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# Water-vapor climate feedback inferred from climate fluctuations, 2003–2008

A. E. Dessler,[1] Z. Zhang,[1] and P. Yang[1]

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[1] Between 2003 and 2008, the global-average surface temperature of the Earth varied by 0.6°C. We analyze here the response of tropospheric water vapor to these variations. Height-resolved measurements of specific humidity (q) and relative humidity (RH) are obtained from NASA's satellite-borne Atmospheric Infrared Sounder (AIRS). Over most of the troposphere, q increased with increasing global-average surface temperature, although some regions showed the opposite response. RH increased in some regions and decreased in others, with the global average remaining nearly constant at most altitudes. The water-vapor feedback implied by these observations is strongly positive, with an average magnitude of $\lambda_q$ = 2.04 W/m$^2$/K, similar to that simulated by climate models. The magnitude is similar to that obtained if the atmosphere maintained constant RH everywhere. **Citation:** Dessler, A. E., Z. Zhang, and P. Yang (2008), Water-vapor climate feedback inferred from climate fluctuations, 2003–2008, *Geophys. Res. Lett.*, *35*, L20704, doi:10.1029/2008GL035333.

## 1. Introduction

[2] The water-vapor feedback is one of the most important in our climate system, with the capacity to about double the direct warming from greenhouse gas increases [*Manabe and Wetherald*, 1967; *Randall et al.*, 2007]. In this paper, we observe and quantify the behavior of atmospheric water vapor and the water-vapor feedback during variations of the Earth's climate between 2003 and 2008.

## 2. Data

[3] Tropospheric specific humidity (q), relative humidity (RH), and atmospheric temperature (T) are obtained from measurements made by the Atmospheric Infrared Sounder (AIRS) [*Aumann et al.*, 2003]. AIRS is part of the payload of NASA's Aqua satellite, which was launched in mid-2002. The q and T data have vertical resolutions of 2 and 1 km, respectively, and accuracies of 10% and 1 K, respectively [*Fetzer et al.*, 2005]. The horizontal resolution of a single retrieval is 40–50 km.

[4] Data in this paper come from version 5 of the AIRS monthly level-3 product, which averages individual retrievals of q, RH, and T from a month into 1° × 1° boxes covering the globe. Sampling biases in the AIRS dataset are minimized by the ability of the instrument to retrieve in the presence of up to 80% cloud cover [*Susskind et al.*, 2003].

## 3. Observed Changes

[5] Figure 1 shows the global-average surface-temperature time series for 2002 through early 2008, along with an El Niño index. The most significant variation over this time was a cooling during 2007. A shift from El Niño to La Niña played a key role in this cooling, along with contributions from shorter time-scale weather variability.

[6] Figure 2a shows the percent difference between zonal-average q for the warm DJF07 (December 2006, January 2007, and February 2007) and the cooler DJF08. Positive Δq values indicate that q was higher during the warmer period (DJF07), consistent with an intuitive expectation of increasing atmospheric moisture with a warming planet. There are also regions where Δq is negative—meaning that q was lower during the warmer period—most notably in the subtropical mid-troposphere between 10°N–20°N.

[7] Figure 3a plots global- and tropical-average Δq profiles—the global or tropical average q for DJF07 minus the average q for DJF08, divided by the average q for DJF07. At all altitudes, global- and tropical-average Δq was positive, meaning that global-average q was higher during the warmer DJF07 period, with the difference growing with altitude. There is virtually no difference between the tropical- and global-averaged Δq. This reflects the fact that q decreases exponentially with latitude as one moves away from the equator, so that tropical- and global-average Δq are heavily weighted toward changes in q near the equator.

[8] Figure 2b shows the change in relative humidity, ΔRH, defined as RH in DJF07 minus RH in DJF08. The data show large regions of both positive and negative ΔRH. Variations in ΔRH tend to cancel, however, and Figure 3b shows basically no change in global-average RH between 800 and 300 hPa.

[9] In the tropical average, we see that upper troposphere RH was lower for the warmer planet, a result consistent with the simple model of *Minschwaner and Dessler* [2004]. Climate models also simulate this reduction in average upper-tropospheric tropical RH with a warming climate [*Minschwaner et al.*, 2006]. See *Pierrehumbert et al.* [2006] for a more general discussion of the evolution of RH during global warming.

[10] The ΔRH and Δq patterns show what appears to be the imprint of a change in the Hadley circulation, which is consistent with expected ENSO variability [*Oort and Yienger*, 1996; *McCarthy and Toumi*, 2004]. Exactly how similar these ENSO variations are to long-term climate

[1]Department of Atmospheric Sciences, Texas A&M University, College Station, Texas, USA.


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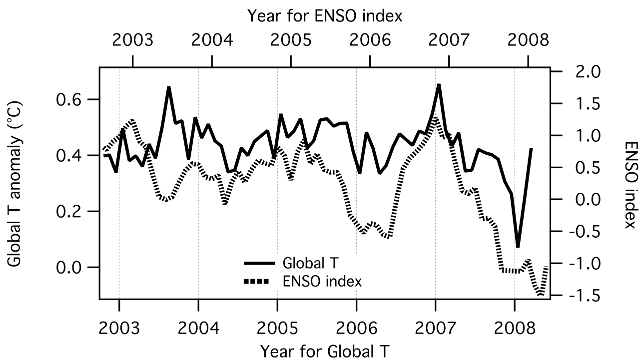


**Figure 1.** Global temperature anomaly (solid line, relative to 1961–1990 average) from the Hadley HadCRUT3 variance-adjusted surface temperature dataset [*Brohan et al.*, 2006] vs. year on the bottom axis, and multivariate El Niño index (dotted line) [*Wolter and Timlin*, 1993, 1998] vs. year on the top axis. The top and bottom axes are offset by 0.17 years to emphasize the correlation between the time series.

change is presently an open question [e.g., *Vecchi and Soden*, 2007].

[11] Figure 2c and 3c show the change in tropospheric temperature, $\Delta T$, defined here as T in DJF07 minus T in DJF08. These plots show positive values over most of the troposphere, showing the expected result that the atmosphere warms with the surface [e.g., *Xu and Emanuel*, 1989; *Wu et al.*, 2006]. Of particular note, the tropical upper troposphere shows greater warming than the surface, which is expected since the atmosphere is constrained to approximately follow a moist adiabat by convection.

## 4. Strength of the Water-Vapor Feedback

[12] We use a conventional definition of the strength of the water-vapor feedback:

$$\lambda_q = \sum_{x,y,z} \frac{\partial R}{\partial q(x,y,z)} \frac{\Delta q(x,y,z)}{\Delta T_s} \qquad (1)$$

where R is the global-average top-of-atmosphere net radiative flux, q(x, y, z) is the water vapor at a particular latitude, longitude, and altitude, and $T_s$ is the global-average surface temperature. The summation is over all longitudes and latitudes, and altitudes from the surface to 100 hPa.

[13] *Soden et al.* [2008] provide pre-computed values of $\partial R/\partial q(x, y, z)$. We then multiply $\partial R/\partial q(x, y, z)$ by the observed $\Delta q(x, y, z)/\Delta T_s$ between two climate states and then sum over latitude, longitude, and altitude to obtain an estimate of $\lambda_q$. Soden et al. also provide $\partial R/\partial q(x, y, z)$ broken down into longwave (LW) and shortwave (SW) components, allowing us to separately compute the LW and SW water-vapor feedbacks, $\lambda_{q,LW}$ and $\lambda_{q,SW}$.

[14] Table 1 lists calculated values of $\lambda_q$, $\lambda_{q,LW}$, and $\lambda_{q,SW}$. Each row lists the feedback calculated using $\Delta q$ and $\Delta T_s$ between January 2008 and one previous January. Calculated $\lambda_q$ range from 0.94 to 2.69 W/m$^2$/K, with an average value of 2.04 W/m$^2$/K. The LW feedback dominates, being about four times bigger than the SW feedback.

[15] Table 1 lists the magnitude of the water-vapor feedback inferred from climate variability. *Forster and Collins* [2004] estimated $\lambda_q$ = 1.6 W/m$^2$/K from the climate variations caused by the 1991 eruption of Mt. Pinatubo. *Soden and Held* [2006] calculated an average $\lambda_q$ of 1.80 W/m$^2$/K from analysis of a 100-year time period from 14 climate models. *Colman* [2003] obtained similar numbers in his analysis of climate models. Despite differing climate forcing, the implied feedback has about the same strength (~1.6–2 W/m$^2$/K), suggesting that the magnitude of this feedback may be a general feature of the atmosphere, and not dependent on the forcing mechanism [*Sherwood and Meyer*, 2006].

[16] We can also calculate what $\lambda_q$ would be if the three-dimensional distribution of RH remained constant as the

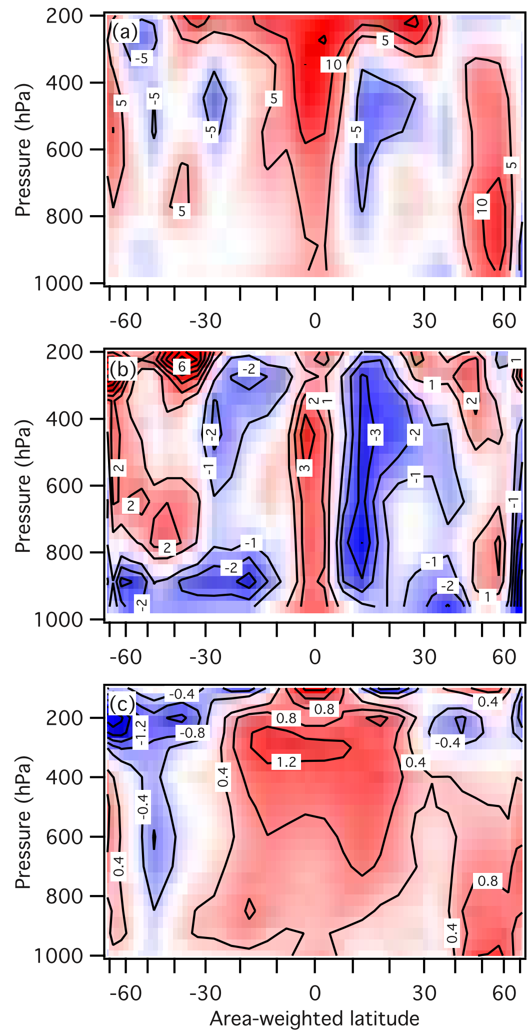


**Figure 2.** Average of DJF07 minus DJF08 for (a) q, (b) RH, and (c) T as a function of area-weighted latitude and pressure (hPa). Blue regions indicate negative values, and red regions indicate positive values. For the q plot, the difference is expressed as a percent (q(DJF07)-q(DJF08))/q(DJF07)). For the RH plot, the absolute difference in RH is plotted (e.g., a decrease in RH from 22% to 20% is plotted as −2%).

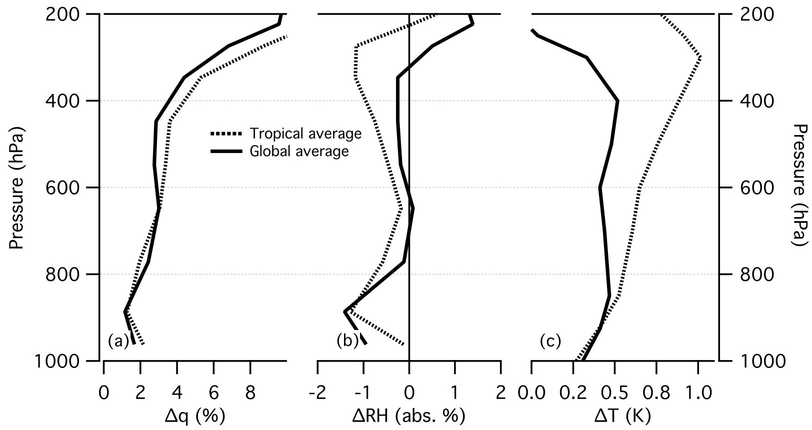


**Figure 3.** Change in global (90°N–90°S) and tropical (30°N–30°S) average (a) q, (b) RH, and (c) T as a function of pressure; change equals DJF07 minus DJF08. For the q plot, the fractional change in % is plotted. For the RH plot, the absolute difference in RH is plotted (e.g., a decrease in RH from 22% to 20% is plotted as −2%).

climate state changed. We do this by calculating the $\Delta$q required at each latitude, longitude, and altitude to maintain constant RH given the observed $\Delta$T between each January 2003–2007 and January 2008. From this $\Delta$q, the constant-RH feedback, $\lambda_q^{RH}$, can be calculated using Equation (1). Calculated values of $\lambda_q^{RH}$ are listed in Table 1.

[17] The average $\lambda_q^{RH}$ is 2.04 W/m$^2$/K, identical to $\lambda_q$, although there are considerable year-to-year variations between $\lambda_q$ and $\lambda_q^{RH}$. The close correspondence between average $\lambda_q^{RH}$ and $\lambda_q$ arises despite the fact that the atmosphere does not actually keep RH fixed, but displays a complex pattern of increases and decreases. *Soden et al.* [2002, 2005] analyzed the LW feedback and concluded that it has a magnitude close to that of a constant-RH feedback, and *Soden and Held* [2006] concluded that $\lambda_q$ and $\lambda_q^{RH}$ differed in climate models by just a few percent.

[18] Figures 4a and 4b show the zonal-average LW and SW components of $(\partial R/\partial q)\Delta q$, where $\Delta$q is the average change in q between January 2003–2007 and January 2008. One can think of this as the spatial distribution of the water-vapor climate feedback over this period. Integrating Figures 4a and 4b over pressure and latitude, we obtain Figures 4c and 4d.

[19] Figures 4a–4d show that the LW water-vapor feedback arises primarily from changes in q in the tropical upper troposphere, while the SW feedback arises from changes in the lower troposphere. Taken together, Figure 4d shows that changes in q from 700 to 200 hPa contribute about equally to the feedback in our data. In addition, Figure 4c shows most of the water-vapor feedback comes from changes in tropical q, with some contribution from $\sim$60° in both hemispheres. There is a significant contribution to the SW feedback from the southern high latitudes, primarily because this region is illuminated nearly continuously in January.

[20] Figure 4 also helps explain the large year-to-year variability in our calculated values of $\lambda_q$ in Table 1. It is tropical q that primarily determines the size of the water vapor feedback, and tropical q is primarily regulated by the tropical surface temperature [e.g., *Minschwaner and Dessler*, 2004]. The definition of $\lambda_q$, however, uses changes in global-average surface temperature. While changes in global and tropical temperatures are related, there are often variations in the global average that are not reflected in the tropical average and vice versa. Such variations lead to large variations in $\lambda_q$.

[21] Consider, for example, the small feedback $\lambda_q$ inferred between January 2007 and January 2008. The difference in the global average surface temperature $\Delta T_s$ between these two months was 0.60 K. Much of this, however, was due to extreme changes in the northern hemisphere mid- and high latitudes. The tropical average surface temperature difference $\Delta T_{tropics}$ was a milder 0.37 K. The relatively small change in tropical surface temperature leads to a relatively small change in q, and therefore a relatively small value of $(\partial R/\partial q)\Delta q$ of 0.57 W/m$^2$. Dividing that by the large $\Delta T_s$ leads to the small value of 0.94 W/m$^2$/K inferred for $\lambda_q$ over that period.

[22] The months with the largest inferred values of $\lambda_q$, on the other hand, are the months where $\Delta T_s$ is *smaller* than $\Delta T_{tropics}$. For example, $\Delta T_s$ between January 2008 and January of 2006 was 0.28 K, while $\Delta T_{tropics}$ between these months was 0.33 K. This arrangement contributes to a large value for the inferred $\lambda_q$ between these months. Given enough data, such variations should average out. In a short data set such as the one analyzed here, however, such variations can be significant.

[23] The existence of a strong and positive water-vapor feedback means that projected business-as-usual greenhouse-gas emissions over the next century are virtually guaran-

**Table 1.** Feedback Parameters Relative to January 2008

| January | $\Delta T_s$ | $\lambda_{q,LW}$ | $\lambda_{q,SW}$ | $\lambda_q$ | $\lambda_q^{RH}$ |
|---|---|---|---|---|---|
| 2003 | 0.44 | 1.67 | 0.43 | 2.10 | 2.31 |
| 2004 | 0.41 | 2.11 | 0.58 | 2.69 | 2.12 |
| 2005 | 0.49 | 1.37 | 0.39 | 1.77 | 1.81 |
| 2006 | 0.28 | 2.09 | 0.61 | 2.69 | 2.29 |
| 2007 | 0.60 | 0.74 | 0.20 | 0.94 | 1.69 |

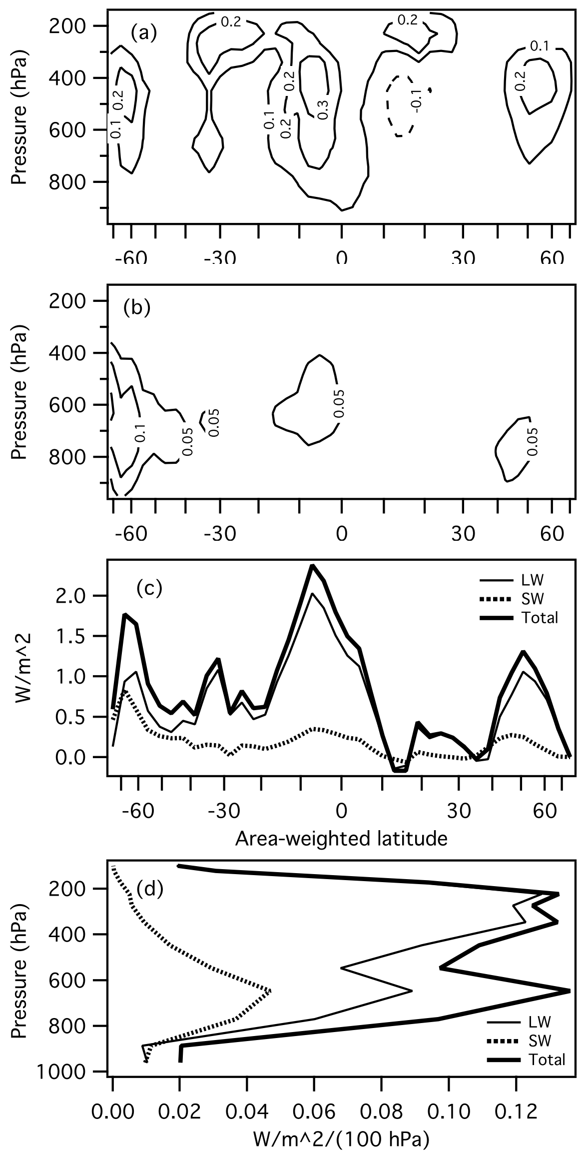


**Figure 4.** (a) Plot of LW component of $(\partial R/\partial q)\Delta q$ (W/m$^2$/(100 hPa)) due to the change in q between the January 2003–2007 average and January 2008, (b) same as Figure 4a, but for the SW component, (c) integral over pressure of the data in Figures 4a and 4b, with units of W/m$^2$, (d) integral over latitude of the data in Figures 4a and 4b, with units of W/m$^2$/(100 hPa). In Figures 4a and 4b, solid contours indicate positive values and dashed contours indicate negative contours.

teed to produce warming of several degrees Celsius. The only way that will not happen is if a strong, negative, and currently unknown feedback is discovered somewhere in our climate system.

[24] **Acknowledgments.** We thank Ken Minschwaner, Rob Korty, R. Saravanan, Gavin Schmidt, Ray Pierrehumbert, Steve Sherwood, and Brian Soden for help on this paper. This work was supported by NASA grants NNG04GL64G, NNG04GH67G, and NNX08AF68G, all to Texas A&M University.

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A. E. Dessler, P. Yang, and Z. Zhang, Department of Atmospheric Sciences, Texas A&M University, College Station, TX 77843, USA. (adessler@tamu.edu)