OBSERVATIONS FOR VALIDATING RADIATIVE TRANSFER PARAMETERIZATIONS

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1. INTRODUCTION

Over the past decade, many research programs have made significant progress toward understanding the potential for global climate change and the resulting consequences. Models of the global climate system have advanced to include realistic geography, the annual cycle of the seasons, and varying cloud cover. More recently, models have evolved to include coupling between the oceans and the atmosphere. Results of global climate models (GCMs) suggest that projected greenhouse gas emissions may lead to a global warming of 1.5 to 4°C and to significant changes in water availability during the next century.

The above mentioned research has also revealed that there are considerable uncertainties in the model predictions due to imprecise knowledge of a variety of physical processes. As a result, we do not know with sufficient accuracy how large the climatic changes will be, how rapidly the changes will occur, or how the changes will be distributed over the globe.

Changes in cloud cover and cloud optical properties are major factors in determining the magnitude of potential warming resulting from increased concentrations of greenhouse gases. Furthermore, the accuracy of radiative transfer calculations affects the accuracy of climate sensitivity. Together they control the radiative forcing that drives the key feedbacks of the global climate system. As a result, the U.S. Committee on Earth and Environmental Sciences has identified cloud-climate interactions as the highest research priority within the U.S. Global Climate Change Research Program to produce the needed improvements in GCMs.

At the heart of improving our knowledge of cloud-climate interactions is the validation of the parameterizations used in climate models. Since climate models are very sensitive to different aspects of the radiation budget, it is particularly important that validity of the radiation models be established.

Several different observation programs have arisen to meet the challenge of improving our knowledge of cloud-climate-radiation interactions, such as FIRE in the U.S. and EUCREX in Europe. A comprehensive discussion of all such programs would be very difficult. Instead, I have decided to review observation programs sponsored by a relative new-comer to climate-related radiation observation programs, the U.S. Department of Energy (DOE).

2. U.S. DOE RADIATION PROGRAMMES

The DOE is charged with developing the national energy strategy (NES). The use of fossil fuels and the projections of potential global climate change play significant roles in the development and evolution of the NES. As such, DOE has played a major role in developing reliable simulations of regional and long-term climate change in response to increasing greenhouse gases.

DOE has begun three major radiation-related programs during the past five years, including the Spectral Radiation Experiment (SPECTRE), the Atmospheric Radiation Measurements (ARM) programme, and the ARM Unmanned Aerospace Vehicle Programme (ARM-UAV). These programmes are described briefly below, and those are followed by preliminary results concerning our ability to calculate one component of the radiation budget, clear-sky longwave radiation.

2.1 The SPECTral Radiation Experiment (SPECTRE)

SPECTRE arose from the InterComparison of Radiation Codes in Climate Models (ICRCCM) which showed large differences between model calculations of longwave fluxes and heating rates - even for clear-sky conditions (see Luther et al., 1988; Ellingson et al., 1991). The discrepancies could not be resolved with either conventional measurements or line-by-line model calculations because:

- Pyrgeometer errors (≈5%) are the magnitude of the discrepancies, and
- Uncertainties in the physics of line wings and in the proper treatment of the continuum make it impossible for line-by-line models to provide an absolute reference.

The 1984 and 1988 ICRCCM Workshops called for a detailed spectral radiation experiment to resolve the discrepancies. After several years of prodding different agencies, the author and Warren Wiscombe of NASA were able to assemble a science team and obtain funding for SPECTRE from DOE and NASA.

Simply stated the goal of SPECTRE is to close the loopholes by which longwave radiation models have eluded incisive comparisons with measurements.

The approach is quite simple in concept, namely: accurately measure the zenith infrared radiance at high spectral resolution while simultaneously profiling the radiatively important atmospheric properties with conventional and remote sensing devices.

Although the goal and approach are simple, the practical aspects of the experiment are not. The execution of the experiment required the construction of a "super satellite on the ground" with instruments from a variety of investigators. In order to minimize costs and to maximize synergistic opportunities, SPECTRE was planned for and carried out as part of the FIRE Cirrus II in Coffeyville, Kansas, USA between 13 Nov. and 7 Dec. 1991.

Some details concerning the experiment are described in Ellingson et al. (1993), and a more detailed description is in preparation. Briefly, high resolution observations of the vertically downwelling spectral radiance in the 3 to 20 μm region were obtained simultaneously by three surface-based FTIR spectrometers. Concurrent with these observations were *insitu* and remote measurements of the atmospheric radiative properties necessary for the calculation of the spectral radiance. The spectral measurements were carried out by groups from the University of Wisconsin, Denver University, and NASA Goddard, led by William Smith, Dave Murcray, and Virgil Kunde, respectively. The spectrometers were self- and-inter- calibrated in the field to achieve close to 1% full-scale accuracy. The remote measurements included temperature profiles with the Radio Acoustical Sounding System (RASS) and the Raman lidar water vapor profiling system developed by NASA (Melfi et al., 1989). Examples of spectra from extreme conditions are shown in Fig. 1.

The proposal for SPECTRE served as the blueprint for the Science Plan of ARM which was inaugurated several months after the planning for SPECTRE. ARM calls for special attention to more general cloud-radiation problems, whereas SPECTRE is directed at case studies of clear-sky and homogeneous cloud cover conditions (particularly cirrus). Nevertheless, the instrumentation deployed during SPECTRE served as prototypes for the ARM central facility discussed below, and the data collected during SPECTRE will serve many ARM scientists as well as ICRCCM participants. A limited set of those data are available electronically from the author (bobe@atmos.umd.edu). The complete set of SPECTRE data will be available on CD-ROM early in 1995.

2.2 Atmospheric Radiation Measurements Programme (ARM)

The ARM program is the flagship of DOE's contribution to the U.S. Global Climate Change Research Program. The DOE initiated ARM in 1990 to provide an experimental test bed for the study of cloud and radiative processes with the ultimate goal of improving the performance of general circulation models for global and regional prediction of climate change. The concept of the program is to acquire high-quality, long-term data at sites representing important climatological regimes, to conduct long-term and campaign experiments and to establish strong coordination among the U.S. National Laboratories, the non-DOE scientific community, and national and international research programs. During the past five years, several key experiment locales have been identified, a science team has been selected, a few short term experiments have been conducted, and the first permanent surface site has been established. ARM is described in detail by DOE (1990) and Stokes and Schwartz (1994). The reader is encouraged to consult those documents for detailed program information.

The heart of ARM is the Cloud and Radiation Testbed (CART), a flexible facility designed to facilitate the comparison of model predictions with observations. The CART site experimental configuration is designed to determine the boundary conditions, the initial conditions of the prognostic variables and the time evolution of the prognostic variables being predicted by the models. As described in the ARM Program Plan (DOE, 1990), CART will consist of a carefully selected complement of instruments at each the permanent base sites. There are three experimental components in the ARM design: a central observing facility, a three-dimensional mapping network and a set of extended observing stations. It should be noted, however, that all sites will not have the same instrument complement, as that is dictated by the scientific objectives of the individual sites. Nevertheless, it is expected that the concept of a nested experimental design built around a central facility will typify each site.

Two classes of instruments will be deployed at the central facility: those for measuring the radiation fields directly and those intended to characterize the local radiative circumstances such as surface and cloud properties. The focus of the observations at the central facility will be the detailed characterization of the atmospheric column above the facility and high spectral resolution instruments.

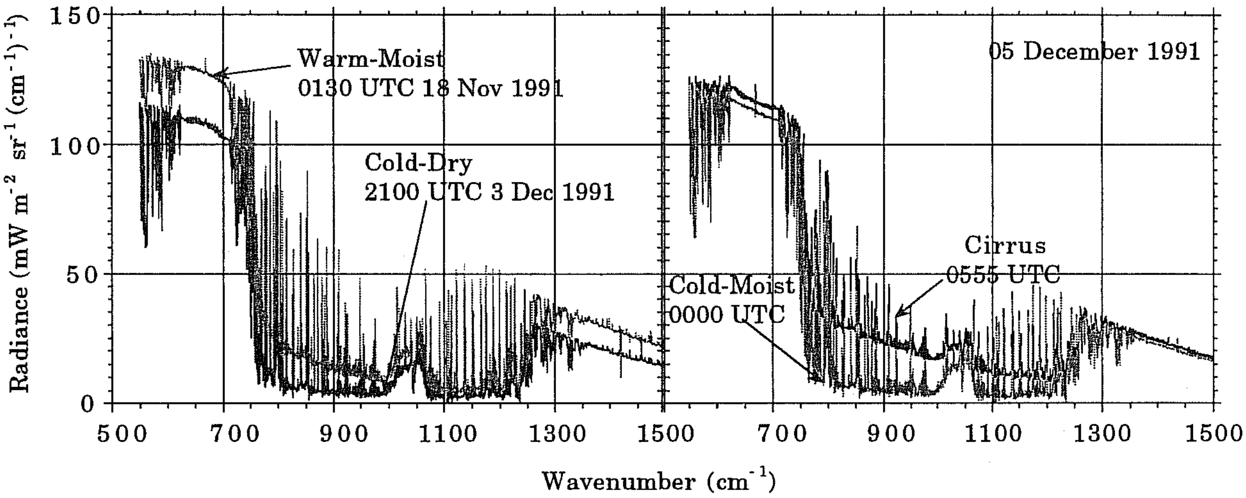

Fig. 1 Examples of spectra measured by the University of Wisconsin AERI interferometer for a range of conditions during SPECTRE.

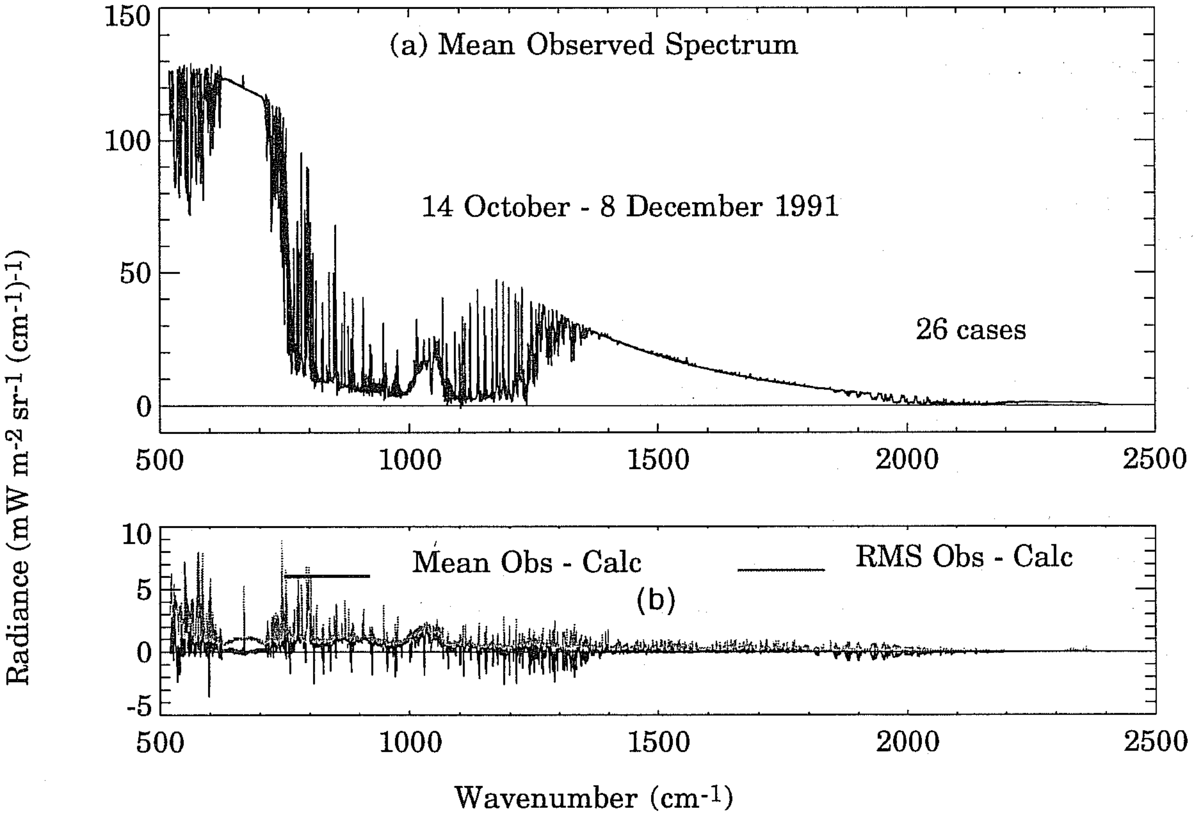

Fig. 2 (a) Mean of spectra observed on 26 clear occasions durring SPECTRE.
(b) Observed minus line-by-line model calculated spectra for the 26 cases.

A series of auxiliary stations will surround the central facility within a 20 km radius. These stations will contain instrumentation designed to measure the three-dimensional structure of the atmosphere near the base site and will make use of fundamental profiling equipment, as well as basic radiometric and meteorological equipment. A focus of the specialized stations will be the reconstruction of the cloud geometry surrounding the base site using state-of-the-art photogrammetric methods. This cloud visualization system will be supplemented with a system of wind profilers capable of measuring large-scale vertical velocities.

Distributed around the central facility and the mapping network will be an array of 16 to 25 smaller observing stations. These stations will support the development and study of methods used to generalize detailed atmospheric models for use in GCMs through the process of parameterization. The extended observing area of a base site will include a region of the order of magnitude expected for GCM grid cells in the near future, about 200x200 km. The instruments at the extended stations will be designed to collect the basic radiometric information and conventional meteorological data needed to characterize the radiative transfer throughout the extended area. Only limited vertical information will be collected, with the more extensive and demanding profiling equipment reserved for the base sites and mapping stations. Wind profilers will, however, be employed on this scale as well to observe the general vertical motions associated with mesoscale phenomena.

Ground-based instrumentation alone will not meet all of the observational requirements of ARM. As a result, both aircraft and satellite observations will play an important role in the experimental strategy. Some aircraft observations will be used on a regular basis to support calibration of remote sensing systems and to profile the radiation field as a function of altitude. Aircraft will also be used for direct sampling of key atmospheric constituents in support of intensive observational campaigns. Likewise, satellite measurements of top of the atmosphere radiative fluxes and profiles of atmospheric conditions beyond the range of ground-based sensors will play an important role.

Five locales have been identified as candidates for long-term occupation. These include: the Southern U.S. Great Plains, the Tropical Western Pacific, the North Slope of Alaska, the Eastern North Pacific/Atlantic Oceans, and the Gulf stream off Eastern North America. Details concerning the rationale for the recommendation of each locale may be found in the cited literature.

An ARM Science Team (AST) has been established by DOE from peer reviewed proposals submitted over the past four years. Additional opportunities for future participation will be widely advertised by the DOE.

The first ARM site became operational during 1993 in the U.S. Southern Great Plains (SGP). The central facility for the SGP site is located near the city of Lamont in the state of Oklahoma. For the past year, the site was instrumented to address primarily clear-sky related radiation problems. The instrument complement includes many of the same instruments that were used during SPECTRE. The deployment of instrumentation for the detection and tracking of clouds began during the past year, and analyses of those data by the AST has begun.

2.3 ARM Unmanned Aerospace Vehicles (ARM-UAV)

ARM-UAV is a research program using unmanned aerospace vehicles (UAVs) to make key climate measurements that cannot be made by other means. UAVs are remotely controlled or autopiloted aircraft and were originally developed for defense surveillance. Because they are unmanned, they have the potential for flying higher and longer than manned aircraft. This long endurance at high altitudes is an important property for calibration of satellite-borne instruments and for studying the interactions of clouds and radiation. By equipping the UAV with the proper payload and flying it at different altitudes one can directly measure the radiative heating rate for a precisely defined region (e.g., the CART site).

Given this potential for UAVs to make key climate measurements, a DOE-led team has undertaken a three phase program to make this a reality. The first phase, completed in April 1994, used an existing UAV, the General Atomics Gnat 750, and modified versions of broadband radiometers originally developed for manned aircraft by Francisco Valero of NASA to make the first-ever climate relevant observations from a UAV. The radiation instruments consist of up-and-down looking hemispheric field of view radiometers that cover the ranges from 0.3 to 4 and 4 to 25 µm and an up-looking, seven channel, Total Direct Diffuse Radiometer (TDDR). The absolute accuracy of the instruments is believed to be of the order of 1 to 2%. Thermistors for air temperature and a chilled mirror hygristor rounded out the instrument package.

Eight flights of the UAV were made over the SGP CART site during April 1994 under generally clear-sky conditions to demonstrate the capability of the UAV approach. The flights consisted of profiles between the surface and about 7 km, and constant level flight legs were flown at about 2.5 km intervals. The resulting data constitute a unique data set for studying atmospheric radiative heating, particularly since detailed data were taken at the CART site and radiosondes were launched while the UAV was above the CART site.

Succeeding phases of the program significantly extend these capabilities through two major thrusts. The first thrust develops compact, high accuracy, climate instruments specially designed for UAVs. These instruments include:

- a novel net flux radiometer for accurately measuring the difference between the up and down-welling radiation;
- a wide field of view, imaging cloud radiometer similar to the AVHRR for retrieving cloud reflectivity and for calibrating various satellite measurements;
- an eye-safe lidar for detecting and profiling thin cirrus which are difficult to measure by other techniques but which may make a significant contribution to Earth's radiation budget; and
- a small interferometer for high resolution spectral measurements that will allow a study of the detailed physics of cloud-radiation interactions.

The second thrust takes advantage of increasingly more capable UAVs to extend operations to higher altitudes and to multiple UAV operations for cloudy-sky measurements and for satellite calibrations. New UAVs, such as Aurora's Perseus-B, are now under development by industry and will be available during late 1994;

Three major campaigns are now scheduled:

- a cloudy-sky/satellite calibration mission, scheduled for fall 1994, takes advantage of higher altitude UAVs to directly measure radiative heating in clouds and to improve the estimation of radiative fluxes from satellite-based measurements;
- a long endurance mid-latitude tropopause mission, scheduled for spring 1995, extends the radiation measurements to multiple days at or slightly above the tropopause (~13 km); and
- a tropical Pacific mission, scheduled for N.H. winter 1995, further extends the measurements to 23 km to study radiation-cloud interactions involving tropical convection.

Additional information concerning the program may be obtained from John Vitko at Sandia National Laboratories, Livermore, CA, USA (510-294-2820; J.Vitko@gateway.omnet.com).

3. Results of COMPARISONS OF OBSERVATIONS WITH CALCULATIONS

3.1 Models used to perform calculations

We have compared SPECTRE, ARM and UAV observations with calculations from a variety of radiation models, including line-by-line, narrow-band and broad-band radiation codes. Identical meteorological sounding data was used as input to each model. All line-by-line calculations shown herein were done with the code LBLRTM, (version 3.2, continuum version 2.4) using the 92'HITRAN line database. Note that LBLRTM is a refinement of FASCODE3 (Clough et al, 1992), and is available from S. A. Clough, AER, Boston, MA.

The broad-band calculations were carried out with codes used in different climate models including: Colorado State University (CSU; Harshvardhan et al., 1987), European Center for Medium Range Weather forecasting (ECMWF, Morcrette, 1991), National Meteorological Center (NMC; Schwarzkopf and Fels, 1991), and the Community Climate Model (CCM1, Kiehl et al., 1987).

All of the radiation codes include effects of H20, CO2 and O3, although with different parameterizations. The LBLRTM and narrow-band calculations also include the effects of CH4 and N2O. The LBLRTM calculations also include the effects of other trace gases including F10 and F11 and CCl4. Note that climatological concentrations of CO2, CH4, N2O, F10, F11 and CCl4 are used throughout. O3 concentrations are specified by the appropriate climatological profile for calculations compared with ARM observations, whereas ozonesonde data are used for the SPECTRE comparisons.

The temperature profiles used in the calculations shown herein were obtained from radiosondes launched within 30 and 60 min of the spectra and UAV data, respectively. The water vapor profiles were specified from the radiosonde observations for comparisons made with UAV data, whereas Raman lidar observations were used to specify the profiles for the comparisons with SPECTRE spectra.

3.2 Results from SPECTRE

3.2.1 *Comparisons with line-by-line calculations*

Shown in Fig. 2 are: (a) the mean observed spectrum of downwelling radiance for 26 clear-sky SPECTRE cases, and (b) the spectra of the mean and rms observed - LBLRTM radiances. In general, the SPECTRE comparisons show mean and rms agreement between the observed and calculated radiances to within the accuracy of the observations (about 1% full scale) across the entire spectral region. The major discrepancies occur the in the region of the 9.6μm O3 band, which we attribute to improper specification of the O3 profile in one sounding.

If the parameterization for the water vapor continuum absorption in the 8-12 μm region were incorrect, there should be a marked correlation of the radiance difference and the total precipitable water (PW). The SPECTRE data show a high correlation of the differences on total precipitable water that is consistent with an underestimated continuum absorption and/or a dependence of aerosol loading on precipitable water. Nevertheless, the differences are within the uncertainty of the observations, and the PW falls but within a small range (0 to 2 cm). Therefore, we must conclude that there are not large errors in the most recent version of the continuum formulation, the form of which was discussed by Clough et al. (1989). Nevertheless, we are continuing to examine this formulation at higher water amounts with the ARM data to ensure its accuracy.

3.2.2 *Flux estimation with spectral data*

Climate modelers are anxious to test the ability of their radiation codes to calculate the total downward flux. The radiance observations can be integrated over the observed portion of the spectrum to yield estimates of the flux uncertainty if one assumes the angular variation is known. Note that for a given plane parallel, horizontally homogeneous atmosphere, the downward flux may be related to the vertically downward radiance I(1) as $F\downarrow = \pi I(1)L$ where

$$L = 2\int_0^1 \frac{I(\mu)}{I(1)}\mu d\mu \qquad (1)$$

$\mu = \cos\theta$, and θ is the local zenith angle. To first order, we assume L to be a property of the temperature and water vapor distributions and not of the ability to calculate I.

We calculated L from (1) using LBLRTM for the SPECTRE soundings at the 0.5 cm^{-1} resolution of the observations and have applied them to the observed spectra. The flux in the unobserved, but primarily opaque, region from 0 to 550 cm^{-1} region was estimated from the LBLRTM calculations. The results of our calculations show the mean and rms observed-model calculated fluxes to be 2.5 and 3.3 W m^{-2}, respectively.

John DeLuisi of NOAA carried out a pyrgeometer intercomparison during SPECTRE, and the data from that study allow the possibility of intercomparing model flux calculations with observations, and it also allows the possibility of calibrating the pyrgeometers with the interferometer. Shown in Fig. 3 is a

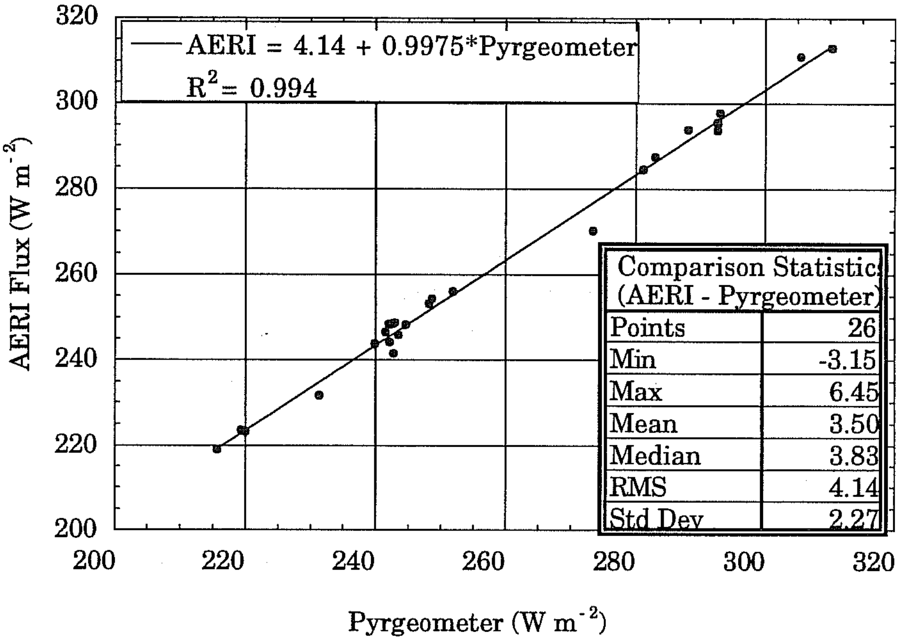

Fig. 3 Comparison of clear-sky pyrgeometer and AERI estimated fluxes during SPECTRE.

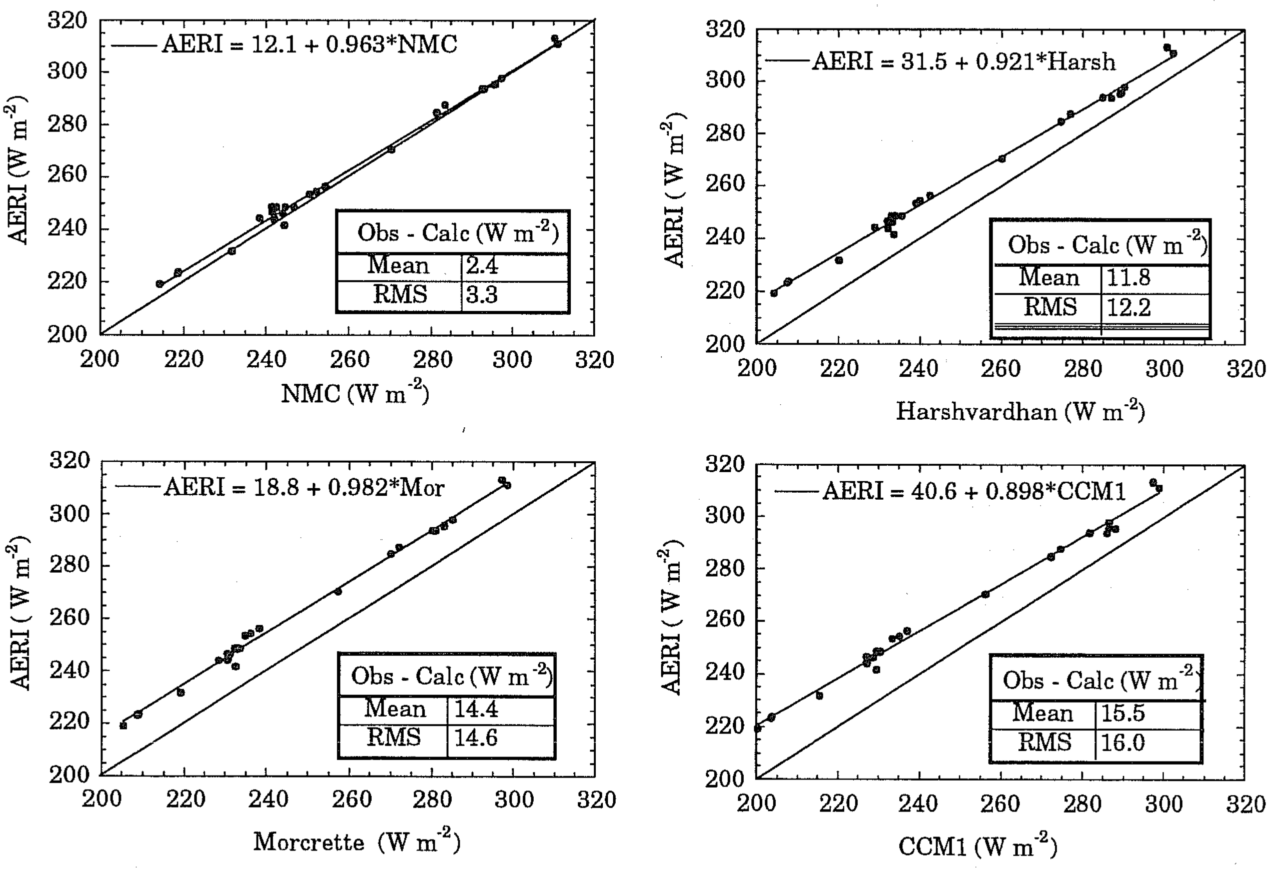

Fig. 4 Comparison of different climate model flux calculations with AERI observations.

comparison of the AERI fluxes with those observed by a pyrgeometer at the launch time of the 26 soundings discussed above. Since the nominal accuracy usually ascribed to pyrgeometer data is about ±5%, the 4 W m^{-2} rms agreement between the two data sets is very impressive. We conclude that this shows that carefully maintained and well-calibrated pyrgeometers may be used to provide meaningful longwave flux data.

3.3.3 *Calibration of climate model radiation codes*

The major unfinished ICRCCM goal is the evaluation of the ability of radiation codes used in climate models to simulate the real atmosphere. As a first attempt at such an evaluation, calculations from a variety of models have been compared with fluxes inferred from the SPECTRE AERI data (Fig. 4). With the exception of the NMC model, the other models tend to underestimate the observed flux, some by as much as 15 W m^{-2} . All the models explain about the same variance, indicating that the differences between them are largely systematic. Thus, they might be expected to have similar heating rates.

Spectral calculations from some of the narrow and broad band models have been compared with integrated AERI spectra for the 800-1200 cm^{-1} interval to determine if errors in the model continua could explain the flux differences shown in Fig. 4. Our analysis shows that only about one-third of the flux differences may be accounted for by the underestimations in this portion of the spectrum.

Further progress on evaluating the various codes awaits the completion of a an ongoing ICRCCM exercise of model-observation comparison. Those wishing to participate are urged to contact the author by email.

3.3 **Results from ARM-UAV**

The clear-sky longwave flux profiles observed by the broad band radiometers on board the UAV during the April 1994 flights over the SGP CART are compared with LBLRTM calculations in Fig. 5. Part of the disagreement of upward fluxes is due to a varying surface temperature that was not accounted for in the calculations. Likewise, the downward flux observations have not yet been screened to remove the effects of small fractions of thin cirrus that were observed during some of the flights. Nevertheless, the agreement between model calculations and the observations is quite good - about 10 W m^{-2} or better.

Fig. 6a shows percentage difference between the observed and calculated downward flux divergence over 2.5 km layers for five clear-sky flights. The agreement is amazingly good - within ±3% on eight of ten cases. Nine of the ten cases fall within the error of the observations, and there appears to be little correlation of the differences between the amount of water or aerosols present during the flights (Fig. 6b).

4. SUMMARY AND CONCLUSIONS

The various radiation observing projects sponsored by the U.S. Department of Energy are providing a variety of interesting data sets useful to the scientific community for validation of radiation codes used in climate models. The initial analyses of clear-sky data from these projects indicate that our ability to calculate longwave radiation quantities with detailed, line-by-line, models is quite good, at least for the

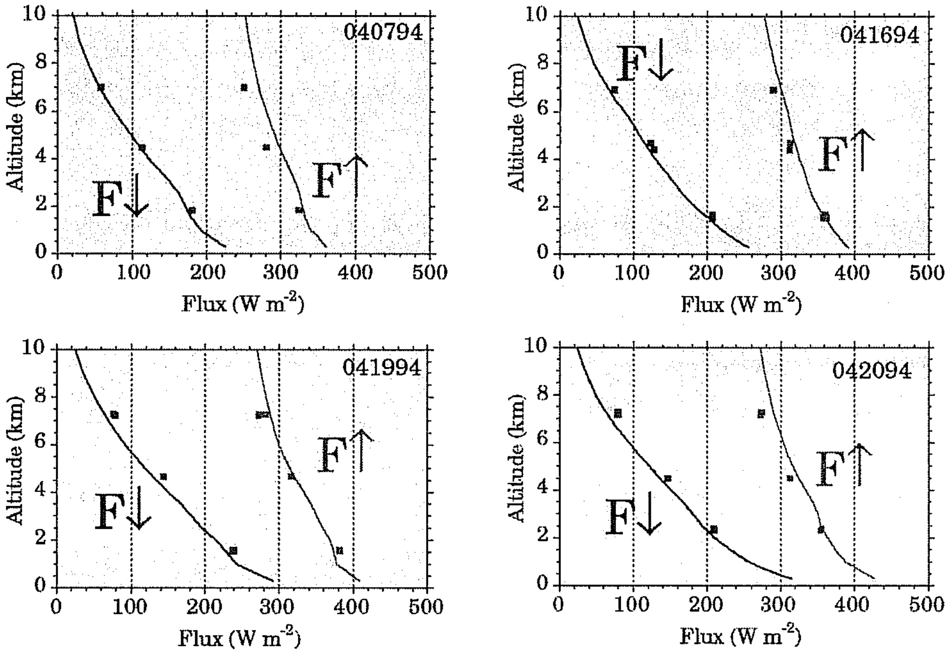

Fig. 5 Clear-sky observed (squares) and line-by-line model calculated (solid) fluxes from the April 1994 ARM/UAV flights. Observations were taken near local noon.

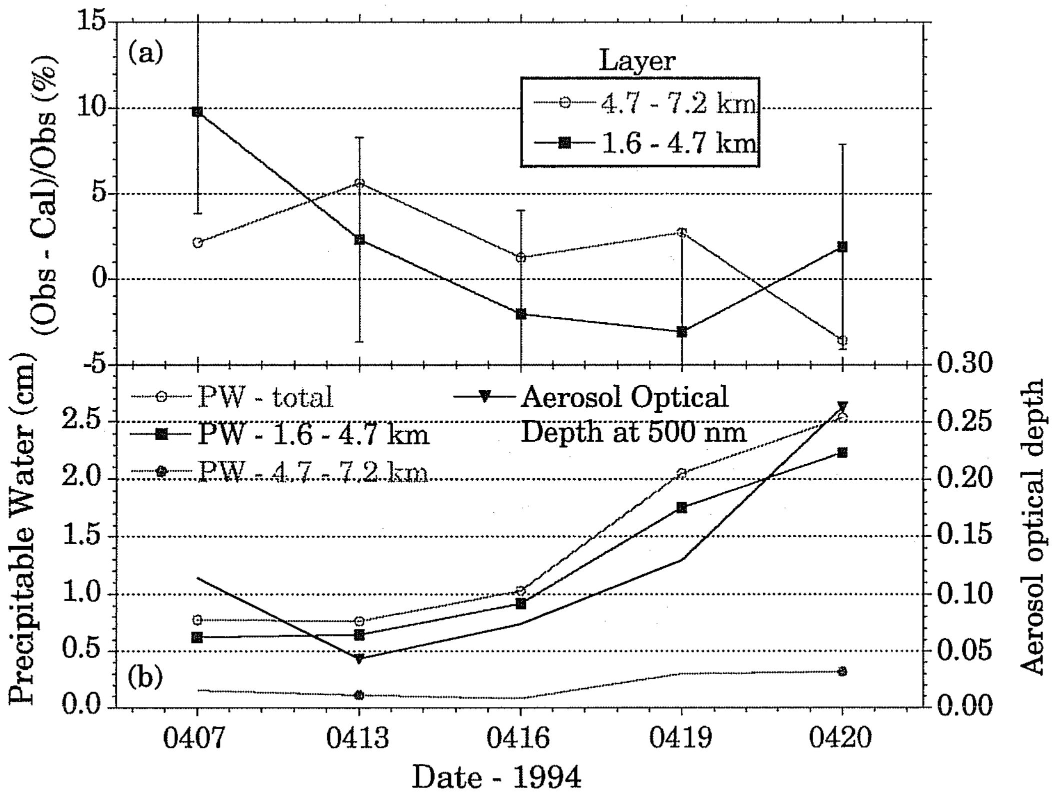

Fig. 6 (a) Percent difference between observed and calculated downward flux divergence.
(b) Precipitable water and aerosol optical depth during April 1984 UAV Flights.

model LBLRTM. This conclusion can not be automatically extended to other LBL models or to the codes commonly used in climate models until they have made similar comparisons with well calibrated data. This is due to the fact that the various models, particularly the climate models, use a variety of untested formulations of the infrared continuum as well as gross approximations for spectral line overlap. An opportunity to perform the necessary comparisons is available through ICRCCM.

Analyses of observations from the DOE programs under different cloud conditions are in their infancy. However, it is expected that these data along with those from other ongoing programs will be of sufficient quality to perform meaningful investigations of our ability to calculate short-and-long wave radiation quantities under general cloud conditions

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