The State of the ARM-IRF Accomplishments through 1997

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Introduction

The U.S. Department of Energy (DOE) launched the Atmospheric Radiation Measurement (ARM) Program in 1989 with a programmatic goal of improving the parameterization of the physics governing cloud and radiative processes in general circulation models (GCMs). One specific goal of ARM is to improve the treatment of radiative transfer in GCMs under clear-sky, general overcast, and broken cloud conditions. This task falls mainly under the auspices of one of ARM's major research working groups—the Instantaneous Radiative Flux (IRF) working group. The purpose of this paper is to summarize the major accomplishments of the IRF activity associated with the noted ARM programmatic goal.

The major emphasis of the IRF to date has been on clear-sky radiation, primarily because the uncertainties in this area had been identified by the Intercomparison of Radiation Codes used in Climate Models (ICRCCM) (Ellingson and Fouquart 1991; Ellingson et al. 1991; Fouquart et al. 1991), and because the instrumentation for this activity, particularly for longwave radiation, was the most mature. Before discussing the IRF accomplishments, it is perhaps instructive to review the ICRCCM findings.

For the clear-sky longwave problem, ICRCCM concluded:

- There is a clustering of many models in the ±2% flux range relative to line-by-line models. This is in the marginal range to meet the accuracy (relative) requirements of major climate programs.
- Uncertainties in the physics of line wings and in the proper treatment of the water vapor continuum make it impossible for line-by-line models to provide an absolute reference.
- The large discrepancies revealed by the model comparisons can only be resolved by well-calibrated spectral observations because the uncertainties associated with broadband observations are the same magnitude or larger of the discrepancies between models (5% or 20 W m^{-2}).

For shortwave (SW) radiation (wavelengths < 4 μm), ICRCCM concluded:

- Different parameterizations for H_2O absorption may lead to significant differences between band model results.
- If the discrepancies attributable to various water vapor transmittances are removed, flux calculations at the surface generally agree to within 1%.
- Provided that the Rayleigh optical thickness is adequately parameterized, climate model codes appear to simulate clear-sky fluxes in reasonable correspondence with results from the high-resolution codes.
- More definitive recommendations will emerge only from comparisons of high-resolution calculations with high precision observations.

In the material that follows below, we summarize the progress of the IRF to ascertain uncertainties in both short- and long-wave radiation model calculations.

Longwave Radiation

The initial IRF thrust was on the validation of longwave line-by-line models because this appeared to offer a relatively fast return since a prototype experiment had already been planned and executed [Spectral Radiance Experiment (SPECTRE); Ellingson and Wiscombe 1996], the necessary spectral radiance measuring devices—particularly the University of Wisconsin-built Atmospheric Emitted Radiance Interferometer (AERI)—had been shown to be accurate and robust, and this was a necessary step prior to major advancement on cloudy-sky problems. The strategy for the validation was to compare AERI measurements of the downwelling spectral radiance with line-by-line model calculations that used simultaneously measured vertical profiles of temperature and water vapor as input. For the most part, IRF studies use the Clough et al. (1992) line-by-line radiative transfer model (LBLRTM), as this model includes an advanced treatment of the water vapor continuum and is readily accessible to ARM scientists.

As an example of AERI data, Figure 1 shows spectra measured by different AERI instruments at the Southern Great Plains (SGP) cloud and radiation testbed (CART) site and at the Surface Heat Budget of the Arctic Ocean (SHEBA) ice station in comparison to the Planck radiance at the near surface temperatures. Note that as the temperature decreases, the peak in the Planck function shifts to longer wavelengths. Furthermore, as the columnar water vapor burden decreases, the 20 µm region of the pure rotation band of H_2O, which is normally opaque at the SGP, opens. The major problem for the IRF has been the determination of uncertainties in the calculations in the atmospheric and "Arctic" windows, since the remaining portions of the spectrum are too opaque at the earth's surface to ascertain model sensitivity to water vapor or the other major trace gases.

Despite the early success from SPECTRE, the ARM IRF initially made very slow progress on the longwave problem, because of several unforeseen problems associated with *operational* use of the instrumentation. Problems included alignment difficulties with the AERI, aerosol scouring and bird droppings on the AERI mirrors, and reoccurring, but different, radiosonde relative humidity calibration errors. The operational difficulties, however, led to major improvements in the AERI and the radiosondes, although those are not the topics of this paper.

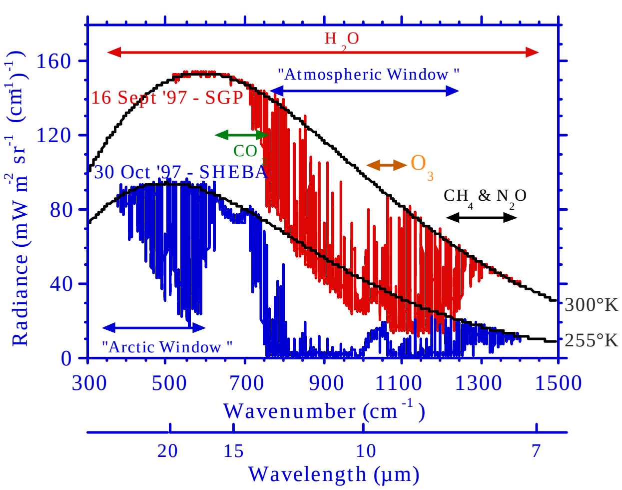

Figure 1. AERI spectra from the SGP and SHEBA in comparison to the Planck radiance (continuous smooth curves) for the respective near surface temperatures. The ranges of absorption by various atmospheric gases are shown for illustrative purposes. (For a color version of this figure, please see *http://www.arm.gov/docs/documents/technical/conf_9803/ellingson-98.pdf*.)

Following an extended study of the AERI, the model calculations and a variety of ARM water vapor measuring devices, the IRF concluded that the most accurate water vapor measurement was the columnar water vapor amount determined from observations by the microwave radiometer (MWR). This conclusion is based on accurate knowledge of the 22-GHz water vapor line parameters. In order to increase the accuracy of the vertical profile of water vapor measured by the ARM-launched radiosondes, the radiosonde specific humidities are scaled by the ratio of the MWR to radiosonde columnar water, as this gives the same columnar water for both the MWR and radiosondes.

As an example of the magnitude of the spectral distribution of differences between AERI observations and LBLRTM calculations, Figure 2 shows the mean spectral differences for all clear-sky days in October 1997 resulting from both the original and MWR-scaled sonde data. For comparison purposes, note that the absolute accuracy of the AERI is about 1 radiance unit. Thus, it is easily seen that on average, the MWR-scaled sonde AERI-LBLRTM residuals are of the order of the accuracy of the observations over most of the 10 µm window region. Similar comparisons in the Arctic window region have just begun.

For many climate applications, it is the total flux error that is of interest rather than the spectral radiance. We estimate the uncertainty of the flux calculations at the SGP by multiplying the spectrally integrated AERI-LBLRTM residuals by the ratio of the LBLRTM flux to LBLRTM vertically downwelling spectral radiance (see Ellingson and Wiscombe 1996). Figure 3 shows the distributions of the AERI-LBLRTM flux differences based on the original and

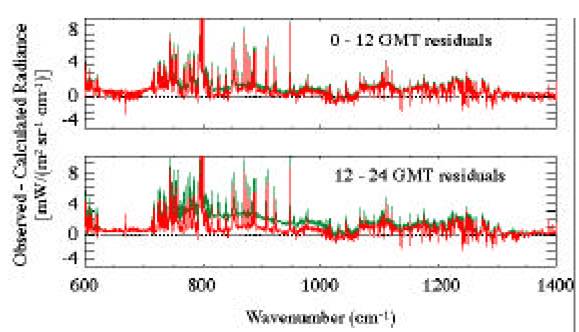

Figure 2. AERI-LBLRTM residuals for October 1997. The larger residuals for each time period result from calculations with the radiosonde water vapor profiles, whereas the smallest ones are the result of using the MWR-scaled profiles. (For a color version of this figure, please see *http://www.arm.gov/docs/documents/ technical/ conf_9803/ellingson-98.pdf*.)

MWR-scaled radiosonde observations for all clear-sky cases dating to 1994. As shown, the MWR-scaled root mean square (rms) flux difference is about 2 W m^{-2}. This is about an order of magnitude improvement over the stated observational (and thus model) flux accuracy at the start of ARM.

Simply stated, the major finding of the ARM IRF is:

- Line-by-line model calculations of downwelling longwave fluxes show agreement with AERI data to within 2 W m^{-2} rms for clear-sky conditions. *Uncertainties in the routine water vapor observations provide the current limitation on these comparisons.*

In addition to the comparison of observations with calculations reported herein, there have been several additional longwave advances by members of the ARM IRF. These include the following:

- Refinements have been made in LBLRTMs, particularly the water vapor continuum (SHEBA is providing very exciting new information).

- A rapid radiative transfer model (RRTM, Mlawer et al. 1997) for use in climate models has been developed that agrees with LBLRTM to 1 W m^{-2}.

- The GCM modeling community has begun incorporating the modeling developments supported by the ARM measurements in their radiation models [Geophysical Fluid Dynamics Laboratory (GFDL), Goddard Space Flight Center (GSFC) to some extent, British Met Office, European Centre for Medium-Range Weather Forecasts (ECMWF), and others].

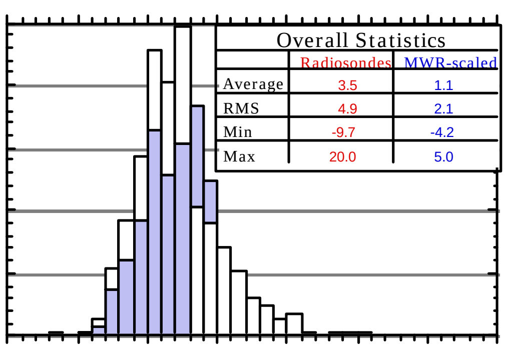

Figure 3. Distributions of the AERI-LBLRTM flux differences from 1994 through 1997 resulting from the use of radiosonde (open) and MWR-scaled (shaded) water vapor profiles in the calculations. (For a color version of this figure, please see *http://www.arm.gov/docs/documents/technical/conf_9803/ellingson-98.pdf*.)

Shortwave Radiation

While pushing the frontiers of SW spectral radiometry, ARM IRF scientists have made significant forays on SW radiation problems using broadband radiometry. Perhaps the most well-known of these is the ARM Enhanced Shortwave Experiment (ARESE) that attempted to measure the absorption of solar radiation by clouds (e.g., Valero et al. 1997; Zender et al. 1997). Although there is not yet universal agreement on the amount or cause for the as-yet unexplained cloud absorption, ARESE has highlighted difficulties in making absorption measurements, uncertainties in model calculations in the presence of clouds, and the lack of standards for making SW spectral and total flux comparisons. As such, it has helped define ARM's future activities in SW cloud-radiation studies.

There have been several clear-sky SW closure studies (e.g., Halthore et al. 1997; Kato et al. 1997; Fu et al. 1998) using broadband radiometry for a limited set of cases. These studies have all highlighted the fact that uncertainty in the aerosol optical depth is the major source of error in the calculations. As an example of the magnitude of the aerosol uncertainty in the calculation of the direct beam flux, the study by Halthore et al. (1997) showed MODTRAN calculations agreeing with active cavity radiometers measurements to within about -1.5 ± 7.9 W m^{-2}. In general, it appears as if the agreement for the diffuse flux is the order of 20 W m^{-2} or greater for near overhead sun conditions. In addition to aerosol effects, the calibration of instrumentation for measuring the diffuse component appears to be a major source of uncertainty of these comparisons.

During the last year, Clough and his group at Atmospheric and Environmental Research, Inc. (AER) have begun to make systematic comparisons of LBLRTM calculations with observations of the spectral direct beam flux by the Absolute Solar Transmittance Interferometer (ASTI). At the January 1997 IRF Workshop, this group showed comparisons for the 500 cm^{-1} to 10,000 cm^{-1} region that result in flux errors of < 1 W m^{-2} . Overall, they found no evidence for gas X, water vapor dimers, or water vapor clusters in this spectral region.

Perhaps the greatest SW achievement during the past year was the first ARM SW Intensive Observation Period (IOP) during September 1997. This IOP emphasized spectral radiometry and calibration of the various sensors much in the manner of the 1991 SPECTRE for the longwave. The SW IOP obtained data for a variety of conditions, and data for six case studies (three cloudy and three clear-skies) are being compiled for use in testing our understanding of solar radiative transfer. Readers are encouraged to contact the leaders of the IOP, Warren Wiscombe and Graeme Stephens, for additional details.

ARM IRF-Related Observational Accomplishments

In addition to the accomplishments outlined above, the ARM Program has seen advances in the observations of radiation quantities that are related to or have resulted from IRF scientific studies. Most notable among these are:

- implementation of the 'Super Satellite on the Ground' with instrument accuracy and precision at or approaching the level required for many IRF studies.
- operational inference of downwelling longwave fluxes with the AERI for homogeneous scenes to better than 5 W m^{-2}—a reduction of observational uncertainty by about a factor of 4.
- demonstration of a ±10 W m^{-2} measurement accuracy for the total horizontal solar irradiance by summing the diffuse and direct components.
- the SGP CART site as a satellite validation location is routinely being used by many different agencies [National Aeronautics and Space Administration (NASA), National Oceanic and Atmospheric Administration (NOAA), U.S. Department of Defense (DOD), and groups using Global Positioning System (GPS)].

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