Climate Monitoring with GPS RO

Achievements and Challenges

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Atmospheric temperature trends from radiosonde and AMSU observation for the satellite era 1979–2012.

- Global warming of the troposphere and cooling of the stratosphere
- Construction of climate records requires intercalibration and homogenization
- Basic agreement in trends, but large uncertainties on rates and vertical structure [Randel et al. 2009; Thorne et al. 2011]
- More accurate data sets are needed.
Climate monitoring principles
- Traceability to reliable reference standards

Fundamental Climate Data Record (FCDR)
- long-term stability
- homogeneity & reproducibility
- global coverage
- accuracy
- adequate resolution in space and time

Essential Climate Variable (ECV) upper-air temperature
- horizontal resolution: 25 km in UT, 100 km in LS
- vertical resolution: 1 km UT, 2 km LS
- accuracy (root mean square) < 0.5 K
- stability of 0.05 K per decade UT, of 0.1 K per decade LS

[GCOS-107, 2006; GCOS-143, 2010; GCOS-154, 2011]
GPS RO Data Characteristics

- Global coverage
- All weather capability
- Best data quality in UTLS
- Vertical resolution
  ~0.5 km to ~1.5 km in the UTLS (GO), sub-km (WO)
- Horizontal resolution
  ~200-300 km, synoptic scales
- Long-term stability
  precise (atomic) clocks
  (SI-traceable to time)
- No inter-satellite calibration
- Error characterization of profiles and climatologies
  [Scherllin-Pirscher et al. 2011a,b]
- Structural uncertainty estimates
  [Ho et al. 2009, 2012; Steiner et al. 2013]
Distribution of occultation events

December 2009: COSMIC-C4 Event Distribution

No. of Events: 8330

RO temperature climatology

December 2009: F3C/FM-4 Dry Temperature

Sampling error

December 2009: F3C/FM-4 Dry Temperature Sampling Error

Number of profiles per 10°-bin

December 2009: F3C/FM-4 Occultation Event Statistics

Average No. of Events per Bin: 483

http://www.globclim.org [Foelsche et al. 2008]
- Consistency of data from different satellites (WEGC)
- Consistency of (CHAMP) data from different processing centers
- Low structural uncertainty of 0.1 K within about 50°S to 50°N and 8 km to 25 km, larger above 25 km and at high latitude ~0.2–0.7 K >25 km

Consistency of data from different satellites

[Ho et al. JGR 2009, 2012; Foelsche et al. TAO 2009, AMT 2011; Steiner et al. RS 2009, ACP 2013]
Monitoring UTLS climate variability – a few examples

- Diurnal tides
- Madden-Julian Oscillation
- Quasi-Biennial Oscillation
- El-Niño Southern Oscillation

- Tropopause variability
- Sudden stratospheric warmings
- Geostrophic winds
- Convective systems
Utility of RO data for monitoring diurnal tide dynamics

**Diurnal temperature variations**

**Spectral amplitude and phase of westward propagating diurnal tide**

[Images of temperature variation maps and spectral amplitude and phase plots]

[Pirscher et al. JGR 2010]
Quasi Biennial Oscillation

- Tropical lower stratosphere, ~5°S–5°N, ~28 months period
- Seasonal changes in radiative heating

El Niño Southern Oscillation (ENSO)

- Phenomenon with quasi-periodicity of 3 to 7 years \textit{in troposphere}
- Changes in sea surface temperature of tropical Pacific
Insights into tropopause structure and variability

- Tropopause parameters (CPT, LRT, altitude, temperature)
- Double tropopause structures

[Randel et al. 2007]

[Rieckh et al. AMTD 2014]
Recent insights into sudden stratospheric warmings (SSW)

- Evolution and structure of SSW (example January 2009)

$\Delta t = 8 \text{ days}$

$\Delta T_{\text{dry}} > 70 \text{ K}$
Recent insights into the characteristics of geostrophic winds

- Deriving geostrophic wind fields from RO geopotential field gradients

[Scherllin-Pirscher et al. GRL 2014, Verkhoglyadova et al. JAOT 2014]
Recent insights into thermal structure of convective systems

- Detection of cloud top height using RO BA and temperature anomalies
Climate change studies using models and simulations

- **Yuan et al. [1993]:**
  "Simulations show the potential of GPS RO for the detection of climate change"

- **Leroy [1997]:**
  Geopotential height useful for climate monitoring

- **Vedel and Stendel [2003], Stendel et al. [2006]:**
  Refractivity useful for climate monitoring

- **Leroy et al. [2006]:**
  Climate model testing
  Detection times of 7 to 13 years

- **Ringer and Healy [2008]:**
  RO bending angle for climate trend detection
  Detection times of 10 to 16 years.

- **Steiner et al. [2001], Foelsche et al. [2008]:**
  OSSE: combined information of RO parameters
  of high value for UTLS climate change monitoring

[Foelsche et al. 2008]
Optimal fingerprinting – climate change signal detected

- Emerging climate change signal in the RO record
- Signal in temperature (90% conf. level) and geopotential height (95% conf. level)
- Warming of the troposphere, Cooling of the stratosphere
- Uplift of geopotential height levels in upper troposphere
- Consistency with detection times of ~7–16 years, Z(p) first

Evaluation of temperature and humidity in deep convection regions

- RO and HadGEM2 model mean temperature profiles and differences

**Temperature**

<table>
<thead>
<tr>
<th>RO</th>
<th>HadGEM2</th>
<th>HadGEM2-RO</th>
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**Specific Humidity**

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<thead>
<tr>
<th>RO</th>
<th>HadGEM2</th>
<th>HadGEM2-RO</th>
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**Deep Convection Regions**

HadGEM2 shows
- warmer tropopause (~4 K) and LS
- colder than RO below ~15 km
- lower humidity

[Steiner et al. OPAC-IROWG 2013]
Validation of observations MIPAS, GOMOS vs RO

Project MMValRO for ESA: Multi Mission Validation against RO
- Assess Envisat MIPAS and GOMOS (here global 10/20km–30km)
- RO is a valuable reference record over complete Envisat period 2002–2012

MIPASv6.0 vs RO

GOMOSv6.01 vs RO

http://validate.globclim.org

[Schwaerz et al. OPAC-IROWG 2013; TR ESA-ESRIN 2013]
Comparison of RAOBS with RO

Distribution Vaisala RAOBs and GRUAN Stations

Vaisala RS 90/92 vs. OPSv5.6; 2012; Global

GRUAN RS V2 vs. OPSv5.6; 2012; Global

[Ladstädter et al. AMTD in preparation]
Comparison of RAOBS with RO

Vaisala RAOBs vs RO

GRUAN vs RO

[Ladstädtet et al. AMTD in preparation]
Comparison of RAOBS with RO

RAOBS V90/92 and GRUAN vs CHAMP, GRACE, COSMIC

- Global 30 hPa – 100 hPa,

[Graph showing temperature differences and number of collocations over time]

[Ladstädter et al. AMTD in preparation]
Conclusions and Outlook

GNSS RO – a unique resource:

- high accuracy and vertical resolution, consistency, long-term stability
- for monitoring climate variability and climate change
- meeting GCOS climate monitoring targets in the UTLS

GPS RO accuracy is within ~0.1 K
(although not for horizontal target resolution <100 km, and not yet globally)

- early detection of (emerging) climate trends demonstrated
- potential for benchmark-quality global climate observing system
- authoritative reference standard in the free atmosphere for validating and calibrating thermodynamic data from other observing systems, and as absolute reference within assimilation systems
Next Steps and Challenges

- Processing advancements in lower troposphere and upper stratosphere to further reduce structural uncertainties
- Assessment of structural uncertainty of multi-satellite RO records
- Improving the maturity of RO climate records (SCOPE-CM RO-CLIM)
- Benchmark records (SI-traceable) with integrated uncertainty estimates (rOPS, WEGC’s reference occultation processing system)
- Contribution to the WMO Integrated Global Observing System (WIGOS) – GRUAN, sounders/GSICS, and GNSSRO (the “3G”s)
- Evaluation of climate models and reanalyses
- Applications in support of WCRP grand challenges: clouds and climate sensitivity, water availability, regional information
- Essential: continuous global observations (polar COSMIC-2) “Ensure the continuity of the constellation of GNSS RO satellites.” GCOS Action A21 [A20 IP-04]
THANK YOU !

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