A comparison of lower stratosphere temperature from microwave measurements with CHAMP GPS RO data

Shu-P. Ho, Ying-Hwa Kuo, Zhen Zeng, and Thomas C. Peterson

Received 29 March 2007; revised 16 May 2007; accepted 15 June 2007; published 1 August 2007.

In this study, we compare the microwave brightness temperature (Tb) for the Lower Stratosphere (TLS) datasets provided by Remote Sensing Systems (RSS) Inc. and University of Alabama in Huntsville (UAH) with the GPS radio occultation (RO) data from Challenging Minisatellite Payload (CHAMP) over 49 months from June 2001 to June 2005. The GPS RO data are used to simulate microwave brightness temperatures, for comparison with Microwave Sounding Unit (Channel 4) and Advanced Microwave Sounding Unit (Channel 9) measurements. Excellent agreement was found between both RSS and UAH TLS and that of CHAMP. This study demonstrates the usefulness of GPS RO observations as independent data for comparison against and use with other satellite observations in climate studies. Citation: Ho, S.-P., Y.-H. Kuo, Z. Zeng, and T. C. Peterson (2007), A comparison of lower stratosphere temperature from microwave measurements with CHAMP GPS RO data, Geoph. Res. Lett., 34, L15701, doi:10.1029/2007GL030202.

1. Introduction

[1] The monitoring and detection of atmospheric temperature trends are key climate change problems. On board the National Oceanic and Atmospheric Administration (NOAA) series of polar orbiting satellites, the Microwave Sounding Unit (MSU) has provided data for climate studies since 1979 [Folland et al., 2001]. Because MSU measurements, which are in the 50 to 70 GHz oxygen band, are directly proportional to the specific atmospheric layer temperatures corresponding to the weighting functions and are not affected by clouds, MSU data are able to provide long-term temperature trend analyses of different atmospheric layers. In 1998, the MSU was replaced by the Advanced Microwave Sounding Unit (AMSU), which has similar channels as MSU. Even though the combined MSU and AMSU data provide unique long-term monitoring of atmospheric temperature from the space, due to changing platforms and instruments, different diurnal cycle sampling, and orbital drift, it remains a significant challenge to use this dataset to construct homogeneous temperature records.

[2] Recently, Christy et al. [2003] from the University of Alabama in Huntsville (UAH) presented climatology of tropospheric and stratospheric temperature trends based on 23 years (from 1979 to 2002) of MSU/AMSU data. However, due to different adjustments and analysis procedures used to (a) calibrate shift of sensor temperature owing to on-orbit heating/cooling of satellite components [Christy et al., 2003] and (b) remove inter-satellite calibration offsets for the different MSU/AMSU instruments, significant differences were found between UAH tropospheric and stratospheric temperature trends and another MSU/AMSU dataset generated by Mears et al. [2003] from Remote Sensing Systems (RSS) Inc. Since the adjustments are complicated and involve expert judgments that are hard to evaluate, the different temperature trends reported from different groups are still being debated [Karl et al., 2006]. Recently, several studies have focused on using radiosonde data to detect climate signals in the troposphere and to compare the detected trends to the microwave tropospheric and stratospheric temperature trends [Sherwood et al., 2005; Christy and Norris, 2004; Randel and Wu, 2006]. However, changing instruments and observation practices and limited spatial coverage, especially over the oceans, complicate climate analysis from radiosonde data. The estimated trend is still sensitive to the choices of radiosonde datasets [Sherwood et al., 2005; Randel and Wu, 2006]. It is important to use an independent dataset with high accuracy to assess the quality of the brightness temperature (Tb) derived from RSS and UAH.

[3] The Global Positioning System (GPS) Radio Occultation (RO) is the first space-based measurement technique that can provide all-weather high vertical resolution (from ~100 m near the surface to ~1.5 km at 40 km) refractivity profile, which depends on pressure, temperature and humidity [Yunck et al., 2000]. Because the basics of the GPS RO observation is a measurement of radio signal time delay against reference atomic clocks on the ground [Steiner et al., 1999], GPS RO data, unlike MSU radiances, do not contain orbit-related drift errors and satellite-to-satellite biases. Therefore, it presents a unique opportunity to independently assess the quality of the analyzed brightness temperature from MSU/AMSU by RSS and UAH, though the varying location and time of day of GPS RO data are obstacles to climate analyses.

[4] In this study, we perform a comparison of the microwave temperature datasets provided by RSS and UAH against 49 months of Challenging Minisatellite Payload (CHAMP) radio occultation data to access the consistency between microwave data and GPS RO data. CHAMP is a German GPS RO satellite, which has produced stable and accurate measurements of high vertical resolution temperature profiles since 2001 [Wickert et al., 2004]. Since CHAMP sample size is much smaller, and they are taken at different local times in different locations than those of MSU/AMSU data, we binned CHAMP data into the RSS and UAH grid boxes to minimize the temporal, spatial and
sampling differences between CHAMP and MSU/AMSU data. To avoid the possible temperature retrieval uncertainty due to the ambiguity of GPS RO refractivity associated with both temperature and moisture in the troposphere, we focus on the comparison of MSU/AMSU temperature in the lower stratosphere (e.g., Tb for AMSU ch9 and MSU ch4), where the moisture effect on GPS RO refractivity is smallest. We describe datasets and analysis method used in the comparison procedure in Section 2 and 3, respectively. The absolute Tb differences between CHAMP and that from RSS and UAH are presented in Section 4. The trend differences of RSS, UAH and CHAMP Tb anomalies are compared in Section 5. We conclude this study in Section 6.

2. Data

[6] The UAH MSU/AMSU Version 5.1 dataset [Christy et al., 2003] is used in this study. This monthly global temperature anomaly dataset contain 2.5 degree × 2.5 degree gridded mean values ranging from 82.5°S to 82.5°N. All MSU/AMSU Tb on board NOAA AM and PM satellites are included in this version. Non-linear correction for time-varying sampling of the diurnal cycle by MSU/AMSU instruments due to drift in the local equatorial crossing time of the satellite orbits are also implemented in this dataset.

[7] We use RSS MSU/AMSU Version 2.1 dataset [Mears et al., 2003] in this study. This is also a monthly 2.5 degree × 2.5 degree gridded dataset, however, the correction and merging procedures are different than those of UAH. Only Tbs in the lower stratosphere (TLS, e.g., AMSU ch9 and MSU ch4) data from both datasets are examined in this study. For both RSS and UAH, only nadir viewing pixels were included in each 2.5 degree × 2.5 degree grid. In total, 49 months of CHAMP, RSS and UAH data from June 2001 to June 2005 are used in this study.

[8] GPS RO limb sounding technique measures phase and amplitude of radio signals propagated through the atmosphere between GPS satellites and GPS receivers on low Earth orbiting (LEO) satellites [Steiner et al., 1999]. From these data the atmospheric refractivity profile, density, pressure, geo-potential height, temperature, and humidity are derived [Kuo et al., 2004]. In this study, we use CHAMP RO dry temperature profiles from June 2001 to June 2005 to compare to RSS and UAH TLS in the same time period. All CHAMP RO dry temperature profiles were downloaded from UCAR Constellation Observing System for Meteorology, Ionosphere and Climate (COSMIC) Data Analysis and Archive Center (CDAAC) (http://cosmic.ucar.edu/cdaac/index.html).

3. Comparison Methods

[9] The CHAMP, RSS and UAH comparisons are based on statistics of Tb differences. To perform the conversion of CHAMP temperature profiles into microwave Tb, we used an AMSU fast forward model from CIMSS (MWF_{CIMSS}) with 100 fixed pressure levels [Woolf et al., 1999], which was operationally employed in the International ATOVS Processing Package [Li et al., 2000] developed at the University of Wisconsin Space Science and Engineering Center (SSEC). High vertical resolution GPS RO soundings were interpolated onto the MWF_{CIMSS} levels. A two-step strategy is employed:

[10] Step 1: To minimize spatial representation errors, we first bin GPS RO soundings into each 2.5 degree × 2.5 degree grid to match the same spatial resolution of RSS and UAH data for each month. To avoid RO retrievals near the surface where signal attenuation and propagation effects related to sharp vertical moisture gradients can be present, only CHAMP profiles containing retrieved temperatures from 500 mb (AMSU weighting function is close to zero, see below) to 10 mb are included in the binning procedure. Because AMSU temperature weighting function (WF) varies for different atmospheric temperature structures (the shape and the magnitude of WF is a function of the actual temperature profile; Figure 1), instead of using a fixed AMSU-9 WF provided by either RSS or UAH, we apply each 2.5 degree × 2.5 degree gridded monthly mean profile to MWF_{CIMSS} to simulate AMSU-9 Tb. This approach is to reduce WF representation error in the simulated Tb. Satellite viewing angle is set to nadir for our calculations to reduce the Tb dependence on viewing geometry.

[11] Step 2: In order to reduce possible spatial and temporal representation errors at each grid box, we further bin each monthly mean MSU/AMSU and CHAMP 2.5 degree × 2.5 degree matched pairs into 10 degree × 10 degree grids. This approach is unlikely to cause a bias in the long-term analysis as it is just a random effect at each grid box. Only 2.5 degree × 2.5 degree MSU/AMSU data that have corresponding pairs in CHAMP are used. Between 80°N to 90°N and 80°S to 90°S, only 2.5 degree × 2.5 degree grids from 80°N to 82.5°N and 80°S to 82.5°S are binned into the 10 degree × 10 degree grids, respectively. In total, 22,353 for RSS, UAH and CHAMP matching pairs are
and that from UAH and RSS dataset as and UAH varies pairs are 0.98 and \(C_0\) at almost all latitudinal zones except for CHAMP = 0.96 K) than that and between UAH \(C_0\) is systematically lower (\(Tb\) anomalies. The de-

are in \(C_0\) pairs and CHAMP \(C_0\) and RSS \(C_176\) pairs are also more closely

produced over 49 months. Hereafter, we refer the forward calculated AMSU-9 \(Tb\) using CHAMP sounding as CHAMP TLS and that from UAH and RSS dataset as UAH TLS and RSS TLS, respectively.

4. Global 10\(^\circ\) × 10\(^\circ\) Averages of RSS, UAH, and CHAMP TLS

[12] Figure 2 depicts the scattering diagrams of global monthly mean TLS for each 10 degree × 10 degree grid between (a) RSS and CHAMP, (b) UAH and CHAMP and (c) RSS and UAH. Matching pairs with systematically negative difference between UAH TLS and RSS TLS are in blue dots in Figure 2c where the corresponding matching pairs for CHAMP and RSS are also in blue dots in Figures 2a and 2b.

Figure 2. The comparisons of global monthly mean lower stratospheric \(Tb\) for each 10 degree × 10 degree grid between (a) RSS and CHAMP, (b) UAH and CHAMP and (c) RSS and UAH. Matching pairs with systematically negative difference between UAH TLS and RSS TLS are in blue dots in Figure 2c where the corresponding matching pairs for CHAMP and RSS are also in blue dots in Figures 2a and 2b.

5. Trend Analysis of RSS, UAH and CHAMP TLS Anomalies

[14] Although there are only about 4 years (49 months) of data pairs, we can still examine the consistency among the CHAMP TLS, RSS TLS and UAH TLS \(Tb\) anomalies. The de-

Table 1. Correlation Coefficients, Mean Differences (K) and Standard Deviations (K) of Mean Lower Stratospheric \(Tb\) Differences for RSS-CHAMP, UAH-CHAMP and RSS-UAH Pairs for Five Latitudinal Zones\(^a\)

<table>
<thead>
<tr>
<th></th>
<th>RSS-CHAMP</th>
<th>UAH-CHAMP</th>
<th>RSS-UAH</th>
</tr>
</thead>
<tbody>
<tr>
<td>60(^\circ) N–82.5(^\circ) S</td>
<td>Correlation Coef.</td>
<td>0.97 (0.97)</td>
<td>0.93 (0.97)</td>
</tr>
<tr>
<td></td>
<td>Std Mean Difference</td>
<td>−0.8</td>
<td>0.41</td>
</tr>
<tr>
<td></td>
<td>Std</td>
<td>1.9 (0.68)</td>
<td>2.8 (0.69)</td>
</tr>
<tr>
<td>20(^\circ) N–60(^\circ) N</td>
<td>Correlation Coef.</td>
<td>0.97 (0.98)</td>
<td>0.96 (0.97)</td>
</tr>
<tr>
<td></td>
<td>Std Mean Difference</td>
<td>−1.45</td>
<td>−0.33</td>
</tr>
<tr>
<td></td>
<td>Std</td>
<td>1.4 (0.16)</td>
<td>1.6 (0.18)</td>
</tr>
<tr>
<td>20(^\circ) S–60(^\circ) S</td>
<td>Correlation Coef.</td>
<td>0.93 (0.95)</td>
<td>0.9 (0.95)</td>
</tr>
<tr>
<td></td>
<td>Std Mean Difference</td>
<td>−0.87</td>
<td>−0.17</td>
</tr>
<tr>
<td></td>
<td>Std</td>
<td>0.6 (0.17)</td>
<td>1.0 (0.2)</td>
</tr>
<tr>
<td>60(^\circ) S–82.5(^\circ) S</td>
<td>Correlation Coef.</td>
<td>0.94 (0.74)</td>
<td>0.9 (0.76)</td>
</tr>
<tr>
<td></td>
<td>Std Mean Difference</td>
<td>0.08</td>
<td>0.69</td>
</tr>
<tr>
<td></td>
<td>Std</td>
<td>1.8 (0.4)</td>
<td>2.47 (0.38)</td>
</tr>
</tbody>
</table>

\(^a\)The values of correlation coefficients and standard deviations of the \(Tb\) anomalies are shown in the parenthesis. The mean differences of \(Tb\) anomalies are all very close to zero and are not listed here.
seasonalized Tb anomalies of RSS\textsubscript{TLS}, UAH\textsubscript{TLS} and CHAMP\textsubscript{TLS} generated for global and five latitudinal zones are plotted in Figure 3. TLS anomalies are computed by subtracting the mean value for each month of the year for the period from June 2001 to June 2005 from each of the TLS time series. Since only 49 months of CHAMP and collocated RSS and UAH pairs are used, temperature trends evaluated here should not be considered climatic trends as the period is too short. The statistics (correlation coefficients and standard deviations) of Tb anomalies are listed in the Table 1. In general, the de-seasonalized Tb anomalies from UAH\textsubscript{TLS} and RSS\textsubscript{TLS} are consistent with that from CHAMP\textsubscript{TLS} globally (Figure 3a), the trends (in K/5 year) found from RSS\textsubscript{TLS}, UAH\textsubscript{TLS} and CHAMP\textsubscript{TLS} Tb anomalies, however, vary for the different latitudinal zones. RSS\textsubscript{TLS}, UAH\textsubscript{TLS} and CHAMP\textsubscript{TLS} all have cooling trends globally and in most latitude bands (Figure 3 and Table 2). Although both RSS\textsubscript{TLS} and UAH\textsubscript{TLS} from 1978 to 2005 show stratospheric cooling trends globally and at all latitudinal zones (RSS website, 2006, http://www.ssmi.com/ssmi/ssmi_description.html), in the 60°S to 82.5°S zone during the period from June 2001 to June 2005, RSS\textsubscript{TLS}, UAH\textsubscript{TLS} and CHAMP\textsubscript{TLS} all show a stratospheric warming trend (Table 2). The cause of the relatively large Tb anomaly

**Table 2.** Trends for the Period 2001–2005 of De-seasonalized Lower Stratospheric Tb Anomalies (in K/5 yrs) for RSS, UAH, CHAMP, RSS-CHAMP and UAH-CHAMP for the Global (82.5°N–82.5°S) and Five Latitudinal Zones

<table>
<thead>
<tr>
<th>Zone</th>
<th>RSS</th>
<th>UAH</th>
<th>CHAMP</th>
<th>RSS-CHAMP</th>
<th>UAH-CHAMP</th>
</tr>
</thead>
<tbody>
<tr>
<td>82.5°N–82.5°S</td>
<td>−1.2</td>
<td>−1.2</td>
<td>−1.3</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>60°N–82.5°N</td>
<td>−1.7</td>
<td>−1.7</td>
<td>−1.3</td>
<td>−0.4</td>
<td>−0.4</td>
</tr>
<tr>
<td>20°N–60°N</td>
<td>−1.4</td>
<td>−1.5</td>
<td>−1.4</td>
<td>0.0</td>
<td>−0.1</td>
</tr>
<tr>
<td>20°S–20°N</td>
<td>−0.7</td>
<td>−0.6</td>
<td>−0.5</td>
<td>−0.2</td>
<td>−0.1</td>
</tr>
<tr>
<td>20°S–60°S</td>
<td>−0.3</td>
<td>−0.2</td>
<td>−0.9</td>
<td>0.6</td>
<td>0.7</td>
</tr>
<tr>
<td>60°S–82.5°S</td>
<td>0.6</td>
<td>0.3</td>
<td>0.1</td>
<td>0.5</td>
<td>0.2</td>
</tr>
</tbody>
</table>
differences between CHAMP and microwave data, especially in the 20°S to 60°S zone for 2001 summer (Figure 3e) and fall of 2002 in the southern-mid latitude band (Figure 3f), may be in part due to the small number of CHAMP observations during those periods.

[15] Compared to trends found in CHAMP_TLS Tb anomalies, both RSS_TLS and UAH_TLS cool in the Tropics by 0.2 K/5 yrs and ~0.1 K/5 yrs, respectively. For the farthest north latitude band (60°N–82.5°N zone) both RSS_TLS and UAH_TLS cool by 0.4 K/5 yrs relative to CHAMP. However, the microwave datasets exhibit a stratospheric warming trend difference compared to CHAMP in the South Hemisphere mid-latitude (Table 2). Globally, UAH_TLS and RSS_TLS from June 2001 to June 2005 exhibit a slight warming trend difference to CHAMP_TLS (both RSS_TLS–CHAMP_TLS and UAH_TLS–CHAMP_TLS are about 0.1 K/5 yrs), where RSS_TLS and UAH_TLS show no trend difference or a slight cooling trend difference to CHAMP_TLS in the North Hemisphere mid-latitude (20°N to 60°N, RSS_TLS–CHAMP_TLS of 0.0 K/5 yrs and UAH_TLS–CHAMP_TLS of ~0.1 K/5 yrs). The trend differences between RSS_TLS and CHAMP_TLS are smaller than that between UAH_TLS and CHAMP_TLS in mid-latitude in both Northern Hemisphere (20°N to 60°N) and Southern Hemisphere (20°S to 60°S). The trend differences between UAH_TLS and CHAMP_TLS are smaller than those between RSS_TLS and CHAMP_TLS in the South Pole regions and the tropical regions (Table 2).

6. Conclusions and Future Works

[16] In this study, we use GPS RO data to compare to 49 months of RSS and UAH microwave lower stratosphere brightness temperature. We reached the following conclusions:

[17] The results in this paper generally demonstrate excellent agreement between RSS_TLS and UAH_TLS monthly mean brightness temperature and CHAMP_TLS data on the 10 degree × 10 degree grids. The CHAMP_TLS matches better with RSS_TLS data in terms of variations (higher correlation coefficient and smaller standard deviations) and matches better with that of UAH_TLS in terms of mean. RSS_TLS is systematically 0.8 K to 1.9 K lower than that of CHAMP_TLS at almost all latitudinal zones except for the 20°S to 60°S zone. Because CHAMP RO has only one GPS receiver, it will take more than three months to complete a diurnal cycle over the low and middle latitudes. Therefore we may not have had enough GPS RO observations to differentiate between the small difference in RSS_TLS and UAH_TLS data during this period caused by different diurnal correction algorithms used by these two groups [Mears and Wentz, 2005].

[18] Despite limited temporal and spatial samples from CHAMP GPS RO data from 2001 to 2005, the de-seasonalized Tb anomalies from CHAMP_TLS in general, agree well with that from both UAH_TLS and RSS_TLS globally. However, trend differences are still found between RSS_TLS and CHAMP_TLS as well as UAH_TLS and CHAMP_TLS. RSS_TLS and UAH_TLS show a cooling trend difference to CHAMP_TLS in the North Pole regions and Tropics. In the Southern Hemisphere, RSS_TLS and UAH_TLS show a warming trend difference to CHAMP_TLS in the mid-latitude and in the South Pole regions.

[19] Some of these differences are likely to be caused by the limited number of CHAMP data points. COSMIC was successfully launched on 15 April 2006. It will provide about 2,500 GPS RO profiles per day after it is fully deployed, which is about an order of magnitude more than the currently available GPS RO soundings from CHAMP and SAC-C. With COSMIC GPS RO soundings, we will be able to determine finer regional patterns and atmospheric temperature trends with smaller spatial and temporal mismatches with that from MSU and AMSU data.

[20] Acknowledgments. We would like to thank Hal Woolf from the Cooperative Institution for Meteorological Satellite Studies for providing the fast AMSU forward Transfer Algorithm package. We would also like to acknowledge the contributions to this work from members of the Constellation Observing System for Meteorology, Ionosphere and Climate (COSMIC) team at UCAR. The National Center for Atmospheric Research is sponsored by the National Science Foundation.

References


S.-P. Ho, Y.-H. Kuo, and Z. Zeng, COSMIC Project Office, University Corporation for Atmospheric Research, P. O. Box 3000, Boulder, CO 80307–3000, USA. (spho@ucar.edu)

T. C. Peterson, NOAA National Climatic Data Center, 151 Patton Avenue, Asheville, NC 28801–5001, USA.