

NOTES AND CORRESPONDENCE

Stability of the MSU-Derived Atmospheric Temperature Trend

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ABSTRACT

Warm target effect and diurnal drift errors are the main sources of uncertainties in the trend determination from the NOAA Microwave Sounding Unit (MSU) observations. Currently, there are two methods to correct the warm target effect: 1) finding a best root-level (level-1c) calibration nonlinearity using simultaneous nadir overpass (SNO) matchups to minimize this effect for each scene radiance, and 2) finding a best-fit empirical relationship between the correction term of the end-level gridded brightness temperature and warm target temperature and then removing the best fit from the unadjusted time series. The former corrects the warm target effect before the diurnal drift adjustment and provides more accurate, warm target effect–minimized, level-1c scene radiances for reanalysis applications. The latter corrects the warm target effect at the end-level merging step, which depend on the diurnal drift correction that occurred at a previous step. Although minimized, the first method still leaves small residual warm target–related errors due to imperfect calibrations. This study demonstrates that when the diurnal drift effect is negligible, a combination of the two methods completely removes warm target effect and produces an invariant trend that is independent of the level-1c calibration in the SNO framework. The conclusion is directly applicable to the MSU channel-2 oceanic mid-tropospheric temperature (T_2) and global channel-3 upper-tropospheric temperature (T_3) and channel-4 lower-stratospheric temperature (T_4), which satisfy the condition of negligible diurnal drift effect. On the basis of these results, version 1.2 of the National Environmental Satellite, Data, and Information Service (NESDIS)–Center for Satellite Applications and Research (STAR) multisatellite MSU time series was constructed, including all T_2 , T_3 , and T_4 products. In addition, a diurnal drift correction based on the Remote Sensing Systems diurnal anomalies was applied to the T_2 product, which produces consistent climate trends between land and ocean. The global long-term climate trends for T_2 and T_4 derived from the STAR V1.2 dataset are, respectively, 0.18 ± 0.05 and -0.39 ± 0.36 K decade⁻¹ during 1979–2006; the T_3 trend is 0.11 ± 0.08 K decade⁻¹ for 1981–2006.

1. Introduction

The atmospheric temperature trends derived from the Microwave Sounding Unit (MSU) and Advanced Microwave Sounding Unit (AMSU) on board the National Oceanic and Atmospheric Administration (NOAA) polar-orbiting satellites have been a subject of debate. Pioneer investigations by Spencer and Christy (1992a,b) and their follow-on work at the University of Alabama

at Huntsville (UAH) (Christy et al. 1998, 2000, 2003) showed small warming trends for the midtropospheric temperature time series derived from the MSU channel-2 (53.74-GHz single sideband) and AMSU channel-5 (53.71- and 53.48-GHz double sidebands) observations (referred to as T_2 hereafter). However, the Remote Sensing Systems (RSS) (Mears et al. 2003; Mears and Wentz 2009) and NOAA/National Environmental Satellite, Data, and Information Service (NESDIS) Center for Satellite Applications and Research (STAR) (Zou et al. 2006, 2009, hereafter Z06 and Z09, respectively) groups obtained larger T_2 trends from the same satellite observations. The most recent analysis of different datasets shows a global ocean-mean T_2 trend of 0.080 ± 0.103 K decade⁻¹

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for UAH, 0.135 ± 0.113 K decade⁻¹ for RSS, and 0.200 ± 0.067 K decade⁻¹ for STAR for the 1987–2006 period (Z09). These differences exceed the widely accepted accuracy requirement of 0.01–0.02 K decade⁻¹ for the trends. Accurate determination of the MSU–AMSU temperature trends is essential for resolving the global warming debate (Karl et al. 2006), validating climate model simulations (Santer et al. 2005, 2008), and framing policy decisions on global change. As such, structure differences and/or similarities among these different groups in constructing the time series need to be sought out to understand the trend differences.

Christy and Norris (2006, 2009) attempted to understand such differences by comparing UAH and RSS datasets with U.S.-controlled VIZ radiosonde and Australian radiosonde time series. The Christy and Norris (2009) study also included a comparison between the Australian radiosondes and the STAR dataset. Furthermore, Christy et al. (2007) compared radiosonde and satellite data for the tropical lower-tropospheric temperature. These inter-comparisons identified several breakpoints in the radiosonde time series and possible, but less certain, shifts in the satellite datasets. Using this breakpoint information to adjust the radiosonde time series, Christy and Norris (2006) and Christy et al. (2007) found that the adjusted radiosonde trends were aligned with the UAH-derived MSU–AMSU trends. However, using seasonally resolving adjustments for radiosonde homogenization that includes wind shear and temperature information, Sherwood et al. (2008) indicated that the adjusted radiosonde trends were closer to the RSS results for the midtropospheric temperature product. In a recent study, Titchner et al. (2009) suggested that most unadjusted radiosonde data have cold biases with magnitudes difficult to determine.

Given these controversial results and the sparseness of radiosonde data over oceans, it appears to be necessary to compare and examine only satellite products derived by different research groups (e.g., Randall and Herman 2008) or even different versions of satellite data produced by the same group. These examinations require, and will also provide in return, an insightful understanding of the error correction and merging steps in the satellite data production. Focusing on the T_2 product, previous investigations indicated that its trends were mainly affected by at least four factors: diurnal drift errors, the warm target effect, short overlaps between *NOAA-9* and *NOAA-10*, and quality control issues. The first effect originates from satellite orbital drifts. Specifically, the orbital drift results in a change of local observation time (or diurnal drift), which, if not corrected, may introduce false long-term temperature trends by aliasing the diurnal cycle into it (Trenberth and Hurrell 1997; Christy et al. 1998; Mears et al. 2003;

Fu and Johanson 2005). Different methodologies were developed to correct the diurnal drift errors: UAH (Christy et al. 2000) used diurnal anomalies estimated by accumulating the local MSU or AMSU observations from different scan positions at different local times, whereas RSS (Mears et al. 2003) adopted diurnal anomaly climatology generated from National Center for Atmospheric Research (NCAR) Community Climate Model (CCM) simulations. The two methods have caused large trend differences over the land areas for the MSU lower-tropospheric temperature product where diurnal drift effects are large (Mears and Wentz 2005). Fortunately, however, the diurnal drift effect is negligible over oceans for T_2 , owing to small diurnal amplitude and cancellation of ascending and descending orbits (Mears et al. 2003). Furthermore, intersatellite bias analyses suggest that diurnal drift effect is small globally for the MSU channel-3 upper-tropospheric temperature (T_3) and channel-4 lower-stratospheric temperature (T_4) for the same reasons (Z09). Thus, the T_2 trend over oceans and the global T_3 and T_4 trends should be ideally mainly affected by factors other than the diurnal drift effect. In the RSS dataset, however, the T_2 trend over oceans may be affected by the diurnal drift correction over land since zonal-mean intersatellite offsets were used to correct residual biases (Mears and Wentz 2009). These zonal-mean biases are determined using both the land and ocean data, so any errors in the land diurnal cycle can affect the final product over the oceans. In this study, we investigate this problem by using geolocation (i.e., grid cell)-dependent bias corrections for satellite merging, which provides consistent T_2 trends over the oceans with and without the diurnal correction.

The warm target was an onboard blackbody used to calibrate the MSU raw observations for obtaining root-level (level 1c) radiances for meteorological applications. The warm target has its own temperature that was measured by the platinum resistance thermometer (PRT) embedded in it. However, this temperature incurred a large variability and trend owing to differences in sun heating on the instrument, which originated from sun angle changes relative to the satellite orbit normal over a year and its yearly differences due to orbital drift. This variability and trend was not accounted for in prelaunch calibration and thus manifested in the subsequent brightness temperature time series (Christy et al. 2000; Mears et al. 2003; Mears and Wentz 2009; Z06; Z09). This effect, if not removed, will bring unwanted warm target temperature trend errors to the brightness temperature time series, a so-called warm target contamination on the radiances. Currently, there are two methods to correct this error: (i) finding a best root-level calibration non-linearity using simultaneous nadir overpasses (SNOs) to

minimize this effect for each scene radiance observation (Z06; Z09), and (ii) finding a best-fit empirical relationship between the correction term of the end-level gridded brightness temperature and warm target temperature and then removing the best fit from the unadjusted time series (Christy et al. 2000, 2003; Mears et al. 2003; Mears and Wentz 2009). The two methods differ fundamentally. The former removes warm target contamination from the level-1c scene radiances that is independent from the diurnal drift correction at a later step; the later corrects the warm target effect at the end-level merging step that depends on the diurnal drift correction that occurred at a previous step. The SNO method provides consistent level-1c radiances with minimized warm target effect and therefore will benefit modeling reanalysis practice. For the second method, however, errors in the diurnal drift correction may influence the merging procedure and hence amplify trend uncertainties (Mears and Wentz 2005).

For global T_3 and T_4 , and for T_2 over the oceans where the diurnal drift effect is small, it is desirable to understand how the two methods affect the trend results. This understanding is essential for assessing the structure and trend differences of the MSU–AMSU temperatures among the UAH, RSS, and STAR groups. In this paper, we intend to demonstrate that despite the apparent advantage of the SNO approach, it still leaves small residual warm target–related errors due to imperfect instrument calibration. However, the combination of the Christy et al. (2000) correction method (hereafter referred to as Christy correction) and the SNO approach completely removes the warm target effect and produces an invariant trend that is independent of the root-level calibration in the SNO framework. The results substantially reduce the trend uncertainties and provide a foundation for selection of appropriate technologies in constructing merged MSU–AMSU time series.

Based on results presented in this study, version 1.2 of the STAR multisatellite MSU time series was constructed, including all T_2 , T_3 , and T_4 products. We had previously produced version 0.5 of the STAR MSU temperature datasets using geolocation (grid cell)–dependent constant bias corrections on top of the SNO calibrated radiances (Z09). Version 0.5 has 20 yr (1987–2006) of T_2 , T_3 , and T_4 products. Christy and Norris (2009) compared T_2 of version 0.5 with RSS and UAH satellite data and radiosonde observations over Australia. However, T_2 of version 0.5 did not include diurnal drift corrections; therefore, it is not expected to perform well over land. In this study, we describe STAR MSU version 1.2 (hereafter STAR V1.2), which includes a few major changes since version 0.5: it extends the 20-yr data in version 0.5 to 28 years (1979–2006), which covers the entire MSU period; it includes a diurnal correction based on the RSS diurnal anomalies;

and finally, it replaces the geolocation-dependent constant bias corrections in previous versions with the Christy correction based on the trend stability.

The next section describes the SNO calibration approach; section 3 describes the trend stability when Christy correction is used on top of the SNO calibration. Section 4 discusses the diurnal drift correction for T_2 , and section 5 provides a summary and conclusions. Throughout this study, we use the same quality control procedure as in our previous studies (Z06; Z09) to prevent differences in data treatment from affecting our conclusions.

2. A root-level calibration approach to remove warm target effect

The SNO root-level calibration approach for removing the warm target effect has been described in detail in our previous publications (Z06; Z09). However, to demonstrate the trend stability using the combination of the root-level calibration and end-level empirical approaches, here we summarize the calibration procedure again. Briefly, MSU uses an on-board calibration method that includes two calibration targets as its end point references: the cosmic space cold target and an onboard blackbody warm target. In each scan cycle, the MSU looked at these targets as well as the earth, and the signals in the form of electric voltage were converted to digital counts through an analog-to-digital converter. These digital counts were output as raw observations. The level-1c calibration equation for converting the raw observations (digital counts) to the radiances using the two calibration targets is written as (Z06)

$$R = R_L - \delta R + \mu Z, \quad (1)$$

where R is the earth scene radiance, $R_L = R_e + S(C_e - C_c)$, representing the dominant linear response, and $Z = S^2(C_e - C_c)(C_e - C_w)$ is a nonlinear response; C represents the raw counts data of the satellite observations and $S = (R_w - R_c)/(C_w - C_c)$ is the slope determined by the two calibration targets. The subscripts e , w , and c refer to the earth view, onboard warm blackbody target view, and cold space view, respectively; δR represents a radiance offset; and μ is a nonlinear coefficient. The cold space radiance R_c is specified to be $9.6 \times 10^{-5} \text{ mW (sr m}^2 \text{ cm}^{-1})^{-1}$ for all scan lines. This corresponds to a brightness temperature of 4.78 K, which includes the cold-space temperature of 2.73 K plus an increase of about 2 K owing to the antenna side-lobe radiation. Both δR and μ are assumed to be constants (Z06; Z09). We follow the algorithm in the NOAA Polar Orbiter Data User's Guide (Kidwell et al. 1998) to compute R_w . Once the radiance is known, the brightness temperature T_b is computed using the Planck function.

A sequential procedure was developed in Z06 to solve for the calibration coefficients (δR and μ) for all NOAA satellites using SNO matchups. The SNO matchups, accumulated using the Cao et al. (2004) algorithm, contain simultaneous observations over the polar region that are less than 2 min apart and within 111 km ground distance apart for the nadir pixels from any NOAA satellite pairs. In the sequential procedure, the calibration coefficients δR and μ of an arbitrarily selected reference satellite were assumed to be known first, and then coefficients of all other satellites were determined sequentially (one by one) from regressions of the SNO matchups between satellite pairs, starting from the satellite closest to the reference satellite. The selection of a reference satellite is necessary since one cannot solve the calibration coefficients of two satellites simultaneously from their SNO matchups owing to a colinearity problem in the SNOs (Z06). *NOAA-10* was arbitrarily selected as the reference satellite and its offset was assumed to be zero. By definition, the sequential regression procedure resulted in zero mean intersatellite biases in the SNO matchups. In addition, global intersatellite differences were also significantly reduced with application of the SNO-derived calibration coefficients (Z06; Z09). Now the sequential procedure reduced the problem to the determination of the nonlinear coefficient μ_{N10} of the reference satellite; once μ_{N10} is known, calibration coefficients of all other satellites can be solved from the SNOs. We tied this reference satellite problem to the removal of the warm target effect.

We demonstrated (Z06; Z09) that, for each satellite, a special μ value (μ_c) must exist that can completely remove its warm target effect. This can be understood by examining the correlation behavior between the radiance and the warm target temperature T_w . From Eq. (1), their correlation is written as

$$\overline{R'T'_w} = \overline{R'_L T'_w} + \mu \overline{Z'T'_w}, \quad (2)$$

where the prime represents an anomaly and the overbar is an average over time. The T_b difference time series for overlapping satellites is the anomaly where the climate signals are excluded from the overlapping observations so that only the instrument characteristics such as the warm target effect remain. The warm target effect is completely removed when the left-hand side of Eq. (2) equals zero; thus, this special value should be equal to

$$\mu = \mu_c = -\frac{\overline{R'_L T'_w}}{\overline{Z'T'_w}}. \quad (3)$$

In the SNO approach developed by Z06 and Z09, differences of the nonlinear coefficients as well as intersatellite offsets between satellite pairs satisfy SNO constraints,

but the μ values determined from the SNO regressions are not necessarily equal to μ_c for all satellites. To obtain μ values that are as close to μ_c as possible, an end-to-end approach was developed to determine the root-level calibration coefficient by minimizing warm target effect in the end-level intersatellite difference time series of the gridded temperature. This approach is summarized in Fig. 1.

In the end-to-end approach, a series of sensitivity experiments was conducted in which μ_{N10} changed from 0 to an arbitrary large value [$12.5 \text{ (sr m}^2 \text{ cm}^{-1}) \text{ (mW)}^{-1}$ for all MSU channels]. For each given μ_{N10} , a set of calibration coefficients for all other satellites were obtained sequentially from regressions of their SNO matchups. These calibration coefficients were then applied globally to every footprint observation to obtain a level-1c radiance dataset for each satellite from Eq. (1). Next, a limb correction (Goldberg et al. 2001) was applied to adjust different incident angles of the off-nadir footprints to the nadir direction. Diurnal drift correction is also needed at this step for MSU channel 2.

In the next step, the limb-adjusted radiances were binned together to generate a pentad T_b dataset with grid resolution of 2.5° longitude by 2.5° latitude. A total of seven near-nadir footprints per scan line were used in the time series. Global mean temperature and their difference time series between satellites were further computed from this gridded dataset. When discussing the warm target effect, however, we focus on the ocean-only area where the diurnal drift effect is negligible. Instead, we use land area to discuss the diurnal drift effect after warm target effects have been removed. This separation decouples the warm target and diurnal drift effects.

Figure 2 shows the mean standard deviation (σ) of the ocean-mean multisatellite difference time series for all different μ_{N10} for the three MSU atmospheric channels in the sensitivity experiments. We only use *NOAA-10* through *NOAA-14* observations from 1987 to 2006 for this discussion so that the short overlap problem between *NOAA-9* and *NOAA-10* can be ignored. Based on previous studies (Christy et al. 2000; Mears et al. 2003; Z09), the magnitude of σ values represents how well the warm target effect is removed. For instance, larger values of σ indicate larger warm target contamination when μ_{N10} is closer to 0 or 12.5. A minimum σ was found for each individual channel, corresponding to minimum warm target contamination. This point, corresponding to the minimum of σ and denoted as $\mu_{N10}(\sigma_{\min})$, was selected as the final calibration point for each individual channel (Z06; Z09). The values for δR and μ corresponding to $\sigma_{\min}$ are provided in Z09 for *NOAA-10* through *NOAA-14* and on the STAR MSU Web site (see <http://www.star.nesdis.noaa.gov/smcd/emb/mscat/mscatmain.htm>) for all other satellites.

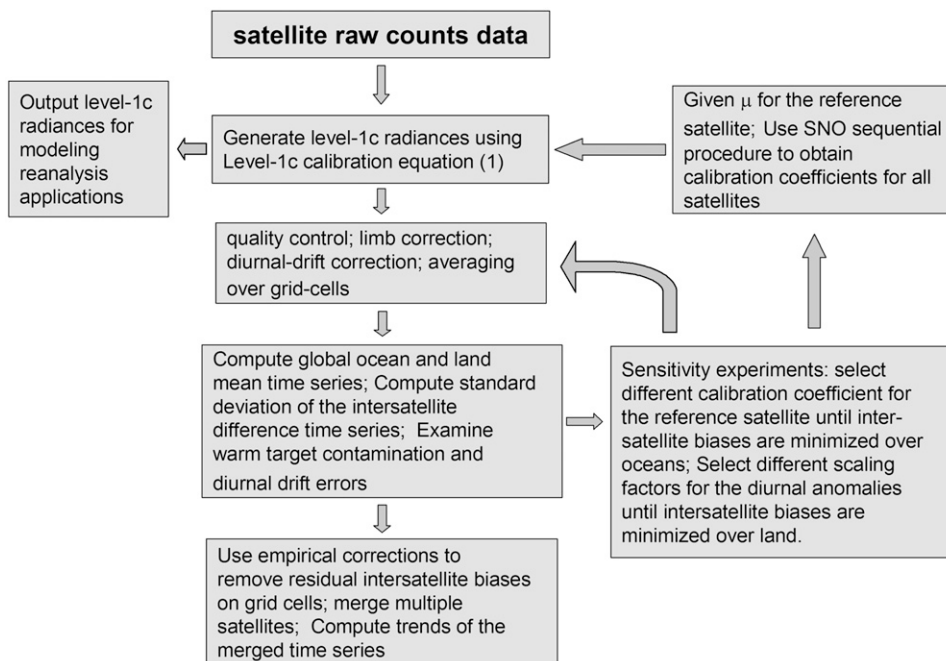


FIG. 1. Flowchart showing the calibration, error correction, data merging, and trend computation processes for the MSU instrument.

The level-1c radiance for this set of calibration coefficients has minimum warm target contamination and the smallest intersatellite bias in a multisatellite averaged sense and therefore is most accurate. As mentioned earlier, however, the μ values so determined are not necessarily equal to μ_c for each satellite. Therefore, small residual warm target errors still exist. This problem is dealt with by the Christy correction as described in the next section.

In Fig. 3, we show a comparison of the T_2 intersatellite difference time series between the NOAA operational calibration (calibration coefficients obtained from pre-launch laboratory testing; Mo et al. 2001) and the SNO calibration for μ_{N10} ($\sigma_{\min}$). The NOAA operational calibrated radiances were used by both the UAH and RSS groups; however, different merging methods were used to remove various errors. It is seen that both the intersatellite biases and warm target contamination found in the NOAA operational calibration (the bottom trace in Fig. 3a) are significantly reduced in the SNO calibration (the second trace from the bottom in Fig. 3a). A detailed discussion of these comparisons was given in Z09 and thus is omitted here.

3. Trend stability with an end-level empirical approach to correct warm target effect

After the SNO calibration, small residual intersatellite biases and warm target contamination may still exist in the

intersatellite difference time series (Fig. 3). There are a few possible causes of this residual error. First, as mentioned earlier, nonlinear coefficients are not exactly equal to μ_c for every satellite. Second, higher-order nonlinearity than the quadratic term in the calibration model may be important for certain satellites and channels, especially for those with latitudinal-dependent biases (Z09). Third, the warm target thermal gradient problem as observed in other satellite microwave sensors (e.g., Twarog et al. 2006) was not accounted for in the warm target calibration. This problem may result in the warm load emission temperature and PRT temperature to be different during sun heating.

We use two different methods to remove the residual intersatellite biases: the constant bias correction and the Christy correction. In the first approach, mean constant biases between satellite pairs are removed and then the bias-corrected multisatellite time series are averaged to obtain a single time series. The anomaly trends for the merged time series for different μ_{N10} in the sensitivity experiments are plotted together with σ in Fig. 2. It is observed that the trend is linearly dependent on μ_{N10} , indicating that the trend is unstable with this correction approach. Note that the constant bias correction removes the residual constant intersatellite biases after the SNO calibration, but σ remains unchanged.

In the Christy correction, the ocean-mean intersatellite brightness temperature differences, represented by

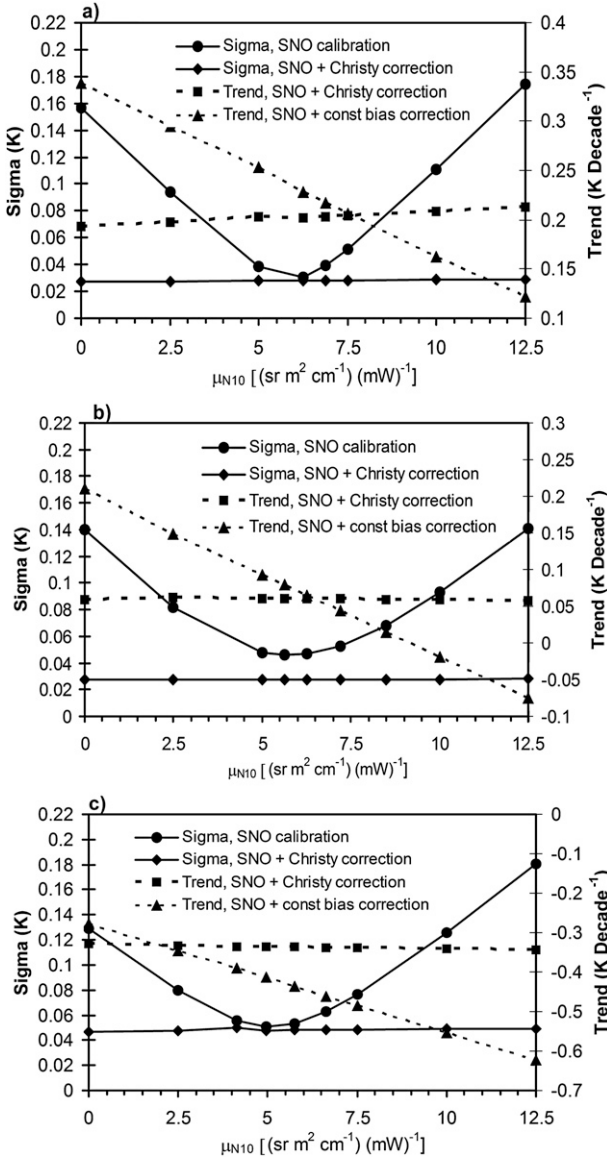


FIG. 2. Temperature anomaly trends and σ vs μ_{N10} in the sensitivity experiments: (a) T_2 , (b) T_3 , and (c) T_4 .

$\langle \Delta T_{j,k} \rangle$ for satellites j and k , are assumed to be linearly related to the warm target temperature anomalies:

$$\langle \Delta T_{j,k} \rangle = \text{bias}_{j,k} + a_j T'_w(j) + a_k T'_w(k), \quad (4)$$

where T'_w is the global ocean-mean warm target temperature anomaly. The unknown constant $\text{bias}_{j,k}$ between satellites j and k and the target factors a_j and a_k were solved simultaneously from a set of multisatellite regression equations using ocean-mean overlapping observations. The correction (4) was then removed from the unadjusted time series and a merged single time series was obtained by averaging the adjusted multiple satellite time

series. The intersatellite difference time series after this correction are shown in Fig. 3 (the top trace), and the anomaly trend and σ after this correction for different values of μ_{N10} in the sensitivity experiments are illustrated in Fig. 2.

The σ values after the SNO calibration plus the Christy correction are extremely stable (0.028, 0.027, and 0.048 K for channels 2, 3, and 4, respectively), and they are smaller than $\sigma_{\min}$ in the SNO calibration (0.031, 0.046, and 0.051 K for channels 2, 3, and 4, respectively). These statistics indicate that the Christy correction further reduces the warm target-related errors, especially for channel 3. It was shown in Z09 that this channel-3 improvement is for the *NOAA-12* and *NOAA-11* difference time series, in which the residual warm target contamination after the SNO calibration are larger than for other satellite pairs.

To further investigate the reasons for the stable σ after Christy correction, we studied the relationship between target factors and μ_{N10} (see Fig. 4). Only *NOAA-10* through *NOAA-14* were used for demonstration purposes; however, the conclusion can be extended to all satellites. It is seen that the target factors vary linearly with increasing μ_{N10} for all satellites. Negative (positive) target factors are obtained for all satellites at near-zero (larger) μ_{N10} . Furthermore, we examine the average of the target-factor square (ATFS) over all satellites:

$$\text{ATFS} = \sum_{l=1}^N a_l^2 / N, \quad (5)$$

where l refers to satellite index and N ($=4$) is the total number of satellites being examined. By definition, ATFS is a measurement of the total correction required to remove the residual warm target contamination after the SNO calibration. Figure 5 shows this quantity plotted together with σ after the SNO calibration. A larger ATFS is needed when residual warm target contamination is larger (large σ). Most excitingly, the minimum ATFS and $\sigma_{\min}$ occur at exactly the same μ_{N10} position. This shows that when residual warm target contamination of different magnitude exists because of different choices of μ_{N10} , ATFS with optimum magnitude was automatically obtained from Eq. (4) to remove these errors and bring the final σ to a minimum constant (Fig. 2). These results indicate that the Christy correction complements the SNO calibration and the correction is smallest at μ_{N10} ($\sigma_{\min}$), where the warm target contamination has already been minimized in the level-1c calibration.

Corresponding to the stable σ , the anomaly trend for T_3 and T_4 for the Christy correction is also stable throughout the sensitivity experiments (Figs. 2b,c). The T_2 trend (Fig. 2a) is less stable compared to T_3 and T_4 , but its variation range is within $0.02 \text{ K decade}^{-1}$ in the considered

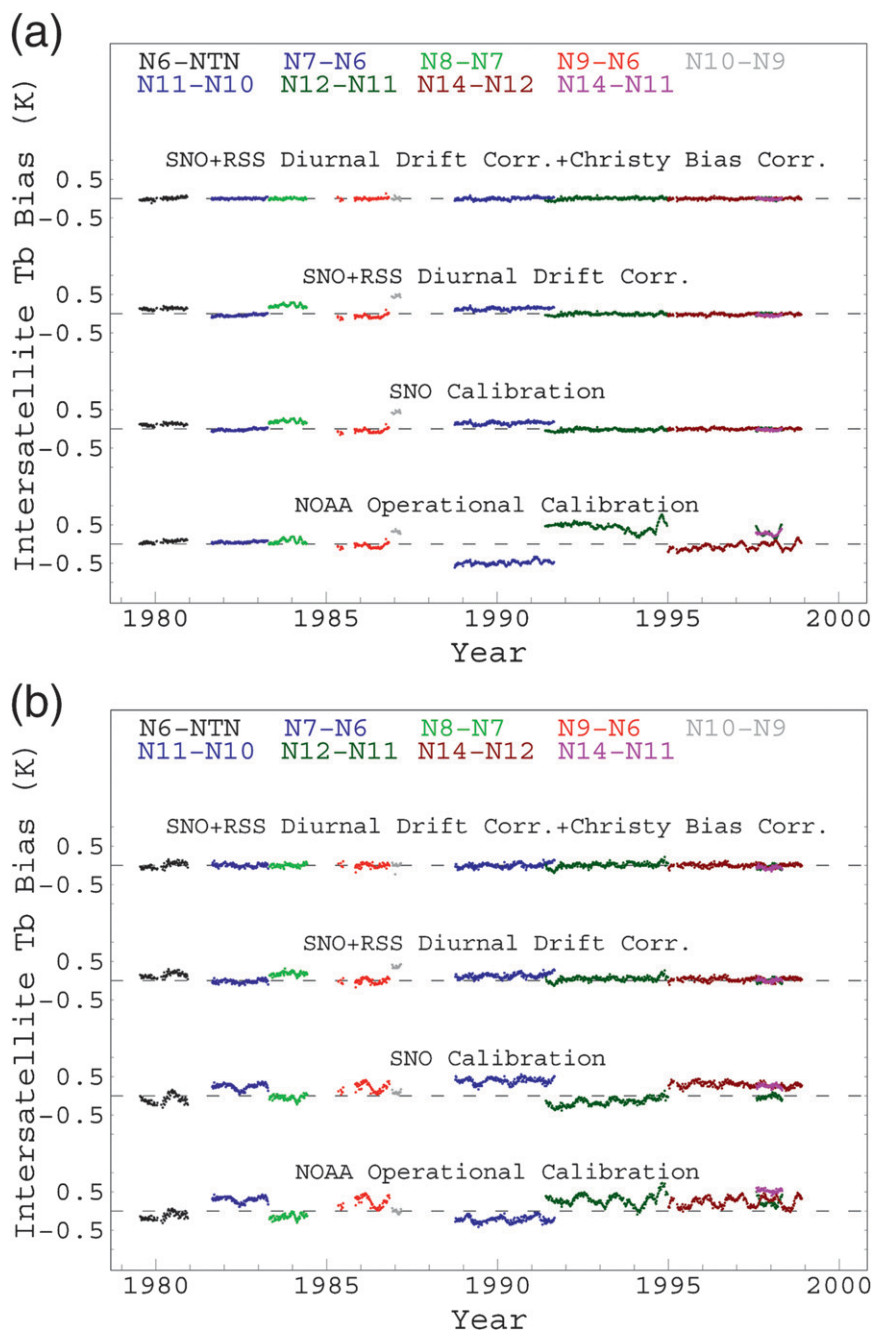


FIG. 3. Intersatellite difference time series for T_2 averaged over (a) ocean and (b) land with different calibration and bias correction procedures.

range of μ_{N10} . As a result, the T_2 trend is considered stable as well. These results again show the complementary effect of Eq. (4) to the SNO calibration procedure.

Based on these trend stability results, the Christy correction shall be chosen for the end-level gridded temperature merging. The trends derived by the constant bias correction at the final calibration point, $\mu_{N10}(\sigma_{\min})$, are close to the stable values from the Christy correction

(e.g., T_3 in Fig. 2). However, it is not recommended for merging applications because it can lead to unstable trends.

Following these results, we have changed the STAR MSU climate data record from previous versions that used the SNO calibration plus geolocation-dependent constant bias corrections to version 1.2, in which the Christy correction is used on top of the SNO calibration.

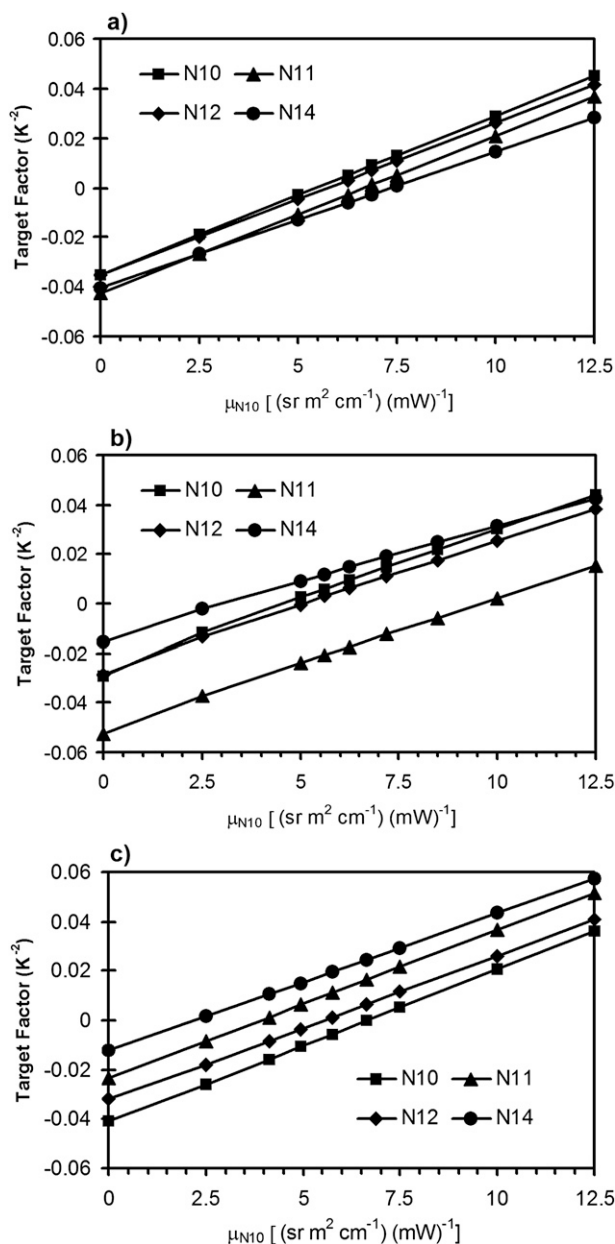


FIG. 4. Target factors vs μ_{N10} in the sensitivity experiments for (a) T_2 , (b) T_3 , and (c) T_4 .

Nevertheless, these version changes results in minor changes in the trends, since the SNO calibrations have already removed most of the warm target contaminations. Note that we use ocean-mean time series to demonstrate the trend stabilities in this study. When generating gridded dataset such as STAR V1.2, the ocean-mean target factor was applied globally for each satellite. Thus, residual intersatellite biases still exist at individual grid cells after the Christy correction. By default, a grid cell-dependent constant bias correction was always applied

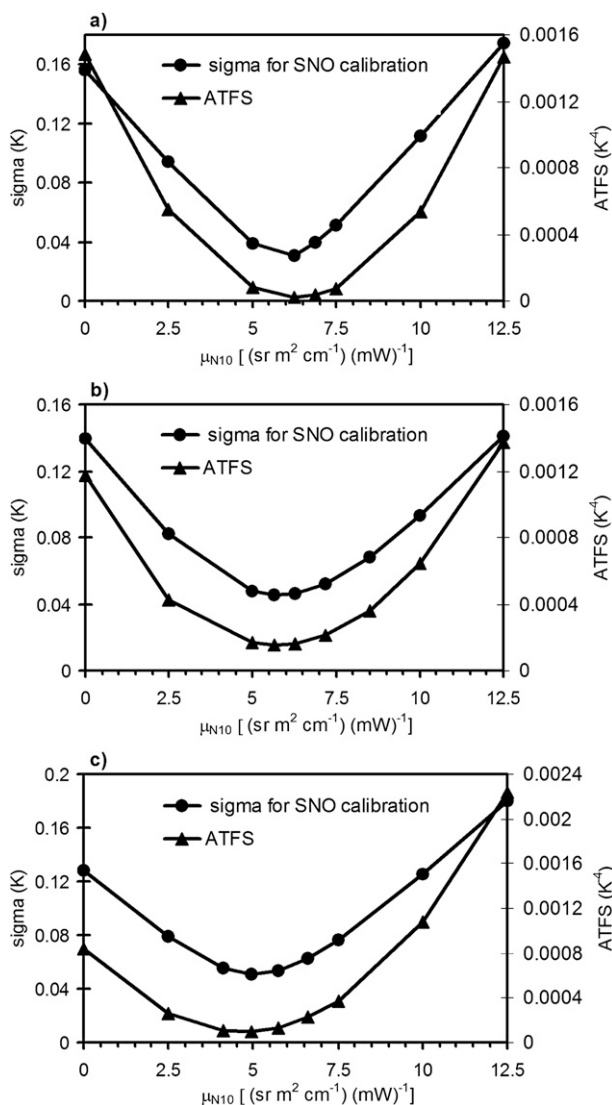


FIG. 5. Average of the target-factor square (ATFS) and σ vs μ_{N10} in the sensitivity experiments: (a) T_2 , (b) T_3 , and (c) T_4 .

to remove these residual biases even after the Christy correction.

Of particular interest, the 28-yr (1979–2006) trends corresponding to the prelaunch NOAA operational calibration were computed and compared to the SNO calibration. The results are summarized in Table 1. Only global ocean-mean trends were presented since we focus on the warm target effect here. As mentioned earlier, the prelaunch NOAA operational calibration resulted in intersatellite biases and warm target-related errors that are much larger than the postlaunch SNO calibration (Fig. 3). However, the anomaly trends of T_2 and T_4 from using the two different calibrations are very close to each other (less than 10%). Since UAH and RSS groups use NOAA operational calibrated radiances in

TABLE 1. Comparison of the global ocean-mean temperature anomaly trends (K decade^{-1}) for MSU channels 2, 3, and 4 derived from radiances of different root-level calibration and bias correction procedures. Time periods for the trends are November 1978–September 2006 for T_2 and T_4 and January 1987–September 2006 for T_3 .

NTN-N14 ocean	SNO calibration + Christy correction	SNO calibration + constant bias correction	NOAA operational calibration + Christy correction	% difference between the second and fourth columns
T_2	0.173 ± 0.044	0.194 ± 0.045	0.173 ± 0.044	0%
T_3	0.060 ± 0.082	0.079 ± 0.085	0.035 ± 0.082	50%
T_4	-0.398 ± 0.183	-0.450 ± 0.194	-0.364 ± 0.175	9%

their time series generation, these results indicate that the trend differences for T_2 and T_4 among UAH, RSS, and STAR are not caused by the use of different level-1c radiances.

For T_3 , the ocean-mean anomaly trend for the NOAA operational calibration obtained in this study is close to the RSS trend ($0.022 \pm 0.125 \text{ K decade}^{-1}$) for the same time period to within $0.01 \text{ K decade}^{-1}$; however, it is 50% smaller than that of the SNO calibration. This occurs partly because the small absolute value of the T_3 trend results in a larger relative error. Most importantly, however, the NOAA operational calibration resulted in large intersatellite biases for T_3 in which the warm target-related errors behave differently from the SNO calibration. This is especially true for the satellite pairs (*NOAA-11* versus *NOAA-12*, *NOAA-7* versus *NOAA-6*, and *NOAA-9* versus *NOAA-6*) where intersatellite biases up to 2 K were found for NOAA operational calibration (not shown). In general, the Christy correction was unable to fully characterize the prelaunch calibrated bias characteristics for T_3 . As a consequence, T_3 trends derived from the NOAA operational calibration are most likely unreliable. With the SNO calibration, however, 26-yr (1981–2006) T_3 data were generated with very stable trend. The channel-3 results demonstrate the advantage of using the SNO calibration in time series generations.

So far, our experiments indicate that the SNO calibration plus the Christy correction generate stable trends for all T_2 , T_3 , and T_4 . Of these, the T_2 and T_4 trends are similar to those derived from the NOAA operational calibrated radiances. Therefore, trend disagreement among UAH, RSS, and STAR for T_2 and T_4 cannot be explained by different treatments of the warm target effect. For T_3 , however, differences in the SNO and NOAA operational calibrations can largely explain the trend disagreement between the RSS and STAR datasets.

4. MSU T_2 trends with diurnal drift correction

We adopt the RSS diurnal anomalies for the diurnal correction in STAR V1.2 T_2 product. The RSS diurnal anomaly is a monthly mean hourly dataset generated from the NCAR CCM simulations and is available from

the RSS Web site. As mentioned earlier, differences in the diurnal anomalies may result in large trend differences. To reduce uncertainties in the dataset, we introduced a scaling factor, f , to multiply the anomaly amplitude; an optimum f is obtained by minimizing intersatellite differences over land. After several tests, we found that σ of the land-mean intersatellite difference time series was minimum at $f = 0.875$. This value was then selected as the optimum scaling factor for the diurnal correction. The fact that this optimum $f < 1$ suggests that the diurnal anomaly magnitude that best fits the SNO calibrated radiances is slightly smaller than the RSS diurnal anomaly that best fits the NOAA operational calibrated radiances.

The effects of the diurnal correction on the intersatellite biases in T_2 are shown in Figs. 3a and 3b. As expected, the diurnal correction has negligible effect on the ocean-mean intersatellite differences after the SNO calibration (the second and third traces from the bottom in Fig. 3a). However, intersatellite differences over land are still relatively large after the SNO calibration (the second trace from the bottom in Fig. 3b), owing to the diurnal drift effect. The intersatellite bias and bias drift were significantly reduced after the diurnal drift adjustment (the third trace from the bottom). Quantitatively, the land-mean absolute intersatellite bias (standard deviation) for all MSU satellite pairs over land is 0.20 K (0.069 K) without the diurnal correction; however, it is reduced to 0.11 K (0.040 K) with the diurnal correction.

Table 2 compares the mean T_2 trends over the ocean, land, and globe with and without the diurnal correction, respectively. Trends for both the SNO and NOAA operational calibrated radiances are presented. Note first that the ocean-mean trend differences with and without the diurnal drift correction are within $0.01 \text{ K decade}^{-1}$. Owing to the small diurnal amplitude and cancellation of the ascending and descending orbits, diurnal drift correction is expected to have negligible impact on T_2 trends over the oceans. This expectation is treated here as an important principle to test whether a diurnal correction scheme is appropriate or not. The results in Table 2 are consistent with this expectation, indicating that the RSS-based diurnal correction is acceptable.

TABLE 2. Comparison of the temperature anomaly trends (K decade^{-1}) for MSU T_2 derived from radiances of different level-1c calibration and with and without the diurnal drift corrections. Time period for the trends is November 1978–September 2006; trend results are presented for areas over land, ocean, and the globe, respectively.

	T_2 trends (K decade^{-1}) for Nov 1978–Sep 2006	SNO calibration + Christy correction	NOAA operational calibration + Christy correction	% difference between the third and fourth columns
Without diurnal correction	Global mean	0.149	0.149	0
	Ocean mean	0.172	0.172	0
	Land mean	0.093	0.093	0
With diurnal correction	Global mean	0.184	0.190	4
	Ocean mean	0.180	0.181	1
	Land mean	0.194	0.212	9

Second, and as expected, the diurnal drift correction has significant impact on trends over the land for both the SNO and NOAA operational calibrated radiances (a difference of about $0.1 \text{ K decade}^{-1}$ with and with the diurnal corrections). After the diurnal correction, trends over the land and oceans are close to each other, with trends over land being slightly larger than the oceans. The expectation of trend consistency between the global land and ocean is treated here as a second important test on the validity of diurnal drift corrections since the atmosphere should be well mixed for long-term climate process.

Finally, trend differences between the SNO and NOAA operational calibrated radiances are within 10% for all land, ocean, and global averages. As mentioned earlier, in datasets derived from the NOAA operational calibration, correction of the warm target effect is made after the diurnal drift correction. In contrast, diurnal drift adjustment is conducted after removal of the warm target contamination in datasets using SNO calibrated radiances. It was speculated that this different order in the warm target and diurnal drift corrections may cause trend differences between different groups (Z09). However, the results in Table 2 suggest that this is not necessarily true.

Several more experiments were conducted to find out potential reasons for the trend disagreements between different groups—especially between RSS and STAR, since they use similar diurnal drift corrections. One set of experiments was designed to examine if different target factors are responsible for the trend differences between RSS and STAR. Figure 6 compares the global ocean-mean difference time series for T_2 between STAR V1.2 and those generated from NOAA operational calibrated radiances plus Christy correction but with target factors obtained from this study and RSS (Mears et al. 2003; Mears and Wentz 2009). The target factors are all different since they depend on other adjustment procedures. These different target factors resulted in subtle differences between different time series in different time periods. However, the 28-yr (1979–2006) trends are close to each other within $0.01 \text{ K decade}^{-1}$ for all these target factors. Therefore, target factor differences cannot explain

the large trend differences between RSS and STAR groups for a longer time period.

Excluding reasons in the warm target effect and diurnal corrections, the T_2 trend disagreement between RSS and STAR can be most likely attributed to different quality control procedures and some other subtle differences in data processing. For instance, RSS used a zonal-mean bias correction with intersatellite offsets depending on both land and ocean data (Mears and Wentz 2009). Thus, any errors in the land bias correction can affect the final product over the oceans. In STAR, however, a grid-cell dependent bias correction was applied after the warm target and diurnal drift corrections; therefore, the trends over the oceans are independent of bias corrections over land. To test if this difference can cause trend disagreement between RSS and STAR, we conducted an experiment by

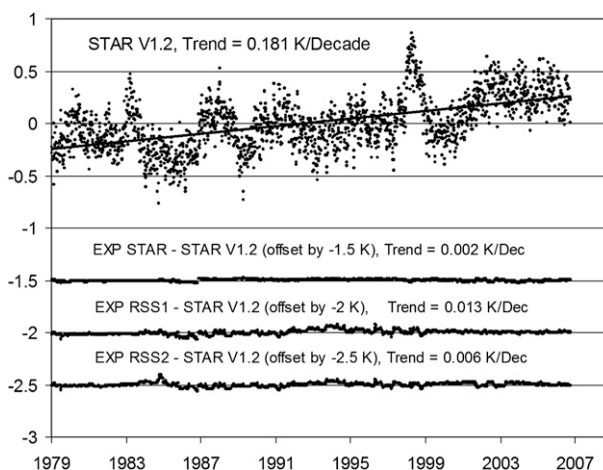


FIG. 6. The T_2 anomaly time series of the STAR V1.2 (SNO calibration plus Christy correction) and its difference time series from those generated from NOAA operational calibrated radiances plus Christy correction but with target factors obtained by different investigators. Here EXP STAR, EXP RSS1, and EXP RSS2 represent experiments in which the target factors used in the Christy correction (on top of the NOAA operational calibrated radiances) are respectively taken from this study, Mears and Wentz (2009), and Mears et al. (2003). Trend values are for the entire data period 1979–2006.

applying zonal-mean bias corrections after the Christy correction. As a result, we obtain a global ocean-mean trend of $0.117 \text{ K decade}^{-1}$ without the diurnal correction. This is $0.055 \text{ K decade}^{-1}$ smaller than the same quantity but is obtained with grid-cell dependent residual bias correction ($0.172 \text{ K decade}^{-1}$; Table 2). This value is significant enough to suggest that differences in residual bias corrections may have caused the trend disagreement between RSS and STAR.

5. Summary and conclusions

In the SNO calibration, changing the nonlinear calibration coefficient of the reference satellite is equivalent to generating different sets of level-1c radiances for subsequent construction of deep-layer temperature time series. In the absence of other problems, we have shown that the anomaly trends for the SNO calibrated T_2 , T_3 , and T_4 are invariant with respect to changes of the reference satellite nonlinear calibration coefficient when the Christy correction is used to remove the residual warm target-related errors. The total correction in the Christy approach (ATFS) is minimal after the root-level SNO calibration minimizes the warm target effects in scene radiances. Our results demonstrate that the Christy correction complements the root-level SNO calibration in removing the warm target effect. Owing to these characteristics, a combination of the SNO calibration and the Christy correction is recommended in construction of the merged MSU time series for deriving consensus climate trends. A STAR V1.2 MSU atmospheric temperature dataset is thus generated on the basis of this combination. The STAR V1.2 includes T_2 and T_4 data from 1979 to 2006 and T_3 data from 1981 to 2006. Diurnal drift correction based on RSS diurnal anomalies is applied to T_2 . For STAR V1.2, the global-mean trends for T_2 and T_4 are respectively 0.18 ± 0.05 and $-0.39 \pm 0.36 \text{ K decade}^{-1}$ for 1979–2006, and the T_3 trend is $0.11 \pm 0.08 \text{ K decade}^{-1}$ for 1981–2006.

Our comparison experiments indicate that the T_2 and T_4 trends derived from the SNO and NOAA operational calibrated level-1c radiances are close to each other to within 10%. These results help exclude differences in level-1c radiances as potential reasons for trend disagreements between different groups, at least between RSS and STAR since they use similar diurnal drift corrections. Differences in treatment of the geolocation-dependent residual inter-satellite biases after the Christy correction were found to be potential reasons for the RSS and STAR trend disagreement. In contrast, relatively large trend differences for T_3 were found between the SNO and NOAA operational calibrations. Therefore, trend differences in T_3 between RSS and STAR can be attributed to using different level-1c radiances.

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