Creating a Consistent Radio Occultation Data Base for Climate Studies in the Upper Troposphere and Lower Stratosphere

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Abstract

Radio Occultation (RO) data are obtained by active limb sounding using Global Navigation Satellite System (GNSS) signals to retrieve near-vertical profiles of atmospheric parameters like refractivity, pressure, geopotential height and (dry) temperature with high vertical resolution. These data can be used to build high-quality climate records of the upper troposphere and lower stratosphere (UTLS). The overall quality of RO data can be estimated, for example, from the fact that their assimilation at ECMWF (European Centre for Medium-Range Weather Forecasts) considerably improved operational analyses. RO data from the German research satellite CHAMP (CHAllenging Minisatellite Payload for geoscientific research) now cover more than seven years, allowing for the first multi-year RO climate record. RO data from the six satellites of the Taiwan/US Formosat-3/COSMIC (Formosa Satellite Mission 3/Constellation Observing System for Meteorology, Ionosphere, and Climate, F3C) mission allow testing the consistency of climatologies derived from different satellites. Altitude- and latitude-resolved zonal mean dry temperature climatologies show excellent agreement when comparing such climatologies from different F3C satellites. After subtraction of the estimated respective sampling errors, differences are smaller than 0.1 K almost everywhere in the considered domain between 8 km and 35 km altitude. Mean differences (over the same domain) are smaller than 0.04 K in any case and can be as low as 0.003 K. Differences between F3C and CHAMP are only slightly larger if phase and orbit data from the same processing center are used. RO data are also especially well suited for the determination of tropopause parameters, which have been identified as potentially powerful indicators for climate change. Monthly mean tropical tropopause (lapse rate) temperatures and altitudes derived from four different RO missions show remarkable consistency and indicate that data from different RO missions can indeed be combined without need for inter-calibration.

1. Introduction

Accurate, consistent, long-term data are required for any attempt to detect, understand, and attribute climate variability and change. Our knowledge about temperature changes in the free atmosphere is still limited (GCOS, 2004; Karl et al., 2006), despite notable efforts to build long-term upper air records. Such records have been built using data from radiosondes (e.g., Thorne et al., 2005; Sherwood et al., 2005) and from MSU (Microwave Sounding Unit) as well as AMSU (Advanced MSU) instruments on board of polar orbiting satellites (e.g., Mears and Wentz, 2005; Christy and Spencer, 2005; Vinnikov et al., 2006). After discussions over many years, temperature trend estimates based on these data sets now seem to be consistent with surface warming estimates and results from climate models but discrepancies still remain (Karl et al., 2006). Independent high-quality upper air records are thus needed.

A new data source for climate monitoring, which can overcome some of the problems of established ones, is the Global Navigation Satellite System (GNSS) Radio Occultation (RO) technique. It has the potential to deliver climate benchmark measurements, since RO data can be traced, at least in principle, to the international standard for the second (Leroy et al., 2006a; 2006b). The RO technique has originally been developed in the 1960s for the study of planetary atmospheres and ionospheres (a detailed review can be found in Yunck et al., 2000). Accurate RO measurements of the Earth's atmosphere became feasible with the precise signals of the GPS (Global Positioning System) satellites, as successfully demonstrated with the GPS

Meteorology (GPS/MET) experiment. Data from several measurement campaigns in the period April 1995 to March 1997 proved most of the expected strengths of the technique, like high vertical resolution, high accuracy of retrieved parameters, and insensitivity to clouds (Rocken et al., 1997; Kursinski et al., 1997; Steiner et al., 1999). Detailed descriptions of the GNSS RO method are given by, e.g., Ware et al. (1996), Kursinski et al. (1997), Steiner et al. (2001), and Hajj et al. (2002). Kirchengast (2004) gives an overview on the general utility of occultation methods for probing atmosphere and climate.

In July 2000 the German research satellite CHAMP (CHAllenging Minisatellite Payload for geoscientific research) was launched into low Earth orbit (LEO). Since September 2001 it has (almost) continuously been recording RO profiles (Wickert et al., 2001; 2004). The mission is expected to last until 2009. RO data from CHAMP, now covering more than 7 years, provide the first opportunity to create RO based multi-year climatologies. The number of RO profiles is sufficient to build monthly and seasonal mean, zonal mean climatologies (Foelsche et al., 2007). Due to technical problems, there is a period of about five weeks (from July 3 to August 8) where no data from CHAMP are available. Fortunately, RO data from the satellite GRACE (Gravity Recovery and Climate Experiment), which has essentially the same receiver and therefore similar error characteristics as CHAMP (Wickert et al., 2005), are available for this time period. GRACE data can thus be used to fill the “gap” in the CHAMP record.

Formosat-3/COSMIC (Formosa Satellite Mission 3/Constellation Observing System for Meteorology, Ionosphere, and Climate), a Taiwan/US RO mission consisting of six receiving satellites (Anthes et al., 2000; Rocken et al., 2000; Wu et al., 2005; Schreiner et al., 2007; Anthes et al., 2008) was successfully launched in April 2006. All six Formosat-3/COSMIC (F3C) satellites have originally been in the same parking orbit with ~515 km orbit altitude. The satellites have then been sequentially raised to their final orbit altitudes of ~800 km. At this altitude the precession due to the oblateness of the Earth is smaller than in the parking orbit, leading to a (desired) deployment of the orbit planes to a final separation of 30°. The final orbit constellation (with optimal distribution of RO events in space and local time) has almost been reached by early 2008. Five of the six F3C satellites are in their final orbits, but orbit rise for Flight Model 3 (FM-3) has been stopped in July 2007 due to problems with the solar panels.

Early results on F3C climatologies have been presented by Foelsche et al. (2008a, 2008c). Here we continue the work of Foelsche et al. (2007, 2008a, and 2008c) and address the accuracy of RO climatologies by comparing to ECMWF-based climatologies and via cross-validation of RO climatologies. Section 2 gives the context to previous work. Data and methods are explained in Section 3. The comparison results are presented and discussed in Section 4, followed by concluding remarks.

2. Background and Context

The climate monitoring utility of RO data arises from the fact that atmospheric profiles are not derived from absolute values (phase delays) but from phase change profiles (Doppler shift). Therefore, RO (raw) measurements require, in principle, no external calibration and only short-term measurement stability over the occultation event duration (1 – 2 min), which is provided by very stable oscillators onboard the GNSS satellites. Potential residual GNSS clock errors and clock errors on the receiving satellites can be corrected by relating the measurements to even more stable oscillators on the ground (Hajj et al., 2002). With this “self-calibration”, it should be possible to combine data from different sensors and different occultation missions without need for inter-calibration and overlap, provided that the same data processing scheme is used (von Engeln, 2006) and spatio-temporal sampling (Foelsche et al., 2007; Pirscher et al., 2007) is well understood. To exploit the full potential of RO data for climate applications it is, however, important to identify, understand and (if possible) avoid steps in the retrieval chain that can lead to systematic errors.

The active use of L-band signals allows for measurements during day and night. With wavelengths of 19.0 cm and 24.4 cm (in case of GPS) the radio signals penetrate clouds. RO data have their highest quality in the altitude range between ~8 km and ~35 km and are therefore well suited to build climatologies of the upper troposphere and lower stratosphere (UTLS, which we regard as the altitude range between 5 km and 35 km). In the lower troposphere the error budget is dominated by horizontal variations of the refractivity and consequent deviations from the spherical symmetry assumption (e.g., Healy, 2001a); the data can be affected by processes like signal multi-path and super-refraction (e.g., Sokolovskiy, 2003; Beyerle et al., 2006), and the temperature (and water vapor) retrieval requires background information. Given the exponential decrease of refractivity with height, and thus a comparatively weak atmospheric signal at high altitudes, error sources like residual ionospheric effects become important above ~35 km (e.g., Kursinski et al., 1997). The horizontal resolution is low (200–300 km, Kursinski et al., 1997) compared to (A)MSU or radiosonde data, but in climate applications, where data have to be averaged anyway, the inherent horizontal averaging of RO data is also an advantage.

The potential of RO data for climate monitoring has been demonstrated with the aid of simulation studies (e.g., Yuan et al., 1993; Steiner et al., 2001; Foelsche et al., 2003, 2008b; Leroy et al., 2006a, 2006b; Ringer and Healy, 2008). RO records have been successfully validated against (A)MSU data (Schrøder et al., 2003; Ho et al., 2007, 2008; Steiner et al., 2007, 2008) as well as data from GOMOS (Global Ozone Monitoring for Occultation of Stars) and MIPAS (Michelson Interferometer for Passive Atmospheric Sounding) on Envisat (Gobiet et al., 2007). They have been validated against climatological analyses (Gobiet et al., 2005, 2007; Foelsche et al., 2006b, 2007) and RO data from different satellites (Hajj et al., 2004; Schreiner et al., 2007; Foelsche et al., 2008a; Ho et al., 2008). The utility of RO data for monitoring tropopause parameters has been shown by Schmidt et al. (2005, 2006), Borsche et al. (2007), and Foelsche et al. (2008a). Von Engeln et al. (2005) and Sokolovskiy et al. (2006) have investigated monitoring of the atmospheric boundary layer with RO data.

3. Data and Methods

3.1. Setup of Climatologies

At the Wegener Center we have developed a retrieval scheme which is focused on minimizing potential biases and on using background information (which is needed for high altitude initialization) in a transparent way (Gobiet and Kirchengast, 2004; Borsche et al., 2006; Gobiet et al., 2007; Foelsche et al., 2007, 2008a). The profile retrieval, termed “Occultation Processing System” (current version: OPSv5.4) starts with phase and orbit data from different processing centers. Currently we use data from GFZ (GeoForschungsZentrum) Potsdam (CHAMP, GRACE) and UCAR (University Corporation for Atmospheric Research) Boulder, CO (Formosat-3/COSMIC, GRACE, and CHAMP), respectively. The most important change to previous processing versions (see Foelsche et al., 2008a) is that we use now short-term forecasts (instead of analyses) from the European Centre for Medium-Range Weather Forecasts (ECMWF) for high-altitude initialization.

RO climatologies are obtained by “binning and averaging”, using the approach explained by Foelsche et al. (2007) and (2008a). All RO profiles in a predefined geographic domain (“bin”) are sampled and averaged (weighted by the cosine of the latitude), using a common (mean-sea-level, MSL) altitude grid with regular 200 m spacing of altitude levels. In a first step we build monthly mean climatologies in “fundamental” bins with 5°x60° width in latitude and longitude. The cosine-weighting accounts for area changes between meridians at varying latitudes. For bins with 5° latitudinal width this effect is almost negligible, but it becomes important when larger bins are used. The 6 fundamental bins in each 5° latitude band are combined to 5° zonal means by weighting with the respective number of occultation events. The basic latitudinal resolution (used for the results shown here) is 10°, i.e., each of the 18 latitude bands (pole to pole) contains two 5° bands, and the mean profiles for these two bands are averaged, weighted with the surface area of the respective bins. Compared to direct averaging (simply averaging all profiles in a 10° zonal band), this particular spatial averaging approach reduces the effect of uneven sampling within the latitude bands. Seasonal climatologies are obtained by averaging three monthly climatologies, annual climatologies by averaging twelve monthly climatologies (within a calendar year), respectively.

For inter-comparison we use analysis data from the European Centre for Medium-Range Weather Forecasts (ECMWF). These data have adequate spatial and temporal resolution, contain a vast amount of observations, assimilated in a statistically optimal way, and have widely recognized quality. Operational analyses are generated by dynamically combining a short-range forecast with observational data via four-dimensional variational data assimilation, producing four time layers per day: 00, 06, 12, and 18 UTC (coordinated universal time) (ECMWF, 2004). On February 1, 2006, a major resolution upgrade has been implemented at CMWF, allowing more atmospheric variability to be represented. The vertical resolution has been improved from 60 to 91 levels, the model top raised from 0.1 hPa to 0.01 hPa. The horizontal resolution has been increased from T511 (spectral representation with triangular truncation at wave number 511) to T799 (Untch, 2006). On December 12, 2006, ECMWF started operationally assimilating RO profiles (Healy, 2007).

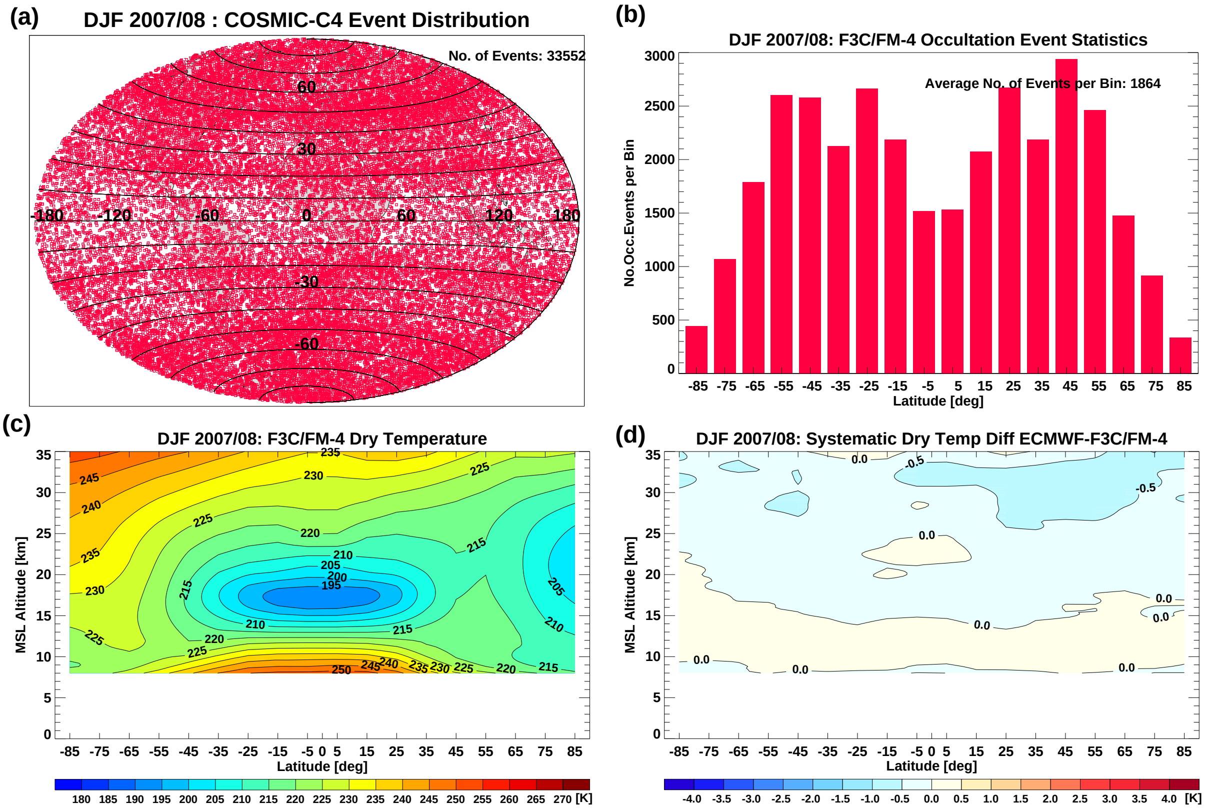

Figure 1: Distribution of ~33 500 F3C FM-4 RO profiles during the winter season (Dec-Jan-Feb) 2007/08 in zonal 10° bands (a), number of RO profiles per 10° band (b), zonal mean dry temperature climatology resulting from these RO profiles (c), systematic difference between F3C profiles and co-located ECMWF profiles (d).

Figure 1 shows a typical example for a single-satellite seasonal climatology. The 18 latitude bands and the geographic distribution of ~33 500 RO events from the F3C satellite FM-4 during the northern winter season December-January-February (DJF) 2007/08 are shown in panel (a). The inclination of the satellite (72°) leads to global coverage, with a markedly lower event density near the equator. This is even more apparent when looking at the number of RO events per 10° latitude band (b). The resulting dry temperature climatology (using UCAR phase and orbit data, version 2007.3200, as input) shows typical features like the cold tropical tropopause and the cold northern polar vortex in winter (c). F3C climatologies are currently cut at 8°km altitude because open-loop data are not yet used. Systematic differences between F3C profiles and co-located ECMWF profiles (d) are small, with differences exceeding 0.5 K confined to altitudes above 25 km. This good agreement is certainly in part due to the fact that F3C data are now assimilated at ECMWF. Nevertheless, it is worth noting that ECMWF temperatures are systematically colder than F3C temperatures between 25 km and 35 km (even though F3C data are assimilated).

3.2. Estimation of the Sampling Error

The quality of RO climatologies is not only determined by the observational error but also by the sampling error due to incomplete sampling of the full spatial and temporal variability. The mean state of the atmosphere is harder to capture when atmospheric variability is high, which is especially true for the high latitudes in winter, as displayed in Figure 2 (panel a). We have to expect that sampling errors are larger here than in the rest of the domain. Figure 2a shows furthermore that the local minimum in the number of RO profiles near the equator does not have to be harmful since temperature variability there is particularly low.

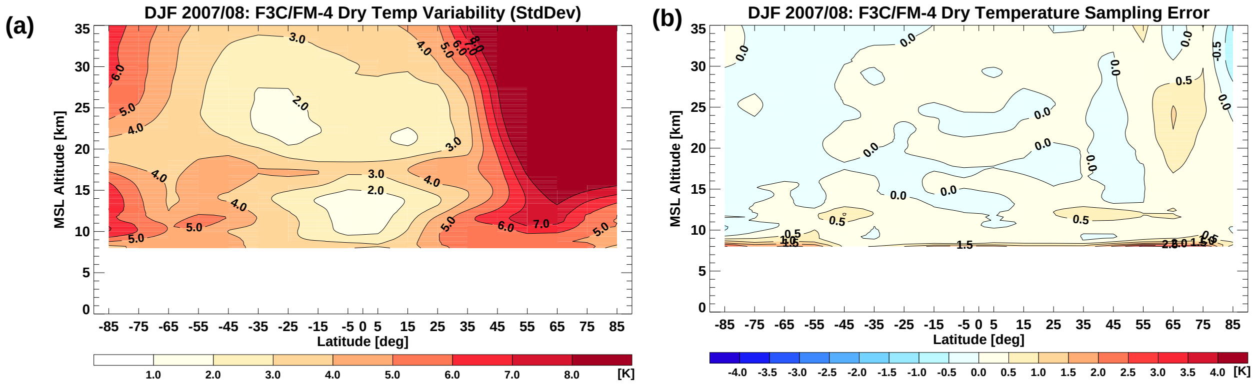

Figure 2: Variability (standard deviation) in F3C FM-4 dry temperature profiles during DJF 2007/08 (a). Estimated sampling error of the F3C FM-4 climatology (b).

We can quantitatively estimate the sampling error when an adequate representation of the "true" state and the spatio-temporal evolution of the atmosphere is available and the times and locations of RO events are known. As a proxy for this atmospheric evolution we use ECMWF analyses, which provide a 3D estimate of the true state of the atmosphere and the its four time layers per day are sufficient to sample the diurnal cycle up to the second harmonic (the semidiurnal cycle). We compute the sampling error as the difference between climatologies derived from vertical ECMWF profiles at the RO times and locations with climatologies derived from the complete 4D ECMWF field (see Foelsche et al., 2007, for further details). In this framework the ECMWF profiles at the RO event locations can be regarded as "perfect measurements" without any observation error. The difference to the climatology derived from the full 4D information is just due to the fact that RO observations do not "see" the entire variability in space and time. Any potential large-scale biases in the ECMWF analyses do not appear in the sampling error estimate because they are removed by computing the differences. The estimated sampling error for the season DJF 2007/08 (Fig. 2b) is, as expected, largest (up to ~1 K) in the region with highest atmospheric variability. In most parts of the domain, however, it is well below 0.5 K, even for a single-satellite climatology. In practice one will use data from all six F3C satellites, which provide a much improved sampling of the atmosphere compared to a single satellite only.

4. Results and Discussion

The absolute accuracy of latitude-resolved RO climatologies is hard to determine to a level < 0.5 K, since all available validation data have their limitations as well (e.g., Gobiet et al., 2007). In this section we want to further test RO data, and raise confidence in their climate utility, by comparing with ECMWF-based climatologies and via cross-validation of RO climatologies from different satellites. Multi-year comparison between ECMWF and RO data from CHAMP (based on UCAR phase and orbit data, version 2007.1200) shows several improvements in agreement over time, in line with improvements in the ECMWF analyses.

4.1. Comparison with ECMWF Analyses

The comparison between RO and ECMWF data is based on difference profiles. For each RO profile we extract a co-located vertical ECMWF profile from the nearest time layer of the analysis at the mean location of the RO profile, using spatial interpolation. We define the mean location as the point, where the straight-line connection between the transmitting and the receiving satellite touches the Earth's ellipsoidal surface during the occultation event (corresponding to the tangent point location of real RO profiles at about 12 to 15 km altitude). We note that ECMWF forecast profiles have been used for the high-altitude initialization of the RO profiles via statistical optimization (Healy 2001b; Gobiet et al. 2007); results above ~30 km are therefore not completely independent from ECMWF data.

In previous work (Gobiet et al., 2005, Foelsche et al., 2007, 2008c) we have analyzed (northern) summer seasons, which showed interesting differences. Here we show systematic differences between annual ECMWF and RO climatologies (taking RO as reference) in order to focus on large-scale and long-term systematic differences (Figure 3). Until the major resolution improvement at ECWMF in February 2006, temperatures in the tropical tropopause region are persistently colder than those from CHAMP, as clearly visible in 2004 (a) and 2005 (b). In 2006 (c) this difference has almost disappeared; it had been caused mainly by weak representation of tropopause height variability in ECMWF fields (Borsche et al., 2007).

The most prominent feature in summer differences from 2002 – 2005 was a wave-like bias structure in the southern winter polar vortex (Gobiet et al. 2005; Foelsche et al., 2007; 2008c). It was caused by deficiencies in the representation of the Austral polar vortex in the ECMWF analyses (see also Healy, 2007). In summer 2006 a similar feature appeared over the Arctic. These effects can also be clearly seen in the annual means, although less pronounced than in seasonal means for June-July-August. The assimilation of RO data at ECMWF (from December 12, 2006, onwards) had an amazingly large impact on mean ECMWF analysis fields and obviously corrected these bias problems (see Fig. 3d).

Above 30 km ECMWF is almost consistently colder than CHAMP by up to ~2 K until 2006. At high latitudes this is partly masked by positive deviations due to the wavelike bias structure. Also these differences became markedly smaller: In 2007 (Fig. 3d), the differences are < 1 K and exceed 0.5 K only in limited regions above 30 km. After the assimilation of RO data, ECMWF analyses are certainly not an independent validation data source anymore. Nevertheless, the continuous convergence between RO and ECMWF with improvements at ECMWF and the assimilation of RO data suggests that the differences known from previous seasons had largely been attributable to the ECMWF rather than the RO data.

Furthermore, F3C results for 2007 from two different satellites (arbitrarily selected FM-1, FM-4; Figure 4) are found closely similar to CHAMP results, even when looking at small-scale structure, e.g., over Antarctica between 10 km and 15 km altitude. This provides a first glimpse on the consistency of RO climatologies from different satellites.

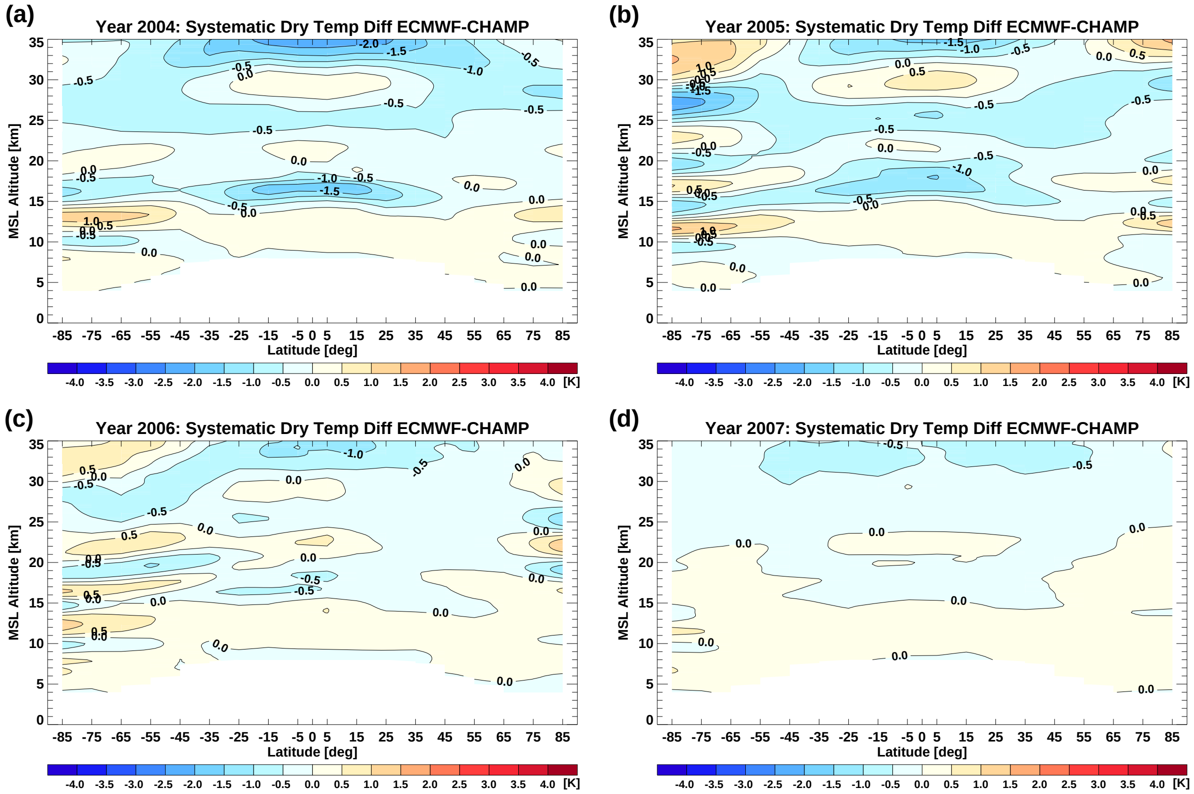

Figure 3: Systematic differences between annual RO dry temperature climatologies from CHAMP and ECMWF analyses for 2004 (a), 2005 (b), 2006 (c), and 2007 (a).

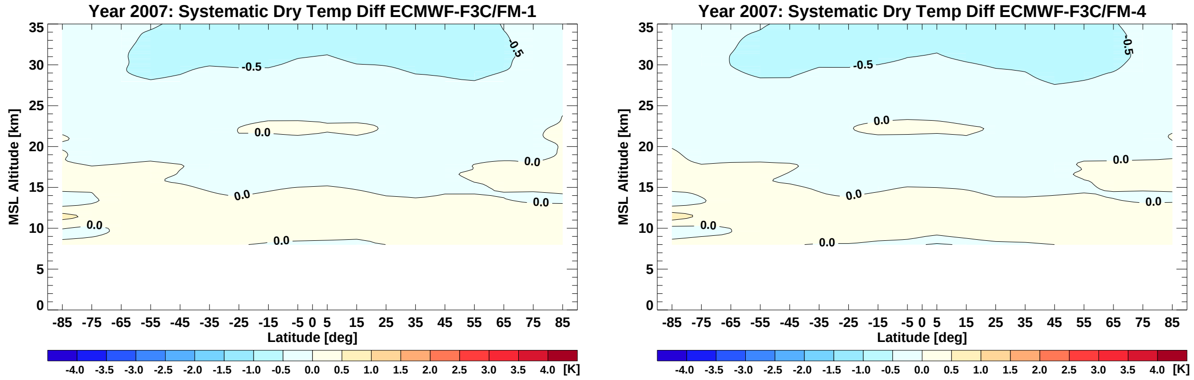

Figure 4: Systematic differences between 2007 annual F3C RO dry temperature climatologies and ECMWF analyses for FM-1 (left) and FM-4 (right).

4.2. Consistency of Climatologies from Different Satellites

Previous studies have addressed the consistency of data from different RO satellites by selecting closely co-located RO profiles (Hajj et al., 2004; Schreiner et al., 2007; Ho et al., 2008). Data from CHAMP and SAC-C (Satélite de Aplicaciones Científicas-C), e.g., showed a remarkable consistency of 0.1 K in the mean between 5 km and 15 km for profiles in close temporal and spatial vicinity (Hajj et al. 2004).

In Foelsche et al. (2008a) we adopted a different approach and looked at systematic differences between zonal mean climatologies from different satellites for seasonal climatologies (focus September-October-November 2006). This is a very rigorous consistency test since these differences contain the sampling errors of both climatologies. Nevertheless, the results were very encouraging with larger differences confined to the polar bins, where the sampling was still sparse in the early phase of the F3C mission (with comparatively low orbit altitudes). In a next step we looked at "double-differences", where we subtracted the estimated sampling error field from each climatology. We found that seasonal temperature climatologies derived from different F3C satellites agree to within < 0.1 K almost everywhere in the considered domain between 8 km and 35 km altitude.

Here we test if these results still hold for the year 2007 (with F3C satellites in significantly more separated orbits, so that they never simultaneously sample the same region of the atmosphere). Figure 5 shows the systematic differences between annual mean climatologies for the year 2007 based on data from FM-1 and FM-4. Even if we consider "pure" differences (left panel) it is remarkable that deviations in low and mid latitudes (up to ~50° north and south) are smaller than 0.1 K almost everywhere. Larger deviations appear at higher latitudes, where the atmospheric variability is particularly high (cf. Fig. 2a) and where the RO data coverage starts to decrease (cf. Fig. 1b).

If we subtract the estimated sampling errors from each climatology (Fig. 5, right panel) we see immediately that the majority of the differences in the left panel is not caused by systematic errors in the measurements but by different sampling of the atmosphere (note the 0.1 K contour lines). These very small differences are even more remarkable when we consider that these double differences contain also the errors in the estimation of the sampling errors for both climatologies (which is on the other hand an indication that the estimation of the sampling error must be fairly accurate).

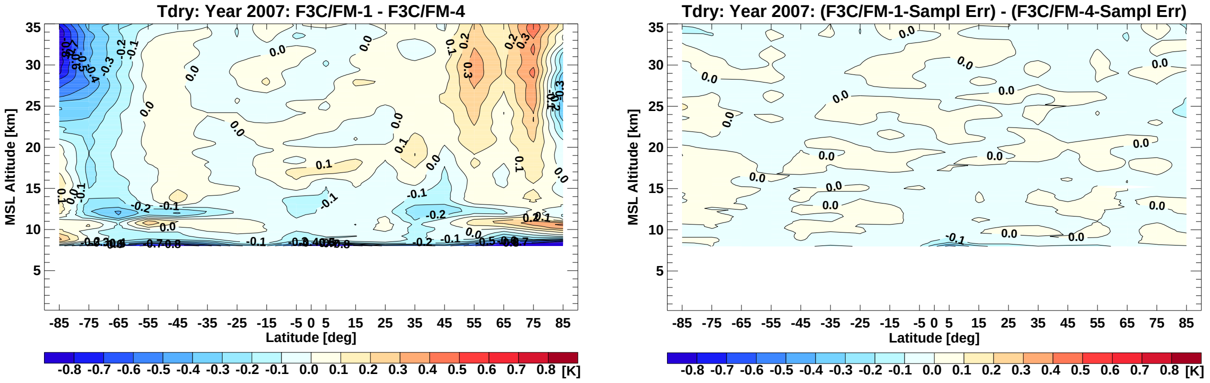

Figure 5: Systematic differences between 2007 annual mean F3C RO dry temperature climatologies from FM-1 and FM-4 (left). The same with the respective estimated sampling errors subtracted (right).

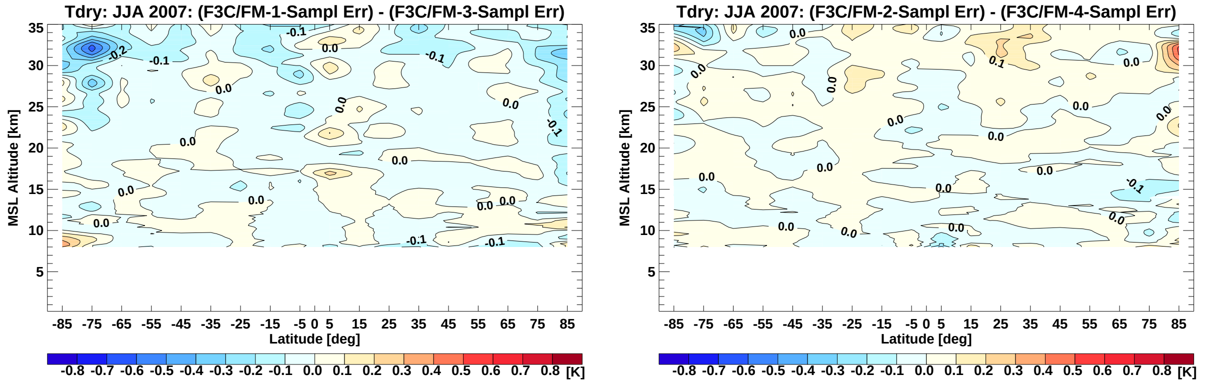

Figure 6: Systematic differences between JJA 2007 zonal mean, seasonal mean dry temperature climatologies from F3C with the estimated sampling errors subtracted: FM-1 minus FM-3 (left) and FM-2 minus FM-4 (right).

Differences between seasonal mean climatologies from different F3C satellite are almost equally small. Figure 6 (left panel) shows the "worst case" we have found so far, FM-1 minus FM-3 for JJA 2007. Even in this case the mean difference over the entire domain between 8 km and 35 km is only –0.04 K. The right panel of Fig. 6 shows a more typical example with a mean difference of +0.008 K. We note that this consistency is not a proof of absolute accuracy, since there is a possibility of common systematic errors. Nevertheless, we regard the results as very encouraging.

Differences between F3C and CHAMP have a mean value of +0.06 K over the entire domain, as long as we use phases and orbit data from UCAR for both climatologies. Largest (positive) differences appear at altitudes above ~28 km. If we use phase and orbit data from GFZ for CHAMP climatologies, but phase and orbit data from UCAR for F3C climatologies, we observe somewhat larger differences (Foelsche et al., 2008c). These results highlight the importance of consistent data processing when attempting to build climate records from RO data.

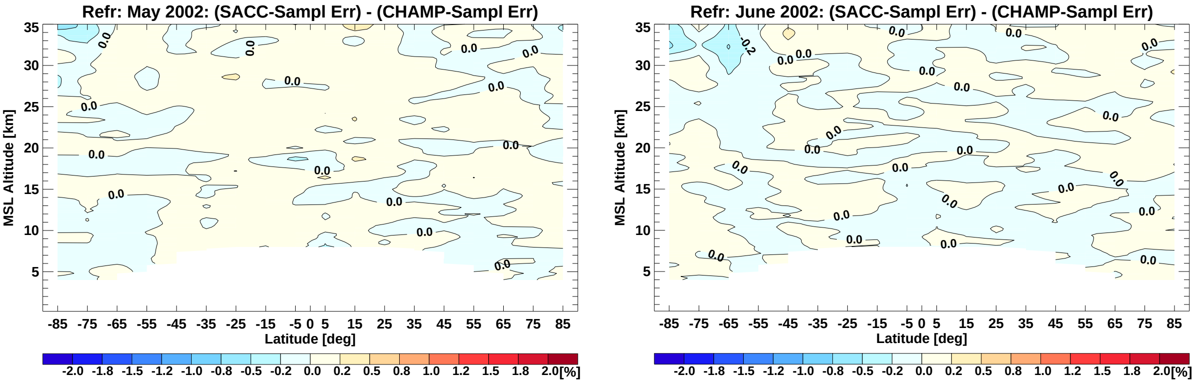

Figure 7: Systematic differences between monthly mean refractivity climatologies from SAC-C and CHAMP with the estimated sampling errors subtracted: May 2002 (left) and June 2002 (right).

Even results for monthly mean climatologies are encouraging: Figure 7 shows relative systematic differences between refractivity climatologies from SAC-C and CHAMP for May 2002 (left) and June 2002 (right). Both data sets are bases on phase and orbit data from UCAR, the estimated sampling errors are again subtracted. The mean values over the entire domain are +0.026 % (May) and –0.002 % (June), respectively.

4.3. Consistency of Tropopause Parameters

RO data with their high vertical resolution are well suited for the determination of tropopause parameters (Schmidt et al., 2005, 2006; Borsche et al., 2007; Foelsche et al., 2008a). We calculate tropopause temperature and altitude using the WMO definition of the lapse rate tropopause (LRTP) (World Meteorological Organization, 1957). The LRTP temperatures and altitudes are calculated for each RO profile and each co-located ECMWF analysis profile. Publicly available NCEP (U.S. National Centers for Environmental Prediction) reanalysis profiles have a too coarse vertical resolution for a fair comparison, but LRTP temperatures are provided by NCEP as a separate product which is thus shown as well.

Here we show the temporal evolution of LRTP parameters in the Tropics (15°S – 15°N) on a monthly-mean basis until early 2008 (Figure 8). Systematic deviations between CHAMP (black), NCEP (green), and ECMWF (yellow) LRTP temperatures are clearly visible in Fig. 8 (left panel). NCEP reanalysis LRTP temperatures exhibited warm deviations of about 3 K compared to CHAMP until the end of 2004, decreasing to about 1 K from 2005 onwards. ECMWF LRTP temperatures are systematically colder than CHAMP by ~1–1.5 K in the early part of the record but converge to CHAMP values after February 2006. "Error bars" for every third month represent the dispersion about the mean of the LRTP temperatures (and altitudes) of individual profiles (one standard deviation). RO data from SAC-C and GRACE have been available for parts of the time (blue).

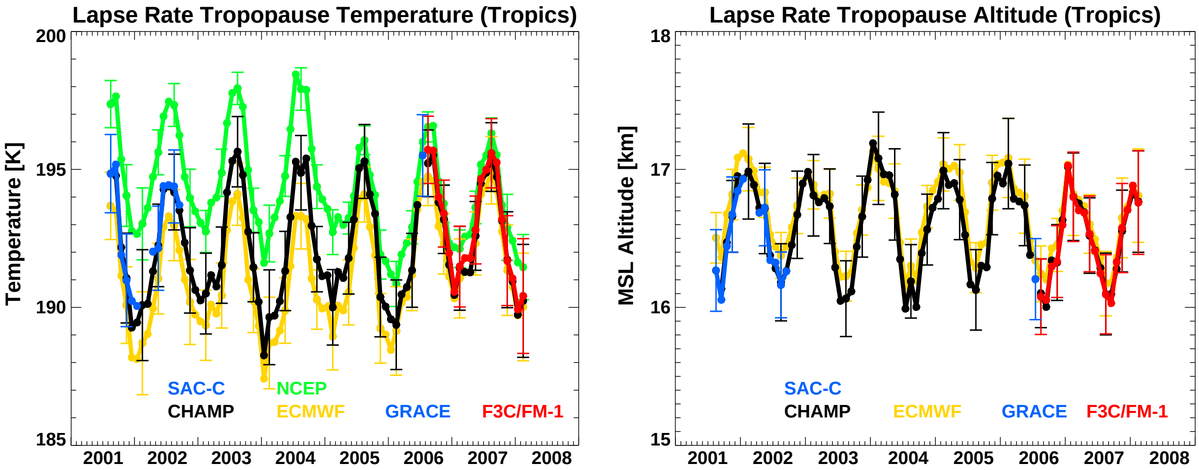

Figure 8: Temporal evolution of monthly mean tropical LRTP temperature (left) and altitude (right) for CHAMP RO data (black), ECMWF analyses (yellow), NCEP reanalyses (green), F3C data from FM-1 and FM-4 (red), and RO data from SAC-C and GRACE (blue).

Figure 9 shows the evolution of the systematic differences in LRTP temperature (left) and altitude (right) with respect to CHAMP. The left panel highlights the good agreement between LRTP temperature estimates from different RO missions. LRTP altitude estimates, which are not available for NCEP data (right), show a very good overall agreement between all RO systems considered, generally within about 50 m. ECMWF data show a positive offset of around 100 m (with fluctuations of ~50–100 m about this value) before 2007. Since beginning of 2007 this appears to have been systematically reduced to < 100 m, however, presumably due to start of RO data assimilation at ECMWF in December 2006 (cf. section 3.1).

Overall, the consistency of the multi-satellite RO records is encouraging also for these tropopause parameters, suggesting high utility for climate applications.

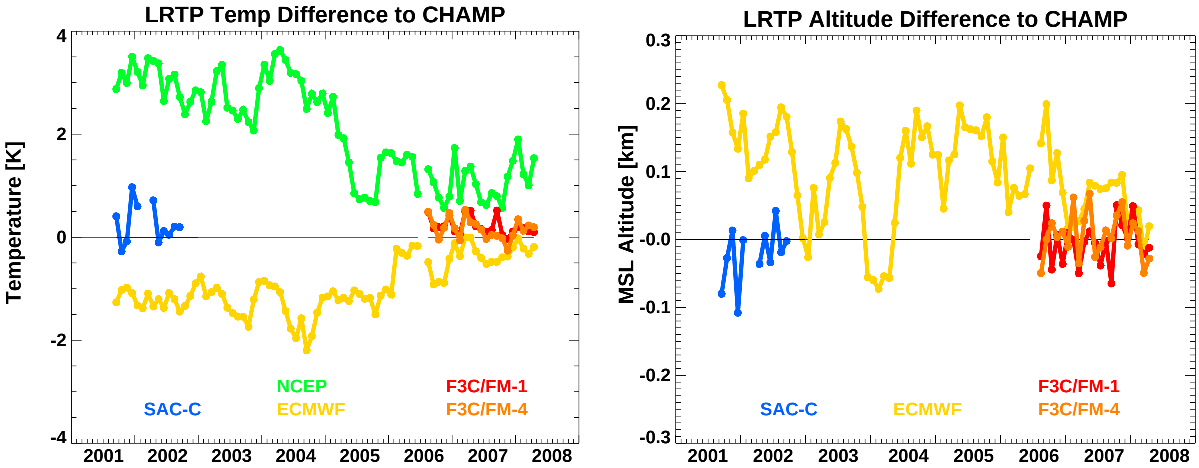

Figure 9: Temporal evolution of systematic differences of monthly mean tropical LRTP temperature (left) and altitude (right) relative to CHAMP RO data: difference of ECMWF analyses (yellow), NCEP reanalyses (green; temperature only), RO data from F3C FM-1 (red), F3C FM-4 (orange), and SAC-C (blue).

5. Concluding Remarks

We showed that accurate monthly, seasonal, and annual mean, zonal mean climatologies between ~8 km and 35 km altitude can be obtained based on Radio Occultation (RO) profiles. The assimilation of RO data at ECMWF (European Centre for Medium-Range Weather Forecasts) has considerably improved operational analyses in regions where the data coverage and/or the vertical resolution and accuracy of RO data is superior to traditional data sources (e.g., in polar regions and at altitudes up to ~35 km). We analyzed the consistency of climatologies derived from different satellites. Systematic differences between ECMWF are now < 0.5 km almost everywhere below 25 km. Climatologies from CHAMP and Formosat-3/COSMIC (F3C) agree very well if phase and orbit data from the same processing center are used, i.e., a consistent data processing chain from raw measurements to atmospheric profiles is ensured.

Climatologies from different F3C satellites show excellent agreement: After subtraction of the estimated respective sampling errors, altitude- and latitude-resolved seasonal dry temperature climatologies derived from F3C satellites in entirely different orbits agree to within < 0.1 K almost everywhere in the domain between 8 km and 35 km altitude. Mean differences (over the same domain) are smaller than 0.04 K in any case and can be as small as 0.003 K. RO data are also well suited for the determination of tropopause parameters, which have been identified in various studies as good indicators for climate change. Monthly mean tropical tropopause (lapse rate) temperatures and altitudes derived from four different RO missions show remarkable consistency.

Future work will focus on identifying possible reasons for small remaining differences between data from different processing centers (see also Foelsche et al., 2008c) but already now RO data are a very valuable data base for climate studies in the upper troposphere and lower stratosphere. Clear evidence was found that consistently processed data from different RO missions can be combined without need for inter-calibration.

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