The heat balance of the tropical tropopause, cirrus, and stratospheric dehydration

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Abstract. If tropical tropopause cirrus lie above convective anvils with tops above about 13km, then net radiative cooling from the cirrus can be produced that is large enough to offset significant subsidence heating, even at the lowest temperatures observed in the tropics. Cirrus clouds near the tropopause are strongly heated by radiation unless they lie above convective anvil clouds. Radiative relaxation in the tropical troposphere is slow above about 14km unless clouds are present. Radiative cooling of tropopause cirrus may be important in processes that dehydrate air before it enters the stratosphere.

Introduction

The central question in this letter is whether thin cirrus near the tropopause can be cooled by radiative energy exchange. The radiative heating rate near the tropical tropopause is critical for determining the water balance of the stratosphere and for explaining observed trends in stratospheric water vapor [*Holton et al.*, 1995]. In addition, cirrus clouds near the tropopause can have an important effect on the energy balance of Earth.

Brewer [1949] explained the observed aridity of the stratosphere by arguing that nearly all air parcels entering the stratosphere must cross the tropopause in the tropics where they are freeze dried to the saturation mixing ratio characteristic of the cold tropical tropopause. Recent analyses of satellite and aircraft data [*Michelsen et al.*, 2000; *Zhou et al.*, 2001] support earlier evidence that the mean mixing ratio of water vapor at entry to the tropical stratosphere is ~3.5 ppmv, whereas the ice saturation mixing ratio at the mean tropopause temperature is typically ~4.5 ppmv. These observations require that air be cooled to a temperature below that of the mean tropical tropopause before it enters the stratosphere. It has been commonly assumed in recent years that transport from the troposphere into the stratosphere is concentrated in the West Pacific "fountain" region during the Northern Winter, where tropopause temperatures are coldest [*Newell and Gould-Stewart*, 1981]. Dessler [1998] argues that the average tropopause temperature is actually cold enough to explain the observed humidity of the lower stratosphere. The fountain hypothesis has also been called into question by an analysis of radiosonde wind data [*Sherwood*, 2000], which indicates that net subsidence rather than upwelling occurs in the vicinity of the tropopause in the west Pacific. The analysis of Sherwood is supported by results from a global chemical tracer model utilizing analyzed wind fields [*Gettelman et al.*, 2000], which shows a downward water vapor flux in the West Pacific region.

This paper has three main points. First, cooling by longwave emission from water vapor becomes very inefficient above 14km in the tropics, and as a result the diabatic forcing for cloudiness that occurs above this level comes from the radiative heating and cooling associated with the presence of the clouds themselves. Second, if a cirrus cloud is introduced above tropical anvil clouds with sufficiently cold tops, then the tropopause can be cooled by radiative emission from cirrus clouds, even at temperatures that are cold enough to explain the observed dryness of the stratosphere. Finally we will sketch a mechanism by which this radiative cooling from tropopause cirrus can be a central part of the explanation for the dryness of the stratosphere.

Tropical Tropopause Heat Balance

Radiative heating rates and radiative relaxation times for clear-sky conditions in the tropics are shown in Fig. 1. These results were obtained with the radiative transfer model described below, for temperature, humidity, and ozone profiles for the tropical mean [*McClatchey et al.*, 1971]. An important, but under-appreciated aspect of clear-sky radiative cooling in the tropics is the steep drop to small values from 250mb to 150mb (14 km). The radiative relaxation time depends on the vertical scale of the temperature anomaly assumed in the calculation. Sinusoidal temperature anomalies with vertical wavelengths of 7 and 14km were added to the climatological profile. The phase of the temperature anomaly was chosen so that the maximum anomaly of 1K occurred at the level of interest. The temperature anomaly divided by heating rate anomaly at the level of interest gives an estimate of the relaxation time scale at that level for perturbations with the chosen vertical wavelength. A sharp increase of the radiative relaxation time is associated with the drop in net cooling rate near 200mb. Both of these changes occur because absorption and emission of longwave radiation by water vapor become ineffective at temperatures lower than that of the tropical atmosphere at about 150mb. It is interesting that this appears to be a fundamental property of water vapor emission tied to temperature, rather than a special property of the current climatology of the tropics on Earth. The cooling near 250mb comes mostly from strong emission from rotational lines of water vapor at wavelengths longer than about 35µm. This cooling cuts off abruptly near 200mb as the saturation vapor pressure falls exponentially with declining temperature.

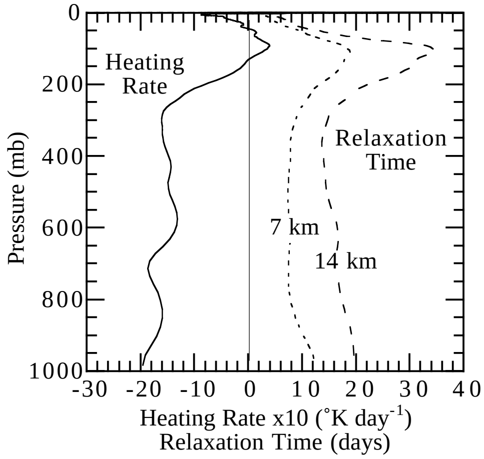

Figure 1. Clear-sky radiative heating rates (solid) and radiative relaxation times calculated for climatological tropical profiles. Relaxation time scales are given for sinosoidal waves with vertical wavelengths of 7 and 14km. Heating rates have been multiplied by 10 and are in units of Kday^{-1}.

Above 150-200mb the rapid clear-sky radiative cooling that destabilizes the temperature profile and encourages convection at lower levels is absent. The clear-sky radiative heating and relaxation time scale profiles in Fig. 1 are thus consistent with the observation that convective outflow peaks near 200mb, rather than higher up. *Folkins et al.* [1999] have provided evidence from in situ chemical measurements from Samoa that surface air is mixed into the layer above 14 km only slowly, while substantial stratospheric air is mixed in quasi-isentropically from the subtropical stratosphere.

Although most convection detrains below 150mb, a large amount of optically thin cloud occurs above this level, especially where deep convection is occurring at lower levels. *Kent et al.* [1995] find that SAGE-II data show clouds at the tropopause about 50% of the time in the west Pacific, generally in the same location where lower altitudes are even more cloudy. *Wang et al.* [1996] show that the highest frequency of tropopause clouds is in the tropical West Pacific in Northern Hemisphere winter. The deductions from SAGE were confirmed by data from the Lidar In-space Technology Experiment (LITE) observations of optically thin laminar clouds during a 10-day Space Shuttle mission [*Winker and Trepte*, 1998]. LITE data showed thin cirrus layers near the tropical tropopause with horizontal extents of up to 2700 km and with thicknesses from a few hundred meters to one kilometer.

If thin layer clouds occur in the upper tropical troposphere in otherwise clear conditions they will be strongly heated by the absorption of upwelling longwave radiation from below. This heating makes it difficult to sustain cirrus in models unless compensating adiabatic cooling is assumed [*Ackerman et al.*, 1988; *Boehm et al.*, 1999; *Jensen et al.*, 1996b]. One can see from a simple calculation, however, that ice clouds near the tropopause can provide cooling if sufficiently cold convective clouds underlie them (Fig. 2). If absorption by the atmosphere is ignored, solar absorption is ignored, the convective anvil cloud (CA) is assumed to be a black body, and the emissivity of the cirrus cloud is ε, then the radiative equilibrium balance for the cirrus cloud is:

$$\varepsilon\sigma T_{CA}^4 = 2\varepsilon\sigma T_{cirrus}^4 \tag{1}$$

So that the radiative equilibrium temperature of the cirrus is

$$T_{cirrus} = \sqrt[4]{\frac{1}{2}}\ T_{CA} \tag{2}$$

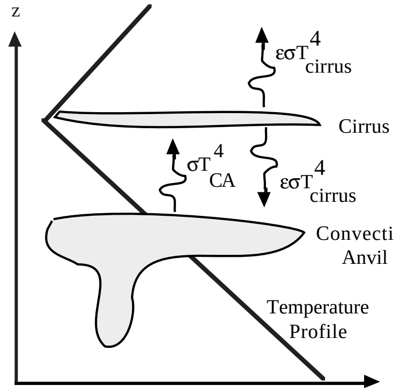

Figure 2. Schematic diagram of cirrus above convective anvil cloud including temperature profile.

To obtain a radiative equilibrium temperature for the cirrus cloud that is less than the mean temperature of the tropical tropopause of about 195K, the emission temperature of the underlying convective anvil must be less than about 232K, which corresponds to the temperature at an altitude of about 10.5km. We will show in the next section that if cirrus cloud forms at the tropopause above convective anvils, then significant cooling rates can be obtained even at the coldest temperatures that the tropopause exhibits.

Radiative Heating Rate Calculations

In this section we describe detailed radiative heating rate calculations for thin cirrus above thick convective anvil clouds in the tropics. The radiative transfer scheme used is the delta-four-stream scheme [*Liou et al.*, 1988]. The non-gray gaseous absorption by H_2O, CO_2, O_3, CH_4, and N_2O is incorporated into the scattering atmosphere using the correlated k-distribution method [*Fu and Liou*, 1992]. The single scattering properties of cirrus clouds containing non-spherical ice crystals, including the extinction coefficient, single-scattering albedo and asymmetry factor, are parameterized in terms of ice water content and generalized mean effective size [*Fu*, 1996; *Fu et al.*, 1998].

Broadband heating rate calculations were made using the standard tropical atmosphere [*McClatchey et al.*, 1971], which has a cold point of 195K at 17 km. The calculations were also performed with atmospheric profiles that are typical for the western Pacific in the winter season: the temperature profile has a cold point of 188K at 17km, the water vapor mixing ratio at 17km is 2.4ppmv, the ozone profile is consistent with data presented in Folkins et al. [1999] and Fujiwara et al. [1998]. We will show only the results for the 188K profile, which is a more stringent test of our cooling mechanism. We used a vertical resolution of 125 m, a surface albedo of 0.05, and a solar zenith angle of 54° with a daytime fractional length of 0.496 (January at 5°N). The thin cirrus considered was 0.5 km thick with a cloud top height at 16.5 km [*Winker and Trepte*, 1998]. The generalized mean effective size used was 13 μm, corresponding to the mean effective size of 22 μm as derived from in-situ aircraft observation for sub-visible cirrus [*McFarquhar et al.*, 2000]. We calculate the heating rate profiles for thin cirrus with different optical depths with and without an underlying thick cloud.

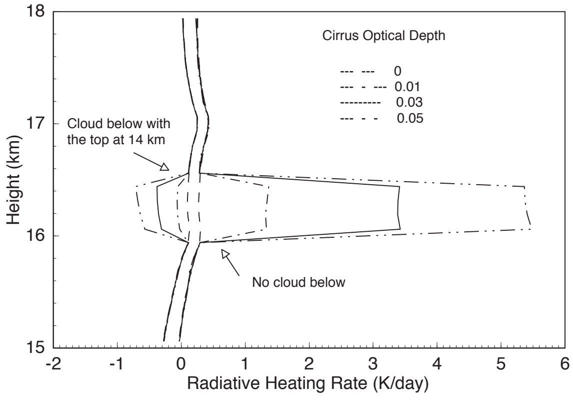

Figure 3. Radiative heating rates near the tropical tropopause with cirrus cloud present between 16 and 16.5 km with various optical depths for: no cloud below (rightmost 4 curves), and thick cloud below with cloud top at 14 km. See text for details.

Figure 3 shows the net (solar plus infrared) radiative heating rate profiles between 15 and 18 km. When the thick cloud is present between 3 and 14 km, the heating rates are 0.1, -0.1, -0.4, and -0.7 K day^{-1}, respectively, for the thin cirrus layer with optical depths of 0 (i.e., no cirrus), 0.01, 0.03, and 0.05. For the same cirrus with no underlying cloud layers, however, the heating rates are 0.3, 1.3, 3.4, and 5.4 K day^{-1}. The contributions from infrared radiation dominate these heating rates, so that at night the numbers given above would be only slightly more negative: 0.0, -0.2, -0.6, and –1.1 K day^{-1} with the underlying cloud and 0.3, 1.3, 3.2, and 5.0 K day^{-1} without the underlying cloud.

Figure 4 gives the dependence of net radiative heating rate profiles on the deep convective cloud top heights for thin cirrus between 16 and 16.5 km with an optical depth of 0.03. In order to obtain net cooling in the cirrus layer, the underlying thick cloud top must be higher than ~13 km, when the tropopause temperature is as cold as 188K. The effective emission height for the thick anvil cloud considered is about one kilometer lower than the top of the cloud.

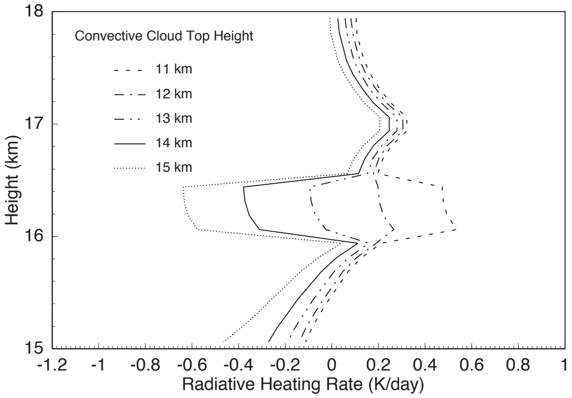

Figure 4. Radiative heating rates near the tropical tropopause with cirrus cloud with an optical depth of 0.03 present between 16 and 16.5 km and with thick cloud below with cloud top at various heights. See text for details.

The radiative impact of subvisible tropopause tropical cirrus has been investigated in several studies. *McFarquhar et al.*[2000] obtained heating rates of up to 1.66 K day^{-1} in the cloud layer. *Rosenfield et al.*[1998] showed that the radiative heating of cirrus would result in temperature increases of 1-2 K and vertical velocity increases of 0.02-0.04 mm s^{-1}. As a consequence of the warmer tropopause, lower stratosphere water vapor increases by as much as 1 ppmv. In the papers mentioned above the radiative heating rates for the cirrus cloud layer were calculated under the condition that no underlying clouds were present. The presence of underlying cloud radically alters the energy balance of tropopause cirrus.

Tropopause cirrus occur frequently above convective anvil clouds in the tropics. Based on the lidar observation during the CEPEX [*McFarquhar et al.*, 2000], nearly 50% coverage by tropopause cirrus was detected during the time period when thick clouds were present below them. Wang et al. [1998] showed that approximately 30% of the SAGE II cloud measurements are isolated single-layer clouds, while 65% are high clouds contiguous with an underlying opaque cloud that terminates the SAGE II profile.

Many possible generation mechanisms for the cirrus exist. Cumulus turrets could carry a substantial burden of ice particles to the tropopause followed by spreading to form a thin cirrus shield. Observations during STEP 1987 [*e.g., Danielsen*, 1993] provided some support for the overshooting mechanism, although temperature profiles indicative of overshooting and mixing of cumulus were only rarely observed during STEP. Another process that could initiate the formation of sub-visible cirrus is the adiabatic cooling of air parcels near the tropical tropopause to temperatures below saturation by uplift associated with Kelvin waves, convectively generated gravity waves, or forced circulations associated with organized convective systems [*Boehm and Verlinde*, 2000].

Even in the absence of clouds at the tropopause, when sufficiently cold clouds lie below, the heating rate at the tropopause above these clouds is about 0.25 Kday^{-1} less than when underlying clouds are absent. It is interesting to compare this number with temperature changes associated with advection. These temperature changes should be similar to those experienced by a parcel following isentropic surfaces. For climatological conditions, temperature gradients are order of 2K in 5,000 km and zonal wind speeds are of order 10 ms^{-1}. Zonal advection gives a scale for adiabatic heating rates of 0.34 Kday^{-1}. So the changes in heating rate at the tropopause associated with the underlying anvil clouds are comparable to those produced by advection of the time mean flow. One can imagine that cirrus would be formed where isentropic surfaces bulge upward and adiabatic cooling occurs. If these cirrus form above underlying anvil clouds, then radiative cooling will be produced near where adiabatic expansion has already produced relatively cool air. The radiative cooling rate is of the same order as the adiabatic temperature changes and would tend to move the coldest air down stream into the subsiding portion of the flow. This is a possible explanation for the coincidence between subsiding motions and cold temperatures that has been suggested to exist in the west Pacific [*Gettelman et al.*, 2000; *Sherwood*, 2000].

One problem with the cooling mechanism proposed here is that heating rates for cirrus above clear skies are much greater than cooling rates for the same cirrus cloud above anvil cloud (Fig. 3). In order to produce sustained net cooling at the tropopause a strong correlation must exist between cirrus optical depth and the presence of underlying anvils. It is plausible that tropopause cirrus would be thicker above convective anvil clouds, but cirrus optical depth measurements to test this are quite rare.

Implications for stratospheric dehydration

Tropopause cirrus in the colder regions above convective anvils can lead to net radiative cooling accompanied by subsidence and contribute to a mechanism for drying the air to the 3.5 ppmv observed in the lower stratosphere. ISCCP data show the average total cloud cover of 75% and high cloud fraction near (tops higher than 440mb) around 60% in zonally elongated regions near the equator. The zonal winds at the tropopause are about –10ms^{-1}, or about 850 km day^{-1}. So if cirrus overlap convective anvils for more than 1000 km or so this will allow time for radiative cooling to take place, and for ice crystals to grow and fall significantly relative to air [*Jensen et al.*, 1996a]. This would leave the water content of the air parcel close to that of saturated air at the temperature of the tropopause above the convective region. Extended cloud decks of this scale with IR temperatures less than 230K can often be seen in satellite images from in Maritime Continent region. Once the parcel leaves the shelter of the underlying anvil cloud, it would again be heated by radiation and could rise into the stratosphere with its moisture depleted. The stratospheric dehydration mechanism envisioned here is thus one of cycling of air by horizontal advection through the cold region above tropical convection and slow ascent of dehydrated air in non-convective regions. It is explored quantitatively in Holton and Gettelman [2001]. Such a mechanism is consistent with the energy balance at the tropopause and the observation of descent in the cold air above convection in the tropics. Cooling from clouds in the convective regions may be part of the explanation for why the tropical tropopause in the western Pacific is colder than elsewhere, but not higher [*Highwood and Hoskins*, 1998]

Conclusion

We have demonstrated that net radiative cooling can be produced at the tropopause in regions where the temperature is relatively cold and observations suggest that the mean vertical motion is downward. The radiative cooling is produced by emission from thin cirrus at the tropopause, if sufficiently cold and optically thick clouds underlie them. The effect of radiation on the maintenance of tropopause sub-visible cirrus and its implications for dehydration of the stratosphere are very different depending on what one assumes about the presence of clouds at lower levels.

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