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Radiatively Driven Stratosphere-Troposphere Interactions Near the Tops of Tropical Cloud Clusters

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1. Introduction

A variety of studies suggest that tropical cloud clusters are associated with interaction between the tropical upper troposphere and lower stratosphere. A minimum in water vapor mixing at an altitude of about 18 km (called the hygropause) is believed to be associated with air entering the stratosphere at temperatures of about -90 deg C (Holton, 1984). There are only two regions of the globe where the tropopause is high enough and cold enough to inject such dry air -- over Indonesia in the Northern Hemisphere winter, and over the Bay of Bengal during summer (Newell and Gould-Stewart, 1981). These regions are characterized by deep penetrative convection in mesoscale cloud clusters during the monsoon season (see review by Johnson and Houze, 1987). Newell and Gould-Stewart suggest that these clouds with their high cirrus tops could play a central role in incorporating dry tropopause air into the lower stratosphere in these regions.

Danielsen (1982) hypothesized that deep convection in the tropics penetrates into the lower stratosphere, and that detrained air parcels mix with stratospheric air and spread out in horizontal layers of cirrus cloud that straddle the tropopause. According to this hypothesis, infrared radiative warming at the bases of cirrus cloud and infrared cooling at cloud top destabilizes the cloud and promotes convective overturning. The convective overturning transports water vapor upward from the base of the cloud toward the top, producing supersaturation with respect to ice. Ice crystals grow in the cirrus and precipitate into the troposphere. The net effect of this process is to mix tropopause air, which has very low water vapor mixing ratios, into the lower stratosphere, producing the hygropause.

In this paper, we present two numerical simulations: one to test Danielsen's hypothesis, the other to suggest an alternative mechanism for "freeze-drying" the air. The two-dimensional model combines water and ice physics parameterizations, infrared and solar radiation parameterization, with a convective adjustment scheme in a kinematic, non-dynamic framework. The model is run until steady-state conditions are obtained, to simulate the long-lasting (order 10 h or greater) cirrus cloud decks observed in the tropics. The model was run with a horizontal resolution of 50 km and vertical resolution of 0.5 km.

2. Model Description

The model is the one described by Churchill (1988), and Churchill and Houze (1990). The thermodynamic energy equation for the model is

$$\frac{\partial S}{\partial t} = -w\frac{\partial S}{\partial z} - u\frac{\partial S}{\partial x} + H_R + H_L + H_E. \qquad (1)$$

where $S = C_p T + g\,z$ is the dry static energy, w and u are prescribed vertical and horizontal winds that remain constant throughout a simulation, H_R is radiative heating, H_L is latent heat release due to changes of phase in the microphysical parameterization, and H_E is heating due to eddy flux convergence.

The microphysical parameterization is similar to that used in studies by Rutledge and Hobbs (1983) and Rutledge and Houze (1987) to examine the precipitation processes in frontal rainbands an a midlatitude squall line. The continuity equations for precipitating hydrometeor species q_η are given by

$$\frac{\partial q_\eta}{\partial t} = -u\frac{\partial q_\eta}{\partial x} - w\frac{\partial q_\eta}{\partial z} - \frac{\partial}{\partial z}(q_\eta V_f) + S_\eta + F_\eta, \qquad (2)$$

where q is hydrometeor mixing ratio, subscript η represents snow, rain, or graupel. V_f is the fallspeed of precipitation; S_η and F_η represent sources and sinks of precipitate η. A similar equation describes the continuity of non-precipitating hydrometeors, where, by virtue of cloud water and cloud ice being suspended in the air, the fallspeed is zero:

$$\frac{\partial q_\eta}{\partial t} = -u\frac{\partial q_\eta}{\partial x} - w\frac{\partial q_\eta}{\partial z} + S_\eta + F_\eta + E_\eta. \qquad (3)$$

An eddy flux term, E_η, was added to the non-precipitating hydrometeor fields to permit mixing of cloud ice and water in regions undergoing convective overturning. We assumed that precipitation falls much more quickly than eddy fluxes can transport precipitation, so we did not apply eddy fluxes to precipitation fields. The eddy flux was parameterized since the kinematic model does not provide information about actual eddy velocities. The latent heat released by changes of phase of water, as determined from Eqs. 2 and 3, determines the values of H_L in Eq. 1.

The model includes infrared emission by water vapor and hydrometeors, and solar absorption and reflection by hydrometeors. No attempt is made to treat the radiative effects of ozone, carbon dioxide, or other trace gases. Radiation simulations extend from the surface into the lower stratosphere. A nested grid with a vertical resolution of 50 m is used. The radiation scheme is the two-stream approximation used by Stephens and Webster (1979). Hydrometeor species diagnosed by the microphysical model are used to compute solar and infrared radiative emissivities, transmissivities and reflectivities. The model allows for multiple reflections of solar radiation in the cloud layers. The heating and cooling diagnosed by the radiative model enters Eq. 1 through the H_R term.

Convective adjustment was used to maintain neutral lapse rates in the model domain. The diabatic heating and cooling associated with convective adjustment enters Eq. 1 through the H_E term.

3. The Cirrus Cloud Simulation

The thermodynamic and wind fields of the model are initialized from a sounding (Fig. 1) obtained from the Winter MONEX experiment. This sounding was obtained in the vicinity of a large cloud cluster. This mesoscale convective system was *Cluster B* studied by Churchill and Houze (1984a, b), who used data collected by land-based radar, two aircraft, and a geostationary satellite. One lateral boundary of the model is assumed to be located at the edge of deep penetrating convection. Hydrometeor contents detrained from a convective cell are specified on the boundary of the model. For the first experiment, we assumed that a thin layer of upper-level cirrus-outflow cloud ice emanated from the convection on the lateral boundary. The experiment was run with several profiles of cloud ice to determine the sensitivity of the results to the boundary values. A typical example of boundary values is shown in Fig. 2. This cirrus cloud straddled the tropopause and was thick enough to be optically black in the infrared.

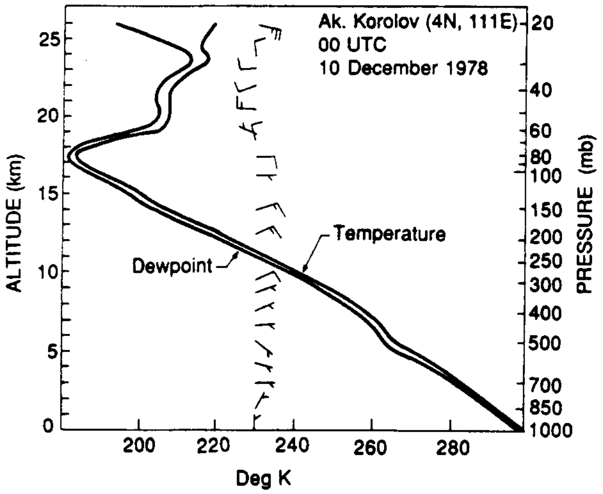

Fig. 1. Sounding used to initialize the simulations. Temperature, dewpoint and winds were obtained from ship Ak. Korolov, located at 4 deg N, 111 deg E, 0 UTC, 10 December 1978.

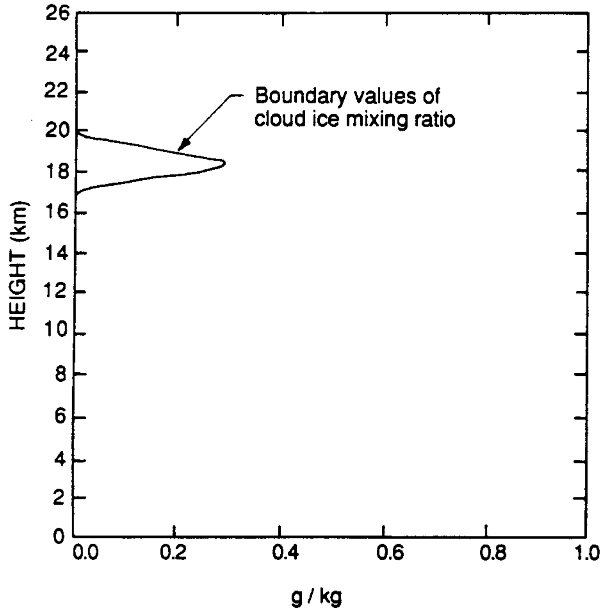

Fig. 2. Boundary values of cloud ice used in the cirrus simulation.

This model produces steady-state two-dimensional profiles of hydrometeors that are consistent with the boundary conditions, the radiative heating and cooling, and the convective adjustment process. In the steady state, a cirrus cloud (Fig. 3) extends across the model domain. Fig. 4 shows horizontally averaged vertical profiles of diabatic heating in the cloud, and horizontal temperature advection. Radiative heating occurred at cloud base, cooling occurred at cloud top, and convective overturning occurred due to radiative destabilization. Although the overturning maintained saturation in the cloud, there was insufficient condensation to produce precipitation-size ice particles. The net effect was that vapor was transported upward into the lower stratosphere *increasing* the water vapor content there.

Several sensitivity studies were conducted to see if the cirrus simulation could produce a drying of the stratosphere. We allowed the ice particles to settle out of the atmosphere at rates of 0.01, 0.1 and 1.0 m s^{-1}. At 1 cm s^{-1} no significant change in results occurred. The water vapor content of the stratosphere still increased, and some of the ice within the model domain precipitated into the troposphere and sublimated. At fallspeeds of 10 cm s^{-1} the horizontal extent and optical thickness of the cloud was reduced as the ice precipitated into the troposphere. This cloud was so optically thin that the entire cloud underwent net infrared heating and some cloud ice sublimated, increasing the water vapor content of the stratosphere. At fallspeeds of 1 m s^{-1}, the cloud settled into the troposphere before radiative heating could produce overturning; no change occurred in the lower stratosphere. Hence if the cirrus is too thin, it will sublimate due to radiative heating and increase the vapor content of the lower stratosphere. If the cirrus is optically thick, convective overturning transports vapor upwards into the stratosphere, but no precipitation size

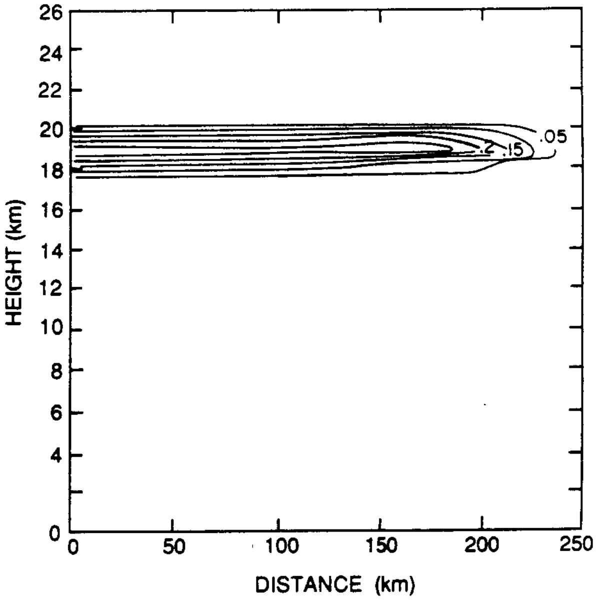

Fig. 3. Steady-state cloud ice distribution in the cirrus simulation. Contours of mixing ratio are in g kg^{-1}.

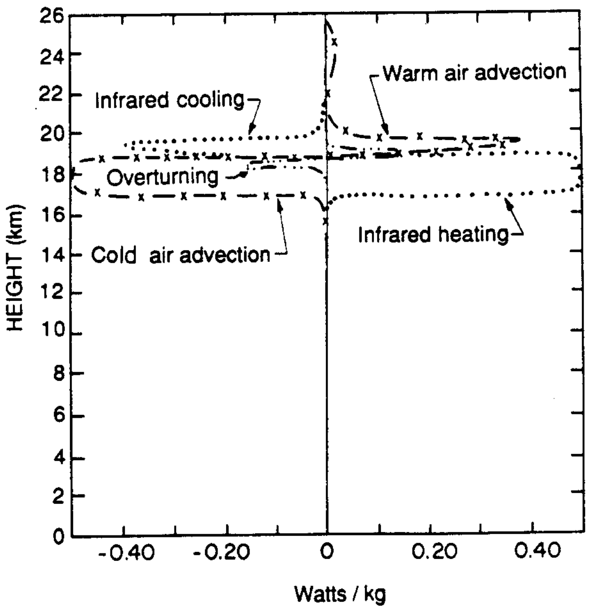

Fig. 4. Horizontally averaged steady-state diabatic heating terms for the cirrus simulation. Infrared heating at cloud base and cooling at cloud top is dotted. Convective overturning is dash-dot pattern. Horizontal temperature advection (dash - X pattern) is due to temperature gradients resulting from radiative heating and cooling.

particles are generated since the mixing ratios of water vapor are very low near the tropopause. Since we found no mechanism in cirrus clouds that could dehydrate the lower stratosphere, we conclude that the Danielsen hypothesis applied to thin cirrus emanating from cumulonimbus tops is not effective in the context of this model.

4. Mesoscale Updraft Hypothesis

Johnson and Kriete (1982) observed cooling of several degrees in the lower stratosphere above the top of clouds in cluster B during Winter MONEX. One possible explanation for this cooling is that a mesoscale updraft in the stratiform region of the cloud cluster was lifting the tropopause. We hypothesize that mesoscale updraft motion lifted the tropopause over this tropical cloud cluster, and that parcels near the tropopause underwent net diabatic heating and became incorporated into the lower stratosphere with the low mixing ratios of the tropopause. If we assume that the ice crystals settle out of the stratosphere before they sublimate, the lower stratosphere may be dehydrated.

To test this idea, we initialized the model to simulate cloud cluster B. The sounding shown in Fig. 1 was again used to initialize the thermodynamic and horizontal wind fields. The mesoscale updraft motions diagnosed by Johnson and Kriete were specified as shown in Fig. 5, and the horizontal winds were adjusted to maintain continuity. We assumed that the mesoscale updraft had a magnitude of 1 cm s^{-1} at the tropopause, and that the ice crystal fallspeed was 10 cm s^{-1}. The hydrometeor boundary conditions (Fig. 6) were obtained by running a one-dimensional cloud model (Ferrier and Houze, 1989), initialized with the sounding of Fig. 1, and run with a water continuity scheme similar to that of Eqs. 2 and 3. The mesoscale model was run with solar and infrared radiation turned on.

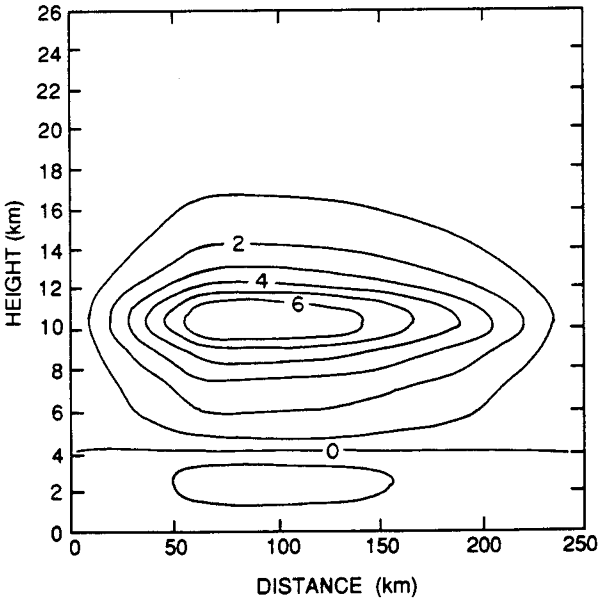

Fig. 5. Two-dimensional vertical wind speeds (cm s^{-1}) specified for the mesoscale updraft in cloud cluster B.

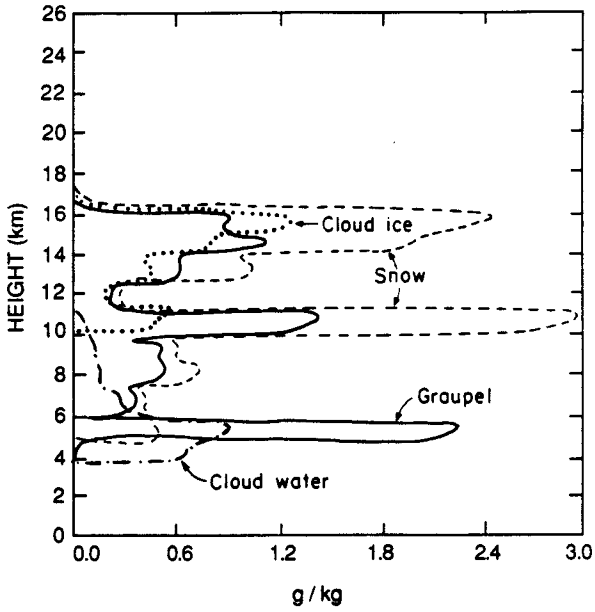

Fig. 6. Hydrometeor mixing-ratio boundary conditions for the cluster B simulation. Separate curves are shown for cloud ice, snow, graupel, and cloud water.

The simulation produced a deep stratiform cloud deck consisting of precipitation particles in the low-to-mid troposphere, and cloud ice in the upper troposphere to lower stratosphere. Fig. 7 shows the two-dimensional total diabatic heating. This shows that net diabatic heating in the presence of solar radiation occurred near the tropopause in the deep stratiform cloud that extended across the model domain. We tracked parcels of air moving in the vicinity of the tropopause of this system and found that parcels of air rising in the updraft increased their potential temperature in sunlight to that of the lower stratosphere. At the same time, ice crystals were settling out of the air (at a 10 cm s^{-1} fallspeed). The water vapor content in the lower stratosphere thus decreased as very dry parcels of air, undergoing diabatic heating near the tropopause, were incorporated into the lower stratosphere.

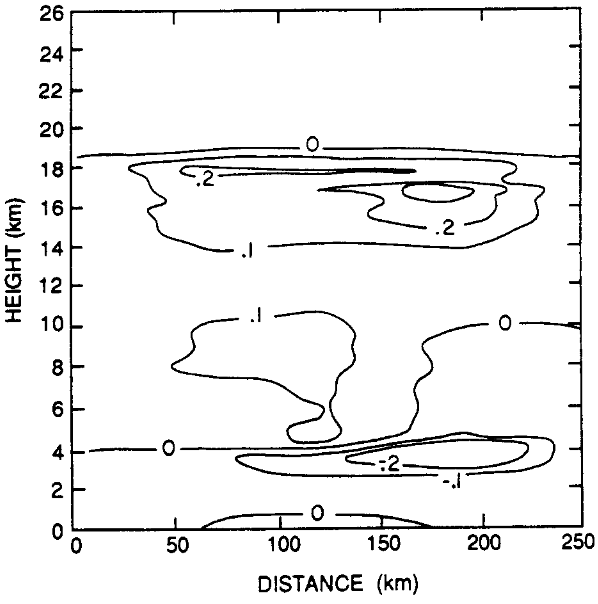

Fig. 7. Two-dimensional steady-state total diabatic heating (W kg^{-1}) in cloud cluster B.

5. Discussion

The physical processes simulated in the mesoscale updraft differ from those in the thin-cirrus simulation. In the thin-cirrus case, eddy fluxes occur in response to infrared radiative destabilization; hence no net mass transfer occurs between troposphere and stratosphere. Infrared radiation emitted from the surface and troposphere is the primary source of diabatic heating. It promotes convective overturning and a net upward flux of water vapor (contrary to a dehydration mechanism).

In contrast, the mesoscale updraft hypothesis has net upward mass transport into the lower stratosphere. This is consistent with large-scale budgets which indicate that net upward transport of mass occurs between the troposphere and stratosphere in the tropics. Solar radiation is the primary source of diabatic heating, and suggests that there should be a distinct diurnal cycle in the troposphere-stratosphere exchange process. The presence of the *deep* stratiform cloud rather than thin cirrus precludes infrared radiative destabilization of cloud in the upper troposphere. Radiatively driven upward eddy fluxes of vapor are thus absent.

We conclude that the mesoscale updraft in the presence of sunlight is a physically consistent hypothesis for the dehydration of the lower stratosphere.

6. Acknowledgements

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