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Vertical correlations of water vapor in GCMs

De-Zheng Sun

Climate Diagnostics Center, NOAA-CIRES, Boulder, CO

Curt Covey

Program for Climate Model Diagnosis and Intercomparison, Lawrence Livermore National Laboratory, Livermore, California

Richard S. Lindzen

Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA

Abstract. Correlations of tropical mean water vapor with its surface values have been calculated for all AMIP1 models and some of the AMIP2 models. The previously noted discrepancy between the GFDL model and rawinsonde data also exists for other models: the interannual correlations of water vapor with its surface values decline to smaller values in observations than in the models. This discrepancy is reduced somewhat after the data from the models were sampled at the same locations where observational data were collected, but remains significant even at low levels. Significant discrepancy between models and observations also exists in the regressions of water vapor on temperature, suggesting something other than differences in the noise level as the main cause for the discrepancy in the vertical correlations between model and rawinsonde observations.

Introduction

Because of the strong temperature dependence of saturation water vapor pressure on temperature, water vapor feedback is potentially the largest feedback that amplifies global warming. Using a one-dimensional radiative convective model, Manabe and Wetherald (1967) demonstrated that the surface temperature with a fixed relative humidity is almost twice as sensitive to CO2 increases as that with a fixed specific humidity. The calculations of global warming by three dimensional general circulation models (GCMs) have generally supported this estimate of the strength of water vapor feedback (Cess el al. 1990). It is not yet understood, however, why estimates of water vapor feedback from three dimensional GCMs are so close to the estimate by the one dimensional radiative convective model in which a constant relative humidity is simply assumed. Noting the penetrative nature of tropical deep convection and its connection with the large-scale circulation, Lindzen (1990) suggested that the upper troposphere may even become drier in response to a surface warming, throwing into the open the question of whether GCMs have correctly calculated the strength of water vapor feedback. The over-simplification of the model for tropical deep convection on which Lindzen's suggestion is based has been recognized (Betts 1990, Sun and Lindzen 1993a,b). It is also clear, however, that it is an assumption that the upper tropospheric water vapor increases with increases in the surface humidity and this assumption has apparently not been fully verified.

Lindzen's argument underscores the fact that deep convection in the tropics creates dry air which can subside thousands of kilometers away from where the deep convection takes place. An example is that the air subsiding in the subtropics may have an origin in the deep tropics. Thus to obtain a relationship between upper tropospheric water vapor and the near-surface water vapor that may be applicable for the global warming situation, one cannot simply consider local relations; averaging over the tropics is more appropriate. In the same vein, one cannot conclude from regional variations of water vapor in the tropics that more deep convection in the tropics should result in more moisture in the entire tropics. This consideration, however, was not fully taken into account in earlier observational studies of water vapor feedback (Raval and Ramanathan 1989, Rind et al 1991).

Using rawinsonde data archived at GFDL (Oort 1983, Sun and Oort 1995) and outputs from GFDL models, Sun and Held (1996) first spatially averaged the specific humidity over the entire tropical domain (30°S-30°N) and then computed interannual correlations with the surface value. They did not find a negative correlation between variations of water vapor in the upper troposphere with the variations at the surface. They noted, however, that the correlations of water vapor, averaged over the entire tropics (30°S-30°N), decrease to much smaller values in observations than in the GFDL model. Similar differences were also noted in data-rich regions, leading them to conclude that it may be prudent to suspect significant errors in the model physics.

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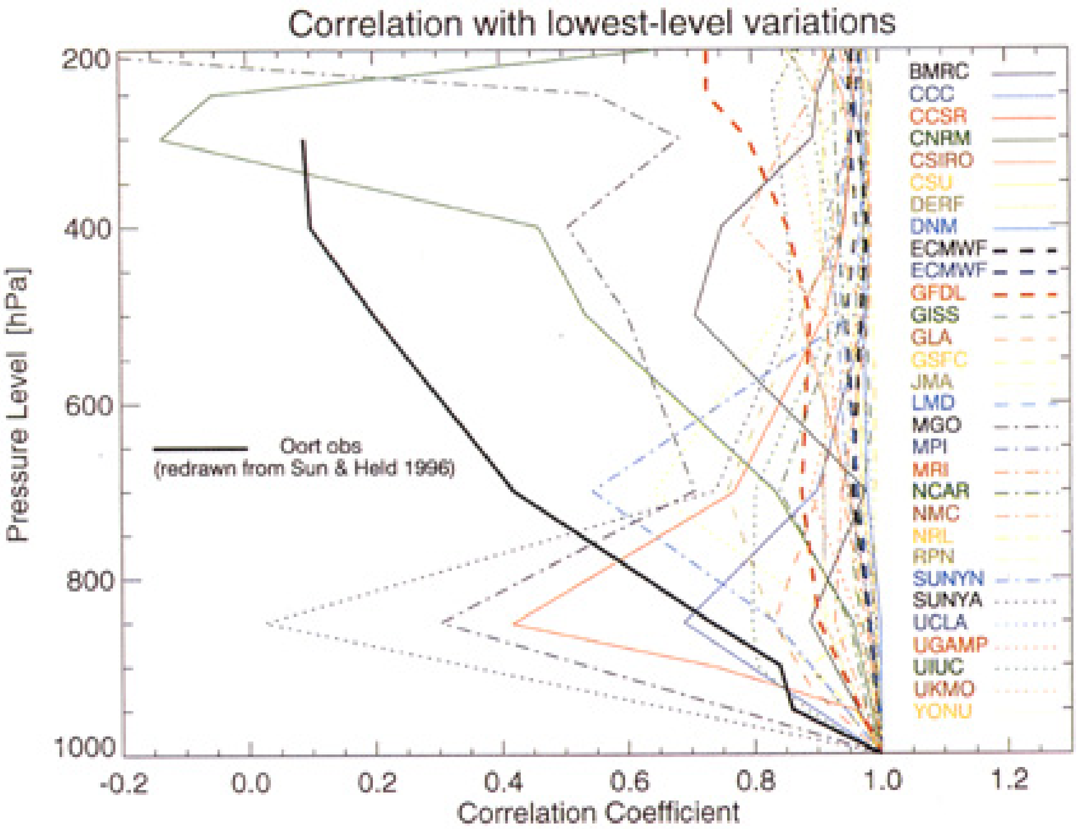

Figure 1. Correlations between interannual variations of tropical mean specific humidity (30°S-30°N) and those at the lowest model level (as in Fig. 9 of Sun and Held (1996)) for the AMIP1 models. The thick red dashed line represents the GFDL R30 model run contributed to AMIP1. It is similar to (though not exactly the same as) the GFDL model results shown by Sun and Held (1996). The thick blue and black dashed lines represent two runs of the ECMWF model with different initial conditions. Definition of the acronyms for the GCMs and their documentation can be found at http://www-pcmdi.llnl.gov/amip/AMIP1/AMIPgroups.html.

In particular, they noted that the convective adjustment scheme, by saturating the adjusted column and ignoring meso-scale circulations, may have exaggerated the coupling between the upper tropospheric water vapor and near surface water vapor. They also mentioned that given the exponential decrease of specific humidity with height, numerical diffusion resulting from vertical truncation may also be a significant source of error. They cautioned, however, that the discrepancy between the model results and observations could also be partly due to the poor spatial coverage of the rawinsonde data.

Results from the AMIP

In the present note, we extend the study of Sun and Held (1996) on two fronts. First, we address the question of whether the vertical correlations of water vapor are also high in other GCMs. Second, we address the question of whether the model-data discrepancy noted earlier could be due to the insufficient sampling by the rawinsonde network. (As noted in Sun and Oort (1995), the rawinsonde stations over the equatorial eastern Pacific are sparse. Consequently, the interannual anomalies of specific humidity can be substantially underes-

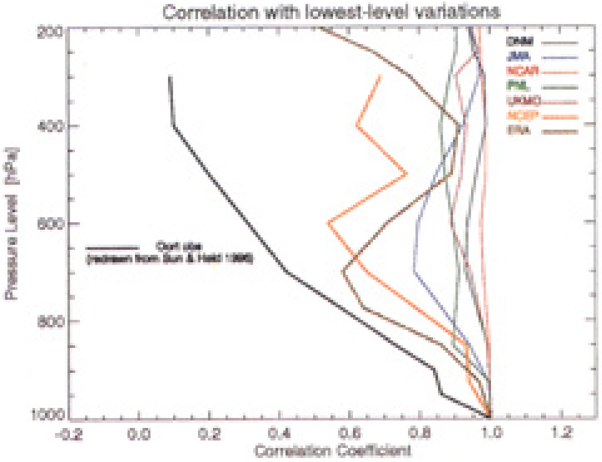

Figure 2. Same calculations as in Figure 1, but for the first five sets of model output available from AMIP2. "Observations" from the NCAR/NCEP and ECMWF ('ERA') reanalyses are also shown. To facilitate comparison with the Oort dataset, which ends in 1989, both model and reanalysis output have been processed for the AMIP1 period 1979-1988. Extending processing to the full AMIP2 period (1979-1995) makes no appreciable difference in these results.

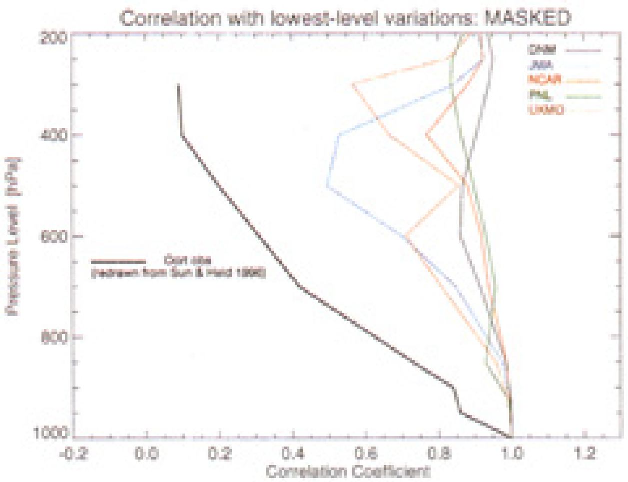

Figure 3. Same calculations as in Figure 2, except that the model data are sampled at the same locations where the Oort's data were collected. The number of rawinsonde stations reporting data during the AMIP1 period 1979-1988 in each 5°x5° grid box was first obtained. Grid boxes with an average reporting number less than 0.1/month were omitted in obtaining the tropical average of the specific humidity. The number of reporting stations per month is typically either zero or 1. This procedure effectively leaves out the eastern tropical Pacific.

timated in Oort's data.) The first question is largely answered by Fig. 1, which shows the relationship between interannual variations of tropical mean water vapor (30°S-30°N) and those at the lowest model level (as in Fig. 9 of Sun and Held) for all the AMIP1 models (Gates 1992, Gates et al. 1999). These models were driven with boundary conditions corresponding to observed sea surface temperature and sea ice coverage for the period 1979-1988. The red-dashed line is for the GFDL model. In most models, the correlation of the variations of water vapor in the upper troposphere with those near the surface is very high. In fact, the correlation is higher in most models than in the GFDL model. The same calculations were also done for the first five sets of model output available from the second phase of AMIP (AMIP2; see http://www-pcmdi.llnl.gov/amip/NEWS/amipnl8.html#TOC). The results are presented in Fig. 2 which again show very high correlations of variations of water vapor in the upper troposphere with the values at the surface level. The orange and brown lines are from the NCAR/NCEP and ECMWF reanalyses, which use models to interpolate and merge the rawinsonde and other observations. The vertical correlations in both reanalyses are higher than the model-independent data of Oort (1983), but below the 500 mb pressure level they are lower than all the AMIP2 models examined here. The fact that injection of observational data into the model analysis lowers the correlations between the variations of water vapor in the free troposphere and those at surface suggests that the correlations in the model may be indeed higher than in reality. The AMIP2 model output was further sampled in the same way as Oort's data were collected before the model output was used in calculating the vertical correlations. This consistent treatment of the model output with the collection of the observational data indeed reduces significantly the vertical correlation, but not sufficiently to explain the discrepancy with the observational data (Fig. 3). Note that significant discrepancy starts about 700 mb where the rawinsonde data are believed to be reliable.

Discussion

The consistency in GCMs is as encouraging as it is alarming. On one hand, it seems that the issue of whether changes in the upper tropospheric water vapor follow changes in the low levels may be indeed trivial: the correlations are almost independent of the parameterization schemes employed or the vertical resolution used. (A variety of cumulus parameterization schemes are used in the models examined here, including plain convective adjustment, Kuo's scheme, and Arakawa and Shubert's cumulus ensemble model. The vertical resolution also varies considerably; see http://www-pcmdi.llnl.gov/modeldoc/amip/01toc.html). The troposphere is highly diffusive even for the dynamically active water vapor. Elements that have been previously suggested to restrict vigorous mixing down below the boundary layer—the existence of the trade wind inversion, the narrow spatial confines of deep convective towers, and the complexity of the microphysics responsible for the creation of rain and the dry subsiding air—do not matter much after all. On the other hand, the rawinsonde data can probably be trusted in the mid troposphere (700mb-500mb) (Elliot and Gaffen 1991). The discrepancies with the rawinsonde observations in the vertical correlations of variations of water vapor then defy the interpretation that the vertical

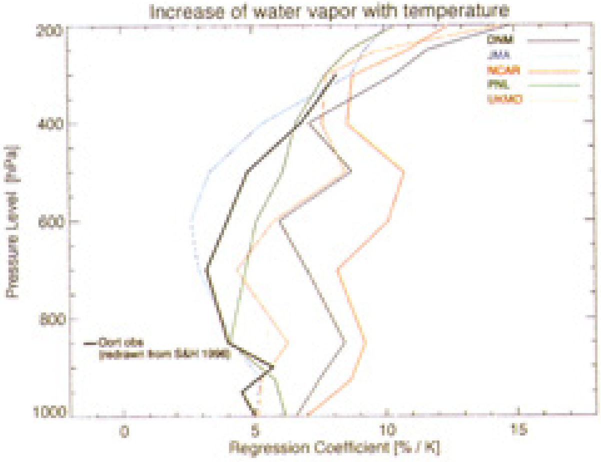

Figure 4. Rate of fractional increase of water vapor with temperature, obtained by regression of water vapor on temperature.

correlations of water vapor are trivial to simulate and available observational data are probably wrong. One possibility is that the noise level in the observations is considerably higher than in GCMs, but regression of water vapor on temperature does not eliminate the discrepancy between models and observations (Fig. 4). In fact, with only one exception, water vapor in models has a stronger dependence on temperature. Nonetheless, it is worth noting that a larger vertical correlation in water vapor field does not always imply that water vapor has a stronger dependence on temperature (Fig. 3 and Fig. 4). Moreover, accepting that the deviations from observations arise from model deficiency in the physics or the vertical resolution also does not necessarily imply that the models overestimate the water vapor feedback in the global warming situation. The consistency between satellite measurements of clear sky greenhouse effect and calculations of the same quantity by the GFDL model over the ERBE period (1985-1989) suggests that a model may get the total greenhouse effect of water vapor right despite the differences with the observations in the vertical correlation of water vapor variations (Soden 1997, Held and Soden 2000). It needs to be cautioned, though, that whether the agreement between the GFDL model and observed greenhouse effect holds for more extended periods remains to be seen. It is also not known whether other GCMs simulate well the variations of the greenhouse effect over the ERBE period. (The study of Soden (2000) appears to suggest considerable spread among simulations by AMIP1 models). To resolve this apparent inconsistency between the present findings and the study of Held and Soden (2000), more in depth studies are needed. These studies should include a quantitative assessment of the effect of the objective analysis scheme that had been used by Oort to interpolate data onto a regular grid. Nevertheless, the present findings should serve as a reminder that on the issue of whether changes in the upper tropospheric water vapor always follow the changes in the water vapor near the surface, there is still room for caution and need for research.

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De-Zheng Sun, Climate Diagnostics Center, NOAA-CIRES, NOAA/OAR/CDC-(RCDC1), 325 Broadway, Boulder, CO 80305-3328. (e-mail: ds@cdc.noaa.gov)

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