Initial Analyses of Surface Spectral Radiance Between Observations and Line-by-Line Calculations

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Introduction

The evaluation and improvement of radiative transfer calculations are essential to attain improved performance of general circulation models (GCMs) for climate change applications. A Quality Measurement Experiment (QME) is being conducted to analyze the spectral residuals between the downwelling longwave radiance measured by the University of Wisconsin Atmospheric Emitted Radiance Interferometer (AERI) and spectral radiance calculated by the Line-By-Line Radiative Transfer Model (LBLRTM). The three critical components of this study are 1) the assessment of the quality of the high resolution AERI measurements, 2) the assessment of the ability to define the atmospheric state in the radiating column, and 3) the evaluation of the capability of LBLRTM. Validations have been performed on spectral radiance data, obtained from April 1994 through July 1994, through the analysis of the spectral residual differences between measured and calculated radiances. These residuals are analyzed by both spectral interval and physical process. The results are archived as a function of time, enabling the retrieval of specific data and facilitating investigations of diurnal effects, seasonal effects, and longer-term trends. While the initial focus is restricted to clear-sky analyses, efforts are under way to include the effects of clouds and aerosols. Plans are well formulated for the extension of the current approach to the shortwave. An overview of the concept of the QME is described by Miller et al. (1994), and a detailed description of this study is provided by Clough et al. (1994).

Spectral Radiance Observations and Calculations

Measurements of downwelling radiance at the surface are obtained from the AERI instrument at the Southern Great Plains (SGP) Cloud and Radiation Testbed (CART) central facility in Lamont, Oklahoma. The AERI is a zenith viewing instrument with a spectral resolution of 0.5 cm^{-1} (wavenumber value to first zero of unapodized spectrum). Radiance calculations are performed using LBLRTM (Clough et al. 1981), which includes a full water vapor continuum model (Clough et al. 1989; CKD) that has been updated to provide improved agreement with atmospheric observations (CKD_2.1). The atmospheric column is partitioned into 54 layers, chosen to accurately model the transfer of radiation to the surface. Quality controlled radiosonde data are ingested directly into the model at all reporting levels from which the temperature and water vapor column amounts are calculated. This layering also facilitates the calculation of cooling rates, which are important for other aspects of the Atmospheric Radiation Measurement (ARM) Program.

Definition of the Atmospheric State

A spectral validation is currently performed for each radiosonde release, four times per day under standard conditions and eight times daily during Intensive Observation Periods (IOP). Temperature and water vapor profiles are obtained from the radiosonde observations. A constant ozone profile has been derived from a retrieval based upon an April 23, 1994, AERI spectral radiance measurement. The characterization of atmospheric state from radiosonde measurements is a major concern, not only from the point of view of accuracy, but from the point of view of spatial and temporal displacement from the radiating column for atmospheres with variability.

Spectral Validations

Spectral residuals are obtained by subtracting LBLRTM calculated results from the measured AERI spectra. The residuals are statistically analyzed using two approaches: 1) by spectral domain, similar to those from GCM bands; and 2) by physical process, as determined by assigning each spectral element to a physical process (e.g., spectral elements associated with H_2Olines). Figure la shows an AERI spectrum taken in June 1994. Channel 1, spanning 550−1800 cm^{-1}, is the current region of principal emphasis because of its importance for climate related studies. Radiance in the saturated regions of CO_2 from 630−705 cm^{-1} and of H_2O from 1350−1800 cm^{-1} are dominated by characteristics of the Planck function associated with the atmosphere near the instrument. H_2O lines provide the dominant structure in the window regions at 800−980 cm^{-1} and 1080−1200 cm^{-1}, and O_3 lines are dominant in the 980−1080 cm^{-1} region. The strong effects of the underlying water vapor continuum between spectral lines is seen throughout the 800−1200 cm^{-1} window region.

The spectral residuals for this observation, as shown in Figure lb, are typical of those observed at the CART site within the time period of this analysis, from April 7 to July 30, 1994. Integration of the residuals over the spectral domain of Figure 1 provides a result of 1.7 W/(m^2 sr) in zenith radiance. An estimate of the difference in flux between the observed and model values for the atmospheric window region may be obtained by multiplying the integrated residual value by five. These large residuals in the window region do not exhibit spectral behavior characteristic of errors in the water vapor continuum.

The QME products include statistical results by spectral domain as well as by physical process. As shown in the expanded plot in the lower left of Figure 1a, spectral elements in the regions denoted by the sharp spikes

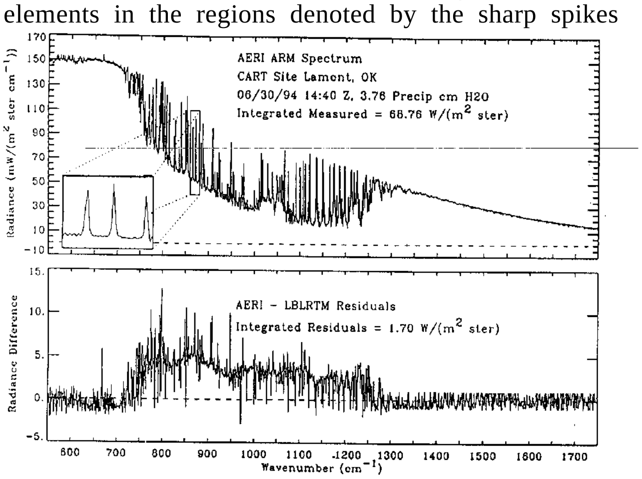

Figure 1. (a) AERI observed radiances and (b) spectral radiances between observed and LBLRTM calculated radiances.

are associated with molecular lines; spectral elements in the regions between the lines, referred to as "transparent" regions, reflect the radiative effects of the water vapor continuum, aerosols and clouds.

An important objective of the QME is to control the quality of the data set. Problems associated with the loss of the liquid N_2 coolant in the instrument, resulting in the degradation of sensitivity in the detector, occurred during this time period. The affected spectra are characterized by a significant increase in measurement noise, and have been excluded from the analyses.

Initial Analyses

Figure 2 shows the equivalent brightness temperature in the channel 1 window versus the equivalent brightness temperature in the channel 2 window. The window brightness temperatures in channels 1 and 2 are determined from the average radiance across the spectral intervals 1142–1147 cm^{-1} and 2506–2511 cm^{-1}, respectively. Circles refer to clear-sky cases, while stars denote non-clear cases. This information is contained in the QME cloud product platform and is currently obtained from the cloud base heights given by the Belfort ceilometer and the National Aeronautics and Space Administration Micro-Pulse Lidar (MPL), as well as the total liquid water in the line of sight of the microwave radiometer (MWR). The dotted line indicates the values at which the brightness temperatures in the channel 1 and channel 2 windows are equal. The stars along this line in Figure 2 are associated with warm, opaque clouds. Cloudy cases with lower

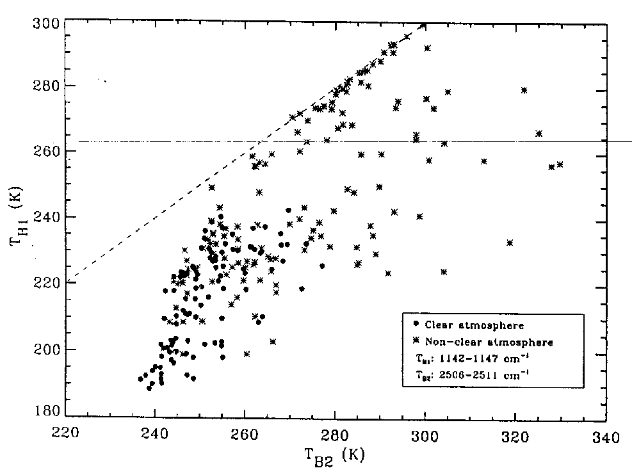

Figure 2. Channel 1 window brightness temperatures as a function of channel 2 window brightness temperatures for clear and non-clear atmospheres.

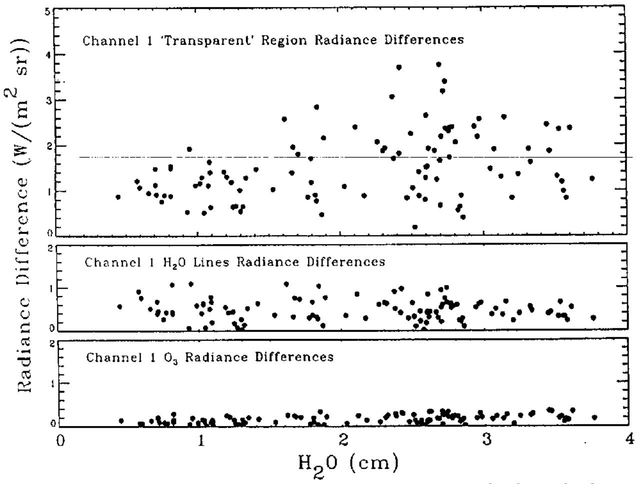

Figure 4. Integrated spectral residuals by physical process as a function of radiosonde observed water vapor amounts.

window temperatures are associated with high, cold, thin clouds. The higher brightness temperatures in the channel 2 window with a high degree of variability are caused by solar scattering from clouds and aerosols. Efforts are currently under way to assess the extent to which solar radiation may be entering the AERI light pipe directly.

Analyses of diurnal variation can be explored, as shown in Figure 3, where integrated spectral differences are analyzed as a function of time of day in Greenwich Mean Time (GMT). There is a difference of six hours between GMT and Lamont local time during daylight savings time. Only clear-sky cases are plotted, distinguished by month. The columns indicate the daily radiosonde launch times, with 3 Z, 8 Z, 11 Z, and 23 Z reflecting the additional radiosonde launches during the April and July 1994 IOPs. The systematic difference from day to night on the order of 1.5 W/(m^2 sr) is currently unexplained.

A plot of integrated spectral residuals by physical process as a function of water vapor amounts is shown in Figure 4. Only clear-sky cases are shown and cover a wide range of precipitable water, from 0.5 to 4.0 precipitable centimeters. The dominant processes in this spectral region are those associated with absorption in the "transparent" regions between the lines, which include the continuum, aerosols and thin cloud, and the spectral elements associated with water vapor lines and ozone lines. The sum of these differences in Figure 4 reflect 98% of the total difference in channel 1. Although a constant ozone profile is used, the differences associated with the ozone region of Figure 4c, on the order of 0.3 W/(m^2 sr), are remarkably good considering the seasonal variation of O_3. It is of interest that the differences associated with

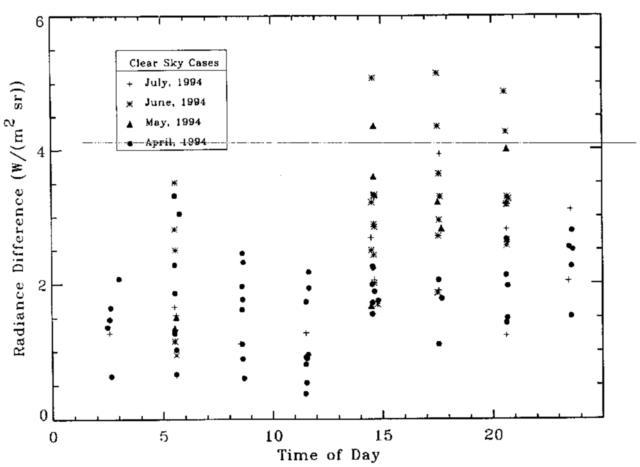

Figure 3. Channel 1 integrated radiance differences as a function of time of day.

H_2O lines, as shown in Figure 4b, are not correlated with water vapor, though there is an apparent small linear correlation between the differences associated with the transport regions with the water vapor column as shown in Figure 4a. Most importantly, the lack of a quadratic correlation between the differences associated with the transparent regions and water vapor indicates that these differences are not attributable to the water vapor continuum. A linear correlation is more consistent with the hygroscopic growth of aerosols and the consequent increase in the aerosol radiative effects.

Conclusions

The AERI/LBLRTM QME has been effective in assessing problems associated with the measurement of downwelling spectral radiance, the characterization of the atmosphere in the radiating column, and the line-by-line calculations. Issues including the loss of liquid N_2 fill in the AERI dewar and the switch from nominal mode to research mode in the processing of the radiosonde data have been identified and addressed. There are two important conclusions that can be drawn from this initial analysis of the QME products: 1) the residuals in the important channel 1 window for the clear sky are anomolously large corresponding to ~ 10 W/m^2 in flux and 2) the specification of atmospheric state for the radiating column to the requisite accuracy is a difficult but tractable task.

Clear-sky analyses show that the integrated radiance differences for validations of AERI measurements taken at the ARM SGP Central Facility are significantly higher than spectral validation between AERI measurement and the LBLRTM calculations from Coffeyville, Kansas, during the Spectral Radiance Experiment (SPECTRE) in November and December 1991. The integrated spectral radiance differences for SPECTRE are on the order of 0.5 W/(m^2 sr) while those from ARM are 2.0 W/(m^2 sr). We have established that this difference in the ARM validations is not attributable to the water vapor continuum. Radiative effects of aerosols or thin clouds may play a role, but the extinctions required appear to be too large. Another possible contributor to the residuals is the AERI calibration at low radiances. Inclusion in the calculation of the effects of HNO_3 and improvements in the halocarbon mixing ratios are expected to provide some reduction in the residuals, but nothing approaching the required amount.

With respect to the task of adequately specifying the atmospheric state, the anticipated availability of Raman lidar and Radio Acoustic Sounding System (RASS) observations is expected to provide improvement in the water vapor and temperature profiles, respectively, particularly with respect to the spatial and temporal sampling issue. Absolute calibration of both instruments remains an important and difficult task. It is clear that more information on aerosols is essential; at an absolute minimum, a value for the extinction in the visible is required.

This initial analysis strongly supports the QME as a strategy to assess our current capability to measure and model longwave radiation in the study of climate change. Before the approach can become fully effective, an explanation for the ubiquitous and anomalous residuals in the window regions must be resolved. Work is under way toward the inclusion of cloud and aerosol effects in the model calculations and in the calculation of atmospheric cooling rates from 10–3020 cm^{-1} for single column model applications. In addition, analyses of validations in the microwave region between the MWR and LBLRTM are currently being implemented. Future plans include the assessment of potential improvement in atmospheric state measurement from the RASS and Raman Lidar, and the extension of the analysis to solar spectra, as measured at the central facility by the University of Denver Solar Radiance Transmission Interferometer and the Absolute Solar Transmission Interferometer, and to the shortwave spectral region.

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