Climate Monitoring based on Radio Occultation Data: From CHAMP to FORMOSAT-3/COSMIC

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Radio Occultation with CHAMP

CHAMP: First Opportunity to create RO Climatologies

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Zonal Mean,
Seasonal Climatologies:
Dry Temperature

Foelsche et al. 2007, *Climate Dynamics*, revised
Example Season – Winter 2003/04

Typical Winter Season
Dec-Jan-Feb (DJF) 2003/2004
Zonal mean fields
Binning and Averaging
18 latitude bands
10° latitudinal with

WegCenter Retrieval, using phase and orbit data from GFZ
Early outlier rejection: “3σ” outlier rejection on 50 Hz sampling rate L1 and L2 phase delay data, based on a one-second moving window over the profile.

Phase delay smoothing: Smoothing of 50 Hz phase delay profiles using regularization (third order norm, regularization parameter = $10^5$, following Syndergaard, 1999).

Bending angle retrieval: Geometric optics retrieval (e.g., Kursinski et al., 1997)

Ionospheric correction: Linear combination of L1 and L2 bending angles (Vorob’ev and Krasil’nikova, 1994). Correction is applied to low-pass filtered bending angles (1 km moving average), L1 high-pass contribution is added after correction (Hocke et al., 2003). L2 bending angles <15 km derived via L1-L2 extrapolation.

Statistical optimization of bending angles: Between 30 and 120 km. Vertically correlated background (corr. length = 6 km) and observation (corr. length = 1 km) errors. Observation error estimated from observed variance of observed profile >65 km. Background error: 15%. Background information: collocated profile derived from ECMWF operational analysis (T42L60; resp. T42L91 as of 01/02/2006). Above ~60 km: MSISE-90 (Hedin, 1991).
Abel transform: Numerical integration over bending angle (Simpson’s trapezoidal rule) from each height (impact parameter) to 120 km.

Hydrostatic integral initialization: No initialization below 120 km. At 120 km: pressure = pressure (MSISE-90).


Reference frame, vertical coordinate: Earth figure: WGS-84 ellipsoid; Vertical coordinate: mean-sea-level (MSL) altitude; conversion of ellipsoidal height to MSL altitude (at mean tangent point location) via EGM-96 geoid smoothed to 2°×2° resolution.
WegCenter Climatologies

Binning and Averaging:

\[ T_{\text{dry}}(z) = \frac{1}{N_{\text{prof}}(z)} \sum_{i=1}^{N_{\text{prof}}(z)} T_{\text{dry}i}(z, \varphi_i) \cos(\varphi_i) \]

- Weighting by the cosine of the latitude.

- “Fundamental” zonal bins with 5° latitudinal width to build zonal mean monthly climatologies.

- Basic latitudinal resolution is 10°, each of the 18 latitude bands (pole to pole) contains two fundamental bins, and the mean profiles for these two bins are averaged, weighted with the surface area.

- Seasonal climatologies are obtained by averaging over three months.

- 200 m vertical spacing was chosen for the altitude gridding.
Climatologies

Sampling Error:
Undersampling of the true spatial and temporal temperature evolution
Estimation of Sampling Error

Based on ECMWF fields – 4 time layers/day
ECMWF is taken as a proxy for the “true”
temporal and spatial evolution

Sampling Error:

“True” profiles at the RO locations minus
“True” mean field
Dry Temperature – DJF 2003/04

DJF 2003/04: CHAMP Dry Temperature

DJF 2003/04: ECMWF Dry Temperature

DJF 2003/04: Systematic Dry Temp Difference ECMWF - CHAMP

DJF 2003/04: CHAMP Dry Temperature Sampling Error

Systematic Difference – Tropical Tropopause
Systematic Difference – Summer

Wave-like bias structure – Antarctica
Sampling Problem – JJA2006

Lack of CHAMP data ~5 weeks
“Gap” can be filled With GRACE data

Number of CHAMP occultations 2006

Number of days: 330
Number of occultations: 73659 52074
Daily mean: 223 157

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Sampling Error – JJA2006

Summer 2006
Lack of CHAMP data
~5 weeks

Sampling error
amazingly small
(for zonal means)

But southern (winter)
polar vortex
clearly too warm
Sampling Error – JJA2006

JJA2006: CHAMP_GRACE Dry Temperature Sampling Error

Summer 2006

CHAMP + GRACE data
Systematic Difference – JJA2006

February 2006: Major change at ECMWF
 Horizontal Resolution: T511 → T799
 Vertical Resolution: L60 → L91
 Top model level: 0.1 hPa → 0.01 hPa

Wave-like bias structure now over the Arctic
Systematic Difference in Tropical Tropopause Region essentially disappeared with new ECMWF scheme


More on the Tropical Tropopause at 9:50
Observing Climate

Preliminary Results for FORMOSAT-3/COSMIC

Foelsche et al. 2007, TAO, submitted
Monthly Mean Dry Temperature

Aug2006: COSMIC Dry Temp

CHAMP retrieval, without any change
(open loop tracking)
Monthly Mean Dry Temperature

FORMOSAT-3/COSMIC  August 2006
All satellites

Aug2006: Systematic Dry Temp Difference ECMWF-COSMIC

WegCenter Retrieval, no open loop data
Seasonal Mean **Dry Temperature**

SON 2006: COSMIC-C1 - CHAMP

**SON 2006** COSMIC-FM1 minus CHAMP

**COSMIC sampling error** at high latitudes in **early phase** due to small Azimuth angle.
Sep 2006: COSMIC-C1 Event Distribution

No. of Events: 5847

Almost no profiles between 85° and 90° lat
Seasonal Mean Dry Temperature

SON 2006 COSMIC-FM1 minus CHAMP

SON 2006: (COSMIC-C1 - Sampl Err) - (CHAMP-Sampl Err)

Respective sampling errors subtracted contains errors in sampling error estimation.
Consistency of RO Data

SON 2006    COSMIC-FM5 minus CHAMP

SON 2006: (FM5- Sampl Err) - (CHAMP-Sampl Err)

Respective sampling errors subtracted
FM5 in final orbit
Consistency of RO Data

SON 2006 COSMIC-FM1 minus COSMIC-FM3

Respective sampling errors subtracted
FM1 and FM3 in adjacent orbits
Consistency of RO Data

SON 2006  COSMIC-FM1 minus COSMIC-FM3

SON 2006: (FM1- Sampl Err) - (FM3-Sampl Err)

Respective sampling errors subtracted
Note different contour spacing!
December 2006: Assimilation of RO data at ECMWF

July 2007: Systematic Dry Temp Difference ECMWF-COSMIC

All 6 satellites
Wavelike bias disappeared with assimilation of RO data

Systematic differences above 30 km considerably reduced
Sampling Error – July 2007

Azimuth angle further opened

July 2007: COSMIC Dry Temperature Sampling Error

Sampling Error at high latitudes considerably reduced
Consistency – July 2007

COSMIC-FM1 minus COSMIC-FM2

July 2007: (FM1 - Sampl Err) - (FM2 - Sampl Err)

Still different orbit heights
Consistency – July 2007

COSMIC-FM2 minus COSMIC-FM4

July 2007: (FM2 - Sampl Err) - (FM4 - Sampl Err)
Conclusions

Radio occultation measurements have a great potential for monitoring of the global climate

Comparison with existing climatologies:

• Deficiencies in ECMWF (Ant)arctic winter stratosphere disappeared with assimilation of RO data

• CHAMP tropical tropopause consistently warmer than ECMWF but only until February 2006

• Differences above 30 km: data from future missions (MetOp)

Comparison CHAMP – FORMOSAT-3/COSMIC:

• Preliminary but very promising: consistency

The FORMOSAT-3/COSMIC teams are especially acknowledged for the early provision of data!
Initialization of RO profiles after Dec 2006 with ECMWF forecasts instead of analyses (since the analyses contain RO data now)

Measure of the degree of influence of the background provided

Cross Validation of RO climatologies from different satellites (especially including MetOp)
Challenges

• High altitude initialization
• Residual Ionospheric errors
• Potential reasons for common systematic errors
• Independent validation data
• SI Traceability
• Continuation of (dedicated) RO missions
Thank you!