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ABSTRACT

### Global Cooling After the Eruption of Mount Pinatubo: A Test of Climate Feedback by Water Vapor

FULL TEXT

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## Supplementary Material

### The Consistency between Model Prediction of Water Vapor Feedback:

The study by Cess *et al.* (1) was one of the first to highlight the relative consistency between model predictions of water vapor feedback. By imposing idealized SST perturbations as a surrogate for climate change, they showed that the sensitivity of the clear-sky radiative fluxes was remarkably similar between models, differing by only about +/-10% from the value expected for a constant-relative humidity change in water vapor. In contrast, the sensitivity of total-sky fluxes was shown to vary by a factor of three, reflecting the large intermodel variability in model predictions of cloud feedback.

Here we provide further evidence that current models consistently predict a strong positive feedback by water vapor using results from the Coupled Model Intercomparison Project phase II (CMIP II). Under CMIP II 18 different coupled ocean-atmosphere GCMs were forced with identical 1% per year increases in CO<sub>2</sub> for 80 years. The simulations were all started from a pre-industrial concentration and the CO<sub>2</sub> increase was compounded annually achieving a doubling of CO<sub>2</sub> by year 70 of the integration.

Web Fig. 1 compares the percentage change in global-mean water vapor as a function of the change in global-mean air temperature from the CMIP II models. Results are shown for both the lower troposphere (lowest model layer; red dots) and upper troposphere (~200 hPa; blue squares). Since the output was archived in 20 year means, we show the difference between the last 20 years of the integration (years 60-80) and the first 20 years (0-20). The rate at which the saturation vapor pressure increases with temperature is also shown. For temperatures typical of the lower troposphere this rate is ~6%/K (red line), whereas for colder, upper tropospheric temperatures the rate is roughly twice as large, ~14%/K.

While the magnitude of the water vapor and temperature changes varies significantly from one model to the next, the rate at which the humidity changes is relatively consistent. For the surface layer, all models show the water vapor concentrations to increase at roughly 6%/K, implying a nearly constant-relative-humidity change in

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water vapor at the global scale. Likewise, for the upper troposphere the magnitude of the change also varies, but the rate of change is, with the exception of two outlying models, again well characterized by a constant relative humidity. Thus, consistent with the idealized study by Cess *et al.*, the models that participated in CMIP II also predict a strong positive feedback from water vapor consistent with that expected from a constant relative-humidity which, as shown by Held and Soden (3), roughly doubles the climate sensitivity.

#### **The Prescription of Cloud Cover in the GFDL Model:**

Because the strength of cloud feedback varies widely from one model to the next (1) and because satellite observations reveal no systematic changes in cloud distribution or optical properties (4), we prescribe a seasonally-varying climatology of cloud cover based upon a previous 10-year control integration of the model. This eliminates much of the noise and uncertainty associated with cloud feedback in the model, allowing us to focus on the water vapor feedback with a smaller ensemble of runs.

#### **The Calculation of Aerosol Radiative Forcing for Mt. Pinatubo:**

Spectral-, space-, and time-dependent aerosol extinction coefficient, single-scattering albedo, and asymmetry factor were calculated from June 1991 to May 1993 using the observed Stratospheric Aerosol and Gas Experiment (SAGE) II aerosol extinction at 1.02 microns and the Upper Atmospheric Research Satellite (UARS) retrieved effective radii. Mie theory, assuming, a refractive index of 75% solution of sulfuric acid, and a unimodal lognormal aerosol size distribution, are employed to calculate the aerosol single-scattering characteristics. Mie calculations were performed for 60 spectral intervals, chosen specifically for better approximation of the sulfate aerosol radiative properties, and then averaged appropriately over the model wave bands. The calculated aerosol optical depth reproduces exactly the SAGE II optical depth at 1.02 microns. The width of the aerosol size distribution was chosen to better fit the UARS-derived optical depth in the longwave region. The calculated total aerosol optical depth at 0.55 microns is within 10-15% agreement with independent observations by the Advanced Very High Resolution Radiometer (AVHRR). Aerosol radiative effect on solar fluxes at surface calculated by Stenchikov *et al.* (5), differs from the ground-based observations roughly by 10-20% in the specific tropical locations. However, some discrepancies exist between current estimates of the Pinatubo radiative forcing. The forcing used here was reduced by ~15% from that reported in Stenchikov *et al.* (5), but still remains ~15% larger than more recent estimates by Hansen *et al.* (9) for the same time period. This uncertainty in radiative forcing implies similar levels of uncertainty in the inferred climate sensitivity and hinders an unambiguous separation of the observed shortwave radiative anomalies between aerosol forcing and cloud response. However, for the purpose of these experiments, where clouds are prescribed and the focus is solely on water vapor feedback, this separation is of less importance provided the modeled shortwave anomalies are consistent with those observed over the period of interest (Fig. 1).

#### **Upper Tropospheric Water Vapor Retrievals:**

Given the uncertainty in retrieving upper tropospheric water vapor, we use retrievals from two different data sets: NVAP (6) and TOVS Pathfinder A (7). To eliminate intersatellite calibration differences and drifts in equatorial crossing time, we consider only the TOVS Pathfinder retrievals from NOAA-12 whose crossing time drifted by less than 30 min, between its launch in June 1991 and December 1995. Although both the Pathfinder and the NVAP data sets use TOVS measurements in their upper tropospheric water vapor retrieval, the algorithms used to invert radiances to water vapor profiles differ significantly between the two data sets. In addition, NVAP includes radiosonde observations over land and, over oceans, scales the operational TOVS retrievals to match SSM/I retrievals of total column water vapor. The discrepancies between the two products may also reflect the effects of a drift in the equatorial crossing time of NOAA-11 on the NVAP product or changes in the operational retrievals used by NVAP. Such changes are most noticeable after 1995,

but could also be present in earlier portions of the record (D. Randel, personal comm.).

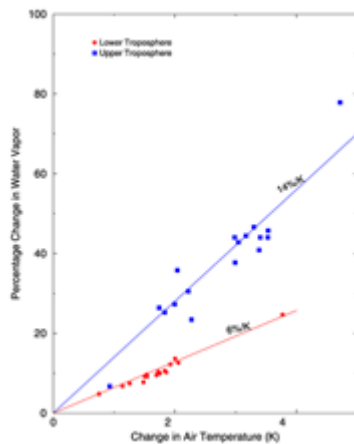
### The "No Water Vapor Feedback" Version of the GCM:

We follow the same procedure as Hall and Manabe (8) in configuring the "no water vapor feedback" version of the GCM. In both the "standard" and no water vapor feedback versions, water vapor is a prognostic variable in the model; meaning that the simulations of precipitation and evaporation, for example, are based on the humidity values predicted by the model. However, in the no water vapor feedback configuration, the water vapor mixing ratio in the longwave portion of the radiative transfer subroutine is replaced with its seasonally-varying climatological value. To simplify the code modifications, water vapor feedback still interacts with the SW part of the radiative transfer subroutine, however this comprises only a small part (~15%) of the total radiative feedback from water vapor (5). See (8) for further details regarding the no water vapor feedback configuration in a lower resolution model.

### Supplementary References and footnotes:

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8. A. Hall, S. Manabe, *J. Clim.* **12**, 2327 (1999).
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**Supplemental Figure 1.** CMIP intermodel comparison of the percentage change in global-mean water vapor as a function of the change in air temperature for the lower troposphere (red) and the upper troposphere (blue) due to increased CO<sub>2</sub>. Spatial averaging for the upper troposphere is restricted to latitudes equatorward of 45° to exclude regions of stratospheric air.



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