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A Study of Longwave Radiation Codes
for Climate Studies:
Validation with ARM Observations
and
Tests in General Circulation Models

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Introduction

Research by the U.S. Department of Energy (DOE) has shown that cloud radiative feedback is the single most important effect determining the magnitude of possible climatic responses to human activity. However, these effects are still not known at the levels needed for climate prediction. Consequently, DOE has launched a major initiative - the Atmospheric Radiation Measurements (ARM) Program - directed at 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. In 1990, we proposed to contribute to this goal by attacking major problems connected with one of the dominant radiation components of the problem - longwave radiation. In particular, our long-term research goals are to:

- develop an optimum longwave radiation model for use in GCMs that has been calibrated with state-of-the-art observations,
- assess the impact of the longwave radiative forcing in a GCM,
- determine the sensitivity of a GCM to the radiative model used in it, and
- determine how the longwave radiative forcing contributes relatively when compared to shortwave radiative forcing, sensible heating, thermal advection and expansion.

Our approach to developing the radiation model is to test existing models in an iterative, predictive fashion. We plan to compare calculations from a set of models with operationally observed data. The differences we find will lead to the development of new models to be tested with new data. Similarly, our GCM studies will use existing GCMs to study the radiation sensitivity problem. We anticipate that the outcome of this approach will provide both a better longwave radiative forcing algorithm and a better understanding of how longwave radiative forcing influences the equilibrium climate of the atmosphere.

This report summarizes the major research results obtained under the categories of Radiation Model Testing Activities and General Circulation Model Testing Activities. Additional details may be obtained from the authors.

Radiation Model Testing Activities

Significant progress has been made in:

- Determining the ability of line-by-line radiation models to calculate the downward longwave flux at the surface,
- Determining the uncertainties in calculated the downwelling radiance and flux at the surface associated with the use of different proposed profiling techniques,

- Intercomparing clear-sky radiance and flux observations with calculations from radiation codes from different climate models,
- Determining the uncertainties associated with estimating N^* from surface longwave flux observations, and
- Determining the sensitivity of model calculations to different formulations of the effects of finite sized clouds

Clear-sky Studies

We have begun to compare clear-sky spectra of the downwelling radiance at the surface observed during SPECTRE (Spectral Radiation Experiment) with FASCOD3P and with narrow-and-broad band radiation models. The mean difference between the observed and FASCOD3P calculated radiance for 26 different spectra is shown in Fig. 1a. In general, the line-by-line model captures most of the features in the observed clear-sky spectra. There is a tendency for the model to underestimate the observed radiance in the window region between 800 to 1000 cm^{-1} and to overestimate it in portions of the 1200 to 1400 cm^{-1} region. The differences in many locations is the order or smaller than the estimated absolute accuracy of the observations (~ 1.5 units on Fig. 1), but we are not yet in the position to make firm conclusions concerning the spectral and absolute character of the differences because the final instrument calibration is not yet complete.

Our sensitivity analysis of the radiation calculations shows that with the expected 5% humidity and 0.5 K temperature accuracies, the uncertainties in the calculations due to errors in the meteorological data should be kept below about 8% in the regions of relatively strong lines and below about 5% in weakly absorbing regions. In the transparent region of the spectrum from 800 to 1000 cm^{-1} , narrow-band model radiances calculated using the Roberts et al. (1976) continuum and those using the more recent continuum of Clough et al. (1992) used in FASCOD differ by about 30%, and they show a particular spectral signal.

The differences between the observed and calculated spectra in the 800 to 1000 cm^{-1} region for the for the highest water vapor amounts seen during SPECTRE show that the FASCOD continuum yields better results than the one of Roberts. The data from the drier cases can not be use to support this conclusion at this time because the absolute error of the observations is larger than the radiance in the more transparent regions of the 800 to 1000 cm^{-1} region. As the instrument calibration is completed, it will be possible to use the high relative accuracy to check the spectral signatures of the differences and to put error bars on them.

We recently completed 26 sets of comparisons of AERI observations with FASCOD calculations using near simultaneous water vapor profiles from radiosondes, Westwater's microwave radiometer and Melfi's Raman lidar. The spectral distribution of the rms differences (Fig. 2b) show that the Raman data yield a more consistent spectral pattern of differences between observations and calculations than occurs when the radiosonde or microwave data are used in the calculations. As the calibration of the AERI is finalized, it will be possible to use the high relative accuracy of the observations to check the spectral signatures of the differences between observations and calculations and to put better error bars on the absolute differences. The improved calibration data and CART site observations over larger water vapor amounts should allow more stringent tests of the continuum formulations than possible heretofore, particularly if a Raman lidar is used for profiling water vapor.

Climate modelers are also 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 $I(0)$ as $F = \pi I(0)L$ where

$$L = \int_0^1 \frac{I(\mu)}{I(0)} \mu d\mu \quad (1)$$

$\mu = \cos \theta$, and θ is the local zenith angle.

Fig. 1. Mean (a) and rms (b) AERI observed minus FASCOD3P calculated radiance spectra from SPECTRE. The calculations were performed using near simultaneous radiosonde temperature and Raman water vapor profiles with surface based trace gas data and the 1992 line compilation as input.

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 . Thus, the soundings may be used with FASCOD to calculate L , and the uncertainty in F for the observed spectral interval is approximated as

$$\delta F = \pi L (I_{\text{obs}}(0) - I_{\text{cal}}(0)). \quad (2)$$

We are in the process of calculating L from (2) using FASCOD3P for the SPECTRE soundings, and we will also do this for CART data as they become available. In the interim, we have estimated δF using the diffusivity approximation as calculated by MODTRAN. When integrated over the 550 to 1500 cm^{-1} interval, the comparisons indicate the mean (observed - calculated) flux uncertainty of the FASCOD calculations to be 0.4 ± 0.2 , 0.5 ± 0.5 , and $1.2 \pm 0.3 \text{ W} \cdot \text{m}^{-2}$ depending upon the use of Raman, radiosonde or microwave water vapor profiles, respectively. For individual soundings, the results show that the downward flux for this interval may be calculated to within about $\pm 2 \text{ W} \cdot \text{m}^{-2}$ for any of the sounding types.

The data do not allow us to estimate the uncertainties in the 0 to 550 cm^{-1} region. However, since this portion of the spectrum is nearly opaque for the conditions we observed during SPECTRE, the uncertainties in calculating the downward flux at the surface from this

portion of the spectrum are relatively small. Thus, we plan to estimate the flux for homogeneous clear and cloudy conditions with model calculations for the 0 to 550 cm^{-1} region and with (1) for the 550 to 3000 cm^{-1} region and compare the results with observations from the pyrgeometers located at the CART and SPECTRE sites. Since the uncertainties in the interferometer data are smaller than those associated with the pyrgeometers, we believe that the interferometer-based flux data will serve as a baseline calibration of the pyrgeometers for homogeneous clear or cloudy conditions.

A disturbing trend of the differences between the AERI "observed" and FASCOD fluxes is that differences become more negative as the total precipitable water (PW) increases, independent of the source of water vapor data. The calculated flux (integrated radiance for the 550 to 1500 cm^{-1} region) is greater than that observed for 6 of the 9 cases with $\text{PW} > 1.4\text{ cm}$. These differences appear to be correlated primarily with PW in the 1100 - 1200 cm^{-1} region and with surface temperature in the 725 - 850 cm^{-1} region. These differences hint at potential problems in the continuum formulation - temperature dependence in the self-broadened term and the magnitude of the continuum coefficients in the foreign broadened regions. We will have to closely examine SGP and TWP CART site observations at higher water vapor amounts and temperatures to see if these differences continue.

During the later portion of the grant we began preparations for operational testing of a variety of narrow and broad band models with CART observations by intercomparing calculations with spectrally integrated AERI observations from SPECTRE. The suite of models include several used in GCMs (including GLA, CCM1, CCC, NMC, RPN and ECMWF) and several detailed models (e.g., AFGL's MODTRAN and LOWTRAN7, and Ellingson's narrow band model). We modified several of the GCM-type models to calculate radiance, rather than flux. Furthermore, we grouped output into common spectral intervals for comparison purposes, although this cannot be done for all models because not all calculate in the same spectral interval, and not all can be modified to give results in those spectral intervals sensed by the AERI.

We started our study by examining the more transparent 800 - 1200 cm^{-1} region first since ICRCCM indicated that this is the most suspect portion of the spectrum due to uncertainties associated with the water vapor continuum. Fig. 2 shows an intercomparison of some of the statistical properties of the various model calculations and AERI observations in the 800 - 1200 cm^{-1} region using the 26 clear-sky radiosonde temperature and water vapor profiles noted above as input.

Fig. 2. Distributions of vertically downwelling radiance at the surface for 26 clear-sky cases as calculated by several different models and observed by the AERI during SPECTRE. The vertical lines in the boxes show the median values. The edges of the boxes mark the limits of $\pm 25\%$ of the population, and the lines extending from the boxes mark the minimum and maximum values. The fraction of the AERI variance explained by each model is shown in the column marked R^2 .

Some large differences occur in the medians, but these appear to be largely systematic for all models as the fractional variance of the AERI observations explained by the different models is about the same. The latter result may largely be due to the 0.5 to 2 cm range of PW sensed during SPECTRE. Clearly, some of the models have deficient parameterizations of the water vapor continuum, and these will have to be changed in order for the models to yield correct radiances and fluxes over the full range of atmospheric conditions. Note also that the correlations decreased for each of the models when the 9.6 μm ozone band was included in the comparisons (Fig. 2b). We believe this to be a result of a few poor ozonesonde profiles in the sample.

Dr. 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 an intercomparison of fluxes calculated by the NMC radiation model and those observed by a pyrgeometer at the launch time of the 26 soundings discussed above. No attempt was made to insure that the sky was *completely* clear during these soundings, although clear sky conditions at the zenith were observed. Overall, the results are quite impressive. For this set, the NMC model underestimates the observed fluxes by about $3 \text{ W}\cdot\text{m}^{-2}$ in the mean, and the rms difference is about $6 \text{ W}\cdot\text{m}^{-2}$. The other models have somewhat greater biases, but all models have about the same RMS error when the biases are removed - about $6 \text{ W}\cdot\text{m}^{-2}$. These comparisons are very consistent with the

Fig. 3 Comparisons of model calculated with pyrgometer observed clear-sky downward fluxes at the surface during SPECTRE. (a) NMC model; (b) Statistics from other models.

model-interferometer comparisons. Since the nominal accuracy usually ascribed to pyrgometer data is about $\pm 5\%$, the comparisons hint that the uncertainties in the pyrgometer data may not be as large as thought heretofore when great care is exercised in the observations.

Broken Cloud Cover Studies

We completed a comprehensive study of the effect of shape and spatial distribution of cumulus clouds on longwave flux (Killen and Ellingson, 1993) in which we were able to derive equations for the effective cloud fraction N^* in terms of geometric cover for several models of clouds with different spatial and size distributions, different aspect ratios and different shapes. Overall, the study has found that N^* is sensitive to cloud shape and aspect ratio but is insensitive to the cloud spatial distribution or distribution of cloud area. N^* is also very sensitive to the thermal gradient between the cloud top and base.

The uncertainty in estimating N^* from observations depends primarily on the uncertainty of the measured flux components. Assuming the error of the flux components to be random with equal standard deviation σ_f , the standard deviation of the uncertainty of N^* , $\sigma_{\delta N^*}$, for one cloud layer may be written as

$$\sigma_{\delta N^*} = \frac{\sigma_f \sqrt{2}}{F_o - F_c} \sqrt{[1 + N^*(N^* - 1)]} \quad (4)$$

Note that F_o depends upon the temperature and water vapor distributions, and F_c depends additionally on the altitude of the cloud base. We have calculated $\sigma_{\delta N^*}$ for the 5 McClatchey soundings and cloud base altitudes ranging from 0.5 to 3 km. The results for $\sigma_f = 5 \text{ W} \cdot \text{m}^{-2}$ are

Fig. 4. (a) Effects of flux estimation error on estimates of N^* . (b) Distribution of N^* with N for different shapes and distributions.

shown in Fig. 4a. The variation of N^* with N for different cloud shapes is shown in Fig. 4b for comparative purposes.

In general, the results show that the uncertainty of individual estimates of N^* is of the order of 0.1 when flux the observations have uncertainties of the order of $5 \text{ W} \cdot \text{m}^{-2}$. This magnitude of uncertainty will not allow us to distinguish between the formulations for random distributions of cubes or cylinders at $N = 0.4$, for example. However, it will allow the validation of the general shape of the form of the variation of N^* with N for different size clouds. We are currently in the process of performing Monte Carlo simulations to allow us to determine the manner to interpret N^* in terms of cloud imagery, radar and lidar observations when they become available

General Circulation Model Testing Activities

Since longwave radiation plays a crucial role in the evolution of climate, its introduction into climate models must be as accurate as possible. We have studied the sensitivity of models which calculate longwave radiative heating to variability of input conditions and to the structure of the model algorithms. In addition, we have begun to assess how GCMs respond to the variability in heating rates provided by the longwave radiation algorithms.

To understand the sensitivity of heating rates to longwave radiation model algorithms (LWRMs), we have intercompared seven such models - most of which are currently used in a unique GCM. The institutions involved are CCC (Canada), ECMWF (United Kingdom), NCAR (United States), CSU (United States), UMCP (United States), RPN (Canada), and NMC (United States). Input data to each of these models includes vertical soundings of temperature, water vapor mixing ratio, ozone and clouds when applicable (as of this date we have tested the models primarily under clear sky conditions). To establish systematic tests of the

selected algorithms, we have prepared several data sets. For reference to previous studies, we have used the standard McClatchey (1971) soundings. For more careful analyses, we have compiled 100 soundings for each of four regional/seasonal domains based on a large data set presented by Phillips et al. (1988). These soundings allow us to look at mean profiles as well as standard deviations from those means. The four Phillips data sets show significant variability in the temperature and moisture profiles both among themselves in the mean and in the standard deviations within each set.

The heating rates produced by the algorithms for the available data sets show significant variability, frequently varying amongst themselves in excess of 0.5°K/day over a large range in the vertical. If one uses more levels in the vertical, the profiles are more smooth, but the general shape is reasonably preserved when comparing a 30 level calculation with an 18 level one. We discuss results with 18 levels because it is in the range of current models, in particular, the NMC model which produces weather forecasts. The horizontal profiles show considerable differences between the McClatchey soundings and the means of the Phillips soundings when comparing over seasons and regions. Analysis of the heating rates and their standard deviations produced by the Phillips soundings shows pronounced variability within each of the four data sets. Finally, if one compares the heating rates produced by the different algorithms using correlation coefficients, large differences appear. One can thus conclude that substantially different heating rates for the same sounding data are made available to a GCM, depending only on which algorithm the GCM applies. Since this conclusion is based on clear sky analysis, one can speculate that cloudy sky calculations would exacerbate this situation.

Does this sensitivity play a role when the chosen LWRM is introduced into a GCM? A systematic test to identify such sensitivity would require the introduction of various LWRMs into the same GCM and integrations to be performed for a variety of climate scenarios. We plan an experiment of this type but as a preliminary study, we utilized archives of climate runs and compared the data derived therefrom to give some indication of sensitivity. Currently available to us are extended climate runs with the NCAR CCM1 and CCM2. The archives include profiles of output of the LWRM heating rates in the model over the entire globe and at frequent intervals during the integration. We have analyzed the heating rates for those models for a January - February period taken from the archives for the CCM1 (R15), CCM1 (T42), and CCM2 (T42). For these three models, the data are taken for the same time period. We have analyzed the data over the two month time period and calculated standard deviations from the means. The data are presented on each model level and in terms of the

expansion coefficients of the spectral components, effectively yielding the amplitudes of the heating rates in terms of spatial scales. To compare the vertical resolution, vertical means were also calculated (external mode) and deviations from those means were evaluated (internal mode).

The results of these calculations, although striking, were not unexpected. Most pronounced was the difference in the horizontal and vertical distribution of heating rates produced by the R15 and T42 models of the CCM1. We can fairly report that these heating rates were completely different, although the total amplitude was in the same range. This was true for all spatial scales except the overall global value with height and the vertical distribution in the mean zonal field. Moreover, the amplitude as a function of meridional scale did not decay with decreasing scale in the R15 model, subjecting that model to potentially serious nonlinear computational errors. The heating rates generated by the T42 model did decay with decreasing scale.

We were able to test the interannual variations relative to the intraannual variations to a limited extent by analyzing a second annual season (a different January - February archive) for the CCM1. If we define the difference in the winter mean of the two annual seasons as the interannual variation and compare it to the standard deviation of heating rates for one of the winter seasons, we find that the intraannual variation (standard deviation) is considerably larger than the interannual variation. We can thus feel more comfortable in an analysis of one of the annual winter periods.

Analysis of the January - February period taken from the CCM2 (T42) shows distributions which differ to some extent from the CCM1 (T42) but have more similarities than the comparison of the CCM1 runs based on truncation. Nevertheless, changes in the CCM2 result in heating rates which decrease more rapidly with decreasing scale when compared to the CCM1.

We currently are setting up a plan to test various LWRMs in a specific GCM, hopefully one available at LLNL. Concurrently, we are collecting heating rate data generated from several models which have produced AMIP data and plan to intercompare that data to assess model sensitivity.

Science Team Activities

During the grant period, Professors Ellingson and Baer have participated in several meetings of ARM Science Team (AST) working groups as well as the annual AST meeting. As a member of the ARM Science Team Executive Committee, Ellingson has attended and

participated in several meetings during the grant. Overall, our project and ARM have benefited from these meetings through the identification of research groups with similar interests and through the development of ideas for successful field and numerical experiments.

It should be noted that Ellingson participated in several projects with other science team members to advance the program. These included:

- a study of the impact of the use of different type H₂O observations on comparisons of longwave radiance observations with model calculations (with H. Melfi and E. Westwater),
- the design of operational procedures for model calculations to be sent to the AST with AERI observations (with S. A. Clough and J. Liljegren),
- providing of access to Clough's line-by-line radiation code via FTP from workstations at the University of Maryland (with S. A. Clough),
- co-chairing the Instantaneous Radiative Flux (IRF) Workshop (with P. Daum), Richland, WA, November 1992
- co-chairing the (with W. Pennel) Special Session on ARM, Fourth Symposium on Global Change Studies. AMS 73rd Annual Meeting. Anaheim, CA. Jan. 1993.
- chairing the Session on Instantaneous Radiative Fluxes, 3rd ARM Science Team Meeting, Norman, OK, 1-5 March 1993.

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Publications, Presentations and Meetings

Publications (1991-1994)

- Charney, J., 1992: Heating rate variability in radiation codes when subjected to different vertical discretizations. Scholarly Paper, Dept. of Meteorology, University of Maryland, July, 1992. (In preparation for submittal to *J Climate*.)
- Delaney, P., 1991: Sensitivity of Atmospheric Radiation to Temperature, Water vapor and Ozone profiles. Scholarly Paper, Dept. of Meteorology, University of Maryland, May 1991, (In preparation for submittal to *J. Quant. Spec. Rad. Trans.*) 22pp.
- Ellingson, R. G., and F. Baer, 1991: A study of longwave radiation codes for climate studies: Validation with ARM observations and tests in general circulation studies. Proceedings of the 2nd ARM Science team Meeting, CONF-9110336, UC-402, U.S. Dept. Energy, Washington, DC, 1-5.
- Ellingson, R. G., W. J. Wiscombe, J. DeLuisi, V. Kunde, H. Melfi, D. Murcray, and W. Smith, 1993: The SPECTral Radiation Experiment (SPECTRE): Clear-sky observations and their use in ICRCCM and ITRA. *IRS'92: Current Problems in Atmospheric Radiation*, S. Keevallik and O. Karner, Editors., A. DEEPAK Publishing, Hampton, VA, 451-453.
- Ellingson, R. G., W. J. Wiscombe, J. DeLuisi, H. Melfi, and W. Smith, 1993: Calibration of radiation codes in climate models: Comparison of calculations with observations from the spectral radiation experiment (SPECTRE). FIRE Cirrus Science Results 1993, NASA Conference Publication 3238, NASA Langley Research Center, Hampton, VA, 181-184.
- Ellingson, R. G., 1993: Atmospheric Radiation Measurement (ARM) Program: Project description and preliminary results. In *Atmospheric Radiation*, K. Stamnes, Ed., Proc. SPIE 2049, 102-106.
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- Takara, E., and R. G. Ellingson, 1994: Monte Carlo simulations of infrared radiative transfer through broken cloud fields. Proceedings of the Eight Conference on Atmospheric Radiation, American Meteorological Society, Boston, MA, 364-365.
- Ellingson, R. G., and F. Baer, 1993: A study of longwave radiation codes for climate studies: Validation with ARM observations and tests in general circulation studies. Proceedings of the 2nd ARM Science team Meeting, CONF-9110336, UC-402, U.S. Dept. Energy, Washington, DC, 1-5.
- Ellingson, R. G., 1993: Radiation parameterizations in climate models: Comparison of calculations with observations from the Spectral Radiation Experiment (SPECTRE) and ARM. In *Clouds and Radiation in GCM's*, E. Kallen Ed., Proceedings from the workshop held at the Stockholm University, Sweden, 24-26 May 1993, ISSN 0349-0467, Dept. Of Meteorology, Stockholm University, Stockholm, 29-32.
- Killen, R. G., and R. G. Ellingson, 1994: The effects of shape and spatial distribution of cumulus clouds on longwave irradiance. *J. Atmos. Sci.*, **51**, 2123-2136.

Patrinos, A. A., D. Renne, G. Stokes, and R. G. Ellingson, 1991: Atmospheric Radiation Measurement: A Program for Improving Radiative Forcing and Feedback in General Circulation Models. Proceedings of the 1991 Annual Conference of the American Meteorological Society, 83-86. Also as Publication PNL-5A-18559, Pacific Northwest Laboratory, Richland, WA.

Presentations (1991 - 1993)

- Baer, F., 1991: A Study of Longwave Radiation Codes for Climate Studies: Validation with ARM Observations and Tests in General Circulation Models. ARM Single Column Model workshop, 14-15 May, Colorado State Univ., Ft. Collins, CO.
- _____, 1992: Longwave Radiation in Climate Models-Column Models and GCM Impacts. Invited lecture, Swedish Meteorological and Hydrological Institute, 1 Sept., Norrköping Sweden.
- _____, 1992: Longwave Radiation in Climate Models-Column Models and GCM Impacts. Invited lecture, Danish Meteorological Institute, 2 Sept., Copenhagen, Denmark.
- _____, 1992: Longwave Radiation in Climate Models-Column Models and GCM Impacts. Invited lecture, Department of Meteorology, Univ. of Stockholm, 27 Aug., Stockholm, Sweden.
- _____, 1992: Global Climate Model Sensitivity to Long Wave Radiation. Second International Conference on Modeling of Global Climate Change and Variability, 9 Sept., Hamburg, Germany.
- _____, 1992: Longwave Radiation and Global Modeling. ARM Single Column Model workshop, Pacific Northwest Laboratories, 28-29 Oct., Richland, WA.
- _____, 1992: Impact of Thermal Forcing in Climate Models. PCMDI, AMIP Diagnostics Subprojects Workshop, 16 Nov., LLNL, Livermore, CA.
- Baer, F., and R. G. Ellingson, 1993: Longwave Radiation Algorithms in Global Climate Modeling. Poster presented at the Fourth Symposium on Global Change Studies. AMS 73rd Annual Meeting, Jan., Anaheim, CA. .
- _____, and _____, 1993: Longwave Radiation Algorithms in Global Climate Modeling. Poster presented at the 3rd ARM Science Team Meeting, 1-5 March, Norman, OK.
- _____, 1993: Longwave Radiation Impacts in Global Climate Modeling. Invited talk, Sixth Workshop, ICE/EUCREX-2, Dept. of Meteorology, 24-26 May, Stockholm University, Stockholm, Sweden.
- _____, 1993: Longwave Radiation Impacts in Global Climate Modeling. Accepted for presentation, IAMAP-93, 19-22 July, Yokohama, Japan..
- Ellingson, R. G., 1991: A Study of Longwave Radiation Codes for Climate Studies: Validation with ARM Observations and Tests in General Circulation Models. Invited Paper given at the JASON Summer Review of the ARM Program, La Jolla, CA, 24-2 June. Also presented at the 2nd ARM Science Team Meeting, Denver, CO, 26-30 October.
- _____, 1991: SPECTRE and ARM: The Challenge of Comprehensive Radiation Experiments. Invited paper presented at the Workshop on Climatic Effects of Atmospheric Trace Gases at the Symposium on Aerosol-Cloud-Climate Interactions at the XX general Assembly of the IUGG, 13-20 Aug., Vienna, Austria.

- _____, W. J. Wiscombe, J. DeLuise, V. Kunde, H. Melfi, D. Murcray, and W. Smith, 1992: The SPECTral Radiation Experiment (SPECTRE): An Overview, Preliminary Results and use in Interpretation of ARM Data. Papers by this or similar titles have been presented at the:
- Session on Radiative Forcing of Climate and Global Warming Potentials, AGU Spring Meeting, 12-15 May, Montreal, Canada,
 - 15th Annual Review Conference on Atmospheric Transmissions Models, 2-4 June, Phillips Laboratory, Hanscom Air Force Base, MA,
 - 1992 Workshop of the IRC Working Group on Intercomparison of Transmission and Radiance Algorithms, July 1992, Helsinki, Finland,
 - International Radiation Symposium, IRS'92. 3-8 Aug. Tallinn, Estonia,
 - Fourth Symposium on Global Change Studies. AMS 73rd Annual Meeting. Anaheim, CA. Jan. 1993.
 - Instantaneous Radiative Flux workshop, Richland, WA, November 1992.
 - Invited Paper, G-Division, Lawrence Livermore National Laboratory, 6 Jan. 1993.
 - 3rd ARM Science Team Meeting, Norman, OK, 1-5 March 1993 (Poster presentation)..
- _____, 1992: Critical Longwave Observations for Tropical Conditions. Invited paper, Workshop on the ARM Tropical Western Pacific Site, 17-18 May, Santa Fe, New Mexico.
- _____, 1992: The Atmospheric Radiation Measurements (ARM) Program: History and Project Description. Invited Paper, Workshop on Clouds, Radiation and Climate, Univ. of Alaska, 7-10 July, Fairbanks, AK.
- _____, 1993: Calibration of Longwave Radiation Codes in Climate Models: Initial Results from SPECTRE and ARM. Invited paper, Sixth Workshop, ICE/EUCREX-2, Dept. of Meteorology, Stockholm University, Stockholm, Sweden, 24-26 May, 1993.
- _____, 1993: The Atmospheric Radiation Measurement (ARM) Program: Project Description and Preliminary Results. Invited paper, To be presented at the International Symposium on High Latitude Optics, 28 June - 2 July, Univ. of Tromsø, Norway.
- Killen, R. and R. G. Ellingson, 1993: The Effect of Shape and Spatial Distribution of Cumulus Clouds on Longwave Irradiance. Poster presented at the 3rd ARM Science Team Meeting, 1-5 March, Norman, OK.
- Renne, D., A. A. Patrinos, G. Stokes, and R. G. Ellingson, 1991: The Department of Energy Initiative on Atmospheric Radiation Measurements: A Study of Radiation Forcing and Feedbacks. Presented at the Annual Conference of the American Meteorological society, January, New Orleans, LA..

Other Meetings and /or Workshops

- Baer, F. and R. G. Ellingson, 1991: ARM Science Team Meeting, 26-30 Oct., Denver, CO.
- _____, and _____, 1991: IUGG/IAMAP, 19-23 Aug., Vienna, Austria.
- _____, and _____, 1990: ARM Science Team Meeting, 4-8 Nov., Las Vegas, NV.
- Ellingson, R. G., 1990: Global Baseline Surface Radiation Network Workshop, 3-5 Dec., Washington, DC.

- _____, 1991: Meeting of the JSC Working Group on Radiative Fluxes, 24-27 Sept., Palm Springs, CA.
- _____, 1991: ITRA Workshop on Intercomparison of Radiance Calculations with Observations, 17 Aug., Vienna, Austria.
- _____, 1992: ITRA Workshop, 30-31 July, Helsinki, Finland.
- _____, 1992: ISLSCP Americas Workshop, 23-26 June, Columbia, MD.

Students And Post-doctoral Support

Students Supported and Degrees Completed

Name: Paul Delaney

Degree: M.S.

Date: August 1991

Title of Thesis or Scholarly Paper

Sensitivity of Atmospheric Radiation to Temperature, Water vapor and Ozone profiles

Name: Jay Charney

Degree: M.S.

Date: August 1992

Title of Thesis or Scholarly Paper

Heating rate variability in radiation codes when subjected to different vertical discretizations.

Name: Dejiang Han

Degree: Ph.D. Qualifying exams completed January 1993,
M.S. degree to be awarded May 1993
Continuing on for Ph.D.

Date: May 1993 for M. S.

Title of Thesis or Scholarly Paper

Estimation of Downward flux at the Surface from AERI Radiance Observations

Name: Juying Warner

Degree: Ph.D. Qualifying exams completed January 1992

Date: Degree completion expected May 1995

Dissertation topic

Evaluation of different GCM longwave radiation models with observations

Name: Anne Costolanski
Degree: Ph.D. candidate
Date: Degree completion expected May 1996

Dissertation topic

Techniques for including multiple scattering in longwave radiation models

Name: Jerry Robaidek
Degree: Ph.D. candidate
Date: Degree completion expected Dec. 1995

Dissertation topic

Global climate model sensitivity to long wave radiative heating.

Name: Natalie Arsky
Degree: Ph.D. candidate
Date: Degree completion expected May, 1996

Dissertation topic

Optimization of long wave radiation codes for global climate predictions.

Post-doctoral Fellows Supported

Rosemary Killen (1991 - 94)

Modeling of geometrical effects of clouds on longwave fluxes and heating rates

Ezra Takara (1993 -94)

Monte Carlo simulations of longwave effects by finite sized clouds

Dr. Suhung Shen (1993-94)

Spectral radiation observation analysis, meteorological data analysis