Global Climate Monitoring based on CHAMP/GPS Radio Occultation Data

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Summary. The global coverage, all-weather capability, high accuracy, and self-calibrated nature of radio occultation (RO) data suggests them as a near-ideal resource to build global climatologies of fundamental atmospheric variables such as temperature and humidity. Such climatologies are not available yet, but some heritage exists from an on-going project on a climate observing system simulation experiment using realistically simulated RO data (GNSS-CLIMATCH, a joint project of IGAM/Univ. of Graz and MPI for Meteorology, Hamburg). The CHAMP (Challenging Minisatellite Payload) RO data will provide the very first opportunity to create real RO based climatologies. We aim at using the complete CHAMP RO data flow for month-to-month, season-to-season, and year-to-year global climate monitoring via temperature, geopotential height, and humidity fields.

The RO based climatologies will be built in two modes: 1) fully independent based on statistical binning and averaging techniques applied to the dataset of original profiles, 2) weakly background-dependent but higher resolved based on optimal fusion (3DVAR assimilation) of RO data into averaged ECMWF atmospheric analysis background fields. Here we describe the set-up for the first approach and show preliminary results based on realistically simulated data. These suggest that reliable season-to-season temperature climatologies resolving scales > 1000 km can be obtained even with RO data received from a single satellite.

Key words: radio occultation technique, CHAMP satellite mission, climate monitoring, forward modeling and inversion, atmospheric remote sensing, anthropogenic climate change

1 Introduction

Over the coming decades climate change monitoring will be of high relevance since there exists global concern (and increasing evidence) that the Earth's climate is significantly influenced by human activities (e.g., IPCC 2001). High quality observations of the atmosphere are particularly required (but not sufficiently available) in this context. The Global Navigation Satellite System (GNSS) radio occultation (RO) technique has the potential to substantially contribute to this scientific challenge.

The GNSS currently consists of the U.S. GPS and the Russian GLONASS with nominal constellations of 24 satellites each. A European system with some thirty additional satellites (GALILEO) is under development and scheduled to be operational by 2008.

Radio signals from these GNSS satellites, received onboard satellites in Low Earth Orbit (LEO), can be used to probe the Earth's atmosphere in a limb sounding mode, since the propagation of the signals is influenced by the atmospheric (and ionospheric) refractivity field. The principle observable is the excess phase path, which can be measured with millimetric accuracy. Such RO phase data are the basis for the calculation of key climate variables such as temperature.

The RO technique (for a detailed description see, e.g., the reviews of Kursinski et al. 1997 and Steiner et al. 2001) provides an encouraging combination of:

- Global coverage,
- All weather capability,
- High accuracy and vertical resolution, and
- Long-term stability.

In contrast to many other conventional (non-satellite) data sources (like radiosondes) observation density over oceans is as high as over land. The use of L-band signals with wavelengths of 19.0 and 24.4 cm, respectively, makes the method almost insensitive to clouds and aerosols (a major advantage given the fact that about half of the Earth is on average covered by clouds). Temperature profiles, for example, can be retrieved with an accuracy of < 1 K in the upper troposphere and lower stratosphere with a height resolution of 1-2 km (Kursinski et al. 1997). The long-term stability of the data is of particular importance for climate studies, it is achieved since precise clocks, driven by very stable oscillators, are the basis for accurate phase measurements during each single occultation event, independent of whether two events are separated by an hour or by decades.

Sensing of the Earth's atmosphere with the RO method was first successfully demonstrated with the GPS Meteorology (GPS/MET) experiment performing measurement campaigns from April 1995 to March 1997. Analysis and validation of GPS/MET data sets confirmed most of the expected strengths of the technique listed above (Kursinski et al. 1997; Rocken et al. 1997; Steiner et al. 1999).

The climate monitoring utility of a GNSS occultation observing system has not yet been tested due to the lack of long-term measurements for such a study. The CHAMP (Challenging Minisatellite Payload) RO data will provide the very first opportunity to create real RO based climatologies. We will use the complete CHAMP RO data flow for global climate monitoring via temperature, geopotential height, and humidity.

In addition, we undertake a large-scale climate observing system simulation study, which aims at testing the climate change detection capability of GNSS occultation sensors and helps setting up the climate monitoring system for the CHAMP RO data. An overview of the main results relevant in this context is given in the following sections 2 and 3.

2 The GNSS Climate Monitoring Study

A detailed description of rationale and design of this study has been given by Steiner et al. (2001). Here we focus on new results, which are relevant for this work. The study involves five main parts of work as follows.

1. Realistic modeling of the neutral atmosphere and the ionosphere over the time period 2001 to 2025.
2. Realistic simulations of occultation observables for a small GNSS receiver constellation (6 satellites) for the same time period.
3. State-of-the-art data processing for temperature profile retrieval in the troposphere and stratosphere to establish a sufficient database.
4. Statistical analysis of temperature trends in the “measured” climatology (database of simulated measurements) and the “true” climatology (model atmosphere).
5. Assessment of how well a GNSS occultation observing system is able to detect climatic trends in the atmosphere.

2.1 Atmosphere and Ionosphere Modeling

In order to obtain reliably simulated occultation data it is of particular importance to use realistic models of the neutral atmosphere and the ionosphere. For the former we employ the ECHAM5 General Circulation Model (the successor of the ECHAM4 model; Roeckner et al. 1999) with a resolution of T42L39, the highest of the 39 model levels being at ~0.1 hPa or ~80 km. Above this height MSISE-90 climatology is used (Hedin, 1991). After successful termination of the control run, a model run for the time period 2001 to 2025 including transient anthropogenic forcings due to greenhouse gases, sulfate aerosol, and ozone is currently performed at the MPI for Meteorology in Hamburg, Germany. The atmospheric fields are stored every three hours in order to capture diurnal variations.

For the ionosphere we use the NeUoG model (Leitinger et al. 1996), a global empirical climatology for the 3D ionospheric electron density field. It is driven by day-to-day variations of the solar activity (including the ~11 year solar cycle), represented by the F10.7 solar flux index. F10.7 data from the solar cycles 21, 22, and 23 are used to obtain quasi-realistic solar activity variations for the time period 2001 to 2025.

2.2 Simulation of Occultation Data

We assumed a reasonable constellation of six LEO satellites equipped with GNSS receivers, comparable to currently planned occultation missions like ACE+ (Hoeg and Kirchengast 2002) and COSMIC (Lee et al. 2001). Under the assumption that occultation events with a high angle of incidence with respect to the LEO Orbit plane are more vulnerable to horizontal structure errors, we restricted to occultations within ± 15° about the LEO Orbit plane (near-vertical events). Recent results (Foelsche and Kirchengast, 2002), however, confirm this assumption concerning the quality of occultation data only below ~7 km altitude. Above this altitude no relevant increase of errors with increasing angle of incidence has been detected, a result which is encouraging for the attempt to monitor climate with a single LEO satellite like CHAMP.

Even with this somewhat conservative azimuth restriction, the selected LEO constellation yields about 2000 rising and setting occultations per day (or more then 18 million within the 25 year period) with nominal GPS and GLONASS constellations. In order to reduce computing time we have to extract a small but sensible subset of these occultation events as the high-precision simulation of observables of an occultation event consumes several hours on a typical workstation. We focus on the summer season (June, July, August) and on a geographic domain between 85°S and 85°N, symmetric with respect to the Greenwich meridian and divided into 17 equal area bins (15° lon. x 10° lat. at Equator). The left panel of Figure 1 shows a geographic map with the selected domain in which about 13000 occultation events can be expected within a summer season for 6 LEO receivers.

In a further step we select a sample of about 1000 events per summer season, as evenly as possible distributed in time and latitude, yielding 50 to 60 events per latitude bin. The latitudinal distribution of the selected events during the JJA 1997 "test-bed" season is shown in the right panel of Figure 1.

For each occultation event, the geometry is calculated based on Keplerian Orbit elements. Then we perform 3D ray tracing, with sub-millimetric accuracy at 10 Hz

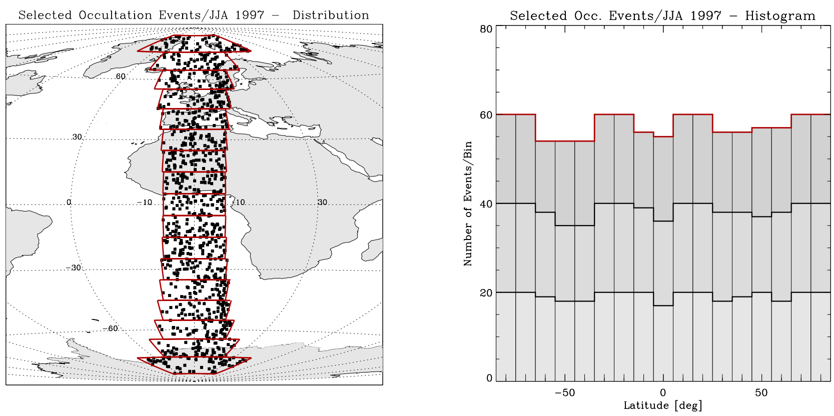

Fig. 1. Left panel: Geographic domain and locations of the ~1000 selected occultation events during JJA 1997 (black squares). Right panel: Cumulative distribution of the selected events in the 17 equal area bins in June (light gray), June + July (plus medium gray), and June + July + August (plus dark gray).

sampling rate through the respective atmospheric and ionospheric fields (the computationally most time consuming part of the study). In a last step, realistic errors (including orbit uncertainties, receiver noise, local multipath and clock errors) are superimposed on the obtained simulated phase measurements. The resulting errors (~2 mm standard deviation) conservatively reflect the performance of modern GNSS receivers.

2.3 Temperature Profiles Retrieval

The excess phase profiles are inverted to bending angle profiles using the algorithm described by Syndergaard (1999), which has been enhanced to include inverse covariance weighted statistical optimization. Thereby the “measured” bending angle profiles are combined with the best-fitting MSISE-90 model bending angle profiles (around the stratopause) employing optimal estimation (Healy 2001; Gobiet and Kirchengast 2002). The variance of the bending angle data at mesospheric heights is used as quality criterion, events which are beyond the “3σ-limit” in the respective latitude bin are excluded from statistics, which typically affects 1-3 % of them.

Temperature profiles are calculated based on standard formulae (Syndergaard, 1999), assuming a dry atmosphere. For more details see Steiner et al. (2001).

Differences between retrieved temperature profiles and co-located “true” GCM (dry) temperature profiles are computed for the set of 50–60 events in each latitude bin, allowing the inspection of systematic and random observational errors. We primarily focus on a ”core region” between 8 and 40 km height where the best results can be expected. Results for two bins during the “test-bed” season are shown in Figure 2. The equatorial bin (5°S to 5°N) is a typical case with small biases in the core region, while the southernmost bin (85°S to 75°S) is the “worst case”, mainly due to weak representativity of the MSIS-90 climatology there.

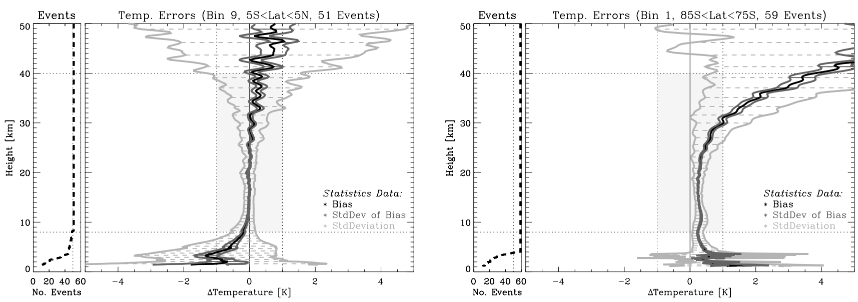

Fig. 2. Temperature error statistics during the JJA 1997 season for the equatorial bin (left panel) and the southernmost bin (right panel): number of ensemble members (dashed), bias (black), uncertainty of the bias (dark gray), and standard deviation (light gray).

2.4 Temperature Trend Analysis

The “measured” temperature profiles during the respective summer season in each of the 17 latitude bins are averaged and interpolated onto 34 height levels between 2 and 50 km, yielding a summer mean temperature field in form of a 17 x 34 matrix. For comparison, a “true” climatology matrix is computed on the same grid directly from the GCM temperature field.

As soon as all the 25 JJA mean temperature fields are computed, linear trends (and their standard deviations) in each matrix element over the 25 year period will be determined based on a multivariate weighted least-squares analysis approach. Model runs of the ECHAM4 GCM in T42L19 mode indicate that temperature trends of up to ~2 K can be expected in parts of the upper troposphere and lower stratosphere during the next 25 years with anthropogenic forcing (Roeckner et al. 1999). Given the accuracy of RO data, such trends should be clearly detectable.

3 Performance Analysis for the Test-bed Season

3.1 Observational Error

Temperature error statistics for each latitude bin have been computed as described in section 2.3. The temperature bias on the 17 x 34 grid is displayed in the left panel of Figure 3 (cf. the black lines in Figure 2). The total climatological observational error (root-mean-square error of the bias) is shown in the right panel of Figure 3; in most parts of the core region between 8 and 40 km it is smaller than 0.2 K. The largest observational errors are found in the southernmost bin (”worst case” in Figure 2).

3.2 Sampling Error

In addition to the observational error we have to consider the sampling or representativeness error. Even with perfect observations at the occultation locations the

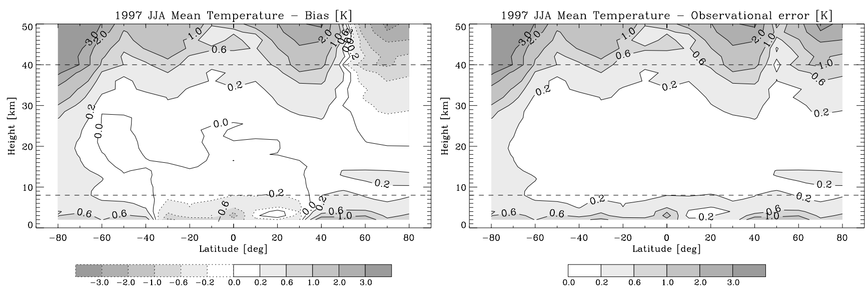

Fig. 3. Systematic error of the JJA 1997 mean temperature (left panel) and total observational error (right panel). The core region between 8 and 40 km is indicated by dashed lines.

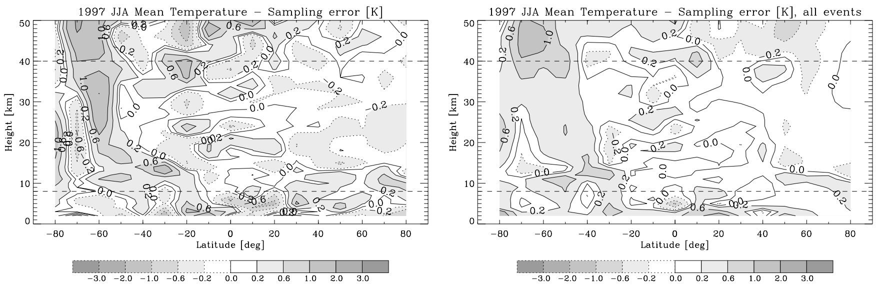

Fig. 4. Sampling error for the JJA 1997 mean temperature using the selected ~1000 events (left panel) and using all ~13,000 events (right panel).

"measured" climatology would differ from the "true" one as the sampling through occultation events is discrete and not dense enough to capture the entire spatio-temporal evolution. This error can be determined by comparison of the "true" mean temperature field and the mean field obtained from "true" profiles at the locations and dates of the occultation events. The sampling error for the 1997 summer season, using the selected ~1000 events, is shown in Figure 4 (left panel).

The largest errors of about 2 K are encountered in high latitude winter areas (around 60°S), where the latitudinal temperature gradient is particularly strong. In the core region the rms error is about 0.5 K (0.3K for the Northern Hemisphere).

For reference we computed the sampling error resulting from the use of all ~13000 events, this one is shown in the right panel of Figure 4. The error reduction is clearly visible but notedly smaller than what one might expect given an increase of occultation events by a factor of ~13. "Additional" occultation events frequently occur in close spatial and temporal vicinity to existing ones, which do not markedly improve the sampling situation.

3.3 Total Climatological Error

The total climatological error, finally, is a combination of the observational error and the sampling error; it is displayed (for JJA 1997) in Figure 5. In the core region and north of 50°S it is smaller than 0.6 K almost everywhere.

South of 50°S the coincidence of large observational and sampling errors leads to total errors of 1 to 2 K, indicating that high latitude winter areas can be a challenging region for GNSS based climatology. Above ~40 km the total error increases markedly, reaching values of 2 to 4 K.

Temperature trends over the next 25 years, however, can be expected to be larger than 1 K in important parts of the core region (Roeckner et al. 1999) and should thus have a good chance to be detected with a small constellation of GNSS receivers if the good performance during the "test-bed" season can be obtained in the "real" world over the entire 25 year period.

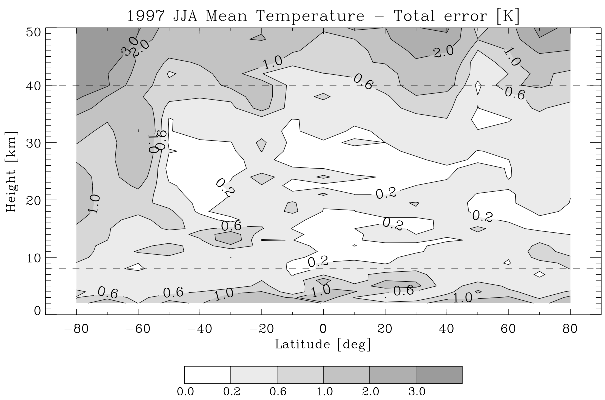

Fig. 5. Total climatological error for the JJA 1997 mean temperature.

4 Climate Monitoring with CHAMP

With the continuous stream of CHAMP RO data it will be possible to generate radio occultation based climatologies. In one approach we will use the profiles as described in section 2 and 3. While the individual profiles can be expected to be of the same quality as the ones in the simulation study (e.g., Wickert et al. 2001) the sampling error has to be considered carefully given the somewhat unfavorable single LEO satellite situation. In this context the recent results of Foelsche and Kirchengast (2002), referred to in the first paragraph of section 2.2, are quite helpful as they give us the justification to use all CHAMP occultation events within ± 45° about the LEO orbit plane if we focus on heights above ~7 km.

We computed realistic CHAMP occultation locations during a summer season (nominal GPS) and calculated the sampling error as described in section 3.2. For easing comparison we used again the JJA 1997 atmospheric fields. Even with a single satellite ~1000 (setting) occultations can be obtained during a 3 month period in the selected geographic region; the distribution is displayed in Figure 6.

Due to the high inclination of the satellite (87.3°), the event density in low latitude bins is particularly small. Comparatively small temperature variations in these bins, however, prevent the sampling error from increasing dramatically as Figure 7 shows. North of 30°N and south of 30°S the sampling error remains smaller than 0.6 K in most parts of the core region, comparable to the sampling error in the Southern Hemisphere in section 3.2.

This situation varies considerably from year to year as the two panels of Figure 7 indicate. For the results displayed in the right panel (termed ”1998”) we used the realistic event locations which would occur one year after JJA 1997 and computed the sampling error (based on the same atmospheric fields as used above).

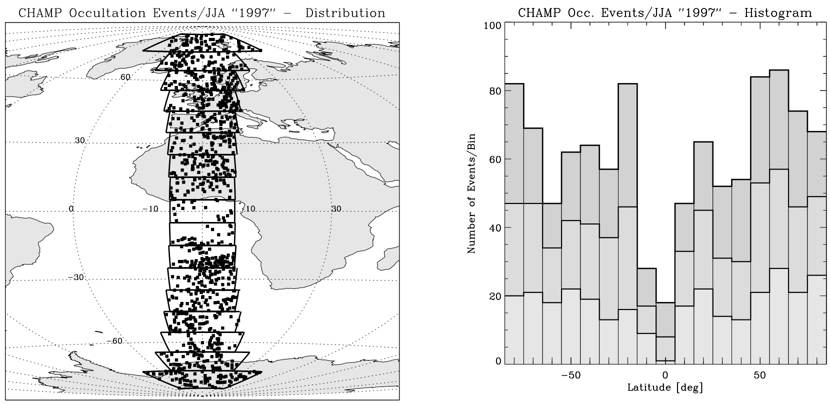

Fig. 6. Left panel: Geographic domain and locations of all ~1000 simulated CHAMP occultation events during "JJA 1997" (black squares). Right panel: Cumulative distribution of the events in the 17 equal area bins in June (light gray), June + July (plus medium gray), and June + July + August (plus dark gray).

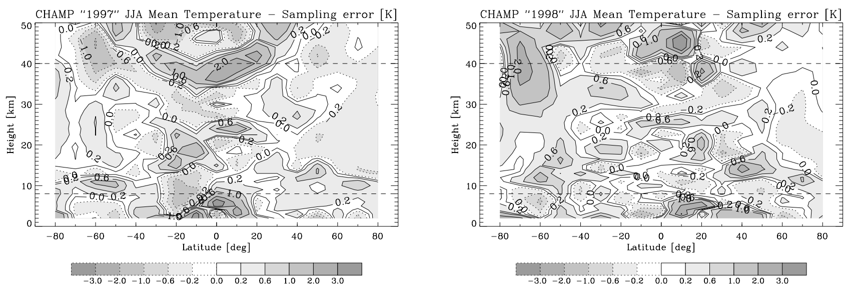

Fig. 7. Sampling error during "JJA 1997" (see text) using all ~1000 CHAMP events (left panel) and during "JJA 1998" using all available ~800 events (right panel).

Even though the total number of available events is reduced to ~800 the sampling error somewhat decreases in most parts of the core region due to the spatial and temporal sampling being better distributed during JJA 1998.

Given the encouraging performance of the GNSS receiver onboard CHAMP (Wickert et al. 2001) we are confident that reliable temperature climatologies can be achieved even with a single LEO satellite for season-to-season climatologies resolving horizontal scales > 1000 km (large-scale climatologies).

5 Summary, Conclusions, and Outlook

After a brief review of the utility of GNSS radio occultation data for climate monitoring we reported on the latest results of the GNSS-CLIMATCH study (a climate observing system simulation experiment using realistically simulated RO data) which suggest that expected temperature trends in the upper troposphere and stratosphere over the coming 25 years could be detected with a small constellation of GNSS receivers onboard LEO satellites.

Even with a single satellite like CHAMP useful temperature climatologies seem to be achievable but the sampling error, being the most important error source in this case, has to be considered carefully. As soon as a sufficient amount of CHAMP occultation data will available, we look forward to implement the described approach and to build real climatologies.

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