Water Vapor, Surface Temperature, and the Greenhouse Effect—A Statistical Analysis of Tropical-Mean Data

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ABSTRACT

Water vapor feedback is one of the important factors that determine the response of the atmosphere to surface warming. To take into account the compensating drying effects in downdraft regions, averaging over the whole Tropics is necessary. However, this operation drastically reduces the number of degrees of freedom and raises questions concerning the statistical significance of any correlative results obtained using observational data. A more involved statistical analysis is performed here, using multiple datasets, including the global water vapor datasets of Special Sensor for Microwave/Imaging (column water), upper-tropospheric relative humidity, the Television Infrared Observational Satellite Operational Vertical Sounder retrieved upper-tropospheric specific humidity, and the surface temperature data from the National Centers for Environmental Prediction–National Center for Atmospheric Research Reanalysis dataset. The tropical-mean correlations between relative humidity and surface temperature cannot be established, but those between specific humidity and the surface temperature are found to be positive and shown to be statistically significant. This conclusion holds even when the averaging is done on the natural logarithm of the upper-tropospheric water vapor content. The effect on the tropical-mean outgoing longwave radiation is also discussed.

1. Introduction

The amount of greenhouse gases such as carbon dioxide, methane, and CFCs in the atmosphere has been observed to increase in recent decades. General circulation models (GCMs) generally predict a global warming of 0.5°–1.2°C in direct response to a doubling of carbon dioxide amounts in the atmosphere (Houghton et al. 1990; Houghton et al. 1992). As global warming leads to increased evaporation of water from oceans, it in turn may lead to increased atmospheric water vapor content and cloudiness. A global warming may also cause decreased snow cover and, therefore, surface albedo. All these factors contribute to enhance global warming (positive feedback) in current GCMs. Model-predicted global warming due to doubling CO_2 becomes 1.5°–4.5°C if these positive feedbacks are included (Houghton et al. 1990; Houghton et al. 1992).

A contrarian view (Lindzen 1990) holds that the increased convection associated with the CO_2-induced warming should act instead to dry the upper troposphere: Air rising in cumulus convective towers would cool and saturate, losing its water vapor content through precipitation. The subsidence outside the convective towers should dry the upper and middle troposphere, thus leading to a negative water vapor feedback.

Houghton et al. (1996) recently noted the large uncertainty relating to upper-tropospheric water vapor and its response to surface warming. The report pointed out that while ‘‘the preponderance of evidence . . . points to it [water vapor feedback effect] being positive in the upper troposphere [chap. 4, summary; also p. 34, technical summary], this is not yet convincingly established’’ (p. 201, section 4.2.1). The observational studies that Houghton et al. (1996) noted are critically reviewed in the following.

a. Review

Soden and Fu (1995) used satellite-derived upper-tropospheric (relative) humidity (UTH) for the period February 1985–November 1988, averaged over the entire tropical region (30°S–30°N), and found it to be positively correlated with the frequency of deep convection (FDC). They found that the correlation coefficient, at 0.45, is significant at the 98% confidence level. Thus they concluded that, even allowing for compensating regions of subsidence, the net effect of convection is to moisten the upper troposphere. However, there is a question involving this otherwise excellent piece of work. The quoted level of statistical significance (98%) was based on the authors' assumption that the monthly data are independent every other month. By examining the tropical-mean UTH data and taking into account the

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autocorrelation of the data series, we found that the data are more likely independent every four months (see discussion later). Under this circumstance, the correlation coefficient found by Soden and Fu is below the 95% confidence level. Soden and Fu did not calculate the correlation between the tropical-mean sea surface temperature (SST) and UTH. Warmer tropical-mean SST does not necessarily increase deep convection, since they also found that the tropical-mean frequency of deep convection was uncorrelated with the tropical-mean SST for the same period. The problem with a lack of statistical significance mentioned above can presumably be remedied by using a longer data record. The available 10-yr record of Television Infrared Operational Satellite Operational Vertical Sounder (TOVS) UTH data (Soden and Fu 1995; Soden and Bretherton 1996) shows periods of negative correlation between UTH and SST along with periods when the correlation is positive. This lack of overall correlation does not necessarily imply that there is no water vapor feedback in global warming, since even a zero correlation between *relative* humidity and SST may still lead to a positive, but smaller, correlation between *specific* humidity and SST. This, however, has not been shown. This task is complicated by the fact that first, the UTH data cannot be easily converted from relative humidity to specific humidity, and second, the multiple satellites used in this 10-yr period may have introduced intercalibration errors.

On the other hand, Chou (1994) found an apparent negative feedback effect in a case study using two months of data. He found that the tropical Pacific receives less radiative energy, by 4.0 W m^{-2}, in the warmer month of April 1987 (an El Niño year) than in the month of April 1985 (a non–El Niño year). He further determined that the reduction in radiation is primarily caused by a reduced atmospheric clear-sky greenhouse effect of water vapor in the Northern Hemisphere subsidence region. Statistical analysis was not possible in such a case study. Furthermore, there appear to be large fluctuations between months. Soden (1997) found that if May 1987–May 1985 were used instad of Aprils, an opposite result would be found. Bony et al. (1995) used both satellite- and model-derived precipitable water and clear-sky outgoing longwave radiation (OLR) data to investigate their dependence on SST. As in Chou's study, the calculation was based on the differences between two cases, but unlike in Chou's study, positive correlation between water vapor and SST was found. Their result was based on local correlations, however.

There are several studies (Bony et al. 1995; Inamdar and Ramanathan 1994; Raval et al. 1994; Raval and Ramanathan 1989) that found positive *regional* correlation between tropospheric water vapor and SST in the tropical region. The relationship between water vapor and convection or temperature, when averaged over circulation cells, may be different from their local relationships, with important implications for the validation of GCMs used in global warming studies. For example, while Soden and Fu (1995) found that the Geophysical Fluid Dynamics Laboratory (GFDL) GCM compares remarkably well with the observation in terms of *local* relationships, Sun and Held (1996) found that the modeled *tropical-mean* upper-tropospheric water vapor responds too strongly to increases in temperature when compared to the rawinsonde observations.

Some of studies (Sun and Oort 1995; Sun and Held 1996) also found that tropical-mean specific humidity is positively correlated with tropical-mean temperature *at the same level.* This is likely caused in part by the atmosphere's capacity to hold more water due to an increase in in situ temperature, although Sun and Oort (1995) also found that the rate of fractional increase of specific humidity with temperature in the observed data is significantly smaller than that given by a model with a fixed relative humidity. The quantity of interest to us—the correlation between the tropical-mean water vapor and the SST below—was not presented in these studies.

In another study, Rind et al. (1991) computed the difference in humidity between summer and winter months in each hemisphere, and the difference in humidity between the convective tropical western Pacific region and the largely nonconvective eastern Pacific region. They found that increased convection leads to increased water vapor above 500 hPa in approximate quantitative agreement with the results from current climate models. However, as pointed out by Sun and Oort (1995), the difference found is more of a reflection of the difference in humidity between the ascending and the descending branches of the Hadley (or Walker) circulation, perhaps unrelated to the water-vapor feedback issue at hand.

The above discussion argues for finding a global relationship between water vapor data and surface temperature as desirable but points out that the only previous work on this subject, that of Soden and Fu (1995), may be subject to questions concerning statistical significance.

b. Lack of a surrogate

In the existing records of upper-tropospheric water vapor, some are long enough to contain a few El Nino–Southern Oscillation (ENSO) events. Can the behavior of upper-tropospheric water vapor during these warming events be used as natural surrogates for global warming? The answer appears to be no, according to Lau et al. (1996), to the extent that ENSO is a manifestation of a shift of the (Walker) circulation pattern that is dependent on the (longitudinal) distribution of the SST in the equatorial Pacific basin, as opposed to the more uniform SST expected in the Tropics from global warming (Manabe and Stoufer 1994). Lau et al. (1996) suggested that regionally based interannual variability should not be used to infer radiative feedback sensitivity for climate change unless proper corrections are made for the effect of the large-scale circulation. These may involve averaging over a global domain, or domains large enough to encompass both rising and subsiding branches of the Walker and Hadley cells. This suggestion is consistent with the earlier argument of Lindzen et al. (1995) that a surrogate for global climate change must, at the least, consider climate change averaged over major circulation systems. Such an average removes the influence of horizontal transport of both small- and large-scale circulations so that the change in the mean upper-tropospheric water vapor reflects the change associated with the mean surface temperature below. This is the approach taken in the present study. However, instead of averaging globally, only tropical means (over 30°S–30°N) are used. This is done in an attempt to avoid the effect of lapse rates, which appears to work differently over seasonal and interannual timescales in the extratropics (Bony et al. 1995). Bony et al. (1995) pointed out that in the Tropics the magnitude of the coupling between SST and water vapor is quite similar for seasonal variations, interannual variations, and climate change experiments. We will further focus on mechanisms that are not unique to seasonal variations. The above consideration notwithstanding, we should still exercise great caution in extrapolating the observed variability on seasonal and interannual timescales to longer-term climate changes.

c. Questions related to the mechanism

In the Tropics, the dominant mechanism for coupling of the surface temperature and the upper-tropospheric water vapor over a range of timescales appears to involve deep convection. To relate the greenhouse effect to surface warming via the mechanism of deep convection, we ask the following series of questions.

1) Does an increase in SST lead to an increase in FDC?
2) Does an increase in FDC moisten the upper troposphere?
3) Does this moistening occur also in the net, taking into account of the drying effects of downdrafts?
4) Does the greenhouse effect increase in response to questions 1 and 3?

If the answer to each of these questions is affirmative, and is so in a statistically significant way, then we can conclude that the effect of water vapor feedback on greenhouse warming is likely positive.

Soden and Fu (1995), and also Roca et al. (1997), found that where it occurs *locally,* deep convection serves to moisten the upper troposphere and that the atmosphere is drier where deep convection is less frequent. This result is statistically highly significant over a range of time- and space scales. Therefore, we say the answer to question 2 is yes.

The answer to question 1 is so far ambiguous. Soden and Fu (1995) found that SST and FDC are not correlated locally. This result, although counterintuitive, does appear to have a reasonable explanation. Bajuk and Leovy (1998) recently showed that FDC is affected by SST *and* low-level wind convergence. They found that there is a consistent positive relationship between FDC and SST in the Pacific east of 140°E, but there is an absence of a consistent relationship between the two over the maritime continent and Indian Ocean regions, where surface wind divergence appear to be the more important factor. The latter instances tend to lower the overall average value of local, point-by-point correlations.

The answer to question 3 is rather controversial. As mentioned earlier, this conclusion depends on the number of the degrees of freedom estimated. When local data are averaged over the whole Tropics, the number of degrees of freedom drops by about three to four orders of magnitude, impacting directly our ability to establish statistical significance. Furthermore, there is some debate on *how* the tropical average should be done. A simple area-weighted average may be faulted on the grounds that, as far as the radiative effect is concerned, a change in water vapor in a dry region should have more impact than the same change in a wet region. These issues are addressed in the following sections, along with question 4.

2. Datasets

Because of Soden and Fu's (1995) positive result on question 2, there is probably no need for us to repeat the calculation relating FDC and UTH. We will deal directly with the correlation of SST and water vapor. Instead of considering local correlations, we will deal with tropical-mean quantities.

The following datasets are used in this study.

a. Relative humidity

The TOVS measures the 6.7-μm radiance ($T_{6.7}$) on board the National Oceanic and Atmospheric Administration's (NOAA) polar-orbiting satellites. The 6.7-μm channel is located near the center of a strong water vapor absorption band. Under clear-sky conditions, this channel is sensitive primarily to the logarithm of the *relative humidity* averaged over a broad layer centered in the upper troposphere (200–500 hPa) (Soden and Bretherton 1993). A simple formula relating the $T_{6.7}$ and UTH was then obtained by Soden and Bretherton as a radiance-to-humidity transformation, assuming that the relative humidity in this layer is constant with respect to pressure. The UTH data used here, for 1982–92, kindly provided to us by B. Soden, are the same as described in Soden and Bretherton (1996), except that humidity here is relative to ice instead of to water, since the former is more relevant to the upper troposphere.

b. Specific humidity

The retrieval algorithm described above cannot be used to deduce specific humidiy. A different retrieval

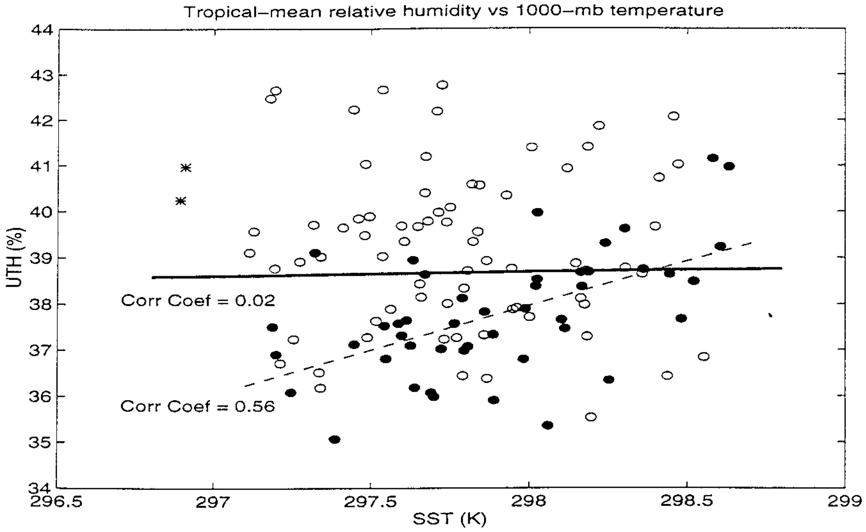

FIG. 1. Scatterplot of monthly TOVS upper-troposphere relative humidity vs 1000-hPa temperature, both averaged over the tropical region (30°S–30°N). A 10-yr period of 1982–91 is plotted. The solid line shows the least squares linear fit to all data. The dashed line shows the least squares linear fit to data in the period of Feb 1985–Nov 1988 (shown in solid dots). The asterisks show data for Dec 1989–Jan 1990. The circles show the rest of the data.

algorithm is needed. Five years (1985–89) of the TOVS Pathfinder Path A Dataset are used in this study. As discussed in Susskind (1993, 1996), the retrieval system uses a 6-h forecast produced by a general circulation model, initialized using data from the last 6 h of retrieved satellite soundings, as well as other in situ concurrent measurements. A moisture profile is iterated so as to obtain a best match to moisture sounding channel radiances and other retrieved temperature and column radiances.

c. *Total column water vapor content*

A 5-yr global water vapor dataset has been produced recently by Randel et al. (1996) under the National Aeronautics and Space Administration (NASA) Water Vapor Project (NVAP). This dataset combines water-vapor retrievals from TOVS, the Special Sensor Microwave/Imager (SSM/I), and radiosonde observations for the period 1988–92. This quality controlled dataset consists of both the total column-integrated and layered product for water vapor. Only the total water-vapor content (TWC), retrieved from SSM/I, is used in this study from the NVAP dataset.

d. *Surface temperature*

The 1000-hPa National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) Reanalysis dataset, as documented in Kalnay et al. (1996), will be used for surface temperature. This is more convenient for the purpose of area average than the actual SST. The TOVS dataset described in section 2b also contains surface skin temperature. This is used when we do correlative studies with TOVS moisture and outgoing longwave radiation. This is again done for convenience. The calculations were repeated with the two temperature datasets switched and the results were not changed in any significant way.

3. Surface temperature and upper-tropospheric relative humidity

Figure 1 shows the scatterplot of the UTH versus surface temperature, both averaged over the tropical region (30°S–30°N). Monthly mean data for the 1982–91 period are employed in this study. The temperature data used are the 1000-hPa temperature from the NCEP–NCAR Reanalysis dataset (Kalnay et al. 1996). As one can see, there is no correlation between the two quantities for the 10-yr period examined; the correlation coefficient (0.02) is practically zero. This appears to be in contrast to the result of Soden and Fu (1995), who found significant correlation between tropical-mean UTH and the frequency of deep convection for the period February 1985–November 1988. The discrepancy is not caused by the fact, also reported by Soden and Fu (1995), that tropical-mean frequency of deep convection was uncorrelated with the tropical-mean SST for the same period. The correlation coefficient between tropical-mean UTH and 1000-hPa temperature is 0.56 for the period chosen by Soden and Fu: February 1985–November 1988 (data shown in Fig. 1 in solid dots), which is even higher than the 0.45 between tropical-mean UTH and frequency of deep convection reported

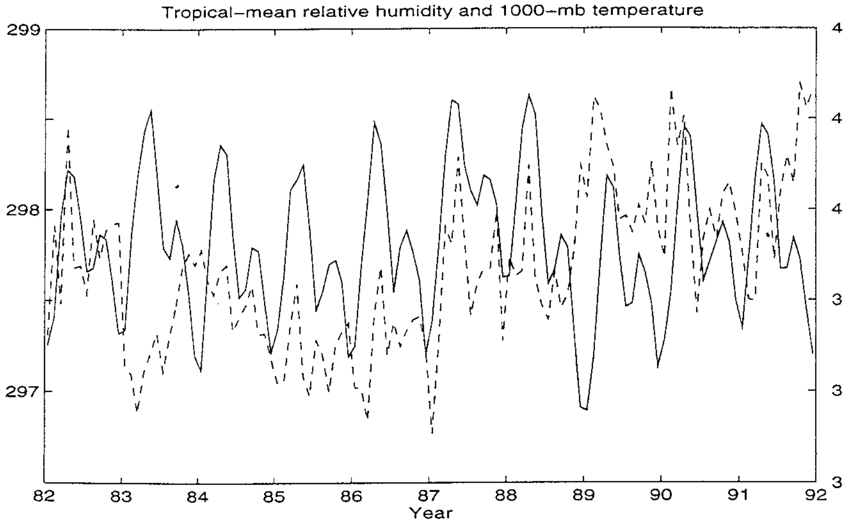

FIG. 2. Time series of monthly TOVS upper-troposphere relative humidity data (dashed line, right scale) and 1000-hPa temperature (solid line, left scale) both averaged over the tropical region.

by them. Rather, the discrepancy is due to the fact that UTH and surface temperature is positively correlated for some periods and negatively correlated for others. This can be seen from Fig. 2, which shows the time series of tropical-mean UTH and 1000-hPa temperature for the period 1982–91. In particular, negative correlation is seen for 1983, early 1989, and late 1991. The period February 1985–November 1988 considered by Soden and Fu can be divided into two halves, separated by a large jump in humidity in January 1987. The first half of the period is characterized by low correlation between UTH and surface temperature. More moist data after January 1987 show up on the upper-right quadrant of Fig. 1 and contributed to the positive correlation found. The Soden and Fu period is followed immediately by several months of negative correlation when surface temperature dropped while the ‘‘moist bias’’ persisted. If two more months of data (December 1988 and January 1989, data shown in the upper-left quadrant of Fig. 1 in asterisks) are added to the above period, the correlation coefficient becomes −0.06 for the resulting 4-yr period (February 1985–January 1989). The large change in correlation as a result of adding merely two data points serves to illustrate the well-known fact that the (Pearson product moment) correlation coefficient is not resistant to outlying data. It may also be an indication of the problems of the data series obtained using multiple NOAA satellites. The much higher (but probably spurious) correlation of UTH with the temperature in the 1985–88 period as compared to the other periods may be due to the addition of the *NOAA-10* satellite in January 1987, which appears to give a more moist reading.

Using a revised statistical test (see later) to take into account the autocorrelation of atmospheric data series, the above-mentioned correlation coefficient of 0.56 between UTH and surface temperature for the period February 1985–November 1988 is found to be statistically insignificant (i.e., below 95% confidence level). The same holds true for the longer, 10-yr record. Thus we cannot find a *statistically significant correlation* between tropical-mean upper-tropospheric relative humidity and surface temperature, when averaged over the whole Tropics in either the 4-yr or in the 10-yr records. Given the problems alluded to with the UTH data, we will now repeat the analysis with other datasets.

4. Surface temperature and specific humidity

The lack of correlation between surface temperature and UTH (relative humidity) does not necessarily mean that there is no water vapor feedback. For example, Manabe and Wetherald (1967) obtained positive water-vapor feedback in their simple model assuming *fixed* relative humidity.

Figure 3 shows the time series of NVAP TWC and the surface temperature, averaged over the tropical region (30°S–30°N). The temperature data used are the 1000-hPa temperatures from the NCEP–NCAR Reanalysis dataset. As one can see, the variation of tropical-mean total water vapor content generally follows that of the tropical-mean surface temperature. The correlation coefficient between the two series is 0.80, statistically highly significant. (We establish statistical significance by using the Student’s *t*-test and also the Monte Carlo procedures. The autocorrelation in the data series has been taken into account when establishing statistical significance. A correlation is considered significant here if it is significant at the 95% confidence level by both

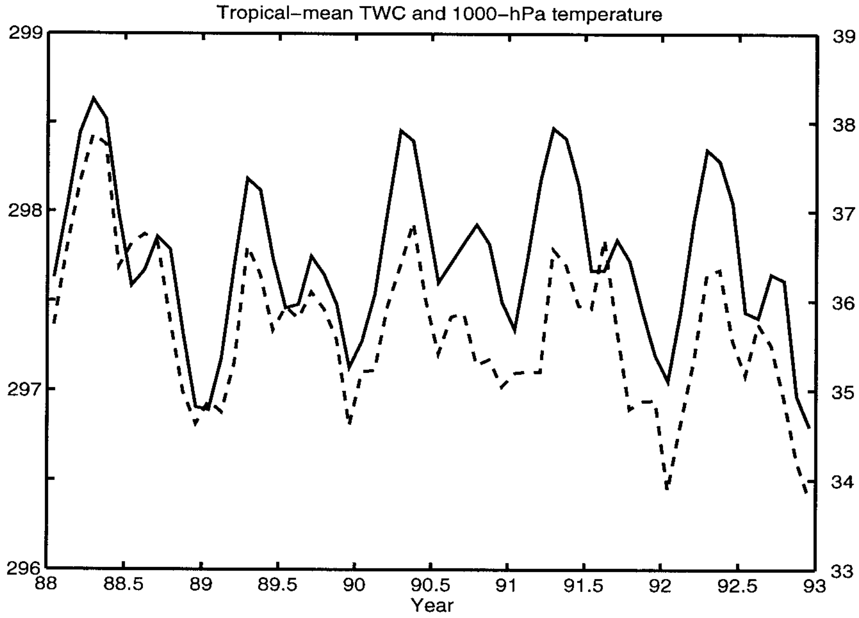

FIG. 3. Time series of monthly NVAP total water-vapor content data (dashed line, right scale in mm) and 1000-hPa temperature (solid line, left scale in kelvins), both averaged over the tropical region (30°S–30°N).

test procedures. More detailed information can be found in the appendix.)

To emphasize the dry regions more than the wet regions, the local natural logarithm of TWC is first taken before averaging from 30°S to 30°N. The scatterplot of this mean quantity versus the mean surface temperature is given in Fig. 4. The two quantities are seen to be highly correlated. The correlation coefficient, at 0.82, is statistically significant at the 99% confidence level.

Total water vapor content is dominated by water vapor in the lower troposphere, and so it is not surprising that such a high correlation exists. It is the water vapor in the upper troposphere that is the subject of debate. Figure 5 shows the tropical-mean TOVS water vapor

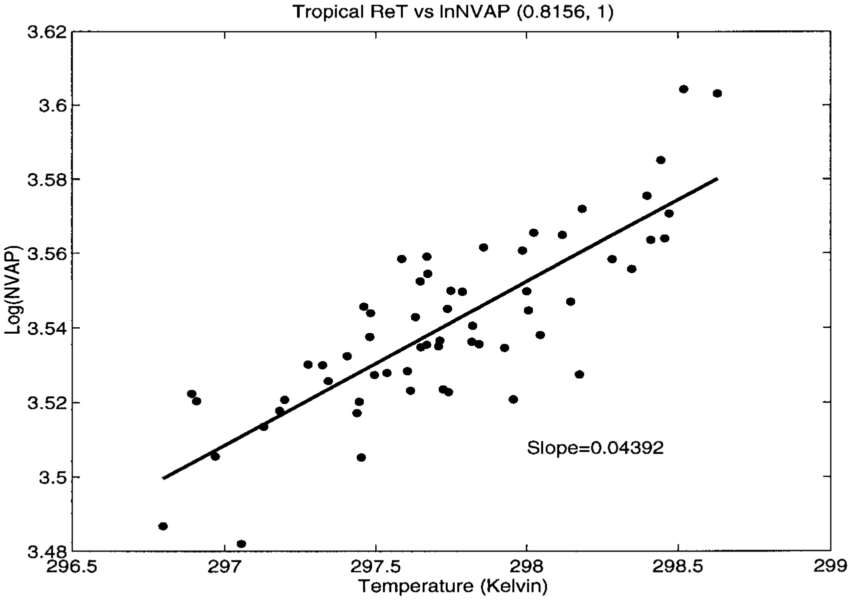

FIG. 4. Scatterplot of monthly values of tropical means of the natural logarithm of NVAP total precipitable water content and reanalysis of surface temperature.

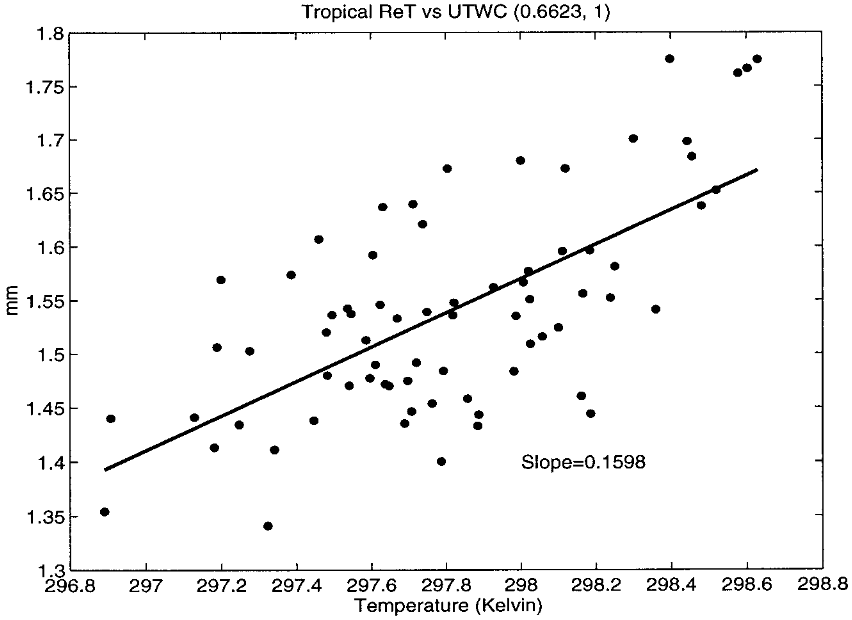

FIG. 5. Scatterplot for monthly TOVS upper-troposphere (300–500hPa) water-vapor content and 1000-hPa temperature, both averaged over the tropical region (30°S–30°N). Data shown are for the 5-yr period 1988–92.

content in the upper troposphere, 500–300 hPa, which is denoted as UTWC here, along with the tropical-mean surface temperature in a scatterplot. The tropical-mean upper-troposphere water vapor content (specific humidity) is positively correlated with the tropical-mean surface temperature even though the corresponding relative humidity is not correlated with the tropical-mean surface temperature. The correlation coefficient of 0.66 is highly

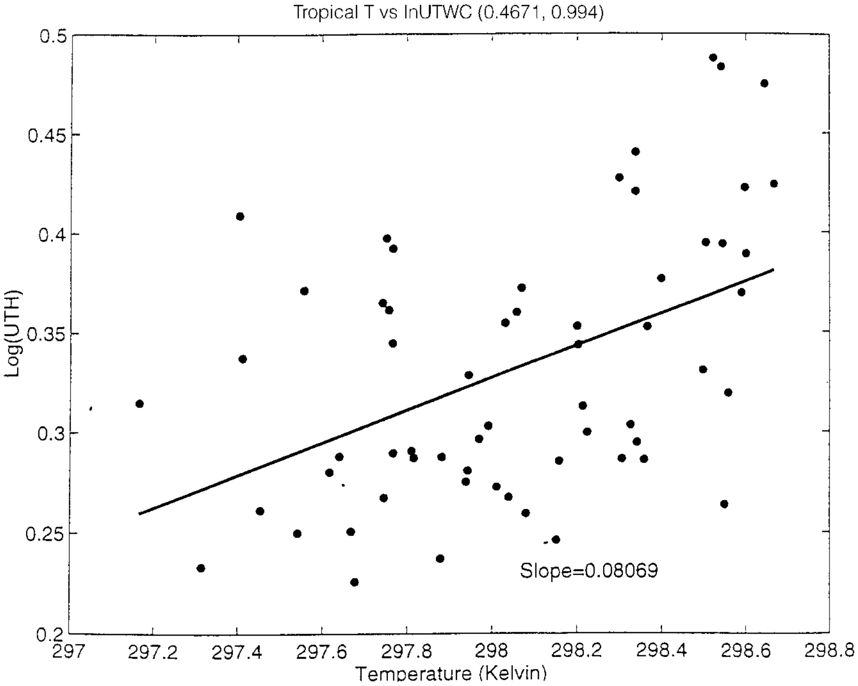

FIG. 6. Scatterplot of monthly values of tropical means of the natural logarithm of TOVS upper-tropospheric (500h–300hPa) precipitable water content and TOV surface temperature.

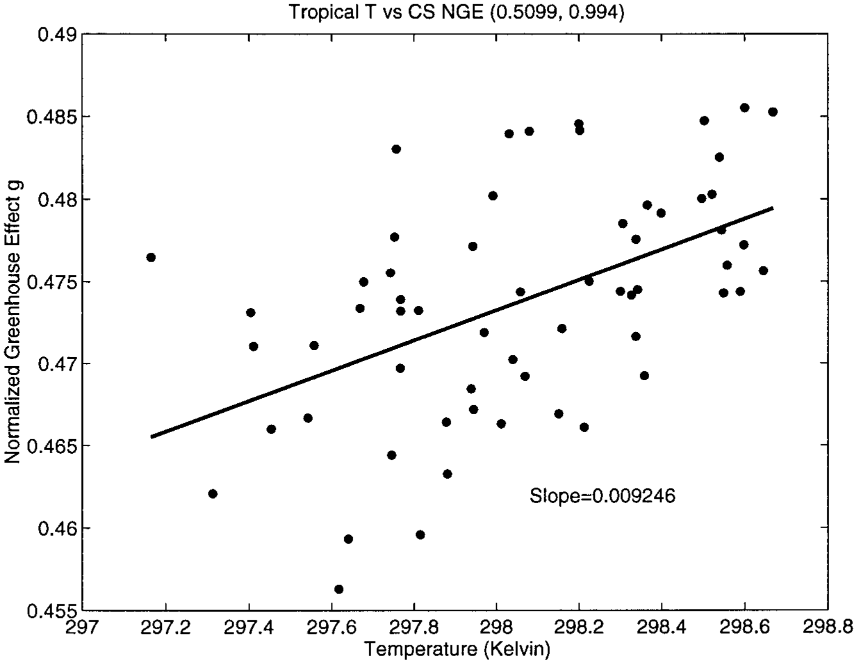

FIG. 7. Scatterplot of monthly values of tropical means of *g*, the greenhouse gain, and surface temperature, from TOVS.

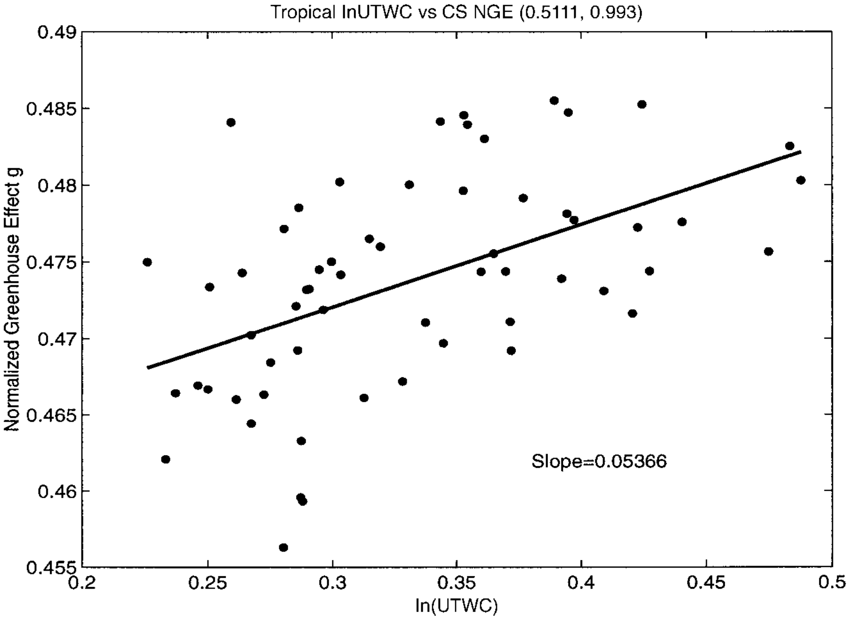

FIG. 8. Scatterplot of monthly values of tropical means of *g*, the greenhouse gain, and the natural logarithm of the upper-tropospheric precipitable water content, from TOVS.

statistically significant, at more than 99% confidence level, as will be shown in the appendix.

In Fig. 6, we plot the tropical area average of the natural logarithm of TOVS precipitable water content in the upper troposphere (500h–300-hPa layer) versus the tropical area average of surface temperature. The logarithm is taken locally of the water-vapor content before the area averaging is taken. The correlation coefficient of 0.47 is statistically significant at 99% confidence level. Thus it appears that when the tropical-mean surface warms, the upper troposphere is moistened in the net, in terms of *specific humidity.*

5. The greenhouse effect

The TOVS dataset also contains OLR. Susskind (1996) compared TOVS OLR against the OLR values determined by the Earth Radiometer Backscatter Experiment (ERBE) team using the ERBE instruments on the *NOAA-10* satellite and claimed excellent agreement. The TOVS dataset is used here for convenience in correlative studies.

The normalize clear-sky greenhouse effect g is defined by

$$1 - g = (\mathrm{OLR} - \mathrm{LWF})/(\sigma T^4),$$

where OLR is TOVS total OLR, LWF is TOVS longwave cloud radiative forcing (or the difference between the cloudy and clear-sky OLR), σ is the Stefan–Boltzmann constant, and T is the TOVS surface-skin temperature.

In Fig. 7, the tropical area average of g and surface temperature T are plotted in a scatterplot. The two quantities are positively correlated. The correlation coefficient, at 0.51, is statistically significant at the 99.7% confidence level.

Consistent with the pioneering work of Raval and Ramanathan (1989), we also find that local (and zonal mean) surface temperature is highly correlated with local (and zonal mean) natural logarithm of the upper-tropospheric precipitable water content (not shown). The latter is also locally highly correlated with the greenhouse effect g (not shown). This appears to demonstrate that the positive correlation found between surface warming and the enhanced greenhouse effect is primarily caused by the moistening of the upper troposphere. The same holds true in the tropical area average. Figure 8 shows the correlation of the tropical area mean of the natural logarithm of upper-tropospheric precipitable water content and the greenhouse effect g. The correlation, at 0.51, is statistically significant at the 99.3% confidence level.

6. Conclusions

Our results, based on statistical analysis, demonstrate that the upper troposphere is *moistened*, in terms of specific humidity, when the surface *warms*. This occurs not just locally, as previous authors have shown, but also in the net, when averaged over the whole Tropics, taking into account the compensating drying effects in the downdraft region. Furthermore, as the surface warms in the area mean, the area-mean outgoing longwave radiation decreases, which is an indication of the enhanced greenhouse effect due to surface warming.

The mechanism of this possible positive feedback appears to be related to deep convection. Combining the present result with the results from other authors reviewed in section 1, it appears likely that increases in SST lead to increases in deep convection frequency locally, that such local events moisten the upper troposphere in the net, and that such net increases in water-vapor content finally lead to the enhanced greenhouse effect.

It is not clear if the present results based on short-term records can be extrapolated to the longer timescales associated with global climate change. Currently, the favored approach is to use GCMs for predicting the longer timescale variations and to use observational data to validate the models. It is probably not sufficient to just compare the observed and modeled local relationships, since the global (or tropical) means may behave differently. For example, although upper-tropospheric *relative* humidity was found to be highly correlated *locally* with the frequency of deep convection, a corresponding relationship does not exist between the *tropical means* of these two quantities. It is hoped that the relationship found here in the tropical-mean data can be useful for the validation of future GCMs designed for global warming studies. The degree of coupling between the tropical-mean upper-tropospheric water vapor and the tropical-mean surface temperature in the observational data can be read in the slope of the correlation charts provided. It appears to be consistent with the GFDL GCM. However, the large scatter in the observational data prevents us from drawing a more quantitative conclusion at this time. Specifically, we cannot tell with any degree of confidence whether the degree of coupling is less than that arising from a fixed relative humidity assumption. Some data points show a higher degree of coupling, while others show a lesser degree. Given the quality of the data available, a more involved statistical analysis on such a quantitative issue may not be warranted at this time.

It should also be pointed out that Spencer and Braswell (1997) recently presented evidence on the extreme dryness of the upper-troposphere dry regions and suggested that many datasets, including the ones used in the present study, may have a moist bias. Our calculations need to be repeated later when newer, and possibly more accurate, data become available.

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APPENDIX

Statistical Significance

A commonly used test for statistical significance of correlation coefficient r is the standard Student's t-test:

For n samples of random variables with bivariate normal distribution,

$$t_{n-2} \equiv \frac{\sqrt{n-2}\,r}{\sqrt{1-r^2}} \tag{A1}$$

has a t distribution with degrees of freedom $n - 2$. Under such a test, an absolute value of at least 0.26 is needed for r to be statistically significant at 95% for $n = 60$.

The standard t-test may overstate statistical significance in the present case because the time series of both water vapor and temperature show serial correlation (or persistence), which is common for meteorological data. Figure A1 shows the lag-1 scatterplot for the tropical-mean monthly NVAP upper-troposphere water vapor content data. A linear correlation is evident for the monthly data. The correlation (lag-1 autocorrelation) coefficient is 0.62. This persistence in data series violates the assumption for the Student's t-test for correlation coefficient. A remedy to this problem sometimes used in the literature is to estimate the actual (linearly independent) degree of freedom in the data series to account for autocorrelation. However, there is no hard rule for accomplishing this. For example, Soden and Fu (1995) assumed that every other monthly tropical-mean value is statistically independent based upon the e-folding time of the autocorrelation. This estimate is less than that estimated by assuming the data to follow a first-order autoregressive process.

The following formula may be helpful in estimating the effectively independent sample size. Under the assumption that the underlying data follow a first-order autoregressive process, the time between *effectively independent samples* can be estimated by

$$T_0 = \frac{1 + r_1}{1 - r_1}, \tag{A2}$$

where r_1 is the lag-1 autocorrelation coefficient of the data series (Wilks 1995). Although this formula is derived for estimating the variance of sample mean, we can nevertheless obtain some guidance from it for estimating the effectively independent sample size, which can be used as the degree of freedom in our case. The lag-1 autocorrelation coefficient r_1 is 0.62 for tropical-mean humidity data. Equation (A2) then suggests that the tropical-mean humidity data are effectively independent every 4 months.

If we accept the estimate that the humidity data are effectively independent every 4 months, then the degree of freedom is about 15 for the 5-yr monthly water vapor series. If such an estimate is used for $n - 2$ in the Student's t-test, the correlation coefficient needs an absolute value of 0.49 to be statistically significant at the 95% confidence level for 5 yr of data ($n = 60$). Under the same assumption, the degree of freedom is about 12 for $n = 46$; the correlation coefficient for that case needs an absolute value of 0.54 to be statistically significant at the 95% confidence level. Soden and Fu used 46 months of data in their calculation of the tropical-mean correlation between TOVS UTH and frequency of deep

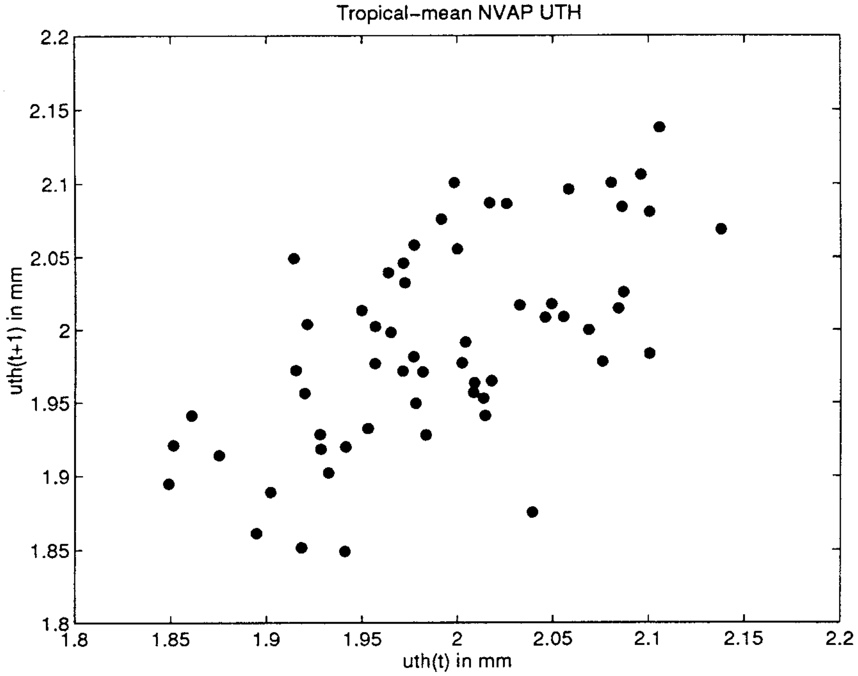

FIG. A1. Lag-1 scatterplot for the tropical-mean monthly NVAP upper-tropospheric water vapor content data.

convection. The correlation coefficient of 0.45 that they found is below the requirement stated above.

A more versatile and also often used procedure that can be applied to many statistical tests is the Monte Carlo simulation. This is the method adopted in the present study. Here we first generate 2000 artificial data series $\epsilon(t)$ from normal distribution. Five percent of the correlation coefficients between $\epsilon(t)$ and the tropical-mean NVAP UTH exceeds 0.26 in absolute value. Similarly, 5% of the correlation coefficients between $\epsilon(t)$ and the global-mean surface temperature exceeds 0.25 in absolute value. Thus a correlation coefficient exceeding 0.26 can presumably be considered as statistically significant at the 95% confidence level. However, these simple calculations may overstate the significance, because, just as in the standard Student's *t*-test, they fail to account for the autocorrelation in the data series.

To take into account the autocorrelation present in our data series, we first represent the data series by autoregression models of order *m*, AR(*m*). The model order *m* is selected using Akaike information criterion, while the model parameters are determined by the Yule–Walker equations (see Wilks 1995) for each time series used. As a result of this procedure, the tropical-mean water vapor content data is found to be represented by the following AR(1) model:

$$x(t) = \phi x(t - 1) + \epsilon_1(t), \qquad \text{(A3)}$$

where the autocorrelation parameter ϕ is determined separately for each time series. The tropical-mean surface temperature series is represented by the following AR(2) model:

$$y(t) = \phi_1 y(t - 1) + \phi_2 y(t - 2) + \epsilon_2(t), \qquad \text{(A4)}$$

where ϕ_1 and ϕ_2 are also determined separately for each time series. The $\epsilon_1(t)$ and $\epsilon_2(t)$ in Eqs. (A3) and (A4) are the residuals in the models for the data series.

We then generate artificial data series using models represented by Eqs. (A3) and (A4), except now with ϵ_1 and ϵ_2 replaced by $\epsilon(t)$ drawn from the normal distribution for random numbers. Two thousand artificial water vapor and temperature data series are generated. For example, the correlation coefficient between *x* and actual global-mean surface temperature is found to exceed 0.35 in absolute value in 5% of the 2000 cases. The correlation coefficient between *y* and actual tropical-mean NVAP upper-troposphere water vapor content data exceeds 0.55 in absolute value in 5% of the test cases. These tests suggest that the actual correlation between tropical-mean NVAP upper-troposphere water vapor content and global-mean surface temperature series is statistically significant at the 95% confidence level only if the correlation coefficient exceeds 0.55 in absolute value. Statistical significance for other time series are determined in a similar fashion. Note that using Eqs. (A3) and (A4) to represent humidity and temperature data gives a lower but more realistic estimate of the significance than the test using purely random numbers.

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