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A multi-year comparison of lower stratospheric temperatures from CHAMP radio occultation data with MSU/AMSU records

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[1] Long-term upper air temperature records have been established by different groups with considerable effort from radiosonde data and from satellite based (Advanced) Microwave Sounding Unit (MSU/AMSU) measurements, the latter providing information on layer-average stratospheric and tropospheric brightness temperatures. Comparisons of the temperature series show discrepancies not only with respect to radiosonde data but also between MSU data sets stemming from different retrievals. In this context the Global Navigation Satellite System radio occultation (RO) technique offers new possibilities by providing high quality observations of the atmosphere in an active limb sounding mode. RO temperature climatologies have been constructed at the WegCenter/UniGraz based on RO observations of the CHAllenging Minisatellite Payload for geoscientific research (CHAMP) satellite since September 2001, and based on a few months of RO data from other satellite missions (SAC-C, GRACE, COSMIC). Focusing on the MSU lower stratosphere channel (TLS), synthetic TLS temperatures were calculated by applying global weighting functions to zonal-mean monthly mean RO temperature climatology profiles for September 2001–December 2006. These synthetic CHAMP TLS temperatures were compared to recent MSU TLS records from the University of Alabama in Huntsville (UAH, USA) and from Remote Sensing Systems (RSS, USA), as well as to synthetic TLS temperatures from HadAT2 radiosonde data (Hadley Centre/MetOffice, UK) and ECMWF (European Centre for Medium-Range Weather Forecasts) analyses. In terms of TLS temperature anomalies, overall very good agreement of CHAMP temperature anomalies with UAH, RSS, and ECMWF anomalies was found for intra-annual variability (RMS difference of de-trended data <0.1 K globally, 0.1 K in the tropics, <0.25 K in the extratropics), while HadAT2 anomalies show larger differences (factor of two globally and more in the extratropics). Regarding 2001–2006 trends, UAH and RSS exhibit a statistically significant cooling trend difference to CHAMP globally (−0.30 to −0.36 K/5 yrs), stemming mainly from the tropics (−0.40 to −0.42 K/5 yrs), while in the extratropics the cooling trend differences are not significant. The contribution of known error sources regarding the RO data and the related synthetic-MSU computation procedure is about an order of magnitude smaller than these trend differences. Resolution of the trend discrepancy thus requires either additional, so far overlooked, sources of error in the RO TLS record or the presence of currently unresolved biases in the MSU records. SAC-C, GRACE, and COSMIC TLS temperatures closely match CHAMP temperatures, indicating the consistency and homogeneity of the RO data series. The results underpin the benefit of having multiple independent estimates of the same variable from different instruments for detecting residual weaknesses in otherwise high-quality climate records. Continued inter-comparison, and exploiting the traceability of the RO data to the universal time standard (UTC), then enables us to further reduce the uncertainty in the climate records in absolute terms.

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1. Introduction

[2] Considerable efforts have been undertaken to establish long term upper air temperature records from radiosonde [*Lanzante et al.*, 2003; *Sherwood et al.*, 2005; *Thorne*

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et al., 2005a] and satellite observations [*Christy et al.*, 2003; *Christy and Spencer*, 2005; *Mears et al.*, 2003; *Mears and Wentz*, 2005; *Grody et al.*, 2004; *Vinnikov et al.*, 2006] for investigating and reconciling discrepancies in temperature trends [*Karl et al.*, 2006]. These temperature trend series now show convergence toward surface warming estimates and provide a better agreement with climate models [*Santer et al.*, 2005; *Karl et al.*, 2006]. Nevertheless, significant divergence still remains in their long-term large-scale mean trends [*Seidel et al.*, 2004; *Thorne et al.*, 2005b].

[3] The principal source of satellite-based upper air temperature records for the last ~25 years was the Microwave Sounding Unit (MSU), since 1998 also the Advanced MSU (AMSU) on U.S. National Oceanic and Atmospheric Administration (NOAA) satellites. The MSU/AMSU is a passive cross-track scanning microwave sensor measuring the Earth's microwave emission in the 50–60 GHz oxygen absorption band in different channels and providing information on layer-average stratospheric and tropospheric brightness temperature. Continuous MSU/AMSU temperature time series have been established by merging of data from multiple satellites in different orbits with slightly different sensors. The retrieval and homogenization process demands inter-calibration and correction procedures to account for time-varying biases, such as diurnal drift, orbital decay, inter-satellite biases, and calibration changes due to heating and cooling of the instrument in space [*Christy et al.*, 1998]. MSU data are provided by two main groups, The University of Alabama in Huntsville (UAH, AL, USA) [*Christy et al.*, 2000, 2003; *Christy and Spencer*, 2005], and Remote Sensing Systems of Santa Rosa (RSS, CA, USA) [*Mears et al.*, 2003; *Mears and Wentz*, 2005]. The main issues addressed differently by the groups are the correction for diurnal drift and the inter-calibration between the series of satellites, the latter being the main cause for global trend differences. As *Thorne et al.* [2005b] expresses, there is no objective way to specify the optimal correction procedure and a degree of subjectivity is inevitably introduced. Thus on the basis of the same raw satellite data, different measures are derived by different construction methodologies.

[4] Radiosondes are launched once or twice per day (00 and/or 12 Universal Time Coordinated (UTC)) with daytime biases in the measurements arising from solar heating of the temperature sensor. The impact is greatest at stratospheric levels, where direct sunlight can cause radiosonde measured temperatures to rise several degrees above ambient temperatures [*Sherwood et al.*, 2005]. Spatial and temporal sampling errors were found to have a minor impact [*Free and Seidel*, 2005] while time-varying biases, different data adjustments and processing methods, changes in stations and in instrumentation type are the main sources of data discontinuities [*Karl et al.*, 2006] with persistent residual cooling biases at tropical stations and in nighttime measurements [*Randel and Wu*, 2006]. Hadley Centre Atmospheric Temperatures (HadAT2) from radiosonde measurements are produced by the Hadley Centre/Met Office, UK [*Thorne et al.*, 2005a]. On the basis of homogenized reference networks [e.g., *Lanzante et al.*, 2003] a larger set (with respect to former data sets) of grossly consistent station records was selected using a sonde-based neighbor composite series to perform bias adjustments. The final data set consists of 676 radiosonde stations biased to continental Northern Hemisphere midlatitudes but with improved coverage over Africa, Southern Asia, and the Southern Pacific Ocean [*Thorne et al.*, 2005a]. The recently identified issues in the raw data as discussed above have possibly been ameliorated in this homogenized data set, even though they had not been specifically considered.

[5] In this context the Global Navigation Satellite System (GNSS) radio occultation (RO) technique offers new possibilities by providing an independent type of high quality observations of the atmosphere. The GNSS RO technique is based on active limb sounding using a satellite-to-satellite radio link to probe the Earth's atmosphere. The GNSS-transmitted radio signals are influenced by the atmospheric refractivity field during their propagation to a receiver on a Low Earth Orbit satellite. Observed excess phases are the basis for retrievals of atmospheric variables such as refractivity, pressure, geopotential height, temperature, and water vapor. A detailed description of the data processing methodology is given by, e.g., *Kursinski et al.* [1997] and *Hajj et al.* [2002]. The first application of the RO method to the Earth's atmosphere was demonstrated with the U.S. Global Positioning System Meteorology (GPS/MET) experiment [*Ware et al.*, 1996]. Analysis and validation of GPS/MET data [*Kursinski et al.*, 1997; *Rocken et al.*, 1997; *Steiner et al.*, 1999] and error analysis studies based on end-to-end simulations [*Steiner and Kirchengast*, 2005] confirmed the high accuracy (temperature RMS errors <1 K) and vertical resolution (0.5–1.5 km) in the upper troposphere and lower stratosphere region. Besides global coverage and almost all-weather capability the most important property regarding climate studies is the long-term stability due to intrinsic self-calibration based on precise timing with atomic clocks. Ongoing GPS RO experiments are placed on board the German CHAMP (CHallenging Minisatellite Payload for geoscientific research) [*Wickert et al.*, 2004] and GRACE (Gravity Recovery and Climate Experiment) satellites [*Wickert et al.*, 2005], the Argentine SAC-C (Satelite de Aplicaciones Cientificas-C) satellite [e.g., *Hajj et al.*, 2004], and the recently started Taiwan/U.S. Formosat-3/COSMIC mission [*Rocken et al.*, 2000; *Wu et al.*, 2005]. The validation of SAC-C [*Hajj et al.*, 2004] and CHAMP temperature retrievals [*Wickert et al.*, 2004; *Gobiet et al.*, 2004; *Steiner et al.*, 2006] confirmed the high quality of RO data. Impact and assimilation studies showed their potential to improve numerical weather analyses already with data from just a single satellite [e.g., *Zou et al.*, 2004; *Healy et al.*, 2005; *Healy and Thépaut*, 2006]. GNSS RO observing system simulation experiments [*Steiner et al.*, 2001; *Foelsche et al.*, 2003] investigate the potential for a contribution to the Global Climate Observing System [*GCOS*, 2003]. The validation of climatological exploitation of RO data from GPS/MET [*Schroeder et al.*, 2003] and CHAMP [*Schmidt et al.*, 2004; *Gobiet et al.*, 2005; *Foelsche et al.*, 2005, 2006; *Borsche et al.*, 2007] indicated the suitability of RO data for global climate monitoring and modeling [*Leroy et al.*, 2006].

[6] This study focuses on a comparison of CHAMP RO data with available MSU/AMSU and equivalent radiosonde data sets and is motivated by the results and recommendations of the Report by the U.S. Climate Change Science Program (CCSP) stating that "In fact, new types of more

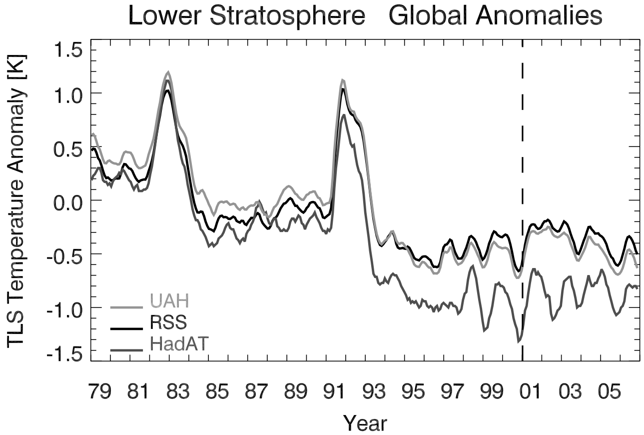

Figure 1. Global temperature anomalies smoothed with a 7-month moving average filter for the lower stratosphere (TLS) derived from UAH (light gray) and RSS (black) brightness temperatures and from HadAT2 radiosonde temperatures (dark gray) shown for the years 1979–2006. The time period 2001–2006 used in this study for comparison with CHAMP RO data is delimited by dashed vertical lines.

accurate data such as temperature and moisture profiles from GPS radio occultation measurements are already available, although, as yet, few efforts have been made to analyze them" [*Karl et al.*, 2006].

[7] Synthetic MSU temperatures were computed from CHAMP RO temperature climatologies, and from a few months of complementary RO climatologies from SAC-C, GRACE, and COSMIC, derived at the WegCenter/UniGraz, Austria, as well as from analyses of the European Centre for Medium-Range Weather Forecasts (ECMWF). We compared them with recent MSU temperature records provided by UAH, RSS, and HadAT2 as presented in the CCSP report and shown in Figure 1 to provide context. We focus on the years 2001–2006 and on the upper troposphere/lower stratosphere region (MSU TLS/T4 channel) where CHAMP RO retrievals have the best data quality.

[8] A short description of the respective data sources is given in Section 2 and the comparison setup is described in Section 3. The results of the study are presented and discussed in Section 4. Section 5 summarizes our findings and conclusions and gives a brief outlook to further investigations.

2. Data

2.1. GPS RO Temperature Climatologies

[9] The CHAMP satellite has been providing RO measurements since September 2001. After an initial phase with a smaller number of observations, about 230 raw RO profiles per day have been recorded since March 2002 [*Wickert et al.*, 2004]. Global coverage is provided almost uniformly, however due to the inclination of the CHAMP orbit (87.2°) there are some more RO observations at high latitudes than at low latitudes. The number of RO events gradually decreases into the troposphere with decreasing height, since the RO event satellite-to-satellite signal tracking is terminated when the GPS signal is lost.

[10] The CHAMPCLIM project, a joint project of WegCenter/UniGraz, Austria, and GeoForschungsZentrum (GFZ) Potsdam, Germany, was undertaken to build the first RO based multi-year climatologies [*Foelsche et al.*, 2005]. On the basis of CHAMP RO orbital data and phase delay measurements provided by the GFZ Potsdam, atmospheric parameters were retrieved at the WegCenter. About 150 quality-controlled atmospheric profiles are obtained per day with the current CHAMPCLIM retrieval version 2.3 (CCRv2.3) [*Borsche et al.*, 2006] and a record of more than five years has been meanwhile established [*Foelsche et al.*, 2007]. At high altitudes the observed data are combined with background information (ECMWF analyses) in a statistically optimal way to minimize residual biases in atmospheric parameters below 35 km [*Gobiet and Kirchengast*, 2004]. The CCRv2.3 atmospheric profiles are background-dominated above the stratopause and observation-dominated below 40 km. For the systematic differences between CHAMP and ECMWF the influence of the background is estimated <0.2 K at 30 km and further decreases quickly below [*Gobiet et al.*, 2005].

[11] From validation with independent data sets (such as from MIPAS on Envisat) it was found that that potential temperature biases are <0.2 K in the global mean within 10–30 km [*Gobiet et al.*, 2007]. Latitudinally resolved analyses show observationally constrained biases of <0.2 to 0.5 K up to 35 km in most cases, and up to 30 km in any case, even if severely biased (about 10 K or more) a priori information is used in the high altitude initialization of the retrieval [*Gobiet et al.*, 2007]. CHAMP biases near 40 km can thus be expected not to exceed about 2 K. The effect of these levels of bias up to 40 km is small in MSU TLS data, due to the small weighting function contributions above 30 km. Perturbation tests showed that biases linearly increasing from 0.2 to 2 K from 30 to 40 km lead to a bias in MSU TLS of <0.015 K. Even an increase to 5 K bias at 40 km (or a trend in bias of 5 K over 5 years) would lead to a spurious TLS change of <0.04 K only.

[12] Currently, so-called dry temperatures are used for establishing climatologies, meaning that in the RO retrieval the contribution of water vapor to microwave refractivity is neglected (dry air assumption). This assumption always holds to <0.1 K differences between actual and dry temperature at altitudes above 8 km in polar winter regimes and above 14 km in the tropics, respectively, with the dry temperature then becoming gradually colder than the actual one deeper into the troposphere as humidity increases [*Foelsche et al.*, 2007]. The CHAMP climatologies are derived by sampling and averaging (weighted by the cosine of the latitude) all available CHAMP profiles to provide seasonal and monthly zonal means in 18 latitude bands (of 10° latitudinal width) with 200 m altitude gridding. Because of selective sampling in dry regions and the decreased number of occultation events at lower altitudes [*Foelsche et al.*, 2007], the CHAMP dry temperature climatologies are cut off below 4 km height at high latitudes with the cut-off height increasing to 8 km at low latitudes. As an example we show the (arbitrarily selected) monthly climatology for July 2005 in Figure 2.

[13] Corresponding error characteristics are provided for CHAMP RO climatologies with respect to analyses from ECMWF [for details see *Gobiet et al.*, 2005; *Foelsche et al.*,

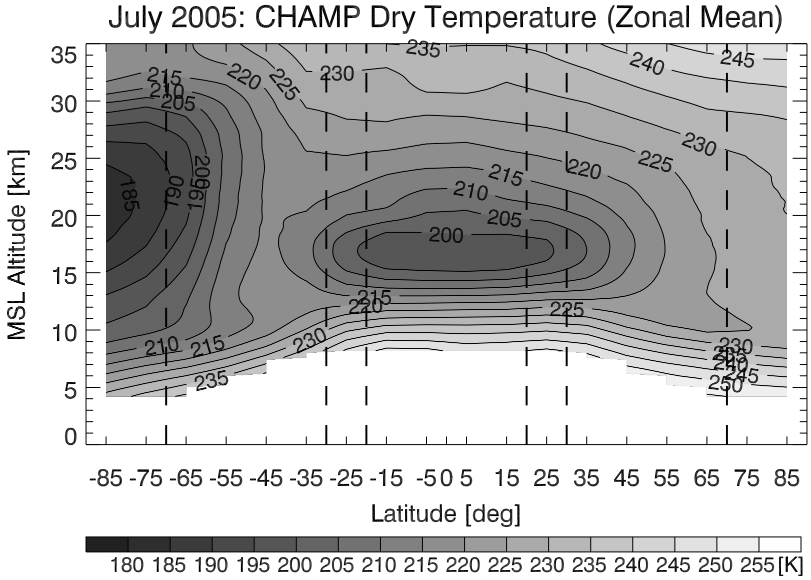

Figure 2. Exemplary CHAMP temperature climatology for July 2005, monthly and zonal means for 10 degree latitude bands on 0.2 km vertical grid. Selected geographic regions for data analysis are indicated by dashed lines: global (70°S–70°N), tropics (20°S–20°N), Northern Hemisphere (NH) extratropics (30°N–70°N), and Southern Hemisphere (SH) extratropics (30°S–70°S).

2006, 2007; *Steiner et al.*, 2006]. The sampling error for these single-satellite climatologies results from uneven and sparse sampling in space and time. The typical average CHAMP dry temperature sampling error for monthly zonal means in 10°-latitude bands is <0.3 K in the upper troposphere and lower stratosphere, with the local time component of sampling error being <0.15 K [*Pirscher et al.*, 2007]. Higher sampling error values occur in restricted regions (mainly high latitudes) and time intervals (individual months) due to occasional spatial clustering of RO events. They are clearly identified with our co-monitoring of the sampling error. Regarding the observational error, the standard deviation for a single RO dry temperature profile ranges from about 0.8 K below 15 km to about 2 K at 35 km altitude, becoming climatologically negligible (<0.01–0.1 K) due to averaging many hundreds to thousands of profiles in monthly/seasonal ensembles for large-scale regions as considered here. Comparison of CHAMP climatologies to ECMWF analyses overall shows a systematic difference of <0.5 K up to 30 km altitude. This systematic difference contains a considerable contribution from ECMWF analyses since we can regard the CHAMP data as essentially unbiased at <30 km [*Gobiet et al.*, 2007], and since we found that larger differences are mainly attributable to errors in ECMWF analyses, e.g., in the Southern polar winter [*Gobiet et al.*, 2005] and in the tropical tropopause region [*Borsche et al.*, 2007], respectively. On the long-term stability of potential residual biases we have currently no evidence or knowledge of processes in the homogenously processed CCRv2.3 data that would significantly change over time. Future inter-comparison of trends in RO data records of independent processing centers, and trace-back to the international time standard [*Leroy et al.*, 2006], is planned to help quantify potential residual bias drifts.

[14] For this study we used monthly mean zonal-mean CHAMP dry temperature climatologies at 10° latitude resolution as a function of pressure up to 2.5 hPa (~40 km) at a 200 m altitude grid for the time span September 2001 to December 2006. No CHAMP data were available for July 2006 due to satellite problems. In addition, we used RO data from three other satellites as independent "anchor points" in the time period, i.e., SAC-C for June, July, August (JJA) 2002, GRACE for July 2006, and COSMIC for December 2006. SAC-C (version 3090 data set) and COSMIC (version 1 data set) phase delay and orbit data were provided by the University Corporation of Atmospheric Research/COSMIC Data Analysis and Archival Center (UCAR/CDAAC), Boulder. CHAMP and GRACE phase delay and orbit data (version 2 data set) were provided by GFZ Potsdam. We note that these different RO data sets ingested into the CCRv2.3 retrieval system are based on different (raw) processing systems at GFZ and UCAR.

2.2. ECMWF Analyses

[15] The ECMWF produces daily analyses through combination of a short-range forecast with observational data based on four-dimensional variational assimilation [*ECMWF*, 2004]. A series of system changes (cycle changes) occurred in the investigated time period (for details see Table 1). Until February 2006, the integrated forecasting system used a resolution of T511L60, i.e., 60 levels and a spectral representation with triangular truncation at wave number 511. A major resolution upgrade was introduced on 1 February 2006 by increasing the horizontal resolution to T799 and the vertical resolution to 91 levels [*Untch et al.*, 2006]. ECMWF analysis fields are operationally used as reference data in the WegCenter/UniGraz processing system, at a resolution of T42L60 until February 2006 and of T42L91 since then, at four time layers per day (00 UTC, 06 UTC, 12 UTC, 18 UTC). ECMWF climatologies used as one comparison data set in the present

Table 1. Characteristics of the Original Data Sets Including Information on Version and Horizontal Resolution as Well as Available Time Period and Basic Sampling[a]

Data Set	Version	Horizontal Resolution	Time Period Monthly Data	Basic Sampling Per Day Globally
CHAMP RO	CCR v2.3	10° zonal means	09/2001–12/2006	~150 profiles
SAC-C RO			06/2002–08/2002	~150 profiles
GRACE RO			06/2006	~150 profiles
COSMIC RO			12/2006	~200 profiles, 2 satellites used
ECMWF	T42L60	10° zonal means	09/2001–01/2006	~8,000 grid points, 4 times/day
	T42L91		02/2006–12/2006	
MSU/AMSU	RSS v2.1	2.5° lat × 2.5° lon	11/1978–12/2006	~30,000 TLS observations
	UAH v5.1	2.5° lat × 2.5° lon	12/1978–12/2006	
HadAT2 MSU	HadAT2	5° zonal means	01/1958–12/2006	1–2 soundings/day, 676 stations

[a]Homogenously processed records are CHAMP RO, MSU/AMSU, and HadAT2. ECMWF record with analysis system changes (Cycle = Cy): Cy23r4/12Jun01, Cy24r3/22Jan02, Cy25r1/09Apr02, Cy25r4/14Jan03, Cy25r5/04Mar03, Cy26r1/29Apr03, Cy26r3/07Oct03, Cy28r1/09Mar04, Cy28r2/29Jun04, Cy28r3/28Sep04, Cy29r1/05Apr05, Cy29r2/28Jun05, Cy30r1/01Feb06 (major change/resolution upgrade), Cy31r1/12Sep06 (information at http://www.ecmwf.int/products/data/operational_system/evolution/).

study were produced from the individual analyses at the same resolution as CHAMP climatologies (i.e., 10° latitude resolution, 200 m altitude grid) for September 2001 to December 2006.

2.3. MSU/AMSU Brightness Temperatures

[16] The MSU sensor measured at 11 scan angles over a swath about 2000 km wide. The spatial resolution of the measurements varies from about 110 km at nadir to near 200 km at the extreme beam positions. During every scan, the MSU calibrates itself by viewing cold space and a hot target [*Spencer and Christy*, 1992; *Christy et al.*, 1998]. MSU as a four channel radiometer provided layer average brightness temperatures for four respective atmospheric layers, i.e., a single temperature value describes the entire layer. Channels 2, 3, and 4 correspond to the temperature in the middle troposphere (TMT), the troposphere/stratosphere (TTS), and the lower stratosphere (TLS), respectively. A temperature for the lower troposphere (TLT) is also retrieved from channel 2 [*Christy et al.*, 1998]. Because of instrument problems TTS data are only provided by RSS after 1986. Since 1998 AMSU samples the atmosphere in a larger number of layers using 20 spectral channels, with channel 5 and 9 closely matching MSU's channel 2 and 4, respectively, ensuring the continuation of the temperature time series [*Christy et al.*, 2003]. In parallel, MSU data have been processed through December 2004 until the satellite NOAA-14, with the last MSU unit aboard, was decommissioned.

[17] In the merging procedure to generate a homogenous MSU time series, the bias of each instrument has to be removed relative to a common base. According to *Christy et al.* [1998] all anomaly time series are adjusted to the anchor satellite NOAA-6 and its reference annual cycle. The representative period to serve as the reference for the complete anomaly time series was chosen January 1984 to December 1990 for T4 [*Christy et al.*, 1998]. AMSU data showed error characteristics indistinguishable from the earlier MSU products justifying the continuation of the time series [*Christy et al.*, 2003]. The bias between AMSU9 (NOAA-15) and MSU4 (NOAA-14) was found to be about 0.3 K, which is a value within the range of biases determined among the MSUs themselves [*Christy et al.*, 2003].

[18] The random error of a single MSU measurement is estimated to be about 0.3 K [*Kidder and Vonder Haar*, 1995], becoming negligible for global averages of about 30,000 observations per day [*Karl et al.*, 2006]. Daily grid point (2.5° × 2.5° bins) noise estimates (single satellite standard error of measurement) for channel 4 (TLS) are usually below 0.2 K in the deep tropics, increasing to 0.3–0.4 K in the Northern Hemisphere midlatitudes, reaching 0.5–0.6 K in the Southern Hemisphere midlatitudes [http://ghrc.nsstc.nasa.gov/uso/readme/msulimb93.html#1].

[19] We used version 5.1 of MSU data produced by University of Alabama, Huntsville. Data were available at http://vortex.nsstc.uah.edu/data/msu for December 1978 to December 2006. We used version 2.1 of MSU data produced by Remote Sensing Systems and sponsored by the NOAA Climate and Global Change Program. Data were available at www.remss.com (with a description at http://www.remss.com/msu/msu_data_description.html) for November 1978 to December 2006. Monthly mean brightness temperature anomalies are provided by UAH and RSS on a 2.5° × 2.5° latitude/longitude grid between ±82.5° together with 20 year monthly means over 1979–1998. The TLS data were used in this study.

2.4. HadAT2 Radiosonde Data

[20] HadAT2 temperatures are provided as monthly anomalies with respect to the monthly 1966–1995 climatology from the year 1958 to present (10° longitude by 5° latitude grid on nine pressure levels). A detailed description of the construction of the HadAT2 data set was given by *Thorne et al.* [2005a] and by *Coleman and Thorne* [2005]. Standard deviations of global monthly temperature anomalies of radiosonde time series are about 0.45 K in the stratosphere [*Seidel et al.*, 2004]. Sampling errors become important especially in the Southern Hemisphere where not even all latitude bands are represented (none at 55–65°S, see *Thorne et al.* [2005a, Figure 7]), and above 100 hPa, where there is a significant reduction of measurements. This

can lead to errors when calculating satellite-equivalent measures.

[21] Static weighting functions on a 5 hPa resolution from UAH have been used for the construction of MSU equivalent measures for TLT, TMT, and TLS. A detailed description of the construction procedure is given at www.hadobs.org. The synthetic MSU temperatures based on HadAT2 were available from the Hadley Centre/Met Office, UK, at www.hadobs.org. For this study we used monthly mean zonal-means at 5° latitude resolution for TLS, which were available for January 1958 to December 2006. No reference climatology is provided, since the monthly mean climatology values were subtracted from the original absolute temperatures prior to the homogenization process. Table 1 summarizes the characteristics of all data sets described and used below in the comparative analysis.

3. Method

3.1. Basic Setup and Study Design

[22] In the present study focusing on lower stratosphere temperature, the TLS products from UAH, RSS, and HadAT2 were used. The analysis was performed for monthly and zonal means for four regions, one global region (more precisely quasi-global, 70°S to 70°N), and three sub-regions: tropics (20°S to 20°N), Northern Hemisphere (NH) extratropics (30°N to 70°N) and Southern Hemisphere (SH) extratropics (30°S to 70°S), respectively. These selected geographic regions are indicated on the example CHAMP temperature climatology in Figure 2. The comparison was made for the years 2001-2006, this time-span being restricted by the availability of CHAMP RO since September 2001.

[23] As a first step the different data sets were brought from their different grids to the same basic setup. MSU/AMSU data from UAH and RSS were first averaged to 2.5° zonal means. Then weighted averages (weighted by the cosine of the latitude) for the global region and the three latitudinal sub-regions were produced.

[24] For the CHAMP data set the average number of occultation events per month in the regions was 3364 globally, 832 for the tropics, 1044 for the NH extratropics, and 951 for the SH extratropics, respectively. For the SAC-C, GRACE, and COSMIC data of the ‘‘anchor point’’ months, the number of events was 3900 (average per month in JJA 2002), 3370, and 4804, respectively. The corresponding average monthly sampling error for the lower stratosphere region was estimated (based on sub-sampling ECMWF analyses at RO event locations only, cf. *Foelsche et al.* [2007]) to 0.08 K globally, 0.05 K for the tropics, 0.16 K for the NH extratropics, and 0.13 K for the SH extratropics, respectively. Consistent with *Pirscher et al.* [2007], this sampling error is found constant from year to year so that the 2001–2006 sampling error drift is bound to <0.02°K. For comparison, there are about 644 HadAT2 radiosonde stations globally (±70°), 72 in the tropical region, 452 in the NH extratropics, but only 35 in the SH extratropics, which went into the HadAT2 MSU data set.

[25] The inter-comparison was performed on basis of the four region data sets, after the calculation of synthetic MSU temperatures also from CHAMP and ECMWF climatologies. This latter procedure is described in Sections 3.2 and 3.3 below.

3.2. Weighting Functions

[26] The vertical weighting function describes the relative contribution that microwave radiation emitted by a layer in the atmosphere makes to the total intensity measured above the atmosphere on board a satellite. Thus the brightness temperature for each MSU/AMSU channel corresponds to an average temperature of the atmosphere averaged over that channel's weighting function. For channels TMT (former T2) and TTS (former T3) also the surface emission is included and different weighting functions over ocean and land are provided. The lower stratospheric channel TLS is monitored by MSU channel 4 at 57.95 GHz while AMSU's channel 9 monitors two bands centered on 57.29 GHz. For the vertical profile of TLS, 90% of the emissions are generated from the layer between 150 hPa (∼12 km) and 20 hPa (∼26 km). In the tropics, about 20% of the emissions contributing to TLS originate below the tropopause, here TLS does not exclusively represent stratospheric temperature anomalies [*Christy et al.*, 2003].

[27] MSU equivalent temperatures can be computed either using a static global weighting function or using a radiative transfer model [e.g., *Saunders et al.*, 1999; *Rosenkranz*, 2003], the latter accounting for land/sea differences in surface emissivity and for variations in atmospheric temperature and moisture as a function of space and time. According to *Santer et al.* [2000] the two methods agree best in the lower stratosphere, since the TLS temperatures are largely insensitive to tropospheric and surface variability. Differences arising from the choice of method for computing an equivalent MSU temperature were found to be <0.01 K/decade globally and <0.02 K/decade on hemispheric scales in terms of trend differences [*Santer et al.*, 1999; 2000].

[28] We tested the validity of our approach of using static global weighting functions based on temperature climatology profiles (described below) by alternatively applying the state-of-the-art RTTOV_8.5 radiative transfer model [*Saunders and Brunel*, 2004; *Saunders et al.*, 2006] to the individual CHAMP RO profile data set for the whole time period under study (September 2001 to December 2006). The RTTOV_8.5 model was available from the MetOffice (Exeter, U.K.) at http://www.metoffice.gov.uk/research/interproj/nwpsaf/rtm/. The difference in absolute TLS brightness temperature between using either the TLS static weighting functions or radiative transfer modeling for the RTTOV channel MSU4 was found on average <0.2 K (individual maxima of monthly values ∼0.3 K) for all four regions used in this study. This is within the MSU4 and AMSU9 bias estimates of *Christy et al.* [2003] (see Section 2.3). Regarding TLS temperature anomalies, the differences were found <0.1 K for all four regions. The differences do not show any appreciable drift over time (i.e., <0.02 K/decade). These results are consistent with those of *Santer et al.* [2000] that using a radiative transfer model or a suitable global weighting function for computing TLS temperatures yields negligible difference for global and large-scale zonal means.

[29] Thus global MSU/AMSU weighting functions for TLS were applied to compute synthetic MSU TLS temperatures from CHAMP RO temperature climatology profiles. Different weighting functions were provided by UAH and

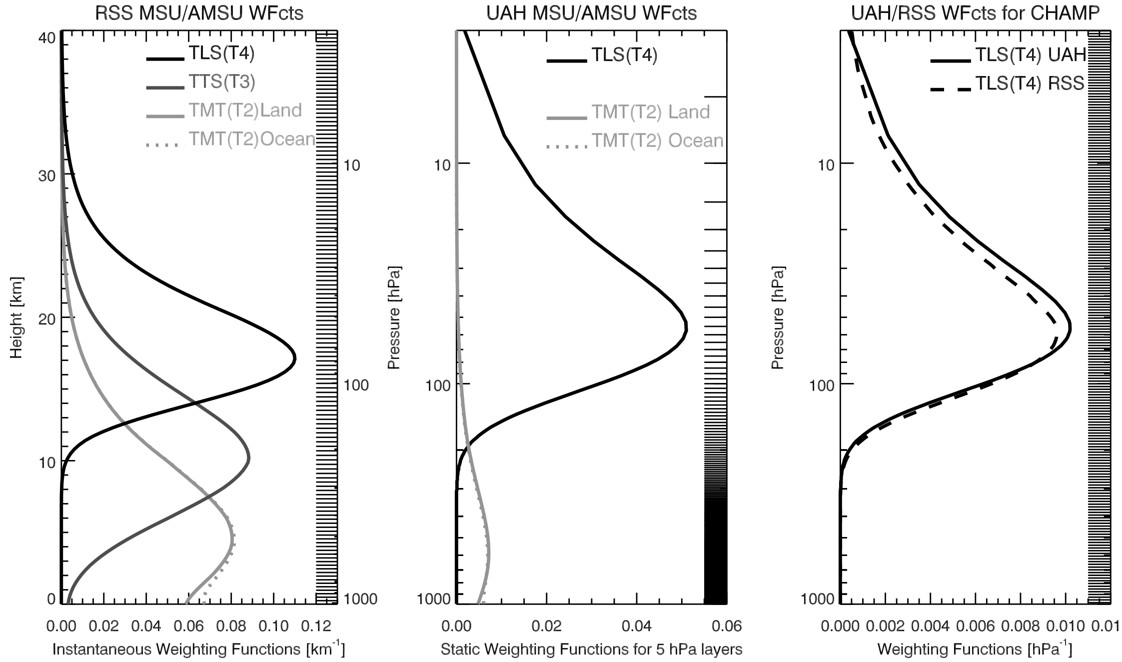

Figure 3. MSU/AMSU weighting functions: Instantaneous weighting functions as function of height provided by RSS (left panel), mean static weighting functions for 5 hPa layers provided by J. Christy, UAH (middle panel), TLS weighting functions from RSS and UAH interpolated to CHAMP pressure levels (right panel). The respective pressure levels vertical gridding is indicated on the right hand side of each panel.

RSS, which were transformed and interpolated to CHAMP pressure levels as illustrated in Figure 3.

[30] RSS provided the weighting functions as instantaneous values at a given height (per km) with 300 m resolution for TLS, TTS, and TLT (Figure 3, left panel). Since we applied the weightings (*w*) to CHAMP temperatures on a pressure grid, we transformed the RSS weighting function to instantaneous values at pressure levels (*p*) (per hPa). We first calculated the total weight over a height layer (*z*), which is the average weighting over that layer multiplied by the height layer's thickness. Then we divided the total weights by the respective pressure thickness, using the corresponding pressure (*p*) levels provided by RSS, which gives the instantaneous values per hPa as follows,

$$w_i^{RSS} = 0.5(w_i + w_{i-1})\frac{(z_i - z_{i-1})}{(p_{i-1} - p_i)}, \qquad i = \text{layer numbers.} \quad (1)$$

These RSS weights were then interpolated to the pressure levels of each monthly mean CHAMP RO temperature climatology profile (one in each 10° latitude band) given at a similar height/pressure resolution (see next subsection). Note that the total weights always sum up to one, i.e., both instantaneous weights per km multiplied by the height layer thickness and instantaneous weights per hPa multiplied by the pressure layer thickness.

[31] John Christy, UAH (personal communications, 2005), kindly provided static mean weighting functions, which are a simple set of geographically and seasonally invariant weights [*Spencer and Christy*, 1992]. The static weighting functions are total weights over 5 hPa layers given for 200 pressure levels (2.5 hPa to 997.5 hPa central pressure levels) provided for channels TLS and TMT (see Figure 3, middle panel). These static weighting functions are considered excellent for anomaly time series, but not as accurate for absolute temperature values (J. Christy, UAH, personal communications, 2005). We calculated the weightings per hPa layer (division by 5 hPa) and then interpolated them to CHAMP pressure levels. Figure 3 presents the original RSS weighting functions as instantaneous weights per km (left panel), the original UAH static weighting functions (middle panel), and the transformed RSS and UAH weighting functions per hPa on typical CHAMP pressure levels (right panel), with the respective pressure levels vertical gridding indicated in each panel. For CHAMP (and ECMWF) this gridding density closely corresponds to the ~200 m altitude grid of these data sets.

3.3. Calculation of Synthetic MSU Temperatures

[32] Synthetic absolute MSU temperatures T_{MSU} from GPS RO (CHAMP, SAC-C, GRACE, and COSMIC) as well as ECMWF temperature climatologies were then computed for the lower stratosphere (TLS) channel using the prepared UAH and RSS weighting functions, respectively. The weighting functions (*w*), interpolated to CHAMP pressure levels (the pressure profiles somewhat vary from month to month on a fixed altitude grid), were multiplied with the respective pressure layer thickness (Δp) and the zonal-mean (10° latitude bands) monthly mean temperature (*T*) at the respective pressure level, summed up vertically and normalized by the sum of the weights as formulated in equation (2),

$$T_{MSU} = \frac{\sum_{i=1}^{N} T_i w_i \Delta p_i}{\sum_{i=1}^{N} w_i \Delta p_i}, \qquad i = \text{layer numbers.} \qquad (2)$$

The MSU equivalent temperatures from GPS RO and ECMWF were then averaged (weighted by the cosine of the latitude) into the four regions, i.e., the global region and the three sub-regions, tropics, NH extratropics, and SH extratropics, respectively.

[33] After investigation of the mean difference between CHAMP MSU temperatures using the UAH weighting function and those using the RSS weighting function we averaged over the two and prepared mean synthetic MSU temperatures for CHAMP and ECMWF, respectively. SAC-C, GRACE, and COSMIC months were treated the same way as CHAMP months. The mean absolute CHAMP TLS temperature differences between using the TLS temperatures of the two weighting functions individually and using the one averaged from the two (as we chose) are 0.1 K (±0.02°K) globally, 0.16 K (±0.03 K) in the tropics, 0.02 K (±0.05 K) in the NH extratropics, and 0.04 K (±0.08 K) in the SH extratropics, respectively. Regarding the time-dependent behavior, the mean differences are essentially constant in the tropics and globally (i.e., small variations about the mean, as the numbers above show), while in the extratropics the difference is cyclic (i.e., variations larger than the mean), following an annual cycle. In terms of TLS anomalies, the mean differences are <0.01 K globally and <0.02 K in the tropics and extratropics, respectively.

[34] Since we use RO dry temperature profiles throughout this study we also investigated the effect on the MSU TLS temperature of either integrating over dry temperature or physical temperature profiles. On the basis of checks with ECMWF analysis data, using both dry and physical temperatures for the full time period 2001–2006, we found a negligible difference of <0.02 K in the tropics and of <0.01 K globally and in the extratropics, respectively.

[35] In addition to absolute temperatures, we also calculated anomalies of the synthetic MSU temperatures (see discussion in section 4 below). As reference data set we constructed for this purpose the four year monthly means averaged over the years 2002–2005 and subtracted these from the absolute synthetic MSU temperatures for CHAMP and ECMWF, respectively. The CHAMP averages were used as basis for the computation of the anomaly values of the SAC-C, GRACE, and COSMIC months as well.

4. Results and Discussion

[36] Absolute TLS temperatures are provided by the GPS RO and ECMWF data sets, while MSU/AMSU records are provided as TLS temperature anomalies together with reference climatologies. RSS described their TLS temperature anomalies as the monthly brightness temperature minus the long-term average values for that month, averaged from 1979 to 1998. UAH recommends the anomaly time series to be preferably used, but also enables to compute absolute temperatures in providing the monthly long-term 1979–1998 average brightness temperatures based on the NOAA-6 MSU brightness temperature reference as a common base (J. Christy, personal communications, 2005; cf. section 2.3). No reference climatology is provided for HadAT2 (see section 2.4) and it is recommended to perform analyses in anomaly space (H. Coleman, personal communications, 2005).

[37] In order to meet the concerns regarding the individual data sets and to account for their characteristics, the comparison of the different TLS data sets was performed primarily in terms of temperature anomalies and secondarily in terms of absolute temperature. Exception was HadAT2, which was compared in anomaly space only.

4.1. Comparison of Reference Data Sets

[38] Regarding the comparison of anomalies, the main task was to relate all data sets to the same reference period. Restricted by the availability of (full-year) CHAMP data and the major resolution change in ECMWF data in 2006, we refer the temperature anomalies to the four year period 2002–2005. Absolute RSS and UAH temperatures were calculated by adding their respective 1979–1998 averaged monthly means to their temperature anomalies. New reference monthly means over 2002–2005 were calculated and subtracted from the absolute data, giving anomalies, which were then re-normalized (by subtraction of the respective mean of each data series). With this procedure we ensured that each data set stayed in its own data space and finally refers to the 2002–2005 period. For HadAT2-MSU temperatures, the 1979–1998 monthly means from UAH as well as those from RSS were used as reference data to build absolute time series from which the respective new reference monthly means over 2002–2005 were computed and subtracted. We averaged over the two time series to get mean HadAT2 anomalies. The differences between the mean anomaly time series and the respective individual UAH- and RSS-based time series are small, with a mean difference of <0.05 K globally and in the SH extratropics, and of 0.08 K in the tropics and NH extratropics, respectively. We corrected by this re-normalization the (much larger) differences that would otherwise have been retained in HadAT2 if it were the only anomaly still referred to the 1979–1998 mean annual cycle.

[39] Figure 4 presents a comparison of the 2002–2005 averaged monthly means derived for UAH, RSS, ECMWF, and CHAMP, which are subsequently used as reference for the respective temperature anomalies. Basically, RSS, ECMWF, and CHAMP show a similar progression in the annual cycle, while UAH shows a more pronounced annual cycle with largest differences occurring especially in the summer months June, July, and August throughout all four considered regions. In the global data set the summer-winter TLS temperature difference is of the order of 1 K for CHAMP and ECMWF, about 1.2 K for RSS, and of the order of 2 K for UAH, respectively. The most pronounced summer-winter temperature difference occurs in the SH extratropics being of the order of 10 K for UAH and of 8 K for RSS, ECMWF, and CHAMP. The offset between CHAMP and RSS is of the order of 1 K in all regions except in the tropics, which exhibit a 0.5 K difference. Overall, RSS shows the lowest monthly mean values throughout the year, closely followed by ECMWF with an offset of about 0.5 K in all regions except in the tropics, where there is almost no offset. The change to higher resolution in ECMWF analyses is clearly visible in ECMWF TLS temperatures as a shift toward CHAMP temperatures since February 2006 (see Figure 5a). This can be explained by the better T799L91 height resolution especially at the heights of the maximum TLS weighting function contributions. *Borsche et al.* [2007] also found this improvement of ECMWF toward CHAMP in context of studying the

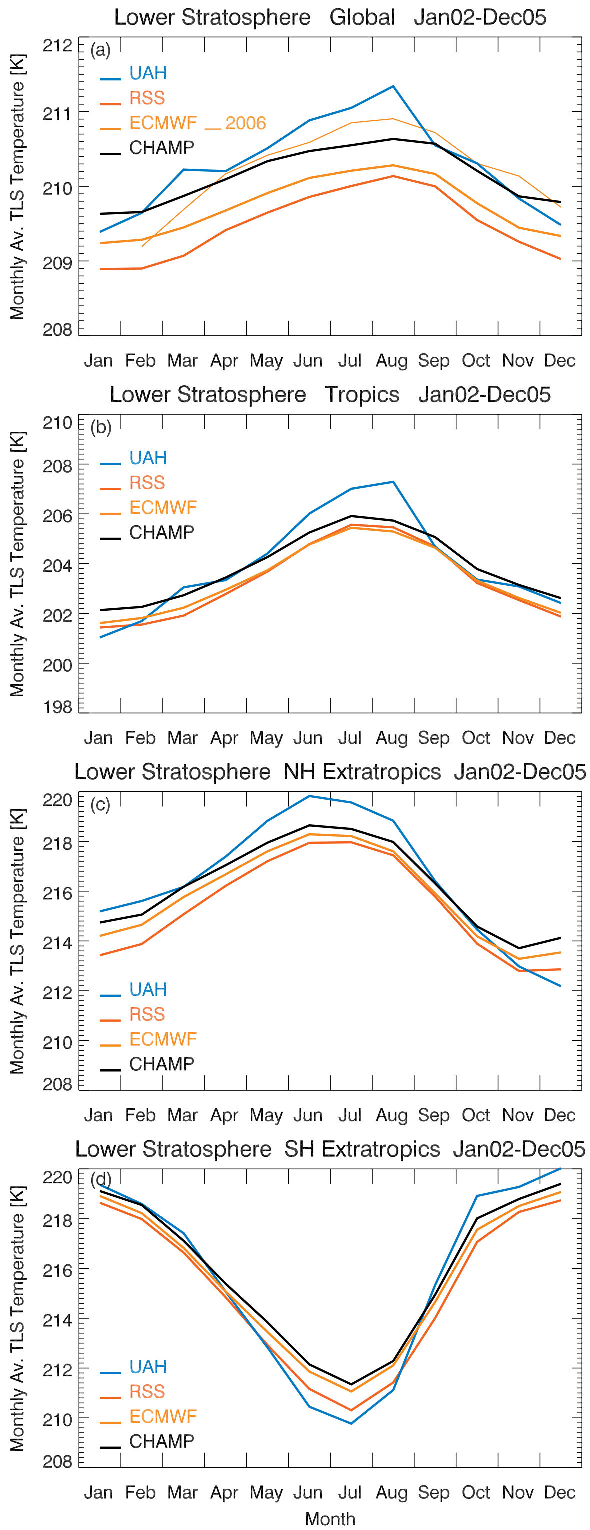

Figure 4. The 2002–2005 monthly means of lower stratospheric (TLS) temperatures for UAH (blue), RSS (red), ECMWF (yellow), and CHAMP RO (black), shown for the global region/70°S–70°N (a), the tropics/20°S–20°N (b), the NH extratropics/30°N–70°N (c), and the SH extratropics/30°S–70°S (d), respectively. ECMWF for the year 2006 (yellow, thin line) is shown for the global region. Note the different temperature range (factor of 3 enlarged) of panel (a).

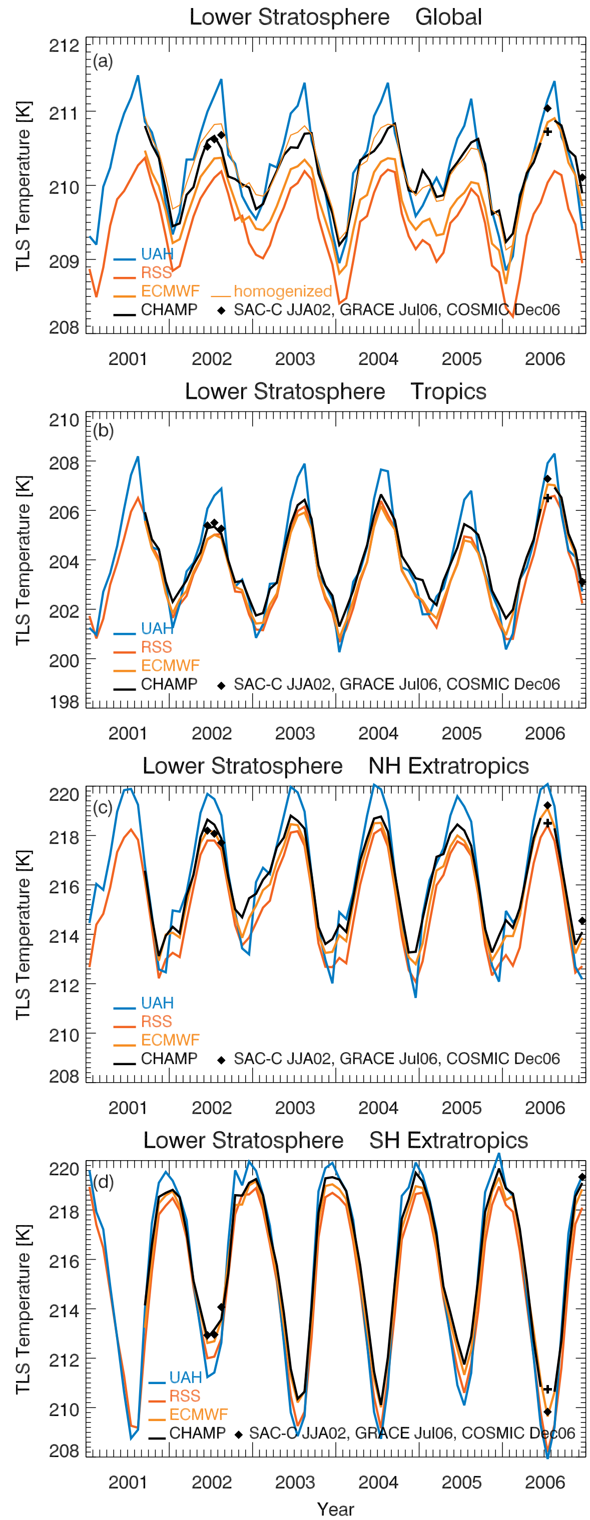

Figure 5. Absolute TLS temperatures for UAH (blue), RSS (red), ECMWF (yellow), and CHAMP RO (black), shown for the global region/70°S–70°N (a), the tropics/20°S–20°N (b), the NH extratropics/30°N–70°N (c), and the SH extratropics/30°S–70°S (d), respectively. SAC-C, GRACE, and COSMIC data are denoted by black diamonds, interpolated CHAMP data for July 2006 by a plus sign. The homogenized ECMWF data series (yellow, thin line) is shown for the global region only. Note the different temperature range (factor of 3 enlarged) of panel (a).

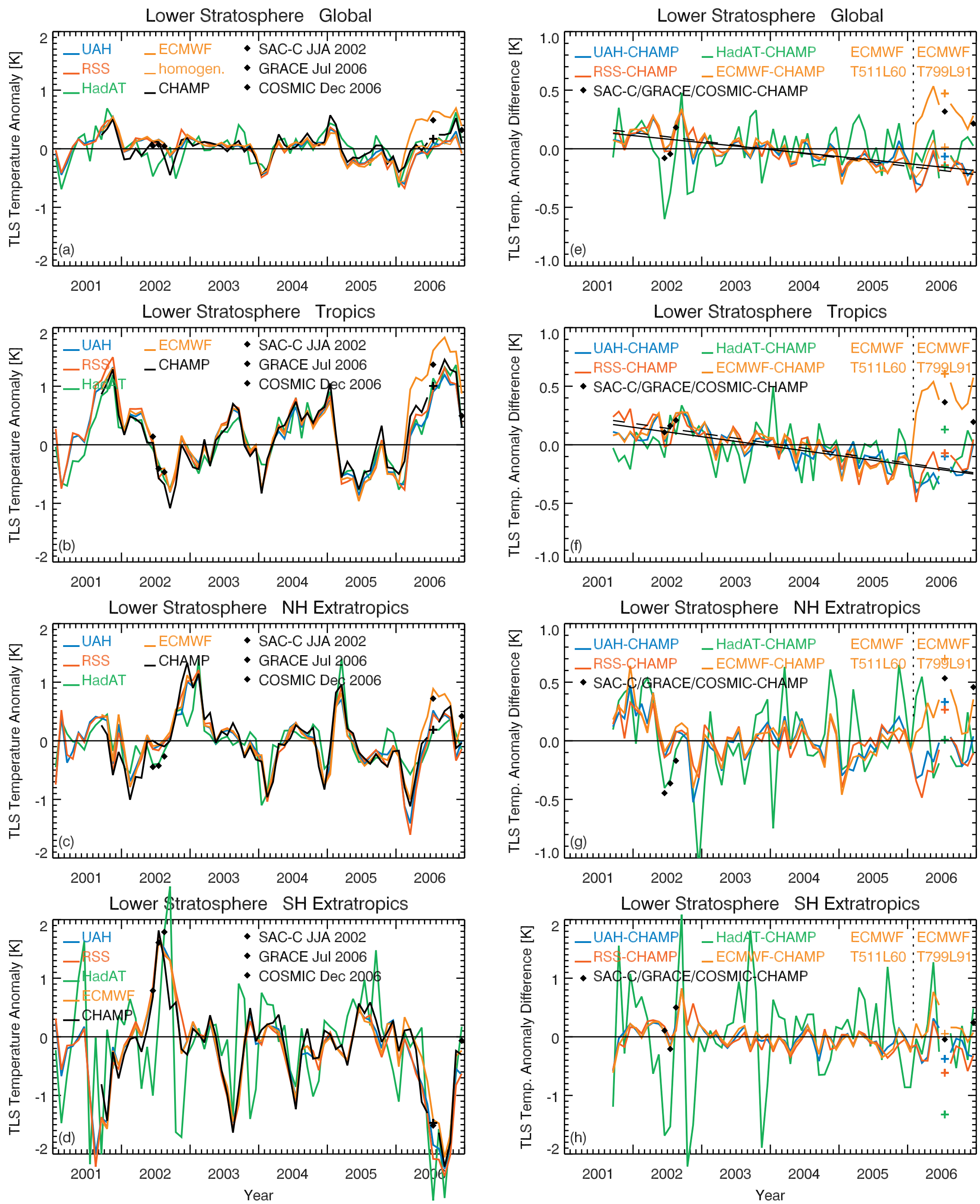

Figure 6. Left Panel: TLS temperature anomalies with respect to 2002–2005 monthly means for the lower stratosphere for UAH (blue), RSS (red), HadAT2 (green), ECMWF (yellow), and CHAMP RO (black) are shown for the global region/70°S–70°N (a), the tropics/20°S–20°N (b), the NH extratropics/30°N–70°N (c), and the SH extratropics/30°S–70°S (d), respectively. SAC-C, GRACE, and COSMIC data are denoted by black diamonds, CHAMP interpolated data for July 2006 are denoted by a plus sign. The homogenized ECMWF data series (yellow, thin line) is shown for the global region only (a). Right Panel: Differences of TLS temperature anomalies for UAH-CHAMP (blue), RSS-CHAMP (red), HadAT2-CHAMP (green), ECMWF-CHAMP (yellow), SAC-C/GRACE/COSMIC-CHAMP (black diamonds) shown for the global data set (e), the tropics (f), the NH extratropics (g), and the SH extratropics (h), respectively. Differences to interpolated CHAMP data in July 2006 are denoted by plus signs with the color of the respective data set. ECMWF homogenized-CHAMP (yellow thin line) is shown for the global region (e). Indicated is the trend for UAH-CHAMP (black) and RSS-CHAMP (black dashed). Note the different temperature range in the right panels relative to the left panels (factor of 2 enlarged), and in the lower right panel (h).

Table 2. Characteristics of TLS Temperature Anomaly Differences (Respective MSU Dataset Minus CHAMP) are Shown[a]

Data Sets	RMS, K	Trend, K/5 yrs	RMSdet, K
GLOBAL			
UAH-CHAMP	0.13	−0.30**	0.08
RSS-CHAMP	0.14	−0.36**	0.08
HadAT2-CHAMP	0.20	−0.02	0.20
TROPICS			
UAH-CHAMP	0.16	−0.40**	0.10
RSS-CHAMP	0.17	−0.42**	0.10
HadAT2-CHAMP	0.18	−0.17	0.17
NH EXTRATROPICS			
UAH-CHAMP	0.19	−0.18	0.18
RSS-CHAMP	0.17	−0.23	0.15
HadAT2-CHAMP	0.33	+0.00	0.33
SH EXTRATROPICS			
UAH-CHAMP	0.22	−0.26	0.20
RSS-CHAMP	0.25	−0.40	0.22
HadAT2-CHAMP	0.84	+0.01	0.84

[a]Derived for the time period September 2001–December 2006: root-mean-square (RMS) deviation of the month-to-month variability of the total datasets, trends, and the corresponding root-mean-square deviation of the month-to-month variability of the de-trended datasets (RMSdet). Trend values which are significant at the >95% confidence level are marked by double-asterisk symbols.

tropical tropopause over 2001–2006. In Figure 4a the global ECMWF TLS temperature is plotted for February 2006 to December 2006, showing a mean offset to the global ECMWF 2002–2005 monthly mean of 0.46 K (with a standard deviation of 0.22 K).

4.2. Comparison of Absolute Temperatures

[40] Absolute CHAMP TLS temperature records were compared to absolute UAH, RSS, and ECMWF TLS temperatures. The SAC-C, GRACE, and COSMIC months are also shown for comparison purpose. The results for the four inspected regions are shown in Figure 5 with the same ordinate axis scaling as Figure 4. For July 2006 we constructed proxy CHAMP data using the average of June and August 2006 (denoted by a plus sign in Figures 5 and 6). The absolute temperatures include the annual cycle (of which the 4-year average was shown in Figure 4). The main differences visible between the temperatures in Figure 5 among the different data sets stem from the seasonal cycle differences. The overall shape of the temperature curves is largely consistent among all data sets, though UAH temperatures show a particularly strong seasonal cycle as has been discussed in section 4.1 above, exhibiting a pronounced summer season (but recall that absolute temperatures is not a recommended data product of UAH).

[41] For UAH relative to CHAMP the global mean TLS temperature difference amounts to 0.11 K (standard deviation of 0.31 K) and for RSS relative to CHAMP it is −0.69 K (standard deviation of 0.16 K). Until 2006 ECMWF TLS temperatures generally agree better with RSS data than with UAH data, especially in the tropics they almost overlap. For 2002–2005, the global mean TLS temperature difference is 0.53 K between UAH and ECMWF, −0.26 K between RSS and ECMWF, and −0.41 K between ECMWF and CHAMP, respectively. Per February 2006 ECMWF was shifted toward CHAMP temperatures as a result of the ECMWF model resolution update. No detectable changes in CHAMP TLS temperatures with respect to ECMWF cycle changes are seen in Figure 5. Regarding top of the atmosphere initialization (as discussed in section 2.1), this indicates the insensitivity of RO data to ECMWF changes. For illustrating the effect of ECMWF improvement, for the global region only, we composed a simple homogenized ECMWF data series by adding the global mean offset of 0.46 K to all ECMWF data before February 2006. These homogenized ECMWF data closely follow CHAMP TLS with a global mean temperature difference of 0.04 K (standard deviation of 0.14 K).

4.3. Comparison of Temperature Anomalies

[42] TLS temperature anomalies with respect to the 2002–2005 monthly means are presented in Figure 6, left column. Synthetic CHAMP TLS temperature anomalies are compared to MSU/AMSU temperature anomalies from UAH and RSS as well as to synthetic ECMWF TLS and HadAT2 TLS temperature anomalies. The anomaly values of the SAC-C, GRACE, and COSMIC months are depicted as well. Comparison with the ECMWF homogenized TLS temperature is performed for the global data set only (Figure 6a). Overall very good agreement between UAH, RSS, ECMWF, and CHAMP is revealed in all analyzed regions. Highest variability of all data sets occurs in the SH extratropics, where especially HadAT2 temperatures show the most variable behavior. The reason for this is that the SH region is a data sparse region, where not even all 5° latitude bands of the basic HatAT2 data set (Table 1) are represented by radiosondes.

[43] For a closer inspection we calculated the differences of the UAH, RSS, HadAT2, and ECMWF temperature anomalies, as well as of the SAC-C, GRACE, and COSMIC anomaly values, with respect to CHAMP RO. These anomaly differences are illustrated in Figure 6, right column, with ECMWF homogenized differences only shown globally (Figure 6e). The global and tropical multi-year trends of UAH and RSS are indicated as trend lines. Detailed values of the multi-year trends and root-mean square (RMS) deviations (of the total and of the de-trended data sets) are presented in Table 2. It can be seen that UAH, RSS, and ECMWF anomaly differences very closely follow each other (see Figures 6e–6h). Still very good agreement of UAH, RSS, and ECMWF is found also with the CHAMP anomalies for intra-annual variability (RMS difference of de-trended data <0.1 K globally, 0.1 K in the tropics, <0.25 K in the extratropics). HadAT2 anomalies exhibit significantly larger RMS differences (about a factor of two; factor of four in the SH extratropics). SAC-C, COSMIC, and GRACE show a difference to CHAMP of 0.1–0.2 K, ~0.2 K, and ~0.3 K (the latter difference to CHAMP-proxy July 2006), respectively, which is consistent with the sampling error of these RO satellites [cf. *Pirscher et al.*, 2007]. The close matching of independent RO data from different satellites in very different orbits indicates the consistency and homogeneity of the RO data set.

[44] Regarding multi-year trend differences, HadAT2 shows no appreciable difference from CHAMP trends. UAH and RSS exhibit a statistically significant (at >95% confidence level) cooling trend difference relative to CHAMP globally (−0.30 K/5 yrs and −0.36 K/5 yrs), with main contributions from the tropics (−0.40 K/5 yrs and

−0.42 K/5 yrs) (cf. Table 2), while in the extratropics the trend differences are not significant.

[45] The contribution of known error sources of RO data and the related synthetic-MSU computation procedure to the 5-year trend differences is about one order of magnitude smaller than the detected trend differences. Recall that our earlier analyses (sections 2.1, 3.1, and 3.2) yielded estimates of uncertainty of <0.02 K for potential initialization bias drifts, of <0.02 K for dry/physical temperature difference, of <0.02 K for mean sampling error drift, and of <0.01 K for weighting function/radiative transfer model uncertainty. Therefore these known sources of error in our RO assessment are insufficient to account for the differences seen in Figures 6e–6f.

5. Summary, Conclusions, and Outlook

[46] A comparison of MSU-type lower stratosphere (TLS) temperatures from CHAMP RO climatologies to recent MSU/AMSU TLS temperature records was performed. The investigated time period spanned September 2001 to December 2006. RO temperature climatologies were produced at the WegCenter/UniGraz based on the complete 2001–2006 CHAMP RO profiles data set and including SAC-C RO data for JJA2002, GRACE for July 2006, and COSMIC for December 2006, respectively. The RO measurements were provided by GFZ Potsdam (CHAMP, GRACE) and UCAR/CDAAC Boulder (SAC-C, COSMIC).

[47] The RO-derived TLS temperatures were compared to recent TLS records from the University of Alabama in Huntsville (UAH) and from Remote Sensing Systems (RSS), respectively, as well as to synthetic TLS temperatures from HadAT2 radiosonde data (provided by the Hadley Centre/MetOffice) and from ECMWF analyses. The reason for focusing on the MSU/AMSU channel TLS (formerly T4), where about 90% of the temperature information stems from pressure levels within 150 hPa and 20 hPa, is the high data quality of RO data in the upper troposphere/lower stratosphere and the fact that the difference between TLS temperatures from RO dry temperature profiles, compared to using physical temperature profiles, is negligible.

[48] Synthetic TLS temperatures from CHAMP RO were calculated by applying global TLS weighting functions to zonal-mean monthly mean RO temperature climatology profiles. RSS provided the weighting functions as instantaneous values at given altitudes while UAH provided static mean weighting functions over 5 hPa layers. Both types of weighting functions were converted to a common pressure level grid and applied to CHAMP temperature climatology profiles. Because of the small differences of the CHAMP TLS temperatures derived with the different weighting functions, the averaged TLS temperature of the two was used for further comparison.

[49] An inter-comparison of the monthly mean data sets was performed for four regions, (almost) global mean (70°S–70°N) and three zonal means, the tropics (20°S–20°N), NH extratropics (30°N–70°N), and SH extratropics (30°S–70°S), respectively. The comparison results were discussed in terms of absolute TLS temperatures and in terms of TLS temperature anomalies. All anomaly data sets were referenced for consistency to the same 4-year time period, 2002–2005.

[50] Inspection of the 2002–2005 monthly means for UAH, RSS, ECMWF, and CHAMP shows basically a similar shape of the annual cycle in all data sets, except UAH exhibits a stronger annual cycle, in particular a (too) pronounced summer season. RSS generally shows the lowest monthly mean values throughout the year, closely followed by ECMWF with a difference of about 0.5 K (relative to RSS), and CHAMP with about 1 K difference.

[51] Regarding absolute TLS temperatures, the overall shape of the temperature records is largely consistent among the UAH, RSS, ECMWF, and CHAMP data sets, the main differences stemming from seasonal cycle differences. UAH absolute temperatures agree best with CHAMP absolute temperatures although UAH shows a particularly strong seasonal cycle. The global multi-year mean offsets relative to CHAMP were found 0.11 K (±0.31 K) for UAH, and −0.69 K (±0.16 K) for RSS, respectively. A shift in ECMWF TLS temperature occurred in February 2006 which is attributable to an improvement in the ECMWF model resolution from T511L60 to T799L91. Until February, ECMWF TLS temperatures generally agree best with RSS data, especially in the tropics they almost overlap. Since February 2006 ECMWF closely follows CHAMP temperatures.

[52] TLS temperature anomalies with respect to the 2002–2005 averaged monthly means exhibit overall a very good agreement between UAH, RSS, ECMWF, and CHAMP in all analyzed regions (RMS of de-trended anomaly differences of the other data sets to CHAMP <0.1 K globally, 0.1 K in the tropics, and <0.25 K in the extratropics). HadAT2 anomalies exhibit significantly larger RMS differences (about a factor of two larger, and more in the SH extratropics).

[53] Regarding 2001–2006 trends, UAH and RSS exhibit a statistically significant cooling trend difference to CHAMP globally (−0.30 to −0.36 K/5yrs), stemming mainly from the tropics (−0.40 to −0.42 K/5yrs), while in the extratropics the cooling trend differences are not significant. The contribution of known error sources regarding the RO data and the related synthetic-MSU computation procedure is about an order of magnitude smaller than the detected trend differences. Resolution of the trend discrepancy thus requires either additional, so far overlooked, sources of error in the RO TLS record or the presence of currently unresolved biases in the MSU records. For a discussion in terms of climatological (cooling) trends, the present record is considered too short.

[54] SAC-C, GRACE, and COSMIC TLS temperatures as "anchor points" for selected months showed a maximum difference to CHAMP of <0.3 K, which is consistent with the space-time sampling error of these RO satellites. This close matching of independent RO data from different satellites, in widely different orbits, indicates the level of consistency and homogeneity of the RO data set.

[55] The results underpin the strong benefit of having multiple independent estimates of the same variable from different satellite instruments for detecting residual yet potentially serious weaknesses in the individual climate records. Continued inter-comparison and scrutiny, and exploiting the traceability of the RO data to the universal

time standard (UTC) [*Leroy et al.*, 2006], then enables us to further reduce observational and structural uncertainty in the climate records in absolute terms.

[56] The next version of the WegCenter/UniGraz RO processing system will include a 1D-Var scheme for the retrieval of (physical) temperature and humidity in the troposphere and deliver CHAMP RO climatologies down into the lower troposphere, enabling reasonable modeling of the middle troposphere (TMT) channel as well. Thus in the future synthetic RO-based TLS and TMT temperature records will be part of the operational provision of Weg-Center/UniGraz RO climatology products.

[57] Furthermore, future RO climatologies will be much advanced in data density and tropospheric data quality by recent satellite missions with RO sensors aboard, such as the Taiwan/U.S. Formosat-3/COSMIC mission (a constellation of six satellites, launched in April 2006) and the European MetOp mission (launched in October 2006). These are expected to soon provide together several thousand RO profiles per day on an operational basis. While this study based on single-satellite RO climatologies from CHAMP clearly demonstrated the value of RO data for use as climate reference data sets and for climate monitoring purposes, the upcoming data will further enhance the utility of RO for improved operational monitoring of climate variability and change in the future.

[58] **Acknowledgments.** The authors acknowledge GFZ (Potsdam, Germany) for the provision of CHAMP and GRACE radio occultation data and ECMWF (Reading, UK) for access to their global operational analyses data. UCAR/CDAAC (USA) is acknowledged for the provision of SAC-C and COSMIC data. UAH (AL, USA), RSS (CA, USA), and Hadley Centre/MetOffice (Exeter, UK) are acknowledged for the provision of MSU records. We thank J. Christy (UAH, AL, USA) for the provision of static weighting functions and his complementary helpful comments. We are grateful to H. Coleman (MetOffice/Hadley Centre, Exeter, UK) for her help regarding the HadAT2 data. The authors thank B. Ho (UCAR, Boulder, USA), M. Schwaerzand B. Pirscher (WegCenter, Graz, Austria) for valuable discussions on the topic. We thank three reviewers for their comments, which helped to improve the paper substantially. The work was supported by the Austrian Aeronautics and Space Agency (FFG-ALR; CHAMPCLIM Project) and the Austrian Science Fund (FWF; START Programme Y103-N03 and Project INDICATE, P18733-N10).

References

Borsche, M., A. Gobiet, A. K. Steiner, U. Foelsche, G. Kirchengast, T. Schmidt, and J. Wickert (2006), Pre-operational retrieval of radio occultation based climatologies, in *Atmosphere and Climate: Studies by Occultation Methods*, edited by U. Foelsche, G. Kirchengast, and A. K. Steiner, pp. 315–323, Springer, Berlin-Heidelberg.

Borsche, M., G. Kirchengast, and U. Foelsche (2007), Tropical tropopause climatology as observed with radio occultation measurements from CHAMP compared to ECMWF and NCEP analyses, *Geophys. Res. Lett.*, *34*, L03702, doi:10.1029/2006GL027918.

Christy, J. R., and R. W. Spencer (2005), Correcting temperature data sets, *Science*, *310*, 972–973.

Christy, J. R., R. W. Spencer, and E. S. Lobl (1998), Analysis of the merging procedure for the MSU daily temperature time series, *J. Clim.*, *11*, 2016–2041.

Christy, J. R., R. W. Spencer, and D. W. Braswell (2000), MSU tropospheric temperatures: Dataset reconstruction and radiosonde comparisons, *J. Atmos. Oceanic Technol.*, *17*, 1153–1170.

Christy, J. R., R. W. Spencer, W. B. Norris, and W. D. Braswell (2003), Error estimates of version 5.0 of MSU-AMSU bulk atmospheric temperatures, *J. Atmos. Oceanic Technol.*, *20*, 613–629.

Coleman, H., and P. W. Thorne (2005), HadAT: An update to 2005 and development of the dataset website, *Internal Rep. for DEFRA, MS-RAND-COO-PROG0407*, pp. 11. (Available at http://www.hadobs.org)

European Centre for Medium-Range Weather Forecasts (ECMWF) (2004), *IFS Documentation CY28rl*, Reading, U. K.

Foelsche, U., G. Kirchengast, and A. K. Steiner (2003), Global climate monitoring based on CHAMP/GPS radio occultation data, in *First CHAMP Mission Results for Gravity, Magnetic and Atmospheric Studies*, edited by C. Reigber et al., pp. 397–407, Springer-Verlag, Berlin Heidelberg.

Foelsche, U., A. Gobiet, A. Löscher, G. Kirchengast, A. K. Steiner, J. Wickert, and T. Schmidt (2005), The CHAMPCLIM project: An overview, in *Earth observation with CHAMP - Results from three years in orbit*, edited by C. Reigber et al., pp. 615–620, Springer, Berlin-Heidelberg- New York.

Foelsche, U., A. Gobiet, A. K. Steiner, M. Borsche, J. Wickert, T. Schmidt, and G. Kirchengast (2006), Global climatologies based on radio occultation data: The CHAMPCLIM project, in *Atmosphere and Climate: Studies by Occultation Methods*, edited by U. Foelsche, G. Kirchengast, and A. K. Steiner, pp. 303–314, Springer, Berlin-Heidelberg.

Foelsche, U., M. Borsche, A. K. Steiner, A. Gobiet, B. Pirscher, G. Kirchengast, J. Wickert, and T. Schmidt (2007), Observing upper troposphere-lower stratosphere climate with radio occultation data from the CHAMP satellite, *Clim. Dyn.*, in press.

Free, M., and D. J. Seidel (2005), Causes of differing temperature trends in radiosonde upper air data sets, *J. Geophys. Res.*, *110*, D07101, doi:10.1029/2004JD005481.

GCOS (2003), The second report on the adequacy of the global observing systems for climate in support of the UNFCCC, *WMO/TD No. 1143*, 74 pp., WMO, Geneva, Switzerland.

Gobiet, A., and G. Kirchengast (2004), Advancements of GNSS radio occultation retrieval in the upper stratosphere for optimal climate monitoring utility, *J. Geophys. Res.*, *109*, D24110, doi:10.1029/2004JD005117.

Gobiet, A., G. Kirchengast, J. Wickert, C. Retscher, D.-Y. Wang, and A. Hauchecorne (2004), Evaluation of stratospheric radio occultation retrieval using data from CHAMP, MIPAS, GOMOS, and ECMWF analysis fields, in *Earth observation with CHAMP - Results from three years in orbit*, edited by C. Reigber et al., pp. 531–536, Springer, Berlin-Heidelberg- New York.

Gobiet, A., U. Foelsche, A. K. Steiner, M. Borsche, G. Kirchengast, and J. Wickert (2005), Climatological validation of stratospheric temperatures in ECMWF operational analyses with CHAMP radio occultation data, *Geophys. Res. Lett.*, *32*, L12806, doi:10.1029/2005GL022617.

Gobiet, A., G. Kirchengast, G. L. Manney, M. Borsche, C. Retscher, and G. Stiller (2007), Retrieval of temperature profiles from CHAMP for climate monitoring: Intercomparison with Envisat MIPAS and GOMOS and different analyses, *Atmos. Chem. Phys.*, *7*, 3519–3536.

Grody, N. C., K. Y. Vinnikov, M. D. Goldberg, J. T. Sullivan, and J. D. Tarpley (2004), Calibration of multisatellite observations for climatic studies: Microwave Sounding Unit (MSU), *J. Geophys. Res.*, *109*, D24104, doi:10.1029/2004JD005079.

Hajj, G. A., E. R. Kursinski, L. J. Romans, W. I. Bertiger, and S. S. Leroy (2002), A technical description of atmospheric sounding by GPS occultation, *J. Atmos. Sol. Terr. Phys.*, *64*, 451–469.

Hajj, G. A., C. O. Ao, P. A. Iijima, D. Kuang, E. R. Kursinski, A. J. Mannucci, T. K. Meehan, L. J. Romans, M. de la Torre Juarez, and T. P. Yunck (2004), CHAMP and SAC-C atmospheric occultation results and intercomparisons, *J. Geophys. Res.*, *109*, D06109, doi:10.1029/2003JD003909.

Healy, S. B., and J.-N. Thépaut (2006), Assimilation experiments with CHAMP GPS radio occultation measurements, *Q. J. R. Meteorol. Soc.*, *132*, 605–623, doi:10.1256/qj.04.182.

Healy, S. B., A. Jupp, and C. Marquardt (2005), Forecast impact experiment with GPS radio occultation measurements, *Geophys. Res. Lett.*, *32*, L03804, doi:10.1029/2004GL020806.

Karl, T. R., S. J. Hassol, C. D. Miller, and W. L. Murray (Eds.) (2006), Temperature trends in the lower atmosphere: Steps for understanding and reconciling differences, *A Report by the Climate Change Science Program and the Subcommittee on Global Change Research*, Washington, D. C.

Kidder, S. Q., and T. H. Vonder Haar (1995), *Satellite meteorology: An introduction*, 466 pp., Academic Press Ltd., London.

Kursinski, E. R., G. A. Hajj, K. R. Hardy, J. T. Schofield, and R. Linfield (1997), Observing the Earth's atmosphere with radio occultation measurements using the Global Positioning System, *J. Geophys. Res.*, *102*(D19), 23,429–23,465.

Lanzante, J. R., S. A. Klein, and D. J. Seidel (2003), Temporal homogenization of monthly radiosonde temperature data, Part I: Methodology, *J. Clim.*, *16*, 224–240.

Leroy, S., J. A. Dykema, and J. G. Anderson (2006), Climate benchmarking using GNSS occultation, in *Atmosphere and Climate: Studies by Occultation Methods*, edited by U. Foelsche, G. Kirchengast, and A. K. Steiner, pp. 287–301, Springer, Berlin-Heidelberg.

Mears, C. A., and F. J. Wentz (2005), The effect of diurnal correction on satellite-derived lower tropospheric temperature, *Science*, *309*, 1548–1551.

Mears, C. A., M. C. Schabel, and F. J. Wentz (2003), A reanalysis of the MSU channel 2 tropospheric temperature record, *J. Clim.*, *16*, 3650–3664.

Pirscher, B., U. Foelsche, B. C. Lackner, and G. Kirchengast (2007), Local time influence in single-satellite radio occultation climatologies from sun-synchronous and non sun-synchronous satellites, *J. Geophys. Res.*, *112*, D11119, doi:10.1029/2006JD007934.

Randel, W. J., and F. Wu (2006), Biases in stratospheric and tropospheric temperature trends derived from historical radiosonde data, *J. Clim.*, *19*, 2094–2103.

Rocken, C., et al. (1997), Analysis and validation of GPS/MET data in the neutral atmosphere, *J. Geophys. Res.*, *102*(D25), 29,849–29,866.

Rocken, C., Y.-H. Kuo, W. S. Schreiner, D. Hunt, S. Sokolovskiy, and C. McCormick (2000), COSMIC system description, *Terr. Atmos. Oceanic Sci.*, *11*(1), 21–52.

Rosenkranz, P. W. (2003), Rapid radiative transfer model for AMSU/HSB channels, *IEEE Trans. Geosci. Remote Sens.*, *41*, 362–368.

Santer, B. C., J. J. Hnilo, T. M. L. Wigley, J. S. Boyle, C. Doutriaux, M. Fiorino, D. E. Parker, and K. E. Taylor (1999), Uncertainties in observationally based estimates of temperature change in the free atmosphere, *J. Geophys. Res.*, *104*, 6305–6333.

Santer, B. C., T. M. L. Wigley, J. S. Boyle, D. J. Gaffen, J. J. Hnilo, D. Nychka, D. E. Parker, and K. E. Taylor (2000), Statistical significance of trends and trend differences in layer-average atmospheric temperature time series, *J. Geophys. Res.*, *105*, 7337–7356.

Santer, B. D., et al. (2005), Amplification of surface temperature trends and variability in the tropical atmosphere, *Science*, *309*, 1551–1556.

Saunders, R., and P. Brunel (2004), RTTOV_8_5 Users guide, NWPSAF-MO-UD-008, EUMETSAT. (available at http://www.metoffice.gov.uk/research/interproj/nwpsaf/rtm/rttov8_ug.pdf)

Saunders, R., M. Matricardi, and P. Brunel (1999), An improved fast radiative transfer model for assimilation of satellite radiance observations, *Q. J. R. Meteorol. Soc.*, *125*(556), 1407–1425.

Saunders, R., et al. (2006), RTTOV-8 – Science and validation report, NWPSAF-MO-TV-007, EUMETSAT. (available at http://www.metoffice.gov.uk/research/interproj/nwpsaf/rtm/rttov8_svr.pdf)

Schmidt, T., J. Wickert, G. Beyerle, and C. Reigber (2004), Tropical tropopause parameters derived from GPS radio occultation measurements with CHAMP, *J. Geophys. Res.*, *109*, D13105, doi:10.1029/2004JD004566.

Schroeder, T., S. Leroy, M. Stendel, and E. Kaas (2003), Validating the microwave sounding unit stratospheric record using GPS occultation, *Geophys. Res. Lett.*, *30*(14), 1734, doi:10.1029/2003GL017588.

Seidel, D. J., et al. (2004), Uncertainty in signals of large-scale climate variations in radiosonde and satellite upper-air temperature datasets, *J. Clim.*, *17*, 2225–2240.

Sherwood, S. C., J. R. Lanzante, and C. L. Meyer (2005), Radiosonde daytime biases and late-20th century warming, *Science*, *309*, 1556–1559.

Spencer, R. W., and J. R. Christy (1992), Precision and radiosonde validation of satellite gridpoint temperature anomalies. Part I: MSU Channel 2, *J. Clim.*, *5*, 847–857.

Steiner, A. K., and G. Kirchengast (2005), Error analysis for GNSS radio occultation data based on ensembles of profiles from end-to-end simulations, *J. Geophys. Res.*, *110*, D15307, doi:10.1029/2004JD005251.

Steiner, A. K., G. Kirchengast, and H. P. Ladreiter (1999), Inversion, error analysis, and validation of GPS/MET occultation data, *Ann. Geophys.*, *17*, 122–138.

Steiner, A. K., G. Kirchengast, U. Foelsche, L. Kornblueh, E. Manzini, and L. Bengtsson (2001), GNSS occultation sounding for climate monitoring, *Phys. Chem. Earth (A)*, *26*, 113–124.

Steiner, A. K., A. Löscher, and G. Kirchengast (2006), Error characteristics of refractivity profiles retrieved from CHAMP radio occultation data, in *Atmosphere and Climate: Studies by Occultation Methods*, edited by U. Foelsche, G. Kirchengast, and A. K. Steiner, pp. 27–36, Springer, Berlin-Heidelberg.

Thorne, P. W., D. E. Parker, S. F. B. Tett, P. D. Jones, M. McCarthy, H. Coleman, and P. Brohan (2005a), Revisiting radiosonde upper air temperatures from 1958 to 2002, *J. Geophys. Res.*, *110*, D18105, doi:10.1029/2004JD005753.

Thorne, P. W., D. E. Parker, J. R. Christy, and C. A. Mears (2005b), Uncertainties in climate trends: Lessons from upper-air temperature records, *Bull. Am. Meteorol. Soc.*, *86*, 1437–1442.

Untch, A., M. Miller, M. Hortal, R. Buizza, and P. Janssen (2006), Towards a global meso-scale model: The high-resolution system T799L91 and T399L62 EPS, *ECMWF Newsl.*, *108*, 6–13.

Vinnikov, K. Y., N. C. Grody, A. Robock, R. J. Stouffer, P. D. Jones, and M. D. Goldberg (2006), Temperature trends at the surface and in the troposphere, *J. Geophys. Res.*, *111*, D03106, doi:10.1029/2005JD006392.

Ware, R., et al. (1996), GPS Sounding of the atmosphere from Low Earth Orbit: Preliminary results, *Bull. Am. Meteorol. Soc.*, *77*, 19–40.

Wickert, J., T. Schmidt, G. Beyerle, R. König, C. Reigber, and N. Jakowski (2004), The radio occultation experiment aboard CHAMP: Operational data analysis and validation of vertical atmospheric profiles, *J. Meteorol. Soc. Jpn.*, *82*, 381–395.

Wickert, J., G. Beyerle, R. König, S. Heise, L. Grunwaldt, G. Michalak, Ch. Reigber, and T. Schmidt (2005), GPS radio occultation with CHAMP and GRACE: A first look at a new and promising satellite configuration for global atmospheric sounding, *Ann. Geophys.*, *23*, 653–658.

Wu, B.-H., V. Chu, P. Chen, and T. King (2005), FORMOSAT-3/COSMIC science mission update, *GPS solutions*, *9*, 111–121, doi:10.1007/s10291-005-0140-z.

Zou, X., H. Liu, R. A. Anthes, H. Shao, J. C. Chang, and Y.-J. Zhu (2004), Impact of CHAMP radio occultation observations on global analysis and forecasts in the absence of AMSU radiance data, *J. Meteorol. Soc. Jpn.*, *82*(1B), 533–549.

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