

# Stratospheric Influences on MSU-Derived Tropospheric Temperature

## Trends: A Direct Error Analysis

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Submitted as a Letter to Journal of Climate, 17 May 2004

### **Abstract**

Retrievals of tropospheric temperature trends from data of the Microwave Sounding Unit (MSU) are subject to biases related to the strong cooling of the stratosphere during the past few decades. The magnitude of this stratospheric contamination in various retrievals is estimated using a vertical profile of stratospheric temperature trends based on observations. It is found that from 1979 to 2001 the stratospheric contribution to the trend of MSU channel 2 brightness temperature is about  $-0.08$  K/decade, which is consistent with the findings of Fu et al. (2004). In the retrieval method developed by Fu et al. based on a linear combination of MSU channels 2 and 4, the stratospheric influence is largely removed, leaving a residual influence of about  $-0.01$  K/decade. In contrast, the trend-error in the angular-scanning retrieval of lower tropospheric temperature from Christy et al. (2003) is about  $-0.03$  to  $-0.04$  K/decade.

## Introduction

The Microwave Sounding Unit (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 microwave radiation measured by MSU channels 2 and 4 are particularly useful for monitoring the temperature changes in the troposphere and stratosphere, respectively (Spencer and Christy 1990; Christy et al. 2003; Mears et al. 2003; Vinnikov and Grody 2003; Seidel et al. 2004). The widely used brightness temperatures of MSU channel 2 ( $T_2$ ) and channel 4 ( $T_4$ ) are averaged observations from five view angles near the nadir direction in order to minimize random measurement errors (Christy et al. 1998).

About 85% of the signal for the  $T_2$  comes from the troposphere and surface, and the remaining 15% is from the stratosphere. To correct for the stratospheric influence, the University of Alabama at Huntsville (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; Christy et al. 1998; Christy et al. 2003). However, this approach amplifies noise and increases satellite inter-calibration biases, and may introduce other complications involving the effects of changes in surface emissivity and mountainous terrain (e.g., Hurrell and Trenberth 1997; Hurrell and Trenberth 1998; Wentz and Schabel 1998; Swanson 2003). For this reason, the better-calibrated  $T_2$  record is often directly used to represent mid-tropospheric temperatures (e.g., Prabhakara et al. 2000; Christy et al. 2003; Mears et al. 2003; Vinnikov and Grody 2003).

Because of the depletion of stratospheric ozone and the increase of greenhouse gases, the stratosphere has been cooling about five times faster than the troposphere has been warming during the last 20 years (Houghton et al. 2001). Therefore  $T_2$  by itself is not a good indicator for the temperature trend in the lower atmosphere, because it reflects the combined influences of stratospheric and tropospheric changes, which largely cancel each other. Fu et al. (2004) recently developed a simple technique for deriving the tropospheric temperature. This method uses data from MSU channel 4 to remove the stratospheric contamination in  $T_2$ , which is free of the complications afflicting  $T_{2LT}$ . Herein we use the observed vertical profile of stratospheric temperature trend to evaluate the errors in different techniques used to remove stratospheric contamination from estimates of tropospheric temperature trends.

## **Data**

We use MSU data compiled by the UAH team (Version 5; Christy et al. 2003) for the 23-year period from 1979 to 2001. Only the UAH team produces the  $T_{2LT}$  product; therefore, we do not consider herein MSU analyses by other groups. We obtain global temperature trends of -0.52 K/decade for  $T_4$ , 0.01 K/decade for  $T_2$ , 0.055 K/decade for  $T_{2LT}$ , and 0.09 K/decade for the temperature of the 850-300 hPa layer ( $T_{850-300}$ ) as inferred from the simple linear regression scheme developed by Fu et al. (2004). Note that the  $T_4$  trend is almost entirely determined by stratospheric temperature changes.

The mean vertical profile of temperature trend for 1979-1994 in the stratosphere at 45°N was provided in Ramaswamy et al. (2001) from 15 to 50 km, compiled from radiosonde, satellite, and analyzed data sets (their Table 6 and Fig. 30). Linearly

extrapolating their trends of  $-0.84$  K/decade at 20 km and  $-0.49$  K/decade at 15 km with respect to height, we obtain a trend of  $-0.27$  K/decade at 11.8 km (200 hPa).

In order to make Ramaswamy's vertical profile of stratospheric temperature trends at  $45^\circ\text{N}$  more representative of global mean conditions, we multiplied it by the ratio

$$\frac{\dot{T}_4(\text{global})}{\dot{T}_4(45^\circ\text{N})} = \frac{-0.52\text{K/decade}}{-0.71\text{K/decade}}, \quad (1)$$

where the numerator is the 1979-2001 trend in the global mean  $T_4$  from Christy et al. (2003), and the denominator is the corresponding trend at  $45^\circ\text{N}$ , estimated applying the weighting function for  $T_4$  from Christy et al. (1998) to the trend profile of Ramaswamy et al. This rescaled profile is shown in Fig.1 from 0 to 200 hPa.

Also shown in Fig.1 are the global temperature trends in the 300-100-hPa layer for 1979-2001 based on four different radiosonde datasets (Seidel et al. 2004), which range from  $-0.13$  to  $-0.41$  K/decade. The trend at the 200 hPa level based on a linear extrapolation with respect to height after rescaling is within this range ( $-0.20$  K/decade), so these radiosonde datasets provide validation of the extrapolation.

### **Effective Weighting Functions**

The retrieval method of Fu et al. (2004) for estimating tropospheric temperature anomaly is given by

$$T_{850-300} = -0.003 + 1.156T_2 - 0.153T_4, \quad (2)$$

where the coefficients were derived by least-squares regression to relate monthly mean, global-average temperature anomalies for the layer 850-300 hPa to the corresponding simulated  $T_2$  and  $T_4$ , using radiosonde observations (Lanzante et al. 2003). Hence, the effective weighting function for their retrieval method is

$$W_{fu} = 1.156W_2 - 0.153W_4, \quad (3)$$

where  $W_2$  and  $W_4$  are the weighting functions for the MSU channels 2 and 4, respectively. As depicted in Fig.2, the sign of this effective weighting function changes from positive to negative above the 90-hPa level. It is not uncommon for effective weighting functions to exhibit layers with negative weights (e.g., see Fig. 6.23 of Grody 1993) by noticing that statistical retrievals are used operationally to produce soundings from NOAA and GOES satellites (e.g., Kidder and Vonder Haar 1995).

Christy (personal communication 2004) suggested an alternative effective weighting function, also by combining MSU channels 2 and 4 but with different weights, using the criterion that the effective weighting function should be positive throughout the atmosphere:

$$W_{pos} = 1.08W_2 - 0.08W_4. \quad (4)$$

Using the effective weighting function defined in Eq.(4), we obtain a temperature trend of 0.053 K/decade, which is about the same as the trend of  $T_{2LT}$ . Also shown in Fig.2 are  $W_2$  and  $W_{pos}$ , which obviously include significant contributions from the stratosphere.

Noted that the coefficients in Eq. (2) are latitudinally-dependent. For the tropical region (30°N-30°S), the effective weighting function becomes  $1.12W_2 - 0.11W_4$ , as derived from Fu et al. (2004). This effective weighting function can also be examined using the stratospheric temperature trend profile in the tropics. In this paper we will focus on testing the global mean effective weighting function.

## Discussion

The stratospheric temperature trend profile based on observations is used to estimate the errors associated with stratospheric contamination in different techniques for deriving tropospheric temperature trends. These errors can be expressed as

$$\Delta\dot{T} = \int_0^{200} \dot{T}(p)W(p)dp, \quad (5)$$

where  $p$  is the pressure,  $\dot{T}$  the temperature trend profile in the stratosphere as represented in Fig.1, and  $W$  the effective weighting functions associated with different techniques used to derive the tropospheric temperatures, as represented in Fig.2. The global mean tropopause is set at 200 hPa.

Shown in Fig. 3 are the errors in temperature trends related to these different methods. The stratospheric contamination in  $T_2$  is  $-0.076\text{K/decade}$ , which is consistent with the finding ( $-0.08\text{K/decade}$ ) of Fu et al. (2004). The error associated with the method of Fu et al. (2004) (Eq. 3) is only  $-0.008\text{ K/decade}$ . This error is small because the positive and negative portions of the integral in Eq. (5) largely cancel each other. Figure 3 also shows that the error based on Eq. (4) is  $-0.040\text{ K/decade}$ .

For a sensitivity test, we also derive the temperature trend below 15 km using a linear extrapolation with respect to pressure instead of height. This temperature trend is shown in Fig.1 as the dashed line. There are slight differences between these two trend profiles above 15 km (120 hPa) because both are rescaled to the observed global  $T_4$  trend of  $-0.52\text{ K/decade}$ . Using the dashed profile, the errors associated with  $W_2$ ,  $W_{\text{pos}}$ , and  $W_{\text{fu}}$  are  $-0.069\text{ K/decade}$ ,  $-0.033\text{ K/decade}$ , and  $0.000\text{ K/decade}$ , respectively, each of which differs from the results based on a linear height extrapolation by  $\sim 0.007\text{ K/decade}$ . Note

that the trend profile based on the linear extrapolation with respect to height is more consistent with radiosonde data (Fig.1).

Given that the stratospheric contribution is  $-0.08\text{K/decade}$  in  $T_2$ , we may derive a tropospheric temperature trend of  $0.09\text{ K/decade}$  based on a UAH trend of  $0.01\text{ K/decade}$  for  $T_2$ . By comparing this tropospheric temperature trend with a trend of  $0.055\text{ K/decade}$  for  $T_{2LT}$ , we can conclude that the error in  $T_{2LT}$  is  $-0.035\text{ K/decade}$ , which is close to that based on  $W_{\text{pos}}$ . However, since the weighting function for  $T_{2LT}$  is near zero at all heights above 200 hPa (Christy et al. 1998), the error in  $T_{2LT}$  is not caused by stratospheric contamination but must be due instead to other problems involving the  $T_{2LT}$  retrievals. One indication of problems is the fact that within the tropical region (30N-30S),  $T_{2LT}$  is cooling at a rate of  $0.04\text{ K/decade}$  relative to  $T_2$ . In view of the cooling trend in the stratosphere at all latitude (Houghton et al. 2001), one would expect that  $T_{2LT}$  should be warming relative to  $T_2$ . The validity of the  $T_{2LT}$  product as a measure of climate change is also in question at high latitudes. Swanson (2003) compared data for high latitudes in the Southern Hemisphere, demonstrating that the  $T_{2LT}$  product does not represent the seasonal cycle of temperature in the lower atmosphere, as seen in radiosonde data from Antarctica. The difference is a result of the yearly sea-ice cycle, thus trends in the sea-ice cycle may impact the  $T_{2LT}$  product. Arctic data are subject to similar influences.

In summary, we have tested the MSU channel 2 and the Fu et al. (2004) retrieval scheme for deriving tropospheric temperature trends using an independent, observation-based estimate of the stratospheric temperature trend profile. According to this test, the Fu et al. (2004) scheme yields a product that is largely free of stratospheric contamination.

**Acknowledgements.** We thank J.M. Wallace, S.G. Warren and D.J. Seidel for valuable discussions. D.J. Seidel provided the radiosonde data presented in Fig.1. We thank J.M. Wallace, S.G. Warren, D.J. Seidel, D.L. Hartmann, T.L. Anderson, and C.F. Mass for the comments and suggestions on the manuscript.

## **References**

- Christy, J.R., Spencer, R.W. & Lobl, E.S. Analysis of the merging procedure for the MSU daily temperature time series. *J. Climate* **11**, 2016-2041 (1998).
- Christy, J.R. et al. Error estimates of version 5.0 of MSU-AMSU bulk atmospheric temperatures. *J. Atmos. Oceanic Technol.* **20**, 613-629 (2003).
- Fu, Q., Johanson, C.M., Warren, S.G. & Seidel, D.J. Contribution of stratospheric cooling to satellite-inferred tropospheric temperature trends. *Nature*, **429**, 55-58 (2004).
- Grody, N.C. Remote sensing of the atmosphere from satellites using microwave radiometry. *Atmospheric Remote Sensing by Microwave Radiometry* (edited by M.A. Janssen), 259-334 (1993)
- Houghton, J.T. et al. (eds) *Climate Change 2001: The Scientific Basis* (Cambridge Univ. Press, London, 2001).
- Hurrell, J.W. & Trenberth K.E. Spurious trends in satellite MSU temperatures from merging different satellite records. *Nature* **386**, 164-167 (1997)

- Hurrell, J.W. & Trenberth, K.E. Difficulties in obtaining reliable temperature trends: Reconciling the surface and satellite Microwave Sounding Unit records. *J. Climate* **11**, 945-967 (1998).
- Kidder, S.Q., and T.H. Vonder Haar, 1995: Satellite Meteorology: An Introduction. Academic Press, 466.
- Lanzante, J.R., Klein, S.A. & Seidel, D.J. Temporal homogenization of monthly radiosonde temperature data. *J. Climate* **16**, 224-262 (2003).
- Mears, C.A., Schabel, M.C. & Wentz, F.J. A reanalysis of the MSU channel 2 tropospheric temperature record. *J. Climate* **16**, 3560-3664 (2003).
- Prabhakara, C., Iacovazzi, J.R., Yoo, J.M. & Dalu, G. Global warming: Evidence from satellite observations. *Geophys. Res. Lett.* **27**, 3517-3520 (2000).
- Ramaswamy, V. et al. Stratospheric temperature trends: Observations and model simulations. *Rev. Geophys.* **39**, 71-122 (2001).
- Seidel, D.J. et al. Uncertainty in signals of large-scale climate variations in radiosonde and satellite upper-air temperature datasets. *J. Climate*, **17**, 2225-2240.
- Spencer, R.W. & Christy, J.R. Precise monitoring of global temperature trends from satellites. *Science* **247**, 1558-1662 (1990).
- Spencer, R.W. & Christy, J.R. Precision and radiosonde validation of satellite gridpoint temperature anomalies. Part II: A tropospheric retrieval and trends during 1979 – 1990. *J. Climate* **5**, 858-866 (1992).
- Swanson, R.E. Evidence of possible sea-ice influence on Microwave Sounding Unit tropospheric temperature trends in polar regions. *Geophys. Res. Lett.* **30**, doi:10.1029/2003GL017938 (2003).

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

Wentz, F.J. & Schabel, M. Effects of orbital decay on satellite-derived lower-tropospheric temperature trends. *Nature* **394**, 661-664 (1998).

### Figure Legends

Fig.1. Mean vertical profile of temperature trend in the stratosphere as compiled by Ramaswamy et al. (2001) using radiosonde, satellite, and analyzed data sets, rescaled to the global trend of UAH MSU  $T_4$  over the 1979-2001 period. The solid and dashed lines represent trend profiles using linear extrapolation with respect to height and pressure, respectively, below 15 km (~120 hPa). Also shown are the global temperature trends for the layer between 100 and 300 hPa for the same time span, as derived from four radiosonde datasets: Angell-63 (#), Angell-54 (+), HadRT (o), and RIHMI (x) (See Seidel et al. 2004 for detailed descriptions of these datasets).

Fig.2. Microwave Sounding Unit weighting function for channel 2 ( $W_2$ ), along with the effective weighting function ( $W_{fu}$ ) following Fu et al. (2004), and an effective weighting function ( $W_{pos}$ ) defined by  $1.08W_2 - 0.08W_4$  where  $W_4$  is the weighting function for MSU channel 4.

Fig.3. Stratospheric contributions to the MSU-derived tropospheric temperature trends using the three different weighting functions shown in Fig.2.





