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Final Technical Report

for

Treatment of Cloud Radiative Effects in General Circulation Models

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Abstract

This report summarizes the final results of the project covering the period 12/1/97-3/31/98, and includes two sections: project accomplishments and key findings.

The objectives of our participation in the Atmospheric Radiation Measurement (ARM) program were: (1) to improve GCM treatment of subgrid-scale variability of cloud-radiation interaction, and (2) to study the effect of variability on GCM climate simulations.

Specifically, the studies focused on:

- The development of a "mosaic" approach to parameterize the variability associated with cloud vertical "geometric association" and horizontal "inhomogeneity"; and
- The evaluation and improvement of radiative effects of aerosols and layer clouds.

These studies were conducted using the shortwave and longwave **radiation and cloud** parameterizations employed in the SUNY-Albany regional climate model (Dudek et al., 1996) and the NCAR-CCM3 global climate model (Kiehl et al., 1996). The measurements at the ARM Southern Great Plains were used to evaluate and improve these GCM parameterizations. In addition, we also used the cloud resolving model simulations to supplement the cloud statistics, in particular the cloud geometric association and vertical water/ice distribution.

1. Introduction

The general circulation model (GCM) is based on the numerical solution of the fundamental equations governing the dynamical and physical processes of the earth-atmosphere climate system. It has been considered to be **the best scientific tool** available to study the climate system as well as to assess future global climate change and its regional distribution due to the "enhanced" greenhouse effect and sulfate aerosols (Houghton et al., 1995, 1996). However, the uncertainties associated with the use of current GCMs in studying regional climate and climate changes are large, caused primarily by **cloud-radiation interactions,** the focus areas of the DOE-ARM program (ARM, 1990, 1996).

One of the major issues associated with cloud-radiation interactions is the **spatial scale** of the GCM physical parameterizations for radiation and clouds. Clouds are often observed to occur with distinct vertical geometric associations (Hahn et al., 1982, 1984). For example, altostratus tends to exist exclusively with cumulus while cumulonimbus and cirrus frequently occur simultaneously in the tropics. In addition, adjacent cloud layers are likely to have maximum association, while discrete cloud layers are independent (Tian and Curry, 1989). Cloud radiative properties not only differ greatly between different genera (Tiedtke, 1996), but also distribute nonuniformly within the same genus (Cahalan et al., 1994). In general, there are three aspects of subgrid-scale variability of cloud-radiation interaction: the cloud *macrogrouping* (geometric association), *inhomogeneity* (within-cloud optical property variance) and *broken-cloud* (interaction among finite clouds). It is unlikely that the variability of different time and spatial scales can be resolved by GCM physical parameterizations. A practical solution is to use a combination of a deterministic radiative transfer for resolved scales and a stochastic approach for unresolved scales (Stephens et al., 1993; Zuev and Titov, 1995; Gabriel and Evans, 1996).

A GCM grid used for climate simulations typically covers an area of $(200\text{-}500\ \text{km})^2$ with large variability in climate processes within the domain (Thunis and Barnstein, 1996; Dudek et al., 1996), especially the three aspects of cloud-radiation interactions discussed above. For example, random overlap (Manabe and Strickler, 1964), which assumes that all cloud layers are independent, has been used in GCMs to treat cloud macrogrouping. Therefore, this treatment tends to yield a larger total cloud cover because it neglects cloud geometric association. To partially correct this, Geleyn and Hollingsworth (1979) proposed a mixed overlap treatment assuming that adjacent cloudy layers share maximum overlap while discrete clouds are randomly overlapped. When compared with observations, Tian and Curry (1989) showed that the mixed overlap yields better agreement in total cloud cover. Among the 30 GCMs participating in the Atmospheric Model Intercomparison Project (AMIP; Gates, 1992), about half use random overlap while the rest adopt various forms of mixed overlap.

Because of the spatial scale of the ARM experimental design, the subgrid-scale variability of cloud-radiation interactions can be critically examined. In addition, the ARM program measures the relevant parameters (microphysics and optical properties) as completely as possible. This offers the best opportunity to validate and further refine the GCM cloud and radiation parameterizations.

2. Project Accomplishments

This section lists the project's publications and participating graduate students.

2.1 Publications

There were eight (8) refereed journal articles, one (1) book chapter, and seven (7) proceedings manuscripts.

Cox, S., W.-C. Wang, and S. Schwartz, 1995: Climate responses by radiative forcings of sulfate aerosols and greenhouse gases. *Geophys. Res. Lett*, *22*, 2509-2512.

Ding, M. and W.-C. Wang, 1996: GCM radiation model-to-observation comparison. *Proceedings of the Seventh Annual Symposium on Global Change Studies*, January 28-February 2, 1996, Atlanta, GA.

Ding, M., W.-C. Wang, and J. J. Michalsky, 1996: Validation of GCM radiation parameterization using measurements from the ARM program. *Proceedings of the International Radiation Symposium*, Fairbanks, Alaska, August 19-24, 1996.

Dudek, M. P. , X.-Z. Liang, L. Zhu, and W.-C. Wang, 1993: Resolution dependence of GCM cloud parameterization. Special Session of ARM Research, *Fourth Symposium on Global Change Studies*, January 17-22, 1993, Anaheim, CA.

Dudek, M. P., X.-Z. Liang, and W.-C. Wang, 1996: A regional climate model study of the scale-dependence of cloud-radiation interactions. *J. Climate*, *9*, 1221-1234.

Johnson, D. W., R. G. Issacs, and W.-C. Wang, 1992: Vertical cloud distribution estimates using AVHRR imagery. *Proceedings of the 1992 American Society for Photogrammetry and Remote Sensing/American Congress on Surveying and Mapping '92 Global Change Convention*, August 3-7, 1992, Washington DC.

Joseph, E. and W.-C. Wang, 1995: Incorporation of an improved cirrus cloud parameterization into the NCAR-GENESIS climate model. *Proceedings of the Sixth Symposium on Global Change Studies*, pp 136-141, January 15-20, 1995, Dallas, Texas.

Joseph, E. and W.-C. Wang, 1997: Using ARM data to validate an interactive high cloud radiative parameterization for GCMs. *Proceedings of the Ninth Conference on Atmospheric Radiation*, Long Beach, California, February 2-7, 1997.

Liang, X.-Z. and W.-C. Wang, 1995: A GCM study of the climatic effect of observed 1979-1992 ozone trend. in *Atmospheric Ozone as A Climate Gas*, (Eds) W.-C. Wang and I. S. A. Isaksen, 259-288, NATO ASI Series, Springer-Verlag, Berlin.

Liang, X.-Z. and W.-C. Wang, 1997: Effect of cloud overlap on GCM climate simulations. *J. Geophys. Res.* (in press; some of the details are described in Section 3)

Liang, X.-Z. and W.-C. Wang, 1996: Cloud overlap effects on GCM climate simulations. *Proceedings of the International Radiation Symposium*, Fairbanks, Alaska, August 19-24, 1996.

Molnar, G. and W.-C. Wang, 1992: Effects of cloud optical property feedbacks on the greenhouse warming. *J. Climate*, *5*, 814-821.

Wang, W.-C., M. P. Dudek, and X.-Z. Liang, 1992: Inadequacy of effective CO_2 as a proxy to assess the greenhouse effect of other radiatively active gases. *Geophys. Res. Lett.*, *19*, 1375-1378.

Wang, W.-C., M. P. Dudek, X.-Z. Liang, and J. T. Kiehl, 1991: Inadequacy of effective CO_2 as a proxy in simulating the greenhouse effect of other radiatively active gases. *Nature, 350*, 573-577.

Wang, W.-C., X.-Z. Liang, M. P. Dudek, D. Pollard and S. L. Thompson, 1995: Atmospheric ozone as a climate gas. *Atmospheric Research, 37*, 247-256.

Wang, W.-C., Y. Zhuang, and R. Bojkov, 1993: Climate implications of observed changes in ozone vertical distributions at middle and high latitudes of the Northern Hemisphere. *Geophys. Res. Lett, 20*, 1567-1570.

2.2 Participation of Graduate Students

Cox, S., Climatic effect of sulfate aerosols. (Ph.D. candidate in the Department of Atmospheric Sciences).

Ding, M., 1997: Evaluation of GCM shortwave radiation parameterization for gases, aerosols and clouds. Ph.D. Department of Atmospheric Sciences, SUNY at Albany.

Fox, S., 1995: Biological processes and the land surface: Influences on global climate change. MS, Dept. of Biological Sciences, SUNY at Albany.

Joseph, E., 1997: Development and application of an interactive cirrus cloud radiative parameterization for global climate models. Ph.D. Department of Physics, SUNY at Albany.

Zhong, M., 1994: The greenhouse effect of the present Earth-atmosphere climate system. MS, Dept. of Atmospheric Sciences, SUNY at Albany.

Zhuang, Y.-C., 1993: Radiative forcing due to changes in tropospheric ozone. MS, Dept. of Atmospheric Sciences, SUNY at Albany.

3. Key Findings

This section summarizes the key findings in two research areas: subgrid-scale variability of cloud-radiation interactions, and radiative effects of aerosols and clouds.

3.1 Subgrid-Scale Variability of Cloud-Radiation Interactions

Objective: To use ARM and supplementary data to evaluate and improve GCM treatment of radiative heating/cooling distributions associated with sub-grid scale variability of cloud-radiation interactions

3.1.1 The "Mosaic" Approach

Current GCMs simulate only cloud fractions in individual model layers without explicitly specifying their association. However, as discussed in Section 1, there exists a strong vertical geometric association for convective (Cc), anvil cirrus (Ci), and stratiform (Cs) clouds (see Figure 1). Because the distribution of radiative heating/cooling is sensitive to cloud cover, it is quite clear that proper consideration of the inherent geometric association of the clouds is needed. Using ARM data and simulations from a regional climate model over the SGP site (Dudek et al., 1996), we have developed a "mosaic" approach to parameterize the subgrid-scale variability associated with cloud macrogrouping and inhomogeneity (Liang and Wang, 1997).

In the "mosaic" treatment, the GCM grid is divided into subcells filled horizontally by a specific cloud genus (or sometimes two cloud genera) with distinct optical properties. Different cloud genera (Cc, Ci, Cs) in each layer are first defined to be geographically distinct and thus minimally overlapped. Second, Cc are assigned to a single subcell, where the area is given by the largest Cc values from the convective top to the lowest layers. Third, Ci (usually in the convection top layer) then fill consecutively the subcells that are equally divided over the remaining grid area. Finally, Cs are distributed to subcells using a special procedure (see "stochastic" cloud radiative forcing below). Separate radiation calculations are performed for each subcell with clouds, whereas clear sky radiative fluxes are computed only once and used for all subcells. The grid mean radiative heating/cooling distributions are the areal averages over all subcells. This framework can treat both the cloud macrogrouping and inhomogeneity more rigorously.

As shown in Liang and Wang (1997), when compared with random overlap treatment, the mosaic treatment that incorporates the "macrogrouping" effect calculates a significantly different atmospheric radiative heating/cooling distribution. In the tropics, it yields a heating in the upper troposphere and a cooling in the lower troposphere especially near the surface; opposite changes are calculated in the middle-to-high latitudes. Differences in climate response are substantial, where the mosaic treatment corrects several major model biases. For example, the middle-to-upper troposphere of the tropics and subtropics are warmed by more than 3°C throughout the year, while the polar night stratosphere in the Northern Hemisphere becomes much warmer, up to 15°C. The study results clearly suggest that the subgrid scale cloud-radiation variability associated with cloud geometric association has an important impact on climate simulation.

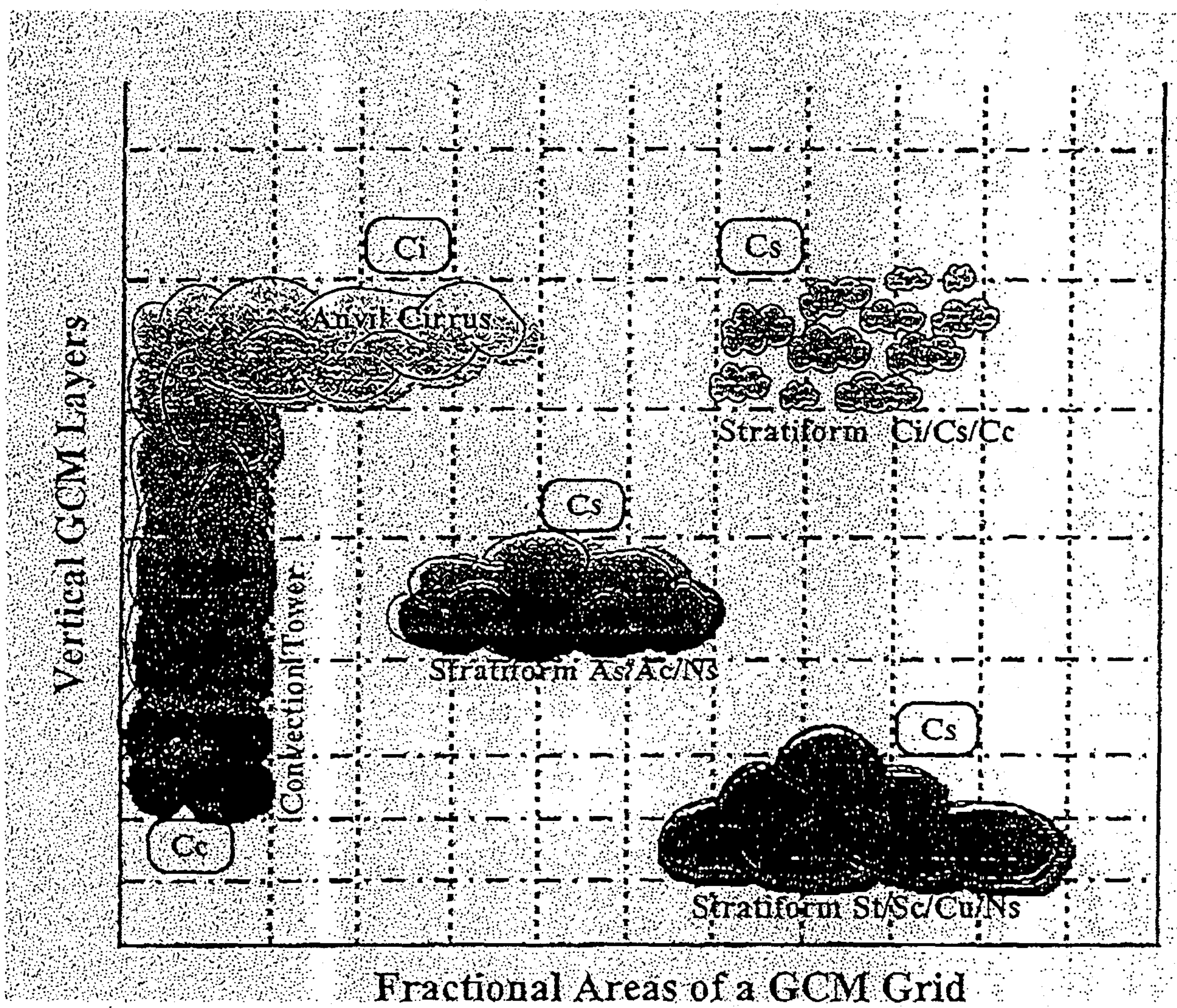

Figure 1. The "mosaic" approach, in which the GCM grid is aggregated into N subcells horizontally so that the vertical association due to increased resolution can be considered more ealistically. GCM predicts individually the fractional coverage of convective (Cc), anvil cirrus (Ci), and stratiform (Cs) clouds, which are therefore subgrid-scale.

3.1.2 "Stochastic" Cloud Radiative Forcing

Perhaps the most interesting aspect of the mosaic approach is the "stochastic" cloud radiative forcing implemented by Liang and Wang (1997) to treat the Cs clouds. The stochastic treatment results from special consideration for this cloud type: adjacent layers that contain Cs are vertically aligned by an identical set of random- order subcells to acquire a maximum overlap, whereas discrete Cs layers use an independent set (i.e., generated randomly each time) to treat the overlap, thus producing the "stochastic" characteristics in the cloud radiative forcing.

Radiative forcing in the "mosaic" approach with its inherent "stochastic" characteristics could differ substantially from those that use random overlap for treating vertical cloud overlap in CCM3 (Kiehl, et al., 1996). For example, as illustrated in Fig. 2, the mosaic approach tends to calculate a smaller solar radiation input (up to 35 Wm^{-2}) to the model climate system (decreases in TOA forcing) with most of the decreases caused by decreases in the surface forcing (SFC).

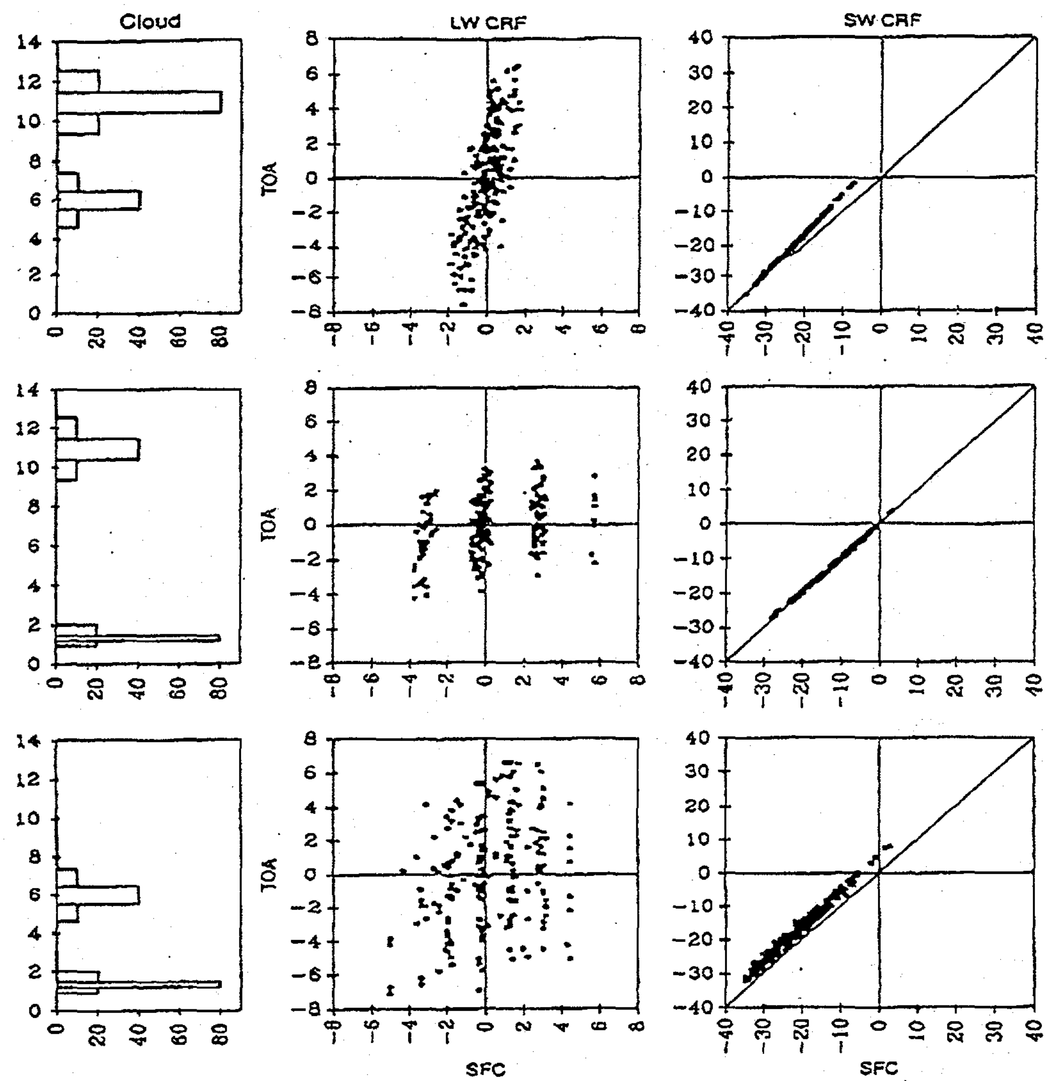

Figure 2. The "stochastic" cloud radiative effects associated with the "mosaic" approach. The longwave (LW) and shortwave (SW) cloud radiative forcing (CRF; Wm^{-2}) at the top-of-atmosphere (TOA) and on the surface (SFC) are the differences between the "mosaic" approach and the CCM3 "random overlap" scheme (Kiehl, et al., 1996) *for the specified* vertical cloud distribution (left panel). Each dot represents one of the 200 mosaic calculations using the McClatchey et al. (1972) mid-latitude summer model atmosphere.

However, it is particularly interesting to note that the atmospheric absorption becomes larger (up to 10 Wm^{-2}) for the two cases of high-middle clouds and low-middle clouds in the mosaic treatment, as reflected in the steeper slopes in the TOA-SFC plots, but not for the case of high-low clouds. The increased atmospheric absorption is caused by the enhanced water vapor absorption that results from multiple reflections between the clouds.

3.1.3 Cloud Cover Probability Distribution Function

One critical assumption used in Liang and Wang (1997) is that binary clouds (i.e., completely overcast or clear skies) are used in the individual subcells. This simplification is based on the statistics that the probability of either completely overcast or clear skies increases as the observation area decreases.

Liang and Wang (1997) used satellite measured total cloud cover with data cells of $(50\ km)^2$ over the SGP during the April 6-30, 1994 IOP to examine the cloud cover probability distribution function (PDF) for specified ranges of cloud mean (CM) amount over a grid of $(1000\ km)^2$ area. The results suggest the dominance of either completely overcast or clear skies in the mesoscale cells for all CM values while the fraction of partial cloudy conditions is quite small. They found that the PDF changes gradually with CM and that PDFs are symmetric about CM=50%. They further found that the PDFs for high, middle and low clouds are essentially similar to those for total cloud cover. In practical applications, given PDFs, the distribution of subcell cloud fractions can be determined based on GCM predicted CM values. Because of the variability of cloud overlap and uncertainties of other cloud information, comparisons of cloud PDFs make the model evaluation more vigorous. Therefore, further analyses of observations and regional model simulations are warranted to examine the PDFs at different climate zones.

3.1.4 Vertical Distribution of Cloud Liquid/ice Water

Because cloud cover is related to the GCM cloud liquid water/ice parameterization, the findings of Liang and Wang (1997) were sensitive to the cloud liquid water/ice vertical distribution. In that study, the model, following Kiehl et al. (1996), assumes that liquid water/ice decreases exponentially with altitude where the scale height is a function of latitude. (Note that the distribution is prescribed in diagnostic approach versus calculated in a prognostic approach; see Slingo, 1987). Therefore the fundamental issue was to determine the degree to which the geographical and vertical distribution of cloud liquid/ice water were realistic. To make an initial evaluation we used two types of data, the measurements at Central Facility/SGP, and simulations from a cloud resolving model (CRM) developed at MMM/NCAR.

For the SGP data, we used the measurements of cloud base heights from micropulse lidar (MPL) and column water vapor and cloud liquid/ice paths from microwave radiometer (MWR). Figure 3 shows the summer and winter frequency of cloud occurrence as a function of liquid water path and cloud base height. Clearly, the distribution function exhibits "stochastic" characteristics with strong seasonal variation. During winter there are more clouds with lower bases and larger liquid water, while during summer the cloud base, with a peak at 4 km, extends to far higher levels. We have also studied cloud frequency as a function of water vapor path and liquid water path (not shown). Again the seasonal contrast is large: the summer clouds with smaller liquid water are usually associated with more water vapor while the winter statistics have quite different characteristics. In collaboration with L. Harrison and Q. Min (SUNYA), we are also in the process of examining the measurements of surface shortwave fluxes from a multifilter rotating shadowband radiometer (MFRSR) and cloud optical properties and droplet effective radius derived from MWR and MFRSR, so that the consistency of the statistics between the clouds and shortwave radiation fluxes can be evaluated.

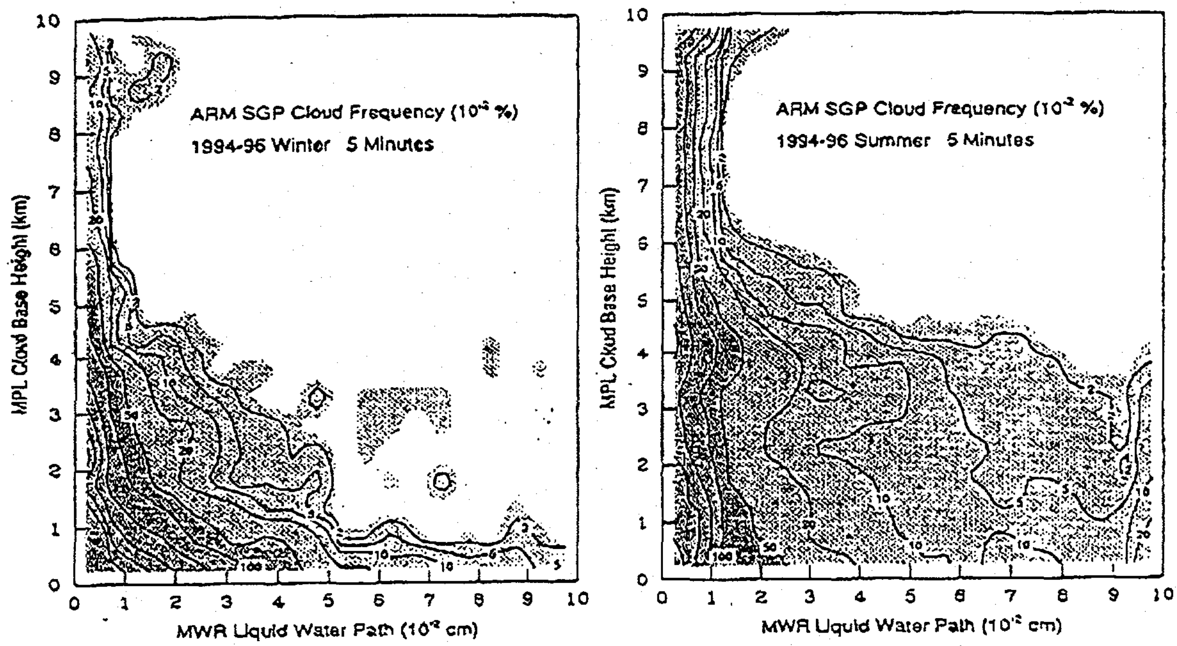

Figure 3. Frequency (in 10^{-4} unit) of cloud as a function of cloud base height and column liquid water path for winter (December-January-February; left panel) and summer (June-July-August; right panel). The height and path were measured, respectively, by the micropulse lidar (MPL) and microwave radiometer (MWR) at the ARM SGP Central Facility during January 1994 - December 1996. All data are averaged over 5 minutes with contours at 2, 5, 10, 20, 50, 100, 200, 300, 400, and 500 units.

For CRM data, we adopted the results of Wu et al. (1997), who used a 2-D model to simulate tropical cloud system for a 39-day period (December 5, 1992-January 12, 1993) during the Tropical Ocean Global Atmosphere (TOGA) Coupled Ocean Atmosphere Response Experiment (COARE). The dataset has 3-km horizontal resolution covering the TOGA/COARE 900-km domain. Averaging over the whole domain, the statistics indicate that clouds occur 54% of the time in single (penetrative) towers, 12% in two distinct cells, and 4% in multiple levels.

As shown in Figure 4, most of the penetrative clouds have a peak water content at 6 km, where ice formation is maximized near local temperature -10°C, and a secondary peak at 4.5 km, where liquid growth reaches the maximum above the updraft mass flux maxima. Note that the peak concentration of cloud water is independent of cloud base height, which is different from the exponential decaying vertical profile adopted by CCM3 (Kiehl et al., 1996).

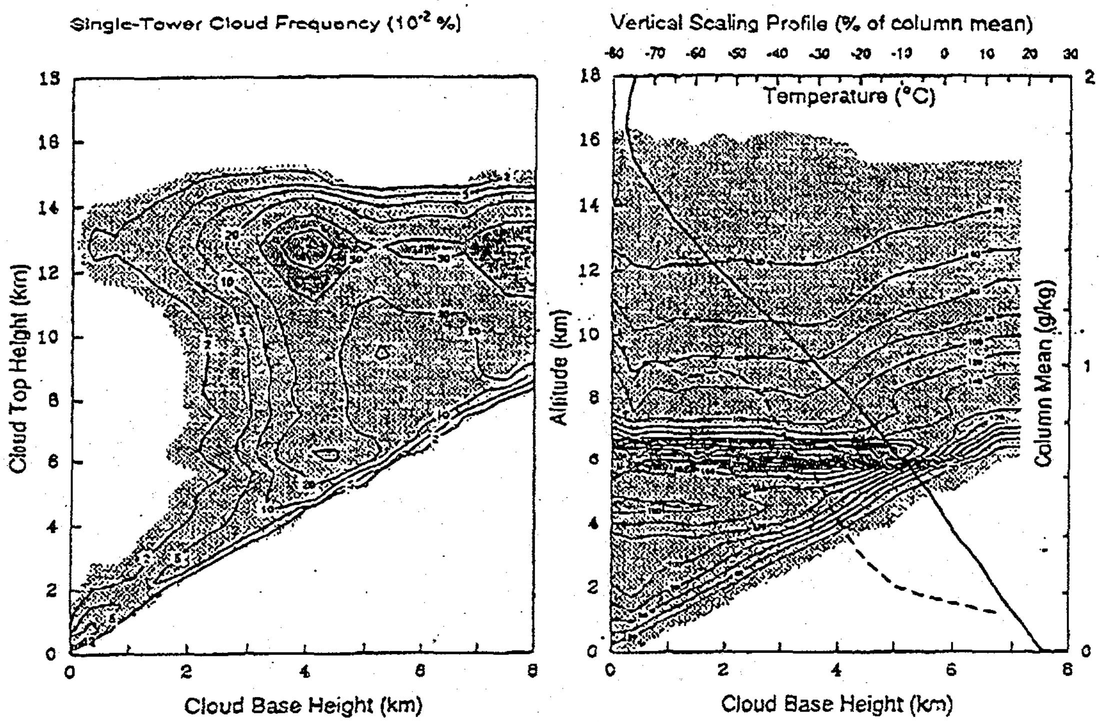

Figure 4. Statistics of a single-tower cloud simulated by the cloud resolving model over TOGA/COARE during 5 December 1992 - 12 January 1993 (Wu et al., 1997). All 15-minute cloud data with 3-km horizontal resolution over a 900-km span are used to identify the statistics of single-tower, which is defined to be an unbroken cloud segment in the vertical. (Left panel) The cloud frequency (in 10^{-4} unit) as a function of cloud base and top heights with contours at 2, 5, 10, 20, 50, and 100 units. (Right panel) The cloud liquid water/ice vertical scaling profile (contours at 20 units) is defined as percentages of the column mean values (dashed line; using the lower and right scales). The domain mean temperature profile (thick solid, using the top and left scales) is also shown.

We have conducted a sensitivity study on the effect of cloud liquid/ice vertical distribution on radiative heating/cooling in the atmosphere. The calculations, shown in Figure 5, are based on an atmospheric model consisting of a 50% clear region and a 50% single cloud tower with two different cloud water profiles (one from CCM3 with exponential decay characteristics and the other derived from the CRM simulations) with identical column amount. It is quite clear that the vertical distribution of cloud water affects substantially the solar and longwave radiative heating/cooling distribution. The most significant difference is the shift of the peak net radiative cooling rate from 2.5°C at 7 km in the exponential profile to 1.5°C at 10 km in the CRM profile.

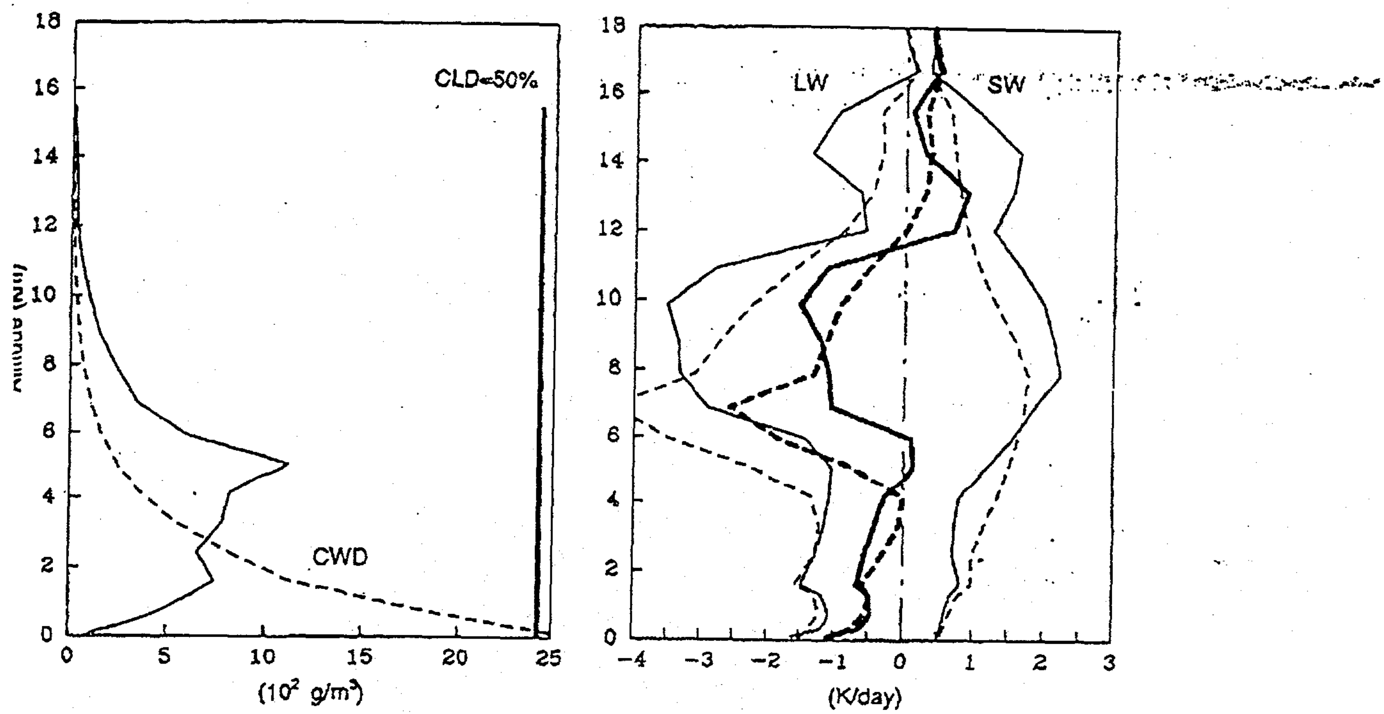

Figure 5. The effect of specified vertical cloud liquid water profiles on the radiative heating/cooling distribution. (Left panel) An atmosphere with 50% clear region and a 50% single cloud tower extending from surface to 15.5 km is used. Two liquid water profiles, an exponential profile from CCM3 (dashed line) and the other from CRM simulation (thin solid line; Fig. 4) with identical column water of 0.551 cm. (Right panel) the shortwave and longwave radiative heating rates are calculated based on the McClatchy et al. (1972) tropical model atmospheric temperature and moisture with April 1 solar zenith angle and surface albedo 0.1. Thick solid line is the net (LW+SW) radiative heating.

3.2 Radiative Effects of Aerosols and Layer Clouds

Objectives: To evaluate and improve the GCM parameterizations for shortwave and longwave radiative effects of aerosols and layer clouds

3.2.1 Aerosols

We have evaluated the longwave radiation code (Wang et al., 1991) and the delta-Eddington shortwave scheme of the NCAR-SUNYA GENESIS and NCAR CCM3 global climate models using surface measurements of shortwave and longwave radiation fluxes at Albany, NY during 10/86-9/92 and the SGP central facility during two IOPs (April 1994 and October 1995). Concurrent atmospheric moisture and temperature data were taken from radiosondes while climatological ozone from TOMS was used. For the aerosols, we used the total optical depth derived from MFRSR measurements while values for single scattering albedo and asymmetry factor were taken from D'Almeida et al. (1991).

Based on the results, the following conclusions can be made:

- For longwave radiation, the model calculations are in good agreement with measured values, especially for the Albany site (within 3 Wm^{-2}). However, the differences become larger for the SGP site. Note that the Albany site covers a much longer period (10/86-9/92) and includes seasonal variations while SGP covers only April 1994;
- For shortwave radiation (see Figure 6 and Table 1), the model systematically overestimates the downward flux, an indication of a smaller model atmospheric opacity. The effect of aerosols is quite large, decreasing substantially the shortwave radiation reaching the surface and increases the atmospheric absorption, thus highlighting the importance to include aerosols in GCM.

To further look into the large difference in shortwave radiation reaching the surface as shown in Table 1, we have conducted sensitivity calculations to examine the effects of the input parameters. The results suggest that the column water vapor and aerosol optical properties play important roles while the effects of surface albedo and column ozone are relatively small.

Table 1. Difference in the shortwave radiation (Wm^{-2}) between radiation model calculations and observations. Values with aerosols are the means over the data shown in Figure 6. Aerosol optical properties were derived from MFRSR measurements at both sites by J. Michalsky of SUNYA.

Site	Data Period	Incident on Surface		Atmospheric Absorption		GCM
		without aerosols	with aerosols	without aerosols	with aerosols	
Albany/NY	10/86-9/92	35.4	19.0	----	----	GENESIS
SGP	4/94 IOP	26.2	12.2	-18.3	-9.1	GENESIS
		19.1	----	-12.9	----	CCM3
	10/95 IOP	29.1	----	-33.0	----	GENESIS
		23.0	10.6	-24.1	-16.7	CCM3

3.2.2 Cirrus clouds

Parameterizations for the shortwave and longwave radiative effects of cirrus clouds for use in GCMs were developed. In the parameterizations, cloud particles are assumed to be composed of randomly oriented hexagonal crystals. For shortwave radiation, the broad band transmittance, reflectance, and absorptance are expressed as a function of single scattering albedo, asymmetry factor and optical depth, which in turn are functions of effective particle radius. For longwave radiation, the optical depth and emissivity are expressed in terms of cloud ice water path. Both the effective particle radius and ice water path are parameterized to be a function of cloud temperature. Details of the new parameterization are described in Joseph and Wang (1995).

Using this new parameterization with satellite derived high level clouds during the April 1994 IOP over SGP, we conducted a model-to-observation comparison of the downward flux at the surface and outgoing flux at the TOA for both shortwave and longwave radiation. The results suggest that the new parameterization with interactive microphysics and optical properties simulates better agreement with observations. For example, when compared with the old parameterization, the new parameterization reduces the rms difference in the TOA shortwave radiation flux by 50%.

Comparisons of the cloud optical properties, and shortwave and longwave radiative fluxes from the calculations using the new parameterization and the current cirrus scheme used in NCAR GENESIS, as well as with observations were conducted. The results indicate that, while the new parameterization calculates a more realistic cirrus cloud optical properties, the biases in the calculated radiative fluxes remain large (Joseph and Wang, 1997).

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(Note that the references related to the project are listed in Section 2.)

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