LETTERS

Decadal Variations in Tropical Water Vapor: A Comparison of Observations and a Model Simulation

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ABSTRACT

Multiple satellite records of tropical-mean water vapor are compared with a general circulation model (GCM) simulation to assess the ability to monitor and to predict low-frequency changes in total precipitable water. Particular attention is focused on the drying between 1979 and 1995 recorded by a TOVS statistical retrieval that is calibrated to radiosondes. Both a GCM integrated with observed SSTs and microwave and TOVS physical retrievals that overlap the drying period show no sustained drying. This discrepancy is consistent with the suggestion by Ross and Gaffen that the TOVS statistical algorithm is vulnerable to radiosonde instrumentation changes over this period that introduce an artificial drying trend into the retrieval.

1. Introduction

It is widely believed that water vapor amounts will increase in response to global warming (Held and Soden 2000). Climate models predict that the column-integrated water vapor, or total precipitable water W, will increase by ~7% per 1°C increase in surface temperature (Garratt et al. 1999). Consequently, if the global warming in response to a doubling of carbon dioxide approaches the upper range of current model predictions (~4.5°C), water vapor amounts could increase in excess of 20% during the next half-century. This amplified moistening in response to a surface warming not only highlights the importance of water vapor feedback in determining the climate sensitivity of GCMs, it also underscores the importance of long-term monitoring of water vapor to the detection and attribution of climate change.

Despite its obvious importance, there have been relatively few observational studies of the long-term variations or trends in water vapor. Moreover, there have been few, if any, attempts to compare observed trends against model-predicted trends or to intercompare observed trends from different observing systems. A few recent studies have used radiosonde observations to demonstrate the presence of generally positive moisture trends over select regions of the globe, including the United States, China, and the western tropical Pacific (Gaffen et al. 1991; Ross and Elliott 1996; Gutzler 1996; Zhai and Eskridge 1997). Unfortunately, the lack of radiosonde observations over most ocean and less-developed land areas limits the accuracy of global or even tropical water vapor trends. More significant, changing to more-responsive instruments introduces spurious drying that can substantially affect the inferred trends (Gaffen et al. 1991; Ross and Gaffen 1998).

Satellite measurements have provided near-global observations of water vapor since the late 1970s. However, changes in the orbit, calibration, or spectral response function of the instruments from one satellite to the next can introduce inhomogeneities in a combined multisatellite record. Fortunately, the timing of satellite instrument changes is precisely documented, even if the effects of these changes are not. Nevertheless, the lack of a consistent, intercalibrated satellite product has limited the use of such observations for trend detection.

Only one study has even attempted to assess the long-term moisture trends from satellites prior to 1987 (Schroeder and McGuirk 1998, hereinafter SM98). This study used radiance observations from the Television Infrared Observational Satellite (TIROS) Operational Vertical Sounder (TOVS) to derive W for the period 1979–95 and, in contrast to regional studies, found a distinct drying after 1988 in the Tropics. SM98 accounted for changes in satellites by statistically regress-

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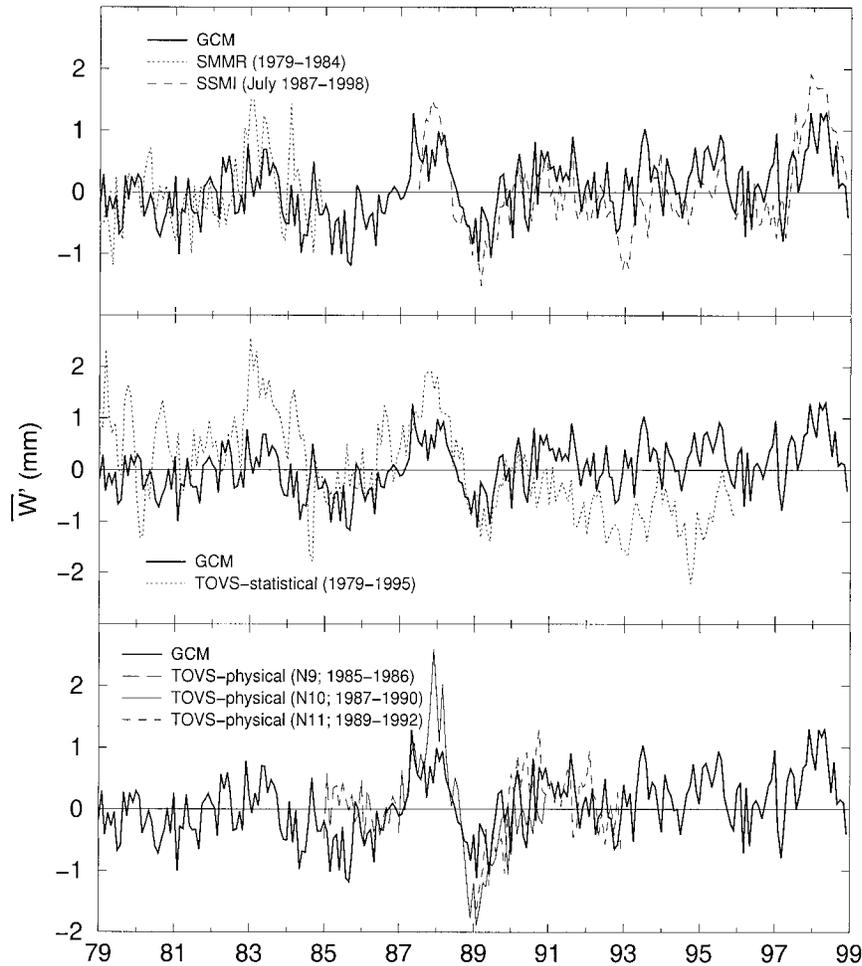E-mail: bjs@gfdl.gov

FIG. 1. Comparison of the interannual anomalies of tropical-mean precipitable water $\overline{W}'$ from GCM simulations (solid) with satellite observations from SMMR and SSM/I (top), TOVS statistical retrieval (middle), and TOVS physical retrieval (bottom) for 1979–98.

ing the satellite measurements to contemporaneous radiosonde observations. Although careful efforts were made to eliminate possible biases from this algorithm, Ross and Gaffen (1998) argued that instrumentation changes in the radiosonde record used by SM98 introduced artificial drying trends into their retrieval.

In this study, multiple satellite records of W are compared with a GCM simulation to assess the current state of our capabilities to monitor and to predict long-term changes in water vapor.

2. Comparison of observed and model-simulated anomalies

This study uses three primary sources of satellite observations: 1) microwave retrievals of W from the Scanning Multi-Channel Microwave Radiometer (SMMR) and Special Sensor Microwave Imager (SSM/I) as derived by Wentz and Francis (1992) and Wentz (1997), respectively; 2) TOVS retrievals of W using the statis-

tical algorithm of SM98, hereinafter referred to as TOVS statistical; and 3) TOVS retrievals of W using the physical algorithm of Susskind et al. (1997), hereinafter referred to as TOVS physical. These observations are compared with the W simulated by a version of the Geophysical Fluid Dynamics Laboratory GCM that has been integrated with observed SSTs from 1979 to 1998. Details about this model and the boundary conditions used for its integration are provided by Lau and Nath (2000). Given the discrepancy between SM98 and previous studies, this comparison will focus on variations in the tropical-mean (30°N–30°S) total precipitable water $\overline{W}$, where the overbar indicates tropical averaging. Because microwave retrievals of W are only performed over ocean surfaces (which compose roughly 70% of the Tropics), all comparisons are restricted to ocean-only averages.

Figure 1 compares the time series of monthly-mean anomalies in total precipitable water averaged over the tropical oceans, denoted as $\overline{W}'$. For clarity, the com-
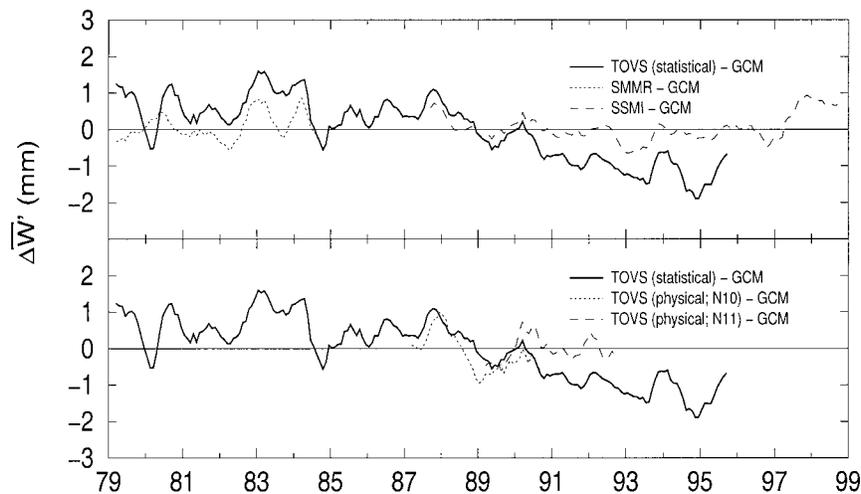
FIG. 2. Comparison of the difference in monthly anomalies of tropical-mean precipitable water $\Delta\overline{W}'$ for a satellite retrieval minus the GCM simulation. The top panel compares the TOVS-statistical and microwave retrievals with the GCM simulations. The bottom panel compares the TOVS-statistical and TOVS-physical retrievals (for *NOAA-10* and *NOAA-11* only) with the GCM simulation. For clarity, all time series have been smoothed using a six-month running mean.

parison with each kind of satellite retrieval is presented in a separate panel. The GCM anomalies are computed using a base period of 1979–95 in all panels. In principle, the GCM anomalies should be recomputed for each comparison using the satellite data period as the base period, but the anomalies are nearly identical in all cases. First we consider the comparison between the GCM simulation and microwave-based retrievals (Fig. 1, top). Note that the SMMR data are composed of observations from a single instrument, whereas the SSM/I retrievals are a calibrated product from multiple instruments (Wentz 1997). The GCM values of $\overline{W}'$ agree well with the satellite retrievals during both the SMMR (1979–84) and SSM/I (1987–98) periods of record. Similar agreement is found when comparing the GCM simulations with the National Aeronautics and Space Administration Water Vapor Project dataset (Randel et al. 1996; not shown), which is also largely based on SSM/I measurements (over oceans) but uses a different retrieval algorithm. These results also support the contention by Wentz and Schabel (2000) that interannual variations in $\overline{W}$ over the last decade are consistent with an idealized model that maintains a constant relative humidity.

In contrast to the microwave retrievals, comparison of the GCM and TOVS-statistical anomalies (middle) shows a clear discrepancy between the two records. In particular, the TOVS-statistical retrievals show a much larger moistening in response to the 1982–83 El Niño event than is simulated in the GCM. The two records are relatively consistent from 1985 to 1989, showing the moistening during the 1987–88 El Niño and drying during the 1985 and 1989 La Niña events. After 1989 the two time series again diverge, with the TOVS-statistical algorithm showing 1–2 mm less water vapor than is simulated by the model by the mid-1990s. Figure 2

reveals the long-term drifts of the satellite retrievals relative to the GCM simulations. The GCM anomalies are subtracted from each of the satellite-retrieved anomalies (e.g., $\Delta\overline{W}' = \overline{W}'_{sat} - \overline{W}'_{GCM}$) and then smoothed using a 6-month running average. In the top panel, the TOVS-statistical retrieval dries relative to the GCM in 1984 and then shows a persistent drying trend after 1989. Neither SMMR nor SSM/I show long-term drifts relative to the GCM. The above comparisons make two key points. First, the TOVS-statistical retrieval differs from the SSM/I retrieval in a manner that is qualitatively consistent with the spurious dry biasing of the statistical algorithm (caused by radiosonde instrument changes) proposed by Ross and Gaffen (1998). Second, the GCM simulation is much more consistent with the microwave retrievals than with the TOVS-statistical retrieval.

These results are supported by comparison with the TOVS-physical retrievals (Figs. 1, 2 bottom), which are available from January 1985 to December 1993. The products are not calibrated between satellites, and therefore the anomalies are presented individually for each satellite (*NOAA-9, -10,* and *-11*). The base periods used to compute the anomalies correspond to the period of observation for each satellite. Although the records are much shorter than the statistical retrieval, both the *NOAA-10* and *NOAA-11* satellites offer 4 yr of observations that overlap the period during which the GCM and TOVS-statistical retrievals diverge. Like the SSM/I data, the TOVS-physical retrievals of $\overline{W}'$ are more consistent with the GCM anomalies and do not support the shift toward drier conditions after 1989 suggested by the statistical retrieval. Although the data presented are for tropical ocean-only averages of the TOVS statistical and physical retrievals, similar discrepancies are noted over tropical land regions (not shown). Thus both the

microwave and TOVS-physical retrievals offer independent evidence suggesting that the long-term drying trend in the TOVS-statistical retrieval may be an artifact of radiosonde instrumentation changes as suggested by Ross and Gaffen. All retrievals also suggest a tendency for the model to underestimate the tropical moistening during El Niño events (e.g., 1982–83, 1987–88, and 1997–98). The model tends to do better in capturing the drying associated with the 1988–89 La Niña, although the magnitude of the anomalies is still smaller than observed. The smaller anomalies may partly reflect the model's dry bias, which causes it to contain 15%–20% less water vapor in the Tropics than is observed. Thus, comparing the relative anomalies produces somewhat better agreement with the observations but does not totally compensate for the dampened response of the model.

3. Discussion

This study intercompares multiple satellite records of tropical-mean water vapor with GCM simulations to assess the current state of our capabilities to monitor and to predict long-term changes in water vapor during the last two decades. The chief results of this comparison are as follows.

1) The shift toward drier conditions from 1979 to 1995 recorded by the TOVS-statistical retrieval is not supported by either microwave or TOVS-physical retrievals. This discrepancy is qualitatively consistent with the argument by Ross and Gaffen (1998) that the TOVS-statistical algorithm is vulnerable to radiosonde instrumentation changes over this period that introduce an artificial drying trend.
2) The GCM simulations also show no drying trend and agree better with the microwave and TOVS-physical retrievals than with the TOVS-statistical retrievals.
3) All satellite retrievals suggest a tendency for the GCM to underestimate the magnitude of tropical moistening associated with the 1982–83, 1987–88, and 1997–98 El Niño events.

Additional efforts are needed to understand fully the cause of the discrepancy between the TOVS-statistical retrievals and the other records. The lack of a long-term (multiple decade) temporally homogenous dataset hampers efforts to monitor the atmosphere and to assess the model's predictive skills. Indeed, it seems premature to conclude whether any of the data sources provides a definitive assessment of the trends over this period. Two strategies are being pursued to resolve this problem.

One effort, currently in progress, systematically searches the time series of multiple variables from nearly all radiosonde stations to identify characteristic signatures of instrument changes documented in Gaffen (1996). Consistent, steplike changes occur in certain variables coincident with known instrument changes, and similar signals can identify the nature and timing of instrument changes for stations with incomplete station history. Over 30 sets of adjacent stations with differing instrumentation can be used to quantify the timing and effect of instrument changes better.

Unfortunately, the highly variable nature of water vapor can make it difficult to separate instrumentation changes from natural fluctuations unambiguously. Therefore, a second approach will intercompare collocated radiosonde and satellite observations. By examining the difference between radiosonde-computed and satellite-observed radiances, one can greatly reduce the (common) natural variability and highlight temporal discontinuities in their record that may be associated with changes in either the radiosonde or satellite instrumentation. This strategy has been shown to be successful for identifying spatial discontinuities in the radiosonde network (Soden and Lanzante 1996) and should be equally well suited for examining temporal discontinuities.

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