Estimation of Tropospheric Temperature Trends from MSU Channels 2 and 4

ROY W. SPENCER, JOHN R. CHRISTY, WILLIAM D. BRASWELL, AND WILLIAM B. NORRIS

Earth System Science Center, University of Alabama in Huntsville, Huntsville, Alabama

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ABSTRACT

The problems inherent in the estimation of global tropospheric temperature trends from a combination of near-nadir Microwave Sounding Unit (MSU) channel-2 and -4 data are described. The authors show that insufficient overlap between those two channels' weighting functions prevents a physical removal of the stratospheric influence on tropospheric channel 2 from the stratospheric channel 4. Instead, correlations between stratospheric and tropospheric temperature fluctuations based upon ancillary (e.g., radiosonde) information can be used to statistically estimate a correction for the stratospheric influence on MSU 2 from MSU 4. Fu et al. developed such a regression relationship from radiosonde data using the 850–300-hPa layer as the target predictand. There are large errors in the resulting fit of the two MSU channels to the tropospheric target layer, so the correlations from the ancillary data must be relied upon to provide a statistical minimization of the resulting errors. Such relationships depend upon the accuracy of the particular training dataset as well as the dataset time period and its global representativeness (i.e., temporal and spatial stationarity of the statistics). It is concluded that near-nadir MSU channels 2 and 4 cannot be combined to provide a tropospheric temperature measure without substantial uncertainty resulting from a necessary dependence on ancillary information regarding the vertical profile of temperature variations, which are, in general, not well known on a global basis.

1. Introduction

Global monitoring of tropospheric temperature trends from the Microwave Sounding Units (MSUs) flying on the National Oceanic and Atmospheric Administration (NOAA) polar-orbiting satellites depends, conceptually, upon the removal of the stratospheric influence from MSU channel 2 (Fig. 1). This was accomplished by Spencer and Christy (1992, hereafter SC92) with a weighted difference ("LT" in Fig. 1) between different view angles of MSU 2 that have large amounts of overlap between their respective weighting functions. Similarly channels 2 and 3, or channels 3 and 4, can be combined to provide lower- or upper-tropospheric temperature sensitivity, respectively (e.g., Bantzer and Wallace 1996).

MSU channels 2 and 4, in contrast, have relatively little overlap. It is not possible to linearly combine the channel-2 and -4 weighting functions in Fig. 2 in any way to physically remove stratospheric influence. Nevertheless, Fu et al. (2004, hereafter FJWS) proposed a statistical method to obtain a tropospheric measure using a weighted difference between channels 2 and 4 (Fig. 2) that relies on interlayer correlations from radiosonde data to minimize errors resulting from the stratospheric influence. The FJWS method represents a substantial departure from the philosophy for physical removal of the stratospheric influence (e.g., SC92) that we believe warrants further investigation and comment. Here we present evidence that the use of MSU channels 2 and 4 to estimate tropospheric temperatures is, at best, problematic.

2. Background

Individual satellite temperature-sounder channel weighting functions often do not have sufficient vertical resolution to provide useful layer temperature information. Given a number of satellite temperature sounder channels with heavily overlapping weighting functions, various linear combinations of those channels can provide higher vertical resolution (e.g., Backus and Gilbert 1968; Conrath 1972; Huang et al. 1992). The greater the overlap of adjacent weighting functions, the greater is

Corresponding author address: Roy W. Spencer, University of Alabama in Huntsville, 320 Sparkman Dr., Huntsville, AL 35805.
E-mail: roy.spencer@nsstc.uah.edu

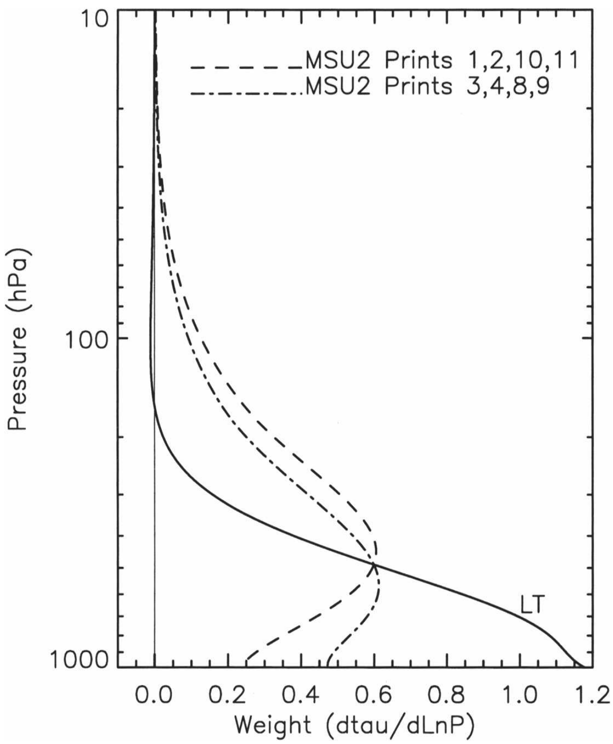

FIG. 1. Lower-tropospheric (LT) effective weighting function of SC92 based upon a weighted difference (4.0, −3.0) of the near-nadir (footprints 3, 4, 8, 9) and off-nadir (footprints 1, 2, 10, 11) average measurements of MSU channel 2 (ocean surface emissivity of 0.5).

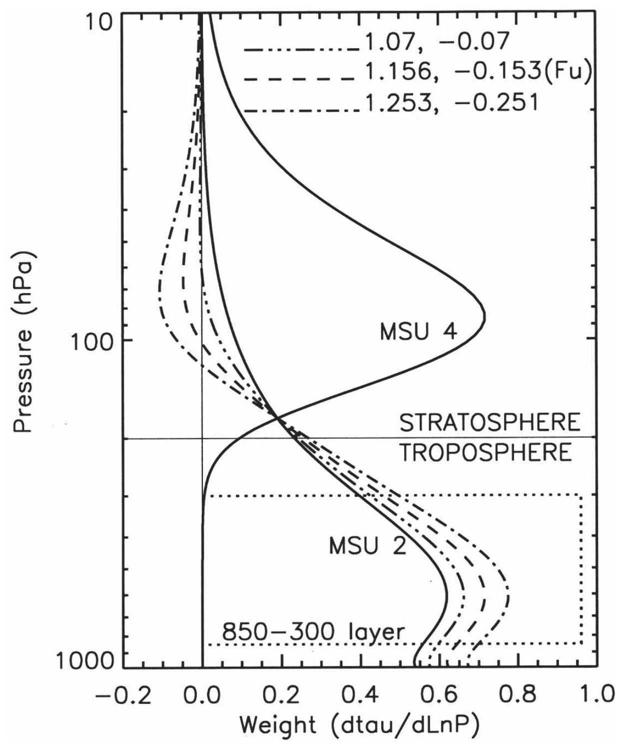

FIG. 2. Effective weighting functions resulting from three different weighted differences between MSU channels 2 and 4: no negative weight (1.07, −0.07), the FJWS ("Fu") radiosonde regression profile (1.156, −0.153), and a profile based on random noise added to a baseline radiosonde profile (1.253, −0.251). The two profiles exhibiting negative weight in the stratosphere are based upon regressions against the 850–300-hPa layer, also shown (ocean surface emissivity of 0.5).

the potential for deconvolution. In the case of MSU channels 2 and 4, however, there is no *weighted difference* that can remove the stratospheric influence on MSU 2 (Fig. 2).

If vertical resolution is desired that is beyond what can be resolved with satellite data alone, then a "retrieval" must be performed with either ancillary information about interlayer correlations (usually from radiosondes) or by imposing a physical constraint on the retrieval (e.g., require the profile to have a vertical structure that can be represented by some mathematical function, or possess some measure of smoothness). Note that retrieval methods do not improve the vertical resolution of the satellite measurements; they merely provide a way of inferring higher resolution given certain assumptions.

It is obvious that retrieval errors can be avoided if the raw channel weighting functions, or the effective weighting functions representing a combination of the raw channels, are taken at face value—that is, a weighted vertical average of the atmosphere. This was the basis of the SC92 method used to measure a lower-tropospheric temperature (LT) from MSU channel 2. In this framework there is no error arising from a misinterpretation of the satellite-sensed layer as a thinner layer than the satellite measurements can actually be resolved. This is why assimilation of raw satellite radiances, rather than retrievals, into numerical weather prediction models (e.g., Eyre and Lorenc 1989) has become popular. The satellite measurements can then be compared directly to a weather prediction or climate model without dependence on statistical relationships that are likely not stationary in space or time.

While retrieval errors for levels can be reduced in a statistical sense with information about interlayer correlations, usually from radiosonde data, this makes the temperature retrieval sensitive to errors arising from the application to data that have different correlation structures than the training data. While satellite temperature retrievals have had considerable success for weather-related temperature variations, much smaller long-term global temperature trends have vertical correlation structures that are not well known. This is why the satellite monitoring of tropospheric and lower-stratospheric temperature trends has traditionally used the effective weighting function (e.g., LT in Fig. 1), or raw channel weighting functions, interpreted directly. We are not suggesting that our LT method is error free—only that it is a direct measure rather than an indirect inference.

We submit that the efforts by FJWS to retrieve a tropospheric-layer temperature from MSU channels 2 and 4 warrants a reexamination of some simple retrieval issues in the context of climate temperature trend monitoring. In section 3, we illustrate some of the problems inherent in combining MSU channels 2 and 4 to estimate a tropospheric-layer average temperature.

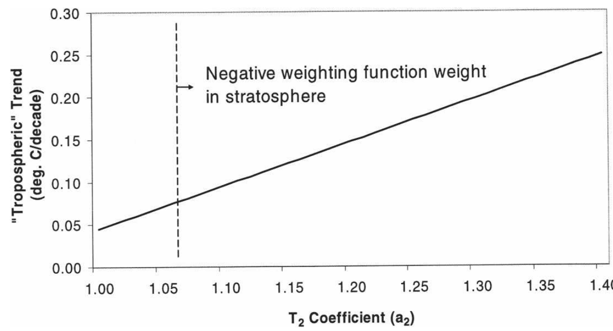

FIG. 3. Sensitivity of estimated 1979–2003 "tropospheric" temperature trends to the size of the T_2 coefficient (and thus the T_4 coefficient a_4, since $a_2 + a_4 = 1$). This is based upon the UAH-calculated T_2 and T_4 trends of +0.045°C decade^{-1} and −0.465°C decade^{-1}, respectively.

3. Regression of MSU 2 and 4 against a tropospheric layer

a. The FJWS regression on radiosonde data

The FJWS regression used monthly T_2, T_4, and $T_{850\text{–}300}$ anomalies, all computed from radiosonde-observed temperature anomaly profiles. Their training dataset was based upon Lanzante et al. (2003) and contained 87 radiosondes over the period 1958–97. A regression of the 850–300-hPa-layer temperature ($T_{850\text{–}300}$) anomalies against T_2 and T_4 anomalies computed from the monthly radiosonde temperature profiles led to coefficients that minimize ε^2 in

$$\mathrm{T}_{850-300} = a_0 + a_2\mathrm{T}_2 + a_4\mathrm{T}_4 + \varepsilon. \tag{1}$$

FJWS obtained regression coefficient (a_2, a_4) values of (1.156, −0.153) that, when applied to the T_2 and T_4 weighting functions, leads to the effective weighting function profile labeled "Fu" in Fig. 2. (The regression constant a_0 was very small, and can be neglected for the purposes of this discussion.) The FJWS coefficients were found to be essentially the same when their training dataset was detrended (Q. Fu 2005, personal communication), indicating that interannual variability was the primary source of signal in the radiosonde data. Even though the FJWS profile fit to the 850–300-hPa layer in Fig. 2 is seen to be poor, interlayer correlations in the radiosonde data led to a very high correlation of the fit (0.986) for monthly global anomalies.

One of our criticisms (Q. Fu 2005, personal communication) of the FJWS effective weighting function has centered around the existence of substantial weight above the tropopause—indeed, as much weight as MSU 2 has. Of particular concern is that the negative lobe of weight (the "Fu" curve in Fig. 2) will "see" stratospheric cooling as tropospheric warming, potentially biasing temperature trend calculations. Since the trends in T_2 and T_4 during 1979–2003 have been weakly positive (+0.045°C decade^{-1}) and strongly negative (−0.465°C decade^{-1}), respectively, a weighted difference will produce a tropospheric warming estimate that will be directly proportional to the magnitude of those weights. Sensitivity of the estimated tropospheric trend to those weights is illustrated in Fig. 3.

It is obvious from Figs. 2 and 3 that the larger the coefficients and the larger the resulting negative weight in the stratosphere, the greater the inferred "tropospheric" warming. Thus, any method for choosing the coefficients, and what those coefficients imply physically, must be critically examined. Fu and Johanson (2004) showed evidence from another radiosonde dataset (Ramaswamy et al. 2001) that suggested that the errors associated with their weights (1.156, −0.153) would be negligible. For reference, the largest coefficients that do not result in a negative lobe are (1.07, −0.07); note, however, that there is still substantial stratospheric weight.

Since we believe that there has been some confusion in the research community (e.g., K. Trenberth and D. Seidel 2005, personal communication) over the negative lobe being somehow related to correlations between tropospheric and stratospheric temperature variations, we first examine its source.

b. Two-channel regression with uncorrelated temperature variations

We performed regressions similar to that of FJWS on synthetic time series of monthly temperature "anomalies" where each month's layer temperatures were computed from a constant base state plus random temperature perturbations with height. This produces time series that have temperature variations that are uncorrelated between layers. The resulting average values for the (a_2, a_4) regression coefficients under these conditions were found to be (1.253, −0.251), which are even larger than those obtained by FJWS. The resulting weighting profile represented by these coefficients is also shown in Fig. 2. Note that, as is the case for the FJWS coefficients, the regression fit to the target layer is not very good, with large errors throughout the troposphere and lower stratosphere.

The negative lobe of weight based upon regression coefficients from vertically uncorrelated temperature structures is even larger than that obtained by FJWS, clearly showing that it is not the result of natural correlations between troposphere and stratospheric temperature variations. It is, instead, the result of attempting to fit a boxcar-shaped layer (850–300 hPa) with two slightly overlapping weighting functions that cannot resolve the structure inherent in that layer. This uncorrelated signal-based weighting profile represents the best fit that can be obtained, in a least squares sense, to the target 850–300-hPa layer.

c. Two-channel regression with correlated temperature variations

When correlations exist between the layers to which MSU channels 2 and 4 are sensitive, a new issue arises that affects the interpretation of the regression results. As a simple example, we introduced perfectly negatively correlated temperature pulses centered near 800 and 22 hPa to generate a synthetic time series. We then repeated the FJWS procedure by regressing T_2 and T_4 against $T_{850–300}$ and obtained regression coefficients (a_2, a_4) of (1.302, -0.306). (If noise was added to the 22-hPa layer that has a standard deviation magnitude 20% of that of the "signal," the coefficients changed only slightly, to 1.298 and -0.301.)

Significantly, even though *only* the 800-hPa layer is contained within the 850–300-hPa layer to which the regression is fitted, substantial regression weight is still assigned to the stratospheric channel. This demonstrated that, as long as there are correlations between layers, it does not matter whether a satellite sounding channel has sensitivity to a particular layer or not; that channel will still receive a nonzero regression coefficient. This example is presented to emphasize the reliance of statistical relationships on correlation and that physical sensitivity of a channel to a given atmospheric layer is not necessary in order for it to be given weight in a regression relationship.

4. Discussion

Despite the fact that both SC92 and FJWS rely upon weighted differences between overlapping weighting functions, the physical basis for each is quite different. SC92 required strongly overlapping weighting functions in order to essentially remove stratospheric influence on the resulting effective weighting functions for the LT measurement. There was no target layer against which it was regressed; whatever tropospheric sensitivity was left after removal of stratospheric influence was accepted.

Because of the relative positioning of the channel-2 and -4 weighting functions, the FJWS method cannot accomplish direct removal of stratospheric sensitivity in the resulting effective weighting function. Instead, correlations inherent in the radiosonde data are utilized by the regression procedure to minimize errors resulting from the lack of fit to the target (predictand) layer throughout the troposphere and stratosphere. The success of the FJWS method thus depends upon knowledge of global statistics of the trend profile throughout the troposphere and lower stratosphere, which is in general not well known, and on the assumption of temporal stationarity of the trend profile statistics. Indeed, if the trend profile were known from radiosonde data on a global basis, there would be no need for the satellite data for global temperature monitoring. We also find it somewhat contradictory that FJWS rejected *tropospheric* trend measurements from radiosondes, which show little or no warming during the satellite period of record (e.g., Christy et al. 2003), and yet depended upon radiosonde-measured *stratospheric* trends, where problems are considerably greater (Parker et al. 1997), for their method to work.

We emphasize that our core criticisms of the FJWS approach, described above, do not depend upon the results that follow; we include these mainly for the sake of completeness.

5. Examples of dataset dependence of MSU 2 and 4 regressions

Since the FJWS regression method depends upon the statistics of a particular radiosonde dataset, it is reasonable to apply the method to other observational datasets. Tett and Thorne (2004) showed a variety of trend results for the FJWS weighting coefficients depending upon what radiosonde or reanalysis dataset was employed. They also demonstrated that the University of Alabama at Huntsville (UAH)-produced LT trends were more consistent with observations than were the FJWS retrievals.

While FJWS developed regression coefficients based wholly upon radiosonde data, a natural question to ask is what coefficients would result from regression of *actual* satellite T_2 and T_4 data against radiosonde-measured 850–300-hPa-layer temperatures? Since the intent of FJWS was to apply radiosonde-derived regres-

TABLE 1. Regression coefficients between MSU T_2 and T_4 global monthly anomalies and NCEP–NCAR reanalyses (or LKS or HadAT2) radiosonde-measured 850–300-hPa temperature anomalies for 11 periods (5 periods for LKS) starting in January 1979 and ending in December of various ending years. The regressions involved the additional constraint that $a_2 + a_4 = 1$.

Predictand ($T_{850-300}$) source	Predictors (T_2 and T_4) source*	Regression				Fu avg trend error (°C decade^{-1})	Regression correlation
		Average a_2	Range in a_2	Trend avg error (°C decade^{-1})	Trend rms error (°C decade^{-1})		
NCEP–NCAR	UAH	1.064	1.039–1.125	+0.002	0.015	+0.045	0.93
NCEP–NCAR	RSS	0.973	0.944–0.996	+0.005	0.014	+0.073	0.94
LKS	UAH	1.138	1.115–1.156	−0.073	0.078	−0.066	0.73
LKS	RSS	1.012	1.008–1.011	−0.070	0.073	−0.032	0.73
HadAT2**	UAH	1.106	1.084–1.145	+0.082	0.093	+0.030	0.91
HadAT2**	RSS	1.054	1.026–1.129	−0.003	0.034	−0.058	0.92

* The UAH and Remote Sensing Systems (RSS) are currently the only providers of the MSU datasets.

** HadAT2 anomalies are seasonal.

sion coefficients to satellite-observed data, we believe it is a physically meaningful exercise to use actual satellite data in the regressions and to use a time period represented by the satellite data record. Also, using global satellite data ensures that truly global troposphere–stratosphere relationships are included, at least on the satellite data side.

We performed regressions using global monthly anomalies for satellite-observed T_2, T_4 versus the National Centers for Environmental Prediction–National Center for Atmospheric (NCEP–NCAR) reanalyses (Kalnay et al. 1996), or the Lanzante et al. (2003, hereafter LKS), or the most recent Hadley Centre (HadAT2; Thorne et al. 2005) radiosonde $T_{850-300}$-layer average temperature anomalies. Eleven different regressions (five for LKS) used time series starting in January 1979 but ending in different years ranging from 1993 to 2003 (1997 for LKS). The results (Table 1) reveal a wide variety of regression coefficients and suggest some important conclusions.

First, the wide range of regression coefficients, depending upon the training dataset end year, illustrates the statistical nature of the regression relationships and their significant dependence on the data. Second, the range of values for a_2 depending on the length of the time series included illustrates the temporal nonstationarity of the coefficients. Third, the average values of the regression coefficients are considerably smaller than those found by FJWS (1.156, −0.153) with the 1958–97 radiosonde data. They average less than (1.06, −0.06), which we note is close to the weights in (Fig. 2) that result in no negative lobe under the weighting function (1.07, −0.07). It can be shown that, when negative weight appears under an effective weighting function, its physical meaning changes to a sum of 1) a weighted layer-average temperature plus 2) the temperature *difference* between the positively and negatively weighted layers. Thus, the (1.06, −0.06) average coefficient values these datasets yield might be related to the (1.07, −0.07) limit at which negative weight begins to appear. Given the positive T_2 and negative T_4 trends during the satellite period of record, these smaller coefficients lead to smaller estimates for "tropospheric" warming than those estimated with the FJWS coefficients (see Fig. 3).

Finally, the much lower regression correlations for the LKS dataset regressions (0.73) versus the global NCEP–NCAR (0.93) or HadAT2 (0.92) fields suggests that the LKS radiosonde statistics, with relatively poor coverage of the earth, are not very consistent with the global satellite data. We note that, while the global temperature spatial patterns in the NCEP–NCAR fields are influenced by satellite (including MSU) data, the temperature changes over time are constrained by radiosondes (Christy et al. 2003). These results suggest that one cannot depend upon radiosonde trend profile statistics to constrain global satellite trend estimates without substantial uncertainty.

In contrast to the LKS sonde regression errors from Table 1 of about −0.07°C decade^{-1}, we find that direct site-by-site trend comparisons between the UAH satellite LT trends and sonde trends for the LT layer (Table 2) reveal median trend differences of less than 0.02°C decade^{-1}. Site comparisons eliminate spatial and temporal heterogeneities and provide the best method of independent comparison.

This suggests, at least for the lower-tropospheric layer represented by the LT profile, that much radiosonde evidence is supportive of the satellite-measured trends. Additionally, the over 150 unique radiosonde comparisons represented in Table 2 supports the result of Christy et al. (2003) in which the global UAH LT trend confidence interval (95%) was calculated as being ±0.05°C decade^{-1}.

TABLE 2. Update of Christy et al. (2003) and Christy and Norris (2004) LT site-by-site comparisons between radiosonde-simulated and MSU-observed trends [version 5.2 with Advanced Microwave Sounding Unit (AMSU)-based diurnal cycle corrections]. U.S. VIZ: distributed from western tropical Pacific to Caribbean to contiguous United States (CONUS) to Alaska, stations utilized a single sonde type (VIZ-B and VIZ-B2; see Christy et al. 2003); LKS: global distribution, stations required 13 of 19 years of data for inclusion; SH87: all Southern Hemisphere stations in the Comprehensive Aerological Reference Data Set (CARDS) database with at least 14 of 23 years of data and no adjustments applied (see Christy and Norris 2004); SH75: All SH stations in CARDS database with 17 of 23 years of data and with adjustments applied for instrument/processing changes (see Christy and Norris 2004). Eleven stations are common between U.S. VIZ and LKS; no stations are common between U.S. VIZ and SH87, SH75; 24 stations are common between LKS and SH87, SH75.

Dataset	Number of stations	Median trend error (°C decade^{-1})	Rms of trend errors (°C decade^{-1})	Period
U.S. VIZ	31	−0.057	0.137	1979–2003
LKS	70	−0.002	0.213	1979–97
SH87	87	−0.012	0.241	1979–2001
SH75	75	−0.023	0.160	1979–2001

6. Summary and conclusions

We have presented evidence of problems inherent in the statistical retrieval method advocated by FJWS for estimating tropospheric trends from a linear combination of MSU channel-2 and -4 data. Because of the small amount of overlap between the near-nadir MSU 2 and 4 weighting functions, these two channels cannot be effectively combined to remove stratospheric influence and provide a direct measurement of the troposphere as was done by SC92 for the lower troposphere (LT).

The dominant feature of the FJWS weighting profile's stratospheric sensitivity is a negative stratospheric lobe of weight that can potentially lead to misinterpretation of stratospheric cooling as tropospheric warming. The FJWS interpretation of their effective weighting profile as a tropospheric measure depends upon an empirical cancellation of signals from the stratosphere. Specifically, it is necessary for the contributions from the positively and negatively weighted stratospheric portions of their weighting function to cancel in the presence of a specific type of trend profile through those layers. This makes the FJWS method dependent upon knowledge of the temperature trend profile, which is in general not well known on a global basis, and on the assumption of statistical stationarity of that trend profile. The FJWS rejection of the tropospheric trends from radiosonde data (which show little warming during the satellite period of record) seems to us to be inconsistent with their method's dependence on the stratospheric trends from those same radiosondes. Even though the above considerations alone are sufficient to cast doubt upon any tropospheric trends inferred from the FJWS approach, we additionally show that if FJWS-style regressions use globally averaged satellite data, rather than the spatially restricted local relationships from radiosonde data, coefficients results that, on average, do not result in negative weighting function weight in the stratosphere. We demonstrate this with regressions between satellite-observed T_2 and T_4 global anomalies and NCEP–NCAR reanalyses (or LKS or HadAT2 radiosonde) of the 850–300-hPa-layer temperature anomalies. The average regression errors resulting from application of the FJWS coefficients are considerably larger that those obtained from site-by-site trend comparisons between individual radiosonde stations and the UAH MSU LT trends. Again, all of these errors arising from statistical estimation do not occur with the selective choice of different view angle weighting functions that directly remove stratospheric influence from channel 2 (SC92).

We conclude that there is substantial uncertainty in tropospheric temperature trends deduced from near-nadir MSU channels 2 and 4, due to the inability of those channels to physically remove stratospheric influence on channel 2, and the necessary dependence of any other (statistical) method on statistically stationary correlations between tropospheric and stratospheric temperature variations, which are not well known on a global basis.

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