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An important constraint on tropical cloud - climate feedback

Dennis L. Hartmann and Kristin Larson

Department of Atmospheric Sciences, University of Washington, Seattle, USA

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[1] Tropical convective anvil clouds detrain preferentially near 200 hPa. It is argued here that this occurs because clear-sky radiative cooling decreases rapidly near 200 hPa. This rapid decline of clear-sky longwave cooling occurs because radiative emission from water vapor becomes inefficient above 200 hPa. The emission from water vapor becomes less important than the emission from CO_2 because the saturation vapor pressure is so very low at the temperatures above 200 hPa. This suggests that the temperature at the detrainment level, and consequently the emission temperature of tropical anvil clouds, will remain constant during climate change. This constraint has very important implications for the potential role of tropical convective clouds in climate feedback, since it means that the emission temperatures of tropical anvil clouds and upper tropospheric water vapor are essentially independent of the surface temperature, so long as the tropopause is colder than the temperature where emission from water vapor becomes relatively small. *INDEX TERMS:* 1620 Global Change: Climate dynamics (3309); 3314 Meteorology and Atmospheric Dynamics: Convective processes; 3354 Meteorology and Atmospheric Dynamics: Precipitation (1854); 3359 Meteorology and Atmospheric Dynamics: Radiative processes; 3374 Meteorology and Atmospheric Dynamics: Tropical meteorology. **Citation:** Hartmann, D. L., and K. Larson, An important constraint on tropical cloud - climate feedback, *Geophys. Res. Lett.*, *29*(20), 1951, doi:10.1029/2002GL015835, 2002.

1. Introduction

[2] In a recent paper *Hartmann et al.* [2001a] showed that the clear-sky cooling rate in the tropics decreases above about 200 hPa and that the relaxation rate of temperature anomalies by clear-sky radiative emission also decreases rapidly above 200 hPa. They pointed out that the cooling rate and the relaxation rate both decline because emission from water vapor becomes inefficient above that level. The low water vapor emissivity is traced to the low saturation vapor pressure, which is related principally to the air temperature. The dependence of water vapor emission on temperature through the Clausius Clapeyron relationship is much stronger than the dependences on pressure or relative humidity. Therefore, the temperature at the level where the longwave cooling by water vapor declines precipitously with height should remain approximately constant as the surface temperature changes.

[3] The global mean heat balance of the atmosphere is between heating by sensible heat flux from the surface, heating by latent heat release during precipitation, and cooling by radiation [*Hartmann*, 1994]. One major consequence of this is that, although the column water vapor increases exponentially with temperature in approximate proportion to the saturation vapor pressure, the precipitation rate is constrained to increase at a slower rate determined by the rate at which atmospheric radiative cooling increases with temperature. Thus, although water vapor pressure increases by about 20 percent for each 3°C of temperature increase, the precipitation rate increases at only about half that rate [*Larson and Hartmann*, 2002a].

[4] The approximate heat balance in the tropical troposphere is between radiative cooling and convective heating by latent heat release. In equilibrium, the magnitudes and vertical structures of convective heating and radiative cooling must conform to each other. As a simplification, one can assume that most of the radiative cooling occurs in clear regions and most of the deep convective heating occurs in regions with deep convective clouds. A large-scale circulation connects these two regions. Radiative cooling in clear regions is an important constraint on convection, since the temperature tendencies that it produces generate instability that can be removed by convection. The implication is then that most active convection will be limited to the altitude range where radiative cooling is efficient.

[5] The convective anvil clouds of the tropics occur at the altitude where the radiative cooling of clear skies decrease rapidly with altitude. The radiative cooling in clear skies is balanced by adiabatic heating through subsidence. The strong decline of radiative cooling with altitude must thus be accompanied by a strong convergence of mass at that level, which is balanced by a strong divergence of mass from the convective regions (Figure 1). This divergence of mass is associated with the frequent occurrence of convective anvil clouds at this level. Satellite data indicate a peak in the probability of optically thick cloud tops in the layer centered on 200 hPa [e.g., *Hartmann et al.*, 2001b], where field programs indicate a peak in detrainment of convection [*Houze and Betts*, 1981], and analysis of large-scale wind fields also indicate maximum divergence. This detrainment and divergence occur well below the tropopause and do not appear to be caused in any direct way by lapse rate changes. All of these observations may be related to the clear-sky radiative cooling profile, which is heavily constrained by the basic physics expressed by the Clausius-Clapeyron relationship.

[6] If the temperature at which tropical convection detrains and convective anvil tops occur is constrained within a narrow range by the Clausius Clapeyron relation through the clear-sky radiative cooling rate, then important implications for climate change ensue that have not been previously recognized. The particular implication that is emphasized here is that the temperature at the top of tropical convective anvil clouds should remain approximately constant during climate change. Since the convective anvil clouds dominate the longwave radiative effects of tropical

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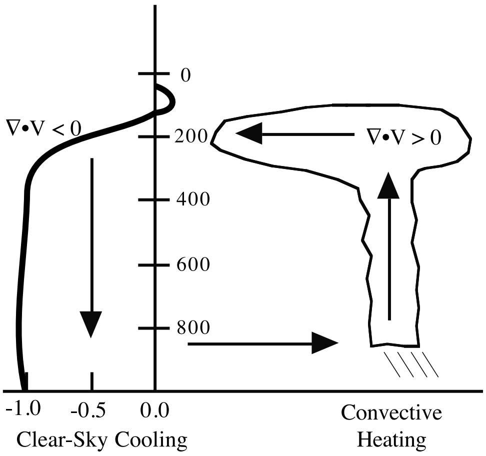

Figure 1. Schematic showing relation of clear sky radiative cooling to upper level divergence (∇oV) and convective anvil outflow.

convection, the implications for the role of convective anvil clouds in climate sensitivity are quite important. It is also true that the emission to space from the strongest lines of water vapor in the rotational bands will always occur at about the same temperature. This means that the emission from a significant portion of the infrared region under clear conditions will also come from a relatively constant temperature source as the surface temperature changes.

2. Model Test of Hypothesis

[7] The purpose of this section is to test the hypothesis that the temperature at the top of convective anvil clouds in the tropics remains approximately constant as the surface temperature is changed. A radiative-convective equilibrium model is used in which we specify the surface temperature and solve for the equilibrium climate of the troposphere as a function of the surface temperature. The model is three-dimensional, so that clear regions and high cloud regions can interact in a realistic manner.

[8] The model and its basic characteristics are described in *Larson and Hartmann* [2002a]. The model framework is the NCAR/PSU MM5 [*Grell et al.*, 1993] model with doubly periodic boundary conditions applied in the horizontal and a radiation condition applied at the top. The model domain is a 16 × 16 array of 120 km square boxes and 24 levels in the vertical over ocean with a uniform SST. The model is run for 90 days and the data taken every 6 hours for the final 30 days are averaged to determine the model equilibrium. Separate model runs are done for SST values of 297, 299, 301 and 303 K. Several integrations with different initial conditions were averaged together for each case to test for uniqueness and to improve temporal sampling.

[9] The model physics include the *Kain and Fritsch* [1990] convection parameterization, and the boundary layer and shallow convection scheme described in *McCaa et al.* [2002] and *McCaa and Bretherton* [2002]. A cloud physics parameterization described in *Reisner et al.* [1998] explicitly treats cloud water, cloud ice, rain water and snow. The model predictions of cloud ice and water interact with the radiative heating, which is calculated using the column radiation model from the NCAR CCM3 [*Kiehl et al.*, 1998]. *Larson and Hartmann* [2002a] show that the sensitivity of the top-of-atmosphere radiation budget quantities obtained from this model agree very well with observed responses of Earth Radiation Budget Experiment Data to SST variations associated with El Niño events. The model produces responses to mean SST and SST gradients similar to those of cloud resolving models shown by *Tompkins and Craig* [1999] and *Grabowski et al.* [2000].

[10] The model used here behaves similarly to observations and to cloud resolving models. Moreover, it includes the basic interactions among radiation, convection and large-scale circulation that are necessary to the mechanism proposed. The convection organizes itself on the scale of the domain, much as in the three-dimensional cloud-resolving model of *Tompkins and Craig* [1998], although the domain in much larger in this case so that the spatial scale of the organization is also larger. High clouds and upward vertical motion occupy approximately a third of the domain and the remainder of the domain is free of deep convection. In the non-convective region large-scale subsidence heating balances radiative cooling. We wish to examine the sensitivity of the temperature of the cloud top and detrainment level to the imposed SST.

3. Results

[11] The convective and non-convective regions of the model are defined to be those with and without ice visible optical depths greater than 0.1, respectively. The convective region is thus that region with visible ice clouds, which occupy 35–40% of the model domain. Figure 2 shows the net radiative heating rates in the non-convective region of the model as functions of pressure for the four cases with uniform SST values of 297, 299, 301 and 303 K. The clear-sky cooling rate decreases rapidly in the vicinity of 200 hPa in very much the same way as the calculation of clear-sky radiative cooling for mean tropical conditions shown in *Hartmann et al.* [2001a]. The pressure at which this decline occurs decreases with increasing SST. One would expect the pressure of the radiative transition to decrease with increasing SST, since the temperature in the upper troposphere will increase even more than the surface temperature, if the lapse rate approximately follows a moist adiabat. Our hypothesis is that the temperature at which the radiative transition takes place is tightly constrained by the Clausius-Clapeyron relationship.

[12] The heating rate profiles in Figure 2 are very similar to the heating rate profile shown by *Hartmann et al.* [2001a], except for the large maximum in the lower troposphere. This lower tropospheric maximum in the radiative cooling rate arises from the strong temperature inversion in the non-convective region of the model and from the presence of clouds below the inversion. An offline calculation of the clear-sky radiative cooling rate performed with the mean temperature and humidity profiles from the non-convective region of the model produces a smaller lower tropospheric cooling maximum between 1.5 and 1.8 K day^{-1}, instead of 2.2 to 2.7 K day^{-1} obtained with the low clouds included. The cooling rate in the upper troposphere under clear sky conditions is dominated by longwave radiation and the clear-sky rates are very similar to those shown in Figure 2.

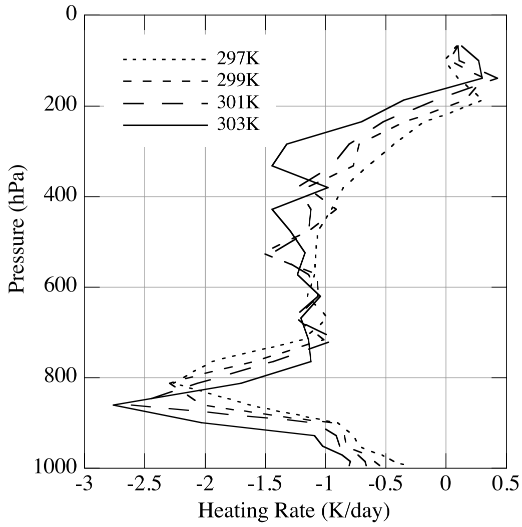

Figure 2. Net Radiative heating rates for the non-convective region for SST values of 297, 299, 301 and 303 K. Heating rates are in units of K day^{-1}.

[13] The main point of Figure 2 is that the cooling rate drops off rapidly with height before the tropopause is reached. The clear sky cooling in the upper troposphere results from emission from the strong rotational lines of water vapor. As the temperature drops below about 200 K, the vapor pressure becomes so low that emission from water vapor is inefficient and radiative relaxation times are very long and mostly dependent on CO_2 emission [*Hartmann et al.*, 2001a; *Thuburn and Craig*, 2002]. As the surface temperature is warmed, Figure 2 indicates that the pressure where the cooling rate drops off decreases. This is because the upper troposphere warms up more than the surface, so that the pressure where the temperature falls below 200 K gets lower.

[14] According to our hypothesis, the temperature where the cooling rate drops off should be approximately constant. Figure 3 shows that this holds true for the model. For each SST experiment, the temperature at the altitude where the cooling rate drops below -0.5 K day^{-1} can be computed by interpolating the cooling rate and temperature between model levels. This temperature is plotted as a function of SST in Figure 3. Also plotted for reference is the temperature at the 200 hPa pressure level. The temperature at the level where the cooling rate reaches -0.5 K day^{-1} is almost constant compared to the temperature at a fixed pressure level.

[15] The position of the high cloud top can be estimated by calculating the level at which the visible optical depth of cloud reaches a value of 0.1, as viewed from above. This number is computed by calculating the average temperature where the optical depth for solar radiation reaches 0.1 when ice cloud is present. The average temperature at the level where the cloud optical depth reaches 0.1 is plotted as a function of SST in Figure 3. This level is colder and therefore higher than the level where the clear-sky cooling rate reaches -0.5 K day^{-1}, but is similarly only very weakly dependent on SST.

[16] The temperature at the level where the large-scale vertical velocity peaks is also nearly independent of the SST (Figure 3). The sawtooth character of the plot of the temperature of the level where the maximum vertical velocity occurs is related to model discretization uncertainty.

[17] The results shown thus far were derived from equilibrium calculations with uniform SST. SST gradients will drive a stronger large-scale circulation and may cause the convection and moisture to rise to levels with lower temperatures. To test this, experiments have been performed with specified SST distributions consisting of mean values of 300 and 301 K, with sinusoidal variations of amplitude 2, 3 and 4 K. These experiments are described in more detail in *Larson and Hartmann* [2002b]. The SST varies sinusoidally with a wavelength of 19,200 km along the axis of the model domain with 160 120 km square grid boxes and is constant along the orthogonal axis of the domain with 16 grid boxes.

[18] To determine the relationship between the temperature of the cloud and the SST the SST used is the average for the 25% of the domain with the highest SST. The most intense precipitation and deepest convection occur in this region. The convection is more concentrated in the region of high SST in the model than it is in nature, as explained in *Larson and Hartmann* [2002b], but we would argue that this strong SST forcing makes the experiments a stricter test of the fixed cloud emission temperature hypothesis. The temperature where the longwave cooling equals -0.5 K day^{-1} is computed for the non-convective region that extends over the colder SST region. Since the model has no planetary rotation, the air temperatures in the convective and non-convective regions are very similar and are controlled by convection in the warm region. The temperatures at the top of the ice cloud are computed for the warmest quarter of the

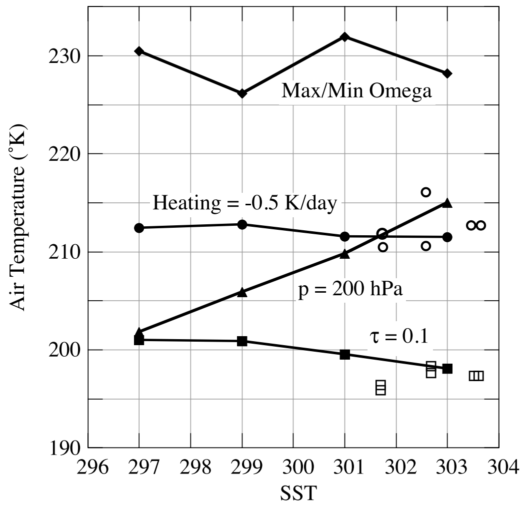

Figure 3. Air temperatures of the levels where the maximum/minimum vertical velocities occur, where the longwave cooling rate in the non-convective region reaches a value of -0.5 K day^{-1}, the 200 hPa level, and the level where the visible optical depth of the ice clouds as viewed from above reaches a value of 0.1. Open circles are air temperatures where the longwave cooling rate reaches -0.5 K day^{-1} from experiments with SST gradients and open squares are air temperatures where the cloud optical depth reaches 0.1 from experiments with SST gradients, as explained in the text. All are plotted versus the SST in K.

domain, where the SST is calculated. The values of the temperature where the longwave heating rate equals -0.5 K day^{-1} and where the cloud visible optical depth equals 0.1 are shown as open circles and open squares in Figure 3, respectively. These values line up very well with the values from the uniform SST experiments, apart from some sampling uncertainty. The near constancy of the temperature where longwave cooling ensures and where the tops of the ice clouds occur is confirmed for experiments in which SST gradients drive large-scale circulations. In nature it is likely that convection will occasionally overshoot the level where clear-sky cooling drives large-scale divergence, but these occasions are relatively rare, particularly over the tropical oceans. The majority of anvil clouds will be limited to levels below which clear-sky longwave cooling is efficient. At the top of this layer clear-sky cooling provides strong divergence that can be balanced by detrainment of convection.

4. Implications for Climate Sensitivity

[19] The above physical arguments and supporting numerical experimentation suggest that the air temperature at which rotational lines of water vapor provide cooling in the tropics will remain constant during climate change. This means that the emission from these water vapor lines will depend only weakly on surface temperature. In addition, the radiatively-driven divergence in the tropical atmosphere will always occur at approximately the same temperature, even when climate changes. This in turn implies that the temperature at the top of convective anvil clouds in the tropics will remain constant during a climate change. Since anvil clouds dominate the longwave radiative effect of tropical convective clouds, the longwave irradiance from tropical convective cloud complexes may be only weakly dependent on surface temperature. All of these effects tend to decouple the tropical outgoing longwave radiation emission from the surface temperature.

[20] If only the longwave emission is considered, these arguments suggest that the tropical climate could be very sensitive, since longwave emission from anvil clouds does not change much with increasing SST. Other effects, such as the shortwave effect of clouds, changes in the relative areas of clear and cloud regions or interactions with the extratropics, will alter these conclusions, since the longwave emission from the upper troposphere is only one part of a complex system. *Hartmann et al.* [2001b] suggest a mechanism whereby the net radiation in tropical convective cloud regions is constrained to be nearly that in adjacent nonconvective regions. This mechanism assumes a nearly constant longwave emission for the convective clouds and uses the sensitivities of the cloud albedo to mean vertical motion and mean motion to SST gradients to equalize the net radiation in convective and nonconvective regions. The area coverage by deep convection may vary with SST and this influences the mean humidity of the upper troposphere [*Larson and Hartmann*, 2002a; *Larson et al.*, 1999].

[21] It is unclear to what extent the vapor emission constraint described here will continue to operate in climates that are radically different from today's, with much different temperatures or greenhouse gas concentrations. Nonetheless, the interaction between clear-sky radiative cooling, large-scale circulation and deep convection places important constraints on climate change that should apply to the climate expected during the next several centuries. The dependence of saturation vapor pressure on temperature and its relation to radiative transfer is so fundamental that it should be possible to accurately simulate the effects described here in global climate models, provided that the anvil clouds respond appropriately to large-scale forcing (Figure 1).

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D. L. Hartmann and K. Larson, Department of Atmospheric Sciences, University of Washington, Box 351640, Seattle, WA 98195, USA. (dennis@atmos.washington.edu; klarson@atmos.washington.edu)