Climatic implications of the seasonal variation of upper troposphere water vapor

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Abstract. Satellite observations indicate that the humidity of the upper troposphere is higher in summer than in winter. We use general circulation model (GCM) simulations to explore the processes that maintain upper troposphere water vapor and determine its seasonal cycle. In the subtropics, drying by Hadley cell subsidence and stratiform condensation is offset primarily by moistening by eddies, with moist convection playing a minor role. Elsewhere, both mean meridional circulation and eddies moisten the upper troposphere and are balanced primarily by stratiform condensation drying. The effect of the seasonal shift of the Hadley cell is limited to latitudes equatorward of 30°. At higher latitudes where the largest observed summer moistening occurs, eddy moisture fluxes are primarily responsible despite the eddies being weaker in summer than winter. The same mechanism causes upper level humidity to increase in GCM climate warming simulations. The observed seasonal variation may thus be a good proxy for decadal climate change. This suggests that upper troposphere water vapor feedback is positive at all latitudes, consistent with GCM predictions.

Introduction

Predictions of Earth's response to greenhouse gas increases are limited by uncertainties about the climate's sensitivity. The positive feedback due to increasing water vapor concentration with warming is an important feature of all GCM simulations to date. Changes in upper and lower troposphere humidity may be of comparable importance despite the small concentration of water vapor at high altitudes. But whether upper troposphere humidity will increase in a warming climate is controversial because it has historically been poorly observed and because the physical mechanisms have yet to be determined.

Considerable attention in this debate has been focused on the low latitude Hadley cell, particularly its subtropical sinking branch [*Lindzen*, 1990; *Betts*, 1990; *Sun and Lindzen*, 1993]. The fact that subtropical subsidence produces a minimum in relative humidity there [cf. *Soden and Bretherton*, 1994] has no direct implication for water vapor feedback in a climate change. The climate feedback depends instead on the unknown climatic change in the strength of the Hadley cell and in the water vapor gradient that determines its transports [*Del Genio et al.*, 1991]. There is also no particular reason to overemphasize the subtropics, since the feedback at other latitudes is likely to be just as important [*Lacis and Sato*, 1993].

Recent satellite observations of the seasonal variation of upper troposphere water vapor by the SAGE II instrument [*Rind et al.*, 1991] have provided the first clues about the nature of externally forced humidity variations. SAGE II detects dramatically larger water vapor concentrations and slightly higher relative humidity in the summer hemisphere upper troposphere at almost all latitudes, even those within the sinking branch of the Hadley cell (Figure 1 a, b). Interpreting these results is difficult, though. The seasonal cycle is traditionally not considered a good proxy for long-term climate change because it is a hemispherically asymmetric forcing whose impact is assumed to be dominated by the seasonal shift in the Hadley cell. The relevance of this seasonal shift to the climate change problem is certainly questionable.

GCMs with sufficiently realistic physics may be able to successfully reproduce the observed seasonal cycle, and thus be used as a tool to understand the processes which maintain the water vapor balance. We use a recent version of the GISS GCM which has a quasi-equilibrium penetrative cumulus parameterization [*Del Genio and Yao*, 1993] and a prognostic stratiform cloud water budget, including detrainment of water vapor and condensate from cumulus updrafts into anvil cirrus [*A.D. Del Genio et al.*, in preparation, 1994]. The model simulates the small upper troposphere relative humidities (<20%) observed in the subtropics [*Soden and Bretherton*, 1994], and is thus a good candidate in particular to address the issue of maintenance of upper level humidity in the sinking branch of the Hadley cell.

Figure 1 c, d shows the model-simulated seasonal difference in water vapor concentration and relative humidity. The GCM reproduces the major features observed by SAGE II: slightly higher/lower relative humidity in the summer/winter upper troposphere at virtually all latitudes, the shift from a summertime increase in lower troposphere relative humidity equatorward of 30° to a decrease in midlatitudes, and large summer-winter differences in vapor concentration at all altitudes. The largest discrepancies occur near the equator and at low altitude, where SAGE II sampling is extremely poor. SAGE II requires clear skies over hundreds of km to measure the limb extinction of sunlight by water vapor. The probability of obscuration by cloud increases with decreasing altitude, especially near the equator. Combined with the sampling pattern of SAGE II's inclined orbit and the availability of data only at sunrise and sunset, this causes very poor and biased sampling of water vapor at low latitudes and altitudes. (In the tropics, 5 Januarys or Julys of SAGE II data contain typically a total of only 10-20 water vapor profiles per 5° latitude in the upper troposphere, and < 10 below the 500 mb level; few of these occur in regions of frequent deep convection. In the GCM, on the other hand, clear sky water vapor values are always obtained if the cloud cover is < 100%.) At low latitudes, the sign of the simulated seasonal difference is correct but the GCM magnitude exceeds the SAGE II result. Elsewhere in the upper troposphere, where SAGE II sampling is adequate, the GCM correctly simulates both the sign and magnitude (10-500 ppmv and 5-10% relative humidity) of seasonal differences.

Simulated Water Vapor Budget

Since the GCM's seasonality is realistic, we can plausibly use it to understand the processes that regulate upper troposphere water vapor. Four different mechanisms play a role in the moisture budget: (1) The mean meridional circulation moistens/dries the atmosphere in its rising/sinking branches [cf. *Sun and Lindzen*, 1993]. (2) Moist convection moistens the upper troposphere by detrainment of water vapor near the tops of deep cumulus clouds and dries it via compensating environmental subsidence below. (Shallow convection moistening by detrainment occurs in the lower troposphere instead.) (3) Eddies, i.e., deviations from the zonal and time mean, moisten/dry the atmosphere in regions of moisture convergence/divergence. (4) Stratiform cloud condensation/evaporation dries where condensation exceeds evaporation due to precipitation formation, and moistens where evaporation of rain dominates. The eddy term represents all fluctuations resolved by the 4°x5° model grid, including transient and stationary modes and both vertical and horizontal transports. Moist convection, a small-scale process not resolved by a GCM, is parameterized separately. Detrained water vapor from convective updrafts which condenses in an anvil cloud is accounted for as stratiform condensation, while parameterized detrainment of convective ice which evaporates from an anvil or from precipitation is accounted for as stratiform evaporation. We focus on three questions of climatic interest: (1) What is the source of the water vapor in the descending branch of the winter Hadley cell, a region assumed to be devoid of deep moist convection? (2) Why is the summer hemisphere wetter than the winter hemisphere? (3) Is the answer to (2) relevant at all to the question of long-term climate change?

Figure 2 shows the zonal mean contribution of each process to the simulated January moisture budget. There is net drying in the descending branches of the winter Hadley cell and adjoining Ferrel cell (10°-40° latitude), except near the tropopause where there is poleward transport into the 10°-20° latitude region (Figure 2a). (Detrained cumulus ice cannot be advected into the subtropics because its lifetime, determined by the large fall speeds of ice crystals, is much smaller than the advection time scale for the Hadley cell.) Moist convection at these latitudes is primarily shallow fair-weather cumulus, which moisten the trade inversion near 700-800 mb (Figure 2b). But a weak secondary moistening peak due to deep convection exists at upper levels.

How can even sporadic deep convection exist in the descending branch of the Hadley cell? The upper troposphere water vapor issue has been framed in convenient zonally symmetric arguments, but there is considerable zonal asymmetry in the subtropics. Although descending motion is the rule at these latitudes, regions of rising motion and deep convection exist over the warm waters west of Central America and at the southern extremity of the midlatitude storm tracks. Local concentrations of deep convective cloudiness [*Fu et al.*, 1994] and upper troposphere humidity [*Soden and Bretherton*, 1994] are observed at these longitudes. Nonetheless, convection is too weak to offset Hadley cell drying to any significant extent.

The most important moistening source for the upper troposphere, both in the subtropics and at higher latitudes, is large-scale eddies, which transport moisture upward and poleward (Figure 2c). Although transient baroclinic eddies are strongest poleward of the Hadley cell, they transport significant moisture in the subtropics because specific humidity increases dramatically with decreasing latitude. Transport is upward because regions of rising motion along fronts tend to be moist tropical air masses while regions of sinking are drier polar air masses. Added to the transient eddies are subtropical stationary eddies associated with topography and land-ocean contrasts. Stratiform condensation (Figure 2d) is a net drying effect throughout the upper troposphere. It mirrors the dynamics, i.e., clouds form primarily where the circulation converges moisture. The similarity of the spatial patterns of condensation drying and eddy moistening demonstrate that large-scale eddies are the primary moisture source for most of the upper troposphere, including the winter subtropics, while cloud formation is the major vapor sink. This is consistent with Lyman-α hygrometer evidence of hemispheric asymmetry in winter midlatitude upper troposphere humidity, caused by the large-scale dynamics and the different temperatures of Antarctic and Arctic air masses [*Kelly et al.*, 1991]. The GCM reproduces the sense of this asymmetry poleward of 45°, suggesting that the processes controlling water vapor in the model are at least qualitatively realistic.

Figure 3 shows July minus January differences in the same elements of the moisture budget. Equatorward of 30°, the seasonal change in humidity is controlled by the seasonal shift in the location of the rising branch of the Hadley cell (Figure 3a), which moistens all altitudes preferentially in summer. This behavior is irrelevant to long-term climate change in any direct sense. In the upper troposphere, stratiform condensation drying (Figure 3d) balances not only the Hadley cell, but cumulus detrainment moistening (Figure 3a) and eddy moisture flux convergence (Figure 3c) as well. Poleward of 30°, though, seasonal variation in the mean meridional circulation acts either to preferentially dry the summer upper troposphere (30°-60° latitude) or to only weakly moisten it relative to winter. At these latitudes, other processes are responsible for the bulk of summer moistening. Convective detrainment moistening is slightly stronger in summer, but is the dominant summer moisture source only from 30°-40° latitude. Stratiform condensation/evaporation provides increased drying/moistening in summer above and below the 300 mb level. Instead, large-scale eddies are responsible for the summertime increase in upper level humidity, especially poleward of 40°. In other words, the seasonal variation of humidity is determined by a summertime intensification of the processes that maintain upper troposphere water vapor in winter.

Discussion

It is this seasonal variation outside of the rising branch of the Hadley cell that is diagnostic of the behavior to be expected in a long-term climate change. A common feature of seasonal and decadal climate change is that the strength of the eddies themselves declines in the warmer climate because a smaller meridional temperature gradient reduces the available potential energy that drives baroclinic instability. In both cases, although the eddies are weaker, they transport more moisture upward because the vertical gradient of specific humidity is stronger in the warmer climate. The gradient is stronger because the atmosphere's capacity to hold water, determined by the Clausius-Clapeyron equation, increases sharply with temperature, thus causing low-altitude specific humidity to increase more than that in the cold upper troposphere. Therefore, in GCM simulations of climate change, the upper troposphere moistens with warming, due mostly to increased eddy transport [*Del Genio et al.*, 1991]. Given that eddies maintain wintertime upper level humidity in latitudes of Hadley cell subsidence, and that eddies provide positive seasonal feedback even at latitudes where Hadley cell subsidence increases in summer, moistening at all latitudes should be expected as climate warms due to increasing greenhouse gases. Regional decreases in subtropical water vapor cannot be ruled out, but neither can they be expected to be a dominant feature.

The recent development of water vapor lidar systems [*Ismail and Browell*, 1989; *Goldsmith et al.*, 1994] offers hope that upper troposphere moisture budgets may eventually be constructed from data to validate the GCM mechanisms. Nonetheless, the satellite-observed summertime increase in upper level humidity, combined with the behavior of well-known features of the general circulation, suggests that the positive upper troposphere water vapor feedback simulated by all GCMs is at least qualitatively correct as a contributor to long-term climate change.

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Figure 1. Zonal mean July minus January difference in clear sky (a) water vapor concentration and (b) relative humidity observed by SAGE II (adapted from *Rind et al.*, 1991), and (c, d) simulated by the GISS GCM. Both figures represent 5-year means. The pressure scale for the observations extends only down to 700 mb, because SAGE II water vapor data rarely exist at lower levels; there are also few SAGE II data poleward of 60°. SAGE II relative humidity is derived using forecast model temperatures.

Figure 2. Contributions to the zonal mean January GCM moisture budget: (a) Mean meridional circulation; (b) Moist convection; (c) Large-scale resolved eddies; (d) Stratiform condensation/evaporation. Positive/negative contours indicate a moistening/drying tendency. The units (10^{13} W) represent the time derivative of water vapor mass multiplied by the latent heat of condensation.

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