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Prepared by C.-Z. Zou
and L. Wang
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NOAA's Stratospheric Temperature Climate Data Record Derived from Recalibrated Stratospheric Sounding Unit Observations

In response to CGMS Recommendation 38.13

Summary of the Working Paper

NOAA/NESDIS has generated a 27-year (1978-2006) stratospheric temperature data record from Stratospheric Sounding Unit (SSU) observations for climate trend and variability detection. The dataset includes gridded global layer temperatures of mid-stratosphere, upper-stratosphere, and top-stratosphere. Calibration algorithms for developing the data record include corrections of gas leaking problem in the SSU instrument CO₂ cells, variation of the atmospheric CO₂ concentration, incident angle effect, diurnal drift effect, and Earth-location dependent residual inter-satellite biases. The products have a grid resolution of 2.5° latitude by 2.5° longitude and both monthly and pentad data are available for seamless climate monitoring. This is the first set of well-documented and well-calibrated global gridded dataset available to the climate community for long-term stratospheric temperature monitoring and investigation and for validating climate model simulations of the stratospheric climate change. For 1979-2006, the dataset had a global mean stratospheric temperature trend around -0.93 to -1.24 K/decade. Spatial trend pattern analyses indicated that this cooling occurred globally with larger cooling over the tropical stratosphere.

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1 INTRODUCTION

The stratosphere has been recognized as an important component in the global change scenario. Similar to the troposphere, the stratospheric temperature trend is an important indicator of climate change. Thus, determining the stratospheric temperature trends is equally important as determining the tropospheric temperature trends. However, the coverage and quality of conventional observations are significantly degraded toward the stratosphere, resulting in large uncertainties in stratospheric temperature trend estimates. On the other hand, satellite observations provide continuous global coverage and thus play an essential role in stratospheric temperature trend estimates with better accuracies.

Satellite stratospheric temperature observations were made by the Stratospheric Sounding Unit (SSU) and channel 4 of the Microwave Sounding Unit (MSU) onboard historical NOAA polar orbiting satellites from 1978 to 2007. Starting from 1998, the Advanced Microwave Sounding Unit (AMSU) on board the NOAA-KLM and their follow-on series and NASA EOS satellites has replaced the MSU. The AMSU's observation covers both the MSU and SSU spectra bands in terms of vertical altitude. As part of the effort in generating high quality climate data record, NOAA/NESDIS has merged MSU observations with AMSU equivalent channels for atmospheric temperature trend monitoring and investigations. The MSU and AMSU recalibration and merging has been reported in previous CGMS publications. This report describes SSU recalibration and associated stratospheric temperature climate data record (CDR) development.

2. Issues in the SSU observations

The SSU is a three-channel infrared radiometer designed to measure the radiance emitted by stratospheric carbon dioxide within the 15- μ m band. Its measurement makes use of the pressure modulation technique by putting a cell of CO₂ gas in the instrument's optical path and having the gas pressure suitably modulated. The spectral characteristics of the channel and, therefore, the height of the weighting function are then determined by the pressure in the cell during the integration period. By modulating the CO₂ cell pressures, weighting function peaking at three different heights ranging from 20 to 1 hPa (25 to 50 km) are obtained (Figure 1).

To develop consistent temperature CDR from the SSU observations, several different types of errors need to be properly treated. First, since the spectral performance of the instrument depends on the mean pressure within the CO₂ cell, its long-term stability is crucial for time-consistent radiance observations. Unfortunately, the CO₂ cell incurred a gas leaking that caused the cell pressure to decrease over time (Figure 2). These cell pressure changes resulted in the channel weighting functions to peak at different layers during satellite operations. As a result, inter-satellite brightness temperature differences on the order of 0.5 to 8 K, depending on channels and satellites, were found for the SSU observations (Figure 3).

Secondly, the SSU instruments sense radiation in the 15- μ m atmospheric CO₂ absorption band and hence their weighting functions are sensitive to changes in the

atmospheric CO₂ concentration. As atmospheric CO₂ slowly increased, the weighting functions of the three SSU channels gradually moved to higher altitude. Consequently,

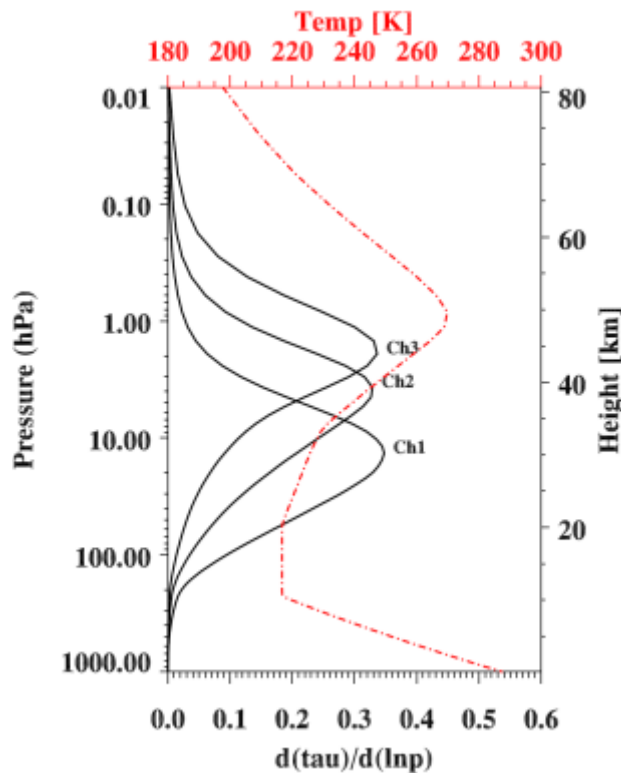


Figure 1 Weighting functions of the three SSU channels, overlaid with the temperature profile from the US standard atmosphere. It was calculated based on the standard atmosphere with a zero scan angle, 330 ppmv atmospheric CO₂ concentration, and cell pressures of 110, 40, 15 hPa for the SSU three channels.

spurious positive temperature trends would be superimposed on the SSU temperature trend, which must be corrected when using the SSU observations to study stratospheric temperature change.

Thirdly, satellite orbital drifts cause diurnal drift errors, which are measured by the slow evolution in the Local Equator Crossing Time (LECT) as a sun-synchronous satellite ages. The satellite orbital drifts result in a change of local observation time that, if not corrected, may introduce false climate trend by bringing diurnal trend in it. Its effect is particularly large in the stratosphere which is periodically heated as ozone absorbs solar radiation during the day, causing temperature fields to have diurnal and semi-diurnal tidal variations. Corrections have to be made to account for this diurnal sampling bias.

Fourthly, limb effect incurred as a result of the increase in optical path as the instrument scans from near nadir to larger angles, which causes the peaks of the channel weighting functions to increase in altitude. Since the temperature increases with altitude in the stratosphere, the SSU measured brightness temperature also increases with instrument scan angles. The brightness temperature differences between near nadir and near limb observations range from 1.0-1.5K, depending on different channels. These effects should be accounted for in the CDR development to increase observation samplings.

Finally, generation of a 27-year SSU data set needs to merge the SSU measurements together from separate satellites. Unfortunately, the SSU instruments were not flown on

NOAA-10 and -12, and no data were available from NOAA-13 because of a spacecraft circuit failure. Additionally, there were almost no overlap observations between NOAA-9 and NOAA-11. These missing data issues cause difficulty in inter-satellite calibration and merging, and thus lead to uncertainties in climate trend determinations.

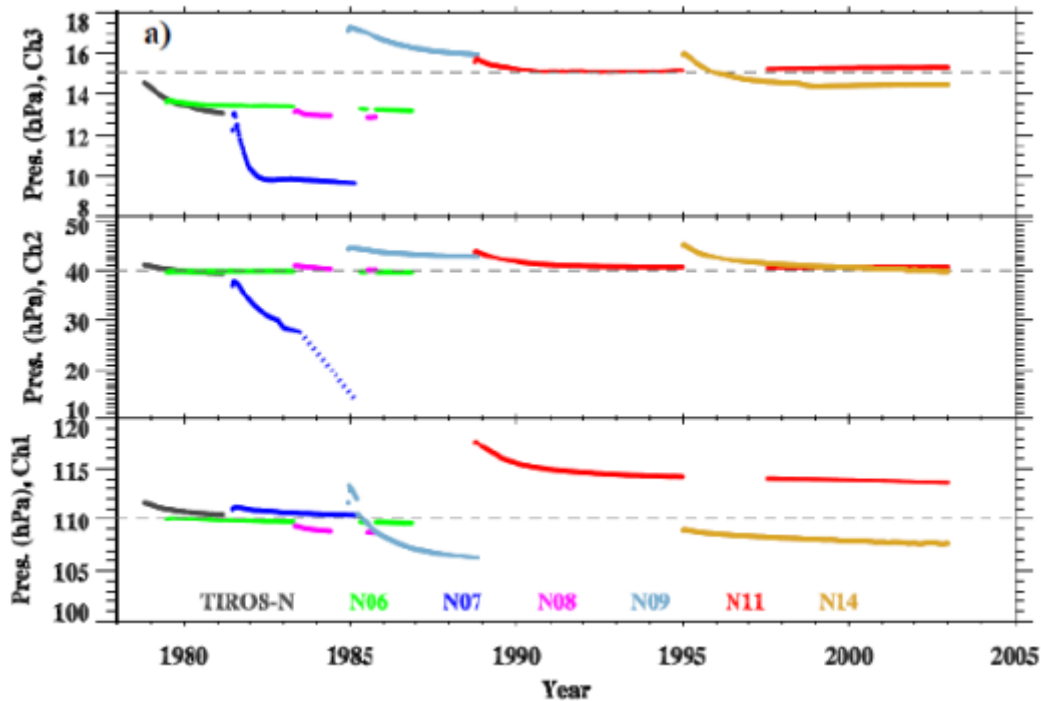


Figure 2 10-day time series of CO₂ cell pressures for SSU channels 1, 2, and 3 of all SSU instruments as a function of time. Time series were interpolated from the UK Met Office's six-monthly cell pressure data records (Kobayashi et al. 2009).

3. Calibration and Merging Algorithms for SSU CDR Development

Corrections of the instrument CO₂ cell pressure, variation of the atmospheric CO₂ concentration, and limb effect are based on simulations of the Community Radiative Transfer Model. Developed recently at the Joint Center for Satellite Data Assimilation (JCSDA), the (CRTM, Han et al. 2006; Chen et al. 2011) CRTM SSU model can well handle the varying cell-pressures and atmospheric CO₂ concentration. Corrections to the original SSU observations are taken as the differences between the CRTM simulations with varying cell-pressures and atmospheric CO₂ concentration and those with these variables fixed at certain constant values. Similarly, limb effect is estimated as the CRTM simulated differences between the nadir and near limb observations.

Temperature profile along each SSU footprint is needed to estimate the adjustments by the CRTM. Currently, the NASA Modern Era Retrospective Analysis for Research and Applications (MERRA, Rienecker et al. 2011) climate reanalysis is selected to provide the atmospheric profiles for CRTM input. MERRA uses the Goddard Earth Observing System version 5 (GEOS-5) atmospheric model that is coupled with the Grid-point Statistical Interpolation (GSI) analysis scheme. The 72 vertical levels in GEOS-5 extend from the surface through the top stratosphere (the top level is 0.01 hPa), providing necessary height for the CRTM to achieve sufficient accuracies for SSU simulations. MERRA data are available from 1979 to present, covering the entire SSU observations. Compared to the newly-developed NCEP Climate Forecast System Reanalysis (CFSR), which suffers large spurious

variability in the stratospheric temperature time series associated with stream transitions (Long et al. 2009), MERRA has much less variability during its satellite transition periods.

There is a concern that uncertainties in the MERRA reanalysis may be brought into the adjustment processes. However, it was shown in our analysis that adjustment accuracies are not sensitive to the errors of the temperature profiles themselves. Instead, they are sensitive to the temperature differences between corresponding SSU layers. Uncertainties of the layer temperature differences are much smaller than those of the temperatures themselves. Thus, the simulation based adjustments are not sensitive to selections of different reanalysis systems.

Diurnal anomalies for the diurnal drift adjustments are derived by interpolating the 3-hourly outputs of the 10-year averaged MERRA reanalysis profiles (2000-2010). The interpolated reanalysis temperature profiles at pressure levels are then converted to the corresponding SSU channel brightness temperatures by CRTM, which are then used to adjust SSU footprint observations at different observation time to the local noon time for all satellites.

After the above adjustments, the orbital SSU observations are converted to those with consistent weighting functions, zero viewing angles, and identical local observational time. These adjusted footprint observations are binned together into grid cells with 2.5° latitude by 2.5° longitude resolution and then averaged to generate gridded CDR temperature products for different channels. Nevertheless, inter-satellite biases still exist for channels 1 and 2 for certain satellite pairs. It is suspected that these are caused by inaccurate instrument calibration. However, lack of longer overlap observations makes inter-satellite instrument calibration difficult. Therefore, statistical merging is conducted to combine the observations from different satellites for trend analysis.

First, a reference instrument is chosen to serve as the baseline instrument. Ideally, the instrument that is better calibrated should be chosen as an unbiased reference instrument. However, such knowledge is unavailable *a priori*. NOAA-14 is thus arbitrarily assumed as a reference satellite, partly because it has a longer operational time and is also closer to present, having advantage that it can be verified by more recent observations from other instruments in the future. This assumption affects the absolute values of brightness temperatures, but not the anomaly trend and variability estimates.

Second, a grid-cell dependent constant bias correction, which was used in the MSU/AMSU CDR development by Zou et al. (2009), is employed to merge the observations. Specifically, for each satellite pairs, starting from those having the reference satellite, a constant bias is derived at each grid cell by calculating the mean of their brightness temperature differences during their overlapping observations. This constant bias is then subtracted from the non-reference satellite for its entire observational time so that it fits to the reference satellite in the mean sense at each grid cell. The adjusted satellite is then assumed to be a new reference satellite to adjust its neighbour satellite. This process continues until all satellites are adjusted.

There are no overlap observations between NOAA-9 and NOAA-11, so the above process breaks between this satellite pair. Fortunately, observations from NOAA-9 and NOAA-11 in channels 1 and 3 are already linked to each other pretty well after recalibration. Therefore, recalibrated channels 1 and 3 from NOAA-9 and NOAA-11 are not mutually

adjusted. Any adjustments applied to the NOAA-11 (NOAA-9) measurements are automatically applied to NOAA-9 (NOAA-11).

For channel 2, however, a big jump occurred between NOAA-9 and NOAA-11. In order to estimate the inter-satellite biases for this channel, a double difference technique is applied. In specific, CRTM simulations of NOAA-9 and NOAA-11 are extended to at least one year on each side of the breaking point between the two satellites. The simulated overlap is used to estimate inter-satellite biases between NOAA-9 and NOAA-11. The hypothesis behind this is that biases between model simulations and observations can well represent the instrument biases and double differencing cancels short term variations.

Effect of the adjustment processes is illustrated by Figure 3 in which the time series of global mean SSU brightness temperatures before and after the above recalibration and merging processes are compared. It is shown that the recalibration processes significantly reduced inter-satellite biases observed in the unadjusted time series.

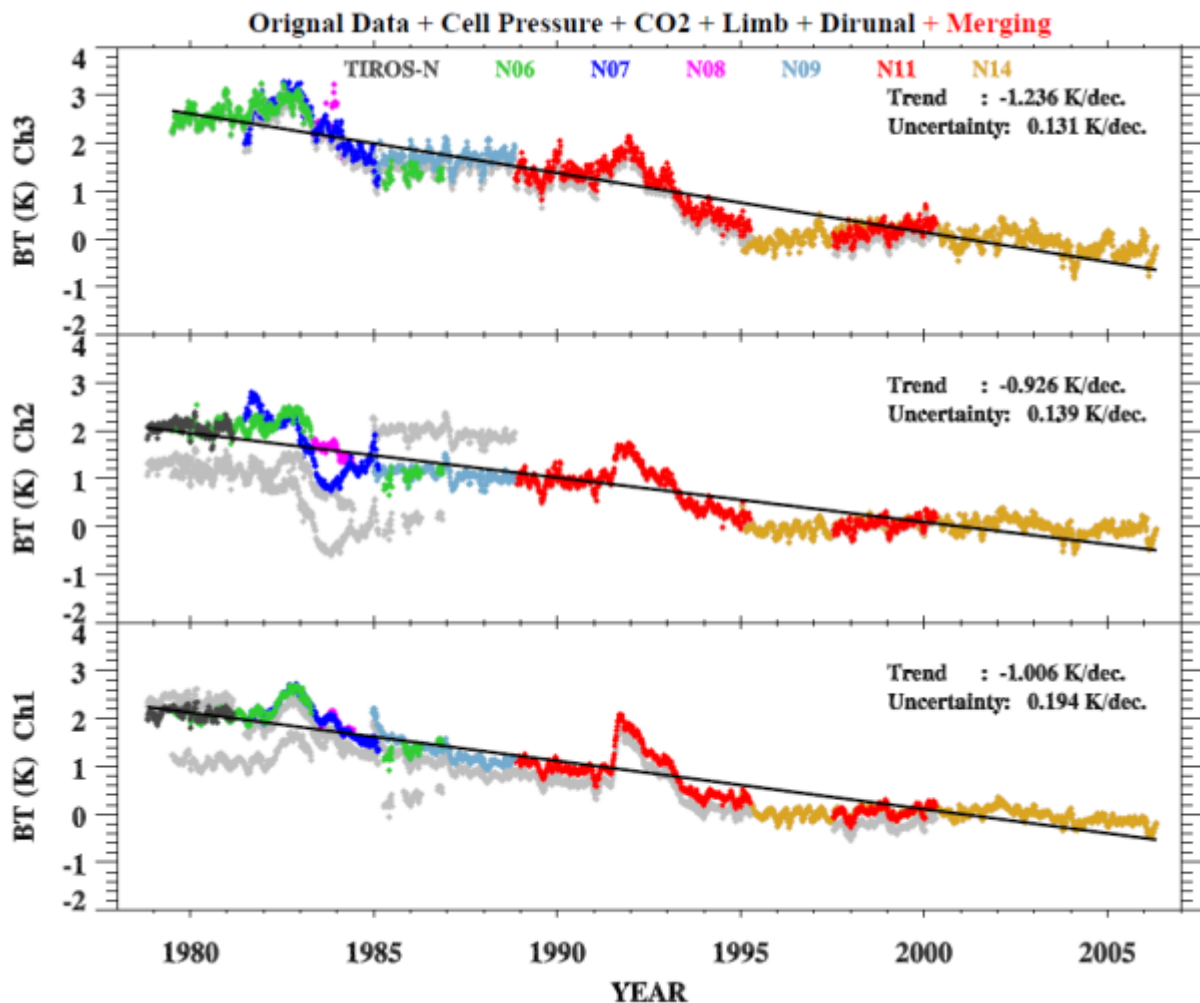


Figure 3 Time series of global mean SSU brightness temperatures for the original unadjusted data (grey) and those after all recalibration and merging processes (color).

4. Version 1.0 SSU stratospheric temperature CDR

With instrument recalibration and bias correction approaches as described in the previous section, Version 1.0, 27-years (1979-2006) of SSU stratospheric temperature CDR has been generated at NOAA/NESDIS/Center for Satellite Applications and Research (STAR). This is a global gridded dataset with 2.5° latitude by 2.5° longitude resolution. Both monthly and pentad data are available for seamless climate monitoring. The CDR includes temperatures of mid-stratosphere (TMS, SSU channel 1), upper-stratosphere (TUS, SSU channel 2), and top-stratosphere (TTS, SSU channel 3).

For 1979-2006, the global mean trends for TMS, TUS, and TTS, are respectively - 1.236 ± 0.131 , -0.926 ± 0.139 , and -1.006 ± 0.194 K/decade (Figure 3). Figure 4 shows the spatial distribution of trends for the three layer temperatures. Enhanced net cooling is found in the tropics and it becomes larger from the mid-stratosphere to the top-stratosphere. Smaller cooling regions are found in the southern polar region. The trend pattern also illustrates an interesting stratospheric wave-1 structure that need to be further investigated.

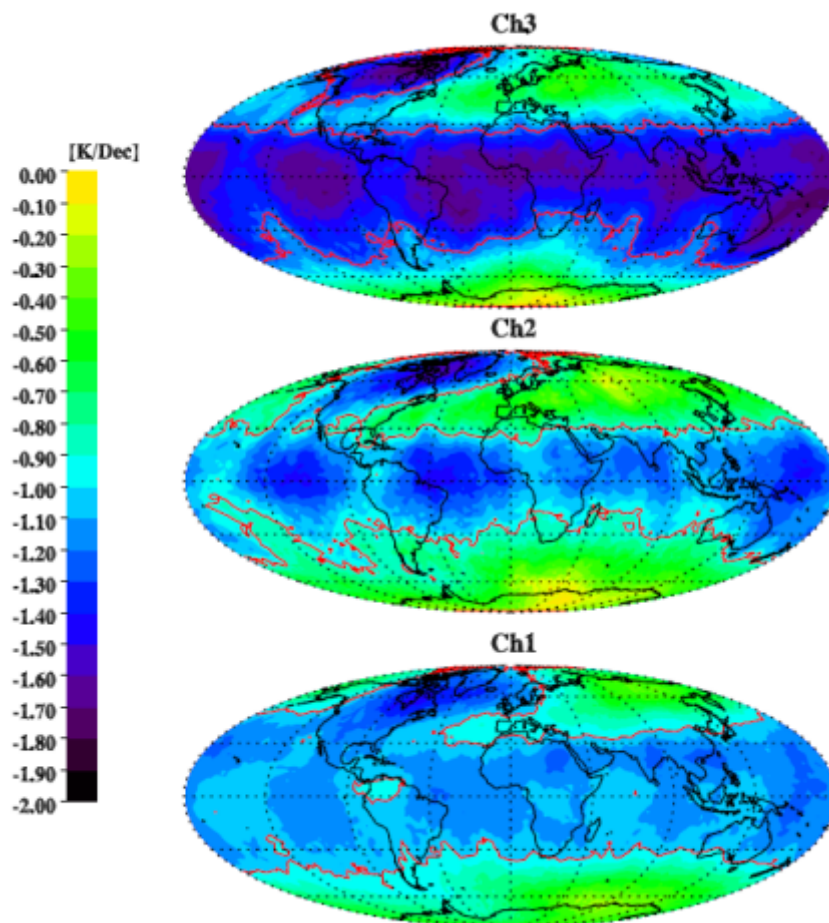


Figure 4 Spatial distributions of linear trends for the three SSU channels. The red lines indicate the global mean trends.

5. Dataset availability



The global gridded STAR Version 1.0 SSU CDR is publicly available from the NOAA/STAR website with the URL address: <http://www.star.nesdis.noaa.gov/smcd/emb/mscat/mscatmain.htm>.

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