospheric radiation practitioners will be essential for forming a consensus on these performance targets and for supporting the continual nature and success of the CIRC effort.

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## FOR FURTHER READING

Clough, S. A., M. W. Shephard, E. J. Mlawer, J. S. Delamere, M. J. Iacono, K. Cady-Pereira, S. Boukabara, and P. D. Brown, 2005: Atmospheric radiative transfer model-

ing: A summary of the AER codes. *J. Quant. Spectrosc. Radiat. Transfer,* **91,** 233–244.
Collins, W. D., and Coauthors, 2006: Radiative forcing by well-mixed greenhouse gases: Estimates from climate models in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4). *J. Geophys. Res.,* **111,** D14317, doi:10.1029/2005JD006713.
Ellingson, R. G., and Y. Fouquart, 1991: The intercomparison of radiation codes in climate models: An overview. *J. Geophys. Res.,* **96**(D5), 8925–8927.
——, and W. J. Wiscombe, 1996: The Spectral Radiance Experiment (SPECTRE): Project description and sample results. *Bull. Amer. Meteor. Soc.,* **77,** 1967–1985.
——, J. Ellis, and S. Fels, 1991: The intercomparison of radiation codes used in climate models: Long wave results. *J. Geophys. Res.,* **96**(D5), 8929–8953.
Fouquart, Y., B. Bonnel, and V. Ramaswamy, 1991: Intercomparing shortwave radiation codes for climate studies. *J. Geophys. Res.,* **96**(D5), 8955–8968.
Moncet, J.-L. and S. A. Clough, 1997: Accelerated monochromatic radiative transfer for scattering atmospheres: Application of a new model to spectral radiance observations. *J. Geophys. Res.,* **102,** 21,853–21,866.
Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Miller, Eds., 2007: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge University Press, 996 pp.
Turner, D. D., and Coauthors, 2004: The QME AERI LBLRTM: A closure experiment for downwelling high spectral resolution infrared radiance. *J. Atmos. Sci.,* **61,** 2657–2675.

## WEB RESOURCES

- http://circ.gsfc.nasa.gov
- http://engineering.arm.gov/~shippert/BBHRP/
- http://www.arm.gov/publications/proceedings/conf12/extended_abs/mlawer-ej.pdf