Some uncertainties with respect to water vapor’s role in climate sensitivity

Richard S. Lindzen
Center for Meteorology and Physical Oceanography
M.I.T., Cambridge, MA 02139

1. Introduction

Given the preponderant role of water vapor in the radiative budget of the troposphere (both through its direct effects on both short and long wave radiation, and through its ability on saturation to form stratiform clouds which are not only important in the infrared but are also the primary determinant of the Earth’s albedo), it is clearly futile to deal with climate change without a sound knowledge and understanding of the behavior of this vital substance. It is equally clear, that our present knowledge of the behavior of water vapor is inadequate to the task. In this paper, I wish to focus on two distinct, but closely related areas of

---

1 This is the text of an invited lecture presented at the NASA Workshop on the Role of Water Vapor in Climate Processes, October 29 - November 1, 1990 in Easton, Maryland.

2 There is a peculiar tendency to reject this claim in the recent IPCC Scientific Assessment (Houghton, et al, 1990). The Executive Summary expresses certainty that "The main greenhouse gas, water vapor, will increase in response to global warming and further enhance it." An ambiguously phrased paragraph on page 48 might suggest to the unwary reader that for the current atmosphere water vapor provides 60-70% of the greenhouse warming while carbon dioxide provides 25%, rather profoundly exaggerating the role of CO₂ vis a vis water vapor. Perhaps the most ludicrous example comes from the discussion of feedbacks in Chapter 3 (Processes and Modelling). In listing feedbacks, water vapor is not even mentioned -- rather, it is referred to as ‘No cloud or snow-ice.’ Moreover, by listing responses rather than feedbacks, and including water vapor first, they make it appear that the effect of the anonymous water vapor is small.

Lindzen: Uncertainties ......
Page 1
uncertainty. The first uncertainty is heat transport. The point here is that the
surface of the Earth is primarily cooled by evaporation and dynamical transport of
heat to higher altitudes and latitudes. It is the infrared opacity above the regions
where the heat is deposited by other transport mechanisms that is of primary
importance in determining the temperature of the surface. Although there is much
uncertainty concerning the dynamic transport (at least in models), there is little
question that the heat is deposited largely in the upper troposphere. This brings us
to what I regard as the second major uncertainty: namely, the response of water
vapor in the upper troposphere to climate forcing. This quantity is essentially
unmeasured at present; moreover, parameterizations used in current large-scale
climate models are clearly wrong on physical grounds.

2. Transport

Central to the possibility of global warming is the greenhouse effect. This
effect, which is due to the fact that the atmosphere is significantly transparent to
visible radiation but blocks cooling by infrared radiation, is responsible for the fact
that the Earth is 33°C warmer than it would be in the complete absence of
greenhouse gases. That said, it must be added that the usual depiction of the
greenhouse effect is profoundly incomplete. A typical example of the usual
depiction is shown in Figure 1, taken from the Policymakers Summary of the
suggests, is that radiative processes are responsible for cooling the surface of the
Earth. This is simply untrue; the surface cools mostly by evaporation, and heat is
carried from the bottom of the atmosphere by mechanical transport which bodily
carries the heat to higher altitudes and latitudes where the greenhouse potential is
much less. This has been understood for almost a century. An example of the
effect of this is seen in Figure 2 taken from Möller and Manabe (1960). Three curves are shown for the vertical profile of temperature (in °K, absolute Kelvin temperature): two are based on the pure radiative picture (including and excluding the infrared properties of clouds); the third includes a crude parameterization of transport (i.e., convective adjustment). What one sees from this figure is that with pure radiative cooling, the surface would have an average temperature of about 350°K; only with transport included is the temperature reduced to the observed 288°K. What happens more generally is illustrated in the accompanying schematic shown in Figure 3. Heat is carried from the tropical lower atmosphere to higher altitudes and latitudes where the infrared opacity is less. It is primarily from the regions above where the heat is deposited that the infrared opacity is important. Thus, without knowing exactly where the heat is deposited, it is impossible to calculate the temperature of the Earth. There are three major components of the transport for purposes of climate: 1) Cumulonimbus convection, 2) The Hadley circulation, and 3) Baroclinic eddy transport. It is well known that none of these processes is accurately simulated in existing large scale models.

A few examples will show the extent of the problem. Figure 4 from Geleyn, et al (1982) compares the heat deposition associated with various parameterizations with a composite observation\(^3\). It is evident that, with the exception of the L/E (Lindzen-ECMWF) parameterization, the parameterizations significantly underestimate the height of heat deposition. In particular, C/A (convective adjustment to the moist adiabat), which is essentially what Arking (1990) used, is particularly faulty. Despite this, Arking found that, on a molecule

\(^3\) The comparison in Figure 4 is not completely consistent. The model results are global averages, while the observations are simply a composite of two tropical analyses. However, this does not alter the fact that the model results for different parameterizations differ greatly in the vertical distribution of heating.
for molecule basis, upper level water vapor was far more important to surface
temperature than lower level water vapor. Figure 5 from Lindzen, et al (1982)
shows response to doubling CO$_2$ from two different convective parameterizations
(C/A and a mechanistic cloud model) in a model where relative humidity was held
fixed at all levels; the response for the mechanistic cloud model was significantly
less.

As concerns other transport processes, it is well known that GCM’s
generally underestimate both the Hadley circulation and the eddy kinetic energy;
they also underestimate polar temperatures. Under the circumstances, one may
reasonably wonder how these models manage to simulate the present globally
averaged temperature of the Earth. The answer, as best I can tell, is that they
don’t. The models are tuned to obtain the correct globally averaged temperature,
and the tuning is usually restricted to radiative parameters. It should be added that
various models have attempted to ‘improve’ the behavior of various defects. The
GISS model uses various forms of friction to increase the intensity of the Hadley
circulation and to reduce equator-to-pole temperature differences. It is
questionable whether these fixes actually address the real problems. Under the
circumstances, the various tuning efforts are likely to actually diminish the ability
of the models to deal with climate sensitivity questions.

Although Hadley circulations and baroclinic eddies are certainly present in
large-scale models, large-scale models are still relatively clumsy tools for studying
processes or for discovering underlying principles. Mechanistic studies of the
physics and parametric sensitivity of the Hadley circulation (viz Lindzen and Hou,
1988), of the role of upper level shear in generating baroclinic eddies (Farrell,
1987; this work contrasts importantly with the traditional emphasis on surface
temperature gradients as in Charney, 1947), and of the possibility of nonlinear

3. Upper level water vapor

Far and away the most important greenhouse gas in the Earth’s atmosphere is water vapor. The downward flux of infrared radiation at the Earth’s surface is about 340 Wm$^{-2}$. Of this amount, 290 Wm$^{-2}$ is due to water vapor and about 40 Wm$^{-2}$ is due to stratiform clouds; the remainder includes carbon dioxide’s contribution. Moreover, as we have just noted, the Earth’s surface does not cool primarily by radiation; rather, it cools mostly by evaporation, and the heat is then carried to the upper troposphere by convection. As a result, it is water vapor in the upper troposphere (above 6 km) that is of primary radiative importance in determining the temperature of the Earth. Unfortunately, current measurements of water vapor between 6 and 9 km are considered totally unreliable, while measurements above 9 km are essentially non-existent.

*Vis a vis* climate, the situation is even more serious. The direct response of most existing large scale climate models to a doubling of carbon dioxide is only about 1°C. Larger responses are due to positive feedbacks, and in all models predicting a large response (2-5°C) to carbon dioxide, the most important feedback is due to water vapor. The response amplification due to feedbacks is given by an expression

$$gain = \frac{1}{1-f} \quad (1)$$

where $f$ is the sum of all contributions to the feedback. In the GISS and GFDL
models, the contributions of feedbacks from water vapor, clouds, and snow/ice are about 0.4, 0.2, and 0.1 respectively. If one shows gain (or response) rather than feedback, and begins with the water vapor feedback -- adding the others sequentially, one gets the impression that water vapor is not important. This, however, is an egregiously misleading way of presenting things. It is clear, from the above equation, that, in the absence of the water vapor feedback, the remaining feedbacks cannot even amplify the direct response to 2°C. As Mitchell, et al (1989) has shown, the cloud feedback may be negative rather than positive. The response is then reduced rather than magnified. The question we need to deal with is whether the water vapor feedback is real.

In present models, the positive water vapor feedback arises from the fact that these models use cumulus parameterizations which increase specific humidity at all levels as temperature increases. Observationally and theoretically, this is correct for the boundary layer; however, in the upper troposphere, we have no observations. We are, therefore, forced to examine the theoretical foundations of the parameterizations used by the models. These parameterizations are of two types: 1) convective adjustment, or 2) Kuo type schemes (Kuo, 1974). The latter is over 16 years old while the former is almost eighty years old. Both have long been known to be grossly inaccurate portrayals of the behavior of cumulonimbus convection (Arakawa and Schubert, 1974, Emanuel, 1990, Geleyn, et al, 1982). Both markedly distort the contributions of deep cumulus convection to both the heat and moisture budgets. In the case of the moisture budget, convective adjustment acts to simply saturate the atmosphere; in order to avoid gross model misbehavior (such as a runaway greenhouse), this is generally reduced arbitrarily to some fixed relative humidity less than 100%. The Kuo parameterizations act to influence the environment by having deep clouds simply mix into the environment at all levels. As Ooyama (1971) and Arakawa and Schubert (1974) noted, this is
not at all the way moist convective plumes behave. Rather, parcels rise rapidly through the convective towers, detraining where they reach neutral buoyancy. Their effects on the environment arise ultimately from the subsidence required outside the clouds in order to balance the upward flow in the clouds. The moisture budget in the Arakawa-Schubert parameterization arises from the fact that the clouds detrain saturated air high in the troposphere where temperatures are so cold that saturation involves minute specific humidities. The subsidence of this air acts to make levels below the detraining levels very dry. I have incorporated this physics into my own cumulus parameterization (Lindzen, 1981, 1988) which has been successfully tested at the European Centre for Medium Range Weather Forecasting (Geleyn, et al, 1982); their current parameterization is of the same type. It should be emphasized that this type of parameterization is far from perfect. In particular, all such parameterizations tend to exaggerate the dryness of the atmosphere between 2 and 6 km (essentially between the trade inversion and 6 km) when they fail to include the effect of reevaporation of falling precipitation.

The question of where drying is actually realized is an important one. As shown in Lindzen (1990), average drying and local drying are two different things. For example, in the neighborhood of the ITCZ there is ascent rather than subsidence and without subsidence to balance detrainment, we actually have moistening rather than drying; only if one averages over ascending and descending portions of the large scale circulation does one find net upper level drying associated with a warming surface. With respect to the seasonal Hadley circulation, we have the entire summer half of the circulation rising (with the most intense rising at the intertropical convergence zone) (Lindzen and Hou, 1988); descent occurs in the winter side of the circulation. Thus we expect the winter side to be drier than the summer half, despite the fact that we expect a net climatological warming of the surface to produce an average drying of the upper
troposphere. Recently, De Zheng Sun (Sun, 1990) and I have been attempting to quantify the effect of cumulonimbus convection on the moisture budget. Assuming an average over an area over which ascent and descent cancel, we use the following one-dimensional equation above the trade wind boundary layer:

\[ M_c \frac{dq}{dz} + \frac{d}{dz} (K_2 \rho \frac{dq}{dz}) - \frac{dM_c}{dz} (q^* - q) + E - C = 0 \]  

(2)

where \( M_c \) is the cumulus mass flux, \( q \) is the specific humidity, \( q^* \) is the saturated value of \( q \), \( K_2 \) is a diffusivity, \( E \) is the reevaporation of precipitation, and \( C \) is the condensation of water vapor. The first term in (2) represents the drying effect of subsidence, the third term represents the detrainment of saturated air from cloud parcels reaching their levels of neutral buoyancy. The meaning of the remaining terms is obvious. In what follows, I will focus on the consequences of a budget involving primarily the first and third terms. A rather arbitrary attempt will be made to accommodate the omission of \( E \) by considering increased values of \( K_2 \).

Warming the surface will affect \( M_c \) in two ways: 1) Detrainment levels will be elevated to higher, colder levels where \( q^* \) is smaller\(^4\); and 2) The magnitude of \( M_c \) may change. Unless one includes the increase in turbulence due to increased evaporation (which, in turn, increases evaporation and \( M_c \)), the second effect is zero to first order. In what follows, we show the affect of item 1).

\(^4\) It might be thought that if the whole depth of the atmosphere warms, the detrainment levels will not be colder. This is not the case, because the moist enthalpy of the ascending parcels depends on both their temperature and their specific humidity in the boundary layer. The latter depends very nonlinearly on temperature (via the Clausius-Clapeyron relation). Incidentally, the detrainment properties of \( M_c \) are determined by the range of potentially buoyant moist enthalpies in the tropical boundary layer. In the present calculation, the magnitude of \( M_c \) doesn’t matter since all the terms (except diffusion) are proportional to \( M_c \). In Sun (1990) -- where the focus was on the Hadley circulation -- \( M_c \) was proportional to average evaporation.
7 show the calculated change in $M_c$ arising from increasing surface temperature 1°C and from increasing the temperature of the whole atmosphere 1°C; the increase of detrainment levels is slightly reduced in the latter case. We next consider the effect of this change for 3 different choices of $K_2$:

$K_2 = 20\text{m}^2/\text{s} \ e^{-(z-2\text{km})/1\text{km}}$, $K_2 = 20\text{m}^2/\text{s} \ e^{-(z-2\text{km})/2\text{km}}$, and $K_2 = 15\text{m}^2/\text{s}$. The distribution of specific humidity for each of these choices is shown in Figure 8. The third case corresponds to using a diffusivity appropriate to the trade cumulus boundary layer throughout the troposphere; not surprisingly, it leads to an atmosphere which is too moist. The first case leads to an atmosphere which is drier than observed between 2 and 6 km; the second case is reasonably consistent with observations at these levels. Figures 9 and 10 show the percentage change in specific humidity for the first choice of $K_2$ when only the surface temperature is increased by 1°C and when the temperature of the whole atmosphere is increased by 1°C. In both cases the upper level drying is profound -- even though integrated water vapor for the whole atmosphere increases. In figures 11 and 12 we show the percentage changes in specific humidity for the remaining 2 choices of $K_2$ -- but only for the case where the temperature of the whole atmosphere increases 1°C. In all cases we continue to find large drying of the upper troposphere. A comparison of our results with Arking's (1990) results for the radiative effects of localized (in height) changes in water vapor (reproduced in our Figure 13) shows that the reductions in specific humidity which we find are capable of significantly counteracting our imposed temperature increases.

At this stage, we do not wish to claim that the above necessarily proves that there will be a strong negative feedback from convectively induced upper level drying. What we do claim, however, is that the quantitative evaluation of terms known to be essential parts of a self-consistent treatment of the water vapor budget leads to drying of a sufficient magnitude to significantly counteract
warming. This is, by no means, a trivial result. We are currently actively improving our complete cumulus parameterization including extensively investigating the role of reevaporation of precipitation (both ice and water), as well as the role of detrained ice crystals. Thus far, we do not find that these modifications alter the fact that higher detrainment levels are associated with drier subsidence. We are also incorporating our parameterization into a variety of models which will consider the moisture budget interactively with radiative transfer and large-scale transport.

Acknowledgements.

This paper was prepared with support from the National Science Foundation under Grant 8520354-ATM, and from the National Aeronautics and Space Administration under Grant NAGW 525.
References


Lindzen, R.S. and B.F. Farrell (1980) The role of polar regions in global climate, and

heating centered off the equator. J. Atmos. Sci., 45, 2416-2427.

choice in calculating the climate impact of doubling CO₂. J. Atmos. Sci, 39,
1189-1205.


Möller, F. and S. Manabe (1961) Über das Strahlungsgleichgewicht der

Pocinki, L. (1955) Stability of a simple baroclinic flow with horizontal shear, AF


general Ph.D. qualifying examination at MIT.
Figure 1: A simplified diagram illustrating the greenhouse effect.
Fig. 2 Radiative equilibrium in the earth's atmosphere.

After Möller and Manabe (1961). (a) —○— Calculations for clear skies. (b) —— —— —— Calculations for 6/10 cloudiness. (c) —— —— ○— Moist-adiabat with same heat content as (b). Conditions correspond to the yearly mean at latitude 40° and a mean $\xi_O = 0.5$. Results were obtained by the matrix method.
Infrared opacity is greatest at the ground over the tropics, and diminishes as one goes poleward and upwards. Air currents bodily carry heat to regions of diminished infrared opacity where the heat is radiated to space.
Figure 4

Heating ($Q_1$) and drying ($Q_2$) vertical profiles, globally averaged over one ten-day forecast at the European Centre for Medium-Range Weather Forecasting, for four convection schemes (Kuo, Arakawa-Schubert, convective adjustment, and Lindzen—ECMWF). On the right are the unscaled averages of the same profiles obtained from the GATE and Marshall Islands experiments by Thompson et al. (1979). From Geleyn et al. (1982).
Table 5. Sensitivities of globally-averaged surface temperatures.

<table>
<thead>
<tr>
<th></th>
<th>6.5 K km⁻¹ adjustment model</th>
<th>Cumulus model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Standard CO₂</td>
<td>Double CO₂</td>
</tr>
<tr>
<td>Climate model</td>
<td>289.38</td>
<td>292.15</td>
</tr>
<tr>
<td>Radiative-convective equilibrium</td>
<td>276.45</td>
<td>278.37</td>
</tr>
</tbody>
</table>

Fig. 14b. Surface temperature increases given by the Hadley-baroclinic climate model for doubled CO₂ content using the radiative-convective cumulus model results.
Fig. 6 Change of the vertical distribution of cloud mass flux when surface air temperature is increased by 1 K. (The perturbation is assumed to be constrained below the height of trade inversion.)
Fig. 7  Change of the distribution of cloud mass flux when the atmospheric temperature is increased by 1 K (The perturbation is constant with height)
Fig 3.8 The vertical distribution of water vapour with different choices of $K_1$ and $K_2$.

- Solid line: $K_1$ and $K_2$ are same as Fig 3.4.3.
- Dense dashed line: $K_1 = 20.0 m^2/s$, $K_2$ decrease with a scale height of $2 km$ from $20.0 m^2/s$ till $1.0 m^2/s$ then keep to be this constant to the tropopause.

- Dashed line: $K_1 = K_2 = 15.0 m^2/s$ all the height.
Fig. 9 Relative change of specific humidity when surface air temperature is increased by 1 K
Fig. 10 Relative change of specific humidity when atmospheric temperature is increased by 1 K. (in percent) (The perturbation is constant with height)
Fig. 11. Relative change of specific humidity when the atmospheric temperature is increased by 1 K. (in percent)
**Fig. 12** Relative change of specific humidity when the atmospheric temperature is increased by 1 K (in percent) (Basic state is the dashed line (longer dash) in Fig 3.4.4)
Figure 13 The change in surface temperature due to a 50% increase in water vapor in a 40mb layer, as a function of the height of the layer.