Sensitivity of Cirrus Cloud Radiative Properties to Ice Crystal Size and Shape in General Circulation Model Simulations

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Introduction

Recent research (e.g., Mitchell and Arnott 1994) has shown that the radiative properties of cirrus clouds (i.e., optical depth, albedo, emissivity) depend on the shapes and sizes of ice crystals. For instance, the cloud albedo may vary by a factor of two, depending on whether hexagonal columns or bullet rosette ice crystals are assumed for a given ice water path (IWP). This variance occurs primarily because, at sizes characteristic of cirrus clouds, bullet rosettes have less mass than columns of the same size. However, their projected areas may be comparable. Thus, for a given IWP and mean cloud ice particle size, the optical depth will be considerably greater for rosettes, since many more rosettes are required to account for the IWP than are columns. The same could be said of hexagonal plates and columns, with plates exhibiting the greater optical depth.

Satellite information suggests that the albedos of tropical cirrus clouds are greater than those of midlatitude cirrus, with albedos as high as 60%-80%[(a)] (Harrison et al. 1990). The reasons for this are not understood, but might be attributed in part to differences in ice particle size and shape. For instance, in the tropical western Pacific, ice crystal size distributions in cirrus near the tropopause exhibited median mass dimensions (D_m around 30 µm (Knollenberg et al. 1993) and contained planar polycrystals (Takahashi and Kuhara 1993). Very small ice crystals (typically 10 µm, often ranging from about 2 µm - 100 µm) of indeterminate shape were sampled in anvil cirrus by an ice particle replicator in this region during the Tropical Ocean Global Atmosphere (TOGA) Coupled Ocean Atmosphere Response Experiment (COARE). If fewer columnar ice crystals were present in tropical versus midlatitude cirrus and/or sizes were smaller, tropical cirrus should exhibit greater size distribution projected area, producing greater optical depth, albedo, and emissivity for the same IWP (Mitchell 1994; Mitchell and Arnott 1994). Smaller crystal sizes would also promote higher albedos via enhanced backscattering (Takano and Liou 1989).

The sensitivity of cloud forcing in the tropics to ice crystal size and shape was investigated by incorporating the parameterization of Mitchell and Arnott (1994) into the Los Alamos general circulation model (GCM) (Kristjánsson and Kao 1993). The GCM carries prognostic cloud water, which, along with solar zenith angle and temperature, constitutes the input to the subroutine that uses the above parameterization to calculate radiative properties. The parameterization of Ebert and Curry (1992), based on the results of Takano and Liou (1989), was used to estimate the asymmetry parameter for the ice crystal size distribution.

(a) Central Equatorial Pacific Experiment (CEPEX) Experiment Design, working copy. February 5, 1993. Published by the Center for Clouds, Chemistry and Climate (C^4), Scripps Institution of Oceanography, University of California - San Diego, La Jolla, California.

Results

The Los Alamos GCM simulated 5-day periods beginning 5 January. In Figures 1, 2, and 3, the control run is depicted by the solid line; all ice crystals in cirrus were assumed to be columns, and D_m was assumed to be 240 µm. In the second simulation given by the dashed line, only tropical cirrus were altered. All ice crystals were bullet rosettes (containing 5 branches) in the tropics ($\leq$ 20 deg. lat.) and columns elsewhere. In the tropics

- for temperatures T < -60°C, D_m = 40 µm
- for -60°C $\leq$ T < -40°C, D_m = 80 µm
- for -40°C $\leq$ T < -20°C, D_m = 240 µm.

Elsewhere, D_m = 240 µm. Clouds warmer than -20°C were not considered to be cirrus. For both simulations, the IWPs were similar

The influence of ice crystal shape and size was comparable, with shortwave cloud forcing affected slightly more by crystal size when globally averaged. Shortwave cloud radiative forcing (C_{sw}), the integrated cooling effect of clouds at the top of the atmosphere, is shown in Figure 1. The stronger forcing associated with rosettes and smaller sizes in higher cirrus was due primarily to the greater size distribution projected area, which increased optical depth.

Longwave cloud radiative forcing (C_{LW}) is shown in Figure 2. The weaker response of C_{LW} to these changes is partially because changing to rosettes and smaller crystals reduces the effective distance over which absorption occurs when light travels through an ice crystal. This results in less absorption per single rosette crystal. Greater projected areas in the rosette simulation, however, offset this effect to yield higher emissivities, but not to the same degree that extinction and optical depth increased. The net effect of rosettes and smaller sizes in the tropics was a negative cloud forcing (cooling). Unlike C_{SW}, differences in C_{LW} also occur somewhat outside the tropics in the 5-day simulation.

Zonally averaged planetary albedos are plotted in Figure 3. Changing from columns to rosettes in the tropics enhanced globally averaged albedo by 0.5%, while reducing crystal sizes in upper tropical cirrus enhanced it by 0.7%, giving a total increase of 1.2%

These preliminary results indicate that ice crystal shape and size are important parameters in climate simulations and that cirrus clouds need to be better characterized in this regard.

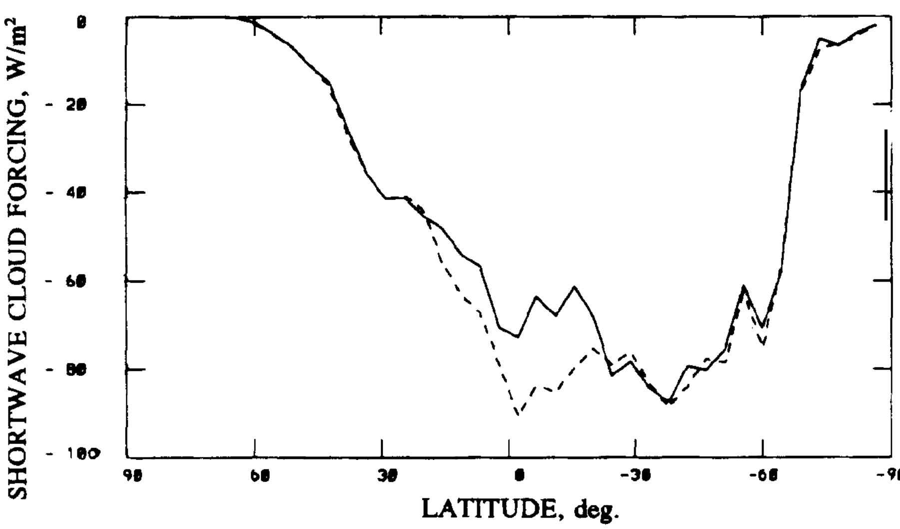

Figure 1. Zonally averaged cloud shortwave forcing. Cirrus clouds contained only columnar crystals (solid line) or only rosettes in the tropics, columns elsewhere (dashed line). Global average shortwave forcings for these two simulations were -50.2 W m^{-2} and -54.7 W m^{-2}, respectively.

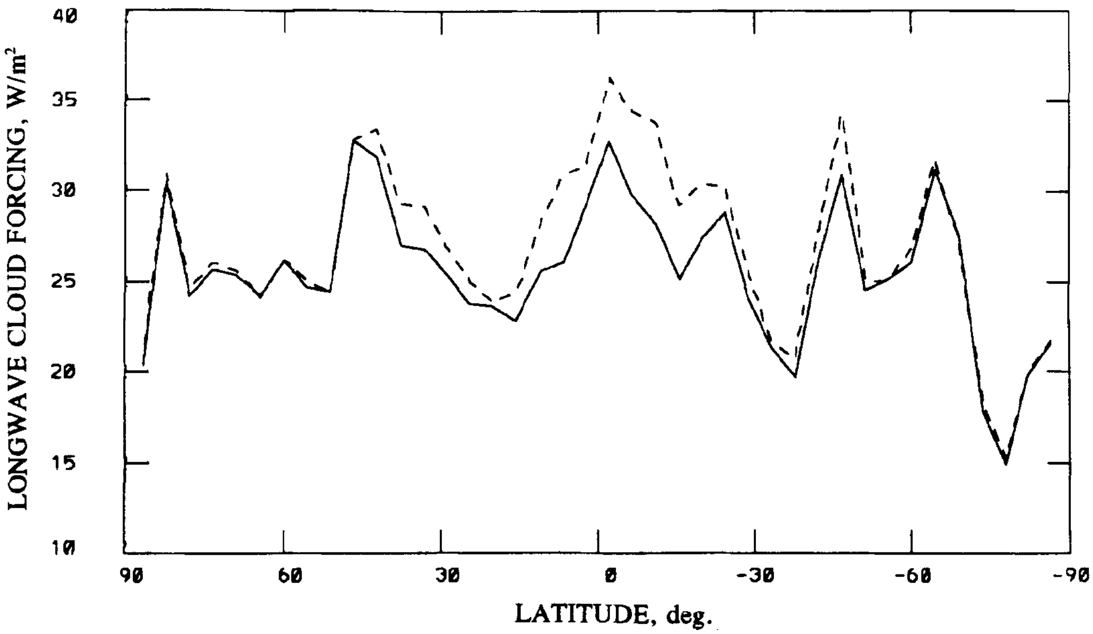

Figure 2. Zonally averaged cloud shortwave forcing. Cirrus clouds contained only columnar crystals (solid line) or only rosettes in the tropics, columns elsewhere (dashed line). Global average longwave forcings for these two simulations were 26.2 W m^{-2} and 28.1 W m^{-2}, respectively.

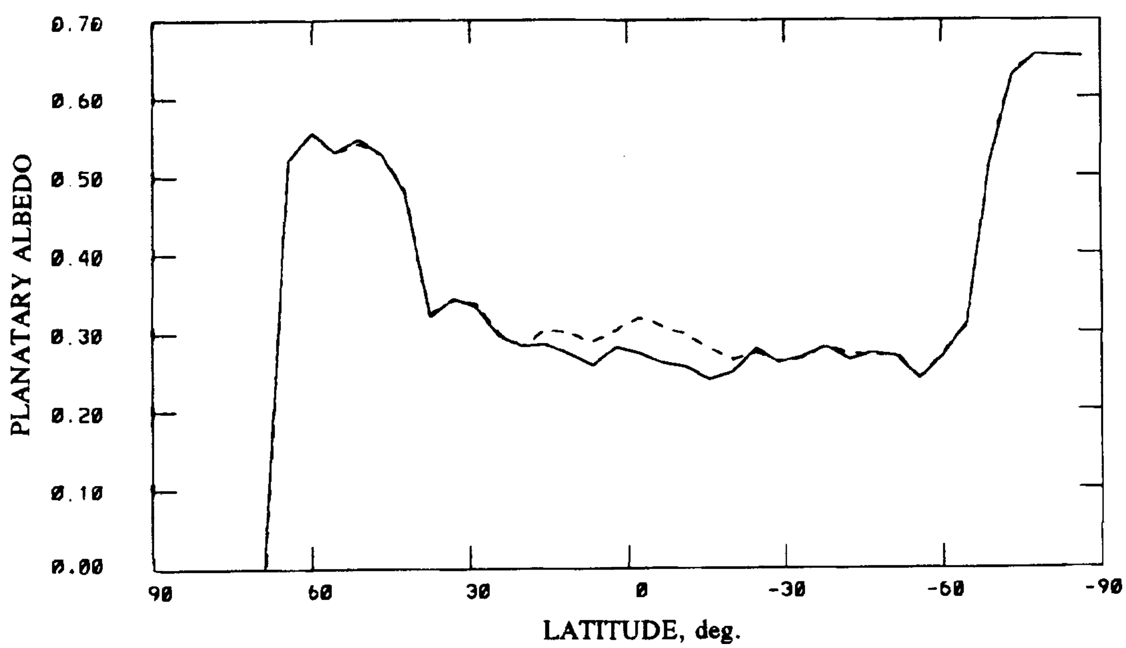

Figure 3. Zonally averaged planetary albedo when cirrus clouds contained only columnar crystals (solid line) or only rosettes in the tropics, columns elsewhere (dashed line). Globally averaged albedos were 31.1% and 32.5%, respectively.

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