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An analytic model of upper cloud in tropical hadley cell

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Clouds and humidity are important quantities in the climate forecast because they control the heat balance of the atmosphere. Clouds reflect solar radiation back to space and trap infrared radiation emitted by the Earth's surface. In particular, the cloudiness and the column water content affect significantly the surface environment through the energy transport due to radiative transfer.

In the tropical regions, optical thin or sub-visible cirrus clouds (SVCs) near the tropopause are observed by many observations. Typical observation shows the sub-visible cirrus in the layer from 14 km to 17 km altitude extending over $¥sim 1000$km. More tenuous clouds, which are named Ultrathin Tropical Tropopause Clouds (UTTCs), are also observed in the vicinity of the tropical cold point tropopause.These thin cirrus clouds are potentially important both as an essential element in the Earth's radiation budget and as an agent to dehydrate the uppermost troposphere.

We construct a kinematic model of the Hadley cell, in which we examine the climatological behavior of upper tropospheric cloud particles, bearing SVCs and UTTCs in our mind. Namely, our model includes evaporation of the cloud particles in the descending air parcel, which is a key process to determine the cloudiness and the column water content in the cirrus layers.

We consider the motion of air parcels containing the cloud particles along the Hadley circulation. The scale and the time span of the circulation are a few thousand kilometers and tens of days, respectively. In the inter-tropical convergence zone (ITCZ), cumuli appear and disappear actively one after another, but we discuss time averaged features. In the ascending region, a fraction of cloud particles stream horizontally from the side of the ascending region, although most of the cloud particles fall down as rains in a short time. At the tropopause, the air parcel containing cloud particles stops ascending and moves toward the horizontal direction pushed by other cumulus clusters up-flowing in the ITCZ. The air parcel descends slowly due to radiative cooling, while the cloud droplets evaporate in the descending air parcel. The horizontal scale of the descending region is very large compared with that in the ascending region. Therefore, the cloudiness and the cloud water content are determined by the distribution of the the cloud particles. Assuming a steady state circulation in the two-dimensional atmosphere, we obtain analytic expressions of the column water content and the cloudiness.

We found that the cloud particles are efficiently evaporated in the middle and the lower layers. Thus in these layers the cloudiness is very small. On the other hand, the cloudiness of the high layer is very large for small cloud particles. Especially, the cloudiness in the vicinity of the tropopause becomes almost unity even if the amount of the cloud particles supplied from ITCZ is very small.The results are consistent with the observation that the thin cirrus clouds are discovered in the wide area near the tropopause in the tropic region. Our results suggest that the thin cirrus clouds are formed by the advection of the cloud droplets supplied from the cumulus system.

The present study demonstrates that the cloudiness and thickness of the tropical upper troposphere can be diagnosed using a rather simple kinematic model if the vertical distributions of temperature, radiative cooling rate, and the amount of cloud particles ejected laterally from the convective clouds. Due to its clear physical structure, the present model may serve as a basis for new type of tools to diagnose the cloud properties in climate models.