On moistening of the tropical troposphere by cirrus clouds

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Abstract. Sublimation of ice crystals in cirrus clouds is often invoked as a moistening mechanism for the free troposphere, particularly in the tropics. An alternative mechanism is investigated here: "pumping" of water vapor into the cloudy atmospheric column from surrounding regions by diabatic transports resulting from the local radiative effects of the cloud. The effectiveness of this mechanism is computed for a variety of cirrus cloud types, using a simple model. For nonprecipitating cirrus clouds it is found that the pumping mechanism can import much more vapor mass into the cloudy column than the clouds contain as ice, especially as the clouds become optically thin. The advected vapor per unit ice mass (or "pumping ratio") also varies with cloud height, is proportional to cloud lifetime, and (for thin clouds) is approximately inversely proportional to effective particle radius. Thin cirrus above 300 hPa can pump vapor rapidly enough to sustain itself against dessication. The overall results are supported by the limited information available from observations and indicate that at sufficient distances from active convection, direct moistening of the environment by the sublimation of ice has significantly less impact on vapor distributions than cloud-radiative-dynamic effects.

1. Introduction

The origin of water vapor in the tropical upper troposphere is undoubtedly convective. Some of this water left convective systems as vapor, the rest as hydrometeors which subsequently evaporated or sublimated into vapor. The proportion of water exiting in the condensed phases is a matter of scale: the farther from convective cores, the less water there is in condensed form. Since the processes linking clouds and vapor are clearly central to understanding both phenomena, it is important to identify and quantify such processes. Water vapor in the upper troposphere exerts significant radiative effects despite occurring in very small concentrations there, making it an important climate variable, about which much uncertainty still exists [Shine and Sinha, 1991; Spencer and Braswell, 1997].

Many investigators have invoked moistening by hydrometeor evaporation as a mechanism for maintaining the vapor distribution above the tropical boundary layer, both in explaining observations and modeling climate but usually without giving much explicit consideration to the horizontal scale issue. It has long been known that in the tropics, humidity is high throughout the troposphere in convective and nonconvective conditions [e.g., Gray et al., 1975]. Satellite observations have shown how upper tropospheric water vapor decreases with distance from the cirrus clouds [Udelhofen and Hartmann, 1995]. Advection, however, suggest that moistening by hydrometeor evaporation may not be important outside of actively convective systems [Pierrehumbert, 1998; Salathé and Hartmann, 1997; Sherwood, 1996]. One investigator recently used geostationary water vapor imagery for both tracking and sounding purposes [Soden, 1998]. He established the Lagrangian (in the horizontal sense only) drying rate of air columns under clear and cloudy conditions, finding the drying rate was apparently reduced or even reversed when partial cloud cover was present.

The drying of atmospheric columns with time, in the absence of deep cloud cover, is a well-known consequence of subsidence in a background state in which humidity decreases exponentially with height. Subsidence is linked through the local energy budget to radiative cooling, which is not highly variable in the absence of clouds [Betts and Ridgway, 1988]. Previous work has determined that clouds, however, do significantly alter net radiative heating rates, an effect sometimes called "cloud radiative forcing" [Ramanathan, 1987]. Tropical cirrus clouds, in particular, have an overall tendency to produce positive heating anomalies in the troposphere [Ackerman et al., 1988; Webster and Stephens, 1980]. The effects of cloud forcing on atmospheric dynamics appear to be modest (though detectable) for mesoscale convective development [Tao et al., 1996], significant for synoptic behavior [Albrecht and Cox, 1975], and very important for the general circulation [Randall et al., 1989]. Cirrus radiative effects are also important in maintaining the time-averaged thermal and convective structure of the atmosphere [Ramawamy and Ramanathan, 1989; Stephens and Wilson, 1980]. Since cloud radiative effects appear to be significant, it would seem that they should be capable of altering the advective drying rate and thereby increasing (in a relative sense) the moisture levels found in their midst.

This possibility is addressed here by performing radiative transfer calculations on several cirrus cloud prototypes, including clouds at limiting cases of vertical and optical thickness. The results show that cloud radiative forcing can be very important when dynamically converted into moisture perturbations. This conversion depends on a model, for
which we make the simplest possible assumption: that radiative heating and cooling effects are first reflected in the temperature profile, then (when critical lapse rates are exceeded) redistributed by convective processes, then finally redistributed by a simple large-scale adjustment process which returns the atmosphere to its state of lowest potential energy. The cloudy column is assumed to be surrounded by a much larger area of clear sky and to be small compared to the deformation radius. Midlatitude cirrus clouds are not considered since the dynamics there are different and would require a more careful treatment.

2. Adjustment Model of Cloud "Vapor Pumping"

This model is now described. It will be assumed that radiative and large-scale processes are slow compared with convective processes. This means that the effects of each process can be executed in a sequential manner, rather than continuously and simultaneously, as would happen in the real atmosphere. This greatly simplifies the analysis without sacrificing too much in the way of quantitative accuracy.

2.1. Concept

The "vapor pumping" process is illustrated in Figure 1. Since cloud radiative forcing is positive for cirrus at most levels, the heating anomalies relative to clear sky cooling will drive upward anomalies in the vertical velocity within and underneath the cirrus, relative to the sinking that occurs in a neighboring, cloud-free environment. This circulation anomaly will accumulate vapor in the cloudy column at the expense of cloud-free surroundings. Use of the vapor "pumping" terminology here will always designate the appearance of extra water vapor, relative to that found in a cloud-free column after the same lapse of time from the same initial condition (even though at most levels the cloudy column may still be getting drier with time during the pumping process). In this sense the concept is analogous to cloud forcing. The final result is horizontal heterogeneity in the moisture field.

At least one previous model study [Sherwood et al., 1994] has noted the ability of planetary-scale, zonal gradients in cloud forcing to bring about similar gradients in moisture, but those changes involved horizontal redistribution of deep convection. The mechanism considered in this paper is independent of convective transports or mixing. Note, however, that at some distance from the (nonconvective) regions being considered here (see Figure 1) a region of deep convection is taken to exist in which convective heating is generated to balance the overall cooling elsewhere, maintaining a quasi-steady temperature field.

2.2. Radiation

In the first step of the procedure the radiative cooling at each level in the atmosphere is computed for a given cloud type, under both cloudy and clear conditions, using separate runs of the Community Climate Model, Version 3 (CCM3) column radiation model. The model's native vertical resolution of 18 layers (that of the CCM3 general circulation model) has been increased to 71 layers for this study, with 5 hPa spacing from the stratosphere to 250 hPa, increasing gradually to 25 hPa spacing at the surface. When tested at the new resolution, the model results are consistent with those of the original resolution model. The model has also been run with a variety of effective ice crystal radii in addition to the standard value of 30 μm included in the source code. For results including solar heating, model runs were repeated at model time intervals of 30 min, with the results averaged, in order to cover the entire diurnal cycle properly. All solar heating values presented are diurnal means.

The temperature and humidity profiles used in the calculation (and in section 2.1) are based on a set of shipboard soundings from the Central Equatorial Pacific Experiment [Kley et al., 1997]. Separate means were taken before and after the ship crossed from a zone of deep convection to one of suppressed conditions, and these two means were averaged to give a profile representative of the mean conditions in the tropics near the boundaries between convective and stable areas. This boundary profile is the most appropriate one for purposes of calculating advection into the column

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Figure 1. Illustration of the radiative pumping effect. (a) Arrows show air flow, with a cloud indicated by the shaded area. Horizontal lines show initial isopleths of moisture. (b) Isopleths after advection by flow field during cloud lifetime are shown. Source due to cloud evaporation has not been included.
from neighboring areas. For simplicity, this same profile is also used in the radiation calculations for all cloud types. No shallow clouds have been included.

The radiative heating rates from the CCM3 are then applied to the atmospheric temperature profile after being multiplied by a predetermined cloud lifetime \( L \). The new temperature profile ends up cooler throughout most of the troposphere but may be warmer within cloud layers when these are present. Note that the heating rates during the entire cloud lifetime are based on calculations using the original sounding, with no radiative feedbacks included. In the real atmosphere, convective and large-scale adjustment processes would operate continuously on short timescales compared to the Newtonian damping time for radiation (\( \sim 20 \) days), short-circuiting these feedbacks on the time and space scales of interest here.

2.3. Convection

If the cloud is sufficiently long-lived, the vertical distribution of cloud heating will produce unstable lapse rates. When this type of destabilization occurs, a second, convective adjustment step is necessary. The adjustment is performed within the cloud by redistributing heat upward within superadiabatic portions of the temperature profile, in an energy-conserving manner, until the saturated equivalent potential temperature \( e_s \) is nondecreasing with height.

In some cases, layers immediately above the cloud will also be involved in the adjustment; in all cases considered here where this occurs, the cloud top is high enough that the moist and dry adiabats there are practically identical, so that we need not be concerned about whether the air is saturated for purposes of computing the convective adjustment. Air below cloud base is not involved in convective adjustment in this study, since the cirrus cloud prototypes considered here all experience net warming both at cloud base and integrated through the cloud. For simplicity, moisture is not redistributed during convective adjustment.

2.4. Large-Scale Adjustment

When the convective adjustment is complete, the result is a temperature profile which differs from that of its distant environment by an amount \( dT_{rad}(p) \). This temperature perturbation should, in fact, be thought of as a virtual change rather than an actual one; most of the warming is never redistributed during convective adjustment.

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3. Discussion and Illustration of the Adjustment Model

The process is now illustrated with a typical cirrus cloud deck. Figure 2 shows tephigrams of temperature and moisture profiles at each stage of the calculation, when performed on a cloud of moderate optical thickness whose properties are listed in Table 1 ("moderate cirrus"). The cloud characteristics will be described in more detail in section 5, and
Figure 2. Tephigrams at each stage of the adjustment procedure for a typical cirrus cloud. (a) Original sounding, (b) after application of radiative heating, (c) after application of convective adjustment, and (d) after application of large-scale adjustment. The left thick traces show dewpoint temperature, and the right thick traces show temperature. The thick traces show (solid) clear sky, (dashed) cloudy, and (dotted) clear-sky adjustment with the cloud ice evaporated into the sounding; the thick grey trace in (d) shows initial moisture. The thin grid lines are (dotted) isopleths of specific humidity, (dashed) moist adiabats, (horizontal solid) isobars, (down-sloping solid) dry adiabats, and (up-sloping solid) isotherms.

the two other types shown in Table 1 will be examined there as well. Readers not familiar with thermodynamic diagrams will find the same results plotted in Figure 6b as temperature and relative humidity (RH) perturbations versus altitude.

Figure 2a shows the initial sounding. In Figure 2b, the radiative heat has been added under clear and cloud-free conditions. The cloud-free profile (solid trace) is cooler than the initial profile at all levels, though by less than a degree. The cloudy profile (dashed trace) is significantly warmed within the cloud levels (250-130 hPa). It is cooler than the
initial profile elsewhere, but this cooling is significantly less than in the cloud-free case, particularly at levels near cloud base (500-300 hPa).

Notice that the addition of cloud-modulated heating has destabilized the atmosphere in the lower part of the cloud. This results from a combination of solar absorption and long-wave heating at cloud base. When the convective instability is removed, the profile becomes that shown in Figure 2c.

Finally, large-scale adjustment is applied to each of the two cases, leading to the temperature and dewpoint traces shown in Figure 2d. In the cloud-free case the adjustment consists of radiatively balanced subsidence, while for the cloudy column there is subsidence at low levels and rising motion at higher levels. Notice that the temperatures have returned to that shown in Figure 2a for both cases, but the final humidity traces have not. The final cloud-free profile is drier than the initial one at all levels below 150 hPa, particularly in the upper troposphere, showing the effects of 12 hours of subsidence. This cloudy column has now been rehydrated towards the original profile. The effect of the cloud (dotted trace) is not as strong as shown in Figure 2c.

Contrast this with the effect of evaporating the cloud water into the atmosphere, without taking into account the radiative effect of the cloud (dotted trace). The effect on relative humidity is an order of magnitude smaller through most of the cloud, and of course, there is no effect outside the cloudy levels. The precipitable water (PW) added by evaporation is only 18 g m⁻², compared with a radiatively induced increase of 112 g m⁻² within just the cloudy levels or 455 g m⁻² integrated from 100 to 700 hPa.

Thus, the water vapor pumped into the column above 700 hPa can exceed the water content of the cloudy layers by a factor of 20 or more, at least for this case, assuming that the cloud lasts for 12 hours. Most of this vapor is pumped into the layers below cloud base, but even the vapor amount pumped into the cloudy layers themselves is several times the condensed water amount. Below 700 hPa, the water budget is dominated by convective transport from the surface, so moistening at these levels was not counted. In part of the cloudy layer the final vapor content is above saturation, indicating that the pumping effect must play a significant role in the maintenance of the cloud. This is discussed further in section 6.

### 3.1. Cloud lifetimes

The amount of cloud pumping is directly proportional to the cloud lifetime \( L \), but data for specifying \( L \) are hard to come by. Typical mesoscale convective systems last \( \sim 1 \) day [e.g., *Maps and Houze*, 1993], but one must be careful since the anvils are being fed by convective moisture fluxes from the surface. The model here applies only to clouds after they have been separated from this source. Consider the case of a tropical squall line. In a frame of reference moving with the anvil droplets the anvil behind the line is no longer being fed; it is dissipating at a rate \( u/L \), where \( u \) is the anvil velocity relative to the line and \( L \) is its horizontal extent. Observations indicate \( L \sim 200 \) km and \( u \sim 10 \) m s⁻¹ [Barnes and Sieckman, 1984], giving a lifetime of \( \sim 5 \) h.

The cloud shield does not completely disappear at this point but only ceases to precipitate; satellite images frequently show cloud shields much larger than 200 km. Cirrus clouds are observed all over the globe, even places quite distant from deep convection [Warren et al., 1988] and usually in the absence of cumulonimbus [Warren et al., 1985], implying lifetimes of many hours or even days for at least some cirrus blow-off. Lifetimes of more than a day have been estimated from models of thin cirrus clouds near the tropopause [Jensen et al., 1996]. The lifetimes of 6-24 hours shown in Table 1 are guesses based on these inferences. Unlike marine stratus, which can quickly break up by cloud top entrainment, cirrus clouds exist at levels where the atmosphere is absolutely stable (\( \partial T/\partial z > 0 \)). It is likely that their lives are prolonged by the pumping mechanism itself (see below).

### 4. Cloud Pumping for Simple Cases

We would like to understand how the radiative "pumping ratio" depends on cloud parameters. Pumping ratio is defined here as the ratio of the pumped vapor to the cloud ice water content. There are at least six relevant variables: ice water path (IWP), effective radius \( r_e \), base height, top height, cloud lifetime \( L \), and the level at which the water vapor change is determined. To cut down the complexity, this section describes the effects of infinitesimal, local temperature perturbations, and then uses these to calculate the effects of vertically thin (i.e. isothermal) clouds or "wafers" in the optically thin and thick limits. In the radiation code these wafers will be taken to fill a single layer (\( \Delta p = 5-10 \) hPa).

#### 4.1. Effect of Local Heating

The local effect of an initial temperature perturbation \( \delta T_{\text{rad}} \) on the final humidity as described in section 2 is simple to approximate for small perturbations. The initial
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temperature perturbation is

\[ dT_{\text{rad}} = \frac{Q_{\text{rad}}}{c_p} dL \]  

(1)

where \( dL \) is the infinitesimal time during which the heating is applied and \( Q_{\text{rad}} \) is the radiative heating rate (power input per unit mass). The water vapor advection equation may be written

\[ \frac{dq}{dt} = -w \frac{dq}{dz} \]  

(2)

while the vertical displacement required to remove a temperature anomaly \( dT_{\text{rad}} \) may be written

\[ w dt = dT_{\text{rad}} \left( \frac{dT}{dz} - \Gamma_c \right)^{-1} \]  

(3)

In these equations, \( q \) is specific humidity, \( T \) is temperature, \( \Gamma_c \) is the critical or dry-adiabatic lapse rate, and other symbols have their usual meanings. Combining (2)-(3), the local moistening \( dq \) which eventuates following a unit heat input is simply proportional to the quotient of the local lapse rate of specific humidity and the difference between the actual and dry-adiabatic temperature lapse rates:

\[ dq = dq \left( \frac{dT}{dz} - \Gamma_c \right)^{-1} \]

Figure 3 shows this moisture sensitivity as a function of height, scaled by a unit temperature increase, calculated from the tropical sounding. Also plotted is the ambient specific humidity. Note the dramatic increase with height in the quotient of these two curves above 500 hPa. At 700 hPa a 1 K warming only produces about a 10% increase in specific humidity, while at 200-300 hPa a similar warming leads to a 100% increase. The increased sensitivity at higher levels is due both to steepening in the logarithmic derivative of specific humidity with respect to altitude and changes in temperature lapse rate. The latter comes rather close to a dry adiabat in the upper troposphere, then begins tailing off at about 150 hPa in the mean profile, which causes the quotient to bend back toward zero.

Figure 3 indicates that while the impact of a given \( dT_{\text{rad}} \) on specific humidity decreases monotonically with the height at which the heat is applied, the impact on relative humidity is maximal at the upper levels where cirrus clouds are usually found.

4.2. Wafer Clouds

The perturbation \( dT_{\text{rad}} \) is related by (1) to radiative heating, which changes in the presence of cirrus clouds due to the extra convergence of radiation, mostly infrared. Cloud forcing occurs at all levels but is largest inside the cloud layer, where its infrared component is given by

\[ Q_{\text{IR}}^\delta \frac{\delta p}{g} = \epsilon (F^+ + F^- - 2aT_\epsilon^4) \]  

(4)

where \( \epsilon \) and \( T_\epsilon \) are the cloud infrared emissivity and temperature, \( g \) is the gravitational constant, \( \delta p \) is the pressure thickness of the cloud, \( F^+ \) and \( F^- \) are the upward and downward infrared fluxes at cloud level, and \( a \) is the Stefan-Boltzmann constant. The total heating \( Q_{\text{rad}}^\delta \) is the sum of \( Q_{\text{IR}}^\delta \) and a small amount of solar heating, which is also roughly proportional to \( \epsilon \) but depends only weakly on height.

4.2.1. Optically thin limit

Cloud optical depth \( \tau \) is proportional to IWP for a given cloud geometry and \( r_c \). For optically thin clouds, \( \epsilon \) and cloud radiative forcing are both proportional to \( \tau \) and thus to IWP. This means that the vapor pumping ratio will be independent of IWP, depending only on cloud height (for thin "wafers") and \( r_c \). Since \( \tau \) is inversely proportional to \( r_c \), so will be the pumping ratio in this limit.

The pumping ratio for cloud wafers has been computed as the change in (1) the water content within the cloud layer itself, and (2) column precipitable water above 700 hPa. These results are shown versus cloud height in Figure 4. The per hour pumping ratios are quite large but only for clouds at certain heights. Since the term in parentheses in (4) is positive only above 280 hPa, the pumping ratio for within-cloud water is only positive above this level, though the inclusion of solar heating increases the ratio at all levels. The maximum within-cloud pumping ratio shown is equivalent to a vapor doubling time of ~2 hours for \( r_c = 30 \) \( \mu m \), or 15 min if \( r_c = 3 \) \( \mu m \), a more likely value for subvisible cirrus [Jensen et al., 1996].

The pumping ratios with respect to column vapor are much larger, with vapor doubling times of order 20 min even for \( r_c = 30 \) \( \mu m \), for clouds layers located between 450 and 200 hPa. Note that the "doubling times" quoted here refer not to the rate at which the vapor increases but to the length of time that the cloud must exert its radiative effect in order for the vapor to double eventually. The actual time for large-scale adjustment to proceed to completion would be of the order of hours.

4.2.2. Optically thick wafers

As we leave the optically thin limit, (4) still holds, and the vertical distribution of radiative heating remains the same as for thin clouds at the same level since it depends only on the atmospheric profile. However, since \( \epsilon \) becomes less than \( \tau \), the pumping ratio loses...
Moistening rate: thin wafer, $\tau \ll 1$

Figure 4. Cloud pumping ratio per hour of cloud lifetime, for $r_e = 30 \mu m$, of optically thin cloud wafers as a function of wafer height. Pumping ratio varies inversely with $r_e$. Solid curves show the ratio of free tropospheric PW to IWP, and dashed curves show the ratio of within-cloud PW to IWP. Heavy lines include solar and infrared radiation; light lines include only infrared.

its independence from IWP, decreasing from its optically thin value (Figure 4) by the factor $e/\tau$.

In the optically thick limit, $dT_{rad}$ becomes independent of both IWP and $r_e$ since the cloud radiative effects saturate. Hence the advective moistening per unit time in this limit depends only on cloud height and moistening height. It is plotted in Figure 5 for black wafers at three levels from 200 to 400 hPa, with infrared radiation only (Figure 4a) and with both solar and infrared (Figure 4b). The wafers are not strictly black to solar radiation but are nontransmissive with an albedo of about 0.75. The solar effects above and below the wafer are relatively small, tending to oppose the larger infrared effects.

The net radiative perturbations moisten the layers below the cloud, especially for higher clouds. A black wafer at 200 hPa produces a 1% increase in relative humidity at 300 hPa for each hour that the cloud persists and >4% per hour just below cloud base. The modest drying above cloud top results from the reduction in upward infrared radiation. The profiles in Figure 5 apply for nonblack clouds if the infrared and solar effects are multiplied by the infrared and solar $e$, respectively.

5. Effects of Typical Cirrus Clouds

In this section the radiative and moistening effects of three cirrus cloud examples are investigated. The examples, whose properties are listed in Table 1, include a "subvisible" cirrus typical of those found ubiquitously near the tropical tropopause [Jensen et al., 1996]; a "moderate" cirrus case (introduced in section 3), which typifies the edges of deep-convective systems, detached, or decaying cirrus decks; and a "thick anvil" which represents the precipitating, stratiform portion of a mesoscale convective system. These examples have progressively lower bases, greater water content and optical thickness, larger particles, and shorter lifetimes. Lifetimes are discussed in section 3.1. The particle sizes have been left at the CCM3 default value of 30 \mu m, except for subvisible cirrus whose $r_e$ value is probably at least an order of magnitude smaller than this [Jensen et al., 1996].

Lower (warmer) parts of cirrus clouds contain much greater water content and somewhat larger crystals than do the higher (colder) parts, according to a available observations [Heymsfield and Platt, 1984; McFarquhar and Heymsfield, 1997]. To account for this, the column IWP values listed in Table 1 are distributed vertically within the cloud according to the following ice water content (IWC) relation from Stephens et al. [1990]:

$$IWC = 10^{-0.041(T_C + 60)}$$

where $T_C$ is the temperature in degrees Celcius, IWC is in g m$^{-3}$, and the constant $c$ is chosen so that the column-integrated water mass equals the chosen value. This distribution shifts both the radiative and evaporative impact of the clouds to lower altitudes, relative to what they would have been for cloud decks of vertically uniform density. The crystal radius is kept constant here within a given cloud, though the observations show that it increases somewhat with temperature.

Figure 5. (a) Effect on final adjusted relative humidity, in percent per hour, of optically thick cloud wafers at three heights via infrared cloud forcing. (b) As in Figure 5a, except solar radiative forcing is also included.
Table 2. Results of the Calculations

<table>
<thead>
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<th>δRH, %</th>
<th>δPW, g m⁻²</th>
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<td></td>
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<td>Rad</td>
</tr>
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<tr>
<td>Moderate</td>
<td>11.7</td>
<td>67.6</td>
</tr>
<tr>
<td>Thick anvil</td>
<td>11.9</td>
<td>1.6</td>
</tr>
</tbody>
</table>

Quantities integrated from 700 to 100 hPa. Sub refers to moistening by sublimation of the cloud in situ, and Rad refers to advection driven by the cloud heating anomaly.

\[ \delta \text{RH} = \frac{1}{600 \text{ hPa}} \int_{700}^{100} \delta \text{RH}(p)dp. \]

As we would expect from the cloud wafer results, the thicker and lower precipitating anvil cloud is the least efficient water pump. The subvisible cirrus is quite efficient due to its tiny optical depth. Its PW ratio is astronomical, though not very meaningful since it is the ratio of two very small quantities. The moderate cloud has the highest pumping ratio with regard to RH.

The thick anvil advects somewhat less precipitable water, and much less RH, than would result from evaporation of the cloud, but these results must be placed in proper perspective. These clouds are usually precipitating, which implies a latent heating anomaly that can well exceed that of radiation [cf. Houze, 1989]. Also, the precipitation rapidly removes water from the cloud, which reduces the amount of condensate available for vaporization. Thus even these clouds may actually have a high pumping ratio, in some sense. On the other hand, these clouds are usually connected to deep cumulonimbus which supply the upper levels with large amounts of water, so the pumping result may be moot. The values calculated here for this cloud example are basically of academic interest, mainly to offer contrast with those of the other cloud types.

The sensitivity of each of the three examples to changing parameters, shown in Figures 7-9, is more or less what we would expect from the "wafer" results. The pumping ratio of the optically thick, anvil cloud is inversely proportional to IWP, while that of the subvisible cirrus is independent of IWP (Figure 7). The IWP is a good predictor overall for the pumping ratio, since the curves do not show a great deal of discontinuity between cloud types.

All cloud types show modest increases in PW ratio with lowering base height (Figure 8), though this tendency is small for the thick anvil cloud. The RH tendency peaks between 200 and 300 hPa for the moderate cloud, and the others increase as this level is approached. This is consistent with the calculation shown in Figure 3, where the relative sensitivity of moisture to heating was found to peak at these levels. The sensitivity of pumping ratio to changes in cloud top height (not shown) is negligible for all cloud types, except that the RH ratio of the moderate cirrus cloud grows somewhat as the top is lowered, presumably since this concentrates more of the cloud’s heating toward the levels of greatest atmospheric sensitivity.

Figure 6 shows the cloud heating, and final result of advective moistening, by each of these example clouds (the second result was shown earlier as a tephigram in Figure 2). The difference in final RH and PW between the cloud-radiative and clear sky calculations, integrated from 700 to 100 hPa, is listed for each case in Table 2. Also shown is the contribution made to these integrals by sublimation of the cloud ice. In the case of RH, the integral is pressure weighted:

Figure 6. (Right) temperature changes in K and (left) resulting moisture changes in % RH for three cloud types listed in Table 1, for clear-sky radiation (solid line), cloudy radiation (dashed line), and clear-sky radiation with sublimated ice (dotted line). Thin dashed lines on right are before convective adjustment, thick dashed lines are after. Note changes of scale.
The dependence on effective radius (Figure 9) is, as expected, converse to the dependence on IWP. Thin cloud pumping ratio is inversely proportional to \( r_e \), while for thick clouds the ratio is independent of \( r_e \), at least in terms of PW. The odd behavior of thick anvil RH pumping is due to the downward shift of the region of maximum infrared cooling with increasing \( r_e \); at \( r_e = 10 \mu m \) the cooling maximum sits near the critical levels of 200-300 hPa, minimizing the vapor pumping. In real clouds, crystal sizes decrease with height, which would mitigate this effect somewhat by increasing the optical thickness near cloud top.

The importance of ice particle effective radius to cloud effects was discussed by Stephens et al. [1990], who established 16 \( \mu m \) as a value most consistent with the cirrus observations available at that time. Use of this value here would increase the RH pumping ratio of the moderate cirrus cloud by about 50%.

6. Falling Crystals

The vapor pumping effect described here would clearly be strong enough to produce a cloud growth instability, if some counteracting, cloud-limiting mechanism were not acting. Previous studies have noted the importance of ice crystal fall speed in the evolution of cirrus; Starr and Cox [1985b] found that modest increases in assumed fall speeds in their model led to significant hastening of cloud dissipation. Large crystals fall faster, thereby dominating the settling process in the Starr and Cox [1985b] simulations, falling through the cloud base and quickly sublimating in the relatively dry air below the cloud.

These large crystals, though not of dominant radiative importance, do contain most of the cloud water. This means that there will be a strong tendency for the net evaporation to occur at dry levels below the cloud and near cloud base, i.e. displaced downward from levels where the ice is radiatively active. To account for this tendency in a simple way, the cloud pumping effect has been recalculated for the case where cloud water falls at constant velocity before sublimating instantaneously. Typical crystal settling speeds are of the order of 1 m s\(^{-1}\) [Starr and Cox, 1985a], which over 12 hours would drop the cloud right out of the troposphere, but individual crystals do not last as long as the entire cloud since water is recycled multiple times in cloud updrafts. Thus a simple cloud fall distance of 2 km has been chosen, starting 1 km above the nominal cloud height. This choice is equivalent to ~4% of the crystal sinking rate over 12 hours. A more sophisticated model with full microphysics would be necessary to explore these effects more realistically, particularly since the radiative effect being simulated here is essential in maintaining the cloud against natural dessication.

The result of a downward sinking cloud is shown in Figure 10. The main difference from the original calculation, aside from a vertical smoothing of the effects, is that sublimation of the cloud ice only increases the mean RH above 700 hPa by 5.2%, compared with 11.7% before, i.e. the pumping
ratio doubles. This is because the sublimated water is delivered at lower levels, where it is less noticeable relative to background amounts. Though excessively idealized to be of much quantitative use, this case conveys some insight as to how cloud settling effects may further enhance the relative importance of cloud radiative effects.

7. Observational Evidence

The results suggest that the moistening tendency with time in the presence of clouds should be significantly greater than what can be accounted for by hydrometeor evaporation alone. Here we attempt to test this with observations.

Though many studies document the moistening tendency in one way or another, observations recently published by Soden [1998] are particularly apt for this purpose, though requiring a bit of further analysis. He obtained a mean drying rate of $d \ln(UTH)/dt \approx -0.01 \text{ h}^{-1}$ for columns tracked in the tropical Atlantic region, where UTH represents a vertical average of the relative humidity weighted mainly between 500 and 200 hPa. This result is reproduced in Figure 11. The plotted magnitudes are rather uncertain due to the nature of the study, since the humidity retrievals probably suffered from contamination effects to some degree. It is somewhat encouraging that the gap between the two curves in Figure 11, the key quantity here, varies relatively little with latitude compared with either the clear or overall drying rates themselves. Though highly variable with latitude, the average clear sky drying rate was approximately equivalent to the expected sinking associated with known net radiative cooling rates.

At all latitudes, the drying rate found by Soden [1998] was reduced when cloudy pixels were included in the average. This reduction was $\sim 0.005 \text{ h}^{-1}$ north of $5^\circ$N, where the frequency of cloudy scenes was $\sim 30\%$; but was only $\sim 0.002 \text{ h}^{-1}$ from $20^\circ$S to $5^\circ$S, where cloudy scenes occurred $\sim 10\%$ of the time. We may conclude from this that the cloudy scenes themselves experienced $\sim 0.015 \text{ h}^{-1}$ less drying than the clear ones, enough to more than cancel out the clear sky drying rate itself. In order to balance subsidence drying at all levels from 200 to 500 hPa, the moisture source causing this difference would have to be 700 g m$^{-2}$ d$^{-1}$ between these levels (this result and others in this section are obtained using sounding data described in section 2). It must be noted that in that study, no retrievals were possible in overcast conditions, so the "cloudy" scenes were probably dominated not by big convective systems or precipitating anvils but by nonprecipitating, broken cirrus and/or mixtures of the outer portions of thick anvils and clear sky. It is possible though that a few of the scenes contained active convection, which would have provided an unknown, additional source.

Away from deep cumulonimbus towers, the rate at which a cloud can supply moisture to its environment (in a Lagrangian sense, moving horizontally with the hydrometeors) is just the ratio of its total water content to its dissipation lifetime. If we take the dissipation time to be 3-12 hours, the cloud's IWP above 500 hPa would have to be 100-400 g m$^{-2}$ or so to supply 700 g m$^{-2}$ d$^{-1}$.

Cirrus is believed to become optically thick (thus obscuring water-vapor retrievals) at an IWP in the neighborhood of 20 g m$^{-2}$ [Stephens, 1980]. If the parameterization of IWP versus temperature obtained by Stephens et al. [1990] is integrated from 500 to 200 hPa, the result is 190 g m$^{-2}$; this assumes that the entire layer is always filled with cloud in any cloudy pixel, which makes it a rather distant upper limit. Sheu et al. [1997] report that 60% of nonprecipitating stratiform cirrus clouds (their cloud class 8) have IWP < 50 g m$^{-2}$ (though it is possible that some precipitating cirrus clouds were present in the cloudy scenes of Soden [1998], only a small fraction of their water content would be evaporated into levels above 500 hPa, since most would precipitate to lower levels or the surface.) Thus it appears that pumping ratios of 3-10 are required to reconcile the observations of ice content and moistening tendency.

8. Conclusion

Cloud layers have a well-known tendency to modify the radiation field in such a way as to decrease the net cooling below, and usually inside, the cloud. This paper investigates the implications for the water budget of columns containing cirrus clouds. The results demonstrate that as long as they are not too optically thick, cirrus clouds operate efficiently as vapor "pumps" for the column, and fairly efficiently for the cloud levels themselves if placed above 300 hPa.

The pumping ratio of a cloud, or ratio of advected vapor...
to cloud water content, depends primarily on cloud ice water path for optically thick clouds and particle effective radius for thin clouds. This ratio also depends on cloud height. Typical ratios are 1-1000 when measured in terms of column precipitable water (PW) above 700 hPa and 0.1-10 when measured in terms of pressure-weighted, column-averaged relative humidity (RH). The former is larger due to radiative heating below the cloud which, though small, is able to import relatively large amounts of water into the column due to the exponential increase of vapor available in the environment as one approaches the surface. Solar absorption is shifted upward by cirrus, thereby reducing the PW ratio and increasing the RH ratio relative to what they would be without solar radiation, but cloud forcing is dominated by infrared radiation for most cirrus. The RH ratio is maximal for clouds near 200-300 hPa due to the moisture and temperature lapse rates.

It is not clear how much of the actual cloud in the tropics is well described by the model, but RH pumping ratios of 3-10 or so for overall cloud conditions would explain the discrepancy between existing estimates of upper tropospheric moisture tendencies in cloudy columns and the anticipated ability of clouds to moisten their environment by sublimation. These ratios are consistent with the range of values found here with reasonable cirrus parameters. Furthermore, the importance of the cloud pumping effect continues below 500 hPa, where no significant cirrus moistening occurs except from precipitating anvils.

The conclusion is that cloud moistening by sublimation is likely to be small compared to the effects of the atmospheric circulation in redistributing vapor, even away from areas of latent heat release. This is important to keep in mind when attempting to interpret observed correlations between clouds and water vapor (or its rate of change) in the upper troposphere. Not all the positive vapor anomaly to be found near a convective system is vapor added to the troposphere by the system, since the pumping mechanism adds no vapor in total but simply redistributes it toward cloudy regions. Another relevant factor is the possibility that high humidity levels enhance cloud development or longevity.

Though fresh outflows in the immediate vicinity of towering cumuli do contain a significant amount of condensed water, this water is being cycled through a number of processes, including precipitation, in an environment that is already near saturation at all levels in the free troposphere. One does not have to travel far from these systems (of order 102 km) before the clouds' ice contents and optical thicknesses have dropped enough for their indirect, radiative effects on hydrology to dominate their direct ones. This probably explains recent findings [Pierrehumbert, 1998; Salathé and Hartmann, 1997; Sherwood, 1996] that quantitatively accurate water vapor distributions in the tropics can be simulated on the basis of advection without any vapor sources outside the immediate vicinity of convectively active areas. Sherwood [1996] also found that outgoing longwave radiation (OLR) values below 220 W m⁻² were associated with near saturation of vapor throughout the free troposphere, while even the "moderate" cirrus cloud considered here was able to depress OLR to 162 W m⁻². Though OLR is mainly a function of cloud top height, the comparison suggests that as one proceeds away from a convective source in the tropics, cloud outflows become thin enough to achieve high pumping ratio well before attainment of the reputed state in which a cirrus layer moistens an otherwise "dry" free troposphere.

Clouds located above 300 hPa experienced enough net heating to import vapor equal the cloud's ice content into the cloud layers in a time much shorter than the apparent lifetime of such a cloud. This implies that in a typical thin cirrus cloud, removal of water by microphysical or other processes not included here must balance supply by pumping, in a quasi-steady state. If cloud optical depth fell too low, however, this mechanism would fail since cloud radiative forcing would not overcome clear-sky cooling, and the cloud would probably dissipate rapidly. Such clouds could thus be destroyed by transient sinking/warming episodes or by being sheared so thin by winds that they fell below the critical optical depth. Cloud particles that are small enough should actually be carried upward by the radiatively driven updraft and might reach the stratosphere before finally sublimating, if they maintained sufficient optical depth. Above 150 hPa, the atmosphere heats radiatively even without clouds, making this easier. Circulations driven by these clouds could play a role in troposphere-stratosphere exchange. Some of these issues are discussed by Jensen et al. [1996].

The conclusions of this study are based on the simplest reasonable model of an upper tropospheric cloud and its dynamical interaction with the greater environment. A much more complicated model, including ice microphysics, would be necessary to explore more fully these interactions and the mechanisms that govern cloud maintenance and dissipation. Such a model would be able to account for the fact that all processes act simultaneously, with timescales that are not completely separated, as was assumed here. Cloud models that have appeared so far have not been able to combine the detailed microphysics and large spatial coverage necessary for this task.

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References


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