

## Stratospheric Influences on MSU-Derived Tropospheric Temperature Trends: A Direct Error Analysis

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### 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 stratospheric temperature trend profiles 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  $-0.08 \text{ K decade}^{-1}$ , which is consistent with the findings of Fu et al. 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 less than  $\pm 0.01 \text{ K decade}^{-1}$ . This method is also found to be more accurate than the angular scanning retrieval technique of Spencer and Christy to remove the stratospheric contamination.

### 1. 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 National Oceanic and Atmospheric Administration (NOAA) polar-orbiting satellites. The time series of microwave radiation measured by MSU channels 2 and 4 from a series of these satellites 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% comes from the stratosphere. To correct for the stratospheric influence, the University of Alabama in 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, 2003). However, this approach amplifies noise and increases satellite intercalibration biases and enhances contamination from the surface, which may introduce other complications involving the effects of changes in surface emissivity and mountainous terrain (e.g., Hurrell and Trenberth 1997, 1998; Wentz and Schabel 1998; Swanson 2003). For this reason, the better-calibrated  $T_2$  record is often directly used to represent midtropospheric temperatures (e.g., Prabhakara et al. 2000; Christy et al. 2003; Mears et al. 2003; Vinnikov and Grody 2003).

The Intergovernmental Panel on Climate Change (IPCC) 2001 report suggested that temperatures have been changing much faster in the stratosphere than in the troposphere during the last 20 yr (Houghton et al. 2001). (The large stratospheric cooling could be due to the depletion of stratospheric ozone and the increase of greenhouse gases.) 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. Fu et al. (2004) recently developed a new technique for deriving the tropospheric temperature alone. This method uses data from MSU channel 4 to remove the stratospheric contamination in  $T_2$ , and is free of the complications afflicting  $T_{2LT}$ . Herein, we use the observed vertical profiles of stratospheric temperature trend to evaluate the errors in different techniques used to remove strato-

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spheric contamination from estimates of tropospheric temperature trends. We find that the technique developed by Fu et al. (2004) is more effective than the angular scanning retrieval method of Spencer and Christy (1992) to remove the stratospheric influences.

## 2. Data

We use MSU data compiled by the UAH team (version 5; Christy et al. 2003) for the 23-yr 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  $-0.52 \text{ K decade}^{-1}$  for  $T_4$ ,  $0.01 \text{ K decade}^{-1}$  for  $T_2$ ,  $0.055 \text{ K decade}^{-1}$  for  $T_{2LT}$ , and  $0.09 \text{ K decade}^{-1}$  for the free tropospheric temperature ( $T_{FT}$ , where FT means “free troposphere”) the subscript using the simple linear regression scheme developed by Fu et al. (2004). That study also shows that the  $T_4$  trend is almost entirely determined by stratospheric temperature changes.

The multidataset mean vertical profile of temperature trend for 1979–94 in the stratosphere at  $45^\circ\text{N}$  was provided in Ramaswamy et al. (2001) from 15 to 50 km, compiled from radiosonde, satellite, and analyzed datasets (their Table 6 and Fig. 30). Linearly extrapolating their trends of  $-0.84 \text{ K decade}^{-1}$  at 20 km and  $-0.49 \text{ K decade}^{-1}$  at 15 km with respect to height, we obtain a trend of  $-0.27 \text{ K decade}^{-1}$  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

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

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 ( $R_H$ ) is shown in Fig. 1 from 0 to 200 hPa. The global mean tropopause is set at 200 hPa.

Also shown on the lower horizontal axis of 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  $-0.41 \text{ K decade}^{-1}$ . The trend at the 200-hPa level based on the linear extrapolation with respect to height after rescaling discussed above ( $-0.20 \text{ K decade}^{-1}$ ) is within this range, so these radiosonde datasets provide a validation of this extrapolation.

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 short dashed line ( $R_P$ ). There are slight differences between these two trend profiles above 15 km (120 hPa) because both are re-

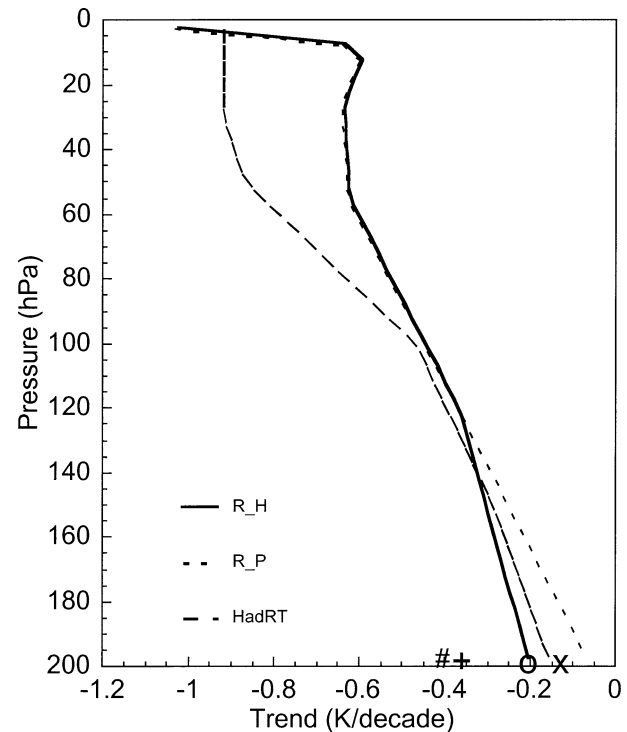


FIG. 1. Mean vertical profiles of temperature trend in the stratosphere. The solid and short dashed lines are based on the trend profile as compiled by Ramaswamy et al. (2001) using radiosonde, satellite, and analyzed datasets, rescaled to the global trend of UAH MSU  $T_4$  over the 1979–2001 period, and using linear extrapolation with respect to height ( $R_H$ ) and pressure ( $R_P$ ), respectively, below 15 km ( $\sim 120$  hPa). The dashed line (HadRT) represents the global mean trend profile from the radiosonde dataset of the Met Office’s Hadley Centre for Climate Prediction and Research for the 1979–2001 period. 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 radiosonde datasets.

scaled to the observed global  $T_4$  trend of  $-0.52 \text{ K decade}^{-1}$ . Note that the trend profile based on the linear extrapolation with respect to height is more consistent with radiosonde data (Fig. 1).

Of the radiosonde datasets used in Seidel et al. (2004), the global mean temperature trend profile compiled by the Met Office’s Hadley Centre for Climate Prediction and Research is available for the 1979–2001 period in the stratosphere up to 30 hPa (Parker et al. 1997; Thorne et al. 2002). This profile is shown in Fig. 1 as the dashed line [Hadley Centre radiosonde temperature (HadRT)] where the trend above 30 hPa is assumed to be constant. The HadRT profile is similar to  $R_H$  below the height at 90 hPa, but the differences become gradually larger above that level.

We will use all three profiles shown in Fig. 1 to examine the stratospheric influences on MSU-derived tropospheric temperature trends.

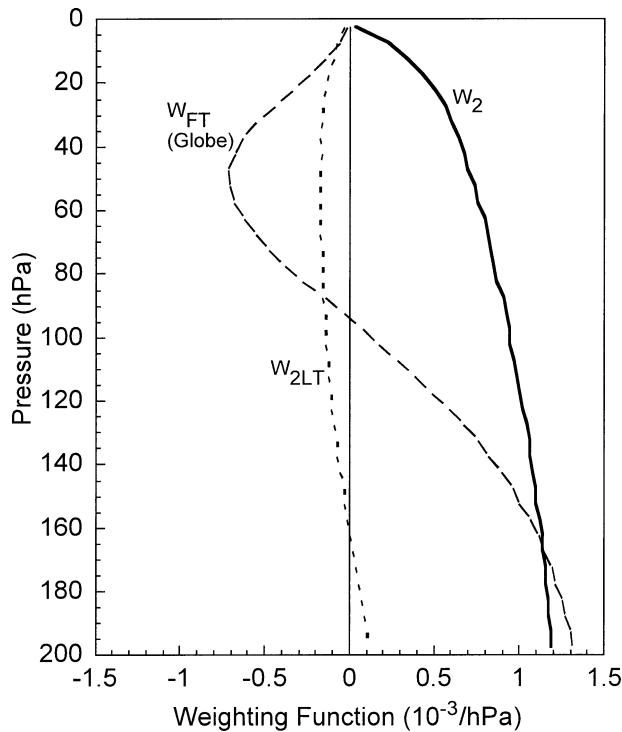


FIG. 2. MSU weighting function for channel 2 ( $W_2$ ), along with the global mean effective weighting function of Fu et al. (2004) ( $W_{FT}$ ), and the effective weighting function of  $T_{2LT}$  of Spencer and Christy (1992) ( $W_{2LT}$ ) in the stratosphere.

### 3. Effective weighting functions

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

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

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

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

where  $W_2$  and  $W_4$  are the weighting functions for the MSU channels 2 and 4, respectively. As depicted in Fig. 2 (dashed line), the sign of this effective weighting function changes from positive to negative above the 90-hPa level. It is common for effective weighting functions to exhibit layers with negative weights (e.g., see Fig. 6.23 of Grody 1993) in statistical retrievals that are used operationally to produce soundings from NOAA and geostationary GOES satellites (e.g., Kidder and Vonder Haar 1995).

Spencer and Christy (1992) devised a synthetic channel,  $T_{2LT}$ , based upon different earth viewing angles

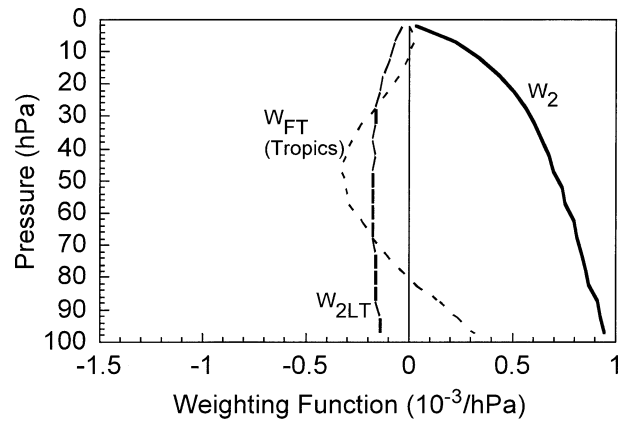


FIG. 3. Same as in Fig. 2, except for the tropical region.

from the MSU tropospheric channel ( $T_2$ ) to remove the stratospheric influence. Its effective weighting function,  $W_{2LT}$ , is shown in Fig. 2 (short dashed line), which is slightly negative in most of the stratosphere. Also shown in Fig. 2 is  $W_2$  (solid line), which contains the stratospheric contamination coming from throughout the stratosphere to the top of the atmosphere.

Note that the coefficients in Eq. (2) are latitudinally dependent. For the tropical region ( $30^\circ\text{N}$ – $30^\circ\text{S}$ ) where the tropopause is at  $\sim 100$  hPa, the effective weighting function becomes  $1.12W_2 - 0.11W_4$  (Fu et al. 2004), as shown in Fig. 3. We can see that  $T_2$  still includes significant contribution from the stratosphere in the Tropics. Figure 3 also shows that both  $W_{2LT}$  and  $W_{FT}$  largely remove this contamination, and there is no reason to expect that  $W_{2LT}$  works better than  $W_{FT}$  in the Tropics. In this paper, we will focus on testing the stratospheric contamination in MSU-derived global-mean tropospheric temperature trends.

### 4. Results and discussion

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

$$\Delta\dot{T} = \int_0^{P_i} \dot{T}(p)W(p) dp, \quad (4)$$

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

Shown in Fig. 4 are the errors in temperature trends related to these different methods. Using the three trend profiles shown in Fig. 1, the stratospheric contaminations in  $T_2$  are  $-0.073$  ( $R_H$ ),  $-0.066$  ( $R_P$ ), and  $-0.083$

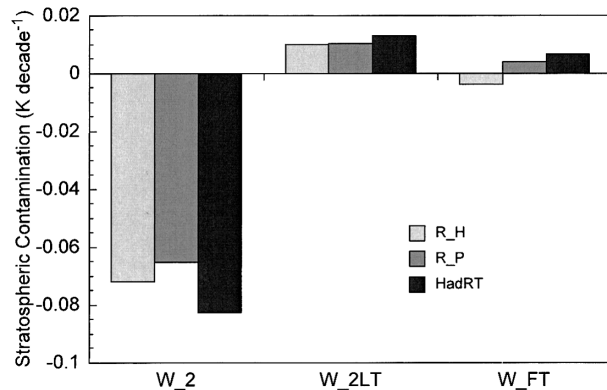


FIG. 4. Stratospheric contributions to the MSU-derived tropospheric temperature trends obtained by applying the weighting functions shown in Fig. 2 to the observed stratospheric trend profiles shown in Fig. 1.

K decade<sup>-1</sup> (HadRT). Thus the results corresponding to the  $R_H$  and HadRT profiles generally agree with the finding ( $-0.08$  K decade<sup>-1</sup>) of Fu et al. (2004). Note that the trend profile based on the linear extrapolation with respect to pressure ( $R_P$ ) is less consistent with radiosonde data (Fig. 1).

The errors associated with the method of Fu et al. (2004) are only  $-0.004$  ( $R_H$ ),  $0.004$  ( $R_P$ ), and  $0.006$  K decade<sup>-1</sup> (HadRT). These errors are small because the positive and negative portions of the integral in Eq. (4) largely cancel each other out. Figure 4 also shows that the errors in  $T_{2LT}$ , due to the stratospheric influences, are  $0.01$  ( $R_H$ ),  $0.01$  ( $R_P$ ), and  $0.013$  K decade<sup>-1</sup> (HadRT). Thus we conclude that the technique developed by Fu et al. (2004) is more accurate than the angular scanning retrieval method of Spencer and Christy (1992) to remove the stratospheric influences.

Given that the stratospheric contribution is  $-0.08$  K decade<sup>-1</sup> in  $T_2$ , we may derive a free-tropospheric temperature trend of  $0.09$  K decade<sup>-1</sup> based on a UAH trend of  $0.01$  K decade<sup>-1</sup> for  $T_2$ . By comparing this tropospheric temperature trend with a trend of  $0.045$  K decade<sup>-1</sup> for  $T_{2LT}$  (after removing a stratospheric influence of  $0.01$  K decade<sup>-1</sup>), we have a temperature trend difference of  $-0.045$  K decade<sup>-1</sup> between the free troposphere and lower-middle troposphere. Further research is required to examine this discrepancy between  $T_{2LT}$  and  $T_{FT}$ , which could be due to either long-term changes of vertical temperature structure in the troposphere or problems involving the  $T_{2LT}$  retrievals. One indication of the problems is the fact that within the tropical region ( $30^\circ\text{N}$ – $30^\circ\text{S}$ ),  $T_{2LT}$  is cooling at a rate of  $0.04$  K decade<sup>-1</sup> relative to  $T_2$  (Fu et al. 2004). In view of the cooling trend in the stratosphere at all latitudes (Houghton et al. 2001), one would expect that  $T_{2LT}$  should be warming relative to  $T_2$  unless there is a very strong warming occurring in the upper troposphere. 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, is particularly because the microwave emissivity of sea ice is much greater than that of ocean water. Arctic data are presumably subject to similar influences.

In summary, we have tested the MSU channel-2 brightness temperature, the angular scanning retrieval scheme of Spencer and Christy (1992), and the two-channel retrieval scheme of Fu et al. (2004) for deriving tropospheric temperature trends, using observation-based estimates 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.

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