Numerical Studies of Tropical Cirrus Clouds Using a Cirrus Model with Explicit Microphysics

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Introduction

Data from the Atmospheric Radiation Measurement (ARM) Program site on Manus Island in the Tropical Western Pacific (TWP) reveal the presence of high cirrus layers 1 km to 2 km thick with lifetimes of several hours to a day. Studies are being conducted of the processes responsible for the development and maintenance of these clouds using a cirrus cloud model.

Model

The cirrus model is a two-dimensional large-eddy simulation (LES) model with coupled dynamics, radiative transfer, and microphysics modules. The microphysics module uses a zero-and-first-moment conserving bin scheme to simulate the evolution of the ice crystal size distributions. Diffusional growth of ice crystals and haze droplets, sedimentation, homogeneous nucleation of haze droplets, and aggregation are explicitly calculated; while deposition nucleation is parameterized. The dynamics module is based on the Poisson equation relationship between vorticity and the stream function. The radiative transfer module is a narrow band two-stream approximation with the independent pixel approximation (IPA) applied at the model grid resolution of 100 m.

The model initial conditions are derived from the observed Manus case of April 28, 1997, when micropulse lidar (MPL) data reveal the persistence of an approximately 1-km thick cirrus layer for more than 18 hours at an altitude of about 17 km. The model was initialized with an existing cloud in the layer 16.1 km to 17.1 km. The observed and model input potential temperature profiles are shown in Figure 1. The difference between the profiles in the cloud layer is necessary to allow reasonable spin-up times for cirrus circulation. Two different simulations were performed. In each case, the initial ice water content (IWC) in the cloud layer was 6.7×10^{-6} kg/m^3. The two simulations differ in modal radius of the assumed log-normal distribution. Values of 10 µm and 20 µm were used in the two simulations, hereafter S10 and S20, respectively. Both simulations were run for 2 hours.

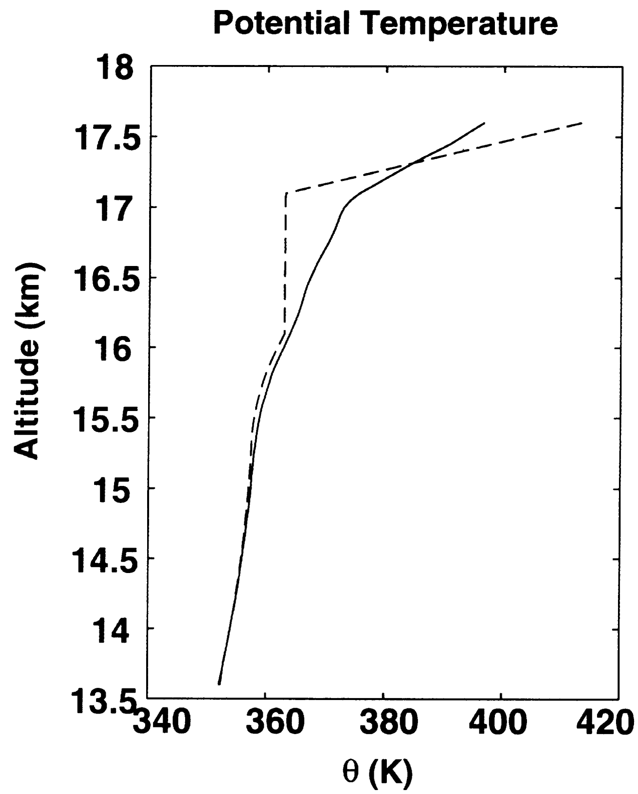


Figure 1. Horizontal mean potential temperature profiles. The solid line is the observed profile from Manus Island on April 28, 1997, and the dashed line is the model input profile.

Results

The results of the two simulations were analyzed by constructing profiles of the horizontal means of all model variables as well as model derived fluxes and tendencies. Figures 2 and 3 are profiles of the ice mixing ratio (IMR) and ice number density (Ni), respectively, for S20;

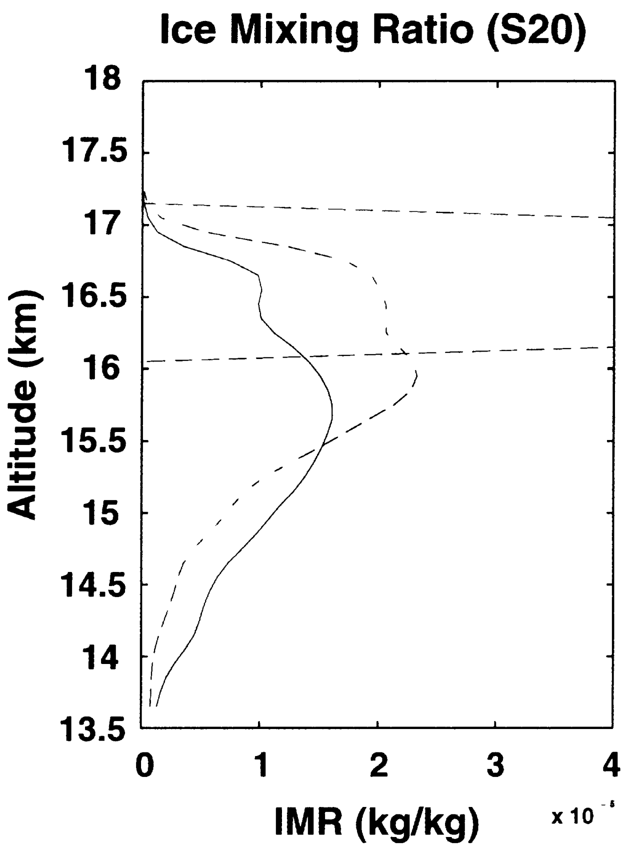


Figure 2. Horizontal mean IMR profiles for simulation S20. The dashed line is the initial profile; the dotted line is the profile at simulation time 1 hour; the solid line is the profile at simulation time 2 hours.

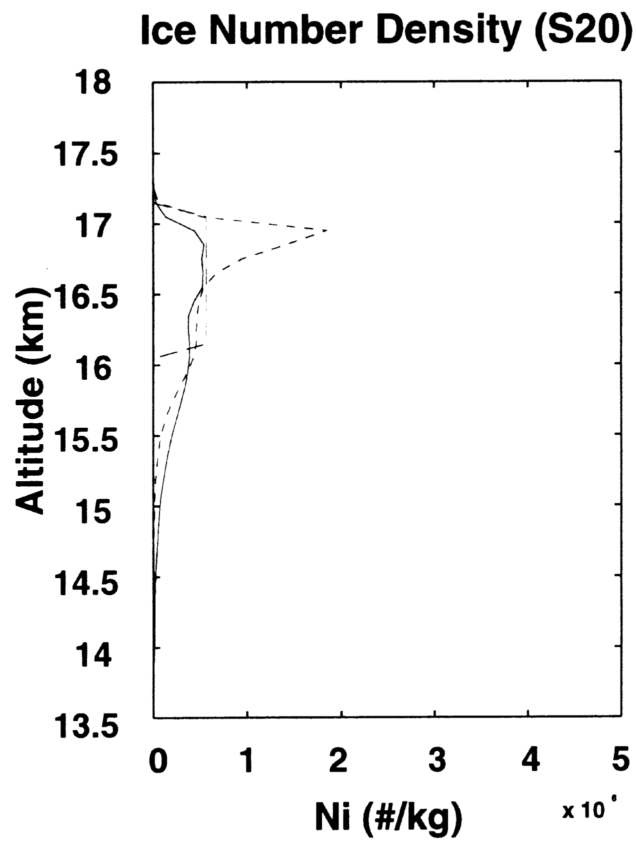
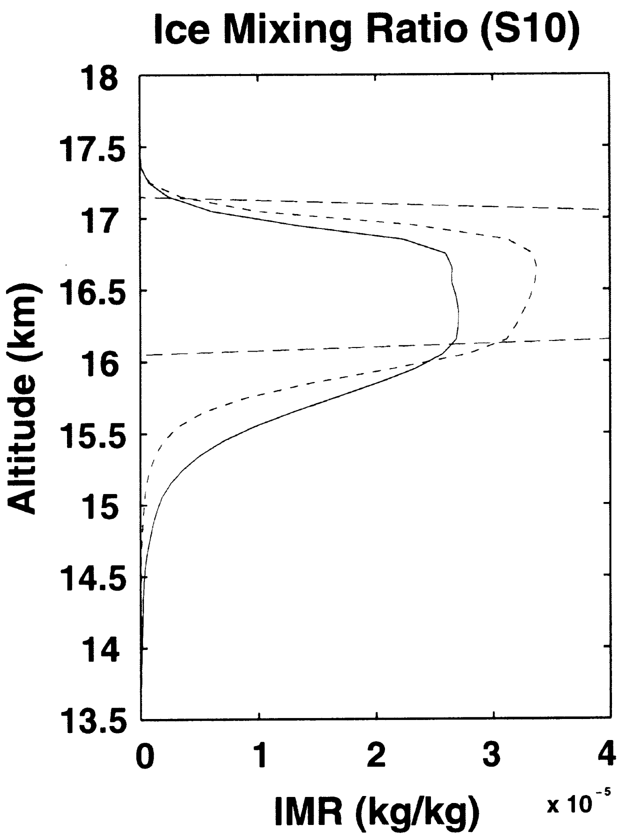


Figure 3. Horizontal mean ice number density profiles for simulation S20. The line conventions are the same as Figure 2.

Figures 4 and 5, respectively, are the same profiles for S10. The results of the two simulations are significantly different. In S20, much of the ice quickly precipitates out of the original cloud layer (Figure 3), reducing the vapor sink in the upper reaches of the cloud. This results in high supersaturation which leads to homogeneous nucleation of ice crystals and high number concentrations (Figure 4) of small crystals in the original cloud layer. Thus, the model naturally evolves toward a solution with small crystals. This result is consistent with S10, in which the ice remains mostly contained within the original cloud layer and the model converges toward a steady state (Figures 4 and 5). In both simulations, the radiative heating rate is about three orders of magnitude greater than the latent heating rate. This suggests that the energetics of cold cirrus is dominated by radiative, rather than latent, forcing. The gradient in radiative heating rate, with warming more rapid at cloud base than cloud top, leads to destabilization of the cloud layer, convective overturning, and regions of ice formation that help maintain tropical cirrus clouds for long periods of time.

Conclusion

A two-dimensional cirrus cloud model with explicit microphysics is used to study tropical cirrus. Simulations indicate that the presence of large number concentrations of small ice crystals leads to maintenance of cloud layers for long time periods. This is consistent with observations of long-lived cirrus layers in the TWP.



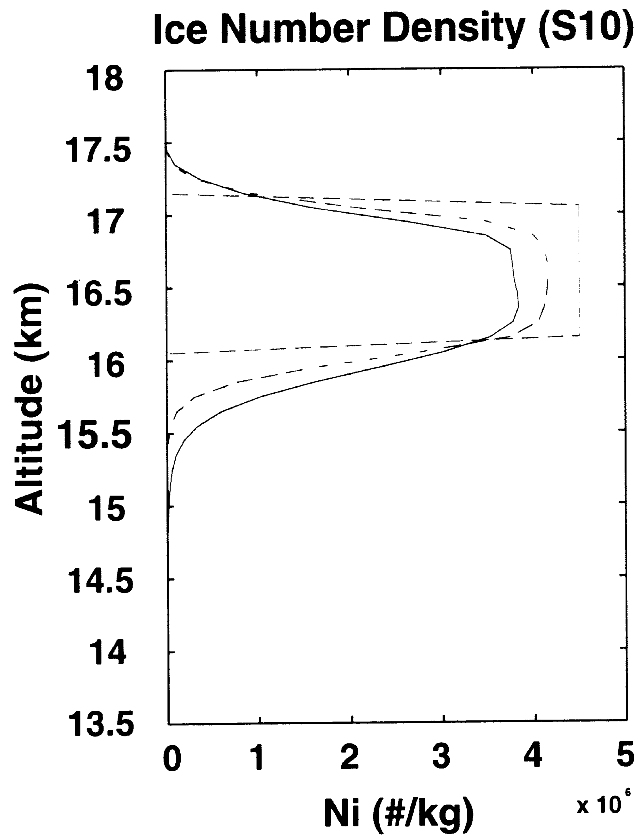


Figure 4. Horizontal mean IMR profiles for simulation S10. The line conventions are the same as Figure 2.

Figure 5. Horizontal mean ice number density profiles for simulation S10. The line conventions are the same as Figure 2.