Tropical Cirrus Maintenance

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Introduction

Data from the Atmospheric Radiation Measurement (ARM) Program sites on Manus Island and Nauru in the tropical western Pacific reveal the frequent occurrence of high cirrus layers with lifetimes of several hours to several days. We are investigating the processes responsible for the development and maintenance of these clouds using observations and a cirrus cloud model. In a recent article we described results of a series of model runs designed to test the hypothesis that cloud circulations associated with radiative destabilization of the layer are responsible for the maintenance of high tropical cirrus (Boehm et al. 1999). In spite of significant differences in cloud circulation strength among the model runs performed, very little difference was found in the ability of the modeled clouds to maintain themselves against the processes of sedimentation and evaporation. When normalized by the initial value, the ice water path of each of the modeled clouds decayed at a similar rate. This led to the conclusion that an internal dynamics-microphysics-radiative transfer mechanism is not sufficient for maintaining tropical cirrus over the periods observed.

We hypothesize that a source of large-scale rising motion is required to maintain cirrus layers for the long time periods that are often observed in the tropical upper troposphere. Important sources of rising motion in this region include tropical waves, such as Kelvin and mixed Rossby-gravity waves, extratropical wave driving, the Hadley circulation, and the Brewer-Dobson circulation in the lower stratosphere. We hypothesize that adiabatic cooling associated with the rising motion leads to cloud formation in a moist layer just below the tropopause. The source of this water vapor is outflow from deep convection, which can be advected great distances from its source by upper tropospheric winds.

Boehm et al. (1999) prompted the following e-mail response from James R. Holton: “The results seem consistent with the conceptual model of an upward circulation at the tropical tropopause forced from the stratosphere. The question is whether a uniform upward motion of order 50-100 meters per day would be sufficient to maintain the thin cirrus observed by LITE and others within a plausible range of particle sizes, etc.”

In this paper, we use Nauru99 observations to search for correlation between tropical stratospheric waves and tropical cirrus layers and a cirrus model to answer Holton’s question by investigating the magnitude of rising motion required to maintain cirrus.

Cirrus and Tropical Waves

Planetary-scale waves have been well documented in the equatorial lower stratosphere and upper troposphere. Two common types are mixed Rossby-gravity waves and Kelvin waves. Since these tropical waves are a source of rising motion near the tropical tropopause, we are investigating the possibility that they play a role in the generation and maintenance of cirrus layers in this region.

The most common method of observing tropical waves is to look at time series of radiosonde data. The Nauru99 data set provides a great opportunity to search for these waves in the tropical western Pacific. Between 4 and 8 sondes were released per day, providing a high-resolution look at the temperature and wind structure near the tropopause. The background field in Figure 1 is a time series of profiles (4 per day) of temperature perturbations from the mean temperature at each level (shown in Figure 2) over the period June 17, 1999, through July 15, 1999. Tropical waves are visible as perturbations in the temperature field descending from the lower stratosphere with periods of several days. The waves are also visible in the time series of profiles of zonal wind deviations shown in Figure 3. The zonal wind deviations were calculated based on the period mean zonal wind profile shown in Figure 4.

A cloudmask algorithm developed by Eugene Clothiaux uses lidar data to construct time series of cloud occurrence (Clothiaux et al. 1998). We have superimposed the cloudmask data (black contours) for the Nauru99 time period on the temperature and zonal wind perturbation fields in Figure 1 and 3, respectively. Careful inspection reveals that cirrus cloud formation generally occurs in the cold phases (blue shades) of the waves descending from the lower stratosphere. A good example of this is seen

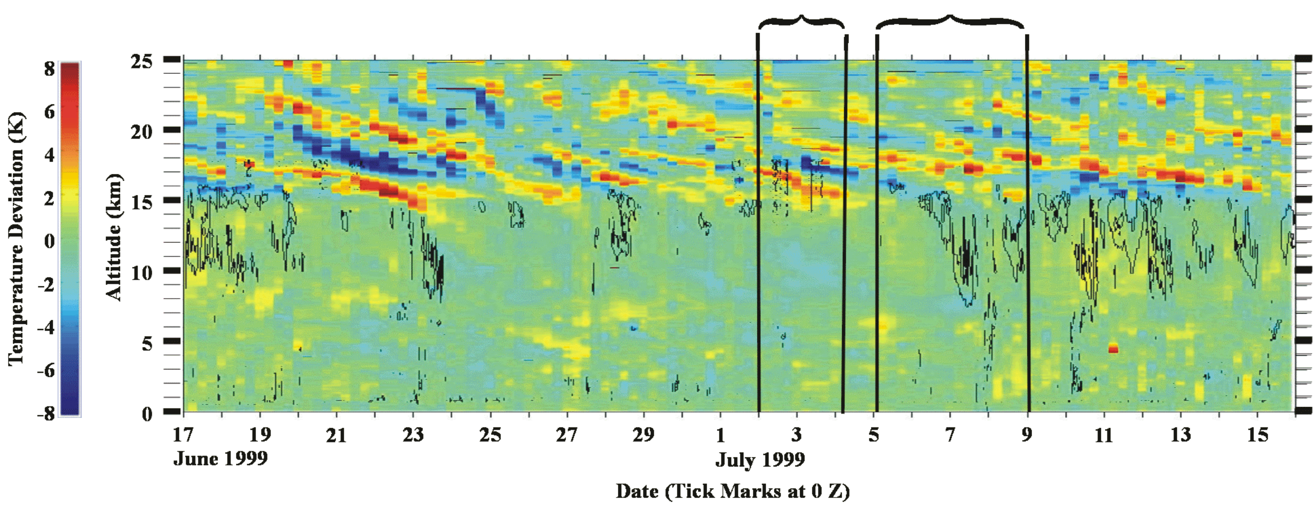

Figure 1. Radiosonde and lidar data from the DOE ARM Nauru99 Field Experiment showing the correlation between stratospheric waves and upper tropospheric cirrus. The background contour field is a time series taken from radiosonde observations (4 per day) of temperature deviations from the mean temperature profile (see Figure 2) for the period June 17, 1999, through July 15, 1999. The black contours superimposed on the temperature data outline clouds detected by the cloudmask algorithm of Clothiaux et al. 1998). Lidar time series for the bracketed periods are shown in Figure 5.

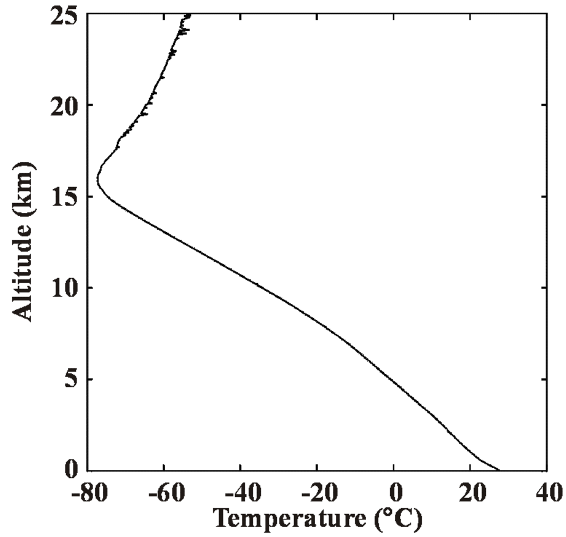

Figure 2. Mean temperature profile at Nauru for the period June 17, 1999, through July 15, 1999.

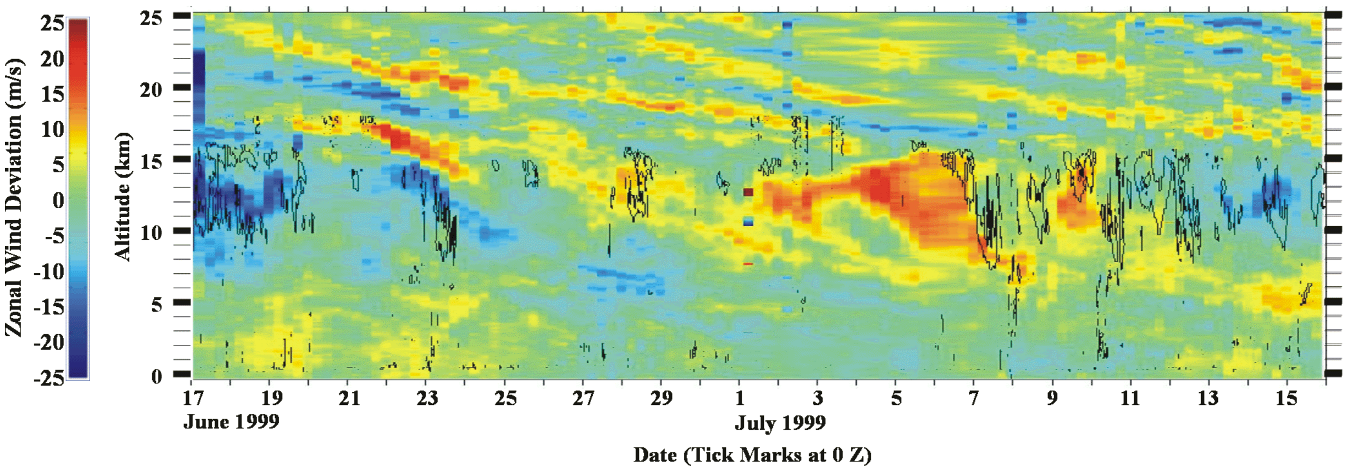

Figure 3. Similar to Figure 1 except background contours show zonal wind deviation from the period mean profile (see Figure 4).

during the first week of July in the lidar time series shown in Figure 5. After clear conditions from the 2nd through 4th, cirrus develop as the cold phase of a wave reaches the tropopause on the 5th. As the wave continues its descent through the 6th and 7th, the cirrus gradually descends as well.

Cirrus Model Runs Forced by Large-Scale Cooling

We have used a one-dimensional version of our 2D cirrus model to study the development of cirrus forced by large-scale cooling. The model simulates microphysics using an explicit bin scheme and radiative transfer using a two-stream radiative transfer model with 18 bands in the IR. Solar radiation is

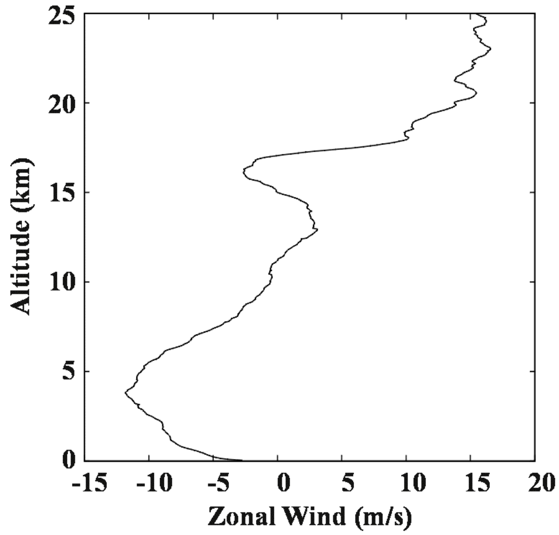

Figure 4. Mean zonal wind profile at Nauru for the period June 17, 1999, through July 15, 1999.

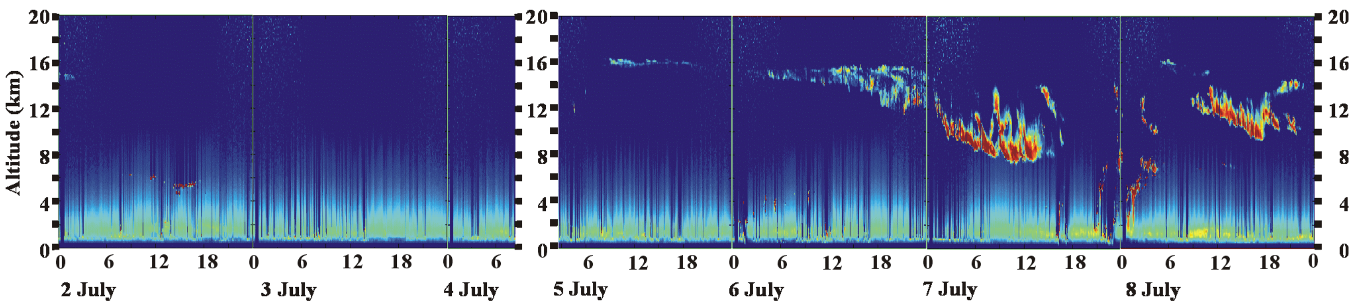

Figure 5. Time series of Nauru99 micropulse lidar profiles for the periods bracketed in Figure 1.

not considered in this preliminary study. The runs considered here were initialized with the temperature and humidity profiles shown in Figure 6, derived from radiosonde data at Nauru. The model domain (12 km to 18 km) is initially cloud-free.

We have found that the model results are very sensitive to the value specified for the turbulent diffusion parameter (K_H). Care has to be taken that the model physics is not dominated by this artificially set parameter. This is of particular concern in these cirrus clouds where the calculated rates of the physical processes can be very small. For the runs considered here, K_H was set to a value characteristic of the upper troposphere (0.01 m^2/s; from Lilly et al. 1974).

Figures 7 and 8 show the results of two runs forced by cooling the domain at a rate that corresponds to a chosen rate of adiabatic ascent. The figures show time series of profiles of model output every 30 minutes through the 24-hour simulations. Figure 7 shows results from a run forced by cooling corresponding to an ascent rate of 0.1 cm/s, which lies within the range of values given in Holton's question above. It is obvious that a cloud is formed and maintained in this run. The ice mixing ratio

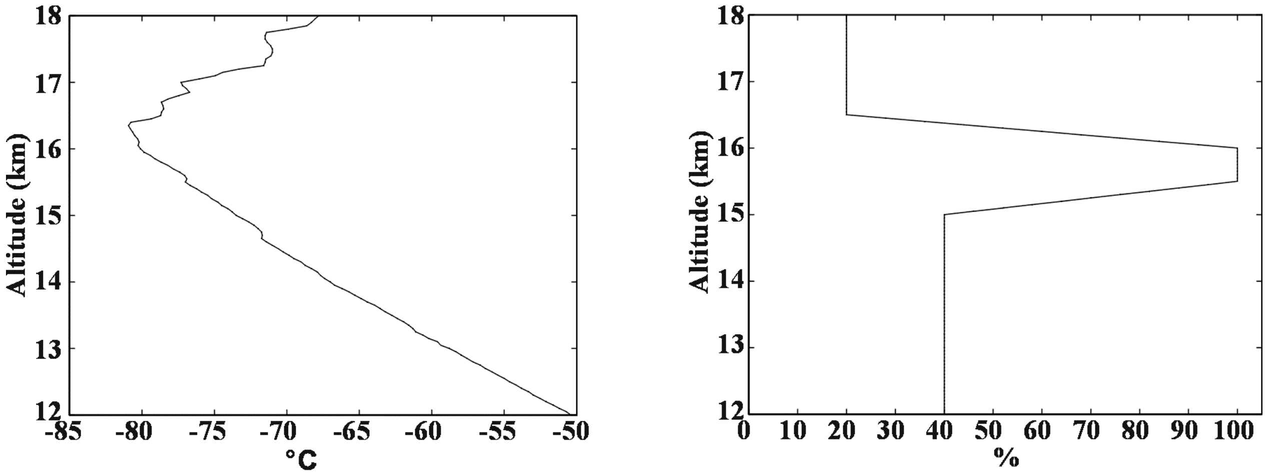

Figure 6. Initial model profiles for temperature (left panel) and relative humidity with respect to ice (right panel).

reaches a maximum value of about 0.9 x 10^{-7} kg/kg (multiply by 200 to convert to g/m^3) and the effective radius reaches 18 μm. Note the pulses of enhanced ice formation and the sublimation occurring below the cloud layer, both particularly visible in the latent heating rate field. This simulated cloud reaches a steady state by around 10 hours, presumably due to interactions between the microphysics and radiation.

Figure 8 shows results from a run forced by cooling corresponding to an ascent rate of 0.5 cm/s, which approximates the cooling rates due to the waves found in the observational portion of this study. The larger cooling rate results in a greater ice mixing ratio (6.0 x 10^{-7} kg/kg) and effective radius (32 μm), with an associated higher precipitation rate. As a result the sub-cloud layer moistens and the cloud extends downward with time. Depending on the forcing the clouds have different visual appearances, both of which are frequently observed.

Conclusions

Observations have revealed the frequent presence of cirrus layers near the tropical tropopause. In a recent article we showed that an internal dynamics-microphysics-radiative transfer mechanism is not sufficient for maintaining these cirrus layers and proposed that large-scale rising motion is required to explain the life cycle of tropical cirrus. Data from the U.S. Department of Energy (DOE)-ARM Nauru99 experiment were used to investigate this hypothesis. Using radiosonde and lidar observations, we have found good correlation between upper tropospheric cirrus clouds and tropical waves near the tropopause during this period. These waves have periods of several days, consistent with the observation that cirrus layers often persist for periods of a day or two.

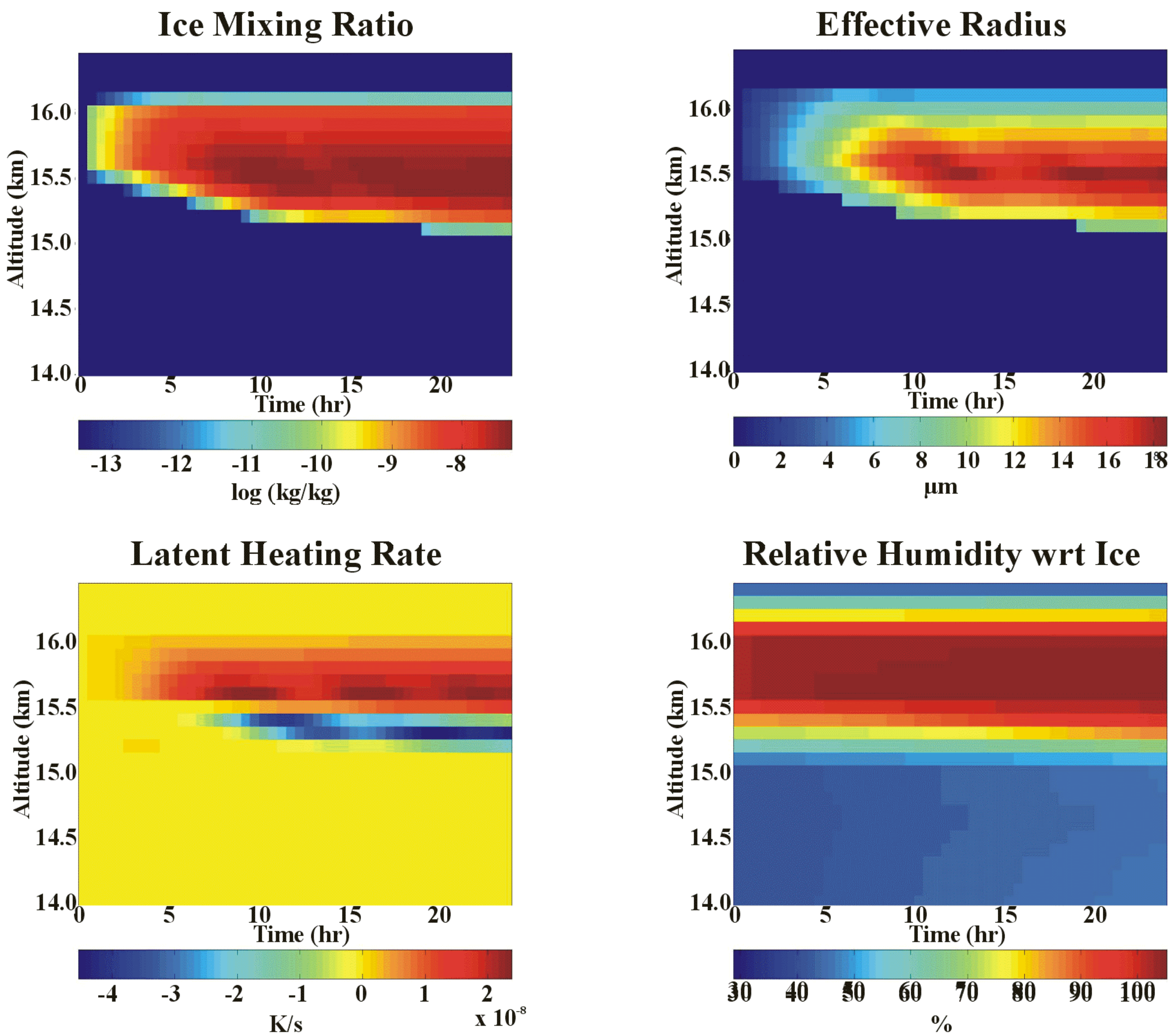

Figure 7. Results from a cirrus model run forced with cooling corresponding to adiabatic ascent of 0.1 cm/2. The four panels show a time evolution of various model quantities over the 24-hour simulation. Note the log scale for ice mixing ratio.

Using a cirrus model we have determined that the answer to Holton's question is yes. Rising motion resulting from stratospheric pumping (Holton et al. 1995) would be sufficient to maintain cirrus clouds for extended periods. However, we have also shown that waves propagating downward from the stratosphere may be responsible. It is likely that both processes work together to produce the variety of observed cirrus.

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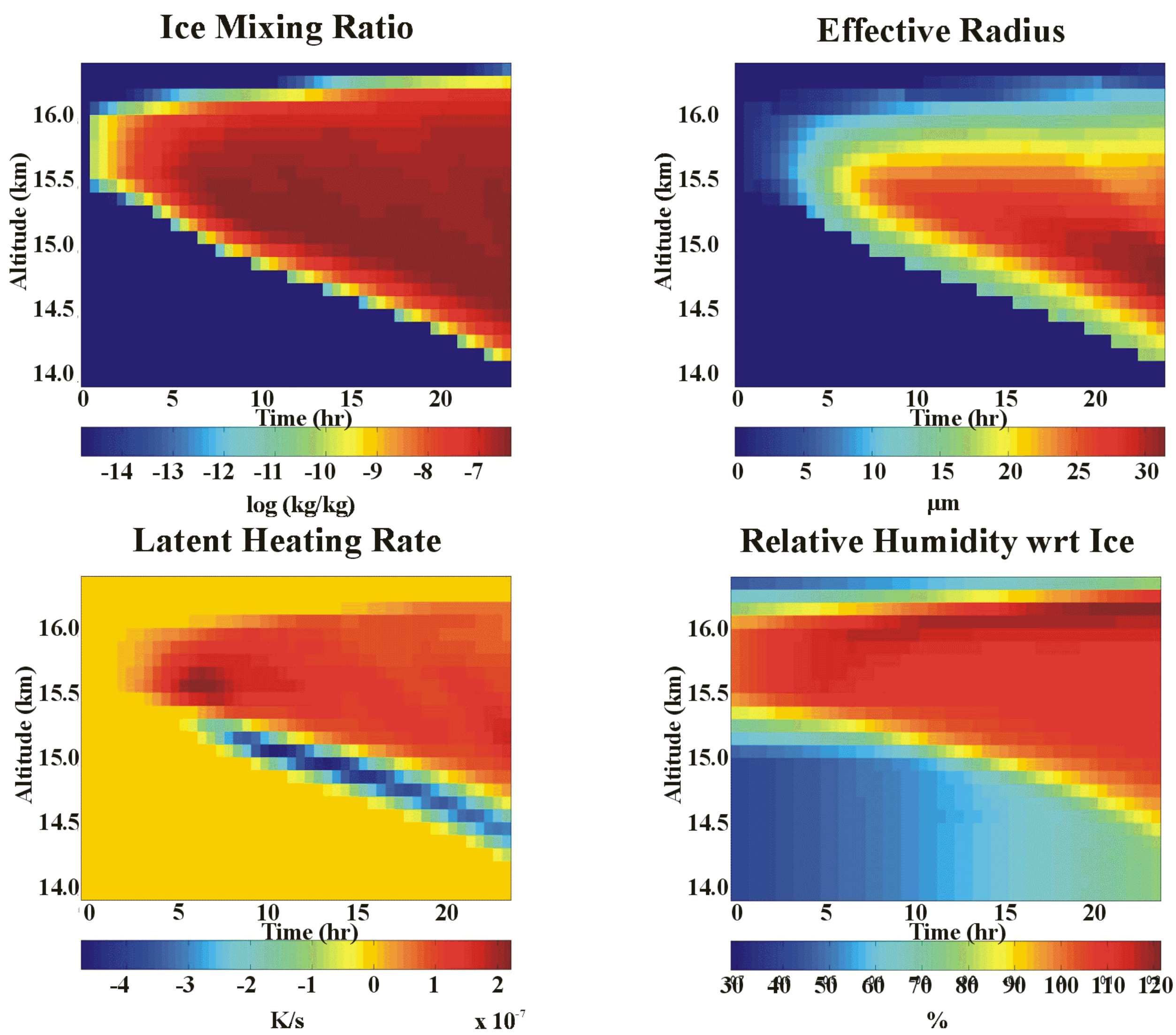

Figure 8. Similar to Figure 7 but for a cirrus model run forced with cooling corresponding to adiabatic ascent of 0.5 cm/s.

References

Boehm, M. T., J. Verlinde, and T. P. Ackerman, 1999: On the maintenance of high tropical cirrus. *J. Geophys. Res.*, **104**, 24,423-24,433.

Clothiaux, E. E., G. G. Mace, T. P. Ackerman, T. J. Kane, J. D. Spinhirne, and V. S. Scott, 1998: An automated algorithm for detection of hydrometeor returns in micropulse lidar data. *J. Atmos. and Oceanic Technol.*, **15**, 1035-1042.

Holton, J. R., P. H. Haynes, M. E. McIntyre, A. R. Douglass, R. B. Rood, and L. Pfister, 1995: Stratosphere-troposphere exchange. *Rev. Geophys.*, **33**, 403-439.

Lilly, D. K., D. E. Waco, and S. I. Adelfang, 1974: Stratospheric mixing estimated from high-altitude turbulence measurements. *J. Applied Meteo.*, **13**, 488-493.