Direct vs. indirect effects of tropospheric humidity changes on the hydrologic cycle

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Abstract. Abundant evidence indicates that tropospheric specific humidity increases in a warmer atmosphere, at rates roughly comparable to those at constant relative humidity. While the implications for the planetary energy budget and global warming are well recognised, it is the net atmospheric cooling (or surface heating) that controls the hydrologic cycle. Relative humidity influences this directly through gas-phase radiative transfer, and indirectly by affecting cloud cover (and its radiative effects) and convective heating. Simple calculations show that the two indirect impacts are larger than the direct impact by roughly one and two orders of magnitude respectively. Global or regional relative humidity changes could therefore have significant indirect impacts on energy and water cycles, especially by altering deep convection, even if they are too small to significantly affect global temperature. Studies of climate change should place greater emphasis on these indirect links, which may not be adequately represented in models.
1. Introduction

Water vapour exerts a strong and well-known greenhouse effect, warming the planet by reducing outgoing longwave radiation (OLR) and absorbing some near-infrared sunlight. It is anticipated that changes in global specific humidity in different climates will be proportional, at least roughly, to changes in the saturation specific humidity as given by the Clausius-Clapeyron equation. This is equivalent to anticipating zero or small changes in relative humidity $R$, the ratio of actual and saturated specific humidities. The result is a strong positive feedback on global temperature.

Simulations by General Circulation Models (GCMs) show some regional changes in relative humidity as climate warms [1, 2]. However, these have little net impact on top-of-atmosphere radiation [3] because they are small and/or have opposing sign in different parts of the atmosphere. There is now abundant observational and theoretical evidence to support, at least approximately, the predicted global- and tropical-mean increase in water vapour and subsequent feedback on global climate [4]. Humidity fields in the real atmosphere, however, do have structure on much smaller scales than represented by GCMs, including filamentary structures from large-scale transport [5, 6] and variations associated with localised convection. Thus the details of model-predicted relative humidity change may still be inaccurate. But given the evidence supporting the water vapour feedback, do we care about these details? This paper presents some simple calculations showing that we should.

Water vapour affects climate in ways other than by restricting OLR. For example, tropospheric radiative cooling is mainly from water vapour, as carbon dioxide (for example) and ozone contribute mostly to heating and cooling in the stratosphere. Models predict that global-mean rainfall will increase by roughly 2% per K of global-mean temperature rise [7]. This outcome is driven by the upward shift in the distribution of where emission to space occurs, which increases the necessary upward transport by other means (mainly evaporative) at and near the ground and hence an overall intensification of the hydrological cycle. The prediction has been challenged by recent observations showing significantly stronger intensification of the hydrologic cycle [9, 10]. Since atmospheric temperature equilibrates rapidly, energy conservation requires that if this observed strengthening is correct it must have been balanced by increased radiative cooling of the atmosphere. Such cooling could have been affected directly, and independently of temperature increases, by climate forcings such as greenhouse gas increases or changes in aerosols [8, 11]. Its response to warming could also be wrong in models, if the models do not predict water vapour and cloud changes correctly.

The above argument applies only to the global mean hydrologic cycle, but regional changes in precipitation are probably more important. Horizontal transports of water vapour concentrate rainfall in certain areas and times; when specific humidity increases, the rainfall is correspondingly expected to become more concentrated and episodic [12, 13]. Also, warming or other influences can shift climate zones such as mid-latitude storm tracks [14], thereby affecting regional precipitation, but the response of precipitation may be sensitive to that of the water vapour that supplies moisture for precipitation.

This raises several questions. First, how little do we actually expect relative humidity to
change globally or regionally at various altitudes, and how uncertain are these predictions? Second, if relative humidity did change significantly in a warmer climate, would this significantly affect the water and energy cycles? Third, how do the indirect impacts of humidity via its influence on clouds or precipitation compare to its direct gas-phase radiative effects?

2. Predicting humidity change

The Planetary Boundary Layer (PBL)—the lowest 2 km or so of the atmosphere—is in frequent contact with the surface and typically has a relatively uniform vertical profile of conservative quantities (particularly, the liquid-water potential temperature $\theta_l$ and the total water mixing ratio $q_t$ [15]). The relative humidity in this layer is widely expected to remain fairly stable under climate changes, at least over oceans, because significant changes in its humidity would drive unsustainable changes in surface evaporation [16].

Above the PBL it has been less clear what controls humidity [17]. The air there is not always in frequent contact with the surface, its specific humidity is highly nonuniform, and relative humidity often reaches values near 1% or less. Upward transport of water vapour occurs almost entirely inside clouds, which are very small compared to the scales resolved by GCMs and host a complex array of microphysical processes (this is strictly true also in much of the PBL, but the transport and the resulting humidity field are more homogeneous). This suggests that prediction of humidity could be a challenge, and that the connection between humidity and temperature may not be as tight as in the PBL.

Nonetheless, diagnostic calculations show that global humidity fields above the PBL (including the stratosphere) can be predicted surprisingly accurately by an advection calculation that includes condensation of supersaturated vapour, even when only winds at very large scales are used [18, 19]. In particular these calculations do a very good job of reproducing the observed dry tail of the tropospheric relative humidity distribution, which is crucial to the radiative effects of water vapour [20]. These calculations show that the specific humidity at any given point is indeed directly controlled by temperature, but it is the temperature somewhere else—namely where the air was last saturated. Since the troposphere warms everywhere, this goes a long way toward explaining why relative humidity might not change much. It does, however, open the possibility of increases in relative humidity as climate warms, if winds or temperature patterns change so as to close the gap between the “dehydration” and final air temperatures—or the opposite if they do the reverse. The few studies that have examined this [17, 2, 21] suggest that changes to the circulation and to the temperature distribution may both be important, and may have partly cancelling effects on global-mean humidity.

A common pattern of relative humidity change occurs in nearly all GCMs when simulating a warmer climate, shown in Fig. 1. The largest changes occur where the current climate shows strong gradients in $R$, with reductions in $R$ on the poleward flanks of the subtropical dry zones, and increases near and just above the tropopause. These changes are qualitatively consistent with dynamically driven poleward shifts of major circulation features, and radiatively driven
lofting of the tropopause, that have been reported in GCMs [22, 23]. The poleward shifts are not yet fully understood; moreover, the subtropical $R$ changes in particular are too large to be fully explained this way and involve deepening of $R$ minima, perhaps because the regions where air is dehydrated do not warm as fast as those where the air arrives [2]. These $R$ changes are everywhere too small to change the rate of increase in precipitable water by more than $\pm 20\%$ or so.

Given that the predicted warming pattern in GCMs at least roughly resembles that in recent observations [24], if large-scale winds are well resolved, the changes in $R$ should be reasonably simulated. While this cannot be confirmed, models successfully simulate humidity changes during natural climate variations [4], and all recently reported trends of column-integrated water vapour from various observing systems are upward as expected [18], as are humidity trends in the upper troposphere [25] when averaged globally.

The meridional pattern of zonal-mean trend in upper-tropospheric $R$ since 1979 closely resembles that predicted by GCMs under warming, but the amplitude of change is several times greater [2]. This is likely related to other observations showing that climate zones are shifting poleward faster than in simulations [26, 27]. It is possible that non-warming effects such as ozone depletion have accelerated observed trends, or that model circulations are insufficiently temperature-sensitive. This fascinating problem has serious implications for weather and hydrology in regions of large change, and is justifiably receiving increased attention.

### 3. Radiative effects of tropospheric humidity on the atmospheric energy budget

Connections between humidity and energy are fundamental in shaping the state of the atmosphere. For example, the $R$ profile predicted by most GCMs (and that seen in observations) has one peak near the surface and another somewhat below the tropopause (that for the National Center for Atmospheric Research (NCAR) CCSM GCM is shown in Fig. 2a). Energy and mass conservation considerations show that the upper peak must occur slightly below the location where the radiative cooling of the atmosphere (Fig. 2b) decreases most sharply with altitude; this is because the horizontal divergence field, which ultimately determines the altitude of peak storm outflow, is determined by the vertical heating gradient [28]. When the opacity of the atmosphere increases due to the increase of greenhouse gases (especially water vapour), the cooling profile shifts upward, hence the height reached by convection and the peak in relative humidity do also [29]. Thus do we expect storms to reach higher in a warmer climate. The reason most often given for this—that warmer and more humid air near the surface drive stronger storms—applies to geographic variations of convection in today’s climate, but does not apply to global warming [30].

Since tropospheric humidity alters the vertical radiative transports of energy, we expect relative humidity variations to influence convection, the general circulation, and the water cycle. Figure 2 shows how radiative cooling is affected by some candidate changes to relative humidity: a modest increase throughout the troposphere, and substitution of that from another GCM (the HadCM3). Each of these perturbations to humidity is much larger than simulated
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by any GCM under a doubling of CO$_2$. The calculations are performed using the CAM column radiation model and the mean simulated atmospheric state from CCSM.

While thin dry or moist layers can significantly influence radiation locally [31], the changes shown here from broad-scale perturbations are surprisingly modest when averaged over the troposphere. The change having the largest impact on total atmospheric cooling is substitution of the HadCM3 $R$ profile. Its substantially drier upper troposphere increases emission to space, while the moister lower troposphere increases the emission to the surface. Despite this, the net power lost by the atmosphere only increases by 3%, equivalent to what happens with about 1.5 K of warming. The impact of a modest but monotonic increase in $R$ is even smaller. Thus, $R$ would have to be radically sensitive to global mean temperature for its direct radiative effect to significantly alter the global hydrologic response to warming. A similar situation holds for the water-vapour feedback: saturation specific humidity increases so strongly with temperature that rapid global changes in $R$ would be needed to significantly change the feedback.

4. Humidity and clouds

Humidity influences cloud development, and clouds have large impacts on radiation. How important is this indirect pathway for humidity to influence the water and energy cycle?

GCMs have long predicted changes in global cloud cover that (at least in the zonal mean) closely resemble those of the changes to relative humidity, and sensitivity tests show that the cloud changes are caused by those of humidity and not vice-versa [1]. This connection persists in recent models and appears to contribute significantly to feedbacks from mid-latitude clouds [2].

This is not surprising because most GCMs predict cloud cover directly from relative humidity, although they may take other factors into account too. A particular location in the atmosphere will be either cloudy or clear depending on whether $R$<1 or not, but when we average over finite volumes, we encounter intermediate cloud fractions and the relationship with humidity becomes uncertain. Typical parameterisations for GCM grid boxes (order 100km) have grid-mean cloud cover approaching zero at grid-mean $R$ below roughly 70%, and have it approach 100% as $R$ approaches 100%[32, 33], a relationship supported by cloud-resolving models [34]. Similar relationships are found in observations; they may be less tight than those assumed in models [35], but inevitable errors in the observations will cause the strength of correlations to be systematically underestimated.

4.1. Comparison of radiative impacts

Clouds have variable optical depth, but most (e.g., easily visible ones) are opaque to infrared radiation. We define an “effective cloud cover” $\sigma_e$ as the fractional coverage of perfect absorber that would have most nearly the same radiative effect as the actual distribution of clouds. If $R$=0 everywhere in the atmosphere, then cloud cover would be impossible and we would have $\sigma_e$=0; if $R$=100% everywhere, then all air would be cloudy and assuming
realistic cloud water contents we would expect $\sigma_e=100\%$. Thus, assuming some continuous relationship $\langle \sigma_e \rangle = f(\langle \mathcal{R} \rangle)$ exists for large-scale mean quantities, its average slope over the interval $[0,1]$ must be unity. Of course this relationship is likely nonlinear; a range of $\langle \sigma_e \rangle$ may be consistent with a single value of $\langle \mathcal{R} \rangle$; and the impact of a change in mean $\mathcal{R}$ will depend on how the change is distributed. But for our exploratory purposes it seems reasonable to expect $d\sigma_e/d\mathcal{R} \approx 1$ on average over a broad range of relative humidity and cloud conditions, at least as a zeroth-order estimate.

Fig. 3 therefore compares the impact of equal changes in $\sigma_e$ and $\mathcal{R}$ at various levels in the troposphere. The impact of changes in $\sigma_e$ is largely governed by cloud top height: high clouds heat the atmosphere by reducing OLR and slow the hydrological cycle, by up to 100 W m$^{-2}$ or more for a 100% change ($\sim$ 1 W m$^{-2}$ per %), while low clouds cool the atmosphere by increasing downward surface emission. By contrast, changes to $\mathcal{R}$ amount to at most 0.4 W m$^{-2}$ per %, and this only for layers with bases near the surface and tops near mid-troposphere which maximises the net cooling and enhancement of the hydrological cycle. The most common clouds above the PBL have tops somewhat below the tropopause and bases somewhere in mid-troposphere [36], for which a 1% increase in $\sigma_e$ has roughly 10 times the impact as a 1% increase in $\mathcal{R}$. This ratio varies substantially for other geometries; it is less than unity for layers extending from near the surface to mid-troposphere (e.g., some cumulus congestus), but very high for upper layers (e.g., thick cirrus). Overall though, for the most common cloud geometries, the cloud impact usually exceeds that of vapour by a factor of at least three and usually closer to 10 or more.

These calculations neglect the presence of any clouds outside the layer, which provides an upper bound on the radiative impact. Since this will have similar effects for both the cloud and humidity perturbations, it should not significantly affect the ratios quoted. Changes to solar radiation have also been neglected, as they are very small in the atmosphere due to the relatively small amount of additional solar absorption by additional clouds or water vapour.

4.2. Humidity impact on convective heating

In addition to affecting (mainly stratiform) cloud coverage and radiative forcing, relative humidity also affects storm development and therefore latent heating of the atmosphere. The latent heat released is directly proportional to rainfall generated. Observations show that rainfall correlates tightly with average $\mathcal{R}$ through the troposphere, increasing from near zero when mean $\mathcal{R}<50\%$ to roughly 30 mm/day ($\sim$900 W m$^{-2}$) for $\mathcal{R}$ near 80% [37]. This relationship results from a mutual interaction between convection and humidity, and therefore cannot automatically be accepted as a causal one where humidity controls convection. However, there is overwhelming evidence of a strong positive influence of humidity through most of the troposphere on convective development under most circumstances [18]. Numerical simulations of precipitating storms in which humidity fields are imposed externally show a $\mathcal{R}$-rainfall relationship essentially identical to that observed [38], indicating that the observations can be explained to leading order as resulting entirely from $\mathcal{R}$ impacts on convective development. The implied heating sensitivity, of order 10 W m$^{-2}$ per % of $\mathcal{R}$, is at least an
order of magnitude larger than the indirect cloud-mediated radiative effect of humidity, thus
two orders of magnitude larger than the direct effect of the humidity anomaly on atmospheric
cooling.

Note that convective heating is part of the hydrologic cycle, unlike radiation which drives
the hydrologic cycle. Thus changes to $R$ cannot alter the global-mean convective heating
through a non-radiative mechanism. They can, however, shift convective heating and rainfall
from one region to another. Cloud-induced perturbations to atmospheric heating are already
leading-order drivers of the atmospheric diabatic circulation [39, 40]; while this provides an
avenue for regional $R$ changes to influence circulations and therefore rainfall patterns, our
results show that the more direct impact of $R$ on convective development should produce far
stronger responses.

5. Conclusions

Recent GCMs predict relative humidity changes of as much as 2-3% per $K$ at some latitudes and
altitudes above the PBL; actual changes could be larger if (as suggested by some observations)
models are underpredicting the spreading or intensification of climate zones. While the impact
of these changes on the planetary energy budget or atmospheric cooling each appear to be
small, their indirect effects on the latter can be much larger. By increasing cloud amount,
a small change in relative humidity can decrease net infrared atmospheric cooling by about
an order of magnitude more than it does through gas radiative transfer effects; by facilitating
more convection, it can increase convective heating by roughly two orders of magnitude more
than the direct effect. All effects are in the same direction. The convective heating effect, of
order $10 \text{ W m}^{-2}$ per % of $R$, would imply substantial regional changes to precipitation and
atmospheric heating in belts where relative humidity changes, although it cannot independently
alter the global hydrologic cycle.

An implication of these results is that unless relative humidity changes in ways far
exceeding those predicted by climate models, it will not change enough to significantly alter
directly the predicted changes in the global hydrological cycle. However, indirect effects on
cloud cover are a more plausible avenue by which atmospheric moisture could alter the rate at
which the atmosphere cools.

These simple calculations highlight the importance of understanding better what controls
relative humidity throughout the troposphere, even if changes in this quantity appear to be small
in GCM simulations and do not affect the water vapour feedback significantly. The calculations
also suggest that systematic changes to humidity that are too small (a few percent) to resolve
with current observational capabilities [41] may have large impacts on clouds and rainfall,
emphasizing the need for better observations. Finally, there is an imbalance between the
strength and evident importance of these relationships, and the crudeness of their representation
in models. Cloud fraction is still usually diagnosed from humidity using empirical rules. The
influence of free-tropospheric humidity on GCM convection schemes is unrealistically weak
[38], and this may be noticeably affecting simulated climate [42]. Such matters probably need
much more attention if regional climate simulations of the future are to become more reliable.
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**Figure 1.** Mean $\mathcal{R}$ from 18 CMIP3 (Coupled Model Intercomparison Project) GCMs (shading) and the change in $\mathcal{R}$ per K of warming (contours) calculated from the difference at time of CO$_2$ doubling in the 1%/yr CO$_2$ increase runs using 10-year means. $\mathcal{R}$ ranges from nearly zero (lightest shading) to roughly 90% (darkest shading); solid contours show regions where $\mathcal{R}$ increases with warming, and dashed show regions of decreases.

**Figure 2.** (A) Global mean relative humidity of the CCSM GCM (solid), this profile arbitrarily moistened by adding 0.67$\mathcal{R}(1-\mathcal{R})$ (dashed), and the $\mathcal{R}$ profile of the HadCM3 GCM (symbols). (B) the thermal cooling of the atmosphere calculated for each of these $\mathcal{R}$ profiles using the global-mean temperature profile from CCSM and the CCSM3 radiation code (the solid curve closely matches the global-mean cooling profile from the CCSM simulation, not shown, except for modest differences near the tropopause). Numbers given at top and bottom refer to the change in OLR (top) or net downward longwave radiation at the surface (bottom), in W m$^{-2}$, for each of the two alternative $\mathcal{R}$ profiles relative to that for CCSM humidity; their sum is the change in net atmospheric cooling.
Figure 3. Impact on atmospheric thermal cooling (in W m$^{-2}$) per 100% change in (top) effective cloud cover $\sigma_e$, (middle) relative humidity $R$, and (bottom) their ratio, as a function of the top and bottom of the humidified or cloudy layer. Dashed lines denote negative values (slowing of hydrological cycle); note change in contour interval from 20 W m$^{-2}$ for cloud to 10 W m$^{-2}$ for vapour. Only ratios of 100 or less are contoured, and light/medium shading indicates ratios exceeding 3 or 10 respectively. Changes per 100% $R$ are computed by rescaling linearly from a 5% additive perturbation to $R$. 