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Pre-Operational Retrieval of Radio Occultation Based Climatologies

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Abstract. CHAMPCLIM is a joint project of WegCenter/UniGraz and GFZ Potsdam. The overall aim of the project is to exploit the CHAMP (CHAllenging Minisatellite Payload for geoscientific research) radio occultation (RO) data in the best possible manner for climate monitoring. This paper focuses on describing the pre-operational status and technical aspects of the CHAMPCLIM processing system at WegCenter/UniGraz. For creating RO based climatologies we ingest, on the one hand, the complete CHAMP RO dataset provided by GFZ at excess phase level (GFZ level 2, ~180 profiles/day), which is processed to obtain atmospheric profiles of refractivity, geopotential height, and temperature (in future also humidity). On the other hand, we use operational atmospheric analysis fields from the European Centre for Medium-Range Weather Forecasts (ECMWF), at T42L60 resolution, as reference for quality control and evaluation. For delivering climatologies operationally, which will be prepared at monthly, seasonal, and annual time scales, our aim is to provide them with a delay of at most two weeks after the last measurement (e.g., JJA 2003 seasonal climatology available by September 14, 2003, latest). The climatologies are set up in overlapping equal-area and non-overlapping almost equal-area grids. In order to monitor the error characteristics of the climatologies, various types of error statistics (vs. ECMWF analyses) are performed. The main emphasis of this paper lies on processing the complete 2002–2004 data – starting from March 2002 when the CHAMP data stream became stable and quasi continuous – and on creation of climatologies including error estimates. The spatial set up of the climatologies, exemplary seasonal climatologies (as far as processed) as well as preliminary climatological error estimates are presented.

1 Introduction

The main advantages of probing the Earth's atmosphere with the self-calibrating radio occultation (RO) sounding method using the Global Positioning System (GPS) are long term stability, high vertical resolution and accuracy, all-weather capability, and global coverage. These characterizations make the RO method near-ideal for climate monitoring.

In July 2000 the German research satellite CHAMP (CHAllenging Minisatellite Payload) was launched and, since March 2002, it continuously records up to 280 RO events per day (Wickert et al. 2004, 2006). Since its lifetime is projected to last until at least 2007, this mission provides the first opportunity to create RO based climatologies over a longer time period.

The CHAMPCLIM project, which is undertaken at WegCenter/UniGraz (Foelsche et al. 2005) in close cooperation with the GFZ Potsdam, aims at exploiting the CHAMP RO data in particular for use in climate monitoring and research. The main focus lies on optimizing RO retrieval algorithms for climate utility and creating global RO based climatologies.

In Section 2, a description of the pre-operational CHAMPCLIM processing system currently under development at WegCenter is given. Section 3 explains the two different binning modes of the climatologies, which are the main product of the pre-operational CHAMPCLIM processing system. Furthermore, the summer season (JJA) 2003 is depicted as an example for the climatology. Finally, in Section 4 the conclusions of the paper and an outlook to further work are given.

2 Pre-Operational Retrieval Status

The CHAMPCLIM retrieval chain starts with CHAMP data provision by GFZ Potsdam. GFZ provides operational occultation measurements and corresponding analysis results such as atmospheric excess phases and vertical profiles of refractivity, temperature, and water vapor via the CHAMP data center (http://isdc.gfz-potsdam.de/champ; for details see Schmidt et al. (2005) and Wickert et al. (2006)). As input data for the WegCenter processing chain serve the calibrated atmospheric excess phase data (level 2, on average ~180 files per day). The GFZ-internal calibration process is described by Wickert et al. (2004).

As reference data, 6-hourly analysis fields of the European Centre for Medium-Range Weather Forecasts (ECMWF) are used (four time layers per day; 6 UTC, 12 UTC, 18 UTC, 24 UTC), which are downloaded directly from ECMWF.

The RO retrieval scheme applied to these data is developed at WegCenter (Gobiet and Kirchengast 2004; Steiner et al. 2004) in close connection with developments of the End-to-end GNSS Occultation Performance Simulator (EGOPS) (Kirchengast et al. 2002). The retrieval is especially focused on minimizing the bias of atmospheric parameters. Table 1 below provides an overview on the main aspects of the retrieval scheme. The retrieval implements statistical optimization in two different ways, one of which uses the MSISE-90 climatology (Hedin 1991) (WegCenter/MSIS) and the other operational ECMWF analysis fields (WegCenter/ECMWF) as background information. This background information is integrated into the retrieval only at one point (bending angle level), resulting in well defined error characteristics and allowing to initialize the hydrostatic integral at very high altitudes (120 km), where the upper-boundary initialization has no effect on the retrieved atmospheric parameters in the height interval under consideration below 50 km (Gobiet et al. 2004).

Table 1. Summary of some main aspects of the CHAMPCLIM retrieval (CCR v2) (after Steiner et al. (2004)).

	WegCenter/MSIS	WegCenter/ECMWF
Outlier Rejection and Smoothing	"3σ" outlier rejection on phase delays and smoothing using regularization (third order norm, regularization parameter = $10^{(\text{sampling rate}/10)}$) (Syndergaard 1999).	Like WegCenter/MSIS
Bending Angle Retrieval	Geometric Optics retrieval.	Like WegCenter/MSIS
Ionospheric Correction	Linear combination of bending angles (Vorob'ev and Krasil'nikova 1994). Correction is applied to low-pass filtered bending angles (1 km sliding average), L1 high-pass contribution is added after correction (Hocke et al. 2003). L2 bending angles < 15 km derived via L1-L2 extrapolation.	Like WegCenter/MSIS
Bending Angle Initialization	Statistical optimization of bending angles from 30 km to 120 km. Vertically correlated background (corr. length L = 6 km) and observation (L = 1 km) errors. Observational error estimated from observed profile > 65 km. Background error: 15 %. Background information: MSISE-90 (Hedin 1991) best fit-profile, bias corrected (Gobiet and Kirchengast 2004).	Like WegCenter/MSIS, but co-located bending angle profile derived from ECMWF operational analysis as backg. information (above ~60 km: MSISE-90). No further pre-processing.
Hydrostat. Integral Initialization	At 120 km: pressure = p(MSISE-90).	Like WegCenter/MSIS
Humidity Retrieval	Optional: 1D-Var using ECMWF short-range forecasts as background.	Like WegCenter/MSIS
Quality Control	Refractivity 5 km to 35 km: $\Delta N/N < 10$ %; Temperature 8 km to 25 km: $\Delta T < 20$ K. Reference: ECMWF operational analysis (T42L60).	Like WegCenter/MSIS

Recent work at WegCenter focused on the establishment of a pre-operational processing system, which includes data transfer from GFZ and ECMWF, retrieval of atmospheric parameters, quality control, creation of climatologies, and storage of data. At this stage, the processing system operates in an automated way up to the RO retrieval and quality control, whilst the automated creation of climatologies is currently integrated. The aim is to establish a data stream, which contains the most recent 7-days of data provided within a time delay of two days. Furthermore, the climatologies are aimed to be provided within a timeliness of 14 days.

So far, the dataset ranging from March 2002 to February 2004 was transferred from GFZ as well as from ECMWF and processed at WegCenter. More than 80 % of the excess phase profiles analyzed pass the CHAMPCLIM quality control yielding ~150 atmospheric profiles per day.

For validation purposes, subsets of the retrieved CHAMP data were compared at refractivity and dry temperature level to various data sources. Figure 1 shows two comparisons, one with ECMWF operational analysis fields (Fig. 1a) and the other (Fig. 1b) with data from the Michelson Interferometer for Passive Atmospheric Sounding (MIPAS) on the ESA satellite ENVISAT (Gobiet et al. 2004). This analysis was carried out by considering 3160 CHAMP occultation events and 184 co-located ENVISAT/MIPAS events, observed during September 2002. Figure 1 depicts the bias (bold) and bias ± standard deviation profiles (light) of dry temperature.

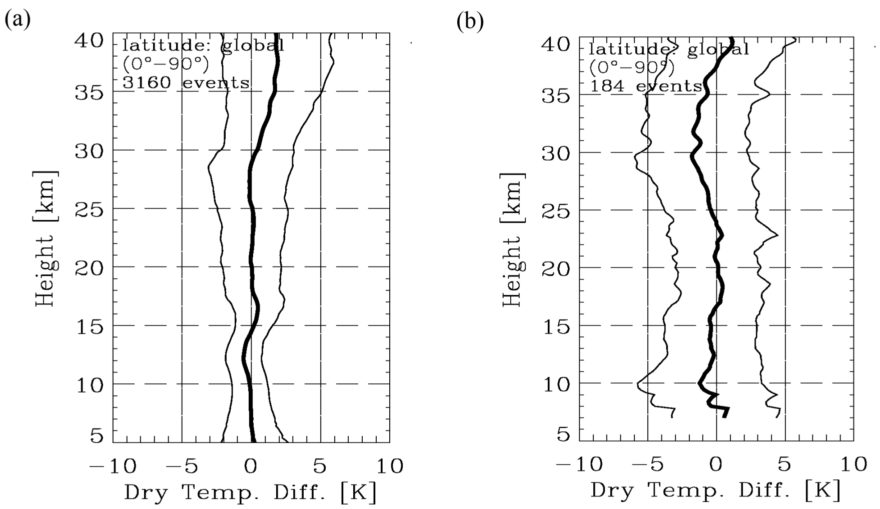

Fig. 1. WegCenter/ECMWF dry temperature profiles retrieval. Comparison with co-located ECMWF analysis profiles (a) and with co-located ENVISAT-MIPAS profiles (b), respectively (after Gobiet et al. 2004).

3 Setup of Climatologies

The implementation of the climatologies as final product is pursued in two different ways. On the one hand, a global 3D-Var analysis by assimilation of CHAMP data into ECMWF short-term forecast fields was developed, which is described by Löscher and Kirchengast (2006). On the other hand, a direct-binning grid strategy is implemented in two modes, which will be the focus of this section.

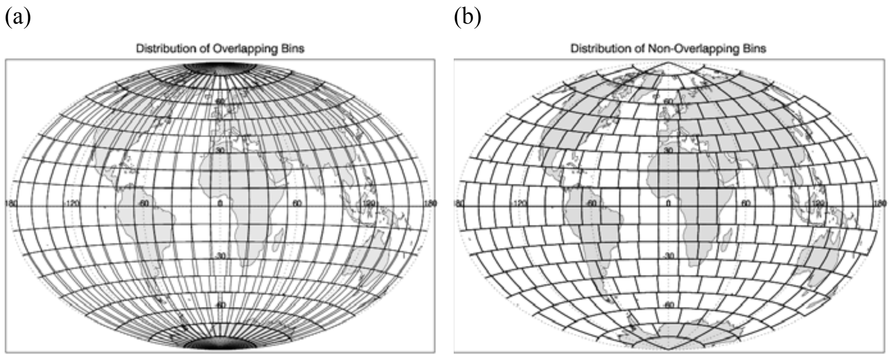

Fig. 2. Two modes of direct binning. Overlapping equal-area bins at regular 18 lat x 24 lon grid (a), and non-overlapping almost equal-area bins at 18 lat x lat-dependent lon grid (b).

The difference between both direct-binning grids is how the equal-area bins are arranged as shown in Figure 2. Along latitude, both modes have the meridian divided into 18 bins of 10° width. Along longitude, the first mode (Fig. 2a) uses 24 fixed bins (baseline) at all latitudes leading to bin overlapping at high latitudes, whilst the second mode (Fig. 2b) uses a latitude-dependent number of bins to obtain non-overlapping almost equal-area bins (within ±0.5° exact; except for polar latitudes where the latitude extension differs up to 7.9° per bin). While climatologies on the regular grid (lat x lon) are most convenient to handle, the second mode allows to avoid horizontal error correlations.

The prime testbed season was arbitrarily chosen to be JJA 2003. Due to the high inclination of the CHAMP satellite the global event distribution varies from sparse sampling in the equatorial region to more dense sampling in the polar region. As shown in Figure 3(a), illustrating the event distribution for a 10° x 15° binning for the testbed season, there are hardly sufficient events in the equatorial region for deriving robust statistics as is required for climatologies. Figure 3(b) depicts the corresponding sampling error climatology field showing sampling errors of up to around ±1.5 K.

There are rare occasions in which an equatorial bin of a 10° x 15° latitude slice does not contain any RO events. In the two year set of CHAMP data there are only a few seasonal latitude slices for which this occurs. In monthly climatologies there are many more latitude slices with no events. Therefore, we have decided to broaden the gridding of the climatologies to 10° x 60° (18 lat x 6 lon grid). Figure 3(c) shows the event distribution of that grid exemplary on the meridional latitude slice in the testbed season. For direct comparison, in Figure 3(d) the corresponding sampling error field is depicted. Here, the sampling error amounts to less than in the previous case ranging up to around ±1 K; additionally, the variability of the sampling error is smaller. If the climatologies are examined as zonal means, the sampling error diminishes even further to below ±0.5 K (compare Foelsche et al. 2006).

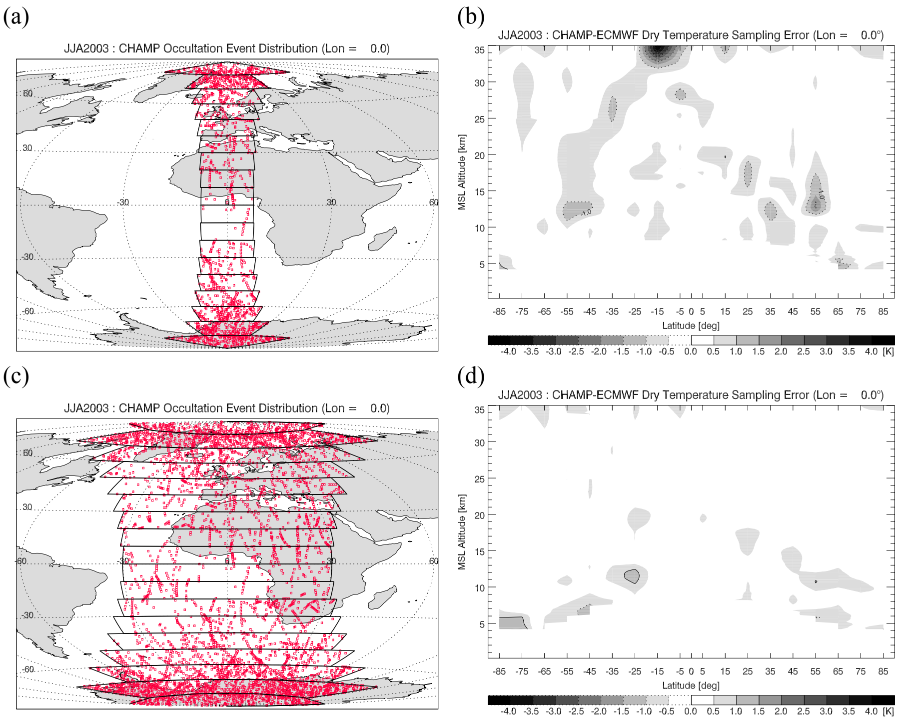

Fig. 3. Event distribution in a latitude slice of 10° x 15° binning (a) and its corresponding sampling error climatology (b) of testbed season JJA 2003; (c) and (d) same as above for 10° x 60° binning.

In Figure 4 an example of a zonal mean climatology is given. Again, the prime testbed season JJA 2003 is depicted for zonal-mean dry temperature (Fig. 4a) and the deviation compared to ECMWF analysis fields (Fig. 4b). The vertical range of the climatologies shown here extends between 4 km at the bottom to 35 km at the top. This range characterizes the area in which the best results for GPS based RO measurements are obtained. Additionally, the climatologies are cut off at the lower end at varying height increasing from the poles towards the equator. From the poles to 60° latitude they reach down to 4 km, the cut-off height then increases over the mid latitude bins to 8 km at low latitudes (equator to 30° north and south). The reason for the cut-off strategy is reasonable due to biased sampling in the region of the lower troposphere and the dry air processing applied. The error in sampling is due to the fact that the tracking of the CHAMP signal tends to stop at higher altitudes in moist compared to dry conditions. Especially in the lower tropical troposphere this can lead to a warm bias in dry temperature in the order of 10 K (compare Foelsche et al. 2006).

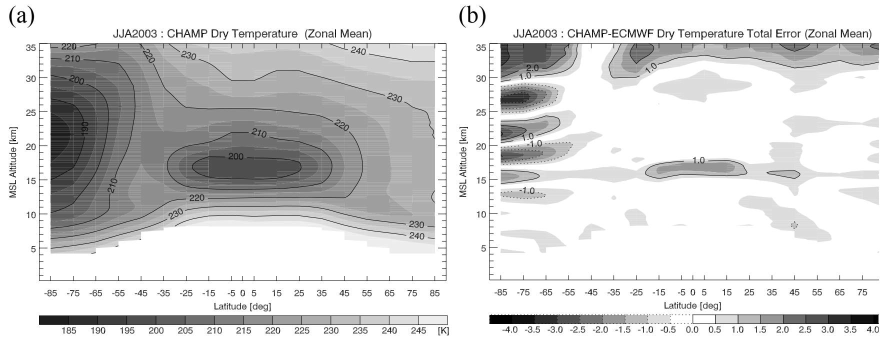

Fig. 4. Zonal mean dry temperatures of JJA 2003 (a), and deviation of CHAMP dry temperatures relative to ECMWF (b).

The temperature deviation field compared to ECMWF analyses (Fig. 4b) mainly equals to zero but there are some distinct features. Above about 30 km a consistent warm bias of about 1 K and more stretches across the whole latitude band. The cause for this bias is ambiguous because at that height the ECMWF analyses are only partly constrained by observational data and the RO measurement errors start to increase. However, validation to independent data (see Section 2) suggest that the CHAMP RO results are still of high quality.

Another feature in the deviation field is a warm bias of up to 2 K in the tropical tropopause region. As has been stated in Gobiet et al. (2005) and is under closer investigation at the moment, this bias may mainly be attributed to the ECMWF analyses and is probably caused by too weak representation of atmospheric wave activity and tropopause height variability.

Probably the most salient feature is located at the southern winter polar vortex. The CHAMP data exhibit a clear alternating deviation in the order of ±3 K compared to the ECMWF data. This deviation can be attributed to be a bias of ECMWF analyses as discussed in and Gobiet et al. (2005), being a good example of the value of RO data as validation.

The processing of the March 2002 to February 2004 time span has been completed in early September 2004 and preliminary results for selected seasons are depicted in Foelsche et al. (2006).

4 Conclusions and Outlook

A description and short report of the pre-operational CHAMPCLIM climatology retrieval scheme was given. It includes data transfer from ECMWF for operational analysis and from GFZ for CHAMP RO data, as well as data provision within a timeliness of at most 14 days.

Two different modes of binning the climatologies were discussed and first results of the summer season 2003 were shown.

In the near future, some already prepared upgrades to the retrieval scheme are planned, which include extraction of tropopause parameters, extraction of ECMWF reference profiles along the 3D tangent point trajectory, geoid reference, wave-optics based tropospheric bending angle retrieval, and 1D-Var based tropospheric processing. Also generation of error-estimate fields and first 3D-Var fields is foreseen.

In 2005 it is planned to set up an operational data stream from GFZ for processing the data within the above noted timeliness targets and to also include processing of the missing time span from March 2004 onwards. Preparations for ingestion of additional data from further missions (e.g., GRACE, Metop/GRAS, COSMIC) will start as well.

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