Correlations Between SSM/I Column Vapor and MSU Tropospheric Air Temperature on Seasonal, Interannual, and Decadal Time Scales

Matthias C. Schabel, Carl A. Mears, and Frank J. Wentz
Remote Sensing Systems
438 First St., Suite 200
Santa Rosa, CA 95404

ABSTRACT

Time series of total atmospheric column water vapor as determined from SSM/I measurements and tropospheric air temperatures from a complete reanalysis of the MSU channel 2 record are analyzed on various spatial and temporal scales in order to elucidate corresponding correlations between these two climate change proxies. Strong correlations between spatial averages over complete circulation systems are observed on time scales ranging from seasonal through interannual to decadal, with the vapor/temperature scaling largely consistent with that expected from the Clausius-Clapeyron thermodynamic relation. As the temperature-water vapor feedback is a critical element in warming amplification by greenhouse gas heat trapping, with much of the variability in global circulation models climate response estimates arising from different vapor parameterizations, application of a hierarchy of correlation and fingerprinting techniques utilizing these two highly stable and precise observational data sets should enable significant improvements in comparative validation of competing model treatments of the T-V feedback dynamics.

SATELLITE DATA AND TIME SERIES METHODOLOGY

SSM/I Integrated Water Vapor

The 1987-2001 water vapor time series is a newly derived climate product based on Special Sensor Microwave Imager (SSM/I) data from satellite radiometers flying on polar orbiting platforms operated by the Defense Meteorological Satellite Program (DMSP). SSM/I measures the Earth's upwelling microwave radiation at 19, 22, 37 and 85 GHz. The 22 GHz channel, centered on a weak water vapor absorption line, enables precise measurements of integrated column water vapor, W. Remote Sensing Systems' Version 5 algorithm matches observations to a radiative transfer model to estimate W given the measured SSM/I upwelling brightness temperature, T_B. The retrieval of W depends on the high contrast between the radiometrically cold sea-surface and warm water vapor, so retrievals are currently only feasible over the oceans (Wentz 1997) due to the lack of accurate models of land surface emissivity. The effective height of the water vapor retrieval is roughly 2.3 km, with the vast majority of total atmospheric water being contained in the lower troposphere.

SSM/I observations are available twice daily on a 0.25° grid (http://www.remss.com) with local crossing times around 06:00 and 18:00. Typical rms differences between the SSM/I retrieved water vapor and radiosonde measurements are 10-15%, the bulk of which arises from the spatial and temporal sampling mismatch between the large satellite footprint (44 km) and point radiosonde observations (Wentz 1997). Error analysis indicates that the rms accuracy of the SSM/I vapor retrieval for a single 44-km footprint is approximately 4%. Zonal and diurnal averaging further reduces noise levels of the vapor time series.

The first SSM/I (F08) was launched in June 1987, with four subsequent imagers becoming operational in January 1991 (F10), January 1992 (F11), May 1995 (F13), May 1997 (F14), and XXX (F15). Series of data from the six satellites are inter-calibrated at the antenna temperature level using a merging algorithm similar to that recently developed for merging MSU temperature records. Monte Carlo simulations of the sensitivity of computed global decadal trends to uncertainty in these offsets give a estimated accuracy of ±0.5%/decade at the 95% confidence level.

MSU Lower Tropospheric Air Temperature

MSU (Microwave Sounding Unit) measurements are available beginning with the TIROS-N platform in 1979, with subsequent MSUs on the NOAA-6/7/9/10/11/12/13/14 satellites. These instruments measure microwave brightness temperature in four channels spanning the oxygen absorption bands in the 50-60 GHz frequency window using passive radiometers similar to those on the SSM/I instruments. Since atmospheric oxygen is well-mixed throughout the troposphere and stratosphere, frequencies with strong oxygen absorption allow direct measurement of thermal emission corresponding to various vertically weighted atmospheric temperature profiles (Spencer et al. 1990). MSU channel 2 (53.74 GHz), which forms the basis of our middle tropospheric temperature retrieval, has a broad weighting function centered at approximately 7 km but retains appreciable weight from the surface well into the stratosphere (Spencer and Christy 1992a, Mears et al. 2002). Time series data presented in this paper use monthly gridpoint MSU2 derived from a complete reanalysis of this data set performed at Remote Sensing Systems (Mears et al. 2002), which avoids complications in the so-called MSU2R lower tropospheric retrieval developed by Spencer and Christy (Christy et al. 1998a, Wentz and Schabel 1998). This new data set is freely available for download at http://www.remss.com.

SATELLITE VAPOR AND TEMPERATURE CROSSTALK

Satellite retrievals of T_A and W all derive from measurements of brightness temperature, in either the infrared or microwave, which depend implicitly on each other as well as sea-surface temperature. Each instrument focuses on a spectral window in which the sensitivity to the physical quantity of interest is high and sensitivity to the other two is minimized. However, the retrieval algorithms are not able to perfectly remove residual crosstalk error arising from the effects of non-retrieved parameters on the retrieved ones, making it important to consider the interplay between parameters.

To remove T_S and T_A crosstalk, the SSM/I vapor algorithm uses the the Reynolds Optimally Interpolated Sea Surface Temperature (OISST) data base to specify T_S (Reynolds et al. 1994) and a statistical relationship, derived from radiosondes (Gaffen et al. 1992b, Wentz 1997) to specify T_A as a function of W. While the SST adjustment should accurately account for long-term drift in SSTs, when the physical variation of T_A differs from the assumed relationship, inaccuracies can be introduced into the retrieved values of W. We estimate the retrieval algorithm's sensitivity to observed seasonal and interannual variations in T_A using a highly refined radiative transfer model (RTM) for emission and atmospheric attenuation of microwave emission over the ocean surface. Two sets of T_B's are calculated from the RTM for a variety of random ocean scenes: one using nominal values for W, T_A, and T_S and a second assuming a 1 K increase in T_A. When these simulated T_B's are processed by the SSM/I algorithm, the water vapor retrieval is found to overestimate the true change in W by 9%, with a retrieved value of 7.1% rather than the actual change of 6.5%. Direct comparison of the seasonal amplitudes of radiosonde observations with those of collocated SSM/I vapor retrievals reveals a similar amplification factor. This spurious magnification of the variability in retrieved values of W has been removed from values of seasonal and biannual amplitudes, interannual variability, and decadal trends in W discussed here in order to improve the correspondence between variability in W and that in T_A.

For MSU2 data no correction is made for water vapor crosstalk, while the effect of T_S is removed using the modeled sensitivity. The effect of water vapor is small due to weak vapor absorption in the MSU frequency window; radiative transfer simulations indicate that the typical water vapor crosstalk error in lower tropospheric temperature is ~0.012 K/mm. Compared to the temperature signal, this will have a negligible effect on the seasonal and interannual trends of T_A. The T_S crosstalk term is also small at ~0.08 K/K, but is not negligible. For example, using the observed T_S trends to remove crosstalk from T_A results in a 5% decrease in the seasonal amplitude and a 0.01 K/decade decrease in the trend.

CALIBRATION DRIFT

Drifts in satellite radiometer calibration are a significant concern in studies involving long-term satellite data records as these can lead to the appearance of spurious values for trend estimates. For the AVHRR instruments, large drifts have been observed which are corrected by blending the satellite retrievals with *in situ* observations from buoys and ships.(Reynolds et al. 1989) Both the SSM/I and MSU radiometers are externally calibrated with warm and cold loads, which are each measured once per scan. The temperature of the warm load is monitored by precision thermistors, while the cold load measures the cosmic background temperature (2.7 K). Unfortunately, because the calibration assumes linearity in the instrument response over a range of temperatures which is much broader than the measurement range in operational mode, nonlinear biases can lead to errors in absolute calibration (Mo 1995). Furthermore, in spite of the robust calibration systems, small instrumental drifts have been noted in, for example, the F10 SSM/I as well as a number of MSU instruments, particularly on NOAA afternoon platforms. These drifts appear to be related to diurnal temperature gradients within the radiometer which change the nonlinear response of the front-end receivers. Because the satellites inevitably experience drift in their local equator crossing time over their life span, these diurnal fluctuations can result in a spurious long-term drift in the retrieved parameters.

Multiple simultaneous observations from independent but otherwise identical instruments, such as are available for SSM/I, allow the discrimination and, in conjunction with surface data, elimination of such drifts through a regression procedure using the instrument target temperature as a prognostic variable (Mears et al. 2002). For the MSU record, empirical diurnal corrections, which must be applied to account for the diurnal variation of temperature across the swath, may compensate for these problems (Christy et al. 1998b, Mears et al. 2002), though the adequacy of these corrections remains a topic of debate. In addition, the fact that the NOAA operational platforms alternate between morning and afternoon orbits means that there no intervals of cotemporaneous observations from multiple satellites, further complicating the data analysis.

TIME SERIES AND DATA ANALYSIS

Time series of water vapor and tropospheric temperature are generated in a consistent manner in order to facilitate their comparison. Gridded data sets (0.25°×0.25° daily W and 2.5°×2.5° monthly T_A) are resampled to a common 2.5°×2.5° degree resolution (with the SSM/I data downsampled by averaging over blocks of 100). Series are generated using the exact observation time, accurate to within +/- 3 minutes for SSM/I and to 2.5 seconds for MSU. Observations with measurable rain which could bias the vapor retrieval algorithm are excluded from series of W. While this procedure could, in principle, lead to a sampling bias in the area-averaged results, in practice the resulting time series are sufficiently oversampled in even the rainiest regions that an adequate fraction of the observations remains for stable regressions. Zonal time series are generated by averaging the resampled 2.5° gridpoint data over longitudes, while hemispheric and global series are computed as latitude and ocean area-weighted averages of zonal series.

Regression Analysis

In order to separate the data into seasonal, biannual, interannual anomaly, and long-term trend contributions, time series of the parameter P = W | T_A are fit by linear regression to an expression of the form:

$$r_P(t) = \alpha_{P0} + \beta_P(t - \overline{t}) + \sum_{k=1}^{2} \alpha_{Pk} \sin\left(2\pi kt + \phi_{Pk}\right),$$

where $r_P(t)$ is the regressed fit to the observed data, $f_P(t)$, and α_{P0}, β_P, α_{Pk}, and ϕ_{Pk} are regression coefficients for the mean value, linear trend, and seasonal and biannual amplitude and phase, respectively, and $\bar{t}$ is the mean time for the interval (Wilks 1995, Ch. 8). Anomaly time series, $\hat{f}_P(t)$, which represent the interannual and long-term variability, are generated by subtracting the regressed mean, seasonal, and biannual cycle from $f_P(t)$, leaving the secular linear trend. Previous studies have demonstrated that the bulk of the total variance in time series of temperatures and water vapor is explained by the first two harmonics of the seasonal cycle (Trenberth 1983, Bony and Duvel 1994). Furthermore, for time scales of climatological interest it is unlikely that higher frequency components will be relevant. Gridpoint maps of the regression coefficients are generated for the period from July 1987 through December 2001 (for which data from both instruments are available) by regressing to the time series in an individual 2.5° latitude/longitude cell. Zonal values are derived from regression to the corresponding zonally averaged mean time series.

SCALING RELATIONS

Simple thermodynamic arguments based on the Clausius-Claypeyron equation and the observation that relative humidity in the atmosphere is generally weakly varying form the basis for water vapor feedback parameterizations in most GCMs. Over the past few years much study has been devoted to the question of water vapor greenhouse feedback and the validity of the assumption of constant RH, in which it has been convincingly demonstrated that the spatial and temporal variations in the distribution of water vapor cannot be explained simply by the observed statistical relationship between W and T_S (Stephens 1990, Wentz 1997). In particular, radiosonde and satellite data show strong seasonal variations of RH in the tropics over both land and ocean, accompanied with seasonal changes in vertical distribution of vapor, which are clearly inconsistent with the assumption of constant RH. Investigations of the clear sky greenhouse effect have demonstrated the importance of changes in vertical distribution of water vapor as well as variations in tropospheric lapse rate (Webb 1993). Despite the fact that satellite-inferred columnar vapor primarily samples the lower troposphere where its radiative effect may be mitigated by convective transport through the boundary layer (Lindzen 1990), radiative transfer studies of the effects of vertical redistribution of water vapor suggest that the net heat-trapping effects of atmospheric vapor scale with total columnar content (Shine and Sinha 1991), although this issue is not yet entirely resolved (Spencer and Braswell 1998). However, on sufficiently coarse spatial scales, particularly when averaging over entire atmospheric circulation systems, the water vapor feedback cycle appears to behave in a manner which is consistent with simple thermodynamic laws (Wentz and Schabel 2000). This observation does not invalidate earlier observations, but instead demonstrates that, when viewed as a coarse-grained system, the mean behavior of this feedback cycle is relatively simple over a range of time scales.

Gaffen has exhaustively analyzed variability of tropospheric water vapor on seasonal through decadal time scales based on a set of radiosonde observations selected for their temporal homogeneity and lack of significant changes in instrumentation (Gaffen 1992a, 1992b, 1992c). Five qualitatively different atmospheric regimes were identified based on temperature and humidity response of the upper air data. It was observed that the mid-latitude regimes show qualitatively similar behavior, with little annual variation and an essentially monotonic decrease in RH with pressure for each of four levels studied (surface, 850mb, 700mb, and 500mb). In contrast, the data over tropical oceans show a nearly constant RH in the lower atmosphere (surface-850mb) which is largely decoupled from the much drier and more variable upper layers showing significant convection-driven fluctuations corresponding to seasonal changes in vapor scale height (Spencer and Braswell 1998). Various other studies have made similar observations that sea surface temperature and precipitable water are relatively well correlated with each other and agree to a reasonable extent with Clausius-Clapeyron behavior in the extratropics, but that variations in W in the tropics are primarily driven by fluctuations in RH rather than T_S, and show much weaker correlation there (Stephens 1990, Gaffen et al. 1992b, Bony and Duvel 1994). A detailed climatological analysis of seasonal changes in the vertical distribution of RH derived from radiosonde data from 1973-1988 also reveals that the most significant seasonal fluctuations in RH are restricted to the tropics (30°S-30°N) where discrepancies are the greatest, and occur primarily between 300-800mb (Peixoto and Oort 1996).

We will present results elaborating on the work presented in Wentz and Schabel 2000, with particular emphasis paid to the existence of strongly correlated spatial patterns of variation between vapor and temperature on a hierarchy of time scales. In addition to providing a set of frequency-dependent fingerprints for model validation (del Genio et al. 1991, Hansen et al. 1997), this work is relevant to the question of long-term teleconnections and their linkage to similar patterns of variability on shorter intervals.

ACKNOWLEDGEMENTS

The production of the SSM/I water vapor data set is being funded under NASA's Earth Science Pathfinder Program, Contract NASW-5038. The MSU reanalysis was funded by the NOAA Climate and Global Change Program and the joint NASA/NOAA Enhance Data Set Project.

8. REFERENCES

Bony, S. and J.-P. Duvel, 1994 : Influence of the vertical structure of the atmosphere on the seasonal variation of precipitable water and the greenhouse effect, **JGR 99**, 12963-12980.

Christy, J.R., R.W. Spencer, and W.D. Braswell, 1997 : How Accurate are satellite 'thermometers'?, **Nature 389**, 342-342.

Christy, J.R., R.W. Spencer, and E.S. Lobl, 1998a : Analysis of the merging procedure for the MSU daily temperature time series, **J. Clim. 11**, 2016-2041.

Christy, J.R. and R.W. Spencer, 1998b, private communication.

Del Genio, A.D., A.A. Lacis, and R.A. Ruedy, 1991 : Simulations of the effect of a warmer climate on atmospheric humidity, **Nature 351**, 382-385.

Gaffen, D.J., 1992a : Observed annual and interannual variations in tropospheric water vapor, NOAA Technical Memorandum ERL ARL-198, United States Department of Commerce (Silver Spring).

Gaffen, D.J., W.P. Elliott, and A. Robock, 1992b : Relationships between tropospheric water vapor and surface temperature as observed by radiosondes, **GRL 19**, 1839-1842.

Gaffen, D.J., A. Robock, and W.P. Elliott, 1992c: Annual cycles of tropospheric water vapor, **JGR 97**, 18185-18193.

Hansen, J.E., M. Sato, R. Ruedy, A. Lacis, and J. Glascoe, 1998 : Global climate data and models: a reconciliation, **Science 281**, 930-932.

Hurrell, J.W. and K.E. Trenberth, 1997 : Spurious trends in satellite MSU temperatures from merging different satellite records, **Nature 386**, 164-167.

Hurrell, J.W. and K.E. Trenberth, 1998 : Difficulties in obtaining reliable temperature trends: reconciling the surface and satellite microwave sounding unit records, **J. Clim. 11**, 945-967.

Lindzen, R.S., 1990 : Some coolness concerning global warming, **Bull. Am. Met. Soc. 71**, 978-982.

Mears, C.A., M.C. Schabel, and F.J. Wentz, 2002 : A Reanalysis of the MSU Channel 2 Tropospheric Temperature Record, **J. Clim.** submitted for publication

Mo, T., 1995 : A study of the microwave sounding unit on the NOAA-12 satellite, **IEEE Trans. on Geosci. and Rem. Sens. 33**, 1141-1152.

Peixoto, J.P. and A.H. Oort, 1996 : The climatology of relative humidity in the atmosphere, **J. Clim**. 9, 3443-3463.

Reynolds, R.W. and T.M. Smith, 1994 : Improved global sea surface temperature analyses using optimum interpolation, **J. Clim**. **7**, 929-948.

Shine, K.P. and A. Sinha, 1991 : Sensitivity of the Earth's climate to height-dependent changes in water vapour mixing ratio, **Nature 354**, 500-503.

Spencer, R.W., J.R. Christy, and N.C. Grody, 1990 : Precise monitoring of global temperature trends from satellites, **Science 247**, 1558-1562.

Spencer, R.W. and J.R. Christy, 1992a : Precision and radiosonde validation of satellite gridpoint temperature anomalies. Part I: MSU Channel 2, **J. Clim. 53**, 847-857.

Spencer, R.W. and J.R. Christy, 1992b : Precision and radiosonde validation of satellite gridpoint temperature anomalies. Part II: A tropospheric retrieval and trends during 1979-1990, **J. Clim. 53**, 858-866.

Spencer, R.W. and W.D. Braswell, 1997 : How dry is the tropical free troposphere? Implications for global warming theory, **Bull. Am. Met. Soc. 78**, 1097-1106.

Sun, D.Z. and R.S. Lindzen, 1993 : Distribution of tropical tropospheric water vapor, **J. Atmos. Sci. 50**, 1643-1660.

Trenberth, K., 1983 : What are the seasons?, **Bull. Am. Met. Soc. 64**, 1276-1282.

Webb, M.J., A. Slingo, and G.L. Stephens, 1993 : Seasonal variations of the clear-sky greenhouse effect: the role of changes in atmospheric temperatures and humidities, **Clim. Dyn. 9**, 117-129.

Wentz, F.J., 1997 : A well-calibrated ocean algorithm for special sensor microwave/imager, **JGR 102**, 8703-8718.

Wentz, F.J. and M. Schabel, 1998 : Effects of satellite orbital decay on MSU lower tropospheric temperature trends, **Nature 394**, 661-664.

Wentz, F.J. and M. Schabel, 2000 : Precise climate monitoring using complementary satellite data sets, **Nature 403**, 414-416.

Wilks, D.S., 1995 : Statistical methods in the atmospheric sciences, Academic Press (San Diego).