Chapter 1

The Atmospheric Radiation Measurement Program: Prelude

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1. Introduction

The U.S. Department of Energy (DOE) was already concerned about the potential impact of the increasing content of CO_2 in the atmosphere on future climate in the early 1970s (see Riches 1983) and commissioned a set of six state-of-the-art reports (e.g., MacCracken and Luther 1985) that attempted to highlight the uncertainties in general circulation models (GCMs) and their underlying parameterizations well ahead of the Intergovernmental Panel on Climate Change (IPCC) program. Of considerable concern was that, although greenhouse warming is forced entirely by a radiative perturbation of a few watts per square meter or less, neither field measurements nor radiation model intercomparisons had ever achieved anywhere near this level of accuracy. Furthermore, there was a considerable range of GCM predictions due to greenhouse warming, and it was not entirely clear how much of the differences could be traced to differences in the initial radiative forcing used in the models and how much was due the range of parameterizations and their resulting feedbacks.

To obtain a better understanding of the GCM conundrum, the DOE instituted several intercomparison studies, two of which have particular importance. One, an intercomparison of longwave radiation codes (wavelengths > 4 microns) was initiated by Fred Luther in 1982. The second, a GCM intercomparison project, was begun by Robert Cess and Gerald Potter in 1984. These projects eventually grew to major international intercomparison studies that led the DOE to the conclusion that cloud–radiative feedback is the single most important effect determining the magnitude of possible climatic responses to human activity. This conclusion, in turn, led to the establishment of the Atmospheric Radiation Measurements (ARM) Program, the subject of this monograph. The DOE conclusion that the role of clouds was a critical knowledge gap was subsequently echoed in the first IPCC report (IPCC 1990).

In light of the importance of these intercomparison studies to the establishment of ARM, a summary of each of the studies and their findings is provided below.

2. ICRCCM

The Intercomparison of Radiation Codes used in Climate Models (ICRCCM) resulted from the unification of independent U.S. and European projects begun almost simultaneously in 1982. Frederick Luther initiated a comparison study of longwave radiative transfer models for the DOE's Carbon Dioxide Research Division. In Europe, Yves Fouquart and Jean-Francois Gelyn proposed a model comparison study that focused on both longwave and solar radiative transfer parameterizations in climate models. The World Climate

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Research Programme (WCRP) and the International Radiation Commission (IRC) established a joint working group on ICRCCM in 1984, and ICRCCM was officially started under the leadership of Frederick Luther and Yves Fouquart. Many of the details concerning ICRCCM are well documented in the literature (see Luther 1984; Luther et al. 1988; Ellingson and Fouquart 1991), and this document repeats or summarizes material contained in them.

The objectives of the ICRCCM studies during 1982–88 were the following:

1) to develop a better understanding of the differences in radiation model approaches,
2) to understand how these differences affect model sensitivity,
3) to evaluate the effects of simplifying assumptions,
4) to evaluate the ability of the radiation models to simulate the real atmosphere, and
5) to evaluate the effect of using different sources of spectral line data in the radiation codes.

The initial focus of ICRCCM was on comparisons of clear-sky longwave radiation calculations using identical atmospheric profiles of radiatively important variables. The models included in the study ranged from very simplified ones used in GCMs to the most sophisticated line-by-line (LBL) models. The study was subsequently expanded to include clear-sky shortwave (solar) and cloudy-sky shortwave and longwave cases. Workshops to discuss preliminary results were held in Frascatti, Italy, in 1984 and in College Park, Maryland, in 1986. A third workshop to finalize conclusions of the various calculations was held in Paris, France, in August 1988. Details concerning the final results may be found in Ellingson and Fouquart (1991), Ellingson et al. (1991), and Fouquart et al. (1991), part of an issue of the *Journal of Geophysical Research–Atmospheres* dedicated to ICRCCM.

Unfortunately, Dr. Fredrick Luther, one of the initial ICRCCM cochairmen, became ill and died in September 1986. His death was a major setback, but his vision and plans for ICRCCM allowed the project to continue under the leadership of Robert Ellingson and Yves Fouquart.

Going into ICRCCM, the assumption was that the physics and absorption line data were well known and that therefore the various models could not possibly disagree much, regardless of the type of parameterization (i.e., the details of the implementation). This complacency was shattered by the actual results of ICRCCM. For the longwave clear cases, with about 40 participants representing almost all the world's major modeling groups, ICRCCM revealed intermodel disagreements ranging from 30 to 70 W m^{-2} (Luther et al. 1988). The disagreements were worse when pure H_2O (Fig. 1-1) and pure CO_2 atmospheres were considered, indicating that the better agreement found in the all-gas cases (Fig. 1-2) was partly accidental. Furthermore, the disagreements proved remarkably robust, surviving for years during which modelers combed their models for errors, omissions, and overly crude numerical procedures. Subsequent ICRCCM calculations, involving cloudy longwave cases, and clear and cloudy shortwave cases, revealed equally large or larger disagreements, ranging up to 20%–30% in fluxes and up to 70% in flux sensitivity to constituent changes (Ellingson et al. 1990). Table 1-1 provides, as an example, the range of agreement between band and LBL model calculations of total shortwave absorption of solar radiation from different participants.

After four years during which participants were allowed to revise their results, the participating LBL models did manage to agree to approximately 1% in clear-sky cases, and the number of less detailed models that agreed with the LBL models to within 2% increased. This good agreement among LBL models was achieved, however, only after the LBL modelers agreed

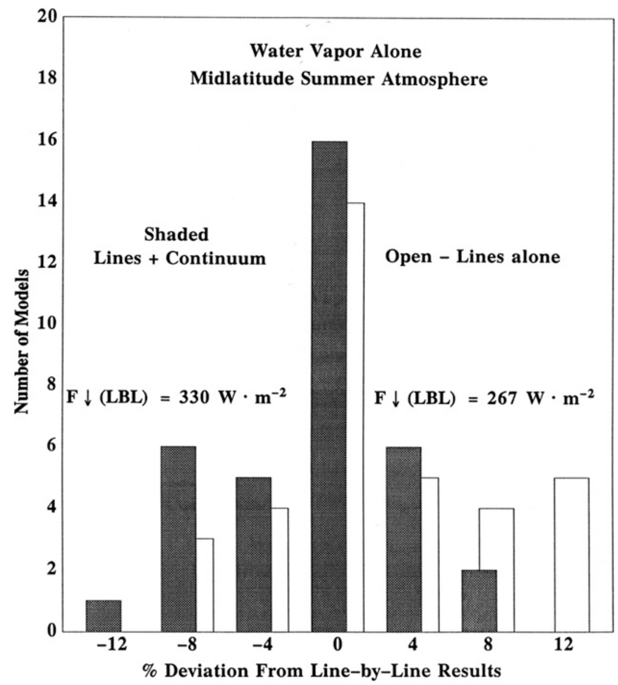

FIG. 1-1. Number distributions of downward fluxes at the surface relative to the GFDL line-by-line results when water vapor lines only and the lines plus the continuum are included in the calculations with the Air Force Geophysical Laboratory (AFGL) midlatitude summer atmosphere. Note that the histogram bars cover a range of ±2% centered on the given value, and they are displaced slightly for better viewing. [From Ellingson et al. (1991).]

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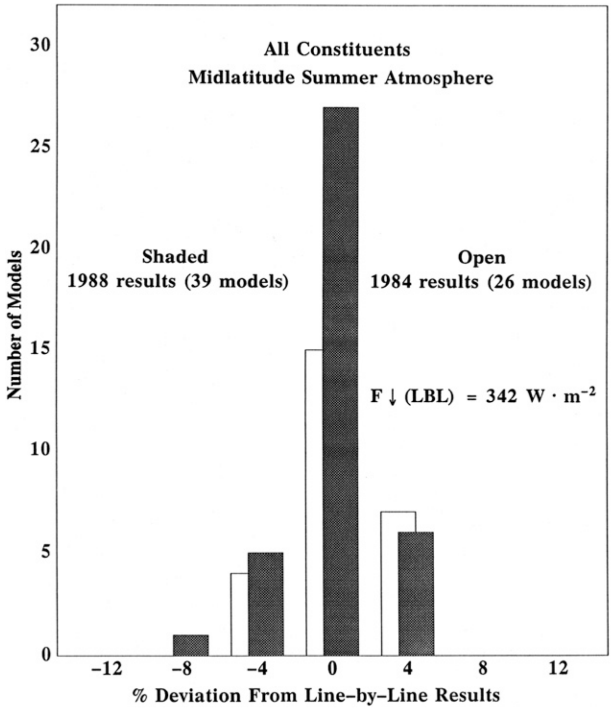

FIG. 1-2. As in Fig. 1-1, but with all constituents included in the calculations. The solid and open bars represent the results from the 1988 and 1994 workshops, respectively [from Ellingson et al. (1991)]. The mean and RMS differences relative to the line-by-line downward flux at the surface were 1.0 and 8.7 W m^{-2}, respectively.

to cut off their lines the same distance from line center and to use the same continuum absorption model. Thus, the ICRCCM community reluctantly concluded that

> [u]ncertainties 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 (Luther et al. 1988, p. 46).

The ICRCCM community considered the gamut of the then available laboratory and atmospheric observations that might be used to validate the LBL models (e.g., broadband hemispheric flux data, aircraft or surface-based spectral data, satellite spectrometers or laboratory spectra). Each was found lacking for a variety of reasons, such as poor calibration, the lack of detailed measurements of the radiatively important variables, or incomplete range of variables found in the atmosphere (laboratory data).

The ICRCCM participants concluded that existing field observations, while they shed light on various issues facing ICRCCM, could not decisively resolve the large intermodel disagreements. As such they recommended a more sophisticated observational strategy, as follows (Luther 1984, p. 31):

> A dedicated field measurement program is recommended for the purpose of obtaining accurate spectral radiances rather than integrated fluxes as a basis for evaluating model performance.

Following the 1988 ICRCCM workshop, the IRC and the WCRP endorsed a second phase of ICRCCM with the primary purpose of validating radiation models through comparison with observations. A primary term of reference of this second phase was stated as follows (Ellingson and Fouquart 1990, p. 37; see also, Bolle 2008, p. 89):

> [The goal is to] determine the requirements for real in situ data for validation of high spectral resolution models and other radiative transfer computations and explore ways of obtaining these data by either a specific dedicated measurement programme or by appropriate enhancement of other experimental activities, such as may be part of ISLSCP [International Satellite Land Surface Climatology Project] and ISCCP [International Satellite Cloud Climatology Project] regional experiments.

3. SPECTRE

Robert Ellingson and Warren Wiscombe took the ICRCCM recommendations and shaped them into a very specific program called SPECTRE (Spectral

TABLE 1-1. Total atmospheric shortwave absorption for the six cases concerning the absorption by water vapor only. The abbreviations MLS, TRO, and SAW denote the midlatitude summer, tropical, and subarctic winter Air Force Geophysical Laboratory atmospheres, respectively. The band models are grouped into two classes according to their spectral resolution (HR and LR for high resolution and low resolution, respectively). Here θ_0 is the solar zenith angle in degrees. [From Fouquart et al. (1991).]

		LBL (W m^{-2})		Median (W m^{-2})		Range (%)		RMS differences (%)		No. of models	
Case	θ_0	1	2	HR	LR	HR	LR	HR	LR	HR	LR
MLS	30	172.4	178.2	171.0	165.7	12	11	6	7	10	11
MLS	75	67.1	69.6	62.4	64.3	21	14	11	10	10	11
TRO	30	187.8	195.4	181.9	181.2	16	12	7	8	10	11
TRO	75	72.3	75.7	66.9	69.2	29	14	14	10	10	11
SAW	30	94.5	99.7	101.7	97.1	49	14	14	4	10	11
SAW	75	39.3	41.1	41.1	39.5	17	10	6	4	10	11

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Radiance Experiment; Ellingson et al. 1990) with emphasis on accurate measurements of emission spectra and proper quantitative characterization of the atmosphere. The idea was to do the following:

- integrate the use of the radiation and profiling technology,
- obtain detailed radiation and atmospheric data for a variety of important conditions,
- distribute the data to the international ICRCCM community, and
- intercompare model results with the data for the purpose of calibrating the various radiation codes used in climate models.

The key features of the proposed experiment were the following:

- spectral radiation measurements in the form of continuous spectra, not broadband measurements nor disjointed spectral bands;
- radiance (intensity) rather than flux measurements;
- redundant measurements of radiance;
- frequent and careful radiometric calibration in the field against known standards; and
- simultaneous, instantaneous profiles of temperature, humidity, aerosol and cloud.

SPECTRE was funded under the DOE ''Quantitative Links Program'' and by the National Aeronautics and Space Administration (NASA) and was carried out in conjunction with the NASA-sponsored First ISCCP Regional Experiment (FIRE) Cirrus II intensive observation period from 13 November to 7 December 1991, in Coffeyville, Kansas. Details concerning the experiment are given by Ellingson and Wiscombe (1996).

During SPECTRE, highly experienced scientists from different universities and government agencies carried out three main functions: spectrometer, remote, and in situ measurements. The spectrometers were Fourier transform interferometers characterized by a large wavelength range (3–18 μm), high spectral resolution (1 cm^{-1} or better), cryogenic cooling of the detectors, and routine blackbody calibration in the field (Ellingson and Wiscombe 1996). The spectrometers and resolutions included the NASA Stratospheric Infrared Interferometer Spectrometer (SIRIS; 0.06 cm^{-1}), the University of Wisconsin Atmospheric Emitted Radiance Interferometer (AERI; (0.5 cm^{-1}), the University of Denver interferometer (1.0 cm^{-1}), and the NOAA Fourier Infrared Spectrometer (FIRS; 0.5 cm^{-1}). The Wisconsin AERI eventually became a prototype ARM instrument designed for autonomous surface operation that calibrates against two internal temperature-controlled black bodies every 10 min. The mature AERI is now operating continuously at the ARM fixed and mobile sites (Turner et al. 2016, chapter 13).

The in situ measurements included frequent radiosonde launches, flask samples of the concentration of trace gases (CO_2, CH_4, N_2O, CO, and Freons F11 and F12) near the surface, and vertical profiles of O_3 using ozonesondes (Ellingson and Wiscombe 1996). The remote sensing measurements included water vapor profiles with a calibrated Raman lidar operated by Harvey Melfi, total column O_3 with a Dobson spectrometer, and vertical profiles of virtual temperature with a Radio Acoustic Sounding System (RASS). The experiment benefited greatly from the deployment of a Millimeter Cloud Radar (MMCR) by Thomas Ackerman as part of the FIRE Cirrus II project that helped identify clear-sky periods. As configured with FIRE Cirrus II, the SPECTRE deployment constituted a supersatellite on the ground for the observing period, and this was the first time this instrument complement was assembled.

Following a scrutiny of the SPECTRE data by the various principal investigators (PIs), atmospheric data from four meteorologically different days were released to the ICRCCM working group to perform calculations for comparison with AERI observations, after which the working group met from May 24 to 26 May 1995, at the University of Maryland at College Park to discuss the comparisons.

Overall, 22 participants submitted 29 sets of calculations, including 10 LBL, 12 narrowband (NB), and 7 broadband (climate model) models. For intercomparison purposes, Ellingson (1995) integrated the various NB and LBL model calculations and the observations to a common grid. A comparison of the average of the four comparison spectra with the average NB spectra is shown in Fig. 1-3, whereas Fig. 1-4 shows a comparison of the distribution of the mean observed minus calculated radiance at the common resolution. To estimate the effects of these differences on the downwelling flux at the surface, the differences were integrated over the 520 to 2600 cm^{-1} interval and converted to flux using model-calculated angular corrections. The distribution of the flux differences is shown in Fig. 1-5.

In general, the ICRCCM participants were very pleased with the level of average agreement between the observed and model-calculated radiances and spectrally integrated downward flux at the surface (4.5 W m^{-2} root-mean-square error), a marked improvement over the 1988 results (cf. Figs. 1-2 and 1-5). However, the quality of the comparisons is somewhat misleading because of the small ranges of water vapor and temperature observed during the one-month experiment in late

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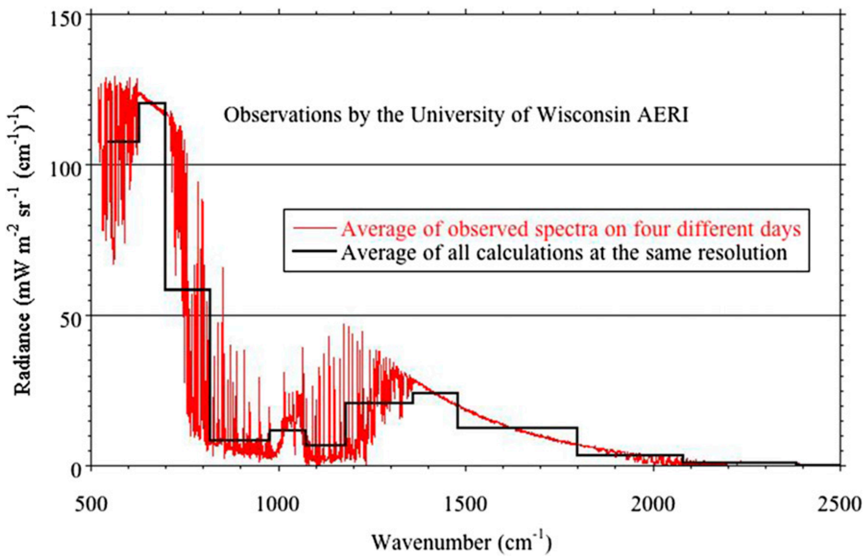

FIG. 1-3. Average AERI spectrum for the four SPECTRE–ICRCCM test cases (red line) and the average spectrum from the model calculations for the intercomparison resolution.

autumn, the lack of observations in the 0 to 500 cm^{-1} portion of the spectrum, the absence of many GCM-type models in the spectral comparisons, and the similarity among several LBL models. The large range of disagreement between the observations and calculations in spectral intervals with large radiance variability (e.g., 800–1000 cm^{-1}) highlights regions that are studied extensively during ARM (Mlawer and Turner 2016, chapter 14). Unfortunately, the SPECTRE observations would not allow estimates on the accuracy of clear-sky fluxes and cooling rate calculations at other levels of the atmosphere nor at other climatologically important locations across the globe.

The 1995 ICRCCM workshop also reviewed the state of shortwave modeling and concluded that the problems associated with shortwave radiation remained as they were following the 1988 workshop. As a consequence, the working group recognized the need for and recommended a SPECTRE-like experiment to ferret out the cause for disagreement between the shortwave models.

Plans for SPECTRE were well underway when the DOE decided to launch the ARM Program, and the SPECTRE proposal was used in large part for the ARM Program Plan (DOE 1990). SPECTRE was viewed as a prototype for what became the ARM Central Facility a

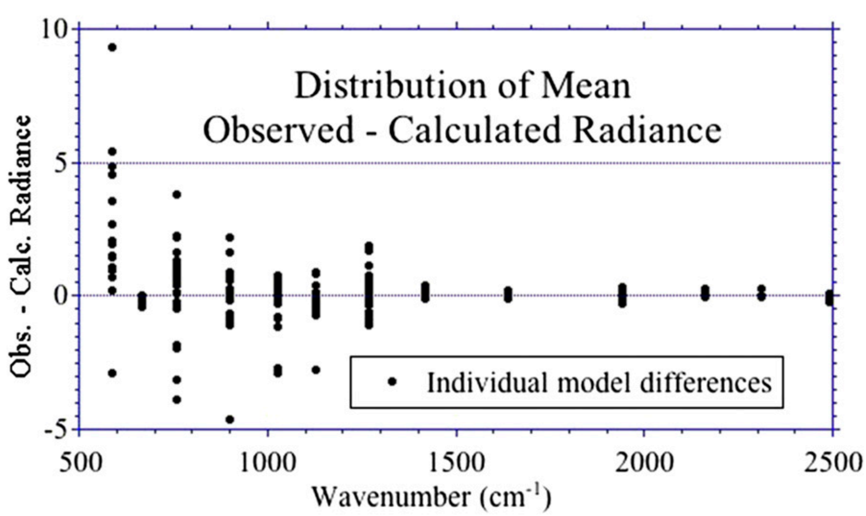

FIG. 1-4. Spectral distribution of the average AERI-observed − calculated radiance spectrum calculated from the four SPECTRE–ICRCCM test cases.

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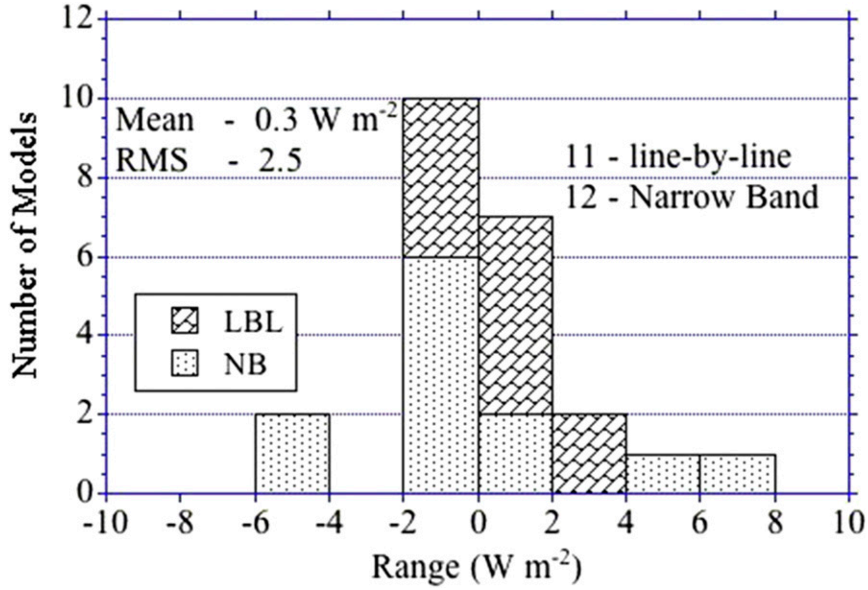

FIG. 1-5. Distribution of the average observed − calculated clear-sky downward fluxes at the surface for the four SPECTRE–ICRCCM test cases.

few years later, and several ARM investigators used data from it for the first case of the ARM Instantaneous Radiative Flux (IRF) experiment (Mlawer and Turner 2016, chapter 14) before the regular ARM data flow commenced.

4. FANGIO

In 1984, the DOE asked Robert Cess and Gerald Potter to organize a GCM intercomparison project. The motivation for this project was to understand the large differences that existed for climate-change simulations among the various GCMs at that time. This evolved into the FANGIO (Feedback Analysis of GCMs and in Observations) project. Cess and Potter devised a procedure for diagnosing cloud feedback in GCMs (see Cess and Potter 1988) that was adopted at the first FANGIO workshop in 1987. There were eight FANGIO workshops held in Europe and the United States from 1987 to 1996. The FANGIO project constituted the first structured intercomparison of GCMs, and the principal conclusion of this study was that model-to-model differences in cloud feedback were largely the cause of the significant differences in climate-change simulations by the models used at that time. In the following, we summarize the salient findings from FANGIO.

To understand cloud feedback, it is useful to first demonstrate how clouds affect the present climate. Figure 1-6 shows Earth's global-mean radiation budget at the top of the atmosphere (TOA) and also a fictitious situation for which there are no clouds, but all else remains unchanged. Numbers have been rounded for the purpose of illustration. Because clouds are bright, their presence increases reflection of shortwave radiation by 50 $\mathrm{W\,m^{-2}}$ (cooling), while the greenhouse effect of clouds results in a longwave warming of 30 $\mathrm{W\,m^{-2}}$. Thus the net effect is a 20 $\mathrm{W\,m^{-2}}$ cooling, conventionally expressed as a cloud-radiative forcing (CRF) of −20 $\mathrm{W\,m^{-2}}$ (Ramanathan et al. 1989). With the subscript c referring to clear-sky fluxes, then

$$\mathrm{CRF} = (F_c - F) - (Q_c - Q), \qquad (1\text{-}1)$$

where F and Q respectively denote the global-mean emitted infrared and net downward solar fluxes at the TOA. It is the change in CRF (ΔCRF), associated with a change in climate, that constitutes cloud feedback. For example, a doubling of atmospheric CO_2 produces roughly a 4 $\mathrm{W\,m^{-2}}$ direct radiative forcing G of the climate system. If the ensuing climate change altered CRF from −20 to −16 $\mathrm{W\,m^{-2}}$, so that $\Delta\mathrm{CRF} = G$, then ΔCRF would amplify the direct radiative forcing by a factor of 2 (a twofold positive feedback). Zero cloud feedback corresponds to $\Delta\mathrm{CRF}/G = 0$, while $\Delta\mathrm{CRF}/G < 0$ denotes negative feedback. Thus $\Delta\mathrm{CRF}/G$ quantifies the net cloud feedback (Cess et al. 1989, 1990).

The direct radiative forcing G of the surface–atmosphere system is evaluated by holding all other climate parameters fixed. It is this quantity that induces the ensuing climate change, and physically it represents a change in the net (shortwave plus longwave) radiative flux at the TOA. For an increase in the

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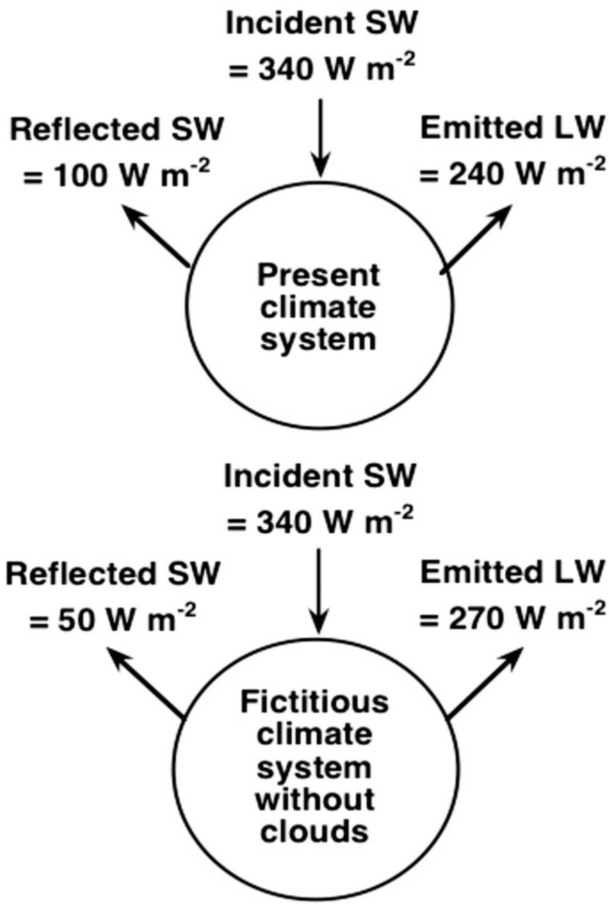

FIG. 1-6. Earth's TOA radiation budget together with a fictitious planet in which there are no clouds, but all else remains the same. LW denotes longwave (infrared) radiation and SW denotes shortwave (solar) radiation. Numbers have been rounded for the purpose of illustration. The fictional planet is used solely as an aid in understanding the radiative impact of clouds and as such is not in equilibrium; i.e., the sum of the emitted LW and the reflected SW do not add to 340 W m^{-2} [from Cess et al. (1996)].

CO_2 concentration of the atmosphere, G is the reduction in the emitted TOA longwave flux resulting solely from the CO_2 increase, and this reduction results in a heating of the surface–atmosphere system. The response process is the change in climate that is then necessary to restore the TOA radiation balance, such that

$$G = \Delta F - \Delta Q. \tag{1-2}$$

Thus ΔF and ΔQ represent the climate-change TOA responses to the direct radiative forcing G, and these are the quantities that are impacted by climate feedback mechanisms. Furthermore, the change in surface climate, expressed as the change in global-mean surface temperature ΔT_s, is related to the direct radiative forcing G by

$$\Delta T_s = \lambda G, \tag{1-3}$$

where λ is the climate sensitivity parameter:

$$\lambda = (\Delta F/\Delta T_s - \Delta Q/\Delta T_s)^{-1}. \tag{1-4}$$

An increase in λ thus represents an increased climate change due to a given climate forcing G.

The methodology proposed by Cess and Potter (1988) was employed by Cess et al. (1990) to quantify cloud feedback in a suite of 19 GCMs. This methodology consisted of imposing ±2-K sea surface temperature (SST) perturbations, in conjunction with a perpetual July simulation, as a surrogate climate change for the sole purpose of intercomparing climate sensitivity. This procedure is in essence an inverse climate change simulation. Rather than introducing a forcing G into the models and then letting the climate respond to this forcing, they instead prescribed the climate change and let the models in turn produce their respective forcing in accordance with Eq. (1-1). This procedure eliminated the substantial computer time required for equilibration of the models. The second advantage was that, since the same SSTs were prescribed, all of the models had essentially the same control climate because land temperatures are tightly coupled, through atmospheric transport, to the SSTs. The models then all produced a global-mean ΔT_s between the −2-K and +2-K SST perturbation simulations that was close to 4 K, and different model sensitivities in turn resulted in different values for G.

The perpetual July simulation eliminated another problem. This study focused solely on atmospheric feedback mechanisms, and inspection of output from all the models showed that climate feedback caused by changes in snow and ice coverage was suppressed through use of a fixed sea ice constraint and because the perpetual July simulations produced little snow cover in the Northern Hemisphere.

As discussed by Cess et al. (1990), there exist differing definitions of cloud feedback. For example, Wetherald and Manabe (1988) have addressed cloud feedback by performing two simulations, one with computed clouds and the other holding clouds fixed at their control climate values. Thus in this definition cloud feedback is referenced to the simulation in which clouds are invariant to the change in climate, while all other feedback processes are operative. For their CO_2 doubling simulations, Wetherald and Manabe (1988) found that cloud feedback amplified global warming by a factor of 1.3. Hansen et al. (1984), again for a CO_2 doubling, employed a radiative–convective model to diagnose three categories of feedback mechanisms within the

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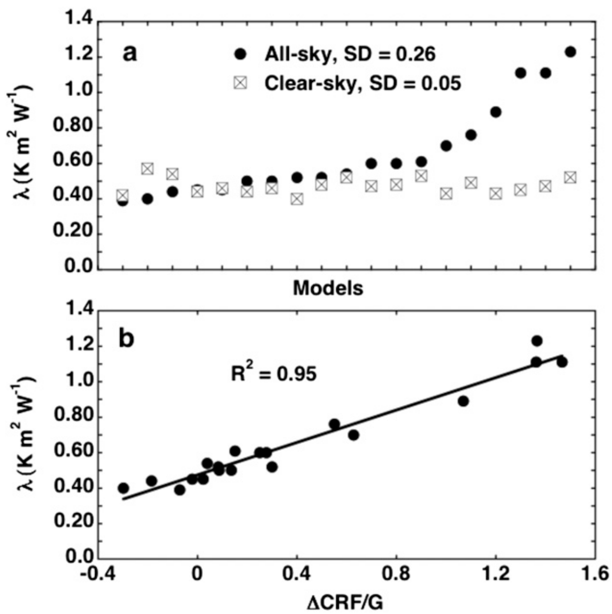

FIG. 1-7. (a) The sensitivity parameter λ, both for Earth with clouds and for the fictitious planet without clouds, for the 19 GCMs. SD denotes the standard deviation. (b) The sensitivity parameter λ, as a function of the cloud feedback parameter ΔCRF, for the 19 GCMs. The solid line is a linear fit, and R^2 is the square of the correlation coefficient.

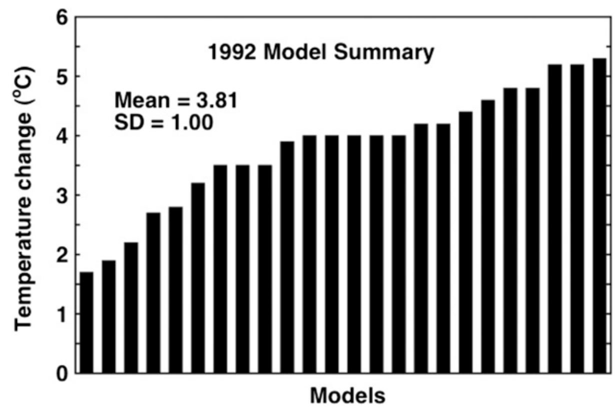

FIG. 1-8. Summary of the increase in global mean equilibrium surface temperature caused by a doubling of atmospheric CO_2 concentrations. These results are from simulations with atmospheric GCMs with a seasonal cycle, a mixed-layer ocean, and interactive clouds. This figure is constructed from Table 3.2(a) of IPCC (1990) and Table B2 of IPCC (1992).

Goddard Institute for Space Studies (GISS) GCM: water vapor, snow/ice–albedo, and cloud feedbacks. As did Wetherald and Manabe (1988), Hansen et al. found that cloud feedback produced a factor of 1.3 amplification. However, their feedback definition differs from that of Wetherald and Manabe; it is referenced not only to fixed clouds but also to the absence of both water vapor feedback and snow/ice–albedo feedback. When their results are reformulated in terms of Wetherald and Manabe's definition, their cloud feedback amplification factor is 1.8. The study by Cess et al. (1990) adopted yet a third definition of cloud feedback as discussed above using ΔCRF/G as a feedback parameter.

Cess et al. (1990) analyzed output from 19 GCMs, and their results for λ are summarized in Fig. 1-7a based on both global-mean all-sky (clear plus clouds) and clear-sky TOA fluxes. The procedure for evaluating the clear-sky fluxes is described by Cess et al. (1990). The clear-sky λ values from the models agree well with one another, but for the all-sky λ there is roughly a threefold variation in climate sensitivity. Since the only difference between the clear-sky and all-sky sensitivities is the inclusion of clouds in the latter, this demonstrates that cloud feedback is a major cause of the differences in model sensitivity. This conclusion is strengthened by the results shown in Fig. 1-7b. Clearly the model-to-model differences in climate sensitivity are mostly caused by model-to-model differences in ΔCRF/G (i.e., cloud feedback).

This study by Cess et al. (1990) thus helped to explain that model-to-model differences in cloud feedback were largely the cause of the significant differences in climate-change simulations by the models used at that time. Shown in Fig. 1-8 is the increase in global-mean surface temperature, caused by a doubling of atmospheric carbon dioxide, as computed by 24 different GCMs up to 1992. Assuredly, much of these differences can be attributed to differences in cloud feedback among the models, and we emphasize that the FANGIO project was the first to elucidate this important point.

5. Summary

By the late 1980s it was quite clear that there were major questions concerning the accuracy of the radiation codes used in climate models and in the predictions by GCMs due to differences in cloud feedback between the models. It was under this backdrop that Dr. Robert Hunter, former director of the DOE Office of Energy Research, commissioned a one-day seminar in November 1988 to summarize the DOE's climate activities as an aid for setting the stage for future initiatives. Hunter and his review team were adamant on devising climate programs that allowed testing hypotheses with observations. Working with Hunter, Dr. Aristides Patrinos, former Associate Director for Biological and Environmental Research for the DOE Office of Science, began the Quantitative Links Program and the subsequent ARM Program that expanded the approach of SPECTRE to include testing of models of the properties and

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occurrence of clouds from which to glean additional information about cloud feedback in GCMs.

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