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The GPS Radio Occultation Record
A Novel Dataset for Atmospheric Change Detection

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Detection of anthropogenic climate change requires high quality observations of the Earth's atmosphere. Radio occultation (RO) measurements based on signals from Global Positioning System (GPS) satellites provide a novel upper air data record in this respect. GPS RO measurements deliver atmospheric parameters such as signal bending angle (*α*), refractivity (*N*), pressure (*p*), geopotential height (*Z*(*p*)), and temperature (*T*) in the upper troposphere/lower stratosphere (UTLS). We report on the current status of RO and present a climate change detection study for *N* and *T* by applying multiple linear regression and optimal fingerprinting methods in the UTLS region within ~9–25 km/300–30 hPa.

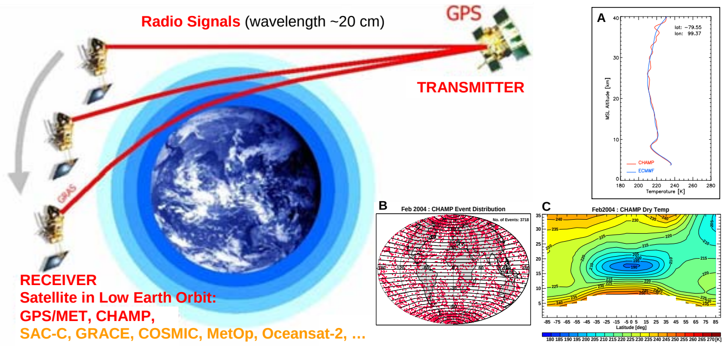

Fig. 1: Radio signals from a GPS satellite are received onboard a LEO satellite such as CHAMP. An occultation occurs whenever a GPS satellite sets (or rises from) behind the horizon and is occulted by the Earth's limb as viewed from the receiver. The relative movement of the satellites provides a scan through the atmosphere. Inserts illustrate a retrieved RO CHAMP temperature profile for a particular RO event (A), a distribution of RO events in February 2004 (B), and a monthly mean temperature field for February 2004 (C).

1. Introduction & Background

GPS satellites continuously transmit radio signals for navigation purposes. The signals are affected by the atmospheric refractivity field, which can intentionally be exploited to gain information on the atmospheric thermal structure with a GPS receiver on a satellite in low Earth orbit (LEO) (Fig. 1). RO phase delay measurements are based on precise timing with atomic clocks (S.I. traceability). This enables RO data to serve as climate benchmark data and allows long-term measurement stability. Atmospheric profiles of *α*, *N*, density, *p*, *Z*, and *T* are retrieved with high accuracy ($T < 1$ K) and vertical resolution (0.5–1 km) in the UTLS, with global coverage and all-weather capability. Data from different RO missions can be combined without need for inter-calibration and overlap provided a consistent processing scheme is used. Structural uncertainties amongst different processing centers are low: <0.03%/5yrs for global-scale *N* trends and <0.06 K/5yrs for *T* trends have been found for current datasets. First RO data are available from the GPS/Met mission intermittently within 1995–1997. Continuous observations are provided by the CHAMP satellite providing the first multi-year RO record covering more than 7 years, complemented by SAC-C and GRACE. Formosat-3/COSMIC (Taiwan/US, 6 sats) and the European MetOp mission started in 2006, the latter providing RO data until 2020.

2. Data & Design

We inspect monthly mean zonal mean RO climatologies (WegCenter OPSv5.4; Fig. 2) within 1995–2008 from GPS/Met (10/1995, 02/1997) and CHAMP (09/2001–02/2008) and coupled climate models (GCM) for trend signals via linear regression methods and optimal fingerprinting. Response patterns to anthropogenic forcings are represented by an ensemble mean of forced A2 and B1 runs of 3 representative GCMs: CCSM3/NCAR, ECHAM5/MPI-M, HadCM3/UK MetOffice. The natural climate variability is given by pre-industrial control runs. We focus on the UTLS (300–30 hPa) between 50°N–50°S.

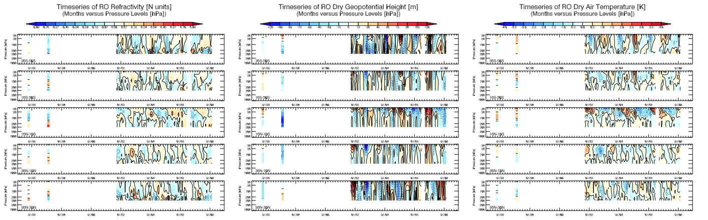

Fig. 2: RO time series of *N* (left), *Z* (middle), *T* (right) for 5 zonal means (07-08/2006 excluded – sparse CHAMP data).

3. Results – Multiple Linear Regression

RO temperatures were investigated with multiple linear regression including El Niño Southern Oscillation (ENSO) and Quasi-Biennial Oscillation (QBO). In the tropical LS (100–30 hPa) a significant cooling trend relative to natural trend variability (95% signif. level) and to inter-annual variability (90% signif. level) was found in February for the period 1997–2008 (Fig.3A). About 50% of the inter-annual variability in the LS is explained by an ENSO-related signal while the QBO shows no appreciable influence (Fig. 4). In the tropical UT (300–200 hPa, Fig. 3B), an ENSO signal explains most of the inter-annual variability, obscuring an emerging warming trend.

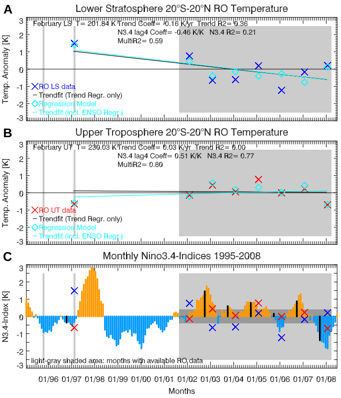

Fig. 3. RO *T* anomalies (crosses) and trends (solid) are shown for February 1997–2008 for the tropical LS (**A**) and UT (**B**). Periods with RO data availability are gray shaded, trend regression only black lines, regression model values diamonds. Trends calculated including ENSO, represented by monthly Nino3.4 SST with a 4-month lag (**C**), are light blue. Nino3.4 exceeds 0.4 K for El Niño or –0.4 K for La Niña (dark gray band).

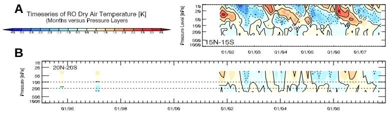

Fig. 4: The QBO pattern is clearly observed in RO CHAMP *T* anomalies in the tropical LS at 15°N–15°S (**A**) but is small for larger area averages 20°S–20°N/100–30 hPa (**B**).

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4. Results – Optimal Fingerprinting

The optimal fingerprinting technique can be viewed as general multivariate regression, $\boldsymbol{y}=\mathbf{X}\boldsymbol{a}+\boldsymbol{u}$, where $\boldsymbol{y}$ contains the observed RO trends, $\mathbf{X}$ the forced ensemble GCM trends, $\boldsymbol{a}$ the scaling factors (which are of interest), and $\boldsymbol{u}$ the internal variability. Scaling factors are estimated using 'optimal weighting' with internal climate variability. A climate trend is detected if its likelihood of occurrence due to internal variability alone is small. A residual consistency test (*Allen and Tett* 1999) is used to check the model-simulated variances at scales that are retained (empirical orthogonal functions/EOFs).

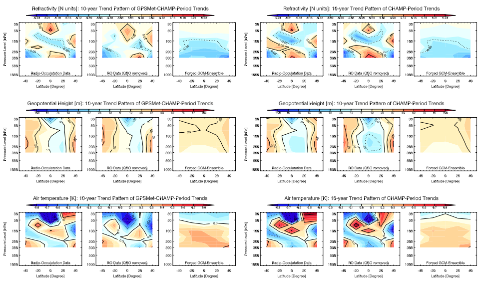

Fig. 5: Trend patterns for GPS/Met-CHAMP period 1995–2008 (left) and CHAMP only period 2001–2008 (right). Each panel shows the trend pattern of RO data for the 3 parameters with (left) and without (middle) QBO signal and the respective GCM pattern of the RO measurement period (right).

Independent of the measurement period (with/without GPS/Met data) *N* passes the residual consistency test for up to around 10 retained EOFs (Fig. 6). Figure 7 depicts the distribution of the scaling factors of the control runs as well as the RO scaling factor for 8 to 10 retained EOFs. In all cases, the null hypothesis can be rejected, meaning that a climate change signal is detected at 90% significance level in the RO *N* record. *T* results are sensitive to the measurement period and *Z* does not pass the residual consistency test.

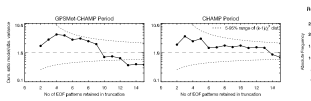

Fig. 6: Values within 5–95% confidence limit: adequate model variability in truncated EOF space.

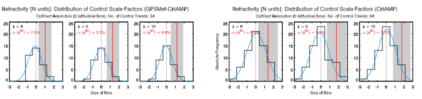

Fig. 7: Distribution of control and observed scale factors (red) ±1 sigma range (gray) for 8–10 retained EOFs for GPS/Met-CHAMP.

Conclusions & Perspective

Trend results from the current RO record are consistent with model data and with radiosonde records (not shown). A cooling trend was found in the LS for February 1997–2008 in the tropics while in the UT an emerging warming trend is obscured by ENSO. With optimal fingerprinting a signal was detected in the 7–12 year refractivity record, which is consistent with detection time estimates of *Ringer and Healy* (2008). This performance of the still short RO record to date underpins its quality and is encouraging to establish an RO-based benchmark climate record in the future.

References: Allen, M. and Tett, S. (1999), Checking for model consistency in optimal fingerprinting, *Clim. Dyn.*, **15**, 419–434.
Ringer, M. A. and Healy, S. B. (2008), Monitoring twenty-first century climate using GPS radio occultation bending angles, *Geophys. Res. Lett.*, **35**, L05708.