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Trends in tropospheric humidity from reanalysis systems

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[1] A recent paper (Paltridge et al., 2009) found that specific humidity in the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis declined between 1973 and 2007, particularly in the tropical mid and upper troposphere, the region that plays the key role in the water vapor feedback. If borne out, this result suggests potential problems in the consensus view of a positive water vapor feedback. Here we consider whether this result holds in other reanalyses and what time scale of climate fluctuation is associated with the negative specific humidity trends. The five reanalyses analyzed here (the older NCEP/NCAR and ERA40 reanalyses and the more modern Japanese Reanalysis (JRA), Modern Era Retrospective-Analysis for Research and Applications (MERRA), and European Centre for Medium-Range Weather Forecasts (ECMWF)-interim reanalyses) unanimously agree that specific humidity generally increases in response to short-term climate variations (e.g., El Niño). In response to decadal climate fluctuations, the NCEP/NCAR reanalysis is unique in showing decreases in tropical mid and upper tropospheric specific humidity as the climate warms. All of the other reanalyses show that decadal warming is accompanied by increases in mid and upper tropospheric specific humidity. We conclude from this that it is doubtful that these negative long-term specific humidity trends in the NCEP/NCAR reanalysis are realistic for several reasons. First, the newer reanalyses include improvements specifically designed to increase the fidelity of long-term trends in their parameters, so the positive trends found there should be more reliable than in the older reanalyses. Second, all of the reanalyses except the NCEP/NCAR assimilate satellite radiances rather than being solely dependent on radiosonde humidity measurements to constrain upper tropospheric humidity. Third, the NCEP/NCAR reanalysis exhibits a large bias in tropical upper tropospheric specific humidity. And finally, we point out that there exists no theoretical support for having a positive short-term water vapor feedback and a negative long-term one.

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1. Introduction

[2] The water vapor feedback is the process whereby an initial warming of the planet, caused, for example, by an increase in long-lived greenhouse gases, leads to an increase in the humidity of the atmosphere. Because water vapor is itself a greenhouse gas, this increase in humidity causes additional warming. This is the most powerful feedback in the climate system, with the capacity by itself to double the warming from carbon dioxide alone [e.g., *Randall et al.*, 2007].

[3] Over the past 20 years, much research has been devoted to quantifying the water vapor feedback, and there is a growing consensus within the scientific community that the water vapor feedback is strong and positive [e.g., *Held and Soden*, 2000; *Dessler and Sherwood*, 2009, and references therein]. Recently, however, *Paltridge et al.* [2009] (hereafter P09) showed that specific humidity in the NCEP/NCAR reanalysis generally declined over time. They pointed out that if these results were borne out, they would cast doubt on the consensus view of a strong and positive water vapor feedback.

[4] In this paper, we extend the results of P09 by examining whether or not their results hold in other reanalyses, as well as examining the time scales on which the negative water vapor trends appear. We conclude from our analysis

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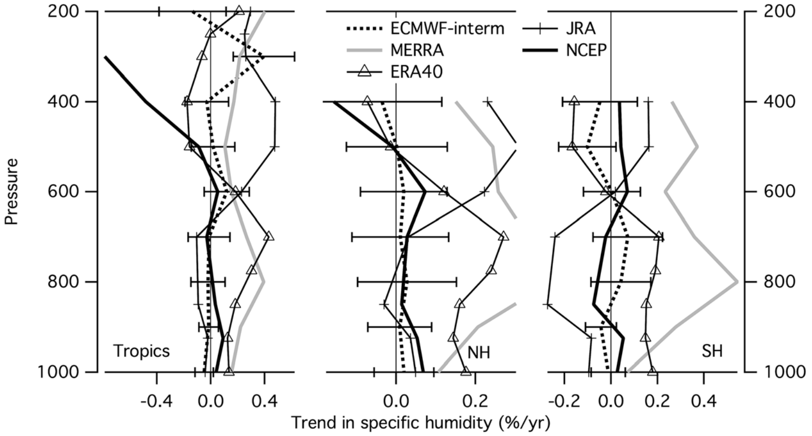

Figure 1. Plots of the trends in specific humidity in the different reanalyses, over the time periods discussed in the text (1979 onward, except for the ECMWF-interim, which begins in 1989). The plots are divided into three geographical regions: tropics (20°S–20°N), NH (20°N–50°N), and SH (20°S–50°S). Trends are divided by the average specific humidity over the entire time period, so they are expressed in percent per year. The 95% confidence interval for trends in the ERA-interim reanalysis are shown for illustration purposes.

that it is doubtful that the negative water vapor trends identified in the NCEP/NCAR reanalysis are realistic.

2. Data

[5] In this paper, we analyze output from several reanalyses: the NASA Modern Era Retrospective-Analysis for Research and Applications (MERRA, 1979–present) [*Suarez et al.*, 2008], the ECMWF interim reanalysis (ECMWF-interim, 1989–present) [*Simmons et al.*, 2007], ERA40 (1957–2002) [*Uppala et al.*, 2005], and the Japanese Reanalysis (JRA, 1979–present) [*Onogi et al.*, 2007]. For comparison to the work of P09, we also analyze the NCEP/NCAR reanalysis (1948–present) [*Kalnay et al.*, 1996]. To minimize the effects of the introduction of satellite data in 1979, we do not include any of the reanalysis fields prior to 1979 in our analysis.

3. Analysis

[6] P09 calculated trends of specific and relative humidity over the time period 1973–2007 for three different regions: the tropics (20°S–20°N), NH midlatitudes (20°N–50°N), and SH midlatitudes (20°S–50°S). Figure 1 shows a similar calculation for specific humidity as a function of pressure for these three geographic regions. We plot the trends for tropical data for altitudes up to 200 hPa (except for the NCEP/NCAR, which only provides humidity for altitudes below 300 hPa) and, similar to P09, for midlatitudes up to 400 hPa. The trend in Figure 1 has been normalized by the average specific humidity at each level, so it is the fractional change in specific humidity per year that is plotted. Our results for the NCEP/NCAR reanalysis are in general agreement with Figure 1a of P09, although some differences exist because our trend calculation begins in 1979 rather than P09's starting point of 1973.

[7] For understanding the water vapor feedback, our focus is on the tropical mid and upper troposphere. The climate is very sensitive to changes in water vapor here [*Soden et al.*, 2008; *Shell et al.*, 2008] because the gas absorbs radiation emitted by a hot surface but radiates at a low temperature. In addition, it is fractional changes in water vapor that matter (because the absorptivity is roughly proportional to changes in the logarithm of the water vapor concentration [*Held and Soden*, 2000]), and the fractional changes in mid and upper tropical troposphere per unit change in surface temperature are larger than most other places [e.g., *Dessler et al.*, 2008].

[8] Comparing the various reanalyses, it is clear that the NCEP/NCAR sees the largest negative trends in the tropical mid and upper troposphere. However, among the other reanalyses, there are variations in the magnitude, and even the sign, in the specific-humidity trends with altitude and latitude. To gain more insight into the regulation of water vapor, we recognize that at its heart the water vapor feedback posits a connection between surface temperature and specific humidity. Thus, we can more directly evaluate the strength of the water vapor feedback by regressing specific humidity directly against surface temperature, as has been done in previous studies [*Minschwaner and Dessler*, 2004; *Dessler and Wong*, 2009; *Gettelman and Fu*, 2008].

[9] Figure 2 plots the slopes of the least squares fit between the annual average specific humidity and the surface temperature, as a function of pressure for the three geographic regions defined in P09. In Figure 2a, the time series of surface temperature and atmospheric humidity are both FFT-filtered to remove variations with a time scale longer than 10 years; in other words, Figure 2a plots the relation between short-term variations in these variables. All five reanalyses produce similar relations, with increasing surface temperature being associated with increasing atmospheric specific humidity. These results agree with previous analyses that the water vapor feedback in response to short-term variations is strongly positive [*Soden et al.*, 2002; *Forster and Collins*, 2004; *Dessler et al.*, 2008]. This is also consistent with P09, who looked at the seasonal cycle in the extratropics in the NCEP/NCAR reanalysis and found that it showed a positive correlation between surface temperature and 500 hPa specific humidity.

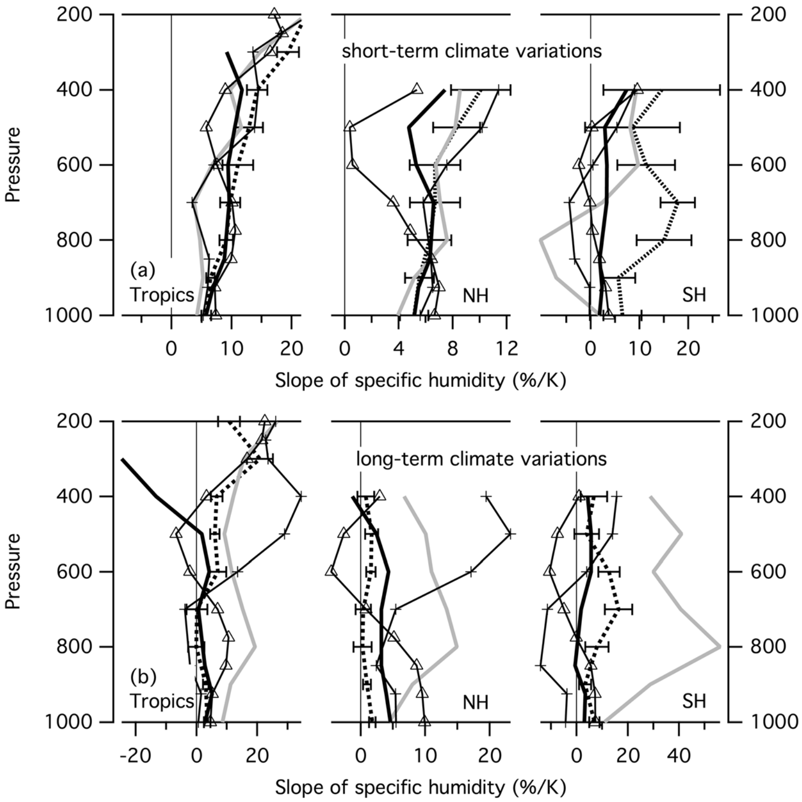

Figure 2. Plots of the slopes of the regression between specific humidity and surface temperature, over the same regions in Figure 1. Trends are divided by the average specific humidity over the entire time period, so they are expressed in percent per degree K. See Figure 1 for the legend. (a) Slopes when the specific humidity and temperature data are filtered to remove long-term variations (time scales greater than 10 years) and (b) slopes when the data are filtered to remove short-term variations (less than 10 years). In Figures 2a and 2b the 95% confidence interval for trends in the ERA-interim reanalysis are shown for illustration purposes.

[10] Figure 2b shows the same slope but with the data filtered only to include the variations with time scales longer than 10 years. There is poorer agreement among the reanalyses, particularly compared to the excellent agreement for short-term fluctuations. This makes sense: handling data inhomogeneities will introduce long-term trends in the data but have less effect on short-term trends. This is why long-term trends from reanalyses tend to be looked at with suspicion [e.g., *Paltridge et al.*, 2009; *Thorne and Vose*, 2010; *Bengtsson et al.*, 2004].

[11] For the ERA-interim and MERRA, the long-term slopes in Figure 2b are close to the short-term slopes in Figure 2a in the tropical mid and upper troposphere. The JRA and ERA40 also show generally positive slopes here. Only the NCEP/NCAR has negative slopes in the tropical mid and upper troposphere.

4. Interpretation

[12] The negative slopes P09 found in the NCEP/NCAR reanalysis clearly reflect the response of water vapor to long-term climate variations rather than the response to short-term climate variations. This leads us to an interesting question: could the water vapor feedback be different in response to short- and long-term time scales variations in climate? Variations of the feedback with time scale certainly cannot be ruled out: *Dessler and Wong* [2009], for example, showed that the water vapor feedback in response to El Niño cycles was indeed different from that in response to century-scale global warming. That difference, however, primarily reflected differences in the pattern of surface warming between ENSO and century-scale global warming, not in any fundamental differences in the behavior of water vapor.

[13] Given all of the work that has been done on the water vapor feedback, it is our judgment that it is extremely unlikely that the short-term feedback would be positive and the long-term feedback would be negative. First, there is no theory about how such an eventuality could occur. Our understanding of upper tropospheric water vapor suggests that it should be in relatively close thermodynamic equilibrium with the surface temperature on time scales of longer than about 1 month [e.g., *Minschwaner and Dessler*, 2004]. Thus, the water vapor response to a climate fluctuation with a time scale of a few years (e.g., ENSO) should be about the same as for long-term warming. Climate models also reproduce this result, as can be seen by comparing the long-term water vapor feedbacks estimated by *Soden and Held* [2006] and the short-term feedback estimated by *Dessler and Wong* [2009].

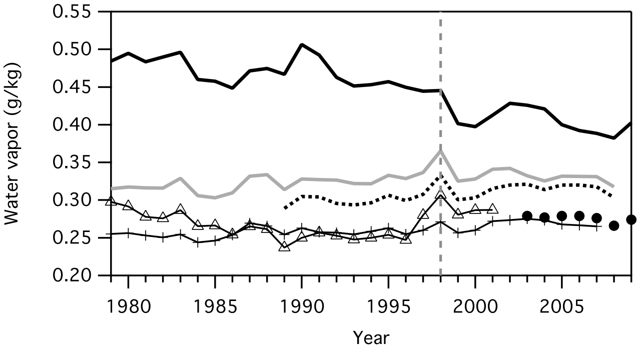

Figure 3. Time series of the specific humidity in the tropics at 300 hPa from the five reanalyses as well as measurement from the AIRS instrument since 2003 (black circles). See Figure 1 for the legend. The dotted vertical at 1998 shows the location of a major El Niño event.

[14] Second, an analysis of a long-term measurement of upper tropospheric water vapor shows a positive water vapor feedback in 22 years of satellite data [*Soden et al.*, 2005]. Finally, analysis of long-term paleoclimate records is also inconsistent with a negative long-term water vapor feedback [*Köhler et al.*, 2010].

[15] Third, only the NCEP/NCAR reanalysis shows the negative slopes in response to long-term climate fluctuations in the tropical upper troposphere. The newest reanalyses, the MERRA and ERA-Interim, use variational bias correction algorithms [*Dee and Uppala*, 2009] to address well-documented contamination of climate signals by changes in the observing system [*Dee*, 2005; *Bengtsson et al.*, 2007]. Thus, we have higher confidence in the ability of these newer reanalyses to accurately simulate the long-term trend. And these newer reanalyses are in better agreement with theory and observations that, for both long- and short-term climate fluctuations, specific humidity in the tropical mid and upper troposphere and tropical surface temperature are positively correlated.

[16] And there are particular problems with the NCEP/NCAR reanalysis. Figure 3 shows time series of annual average specific humidity at 300 hPa from the reanalyses as well as direct measurements made by NASA's Atmospheric Infrared Sounder (AIRS) [*Fetzer et al.*, 2008; *Read et al.*, 2007]. The NCEP/NCAR reanalysis clearly has large biases in specific humidity in the tropical upper troposphere. Other analyses are much closer to the AIRS measurements. Additionally, the NCEP/NCAR reanalysis does not see the large increase in specific humidity during the 1998 El Niño. Direct measurements indicate that the tropical atmosphere does indeed moisten during El Niño events [e.g., *Dessler et al.*, 2008; *Trenberth et al.*, 2007], and such moistening is seen in the other reanalyses, so this provides more evidence of problems in the NCEP/NCAR water vapor in this region.

[17] One possible explanation is that radiosonde humidity observations are the only assimilated measurements that directly affect the specific humidity field, whereas all of the other reanalysis humidity fields are additionally affected by the assimilation of TOVS radiances or humidity retrievals. As P09 point out, there are well-documented problems with radiosonde humidity observations and reporting practices in the upper troposphere [e.g., *Elliott and Gaffen*, 1991; *Wade*, 1994; *Wang et al.*, 2003].

[18] Given the weight of this evidence, it is our judgment that the negative trends in the NCEP/NCAR and ERA40 reanalyses are spurious. This should not be surprising, and P09 themselves acknowledged that there was good reason to doubt the trends they derived in the NCEP/NCAR reanalysis.

5. Conclusions

[19] P09 calculated trends of specific humidity with time over the past few decades in the NCEP/NCAR reanalysis and found that the specific humidity, in particular in the tropical mid and upper troposphere, was decreasing. They concluded that this potentially cast doubt on the general consensus that the global water vapor feedback was strongly positive [e.g., *Dessler and Sherwood*, 2009]. We have extended the analysis of P09 by addressing two crucial issues, namely whether other reanalyses reproduce this and what time scale of climate fluctuation is associated with the negative water vapor trends.

[20] We have analyzed five different reanalyses, including the NCEP/NCAR reanalysis. Rather than calculate trends with time, as P09 did, we instead regressed atmospheric humidity against surface temperatures for the tropics and midlatitudes. In response to short time scale climate variations (e.g., ENSO cycles), there is good agreement among the reanalyses on the connection between atmospheric water vapor and surface temperature: specific humidity increases with increasing surface temperature in the tropical mid and upper troposphere, as well as almost everywhere else. This is in good agreement with both theory and observation.

[21] The picture is different when long-term climate variations are considered. The NCEP/NCAR reanalysis shows decreases in specific humidity in the tropical mid and upper troposphere with increasing tropical surface temperature. Such behavior implies that the water vapor feedback in response to long-term climate fluctuations would be negative, and would therefore have a different sign depending on the time scale of the climate variation. No theory or model supports this, nor do analyses of long-term water vapor measurements or paleoclimate data.

[22] In addition, the other reanalyses, including the newest reanalyses (ERA-interim and MERRA), which were specifically designed to better reproduce long-term trends, do not manifest this behavior. Finally, we pointed out that the NCEP/NCAR reanalysis contains large biases in the tropical mid and upper tropospheric specific humidity and does not reproduce the moistening of the tropical upper troposphere during the strong 1998 El Niño, further casting doubt on that reanalysis' water vapor fields in that region.

[23] Based on the available evidence, it is our judgment that negative trends in the tropical mid and upper troposphere in response to long-term climate change are spurious. This is clearly the most parsimonious explanation, and it is in accord with virtually all of the independent lines of evidence (models, observations, theory, and newer reanalyses). Clearly, however, our analysis emphasizes the need to understand and reduce the uncertainties in long-term trends from reanalyses, and this goal should be a high priority of the community.

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