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ICE MICROPHYSICS AND RADIATIVE TRANSFER IN DEEP CONVECTIVE SYSTEMS

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1. INTRODUCTION

High-resolution, two- and three-dimensional models have been used to examine interactions among deep convection, upper-tropospheric cloud systems, and radiation. These models have horizontal domains in three dimensions extending to several hundred kilometers with horizontal resolutions of one to two kilometers. In the vertical they can extend into the stratosphere with vertical resolutions of 500 meters or less. The models include prognostic microphysics parameterizations and radiative transfer.

The TOGA-COARE experiment (Godfrey *et al.*, 1998) provided a detailed characterization of both the large-scale dynamic environment in which deep convection developed and the radiation balance at the top of atmosphere and surface. The observed radiation balances provide an important constraint on the convective systems which developed during COARE. The purpose of this paper is to demonstrate that the modeled radiation balance depends strongly on the treatment of several of the controls on the ice in a high-resolution cloud-system model: its lateral advection across the model horizontal boundaries, its sedimentation rate, and the size and shape of its crystals. With appropriate treatments for these processes, it is possible to reproduce the observed evolution with time of the radiation balance of an intense convective system observed during COARE.

2. EXPERIMENTAL DESIGN

This study employs a cloud-system model described by Held *et al.* (1993) in two dimesnions. Three different procedures for calculating ice sedimentation are employed: (1) "No Fall," in which cloud ice (as opposed to snow) does not fall, (2) "HeyDon 90," in which cloud ice falls as a function of ice content, based on experimental results from aircraft (Heymsfield and Donner, 1990), and (3) "PC97," in which an averaged ice-crystal mass is used to estimate fall speed (Petch *et al.*, 1997), based on ice content and observed crystal concentrations (Chen *et al.*, 1997). In "Open" experiments, ice is allowed to flow away from the domain when the flow is outward; experiments not so designated use periodic lateral boundary conditions. In "FL" experiments, ice particles are treated as crystals (whose size is estimated from the ice fall speed), using the radiative parameterization of Fu and Liou (1993); experiments not so designated treat ice crystals as spheres of uniform size (effective radius of 10 μm).

3. RESULTS

Figs. 1 and 2 show that both surface and top-of-atmosphere (TOA) fluxes depend strongly on the aspects of microphysics and radiation under consideration. At the surface (Fig. 1a), downward solar flux is underestimated significantly if cloud ice does not fall or falls using the "PC97" method, although the underestimate is consistently less serious in the latter. The "HeyDon 90" method improves the downward surface solar flux significantly. On some of the days, "Open" boundary conditions and "FL" crystal treatment are also important, and there are interesting daily variations in the relative fluxes among the experiments with more realistic surface solar fluxes.

The downward infrared flux at the surface (Fig. 1b) varies little among the experiments in which the ice crystals are treated as uniformly sized spheres but decreases appreciably when the ice crystals are allowed variable sizes and treated as hexagonally based cylinders in "FL."

Modeled upward TOA solar fluxes (Fig. 2b) generally exceed observed values unless "Open" boundaries, "FL" crystals, and "HeyDon 90" fall rates are used. There is more variation in the TOA upward infrared fluxes (Fig. 2b) for experiments without "FL" crystals than was the case as the surface. Emissivities are

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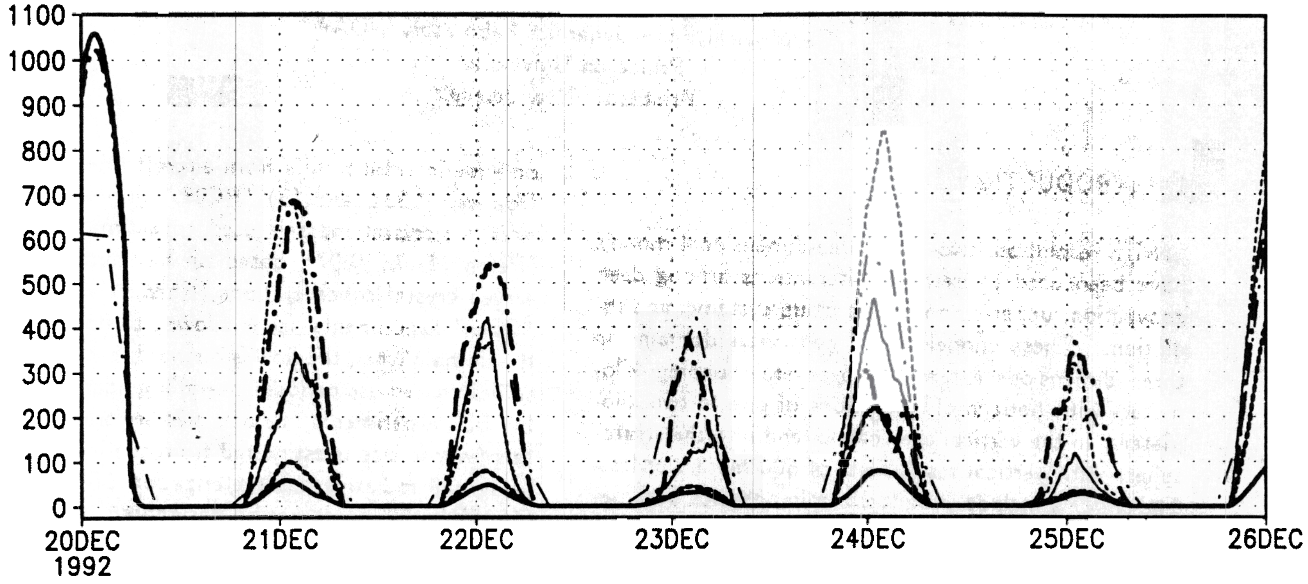
GCSS 2 CASE A2 SURFACE RADIATION FLUXES

(a) Downward Solar Flux (Wm^{-2})



(b) Downward Infrared Flux (Wm^{-2})

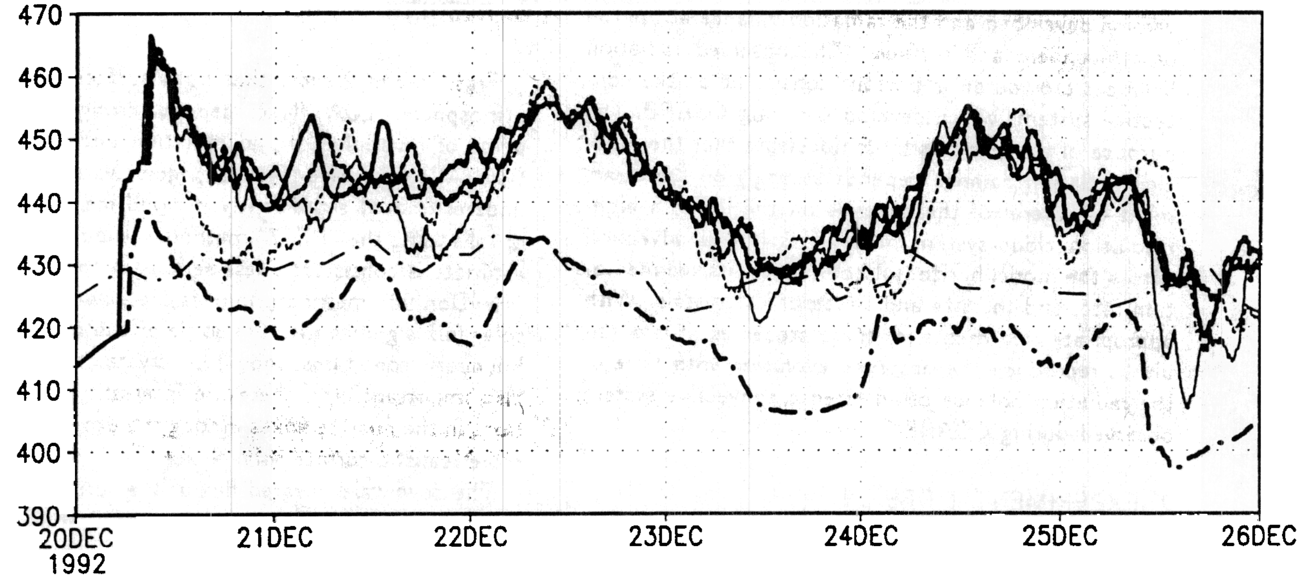
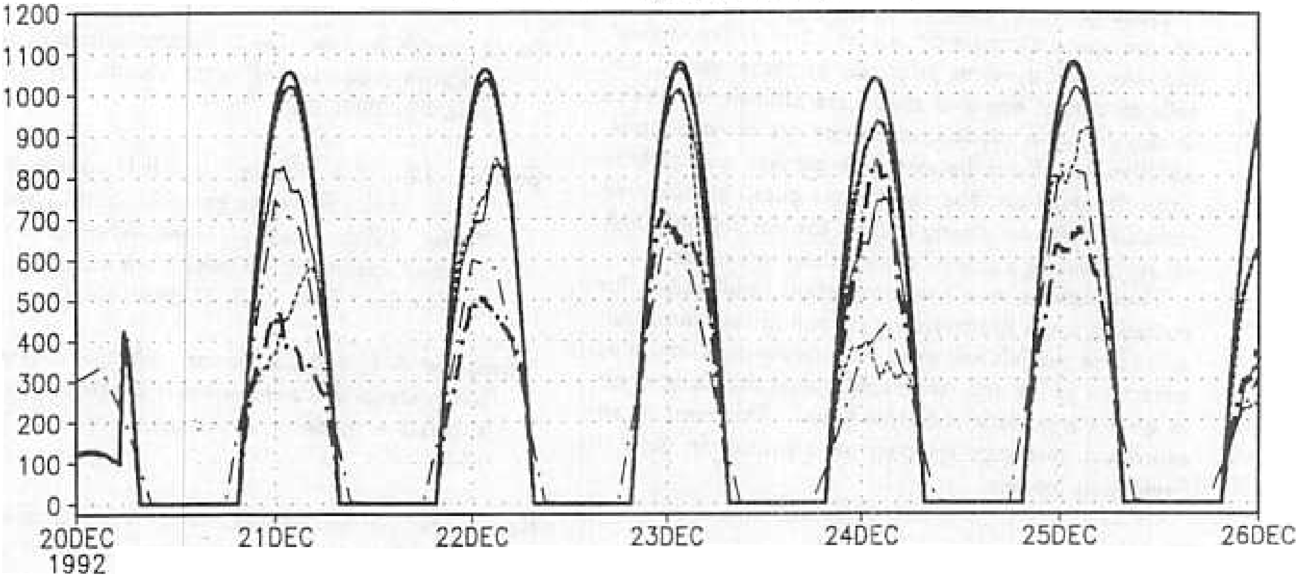


Figure 1. Surface radiative fluxes. "No Fall" is indicated by thick solid line; "HeyDon 90," thin solid; "PC97," thick dashes; "Hey Don 90 Open, thin dashes; "HeyDon 90 Open FL," thick dots and dashes; and GCSS observations, thin dots and dashes.

GCSS 2 CASE A2 TOA RADIATION FLUXES

(a) Upward Solar Flux (Wm^{-2})



(b) Upward Infrared Flux (Wm^{-2})

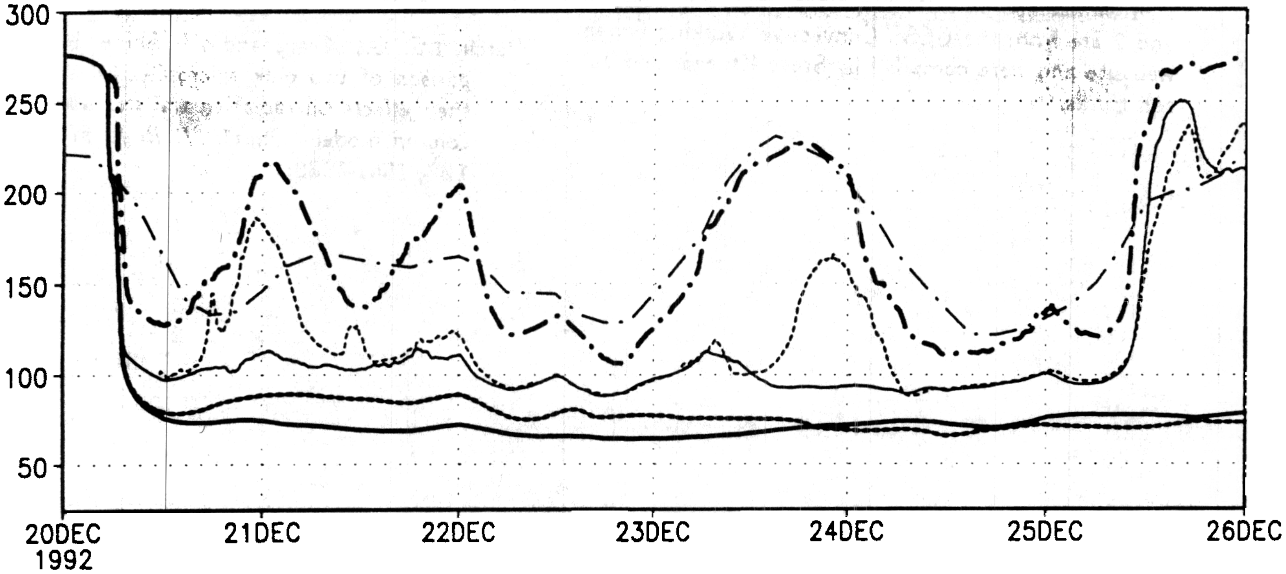


Figure 2. Top-of-atmosphere radiative fluxes. "No Fall" is indicated by thick solid line; "HeyDon 90," thin solid; "PC97," thick dashes; "Hey Don 90 Open," thin dashes; "HeyDon 90 Open FL," thick dots and dashes; and GCSS observations, thin dots and dashes.

clearly too large unless crystal sizes are adequately taken into account.

4. CONCLUSION

Cloud-convective-radiative interactions are shown to depend quite strongly on a myriad of microphysical, radiative, and dynamic processes by these results. Details of crystal size and shape are difficult to predict in cloud-system models, and there are obviously possibilities for offsets between ice content and particle sizes. Nonetheless, the constraints posed by observed radiative balances clearly narrow the possible methods for representing some of the modeled processes.

These results also have important implications for modeling these processes in general circulation models. These models will need to consider such issues as advection of ice and its microphysical details in order to generate realistic radiative fluxes. This remains an enormous challenge for parameterizations in general circulation models.

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