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THE ROLE OF ICE SEDIMENTATION IN THE MICROPHYSICAL AND RADIATIVE BUDGETS OF COARE CONVECTIVE SYSTEMS

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1. INTRODUCTION

The microphysical properties of the stratiform mesoscale anvils associated with COARE convective systems are important controls on the fluxes of shortwave and longwave radiation at the ocean surface. These microphysical properties are modeled using a high-resolution, two-dimensional cloud-system model (horizontal domain size of several hundred kilometers with horizontal resolution of two kilometers) with prognostic equations for cloud liquid, cloud ice, rain, and snow. The model's dynamics are built around the elastic system (Held *et al.*, 1993). Large-scale forcing is imposed using COARE observations. Radiative fluxes are calculated interactively and depend on cloud microphysical properties.

The microphysical properties of these cloud systems depend strongly on the rate at which ice particles in the mesoscale component of the system are removed by sedimentation. Many bulk prognostic microphysics parameterizations used in cloud-system models have separate prognostic equations for cloud ice and snow and often treat cloud ice as suspended (no sedimentation). By contrast, experimental aircraft measurements have established relationships between ice terminal speeds and ice mixing ratios which suggest appreciable ice sedimentation (terminal speeds of the order of several tens of centimeters per second) at concentrations where prognostic microphysics parameterizations indicate insignficant sedimentation. The microphysical and radiative properties of convective systems modeled using this range of treatments of ice sedimentation vary widely, impacting the underlying ocean surface heat balance. This paper describes the dependence of radiative budgets in COARE convective systems on the treatment of ice sedimentation and presents an intermediate formulation of cloud-ice terminal speeds based on microphysical measurements obtained during the the Central Pacific Experiment (CEPEX).

2. ICE SEDIMENTATION RATES

A recent survey of cloud models participating in the Global Cloud System Study revealed a wide range of ice sedimentation rates in cloud models (Phil Brown, United Kingdom Meteorological Office, personal communication). For example, at an ice content of .0001 g m^{-3}, mass-weighted fall speeds for ice ranged from zero to 1 m s^{-1}. Three formulations for ice fall speed are used in the present experiments to demonstrate the sensitivity of radiative fluxes to ice sedimentation: (1) In "No Fall," cloud ice does not fall, as described in Held *et al.* (1993). (2) In "HeyDon90," the terminal speed for cloud ice follows Heymsfield and Donner (1990). (3) In "P98/C97," the relationships between ice-particle mass, size, and fall speed in Petch *et al.* (1998) are used. The average particle mass is determined from the mixing ratio assuming an ice number density of 10^6 m^{-3}, following Chen *et al.* (1997). In the latter two methods, the fall speeds are assumed to hold for snow and cloud ice together. Snow fall speeds follow Held *et al.* (1993), and cloud-ice fall speeds are calculated so the fall speeds given by methods (2) and (3) will hold for snow and cloud ice together. Fall speeds represented by these three methods for an ice content of .0001 g m^{-3} range from zero through around .2 cm s^{-1}(P98/C97) to around 25 cm s^{-1}(HeyDon90).

3. SENSITIVITY OF RADIATIVE FLUXES

Figure 1 shows the dependence of surface shortwave flux and outgoing longwave radiation on ice fall speed. A very strong dependency of outgoing longwave radiation and surface shortwave radiation on the treatment of ice sedimentation is evident. Over the period depicted in the figure, the average shortwave downfluxes are 47.5, 103.6, and 61.5 W m^{-2} for "No Fall," "HeyDon90," and "P98/C97," respectively. For outgoing longwave radiation, the corresponding fluxes are 80.6, 118.1, and 85.7 W m^{-2}. Note that the ice is assumed to be in the form of 10-μm spheres in these calculations. Both observed surface shortwave fluxes (Weller and Anderson, 1996) and outgoing longwave radiation (ISCCP) are greater than any of the model results. Model assumptions regarding particle shape and size, as well as treatment of lateral boundary conditions, which may lead to upper-tropospheric ice build-up, are possible explanations.

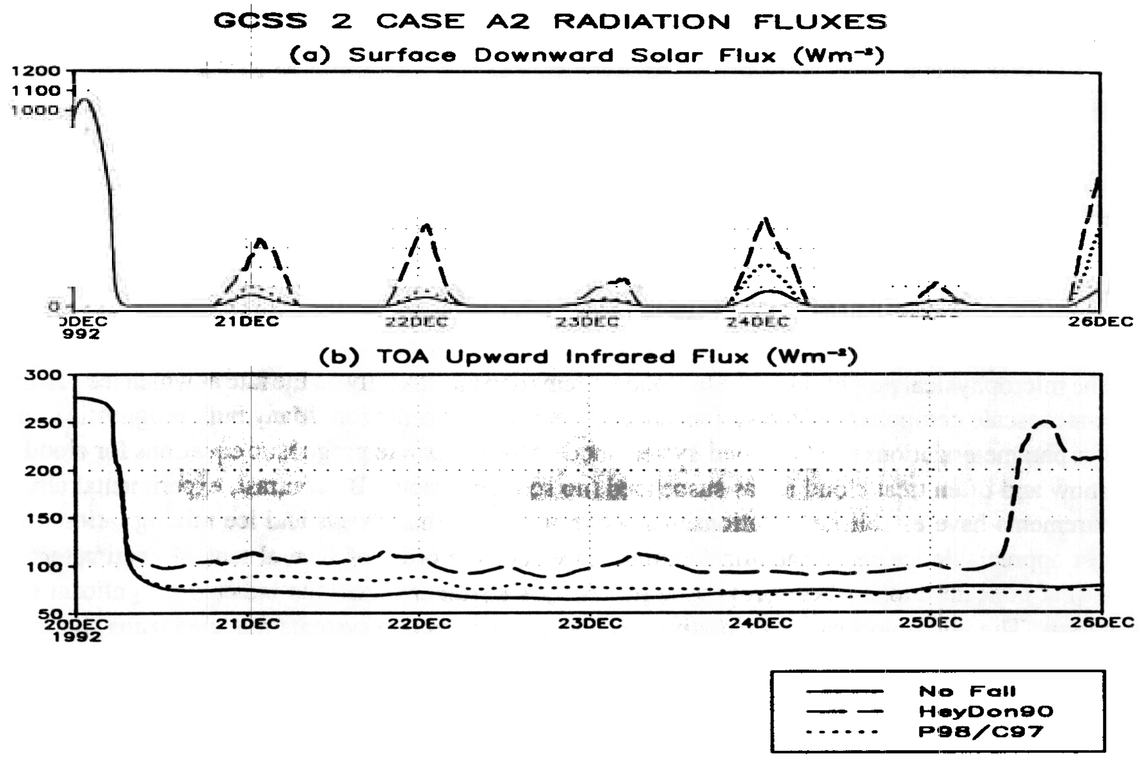

Figure 1-Radiative fluxes during TOGA-COARE and their dependence on the rate of ice sedimentation.

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THE ATMOSPHERIC RADIATIVE HEATING RATE DURING COARE: ESTIMATION FROM OBSERVATIONS AND MODEL SIMULATIONS †

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1 SUMMARY

The column-integral radiative diabatic heating term, $\langle Q_R \rangle$, has been calculated using satellite-derived fluxes at the tropopause and surface radiation measurements from COARE. The observational estimates are compared with the residual values obtained from atmospheric budgets and other methods. The largest uncertainties in $\langle Q_R \rangle$ are introduced by the considerable spread in TOA albedo retrievals and by the inclusion or omission of enhanced shortwave cloud absorption. The observational estimates of the magnitude and variability of $\langle Q_R \rangle$ are compared with a simulation of the COARE IOP using the NCAR Community Climate Model CCM3.

2 METHODOLOGY AND DATA SOURCES

The column-integral radiative diabatic heating $\langle Q_R \rangle$ is defined by (Lin and Johnson, 1996):

$$\langle Q_R \rangle = \langle Q_1 \rangle - \langle Q_2 \rangle - LE - S \qquad (1)$$

where $\langle Q_{1,2} \rangle$ are pressure integrals of the apparent heat source and moisture sink, respectively, LE is the latent heat flux, and S is the sensible heat flux. Estimates of the all-sky IOP-mean $\langle Q_R \rangle$ for the IFA range between −0.88°C/day to −0.39°C/day (Bradley et al., 1997). These estimates are derived from residuals of atmospheric budgets (e.g., eq. 1) (Lin and Johnson, 1996), model calculations of fluxes based upon satellite retrievals of cloud and atmospheric properties (Rossow and Zhang, 1995), and combinations of both. The present values are obtained by differencing observed surface fluxes from satellite estimates of radiative fluxes at the tropopause (Collins et al., 1997). The surface fluxes are averages of data from the IMET buoy and the ISS onboard R/V Kexue 1 and R/V Shiyan 3. The observational estimates are compared against a simulation of the COARE IOP with the NCAR general circulation model CCM3 (Kiehl et al., 1998) using observed SSTs.

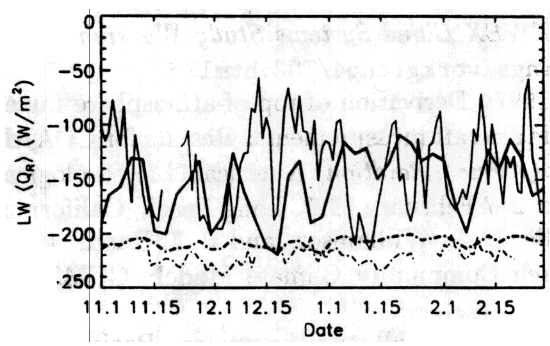

Figure 1–Diurnally Averaged LW $\langle Q_R \rangle$. Observed all-sky (solid) and clear-sky (dot-dash); CCM3 all-sky (thick solid) and clear-sky (thick dot-dash).

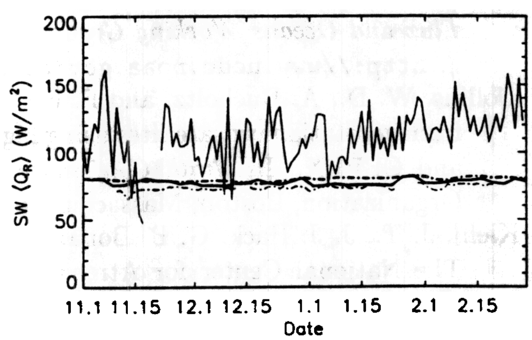

Figure 2–Diurnally Averaged SW $\langle Q_R \rangle$. Observed all-sky (solid) and clear-sky (dot-dash); CCM3 all-sky (thick solid) and clear-sky (thick dot-dash).

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Table 1-IOP/IFA-mean Observed $\langle Q_R \rangle$

Regime	Term	W/m^2	°C/day
Clear	LW $\langle Q_R \rangle$	-204 ± 10	-1.9 ± 0.1
	SW $\langle Q_R \rangle$	73 ± 4	0.68 ± 0.02
	$\langle Q_R \rangle$	-131 ± 11	-1.2 ± 0.1
All-sky	LW $\langle Q_R \rangle$	-139 ± 10	-1.4 ± 0.1
	SW $\langle Q_R \rangle$	111 ± 15	1.0 ± 0.1
	$\langle Q_R \rangle$	-28 ± 18	-0.3 ± 0.2

Table 2–IOP/IFA-mean CCM3 $\langle Q_R \rangle$

Regime	Term	W/m^2	°C/day
Clear	LW $\langle Q_R \rangle$	-208	-1.9
	SW $\langle Q_R \rangle$	80	0.75
	$\langle Q_R \rangle$	-128	-1.2
All-sky	LW $\langle Q_R \rangle$	-154	-1.4
	SW $\langle Q_R \rangle$	78	0.73
	$\langle Q_R \rangle$	-76	-0.71

Clear-sky heating rates and the downwelling solar and longwave fluxes at the tropopause for the observational estimates are calculated from the ISS soundings using the NCAR Column Radiation Model. $\langle Q_R \rangle$ is expressed both as a flux divergence over the troposphere and as a heating rate (1°C/day $\simeq$ 107 W/m^2).

3 DISCUSSION OF RESULTS

Time series of the observed and modeled tropospheric flux divergences are shown in Figure 1 for the longwave (LW) and Figure 2 for the shortwave (SW). The modeled and observed clear-sky LW $\langle Q_R \rangle$ are in excellent agreement, as are the time-average all-sky LW $\langle Q_R \rangle$ (Tables 1 and 2). The discrepancy between the measured and modeled LW $\langle Q_R \rangle$ on daily time-scales is expected for GCM simulations run without relaxation to observations. The modeled and observed clear-sky SW $\langle Q_R \rangle$ are also in excellent agreement. However, CCM produces an all-sky SW $\langle Q_R \rangle$ very similar to the clear-sky values, while the observational all-sky SW $\langle Q_R \rangle$ is consistently larger than the corresponding clear-sky estimates. The error estimates in Tables 1 do not include effects of systematic biases. ERBE WFOV observations of TOA albedo and comparison against SW $\langle Q_R \rangle$ derived from preliminary NASA LBTM fluxes suggest that the SW $\langle Q_R \rangle$ and total $\langle Q_R \rangle$ may be closer to -0.5 ± 0.2 °C/day. Systematic uncertainties will be reduced when final versions of the TOA flux data sets are produced. Current evidence suggests that the magnitude of the IOP/IFA-mean radiative diabatic heating rates are close to the minimum obtained by atmospheric budgets, and approximately 0.4 °C/day below model estimates (Bradley et al., 1997).

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NEW RADIATIVE TRANSFER MODEL AND POTENTIAL IMPROVEMENTS OF TOGA SURFACE FLUX CALCULATION

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1. INTRODUCTION.

Since we produced our first surface radiative fluxes (version FC-94) for TOGA-COARE before the Toulouse meeting, the NASA GISS radiation model has been under substantial revision. Meanwhile, the main input data for our flux calculation, ISCCP D1 and DX, have also undergone their final production stages. This is a progress report on radiation modeling.

2. FEATURES OF NEW GISS RADIATIVE TRANSFER MODEL.

The improvements that have been implemented as of this report ("current new model") include: (1) The spectral resolution of the correlated k-distribution method has been increased to 33 k's from 25 k's; (2) better water vapor continuum parameteriztion for LW calculation; (3) treatment of ice clouds (spherical shape); (4) better dependence of solar zenith angle in SW scattering calculation for aerosols and clouds; (5) better ocean albedo; (6) correction of land surface albedo for D1 due to aerosols; (7) introduction of non-unit emissivity for surface skin temperature and (8) better interpolation scheme for surface air temperature.

Other new features that either have been finished but not yet implemented or will be finished soon include: (1) non-spherical ice cloud model; (2) inhomogeneous cloud parameterization; (3) introduction of cloud particle size climatology; (4) new land surface albedo climatology; (5) better and updated aerosols climatology; (6) better cloud vertical climatology and (7) introduction of climatology of diurnal variation to temperature profile of TOVS that is used in our standard flux production.

3. GENERAL IMPROVEMENTS ON GLOBAL SCALE.

We have tested the current new radiation code as defined above using the current ISCCP D1 data as main input for July 1986. Compared with ERBE ("EB"), the new code with D1 data (version "SX") has improved TOA global mean fluxes about 5 W/m^2 in overall against our old code with ISCCP C1 data (version "KW", Rossow and Zhang, 1995) as shown in table I, where CR means clear-sky, alb means albedo and all fluxes are in W/m^2. The new code has also made surface downwelling SW decrease about 4 W/m^2 which increases the atmospheric absorption of about the same amount. The difference in SW↓ (at TOA) is due to different astronomical formulas and averaging methods of cosine solar zenith angle between ours and ERBE's.

Table I comparison of global mean TOA fluxes against ERBE (mean difference/standard deviation)

	SW↑	LW↑	alb (%)	SW_CR↑	LW_CR↑	alb_CR (%)	SW↓
KW - EB	10. / 9.4	0.23 / 7.8	4.0 / 4.1	4.9 / 11	-7.8 / 8.4	1.3 / 3.2	0.36 / 1.2
SX - EB	0.12/10	4.5 / 7.3	0.46 / 3.4	0.59 / 11	-3.3 / 7.7	0.36 / 3.8	0.56 / 1.0

4. FLUX PRODUCTS FOR TOGA.

We have worked on TOGA flux calculation at two different resolutions: 2.5° X 2.5° equal-area map (called FC) based on ISCCP D1 datasets which include TOVS temperature/humidity profile and 0.5° X 0.5° equal-angle map (called FCX) based on ISCCP DX data sets (nominal 30 km resolution) with 1.0° X 1.0° radiosonde temperature/humidity profile produced by Colorado State University. The earlier D1 (D1-94) and DX (DX-94) is different from the final D1 (D1-98) and DX (DX-98) mainly in ice cloud treatment. We have produced two FC versions: FC-94 and FC-97, covering IOP and 20 S to 20 N, and 120 to 190 E and 290 E, respectively, using old radiation code (but with minor revisions on FC-97), but not yet finished the final FC using D1-98 and final new code. We have also produced two experiment FCX versions: FCX-97 and FCX-98, using old code and the current new code with spherical ice cloud implementation, respectively, with the same input of DX-94, covering a 10° X 10° area of 5 S to 5 N and 150 to 160 E and IOP; We plan to produce final FCX version that covers LSD area (as the CSU radiosonde data does) using final new code.

5. COMPARISON RESULTS.

Based on daily means available for five stations (2 island stations: Kapingamarangi and Kavieng, and 3 ships: Kexue 1 = sc1, Shiyan 3 = exp and Moana Wave) during TOGA IOP, the grid box values matched to the observation sites from the above four products are compared with surface observations as shown in Table II, where all are the calculated versus the observed.

Table II. Correlation coefficient, mean difference and standard deviation (in W/m^2) for daily means between calculated grid box fluxes and observations of 5 sites during TOGA IOP

	surface downwelling SW (W/m^2)			surface downwelling LW (W/m^2)		
	corr coef	mean diff	Stdv	corr coef	mean diff	Stdv
FC-94	0.8058	19.5	38.6	0.3122	30.9	19.0
			[illegible]			
						9.1
						9.7

6. DISCUSSION.

For the surface downwelling SW, both D1-94 and DX-94 have larger (liquid) cloud optical thickness (τ) than D1-97 (both ice and liquid clouds): the mean difference over the 10° X 10° area and IOP is about 4 to 5, that makes FC-97 have about 20 W/m^2 more bias than the other three. The smaller τ of D1-97 is due to introduction of ice clouds in new ISCCP D1 (and DX) production and such bias will be reduced when the full implementation of ice cloud parameterization in the final radiation code. That FCX-98 has 2 W/m^2 less bias than FCX-97 may be due to the current new code. For LW, the most prominent improvement from two FC's to two FCX's are due to improved temperature/humidity profile from CSU over TOVS': The mean temperature difference of first atmospheric layer (1000-800 mb) is about 4 degree K between TOVS and radiosonde's over the 10° X 10° area and IOP. As we presented in TOGA96 workshop, if a single-site radiosonde T/Q profile at Moana Wave is used, our calculated LW has virtually no bias against the observed.

In conclusion, the new GISS radiation code improves TOA fluxes by about 5 W/m^2 overall and reduces TOA uncertainty to below 10 W/m^2, i.e., 5 W/m^2 less than our previous results (Rossow and Zhang, 1995), while the surface fluxes are hardly improved using the new code. However, if all the input datasets have reasonably higher quality, it is possible to reduce the uncertainty of the surface fluxes to below 15 to 20 W/m^2 in the future.

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