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Satellite-derived vertical dependence of tropical tropospheric temperature trends

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[1] Tropical atmospheric temperatures in different tropospheric layers are retrieved using satellite-borne Microwave Sounding Unit (MSU) observations. We find that tropospheric temperature trends in the tropics are greater than the surface warming and increase with height. Our analysis indicates that the near-zero trend from Spencer and Christy's MSU channel-2 angular scanning retrieval for the tropical low-middle troposphere (T_{2LT}) is inconsistent with tropical tropospheric warming derived from their MSU T_2 and T_4 data. We show that the T_{2LT} trend bias can be largely attributed to the periods when the satellites had large local equator crossing time drifts that cause large changes in calibration target temperatures and large diurnal drifts.

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1. Introduction

[2] General circulation model (GCM) predictions of the equilibrium response of global surface temperatures to a $2xCO_2$ are still uncertain to at least a factor of three [e.g., *Intergovernmental Panel on Climate Change* (*IPCC*), 2001]. This uncertainty is due to our poor understanding of climate feedback processes internal to the climate system that control the sensitivity of Earth's climate to forcing. Among these processes, the water vapor and lapse rate feedbacks are largely controlled by the changes of tropical tropospheric temperatures and their vertical structure [e.g., *Colman*, 2001].

[3] For the tropical troposphere's response to greenhouse forcing, GCMs predict a positive temperature trend that is greater than that at the surface and increases with height [e.g., *Hansen et al.*, 2002]. However, there are still large inter-model spreads of water vapor and lapse rate feedbacks [*Colman*, 2003]. A reliable observational dataset on the vertical structure of tropical tropospheric temperature trends is desirable to improve our understanding of these feedbacks.

[4] Whether the observational data are consistent with the GCM tropical simulations is still a subject of debate [*Fu et al.*, 2004a; *Douglass et al.*, 2004]. For example, the analysis of the satellite microwave sounding unit (MSU) observations by the team at the University of Alabama at Huntsville (UAH) [*Christy et al.*, 2003] suggests almost no temperature trend in the low-middle troposphere for 1979–2002 in the tropics, where surface temperatures based on in situ observations exhibit a significant warming of 0.13K/decade [*Jones and Moberg*, 2003]. In contrast, using the MSU channel 2 and 4 data processed by the UAH and Remote Sensing Systems (RSS) teams [*Mears et al.*, 2003], the tropical tropospheric temperature trends inferred for the same period following *Fu et al.* [2004a] are 0.11K/decade and 0.18K/decade, respectively [*Tett and Thorne*, 2004; *Fu et al.*, 2004b]. Understanding the trend discrepancy between T_{2LT} and those based on *Fu et al.* [2004a] requires an analysis of tropical tropospheric temperature trends in several atmospheric layers.

[5] In this study, we explore retrievals of tropical atmospheric temperatures in two tropospheric layers: entire troposphere (T_{TT}) and lower troposphere (T_{TLT}), using the MSU observations. The development of methodology is presented in section 2. The data used are described in section 3, along with the test of the retrieval method. Our MSU-derived tropical tropospheric temperature trends and the UAH T_{2LT} trend are discussed in sections 4 and 5, respectively. The summary and conclusions are given in section 6.

2. Formulation of the Retrieval Method

[6] The MSU, since 1979, and its successor, the Advanced MSU (AMSU), from 1998, provide global coverage of temperature for several atmospheric layers from NOAA polar-orbiting satellites. The nadir brightness temperatures measured by MSU channels 2 (T_2) and 4 (T_4) are widely used for monitoring the temperature changes in the troposphere and stratosphere, respectively [e.g., *Christy et al.*, 2003; *Mears et al.*, 2003; *Vinnikov and Grody*, 2003]. However, little attention has been given to the use of MSU channel 3 brightness temperatures (T_3) for long-term climate monitoring, partly owing to its drifting problems before 1987 [*Spencer and Christy*, 1992]. The time series of T_3 has become available from 1987 [*Mears et al.*, 2003].

[7] To minimize measurement errors, T_2, T_3, and T_4 come from observations averaged over five near-nadir view angles [*Christy et al.*, 1998]. The weighting functions for T_2, T_3, and T_4 are shown in Figure 1a in units of 1/hPa [*Christy et al.*, 1998]. In the tropical region where the tropopause is $\sim$100 hPa, the signal for T_3 comes from both the stratosphere and troposphere while the T_4 signal is mainly from the stratosphere. The T_2 weighting function has less vertical structure: it reaches its maximum at $\sim$350 hPa and has half maxima at $\sim$40 and $\sim$800 hPa. Although the T_2 signal is mainly from the troposphere, the stratospheric contribution in the T_2 trend is significant [*Fu et al.*, 2004a; *Fu and Johanson*, 2004]. This is because for the last few decades the stratosphere has been cooling

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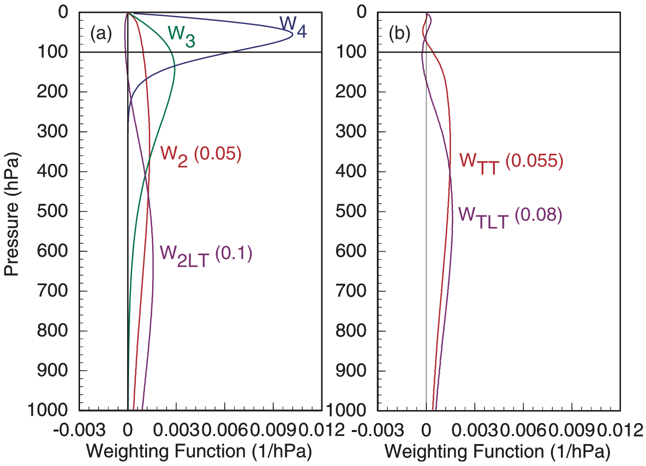

Figure 1. (a) Microwave Sounding Unit (MSU) weighting functions for T_2 (W_2), T_3 (W_3) and T_4 (W_4) along with the effective weighting function of T_{2LT} (W_{2LT}). (b) Effective weighting functions for tropical troposphere (W_{TT}) and tropical lower-troposphere (W_{TLT}). The tropical tropopause is set at 100 hPa. The numbers in parentheses are surface weights over ocean.

several times faster than the troposphere has been warming [*IPCC*, 2001]. *Fu et al.* [2004b]found a stratospheric contamination of about −0.05 K/decade in the tropical T_2 trend for 1979–2002.

[8] To correct for the stratospheric influence, the UAH team created a synthetic channel called T_{2LT}, where LT means "lower-middle troposphere", by subtracting signals at different view-angles of MSU Channel 2 [*Spencer and Christy*, 1992]. However, this approach amplifies noise [*Christy et al.*, 1998], increases satellite inter-calibration biases and enhances contamination from the surface [*Hurrell and Trenberth*, 1998]. The effective weighting function for T_{2LT} is also shown in Figure 1a. *Christy et al.* [1998] pointed out that confidence in the MSU T_2 and T_4 is much higher than T_{2LT} for trend analyses.

[9] Recently *Fu et al.* [2004a] developed a simple technique to derive the tropospheric temperature based on a linear combination of T_2 and T_4, which is free of the complications affecting T_{2LT}. Note that T_{2LT} and the tropospheric temperature retrieved from *Fu et al.* [2004a] are not attributed to the same deep-layer of the atmosphere. The latter has an effective weighting function that is not much different from W_2 in the troposphere but excludes the stratospheric influence.

[10] Herein we explore retrievals by combining different MSU channels to derive tropical tropospheric temperatures of different layers. The effective weighting function, W_{ij}, is defined in the form $W_{ij} = a_{ij}W_i + (1 - a_{ij})W_j$ where W_i and W_j are the physical weighting functions for MSU channels i and j, respectively. The combinations of MSU channels 2 and 4 [*Fu et al.*, 2004a], and 2 and 3 are considered. We derive the coefficients, a_{ij}, by minimizing $\int_0^p W_{ij}^2 dp$, where p is 100 hPa for a_{24}, and 250 hPa for a_{23}. This leads to an a_{24} of 1.1 and a_{23} of 1.69. The a_{24} here is consistent with the coefficients derived by *Fu et al.* [2004a] in the tropics based on radiosonde data. In this paper, the W_{24} and W_{23} are also represented as W_{TT} and W_{TLT}, respectively.

[11] The effective weighting functions, W_{TT} and W_{TLT}, are shown in Figure 1b. It demonstrates that a combination of T_2 and T_4 effectively removes the stratospheric influence [*Fu et al.*, 2004a]. The layer-mean temperature corresponding to W_{TT} is called T_{TT}, where the subscript "TT" means "tropical troposphere". Note that T_{TT} is attributed to the entire troposphere from the surface to the tropopause. Figure 1b indicates that the contribution from the atmosphere above ∼250 hPa is small for T_{TLT}, where "TLT" means "tropical lower troposphere" (relative to T_{TT}). It is noted that the temperature in the tropical upper troposphere between ∼400 to 100 hPa can be derived by combining the MSU channels 3 and 4. But this MSU-derived temperature is not independent of the T_{TT} and T_{TLT}.

3. Data and Test of Retrieval Method

[12] We use MSU gridded (2.5° by 2.5°) monthly anomaly data compiled by the RSS team [*Mears et al.*, 2003] and the UAH team [*Christy et al.*, 2003]. The RSS team produces datasets for T_2, T_3, and T_4 and the UAH team produces T_2, T_4, and T_{2LT}. Since the time series of T_3 starts from January 1987, we only consider the 17-year period in 1987 through 2003 in the tropics (30N to 30S).

[13] We use surface temperatures (5° by 5°) of HadCRUT2v [*Jones and Moberg*, 2003]. These in-situ observations are for the near-surface air temperatures over land and surface sea temperatures (SST) over ocean. Confidence in the surface temperature trend is high since analyses from three different groups including UKMO, NOAA, and NASA, each of which has been independently adjusted for various homogeneity issues, show consistent results [*IPCC*, 2001].

[14] We need to evaluate the stratospheric influences related to our retrieval method. For this purpose, we use tropical mean profiles of stratospheric temperature trend from two different radiosonde datasets [*Seidel et al.*, 2004]: LKS as compiled by Lanzante et al. for 1979–1997 and HadRT by the U.K. Met Office's Hadley Center for Climate Prediction and Research for 1979–2001. Following *Fu and Johanson* [2004], the stratospheric influences are estimated from $\int_0^{100} \dot{T}(p)W(p)dp$ where $\dot{T}$ is the temperature trend profile and W is the effective weighting function. We find small stratospheric contaminations in T_{TLT} and T_{TT} (<±0.005 K/decade) and T_{2LT} (about 0.015 K/decade). These small stratospheric contaminations are due to small deviation of the effective weighting functions from zero throughout the stratosphere (Figure 1).

4. Tropical Tropospheric Temperature Trends

[15] The tropical tropospheric temperatures in two different layers, T_{TLT} and T_{TT}, are derived using the satellite-observed brightness temperatures, T_2, T_3, and T_4 as follows

$$T_{TLT} = a_{23}T_2 + (1 - a_{23})T_3, \tag{1a}$$

$$T_{TT} = a_{24}T_2 + (1 - a_{24})T_4, \tag{1b}$$

We compute tropically averaged time series of T_{TLT} and T_{TT} from 1987 to 2003. Shown in Figure 2 are the trends in

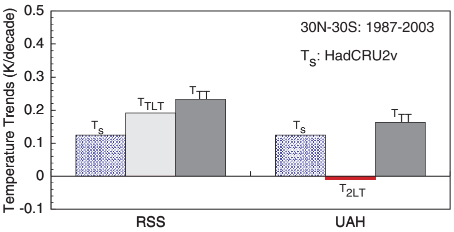

Figure 2. MSU-derived atmospheric layer temperature trend for tropical troposphere (T_{TT}) and tropical lower-troposphere (T_{TLT}) along with tropical surface temperature trend. The monthly anomalies of RSS T_2, T_3, and T_4, and UAH T_2 and T_4 data are used. The trend of T_{2LT} from the UAH is also shown. The statistical trend uncertainties for the difference time series between the tropospheric temperature retrievals (T_{TLT}, T_{TT}, and T_{2LT}) and T_S all have a 95% confidence interval of about ±0.09 K/decade. The T_{2LT} trend is significantly different from the T_S trend at much less than the 0.1% level.

MSU-derived T_{TLT} and T_{TT} from the RSS dataset, as well as the T_{TT} trend from the UAH data. The surface temperature trend based on in situ observations [*Jones and Moberg*, 2003] is shown for comparison.

[16] Figure 2 demonstrates that, using the RSS dataset, the tropical troposphere is warming faster than the surface, and the tropical tropospheric temperature trends increase with height, which confirms the GCM predictions [e.g., *Hansen et al.*, 2002]. The UAH T_{TT} trend is also larger than the surface warming, but it is ~0.07 K/decade less than RSS T_{TT} trend.

[17] The difference between the UAH and RSS T_{TT} trends is due to differences in data adjustments related to instrument calibration and diurnal drift correction applied to generate the respective T_2 and T_4 time series. Figure 3 shows the difference time series of T_{2_RSS}-T_{2_UAH} in the tropics for (a) ocean and (b) land. The difference time series of T_{4_RSS}-T_{4_UAH} over ocean is plotted in Figure 3c (the result over land is similar).

[18] As noted by *Mears et al.* [2003], the large difference during 1985–1987 is caused by disagreement in the non-linear target factor for the NOAA-9, due to its short overlaps with other satellites. (Another difference between the RSS and UAH T_2 products after mid 1998 is that UAH includes data from AMSU [*Christy et al.*, 2003].) Although much of the global-mean trend discrepancy is associated with the adjustment for NOAA 9 [*Mears et al.*, 2003], the difference after 1987 is also significant in the tropics (Figure 3). We notice an increase of the T_2 difference from 1991 to 1995 over ocean (Figure 3a), corresponding to the large drift in local equator crossing times (LECT) for NOAA-11 [*Mears et al.*, 2003]. The two jumps over land near 1992 and 1995 seem to be related to satellite transitions, respectively, from NOAA 10 to 12, and from NOAA 11 to 14. Figures 3a and 3b also indicate a small discontinuity near 1998 and an increase starting from 2001. Figure 3c shows a jump of the T_4 difference at 1995.

[19] We obtain trend differences of 0.072 K/decade in T_2 and 0.088 K/decade in T_4 between RSS and UAH for 1987–2003. Such uncertainties for this period in the tropics, which have received little attention thus far, reinforce the importance to fully understand the MSU instrument calibration [e.g., *Grody et al.*, 2004] and diurnal impact on the MSU data. Comparison of Figures 3a and 3b suggests that the MSU inter-satellite calibration and diurnal drift correction are intricately coupled together.

5. Discussions of T_{2LT}

[20] Also shown in Figure 2 is the trend of T_{2LT} as analyzed by the UAH team for the lower-middle troposphere, using the differences of MSU channel 2 brightness temperatures between near-limb and near-nadir viewing angles. The T_{2LT} trend has a small negative value that is inconsistent with the large positive trend in both in-situ T_s and UAH T_{TT}. Since the contribution to T_{2LT} is mainly from the surface and atmosphere below 300 hPa (Figure 1a), it is instructive to estimate the mean atmospheric temperature trend for the layer between the surface and 300 hPa ($T_{1000-300}$), and that from 300 and 100 hPa ($T_{300-100}$), which are required to reproduce the UAH T_{TT} and T_{2LT} trends shown in Figure 2. Using surface weightings over ocean for T_{2LT} (0.1) and T_{TT} (0.055) along with an observed surface trend of 0.13 K/decade, we obtain a trend of −0.06 K/decade for $T_{1000-300}$ and a trend of 0.85 K/decade for $T_{300-100}$. Thus, in addition to the concern about a cooling lower-middle atmosphere over a warming surface, we face another even more serious difficulty to explain at the same time a huge warming in the tropical upper troposphere below which the atmosphere is cooling. This is an unlikely scenario, if not impossible. Noting that confidence in trends of T_S and UAH T_{TT} is much higher than UAH T_{2LT}, we argue that the T_{2LT} trend in the tropics is physically implausible. The near-zero T_{2LT} trend is also inconsistent with the observed trend in precipitable water [*Trenberth et al.*, 2005]. The large discrepancy between UAH T_{2LT} and T_{TT} trends with a much lower confidence in T_{2LT} also raises a question as to the suitability to discriminate the T_2 datasets by comparing T_{2LT} only with radiosonde data [*Christy and Norris*, 2004].

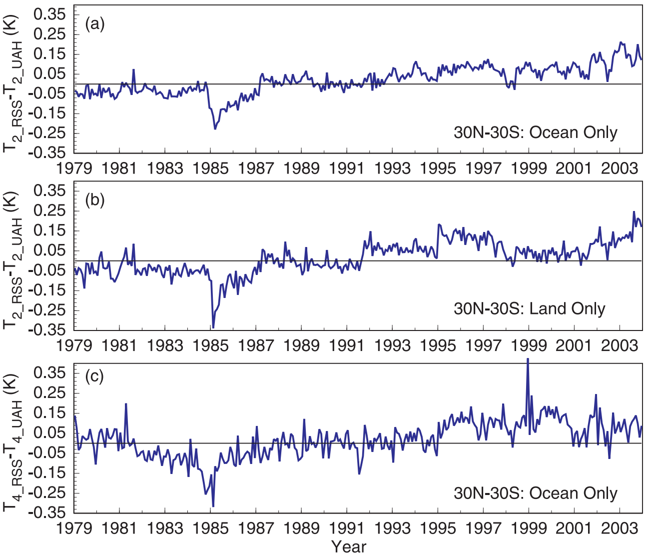

Figure 3. Difference time series between RSS and UAH datasets in the tropics for (a) T_2 over ocean, (b) T_2 over land, and (c) T_4 over ocean.

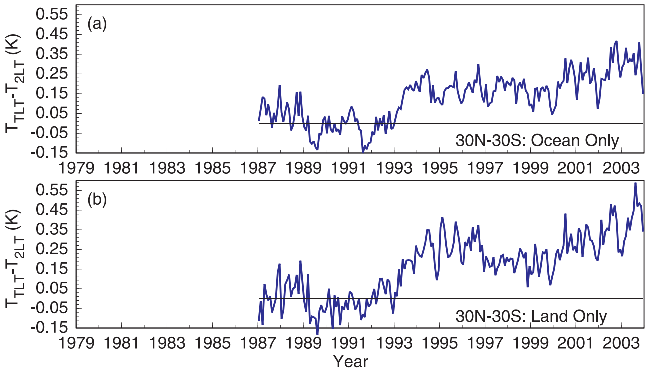

Figure 4. Difference time series between RSS T_{TLT} and UAH T_{2LT} in the tropics over (a) ocean and (b) land.

[21] The weighting functions for T_{2LT} and T_{TLT} (Figure 1) are similar, peaking at ∼600 and ∼500 hPa with half maxima at ∼350 and ∼300 hPa, respectively. Both have small contributions from the upper troposphere and also have similar surface weighting (e.g., 0.1 versus 0.08 over ocean). However the trend difference between the UAH T_{2LT} and RSS T_{TLT} is −0.2 K/decade, much larger than the difference between RSS T_{TT} and UAH T_{TT}. Since the resultant value of T_{2LT} is a small residual of two large numbers [*Christy et al.*, 1998], T_{2LT} is more sensitive to both instrument calibrations and diurnal drift corrections than T_2, T_3, and T_4. Thus confidence in trends of T_{2LT} is also lower than T_{TLT}.

[22] Figure 4 shows the difference time series for T_{TLT}-T_{2LT} in the tropics over (a) ocean and (b) land. It indicates a large increase of the difference during 1991–1995 when the NOAA-11 satellite had a large LECT drift, causing both large changes in the calibration target temperatures and a large diurnal drift. (*Christy et al.* [2000, Figures 3–5] documented the effect of LECT drift on both T_{2LT} and MSU channel-2 warm target temperatures. Note that the heat balance of a satellite and thus the warm target temperatures depend on the LECT.) *Grody et al.* [2004] suggest that the empirical adjustment used by both UAH and RSS teams to remove errors due to variations in the MSU warm target temperatures [*Christy et al.*, 2003; *Mears et al.*, 2003] may not fully resolve the nonlinear calibration problem that has a latitudinal dependence. Thus we would expect errors owing to incomplete corrections of instrument calibration, as well as residual errors associated with diurnal corrections: both would be amplified in T_{2LT}. Figure 4 also indicates an increase of the difference after 1999, which can be attributed to the large LECT drift for NOAA-14. The effects of LECT drifts due to NOAA-12 and NOAA-14 during 1995–1999 may partly cancel each other.

6. Summary and Conclusions

[23] We have developed retrievals of tropical atmospheric temperatures in different tropospheric layers using satellite-borne MSU observations. We show that tropical layer-mean temperatures for the entire troposphere (T_{TT}) and lower troposphere (T_{TLT}) can be derived from linear combinations of T_2 and T_4, and T_2 and T_3, respectively. The stratospheric contaminations in T_{TT} and T_{TLT} are negligible (<±0.005 K/decade) because of their near-zero effective weighting functions throughout the stratosphere.

[24] Our retrievals applied to satellite-observed MSU time series compiled by the RSS team for 1987–2003 demonstrate that the tropical troposphere is warming faster than the surface, and that tropical tropospheric temperature trends increase with height, which confirms the GCM predictions. The T_{TT} trend based on the UAH T_2 and T_4 data is also found to be larger than the surface warming but it is about 0.07 K/decade less than RSS T_{TT} trend.

[25] This study indicates that the near-zero T_{2LT} trend in the tropics is inconsistent with both in-situ observed surface warming AND tropical tropospheric warming derived using UAH T_2 and T_4 data. We show that the T_{2LT} trend bias can be largely attributed to the periods when the satellites had large LECT drifts, causing both large changes in the calibration target temperatures and large diurnal drifts. The errors owing to incomplete corrections of instrument calibration and diurnal biases would be largely amplified in T_{2LT} analyses.

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References

Christy, J. R., and W. B. Norris (2004), What may we conclude about global tropospheric temperature trends?, *Geophys. Res. Lett.*, *31*, L06211, doi:10.1029/2003GL019361.

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

Christy, J. R., R. W. Spencer, and W. D. Brasell (2000), MSU tropospheric temperatures: Dataset construction and radiosonde comparisons, *J. Atmos. Oceanic Technol.*, *17*, 1153–1170.

Christy, J. R., et al. (2003), Error estimates of version 5.0 of MSU-AMSU bulk atmospheric temperatures, *J. Atmos. Oceanic Technol.*, *20*, 613–629.

Colman, R. A. (2001), On the vertical extent of atmospheric feedbacks, *Clim. Dyn.*, *17*, 391–405.

Colman, R. A. (2003), A comparison of climate feedbacks in general circulation models, *Clim. Dyn.*, *20*, 865–873.

Douglass, D. H., B. D. Pearson, and S. F. Singer (2004), Altitude dependence of atmospheric temperature trends: Climate models versus observation, *Geophys. Res. Lett.*, *31*, L13208, doi:10.1029/2004GL020103.

Fu, Q., and C. M. Johanson (2004), Stratospheric influences on MSU-derived tropospheric temperature trends: A direct error analysis, *J. Clim.*, *17*, 4636–4640.

Fu, Q., C. M. Johanson, S. G. Warren, and D. J. Seidel (2004a), Contribution of stratospheric cooling to satellite-inferred tropospheric temperature trends, *Nature*, *429*, 55–58.

Fu, Q., D. J. Seidel, C. M. Johanson, and S. G. Warren (2004b), Reply to "Tropospheric temperature series from Satellites," *Nature*, *432*, doi:10.1038/nature03210.

Grody, N. C., K. Y. Vinnikov, M. D. Goldberg, J. T. Sullivan, and J. D. Tarpley (2004), Calibration of multisatellite observations for climatic studies: Microwave Sounding Unit (MSU), *J. Geophys. Res.*, *109*, D24104, doi:10.1029/2004JD005079.

Hansen, J., et al. (2002), Climate forcings in Goddard Institute for Space Studies SI2000 simulations, *J. Geophys. Res.*, *107*(D18), 4347, doi:10.1029/2001JD001143.

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.

Intergovernmental Panel on Climate Change (IPCC) (2001), *Climate Change 2001: The Scientific Basis: Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*, edited by J. T. Houghton et al., 881 pp., Cambridge Univ. Press, New York.

Jones, P. D., and A. Moberg (2003), Hemispheric and large-scale surface air temperature variations: An extensive revision and an update to 2001, *J. Clim.*, *16*, 206–223.

Mears, C. A., M. C. Schabel, and F. J. Wentz (2003), A reanalysis of the MSU channel 2 tropospheric temperature record, *J. Clim.*, *16*, 3560–3664.

Seidel, D. J., et al. (2004), Uncertainty in signals of large-scale climate variations in radiosonde and satellite upper-air temperature datasets, *J. Clim.*, *17*, 2225–2240.

Spencer, R. W., and J. R. Christy (1992), Precision and radiosonde validation of satellite gridpoint temperature anomalies. Part II: A tropospheric retrieval and trends during 1979–1990, *J. Clim.*, *5*, 858–866.

Tett, S., and P. Thorne (2004), Tropospheric temperature series from satellites, *Nature*, *432*, doi:10.1038/nature03208.

Trenberth, K. E., J. Fasullo, and L. Smith (2005), Trends and variability in column-integrated atmospheric water vapor, *Climate Dynamics*, *24*, (in press).

Vinnikov, K. Y., and N. C. Grody (2003), Global warming trend of mean tropospheric temperature observed by satellites, *Science*, *302*, 269–272.

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