On the Maintenance of High Tropical Cirrus

M. T. Boehm, J. Verlinde, and T. P. Ackerman
The Pennsylvania State University,
University Park, Pennsylvania

Introduction

Thin tropical cirrus layers sometimes extend hundreds of kilometers horizontally and often persist for time periods of several hours to more than a day before dissipating. Due to their ubiquity and location in the very cold tropical upper troposphere and above the very warm tropical ocean, tropical cirrus clouds play a major role in the earth's radiation budget (Liou 1986). Despite their impact on the climate of the earth, relatively little is known about tropical cirrus processes.

The purpose of this study is the exploration of radiative destabilization as a maintenance mechanism for tropical cirrus. A series of numerical experiments are performed using a cirrus model to determine the factors to which the evolution of the simulated cloud is most sensitive. The model results are evaluated by comparing the lifetimes of the simulated cloud layers with the long lifetimes that have been observed for tropical cirrus layers to determine the ability of the model to maintain cloud layers using varying initial conditions.

The Model

Lin (1997) describes the cirrus model used in this study. It is a two-dimensional cloud-resolving model with coupled dynamics, radiative transfer, and microphysics. The dynamics module is based on the Poisson equation relationship between vorticity and the stream function. The radiative transfer module is a narrowband two-stream approximation with the independent pixel approximation applied at the model grid resolution of 100 m. The microphysics module uses a zero-and-first-moment conserving bin scheme to calculate explicitly the evolution of the ice crystal size distributions. Diffusional growth of ice crystals and haze particles, homogeneous nucleation of haze droplets, and sedimentation are explicitly calculated; while deposition nucleation is parameterized.

The model domain represents a vertical cross section that is advected, along with the cirrus cloud, by the mean horizontal wind. The model domain therefore represents a Lagrangian evolution of the cirrus cloud. For the experiments described here, the domain extends 6 km vertically, with the domain base and top at 13.5 km and 19.5 km, respectively, and 6 km horizontally. The upper and lower boundary conditions are free slip, while the lateral boundary conditions are cyclic. Boundary conditions required by the radiative transfer module include upward and downward radiative fluxes at the upper and lower boundaries of the model domain.

The model is initialized with specified pressure, temperature, water vapor mixing ratio, and ozone mixing ratio profiles. A cloud is initialized by specification of the parameters for the lognormal distribution of ice crystals at each vertical grid level in the cloud. The required parameters for this distribution are the ice water content, modal radius, and standard deviation of the distribution. Random perturbations in the potential temperature field are used to induce convection in the cloud layer in order to produce a dynamically active cloud.

In the simulations, the sub-cloud layer is artificially dried to prevent the cloud from spreading too far vertically, in agreement with observations that the tropical cirrus layers under consideration maintain relatively constant thickness for long time periods. This drying has a very minor impact on the evolution of the cloud in the simulations performed and no impact on the main conclusions of the study.

The simulations performed for this study were run under nighttime conditions (no solar radiation), even though cirrus layers are sometimes observed to persist through an entire day. Nighttime conditions are thought to be more conducive to long lasting cirrus than daytime conditions. Starr and Cox (1985) found that cirrus modeled under daytime conditions had horizontal mean ice water contents about 20% smaller than similar cirrus modeled under nighttime conditions.

Model Results

One mechanism proposed to explain the persistence of tropical cirrus is that radiative destabilization leads to cloud circulations consisting of cells of upward, downward, and compensating horizontal motion that act to maintain ice in the cloud layer (Ackerman et al. 1988). Radiative destabilization of a cloud layer results from a decrease in the radiative heating rate with height. Under nighttime conditions, the radiative heating in the cloud layer is dominated by the absorption of infrared radiation emitted by the earth’s surface. The magnitude and distribution of the radiative heating rate, factors that determine the extent of the radiative destabilization, depend on the distribution of ice water content and ice crystal size within the cloud. The radiative heating rate increases with increasing ice water content and, for a given ice water content and for the crystal sizes considered here, decreasing crystal radius (Heymsfield and Platt 1984).

Simulations have shown that the modal radius of the initial ice distribution needs to be relatively small (10 μm) to produce reasonable circulations in the cloud. Otherwise, much of the ice sediments out of the cloud layer before circulations can develop. In experiments initialized with distributions with larger modal radii (20 μm), the cloud quickly evolved via differential sedimentation and nucleation to a cloud with a distribution with a smaller modal radius (Boehm et al. 1998). Thus, small ice crystals (modal radii less than 10 μm) are used here.

To determine the sensitivity of the simulated cloud to the properties of the initial ice distribution, the characteristics of the distribution are varied in a systematic manner. We consider six model runs in which the ice crystals were assumed to be plates. These runs are denoted by the letters A through F. The letters A, B, and C represent runs with vertically varying initial ice crystal distributions with total ice water paths (IWPs) of 1.7×10^{-3} kg M^{-2}, two times this amount, and four times this amount. Vertical profiles of the modal radius, standard deviation, and IWP for the initial log normal distribution are

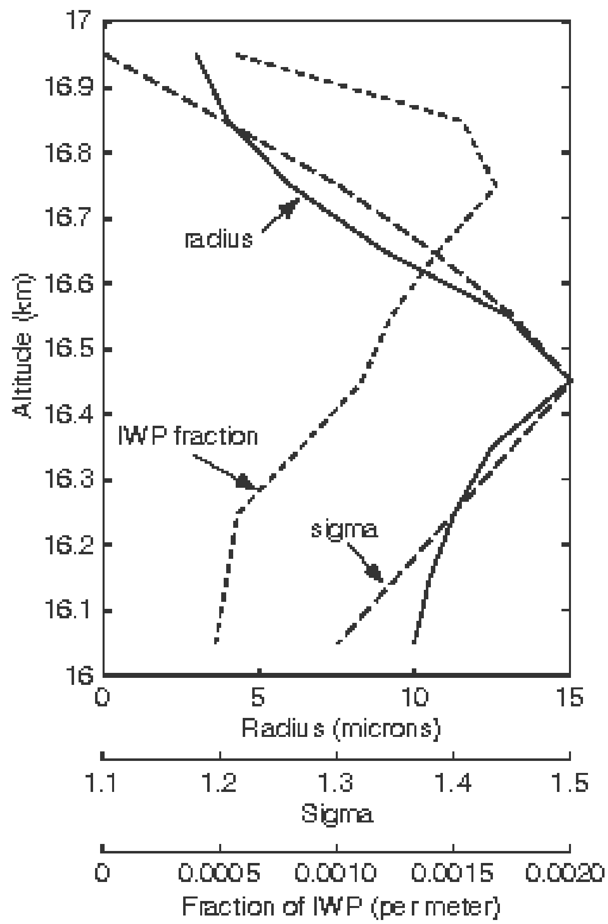

Figure 1. Profiles of parameters required to define the vertically varying initial log normal ice distributions for runs A, B, and C. The solid line is the mean radius, the dashed line is the standard deviation, and the dotted line is the distribution of IWP, given as a fraction of the IWP per meter. The IWP distribution integrates to unity over the cloud layer. The three runs differ only in initial IWP.

shown in Figure 1 for these runs. The letters D, E, and F represent runs with initial ice crystal distributions constant with altitude in the cloud layer with total IWPs of 1.7 x 10^{-3} kg M^{-2}, two times this amount, and four times this amount. This distribution was calculated by spreading the total number of crystals in each size bin in the variable cases equally over the entire depth of the initial cloud layer. Thus, for a given initial IWP, the variable and constant ice crystal distributions summed over the entire cloud layer were identical. The cloud is initialized in a neutrally buoyant, moist layer between 16 km and 17 km, just below the model tropopause. The thermodynamic profiles reveal that the initial potential temperature in this layer is constant with altitude and that the layer is initially saturated with respect to ice.

Beginning with the initial conditions for runs A through F; 6-hour simulations were conducted. A dynamically active cloud quickly evolved from the initial state of rest as a result of the initial random temperature perturbations. After about 30 minutes, the impact of the initial temperature perturbations abated and the cloud circulations were maintained by the process of radiative destabilization. These cloud circulations were made up of cells with horizontal extent of 1-2 km, consisting of upward motion, downward motion, and compensating horizontal motion near cloud top and base. Regions of enhanced ice water content were associated with upward motion, while regions of reduced ice water content were associated with downward motion.

Profiles of the horizontal mean radiative heating rate show large difference among the six simulations. In runs A, B, and C, with initial ice crystal distributions that varied with height, the radiative heating rate increases with altitude in the cloud layer and is sharply peaked near cloud top. Thus, in these runs much of the layer is radiatively stabilized, and only a thin layer near cloud top is radiatively destabilized. The cloud circulations, driven by radiative destabilization, occupy only a narrow layer near cloud top. In the runs with initial ice crystal distributions that were constant with height, the radiative heating rate increased with altitude for run D, but decreased with altitude for runs E and F. Thus, the cloud layer was radiatively stabilized in run D and radiatively destabilized in runs E and F. Consequently, weak cloud circulations were found in run D, being mainly the residual of the circulations generated by the initial temperature perturbations, while strong circulations occupied the entire cloud layer in runs E and F. For all the simulations considered here, the magnitude of radiative destabilization and strength of cloud circulations increased with increasing IWP.

To compare the evolution of the simulated clouds over time, time series of key domain integrated variables were constructed. Figure 2 shows time series of the domain average of turbulent kinetic energy (TKE) for the six simulations. The TKE among the simulations varies by about three orders of magnitude, which is not surprising considering the significant differences in circulation strength found among the simulations. The rapid fluctuations in TKE near the end of each 6-hour simulation result from the formation of unphysical circulations in the stable layer above the cloud. These circulations are caused by the reflection of both gravity and numerical waves from the upper model boundary.

Given the significant differences in the strengths of the cloud circulations among the six simulations, one would reasonably expect the clouds to be maintained to varying extents by the different simulations; however, this expectation is not fulfilled. Figure 3 shows time series of the IWP contained within the boundaries of the initial cloud layer normalized by the initial IWP for each simulation. The six simulations, enclosed by brackets on the right-hand side of Figure 3, all fall on very nearly the same line, indicating that there is very little difference in the extent to which the cloud is maintained. This finding leads to the conclusion that the small-scale dynamical structure of the cloud plays only a minor role in the maintenance of these clouds. Rather, the ice is simply precipitating out of the cloud layer without being replaced. The e-folding time for these simulations is about 5.1 hours.

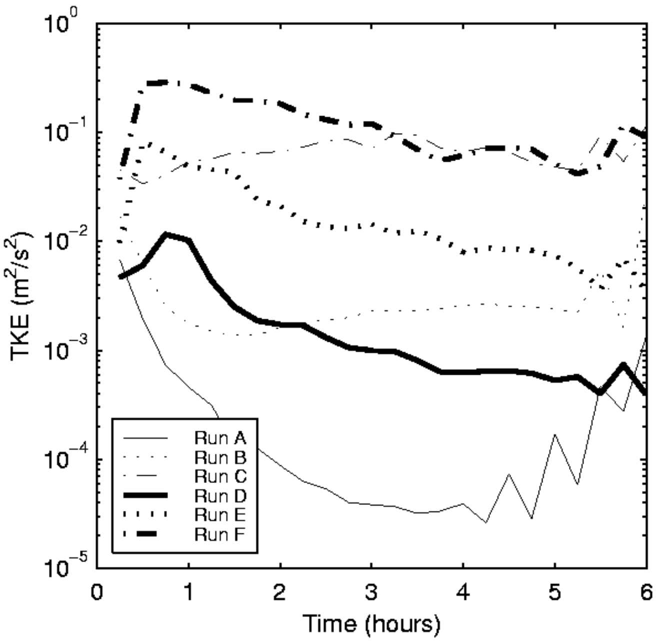

Figure 2. Time series of the domain averaged TKE. Note that the TKE is plotted on a log scale. The thin lines correspond to the runs with vertically varying initial ice distributions, while the thick lines correspond to the runs with vertically constant initial ice distributions. The solid line represents the lowest initial ice water content, the dotted line the middle initial ice water content, and the dash-dotted line the highest initial ice water content.

Assuming that the cirrus decay is due to crystal sedimentation alone, a theoretical curve for the decay of the cloud initialized in runs D, E, and F was calculated using the initial crystal distribution for these runs and the model's fall speed parameterization. This curve, labeled "Theory", has an e-folding time of 8.5 hours. The simulated clouds are therefore decaying considerably faster than predicted assuming sedimentation is the only decay process, and there must be additional processes that lead to the decay of the cloud. The most important such process is the evaporation of ice crystals due to radiative warming of the cloud layer. Thus, rather than serving to maintain the cloud layer, the radiative effects are actually speeding the decay process.

Conclusions

The results of simulations comparing crystals with modal radii of 10 μm and 20 μm suggest that ice crystals in tropical cirrus must have modal radii less than 10 μm, otherwise, according to model simulations, a significant portion of the ice sediments out of the layer, and the cloud dissipates before significant cloud circulations develop. Therefore, very small ice crystals (modal radii of the initial lognormal distribution less than 10 μm) were used in the current study, allowing cloud circulations to develop due to radiative destabilization of the cloud layer.

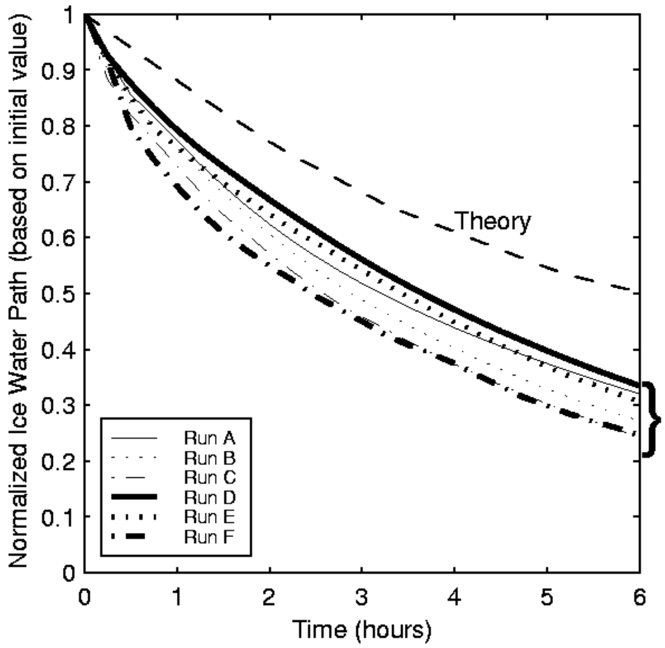

Figure 3. Time series of the normalized, horizontally averaged, IWP. Each line is normalized with the initial IWP for the simulation. The bracket encloses the results of the simulations, and the line labeled "Theory" represents the theoretical cloud sedimentation curve (see text for explanation). Line conventions same as Figure 2, with the addition of the dashed line for the theoretical curve.

A series of simulations were performed under nighttime conditions using different initial ice water contents and ice crystal size distributions. Significant differences among the simulations were observed in the vertical distribution of radiative heating, and as a result, in the strength of the cloud circulations. However, for all simulations the evolution of the IWP as a fraction of the initial IWP was quite similar, decreasing with an e-folding time of approximately 5 hours. This decay of the cloud was due mainly to the processes of sedimentation of ice from the cloud layer and evaporation of ice due to radiative warming of the layer. Therefore, for the conditions and processes simulated here, the detached cirrus outflow was not maintained for the long time periods of 12 or more hours that are observed, but rather began to dissipate as soon as the simulations were started.

These results indicate that the mechanism of radiative destabilization and associated cloud circulations is inadequate to explain the persistence of tropical cirrus. Though the cloud circulations do create localized regions of upward motion and ice formation, these regions are balanced by localized regions of downward motion and ice destruction. Thus, without a large-scale moisture source, cooling mechanism, or both, the cloud as a whole has no way to maintain itself against the processes of sedimentation and evaporation.

Some other mechanism is thus required to explain the persistence of tropical cirrus. One possible explanation is that moisture in the cloud layer is being replenished by outflow from deep convection on a regular basis. However, cirrus layers are sometimes observed in areas far removed from deep convection. In these cases, it is hypothesized that some source of large-scale upward motion must be present. Upward motion helps maintain the cloud by cooling the layer adiabiatically and by transporting moisture into the cloud layer.

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