A 20-year MSU dataset for atmospheric temperature change studies

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ABSTRACT

The Microwave Sounding Unit (MSU) on board the National Oceanic and Atmospheric Administration (NOAA) polar-orbiting satellites were designed to measure the atmospheric temperature from the surface to the lower stratosphere under all weather conditions, excluding precipitation. Although the instrumental design and calibration were made primarily for monitoring the atmospheric weather processes, the MSU observations have been extensively used for detecting climate trend. However, calibration errors have been a major uncertainty in climate trend detections. In order for the MSU data to be of high quality for climate trend and variability research, we have recently recalibrated the MSU satellites NOAA 10, 11, 12, and 14 using simultaneous nadir overpass (SNO) method. The calibration results in a well-merged 20-year radiance dataset for the MSU channels 2, 3, and 4. Limb-correction is applied to adjust the incident angles of the footprints. The limb-corrected radiances are further binned into 2.5^0 longitude by 2.5^0 latitude grids to generate deep-layer temperature datasets for the mid-troposphere (T_2), tropopause (T_3), and lower-stratosphere (T_4). The global ocean averaged trends for the recalibrated T_2, T_3, and T_4 are respectively 0.234±0.071 K/decade, 0.079±0.085 K/decade, and -0.414±0.287 K/decade for the 20-year time period from 1987 to 2006. Both the recalibrated radiance and deep-layer temperature datasets are freely available through the NESDIS/STAR website http://www.orbit.nesdis.noaa.gov/smcd/emb/mscat/mscatmain.htm.

Keywords: MSU dataset; MSU atmospheric temperature trend; satellite intercalibration; simultaneous nadir overpasses; satellite merging; warm target contamination.

1. INTRODUCTION

Global warming has been a subject of scientific as well as a public debate for several decades. An accurate determination of the temperature trends in global as well as in regional scales is crucial for supporting policy changes in those scales in every aspect of human life and economies. The trend determination is also important for understanding local weather responses and help improving local weather prediction. As such, scientists have devoted significant efforts to obtain temperature trends from various measurements to provide observational evidence for the global warming debate. Currently, a close agreement has been achieved by different observational analyses indicating that the Earth's surface is warming at a pace of 0.17 K per decade during the last 30 years (Trenberth et al 2007, IPCC 4^{th} report). The confidence on the earth's surface temperature trend is largely relied on the relatively denser surface observational network. However, determining the atmospheric temperature trend and its horizontal and vertical structure still remains a challenge. On one hand, temperature trends derived from conventional radiosonde observations are questionable because they are subject to large regional and temporal errors due to different observational practice in different countries. In addition, these observations are sparse in the atmosphere so they cannot provide a complete spatial trend pattern. On the other hand, the Microwave Sounding Unit (MSU) on board the NOAA polar-orbiting satellites is uniquely positioned to provide long-term temperature measurement with global coverage and vertical scales that other traditional measurements cannot offer. However, the temperature trends obtained for these observations are still under debate because different approaches used to process and merge the multiple

MSU satellite data by different research groups yield different trend results (Trenberth et al 2007, IPCC 4th report). As such, further investigation is required to reconcile the differences.

Calibration errors are one of the major uncertainties in the MSU trend detection. To reduce these uncertainties, we have recently developed an intercalibration approach using simultaneous nadir overpass (SNO) matchups to merge the MSU satellites (Zou et al. 2006). A SNO matchup dataset contains nadir observations of two overpass satellites within a time interval of 100 seconds and a ground distance of 111 km. The SNO intercalibration removes intersatellite biases and warm target temperature contamination at the radiance level by providing more accurate measurement for the sensor nonlinearity, and thus reduces the trend uncertainties associated with these problems. This paper presents the latest calibration results for the MSU channels 2, 3 and 4 for NOAA 10, 11, 12, and 14. Those results include the calibration coefficients for converting raw count data into radiances and long-term MSU trends of the merged channel observations.

2. THE SNO INTERCALIBRATION

The SNO calibration procedure starts from the root-level (level 0) calibration equation that deals directly with the raw count data of the MSU observations. Essentially, MSU uses in-orbit calibration method that includes two calibration targets: the cosmic cold space and an onboard blackbody warm target. The cold space has a temperature of 2.73 K and the warm target temperature is measured by the platinum resistance thermometers (PRT) embeded in the blackbody target. In each scan cycle, the MSU looks at these targets as well as the earth and the signals from these "looks" are recorded as digital counts. The level 0 calibration is to convert the digital count of the earth scene look to the earth scene radiance using the two calibration targets as the end-point references. The calibration equation is written as (Zou et al. 2006)

$$R = R_L - \delta R + \mu Z \tag{1}$$

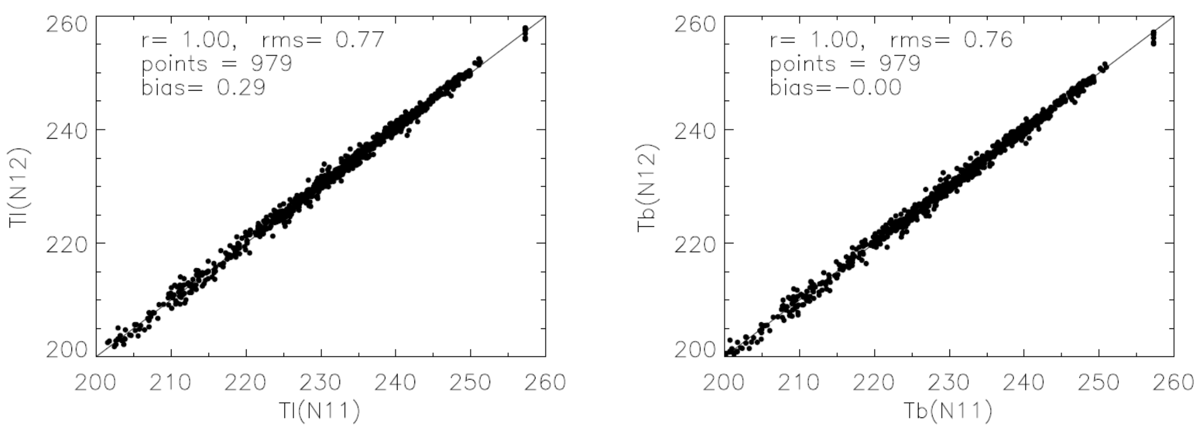
where R is the Earth radiance, $R_L = R_c + S(C_e - C_c)$ represents the dominant linear response and $Z = S^2(C_e - C_c)(C_e - C_w)$ is a nonlinear response; C represents the raw counts and $S = \frac{R_w - R_c}{C_w - C_c}$ is the slope determined by the two calibration points; the subscripts *e, w* and *c* refer to the Earth-view scene, onboard warm blackbody target, and the cold space, respectively; δR represents an offset and μ is a nonlinear coefficient. The cold space radiance R_c is specified to be 9.6×10^{-5} mW (sr m^2 cm^{-1})$^{-1}$ for all scan lines. This is corresponding to a brightness temperature of 4.78 K that includes the actual cold-space temperature of 2.73 K plus an increase of about 2 K due to the stray radiation entering the antenna side-lobes by active and passive sources onboard the satellites. Once the radiance is known, the brightness temperature is computed using the Planck function. In the microwave region, the Planck function is given by the Rayleigh-Jeans Approximation which results in a linear relationship between the radiance and brightness temperature. Therefore, calibration results are often expressed in brightness temperature units rather than radiance.

In Eq. (1), the counts are the measured variables and the warm target temperature is computed using a method described in the NOAA Polar Orbiter Data User's Guide, so once the calibration coefficients δR and μ are known, the earth scene radiance R can be uniquely determined. The purpose of the SNO calibration is to obtain the calibration coefficients from the SNO matchup datasets. The following steps describe how to obtain these coefficients and generate merged radiance and gridded deep-layer temperatures.

(i) An error model for the SNO matchups is established first. This error model relates the radiance differences between the satellite SNO pairs to the instrumental raw count data and calibration coefficients. The SNO error model for the MSU instrument and its detailed error analysis can be found in Zou et al. (2006).

(ii) We use regressions to obtain the calibration coefficients from the error model and the SNO matchups. The error model includes calibration coefficients of both satellites in the SNO pair; however, the regression can be used to obtain coefficients for only one satellite in the satellite pair due to a co-linearity problem (Zou et al. 2006). Therefore, one satellite in the SNO pair is assumed as the reference satellite and its calibration coefficients are assumed to be known. In our calibration, NOAA 10 is assumed to be the reference satellite.

(iii) For a given μ (and δR =0) for NOAA 10, the calibration coefficients μ and δR for NOAA 11 are obtained from regressions of the SNO matchups between NOAA 10 and 11. After this is done, the coefficients for NOAA 12 are then obtained from the SNO matchups between NOAA 11 and 12. This is referred to as the sequential calibration procedure and it can go on until coefficients of all satellites are obtained. These calibration coefficients are used to calibrate the global MSU data, although the SNO is confined in the polar region. The calibrated radiance is well-merged in the SNO sense because the intersatellite bias has been completely removed and the bias dependency on temperature has been significantly reduced. Figure 1a and 1b show an example of the SNO matchups before and after the calibration. It is seen that if the linear calibration (linear part in Eq. 1) is used to calibrate the raw counts, an intersatellite temperature bias of 0.29 K occurs for the matchups (Fig.1a). In addition, the brightness temperature differences in the SNO matchups become larger with increasing temperature. However, after the SNO intercalibration, both the bias and its temperature dependency disappear (Fig. 1b).



(a) (b)

Fig. 1 The SNO radiance matchups between NOAA 11 and NOAA 12 before (a) and after (b) the SNO intercalibration. The symbols T_L and T_b represent respectively the linear calibrated and SNO calibrated brightness temperatures.

(iv) For the SNO-calibrated radiance data, a limb-correction is applied to correct different incident angles of the off-nadir footprints to the nadir direction. This correction is needed so that the off-nadir footprints can be used in the time series to increase observational sampling and reduce noise and sampling-related biases. The scheme suggested by Smith et al. (1974) that uses all available channels in a linear combination is used for the limb-adjustment. The limb-correction coefficients are obtained using a statistical method developed by Goldberg et al. (2001).

(v) After the angle correction, the limb-corrected radiance data are binned together to generate a pentad dataset with grid resolution of 2.5^0 latitude by 2.5^0 longitude. A total of 7 near-nadir footprints are used in the gridded datasets. Global ocean mean time series are obtained from the binned dataset for trend and bias analyses.

(vi) The nonlinear calibration coefficient for the reference satellite is determined from an additional constraint that the standard deviation of the intersatellite difference time series for all the satellites reaches a minimum. This minimum position is obtained from a series of sensitivity experiments in which the μ for NOAA 10 changes from 0 to 12.5 (sr m^2 cm^{-1}) (mW) $^{-1}$. An example of the relationship between μ_{N10} and the standard deviation (STD) of the intersatellite difference time series for NOAA 10, 11, 12, and 14 is shown in Fig. 2. This is for the MSU channel 4 observations. The plot clearly shows a minimum STD where μ_{N10} should be selected.

At this point, the orbital-drift related warm target contamination in the calibrated time series reaches a minimum. The STD value at this point is 0.05 K for MSU channel 4. This value represents the measurement uncertainty of the merged, ocean mean time series for climate detections in the overlapping period.

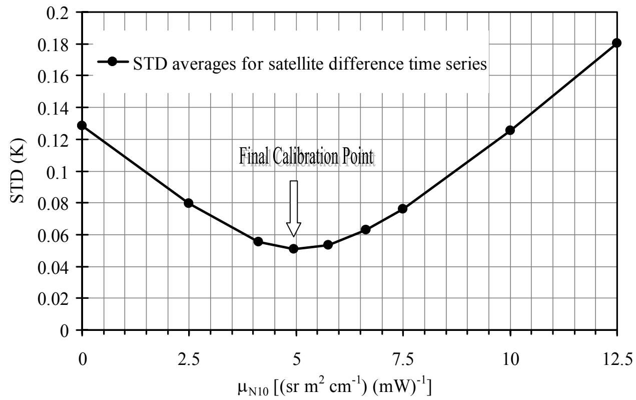


Fig. 2 Averaged standard deviation (STD) of the intersatellite difference time series for the ocean means versus the NOAA 10 nonlinear calibration coefficient. Result is for the MSU channel 4 and satellite differences include NOAA 10, 11, 12, and 14.

With the calibration procedure described above, we have obtained the calibration coefficients for MSU channels 2, 3, and 4 for NOAA 10, 11, 12, and 14. These coefficients are listed in Table 1. The ocean mean difference time series for NOAA 10, 11, 12, and 14 corresponding to the above calibration coefficients are shown in Fig. 3 (the upper panel). Also shown in the plot is the brightness temperature difference time series for the same satellites, but corresponding to the NOAA operational calibration (the lower panel). We see that the intersatellite biases are on the order of 0.5 K for the NOAA operational calibration. In addition, there are orbital-drift related fluctuations in these biases. These offsets and their fluctuations are mostly removed in the SNO calibration. Because of the small uncertainty (STD = 0.05 K) in the satellite difference time series, we expect that the SNO merged time series will provide climate trend results with good confidence.

Table 1 Calibration coefficients for channels 2, 3 and 4 for different satellites obtained from the SNO calibration procedure. Units for δR and μ are 10^{-5} (mW) (sr m^2 cm^{-1}) $^{-1}$ and (sr m^2 cm^{-1}) (mW) $^{-1}$, respectively. The Channel 2 coefficients are obtained in Zou et al. (2006) and are listed here again for completeness.

Satellite	δR (Ch2)	μ (Ch2)	δR (Ch3)	μ (Ch3)	δR (Ch4)	μ (Ch4)
N10	0	6.25	0	5.63	0	4.95
N11	-2.4641	9.5909	-1.9983	7.1892	-0.7271	5.4574
N12	-0.0996	6.7706	-2.3979	8.3282	-4.6074	7.1040
N14	-0.6363	7.4695	-3.0810	8.7525	-0.7753	5.4175

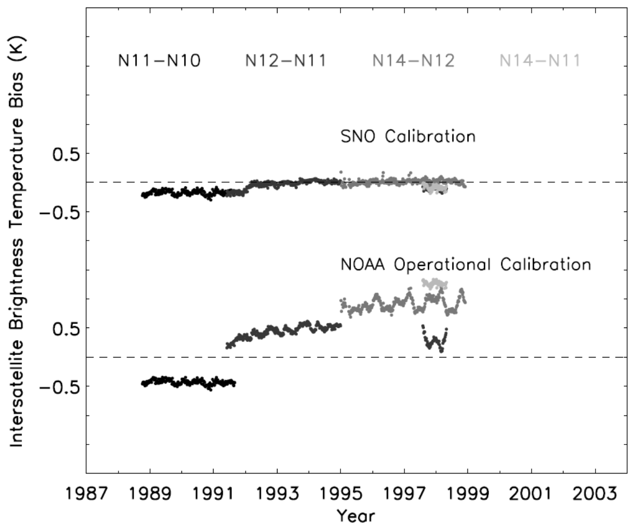


Figure 3. Intersatellite difference time series of the ocean mean brightness temperature for the SNO and NOAA operational calibration procedures.

3. TREND RESULTS OF THE MERGED TIME SERIES

The SNO calibrated ocean mean time series for different satellites are plotted together in Fig. 4. It is seen that in the overlapping periods, observations of different satellite agree with each other on a point-by-point basis due to the small STDs in their difference time series. The merged time series are obtained by simply averaging the available observations from different satellites for any time period. Small constant intersatellite biases have been removed prior to the merging. The trends for the merged ocean mean anomaly time series for T_2, T_3, and T_4 are respectively 0.234±0.071 K/decade, 0.079±0.085 K/decade, and -0.414±0.287 K/decade for the 1987-2006 time period.

4. DADA AQUISITION

A website has been created for the public to freely acquire the SNO calibrated MSU datasets. The website is under the main page of NESDIS/Center for Satellite Applications and Research and its URL address is http://www.orbit.nesdis.noaa.gov/smcd/emb/mscat/mscatmain.htm. The website contains both the level 2 radiance and level 3 gridded deep-layer temperature datasets. These datasets cover the period from January 1987 to September 2006 that include observations from NOAA 10, 11, 12, and 14. The radiance datasets with both the SNO calibration and NOAA operational calibration are available from the website. Gridded datasets include 5-day and monthly averages with spatial resolution of 2.5^0 latitudes by 2.5^0 longitudes. The monthly data include merged T_2, T_3, and T_4 time series and their anomalies. The pentad data include time series of the merged and individual satellite for these variables. Anomaly time series for the merged panted time series is also available. All the gridded data files are in ASCII text format and reading programs for these data are provided on the website. All these datasets can be downloaded directly from the website.

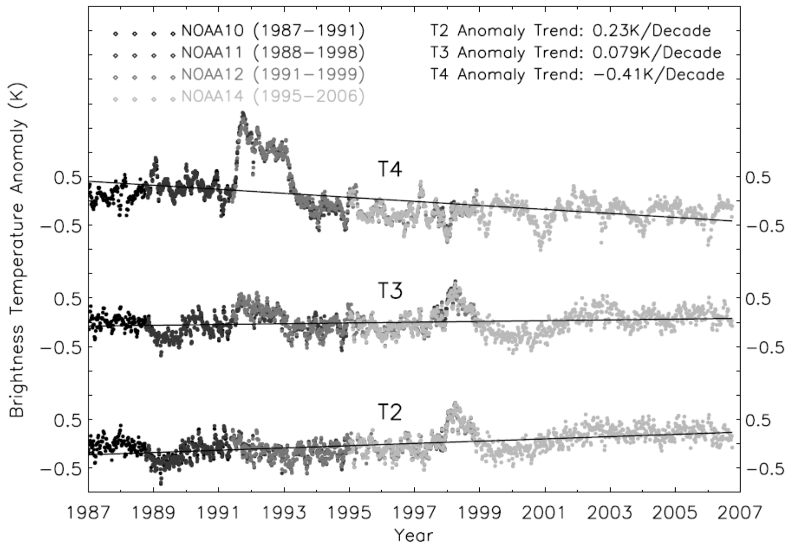


Figure 4 Anomaly time series and trends for the ocean-mean T_2, T_3 and T_4 for 1987-2006 using the SNO calibration.

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