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Tropical tropopause climatology as observed with radio occultation measurements from CHAMP compared to ECMWF and NCEP analyses

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[1] A temperature climatology from radio occultation measurements of the CHAllenging Minisatellite Payload (CHAMP) satellite, comprising five years of measurements from September 2001 to August 2006, was analyzed in the tropical (15°S–15°N) tropopause region. Validation against operational analyses of the European Centre for Medium-Range Weather Forecasts (ECMWF) showed excellent overall agreement except near the tropical tropopause, where systematic differences generally amount to −1 K to −2 K. Validation against tropopause temperatures from the U.S. National Centers for Environmental Prediction (NCEP) reanalyses showed NCEP deviations of about +2 K to +4 K. The ECMWF deviations can be attributed to the lower vertical resolution and weaker representation of atmospheric wave activity in ECMWF analyses. This evidence is confirmed by improved data from February 2006 onwards, where an enhancement of the ECMWF analyses became effective. Initial inspection of extreme tropical tropopause profiles provided evidence that extremely cold tropopause temperatures can reach −100°C. **Citation:** 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.

1. Introduction

[2] The tropopause region plays an important role in the atmospheric system marking the transition layer between the convectively mixed troposphere and the stably stratified stratosphere. Accurate knowledge of the tropopause temperature and height are of high value. Climatological studies determining trends in tropopause height and temperature used radiosonde and reanalyses data. Radiosonde data are characterized by high vertical resolution which predestines them for determining tropopause parameters. However, this data set is limited by the continent bound distribution. *Seidel et al.* [2001] found a multi-decadal increase in tropopause height of 20 m per decade and an accompanying decrease in temperature of −0.5 K per decade. This trend was intermitted by short and strong decreases of tropopause height due to volcanic eruptions. *Randel et al.* [2000] also found a trend of decrease in tropopause temperature of −0.5 K per decade but could not find it in reanalyses of the National Centers for Environmental Prediction (NCEP) during 1979–1997. *Santer et al.* [2003a] found a decrease of lapse rate tropopause pressure of −2.16 hPa per decade in NCEP data for the time range 1979–2000 and −1.13 hPa per decade in data of the European Centre for Medium-Range Weather Forecasts (ECMWF) for 1979–1993. *Santer et al.* [2003b] and *Sausen and Santer* [2003] investigated the role of climate forcings on tropopause height and temperature variability and found that natural variability alone cannot explain the observed increases in tropopause height and decreases in tropopause temperature which are rather mainly attributed to anthropogenic climate change.

[3] *Randel et al.* [2000], *Seidel et al.* [2001], *Santer et al.* [2003a, 2003b], and others note that the difference in vertical resolution of radiosonde and reanalysis data makes it hard to compare these two data sets and rises the question whether it is feasible to determine such small changes as the above cited tropopause height and temperature trends. However, *Randel et al.* [2000] state that the biases of NCEP reanalyses are approximately constant in time so that seasonal and interannual variability is reasonably well captured. *Santer et al.* [2003a] found that despite relatively coarse vertical resolution two atmosphere-ocean general circulation models in a climate change experiment showed similar decadal-scale increases in tropopause height.

[4] Radio occultation (RO) data [e.g., *Kursinski et al.*, 1997] is ideally suited for observing tropopause parameters due to its high vertical resolution and roughly globally uniform distribution from a climatological point of view. The RO method utilizes the refractive nature of Earth's atmosphere by measuring the phase delay induced on GNSS (Global Navigation Satellite Systems) radio signals which are recorded in low earth orbit. These delays are the basis for deriving atmospheric profiles of refractivity, density, pressure, geopotential height, temperature, and humidity [e.g., *Kursinski et al.*, 1997; *Foelsche et al.*, 2006b] with moderate horizontal (~300 km) and high vertical (~1 km) resolution. The RO technique is especially useful to derive high quality climatologies because of high accuracy <0.5 K [e.g., *Foelsche et al.*, 2006a; also Observing upper troposphere-lower stratosphere climate with radio occultation data from the CHAMP satellite, submitted to *Climate Dynamics*, 2006, hereinafter referred to as submitted manuscript, 2006] and stability (drift of <0.1 K/decade expected).

[5] *Nishida et al.* [2000] demonstrated with data of the first RO mission GPS/Met [*Rocken et al.*, 1997] the feasibility of determining tropical cold point tropopause temperature. They compared their results to radiosonde data which showed deviations of 1 K in the troposphere and 2 K in the

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lower stratosphere. *Randel et al.* [2003] extended that study by determining the temporal and spatial variability of tropical tropopause temperature and height. Examining outgoing longwave radiation they found evidence that the subseasonal variability appeared to be related to wave-like fluctuations such as Kelvin waves. Furthermore, they found clear evidence for the stratospheric quasi-biennial oscillation. *Schmidt et al.* [2004] have investigated the global and tropical tropopause in a thorough study with CHAMP (CHAllenging Minisatellite Payload) RO data. They investigated the time period May 2001 to November 2003 and found close agreement between RO measurements, radiosonde data, and ECMWF operational analyses, the bias amounting to only 0.5 K in the height range of around 8 km to 25 km (300 hPa to 30 hPa). They showed the annual cycle of lapse rate as well as cold point tropopause temperature and height based on RO data. *Schmidt et al.* [2005] extended that study by including SAC-C (Satéllite de Aplicationes Científico) RO data and extending the data range to December 2004 for CHAMP data, this time concentrating on global tropopause temperature characteristics.

[6] Temperature variability found in RO data in the tropics in the height range 10 km to 25 km including the tropopause region, can be associated with equatorial planetary waves and internal gravity waves. *Randel and Wu* [2005] and *Tsai et al.* [2004] have investigated equatorial Kelvin waves with CHAMP and SAC-C RO data and found typical characteristics such as the eastward phase tilt and typical wavelengths and amplitudes. It was found that in general temperature fluctuations due to Kelvin waves amount to about ±2 K in the tropopause region [*Tsai et al.*, 2004] but for single events they can reach up to more than ±10 K [*Randel and Wu*, 2005].

[7] The CHAMP satellite [*Wickert et al.*, 2005] provides the first opportunity to create multi-year RO-based climatologies which was realized within the CHAMPCLIM project [*Foelsche et al.*, 2006a]. Five years of CHAMP RO data from season SON 2001 (September–October–November 2001) to season JJA 2006 (June–July–August 2006) were processed into climatologies. They were used as reference in comparisons to ECMWF operational analyses, which showed excellent agreement with systematic differences generally smaller than 0.5 K in most parts between 4–8 km to 35 km. Salient differences, however, occurred in the southern winter polar vortex and in the tropical tropopause region [*Gobiet et al.*, 2005]. *Gobiet et al.* [2005] focused on explaining the former and pointing to the need of closer study of the tropopause differences. These latter differences will be explained in this paper.

2. Data

[8] In this study we used CHAMP RO phase delay profiles, received from the German GeoForschungsZentrum (GFZ) Potsdam (version 2 dataset), and processed those to dry temperature profiles using the CHAMPCLIM Retrieval version 2.3 (CCRv23) [*Borsche et al.*, 2006]. The dataset comprises five years of CHAMP data (09/2001 to 08/2006) divided into 20 seasons including 246,021 temperature profiles which passed the quality control in total, of which 32,858 were located within the tropical region (15°N to 15°S). In the last season (JJA 2006) due to satellite problems a 40 day lack of measurements from July 3rd to August 8th had occurred.

[9] We calculated the so-called dry temperature for this study, which is directly derived from RO refractivity without need for a priori data [e.g., *Kursinski et al.*, 1997]. In the tropics, the difference between dry and physical temperature is negligible above 14 km (<0.1 K) and can reach up to ~5 K at 8 km height (Foelsche et al., submitted manuscript, 2006).

[10] Tropopause temperature and altitude were calculated using the WMO definition of the lapse rate tropopause (LRTP) [*World Meteorological Organization*, 1957]. The cold point tropopause (CPTP) temperature and according altitude were determined as the coldest temperature above the LRTP. The LRTP and CPTP temperature and altitude were calculated for each CHAMP and co-located ECMWF analysis profile (see below). The latter was computed by spatially interpolating to the CHAMP profile location using the nearest time layer of the six-hourly analyses. The altitudes of all profiles are above mean sea level (MSL), i.e., referenced to the geoid.

[11] As comparison data we used ECMWF operational analyses which are generated four times daily by the Integrated Forecasting System (IFS) assimilating millions of satellite, radiosonde, and ground based observational data [*Untch et al.*, 2006]. Until February 2006, the IFS used 60 vertical levels and spectral representation with triangular truncation at wave number 511 (T511). Starting February 2006, the vertical resolution increased to 91 levels, effectively doubling the number of vertical levels in the region of the tropical tropopause, and the horizontal resolution increased to T799 [*Untch et al.*, 2006]. By increasing the vertical and horizontal resolution it is expected that especially in the tropopause region the representation of atmospheric wave activity would be represented more accurately than before.

[12] The calculation of the systematic ECMWF–CHAMP differences, as shown below, is based on difference error statistics for the tropical region between 15°S and 15°N, using a co-located ECMWF profile for each CHAMP RO profile, taking CHAMP as reference. The sampling error (shown for context), is defined as the difference of the mean of co-located ECMWF profiles to the mean of the complete ECMWF field [*Foelsche et al.*, 2006a]. In addition to ECMWF data, LRTP temperature data were available for comparison from NCEP reanalyses; no full profiles were used from NCEP as the vertical resolution in the tropopause region is too low for a fair comparison.

3. Results and Discussion

[13] The temporal evolution of temperature differences in the tropical tropopause region between ECMWF and CHAMP seasonal mean profiles is shown for SON 2001 to JJA 2006 in Figure 1. The differences are largest around the tropopause at about 16 km to 18 km amounting to −1 K to −2 K throughout the whole time period except for seasons MAM and JJA 2006. The varying features such as the increase of temperature difference towards JJA 2004 and the increased height of maximum difference by DJF

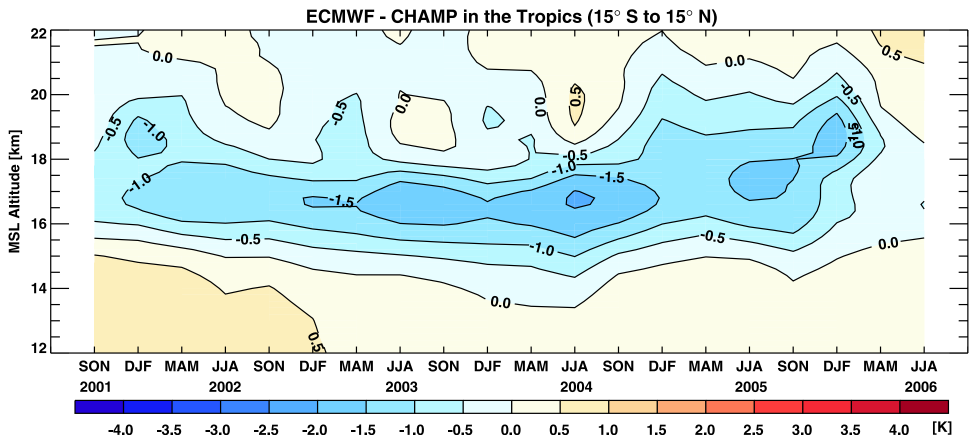

Figure 1. Temporal evolution of seasonal temperature differences between ECMWF analyses and CHAMP RO data in the tropical region SON 2001 to JJA 2006.

2005/06 point to changes in ECMWF tropical tropopause representation over the years.

[14] To closer understand MAM (and JJA) 2006, which were computed with the new higher-resolution ECMWF analysis data [*Untch et al.*, 2006], we arbitrarily chose the season MAM 2002 for comparison, which is representative of any other season previous to MAM 2006.

[15] The change in ECMWF-CHAMP temperature difference between seasons MAM 2002 and MAM 2006 is best visible looking at the single profiles of both CHAMP and ECMWF data clustered as in Figure 2. We first explain MAM 2002 (Figure 2, top). Above about 14 km, individual CHAMP profiles start to increasingly deviate from the mean, representing atmospheric variability and wave activity. At the mean tropopause, the min-max deviation of individual profiles about the mean profile amounts to more than 25 K, in the stratosphere above to about 20 K. Furthermore, the CPTP altitudes of individual CHAMP profiles vary considerably as a consequence of atmospheric variability. This leads to the seasonal mean CHAMP tropopause profile being somewhat smoothed around the seasonal mean CPTP altitude, i.e., the profile peak is dragged towards warmer temperatures. Individual ECMWF profiles, on the other hand, show rather small deviations from the mean, of 10 K or less, and also rather less variation in CPTP altitude. That is why the seasonal mean ECMWF tropopause profile is in effect sharper and the seasonal mean tropopause temperature colder than for CHAMP.

[16] Additionally, two profiles with extremely cold tropopause temperatures are shown in this panel, the coldest of the season (min) recorded April 12, 2002, reaching 175 K, and the coldest of the whole dataset (MIN), respectively, recorded February 10, 2003, reaching 173 K (−100°C).

[17] For MAM 2006, shown in Figure 2 (bottom), the mean profiles of both data sets deviate significantly less than at any other season before. This is evidently achieved by allowing for enhanced variability in the ECMWF analyses due to increased vertical and horizontal resolution. As a result, atmospheric variability is much more realistically resembled in ECMWF since February 2006, reducing the difference to CHAMP measurements. Thus, the previous inability of the analyses to adequately reproduce the atmospheric variability, together with the fact that a mean of highly deviating profiles is calculated, explains the difference between the mean CHAMP and ECMWF profiles. An important fact to be aware of is that the cold point of the mean profile is always systematically warmer than the mean of the cold point tropopause temperatures of the individual profiles, since the latter provide a genuine average of all "cold points" while the former emerges from fixed-height averages. The coldest profile of season MAM 2006 (min) reaches 180 K. Given the initial evidence that extremely cold tropical tropopauses reach at least 180 K typically in

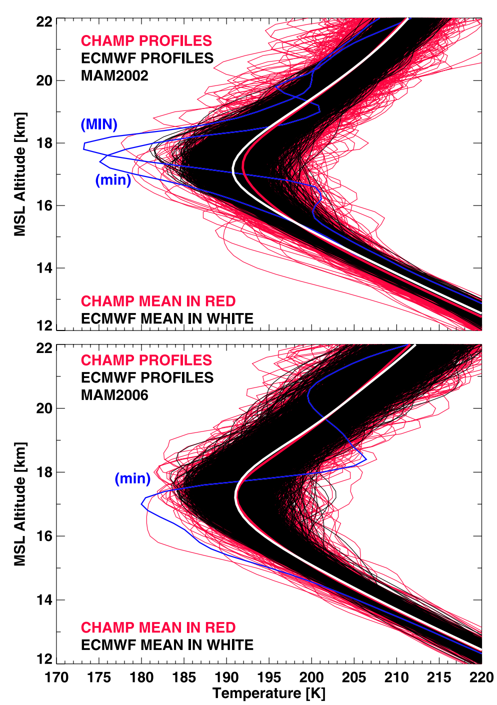

Figure 2. Cluster plot of individual CHAMP and ECMWF profiles for (top) MAM2002 and (bottom) MAM2006. Mean profiles for CHAMP and ECMWF are shown in red and white, respectively. Profiles denoted (min) represent the coldest CHAMP profiles of the season, the profile denoted (MIN) represents the coldest profile in the whole five year CHAMP dataset.

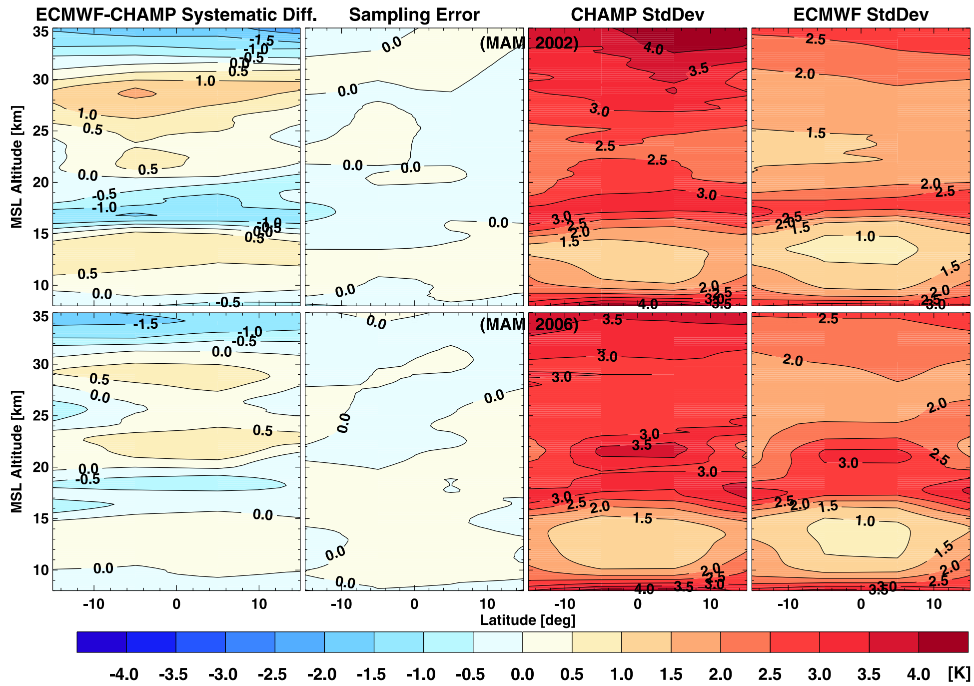

Figure 3. (left to right) Systematic difference between ECMWF analyses and CHAMP data, sampling error of CHAMP data compared to ECMWF model fields, standard deviation of CHAMP profiles, and standard deviation of ECMWF profiles. (top) MAM 2002, (bottom) MAM 2006.

every season, and that one even reached −100°C, a future study will more closely explore the meteorological conditions for tropopause temperatures <180 K.

[18] Further backing the above explanations, Figure 3 shows (from left to right) the systematic difference, sampling error, and CHAMP and ECMWF standard deviations for MAM 2002 (top) and MAM 2006 (bottom). Here, for each panel, four seasonal mean profiles were calculated in 10° latitude bins showing the latitudinal variation. The systematic difference panel confirms the strong reduction of deviations of ECMWF from CHAMP in MAM 2006. The very small sampling error for both seasons (Figure 3, middle left panel) shows that insufficient sampling by the CHAMP satellite does not play a significant role in climatological ECMWF-CHAMP differences discussed here. The depiction of standard deviations of both datasets (Figure 3, middle right and right panels) highlights in addition the ECMWF quality enhancement since MAM 2006. The structure of standard deviation and the absolute amount of variability about the mean are reproduced much more accurately in MAM 2006 than in MAM 2002.

[19] In Figure 4 the temporal evolution of the seasonal mean LRTP temperature (left) and altitude (right) of all profiles is shown over the five years of CHAMP data. Depicted are the mean values and their standard deviations (“error” bars) within each season for both CHAMP and ECMWF. In addition the LRTP temperature of NCEP reanalyses (green line) are included as provided by NCEP.

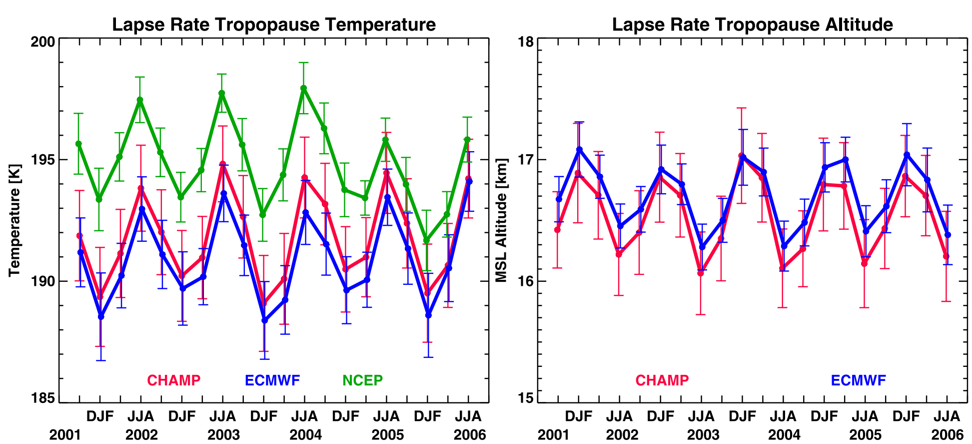

Figure 4. (left) Temporal evolution of seasonal mean LRTP temperature for CHAMP data (red), ECMWF analyses (blue), and NCEP reanalyses (green) with corresponding standard deviations (“error” bars). (right) LRTP altitude for CHAMP data (red) and ECMWF data (blue) with corresponding standard deviations (“error” bars).

These latter LRTP temperatures exhibit a salient offset compared to CHAMP LRTP temperatures of about 4 K until end of 2004, which is consistent with the one found by *Randel et al.* [2000] when comparing to radiosonde data. The offset decreased to about 2 K from 2005 onwards. Up to MAM 2006 the ECMWF LRTP temperatures are constantly colder than CHAMP by 0.9 K on average and the standard deviation is 0.8 K lower than for CHAMP.

[20] In Figure 4 (right panel), the LRTP altitude is shown for ECMWF and CHAMP data (not publicly available for NCEP). The ECMWF LRTP altitude is systematically higher than CHAMP's including in MAM and JJA 2006, except for DJF 2003/04 where the difference diminished. On average, the standard deviation of CHAMP LRTP altitude (~0.35 km) is considerably higher than that of ECMWF (~0.2 km). Evidently, the ECMWF enhancements since MAM 2006 did not improve the systematic LRTP altitude deviation.

[21] The seasonal evolution of the CHAMP LRTP data reveals known patterns [e.g., *Randel et al.*, 2000; *Seidel et al.*, 2001]. In winter, the tropical LRTP temperature is lowest, reaching 189.0 K in DJF 2003/04 and highest in summer, reaching 194.8 K in JJA 2003. The average value of the seasonal tropical LRTP temperature throughout the whole time period amounts to 191.7 K. The seasonal evolution of the LRTP altitude proceeds opposite reaching highest in winter with 17.0 km (DJF 2003/04) and lowest in summer with 16.1 km (JJA 2003). The average of the seasonal LRTP altitude amounts to 16.6 km. For commenting on potential LRTP trends, the time record is considered still to short.

4. Summary and Conclusions

[22] Five years of RO data taken onboard the CHAMP satellite were analyzed, focusing on characteristics near the tropical tropopause, and compared to ECMWF operational analyses and NCEP reanalyses. Systematic deviations in mean temperatures persisted throughout the whole time period except for the last seasons MAM and JJA 2006. It was shown that the observed deviations until MAM 2006 resulted from too low vertical and horizontal resolution in ECMWF analyses preventing them from representing atmospheric wave activity in the tropopause region in the same highly resolved manner as the CHAMP RO tropopause profiles.

[23] With a comprehensive update of the ECMWF system in February 2006, effectively doubling the amount of levels in the UTLS region, the observed deviations between CHAMP and ECMWF were significantly reduced. The mean seasonal LRTP temperature of both datasets converged and the representation of atmospheric wave activity was evidently enhanced though still the RO data represent somewhat more variability. Systematic deviations of LRTP altitudes, generally higher in ECMWF by ~150 m, persist. NCEP reanalysis LRTP temperatures exhibit warm deviations of about 4 K against CHAMP until the end of 2004, decreasing to about 2 K from 2005 onwards. Initial inspection of cold extremes in tropical tropopause temperatures showed that seasonal minima reaching 180 K are generally occurring, the coldest profile of the dataset reached −100°C. The meteorological conditions leading to extremes <180 K deserve further explanation in the future.

[24] With the high precision of RO data, trend detection will be much more reliable in the future when lengths of records grow. Artifacts as have occurred in reanalysis data (e.g., in 1978/79, when satellite data started to be included) or in radiosonde data due to different measuring instruments can be overcome.

[25] RO measurements taken from the CHAMP satellite are currently the only ones available on a multi-year basis. Continuous measurements from the GRACE satellite mission should be available in the near future [*Wickert et al.*, 2005]. Two new and promising missions, the European MetOp (launched in October 2006) and the Taiwan/U.S. FORMOSAT-3/COSMIC mission (a constellation of six satellites, launched in April 2006), are expected to soon provide together several thousand RO measurements per day on an operational basis. These data will further strongly enhance the utility of RO data as accurate climate reference datasets as used in this study, and for improved operational monitoring of climate variability and change in the future.

[26] **Acknowledgments.** We acknowledge GFZ (Potsdam, Germany) for providing CHAMP radio occultation data on a continuous basis, ECMWF (Reading, UK) for access to their global operational analysis data, and NCEP (Camp Springs, Md.) for access to their tropopause reanalysis data. The authors also thank A. Gobiet (WegCenter) for his valuable comments throughout the process of the work. This work was funded by the Austrian Aeronautics and Space Agency (FFG-ALR; CHAMPCLIM project) and the Austrian Science Fund (FWF; START Programme Y103-N03 and CLIMROCC project).

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