Climate monitoring with GPS-RO: Towards SI-traceable records

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plus thanks to EUMETSAT ROM-SAF for co-funding of the travel to this workshop!

Presentation Outline

- Context and background
- Characteristics of RO data
- Accuracy and structural uncertainty
- Monitoring climate variability
- Climate change monitoring and trend detection
- Conclusions and outlook–towards SI-traceable records

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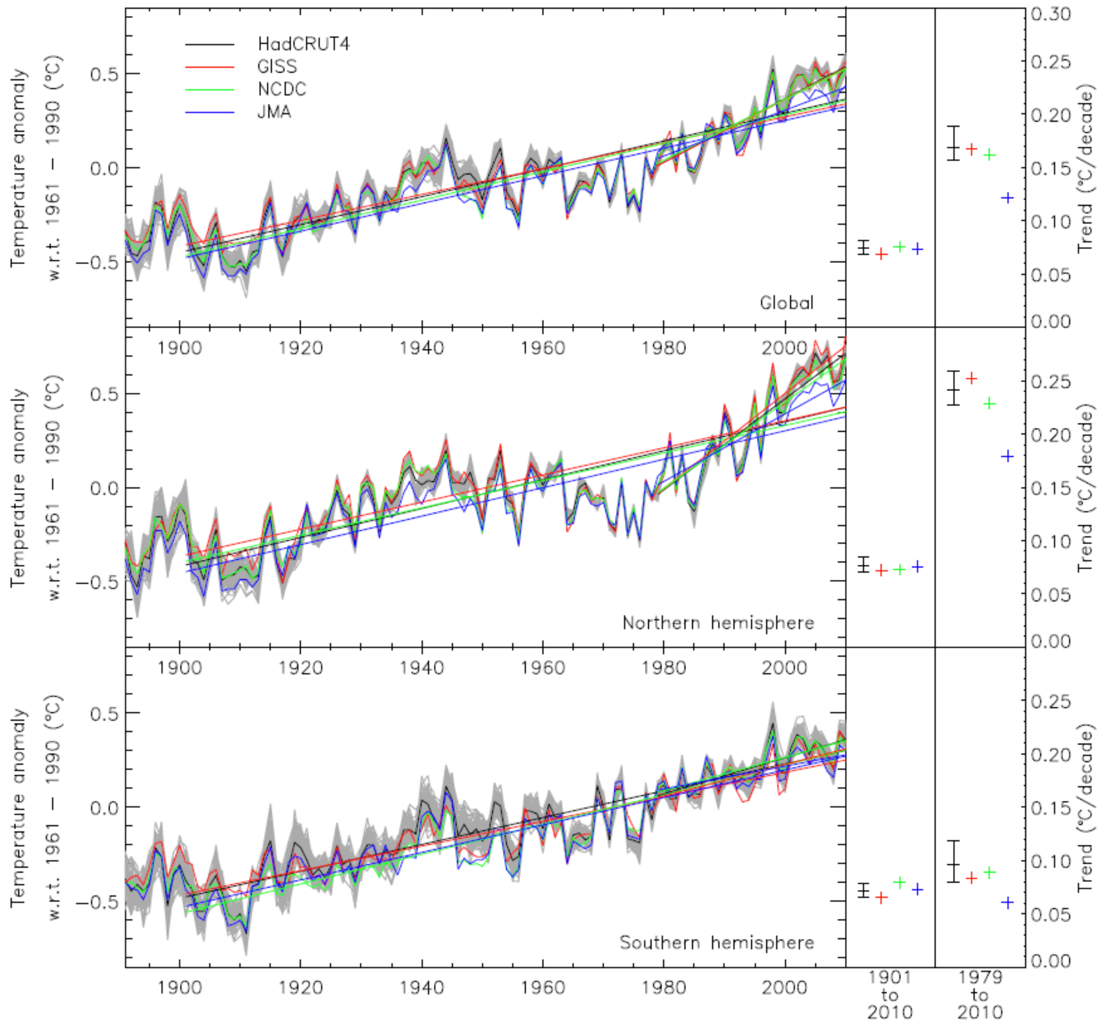
Temperature change – surface observations

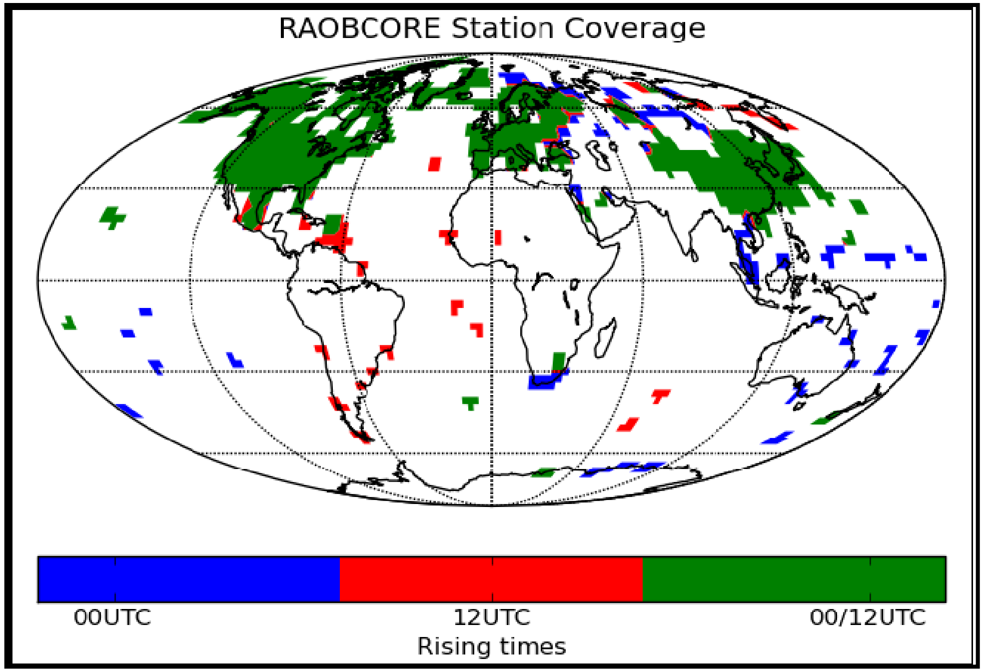


[Morice et al. 2012]

- **Global mean temperature**
- 1901 to 2010:
  Change: ~0.8 K
  Trend: ~0.07–0.08 K/decade
- 1979 to 2010:
  Increased trends (to ~2000),
  ~0.12–0.18 K/decade
- *There has been no reduction in the underlying global warming since the late 1970's.*
  [Hansen et al. 2012]

Radiosondes

- Time series since 1958
- Grossly consistent station records
- Stations biased to continental NH, lack of data in SH
- Homogenization is a demanding task to construct climate records

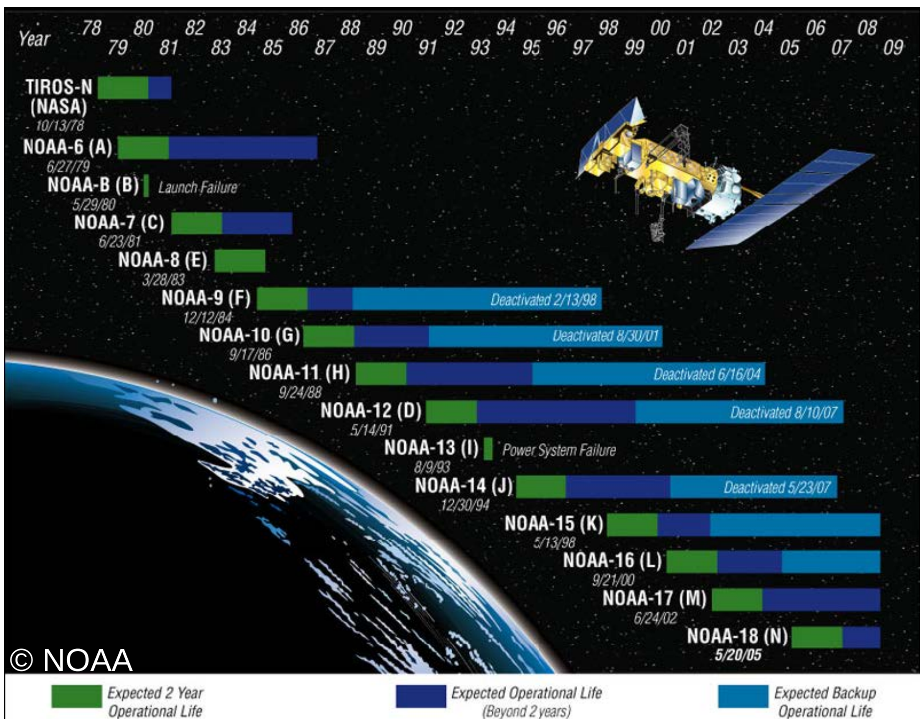


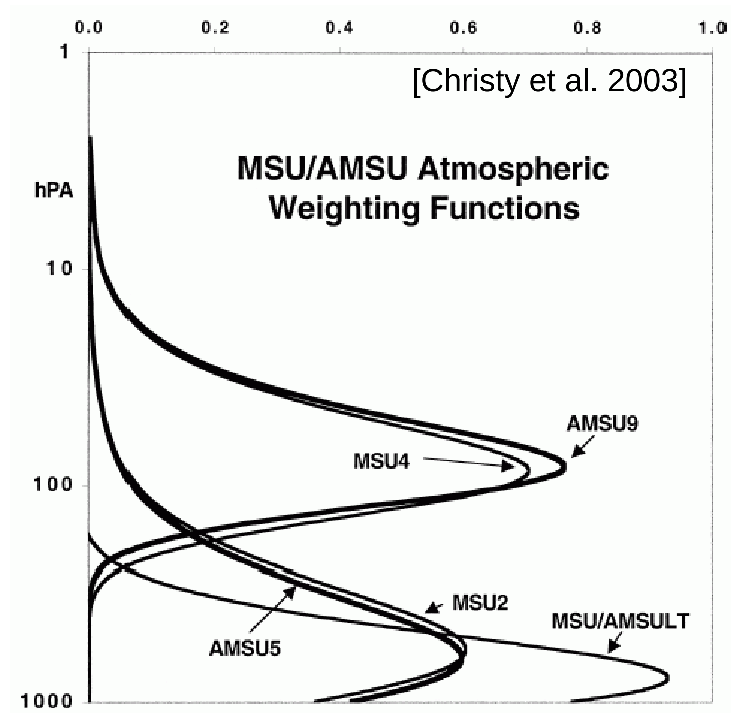
[Ladstädter et al. 2011]

[Karl et al. 2006]

(Advanced) Microwave Sounding Unit – (A)MSU

- Monitoring atmospheric temperatures since 1979
- Passive microwave nadir sounder (~50−60 GHz oxygen absorption)
- Layer-average stratospheric and tropospheric brightness temperatures
- Very good global coverage
- Demanding calibrations/corrections to construct climate records





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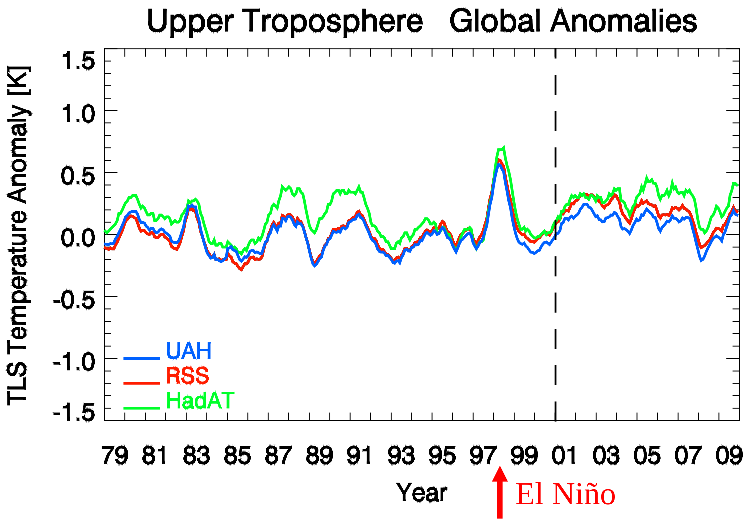
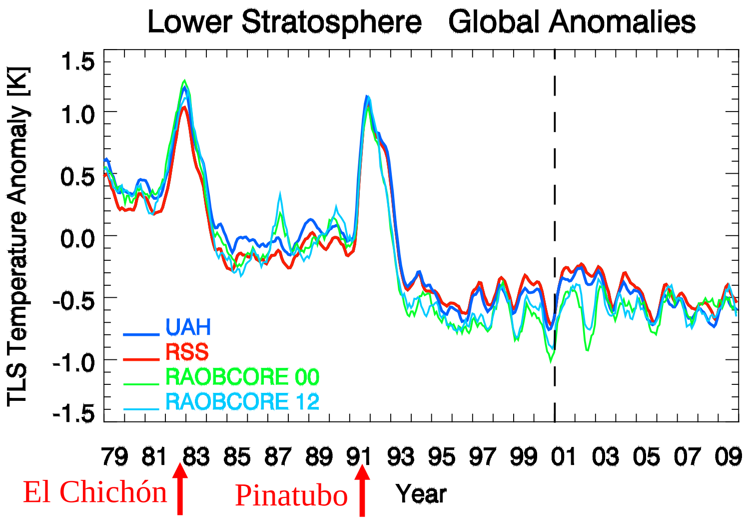
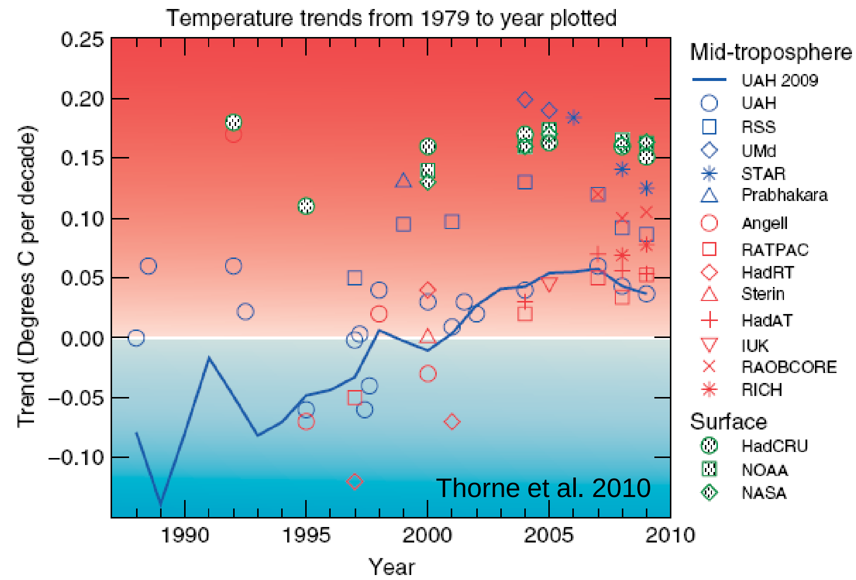
Tropopheric Warming



Stratospheric Cooling





- Construction of climate records requires intercalibration and homogenization
- Basic agreement in trends, but large uncertainties in magn. & vertical structure [Randel et al. 2009; Thorne et al. 2011]
- *"In fact, new types of more accurate data such as temperature and moisture profiles from GPS radio occultation measurements are already available, although, as yet, few efforts have been made to analyze them."* [Karl et al. 2006]

Global Climate Observing System (GCOS)

World Meteorological Organization (WMO)
Intergovernmental Oceanographic Commission (IOC)
United Nations Environment Programme (UNEP)
UN Educational Scientific & Cultural Org. (UNESCO)
International Council for Science (ICSU)

Objectives are to provide the observations required for

- Monitoring the climate system
- Detecting and attributing climate change
- Improving understanding, modeling, and prediction of the climate
- Assessing impacts of climate variability and change
- Climate information and prediction services
- Application to sustainable economic development of countries

GCOS climate monitoring principles for satellite observations

- Continuity, homogeneity and overlap
- Orbit stability
- Sensor calibration
- Data interpretation, sustained data products and archiving
- Data sets from different platforms need to be comparable for reliable long-term records
- Traceability to reliable reference standards (preferably to fundamental standards of the international system of units = SI traceability)

[GCOS-138, 2010; GCOS-143, 2010]

Fundamental Climate Data Record (FCDR)

- long-term stability
- homogeneity
- reproducibility
- global coverage
- accuracy
- adequate resolution in space and time
- product description and validation

Essential Climate Variable (ECV) upper-air temperature

- horizontal resolution: 25 km upper troposphere (UT)
  100 km lower stratosphere (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]

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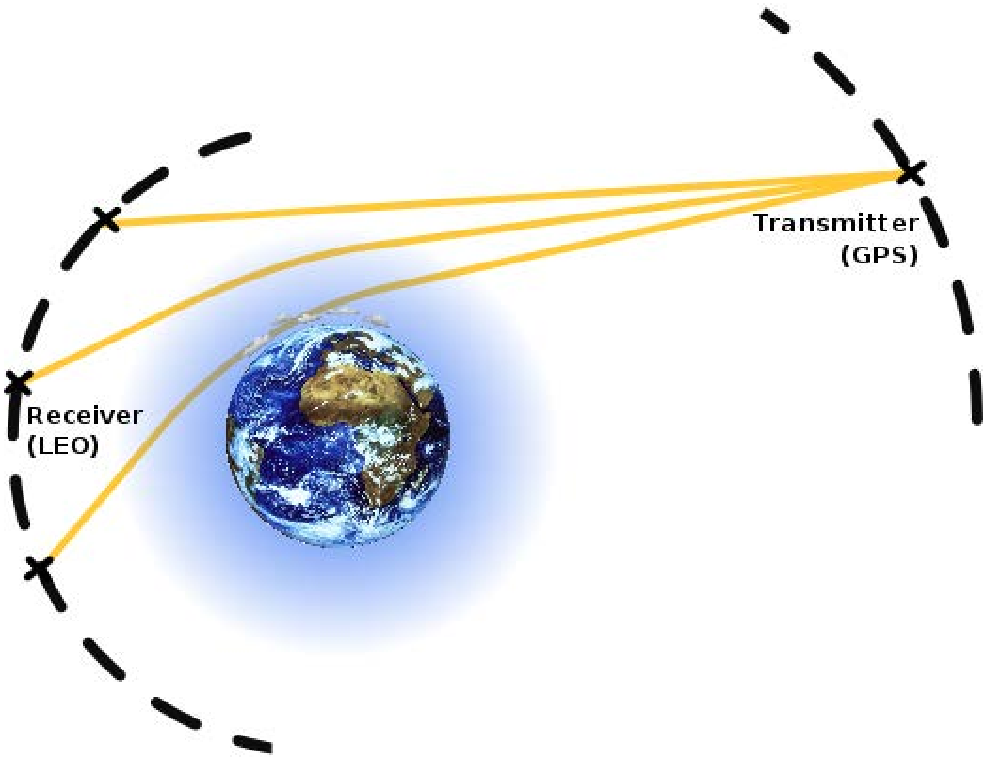
Inter-satellite radio links of GPS(GNSS) & LEO satellite constellations (RO is essentially a "planetary in-situ instrument", scale space metrics by *c* to appreciate)



- **Global Positioning System (GPS)** radio signals at 2 frequencies
  L1 1575.42 MHz (19 cm)
  L2 1227.60 MHz (24 cm)
- **Receiver on LEO satellite**
- **Occultation geometry**
- **Atmospheric refraction** of signals
- **Measurements of excess phase, based on precise (atomic) clocks**
- Retrieval of **key atmospheric/ climate parameters**
  e.g., refractivity *N*, pressure *p*, geopotential height *Z*, temperature *T*, humidity *q*

(Fig. courtesy: T. Rieckh/WEGC)

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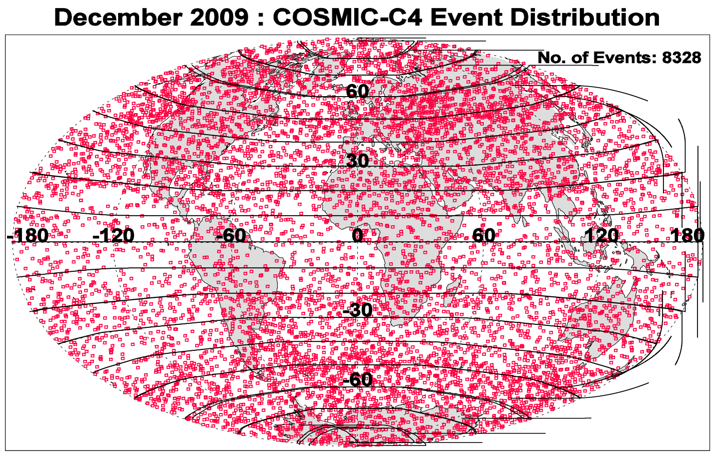
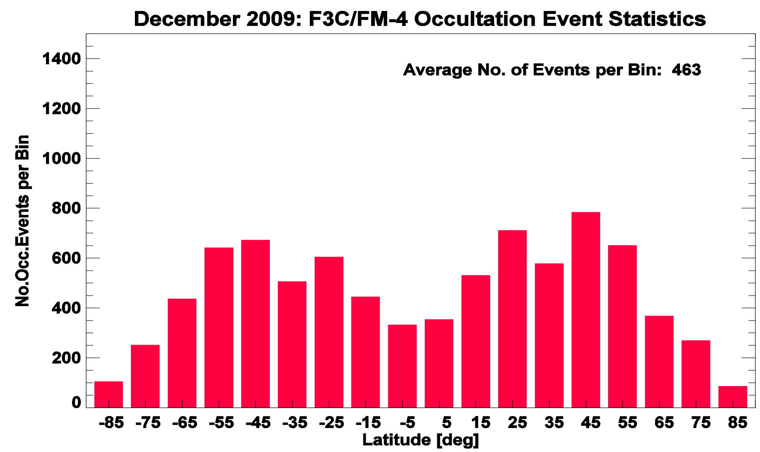
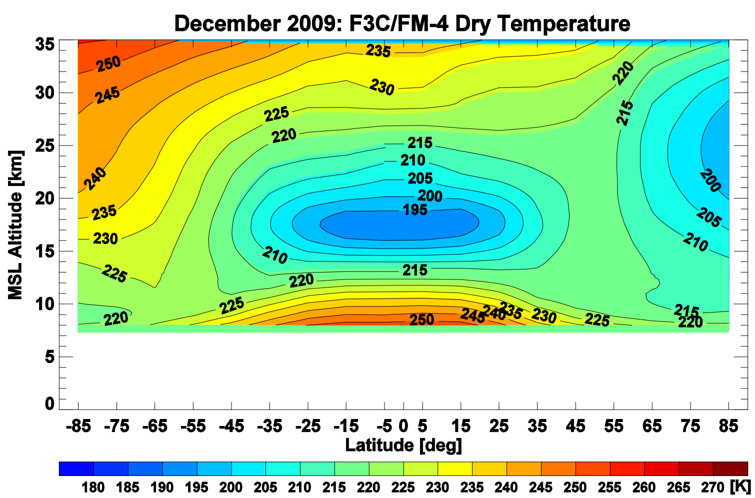
Distribution of occultation events

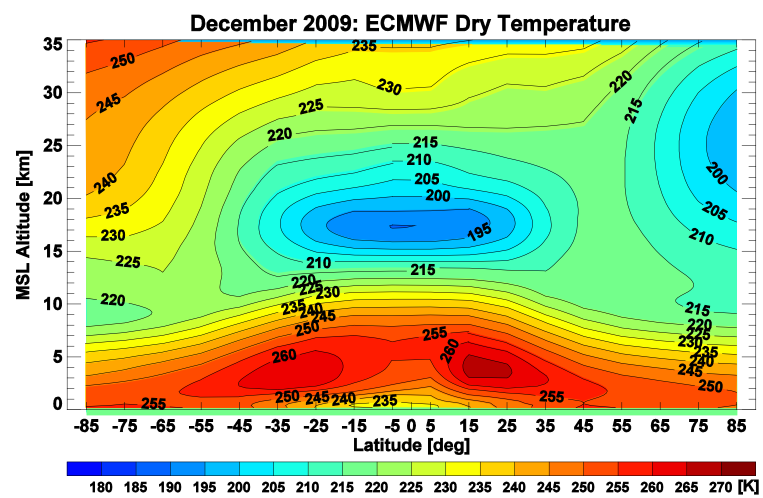


Number of profiles per 10°-bin



RO climatology Dry Temperature Reference ECMWF





http://www.globclim.org [Foelsche et al. 2008]

RO Data Characteristics

- **Global coverage**
- **All weather capability**
- **Best data quality in upper troposphere–lower stratosphere (UTLS)**
- **Vertical resolution**
  ~0.5 km to ~1.5 km in the UTLS (GO), sub-km (WO)
- **Horizontal resolution**
  ~200-300 km, synoptic scales, climate
- **Long-term stability**
  measurements based on precise (atomic) clocks (SI-traceable to time)
- **No** need of **inter-satellite calibration**
- **Error characterization** of profiles and climatological fields
- **Structural uncertainty** estimates

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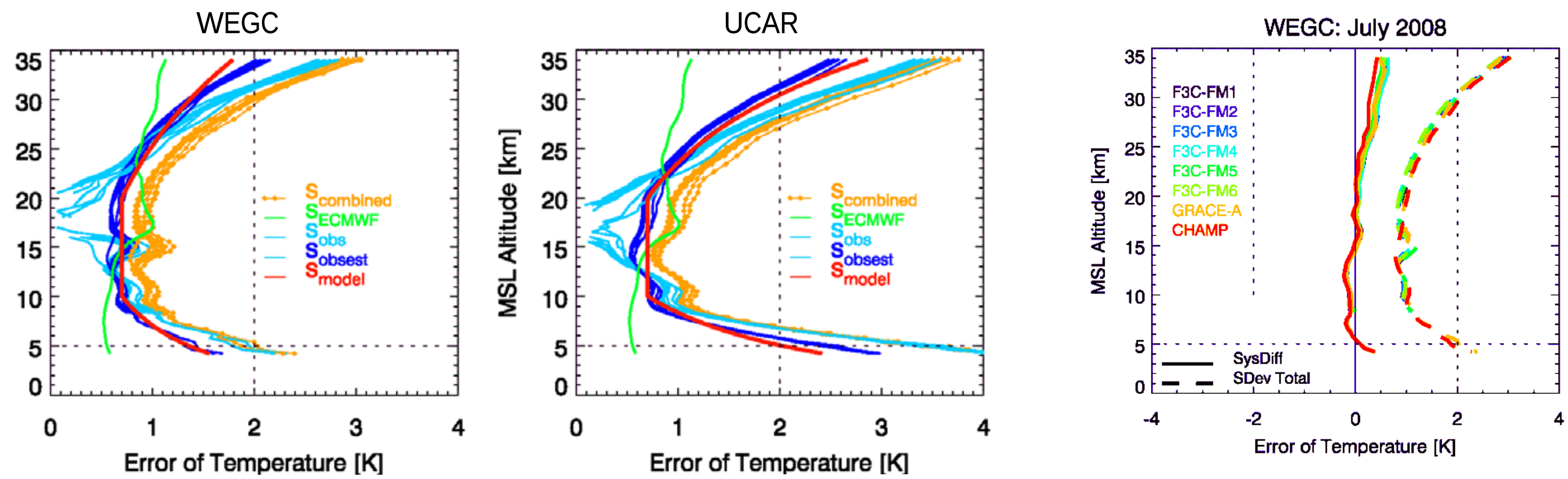
RO Data – Accuracy of Individual Profiles

- **High accuracy (individual profiles):**
  Temperature < 0.7–1 K within ~8–25 km, <2 K outside
  α < 1%, *N* < 0.5%, *p* < 0.3%, *Z* < 15 m
- Agreement in error characteristics of different missions and processing centers
- Analytical error model based on empirical error estimates



[Scherllin-Pirscher et al. 2011a]

Statistical (observational) **error**

- **<0.01–0.1 K for 10°-zonal means** averaging over profiles (~200–600)

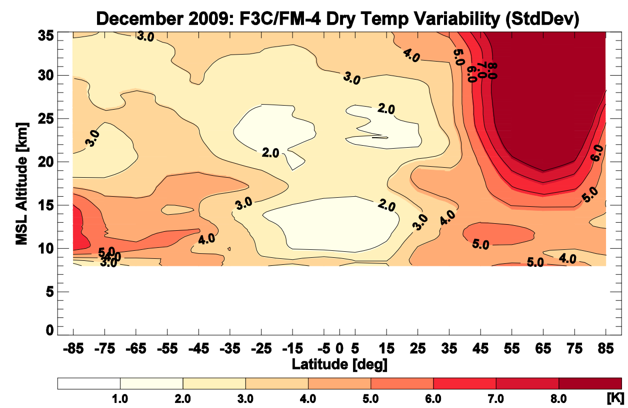
Sampling error

- **<0.3 K for 10°-zonal means** within 40°N/S, larger at high latitudes in winter
- Subtraction of SE
- **Residual SE: ~30%, <0.03–0.1 K**

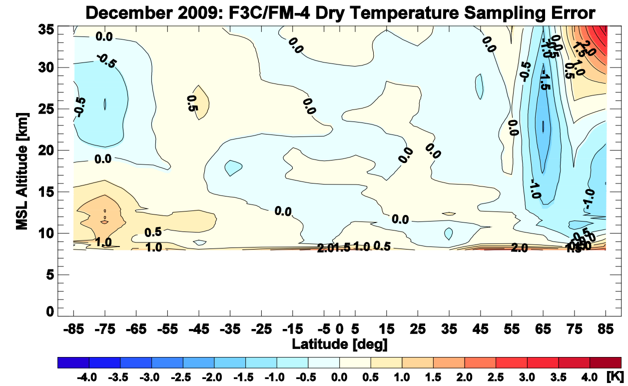
Potential residual systematic error

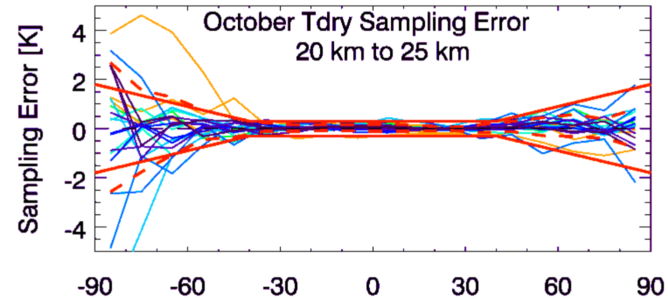
- Stratosphere: Ionospheric correction, Initialization of bending angle
- Troposphere: GPS L2 signal degraded, horizontal gradients, multipath/PBL…

Variability



Sampling error





Latitude [deg]

[Scherllin-Pirscher et al. 2011b]

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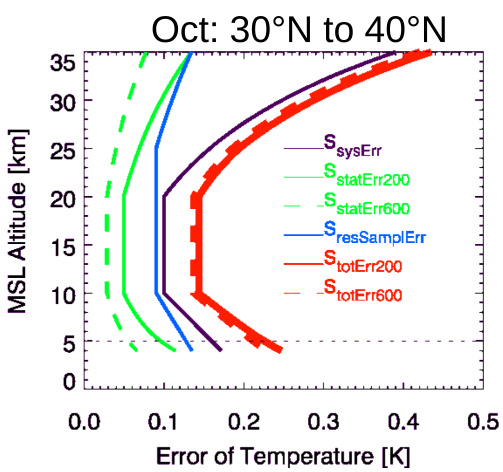
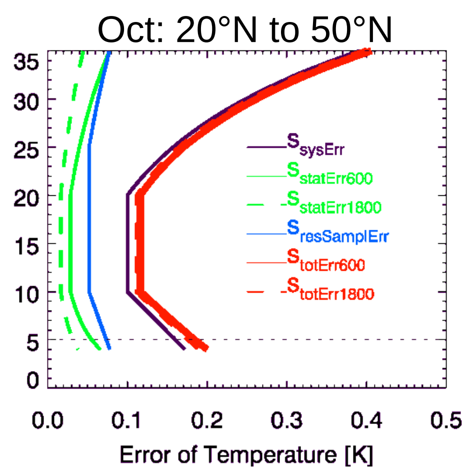
- **High accuracy (10°-zonal monthly means):**
  Temperature <0.2 K within ~8–25 km, outside ~factor 2
  α < 0.2%, *N* < 0.1%, *p* < 0.15%, *Z* < 10 m

- **Climatological error model:**
  Statistical error negligible
  Residual sampling error gets smaller for larger zonal means
  Systematic error dominating (potential residual biases, best guess)





[Foelsche et al. 2008; Steiner et al. 2009; Scherllin-Pirscher et al. 2011a,b]

Structural uncertainty in data sets

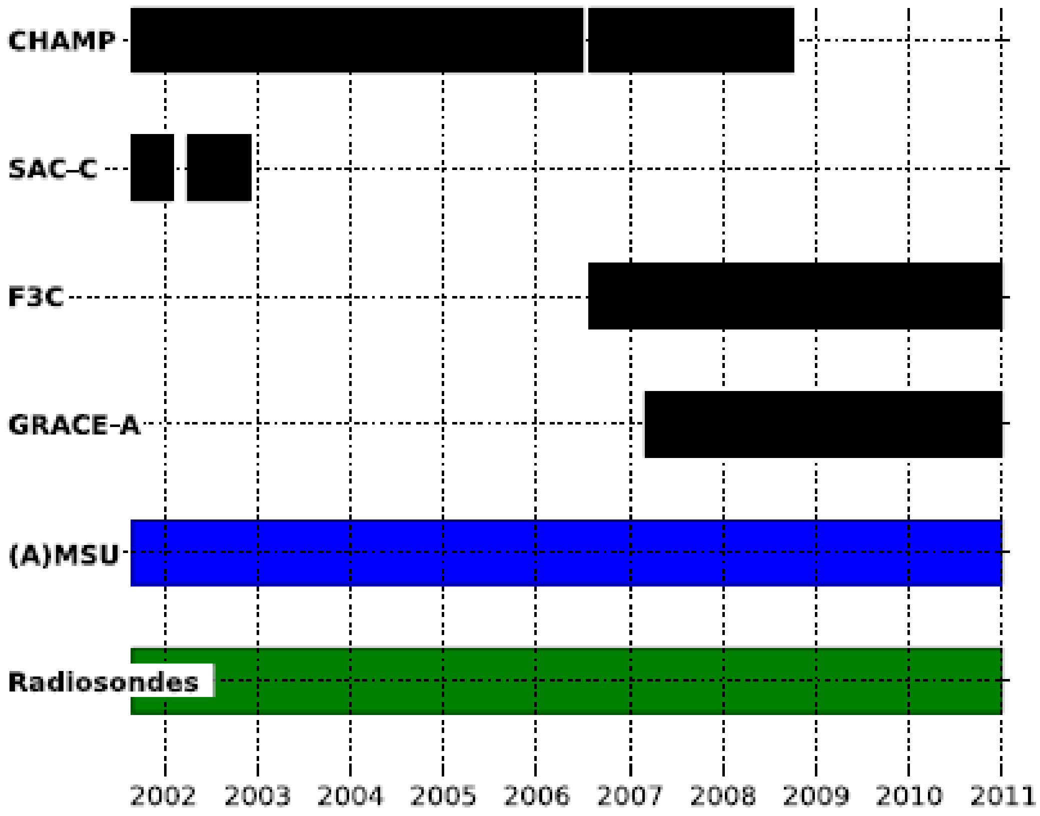
- Different methods in data processing and in the construction of climate records
- Differences in climate records from same basic measurements

Comparison of

- **Different observational upper-air data sets**
- **RO data sets of different processing centers**

Assessment of differences in TLS records: (A)MSU, radiosondes, and RO

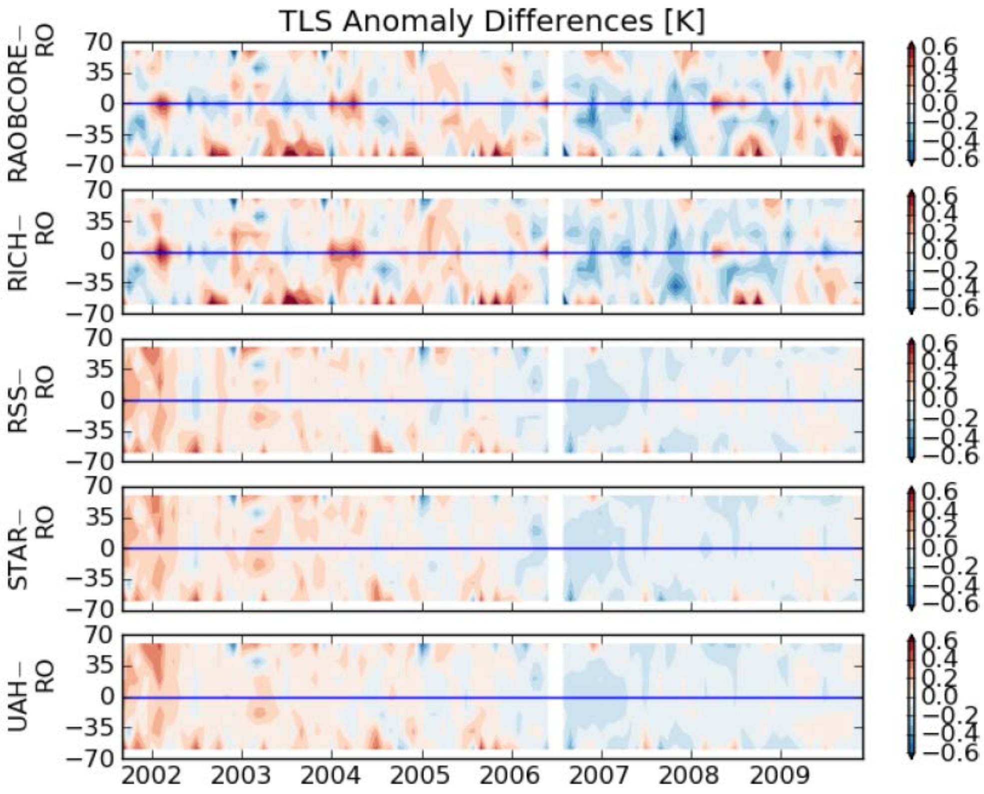
- Differencing removes climatological variability common to both data sets
- Remaining differences due to structural uncertainty

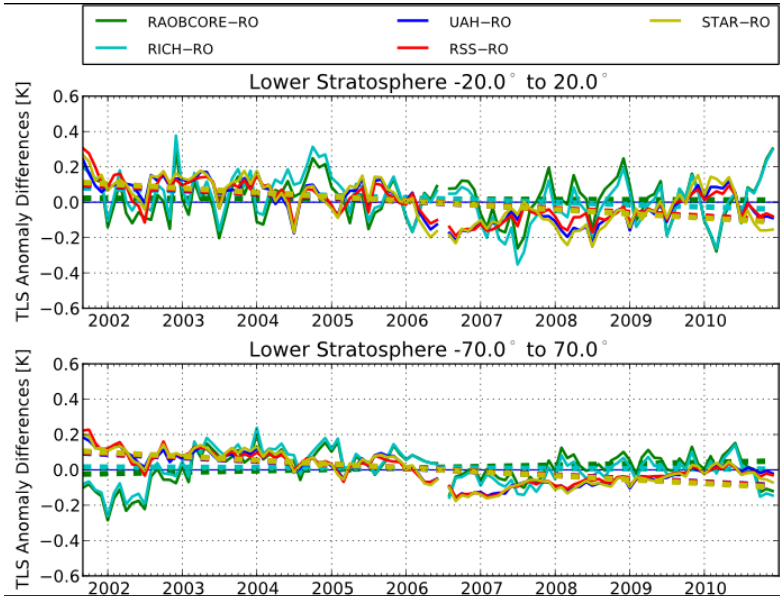


[Schroeder et al. 2003; Steiner et al. 2007; 2009; Ladstädter et al. 2011]

TLS anomaly differences and trends

- Radiosondes–RO agree well, neglible trends in their difference
- (A)MSU–RO: show statistically significant difference trend (–0.2±0.06 K)/10 yrs
- Potential errors due to RO could be ruled out (sampling error, TLS computation,…)

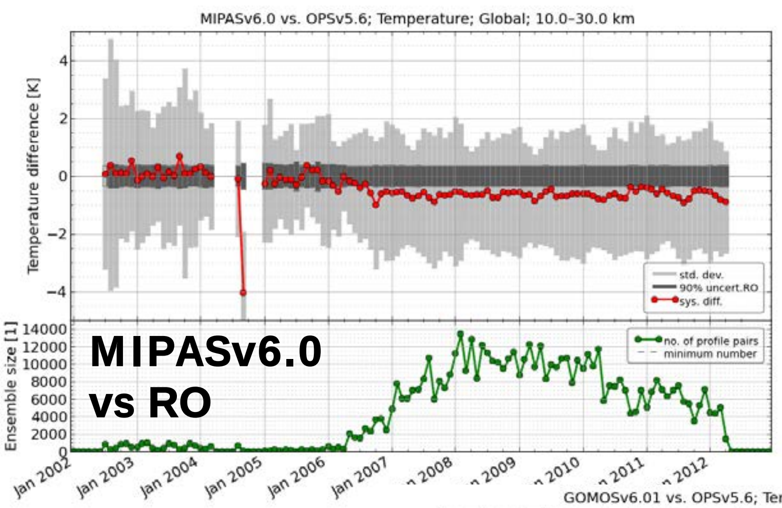


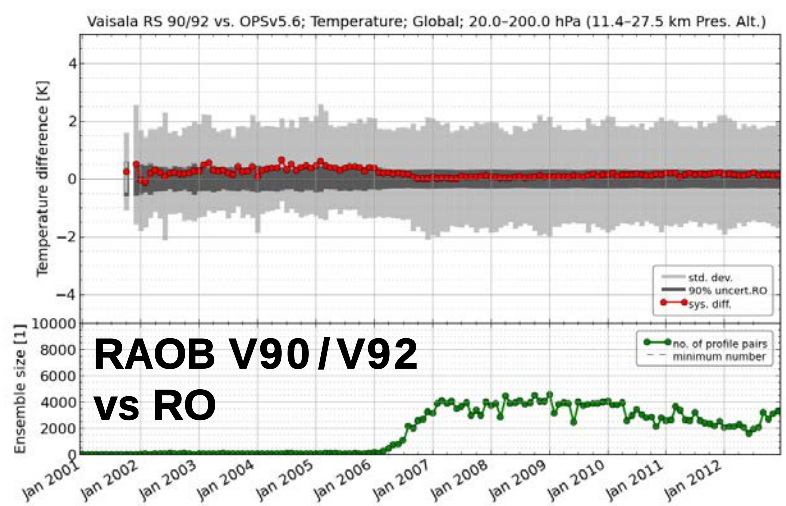


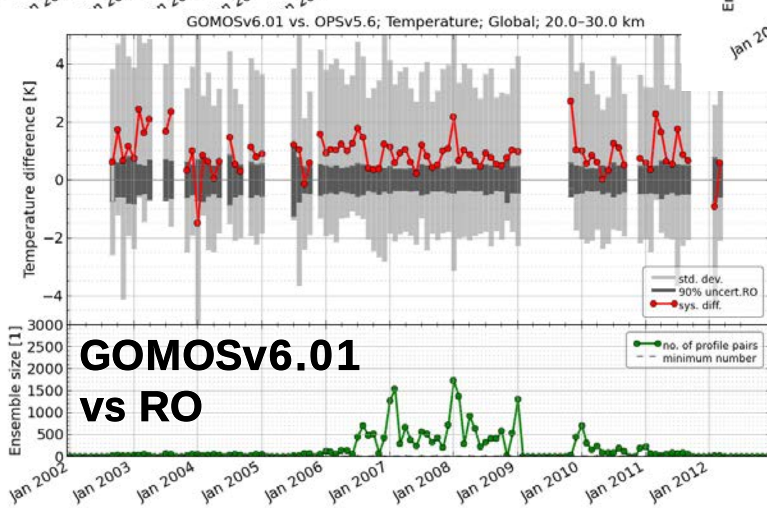
[Ladstädter et al. 2011]

Project MMValRO for ESA: Multi Mission Validation against RO

- Assess Envisat MIPAS, GOMOS & Vaisala RAOBs (here global 10/20km–30km)
- RO is a valuable reference record over complete Envisat period 2002–2012





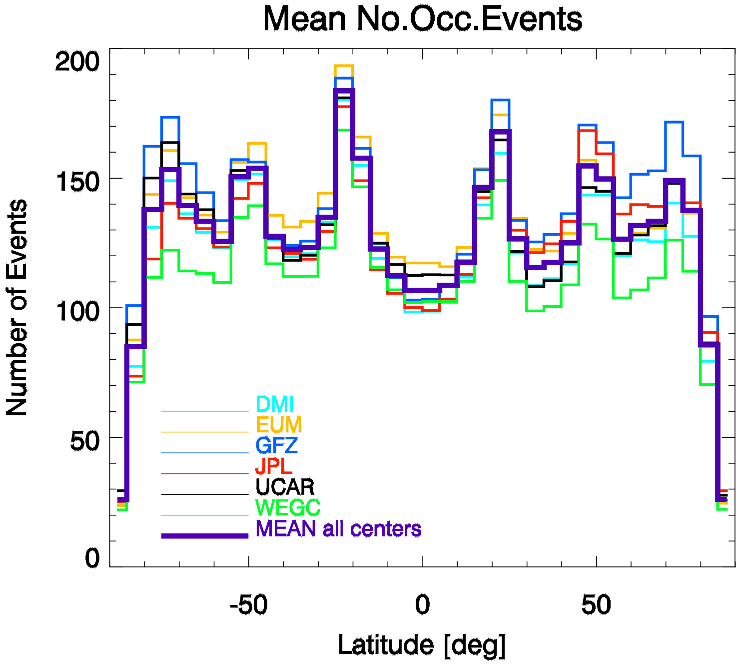


http://validate.globclim.org

[Schwaerz et al. *OPAC-IROWG* 2013; *TR ESA-ESRIN* 2013]

Assessment of differences in RO record

- Structural uncertainty of RO data due to different processing
- RO Trends Intercomparison Working Group
- Data provided by 6 processing centers
  DMI – Danish Meteorological Institute, Denmark
  EUM – EUMETSAT, Germany
  GFZ – German Res. Centre for Geosciences, Germany
  JPL – Jet Propulsion Laboratory, USA
  UCAR – Univ. Corporation for Atmospheric Res., USA
  WEGC – Wegener Center/Univ. of Graz, Austria
- CHAMP Sep 2001 to Sep 2008
- Study using same set of individual profiles [Ho et al. JGR 2012]
- Study using climatological data products; different number of profiles due to quality control [Steiner et al. ACP 2013]

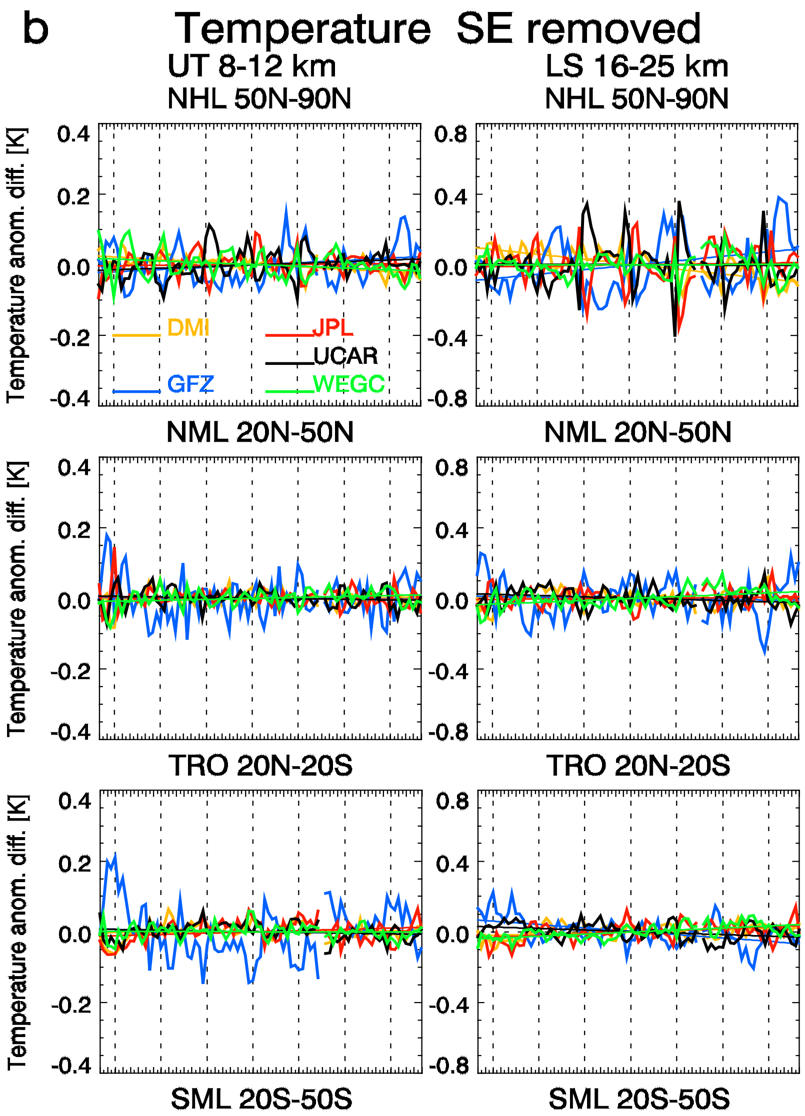


[Ho et al. 2009 *JGR* 2012; Steiner et al. *ACP* 2013]

Structural uncertainty

- low in tropics & mid-latitudes UTLS within 50°S to 50°N and 8 km to 25 km

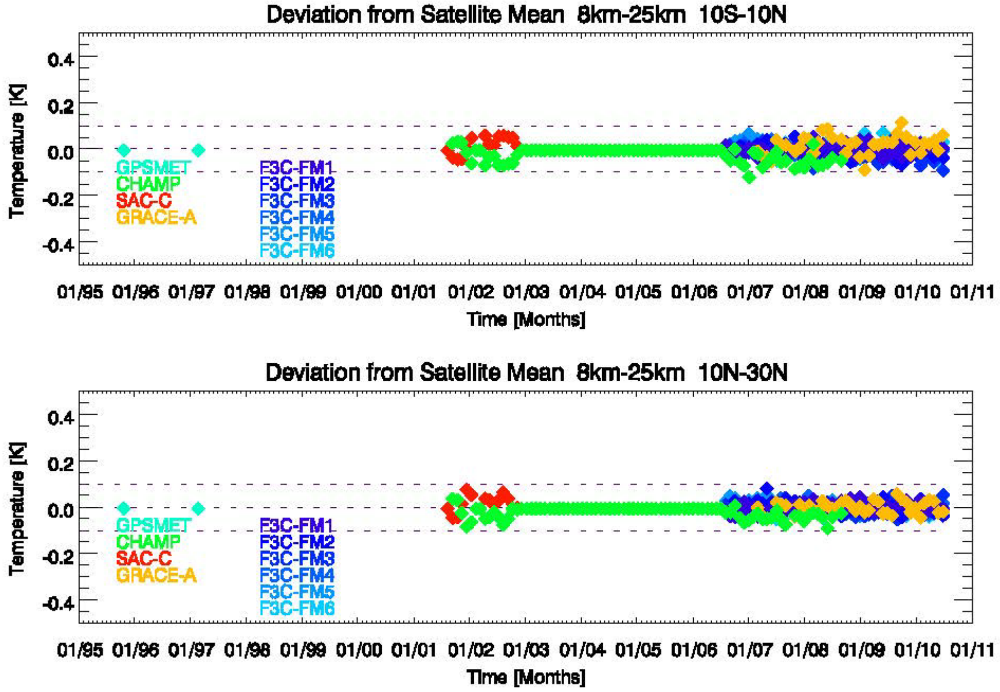
  Uncertainty in trends per 7-yrs:
- ~0.02% bending angle, refractivity
- ~0.03% for pressure (0.2–0.4% HL, LS)
- ~2.5 m for geop.height (10–20 m HL, LS)
- **~0.05 K for temperature (~0.02 K in UT, ~0.09 K in LS)**
- **fulfills GCOS requirements**
- **trends essentially independent of processing center**
- larger above 25 km and at high latitudes
- ~0.2–0.7 K >25 km
- due to different BA initialization with different background data



[Ho et al. *JGR* 2009, 2012; Steiner et al. *ACP* 2013]

- Consistency of data from different satellites
- Consistency of data from different processing centers
- RO data very useful for investigating climate variability
- Low structural uncertainty within about 50°S to 50°N and 8 km to 25 km
- RO data can be used for climate trend detection in this region

Consistency of data from different satellites



[Ho et al. *JGR* 2009; Steiner et al. *RS* 2009; Foelsche et al. *TAO* 2009, *AMT* 2011]

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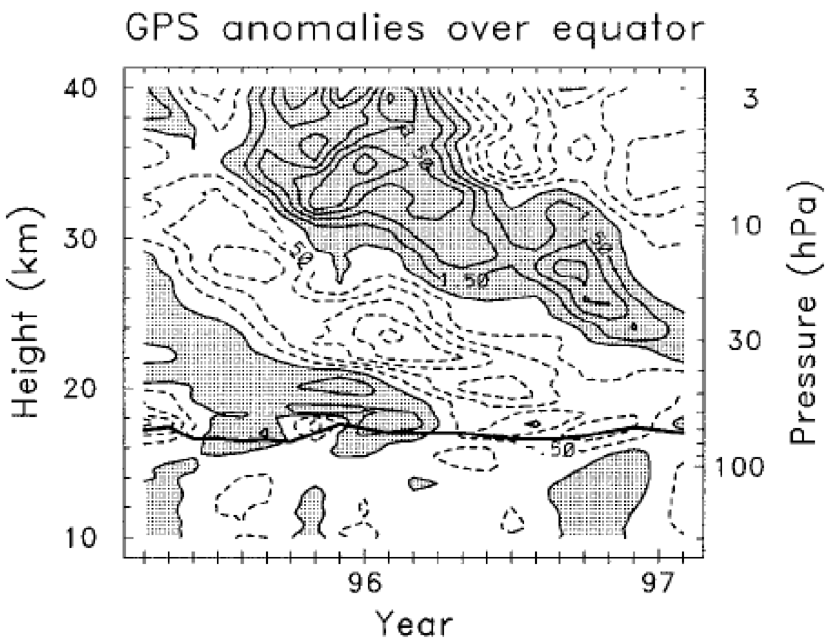
Monitoring UTLS climate variability – a few examples

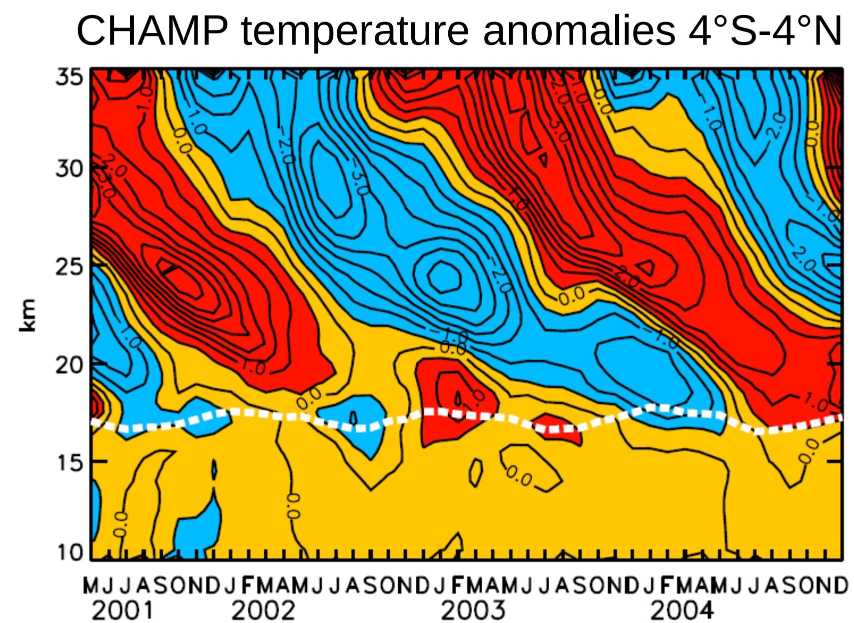
- Quasi-Biennial Oscillation
- El-Niño Southern Oscillation
- Madden-Julian Oscillation
- Diurnal tides

- Tropopause variability
- Sudden stratospheric warmings
- Geostrophic winds
- Convective systems

QBO pattern in RO anomalies

- Tropical lower stratosphere, ~5°S–5°N, ~28 months period
- Seasonal changes in radiative heating
- Downward propagating wind/temperature anomalies
- up to about ±6 K at ~16–30 km

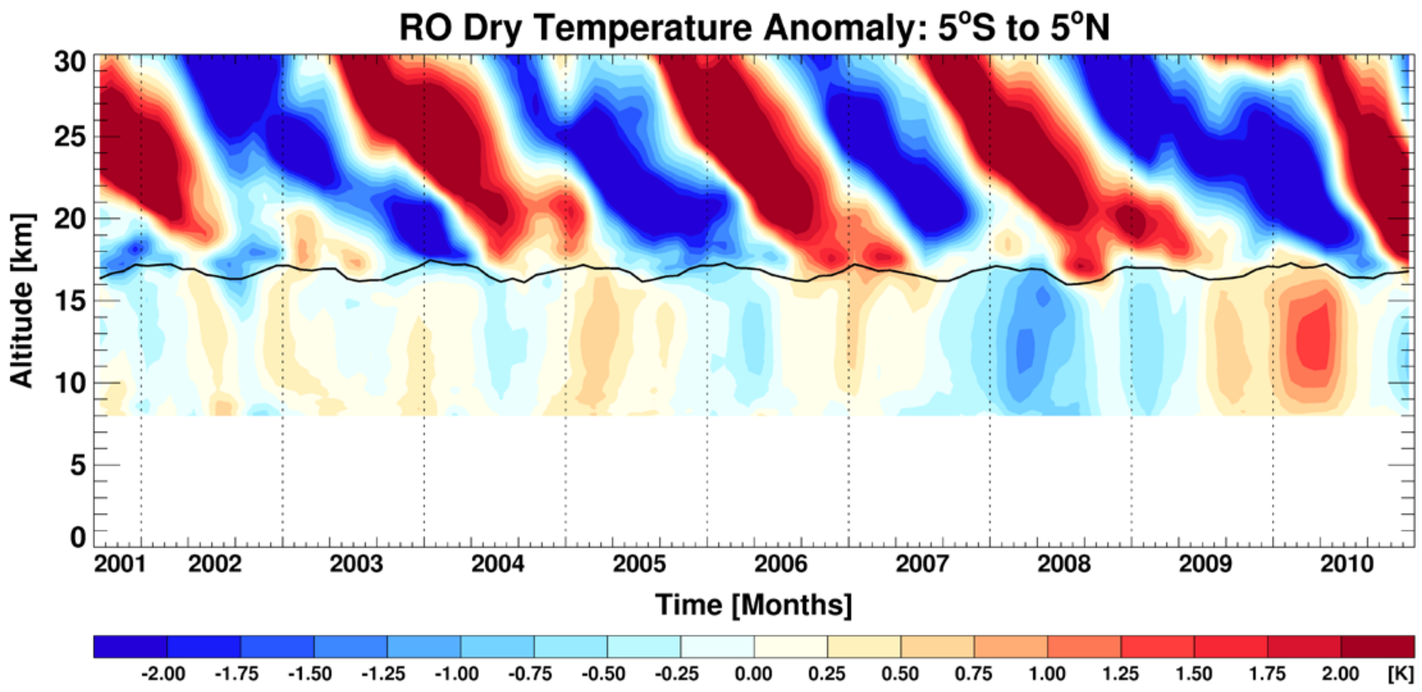




[Randel et al. 2002; Schmidt et al. 2004;2005]

El Niño Southern Oscillation (ENSO)

- Phenomenon with quasi-periodicity of 3 to 7 years **in troposphere**
- changes in sea surface temperature of tropical Pacific
- ocean-atmosphere coupling
- **ENSO, QBO – natural variability modes in trend detection**



[Scherllin-Pirscher et al. 2012]

Madden-Julian Oscillation in RO Parameters

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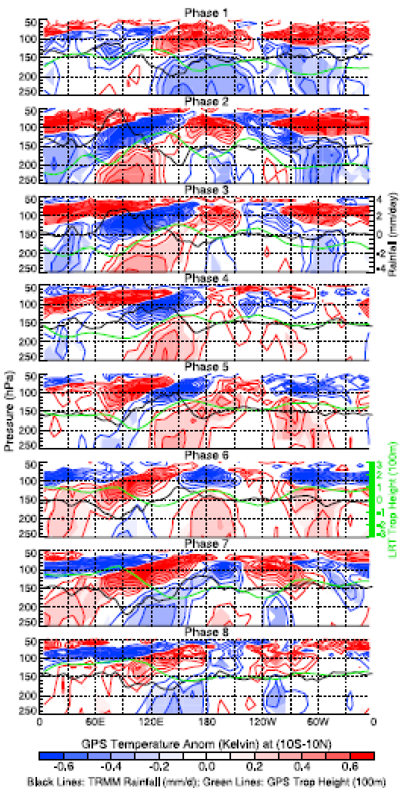
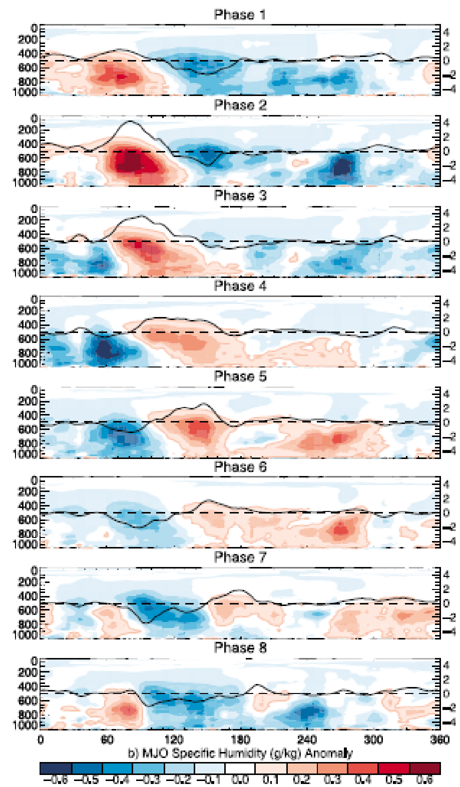
Structural evolution of the Madden-Julian Oscillation (MJO)

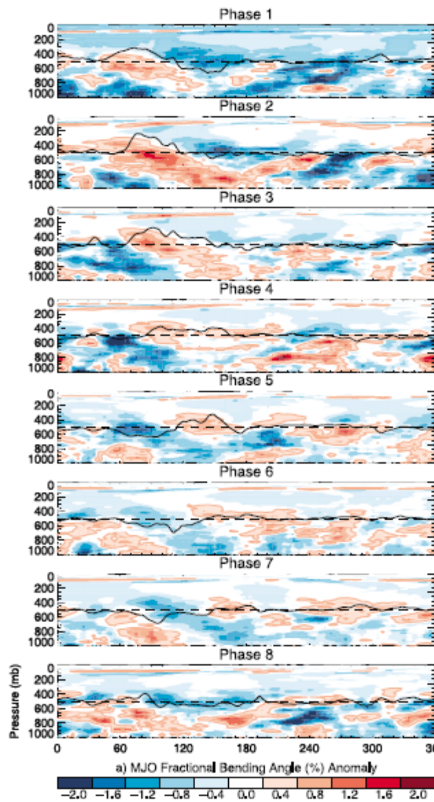
- Tropics, Indian, Western Pacific, period between 30 and 90 days,
- Large-scale coupled patterns in atmospheric circulation and deep convection
- Slowly eastward moving center of deep convection and precipitation



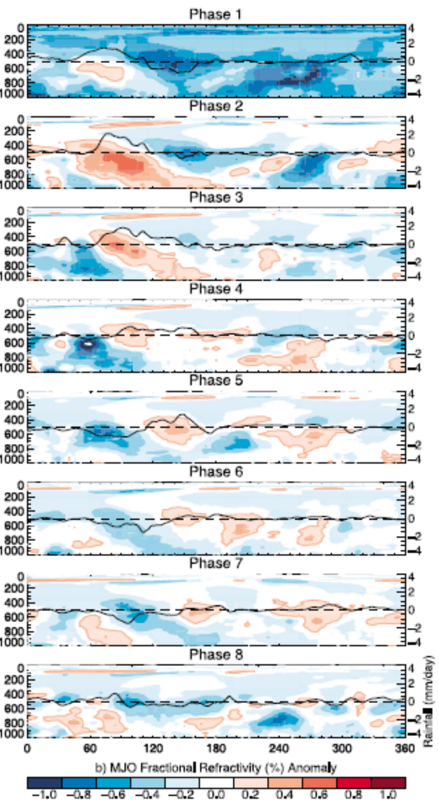
Temperature



Spec. humidity



Bending angle



Refractivity

[Tian et al. 2012; Zeng et al. 2012]

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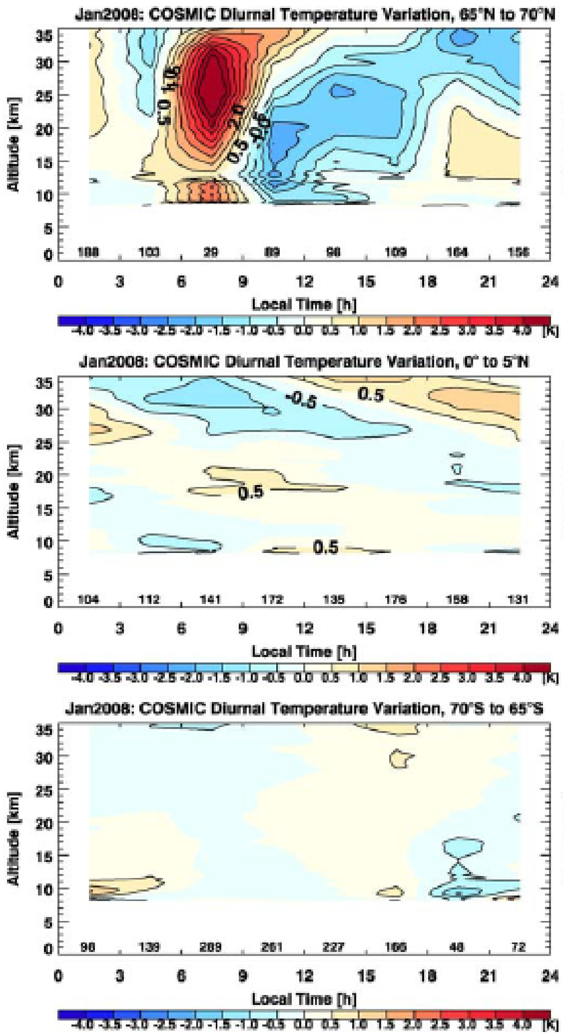
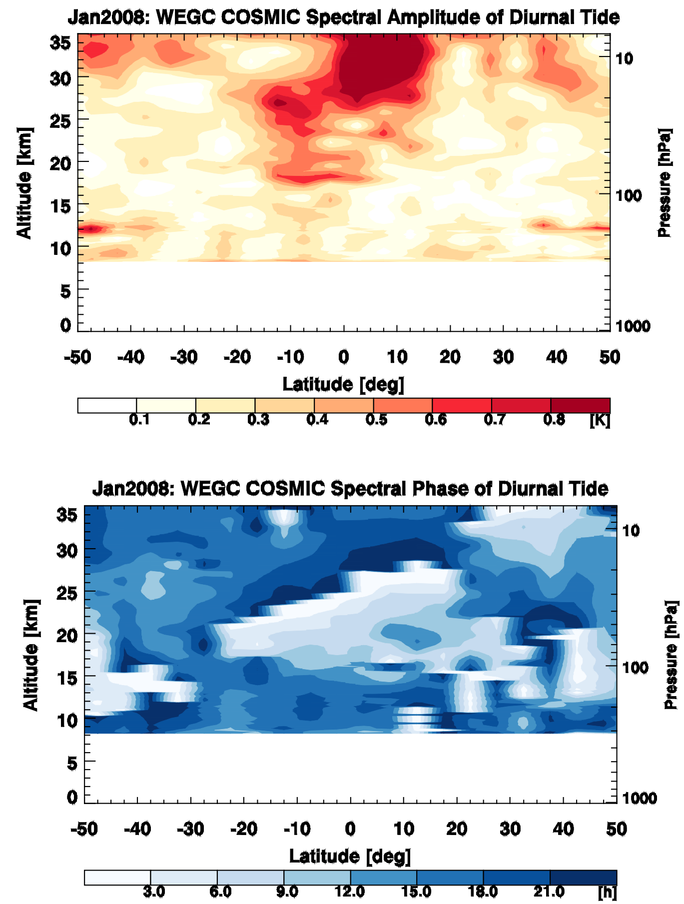
Utility of RO data for monitoring diurnal tide dynamics

Diurnal temperature variations



Spectral amplitude and phase of westward propagating diurnal tide



[Pirscher et al. *JGR* 2010]

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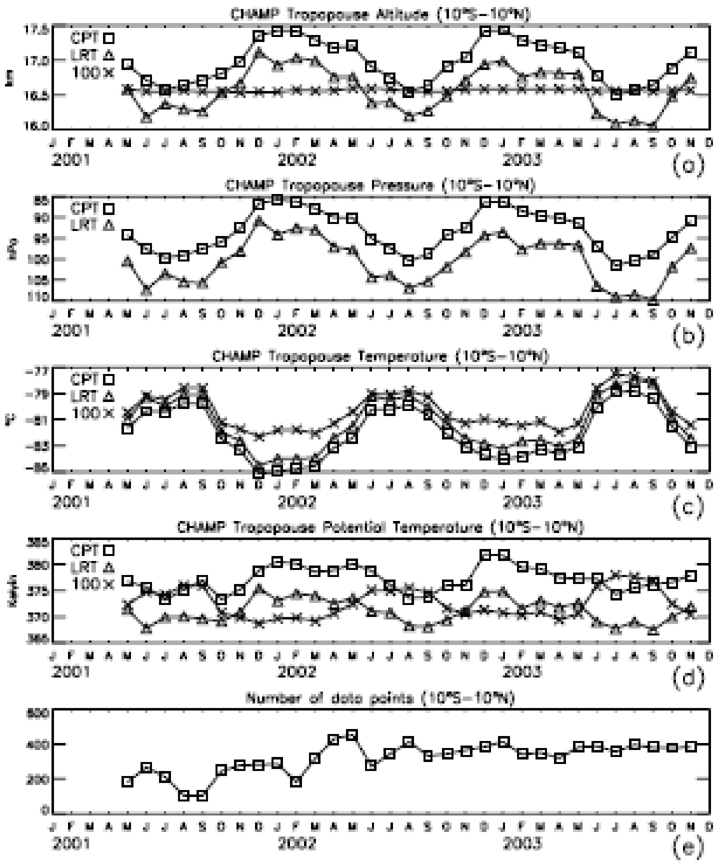
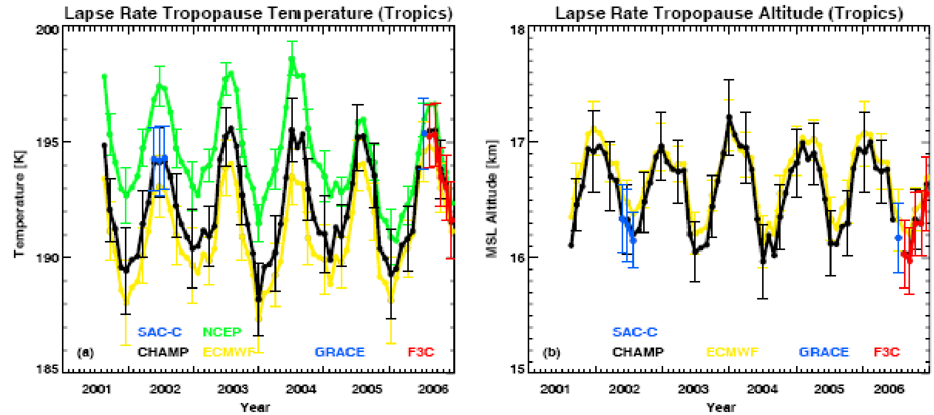
Insights into tropopause variability from RO

- Monitoring of tropical tropopause variability
- Tropopause parameters (CPT, LRT, altitude, temperature) and climatologies

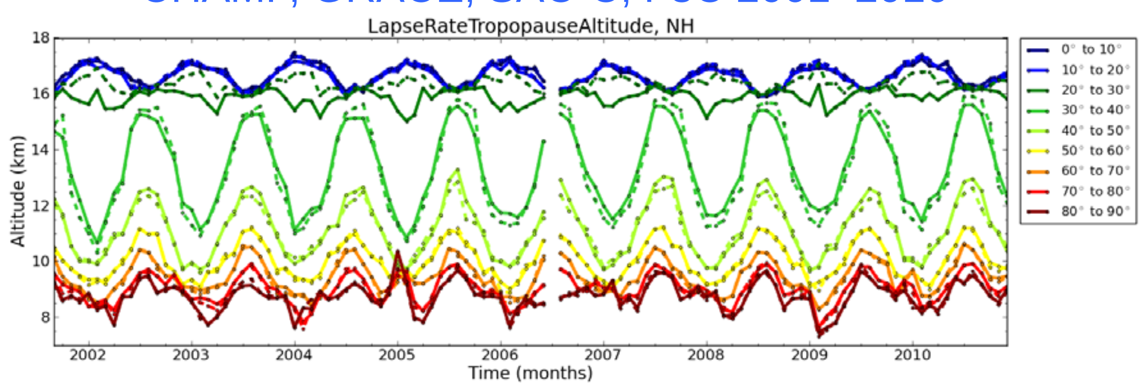
CHAMP 2001–2003



CHAMP, SAC-C, F3C 2001–2006



CHAMP, GRACE, SAC-C, F3C 2001–2010



[Schmidt et al. 2004; Borsche et al. 2007; Foelsche et al. 2009; Rieckh et al. 2014]

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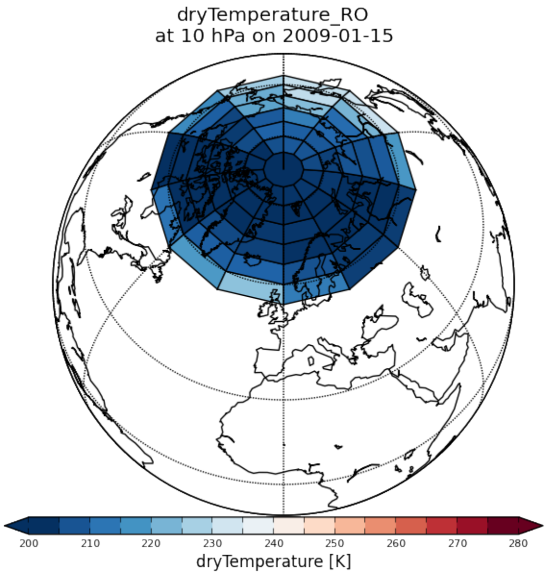
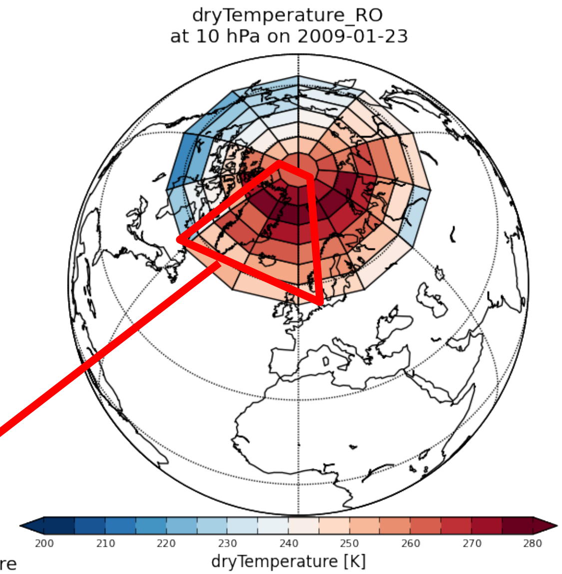
Recent insights into sudden stratospheric warmings (SSW)

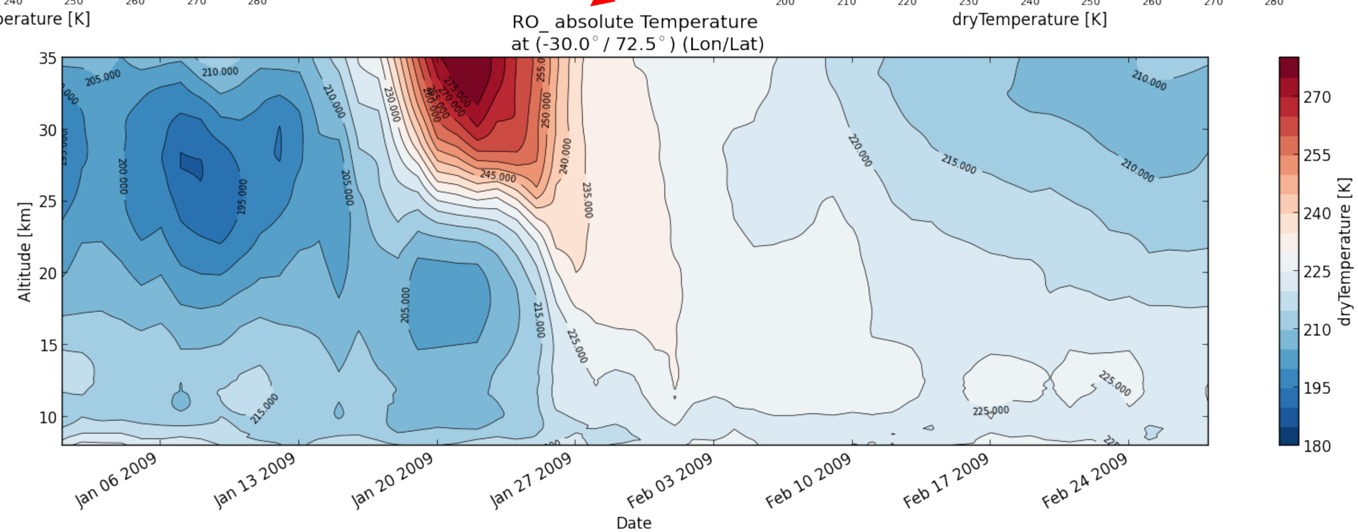
- Evolution and structure of SSW (example January 2009)



Δt = 8 days

ΔT_{dry} >70 K

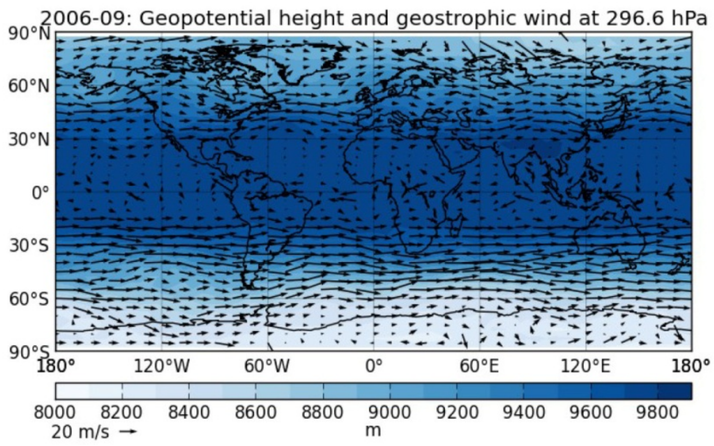


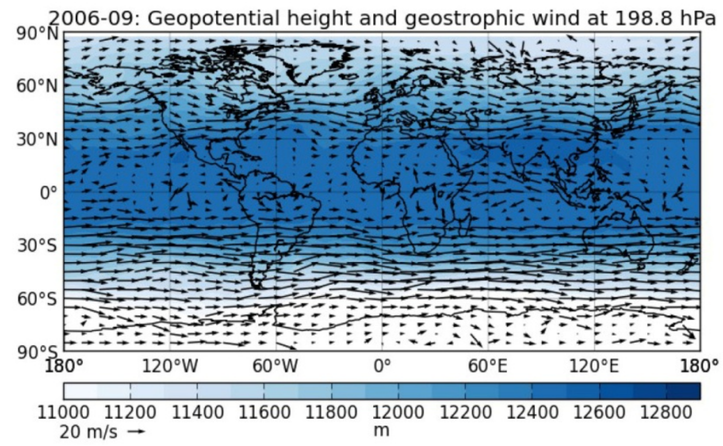


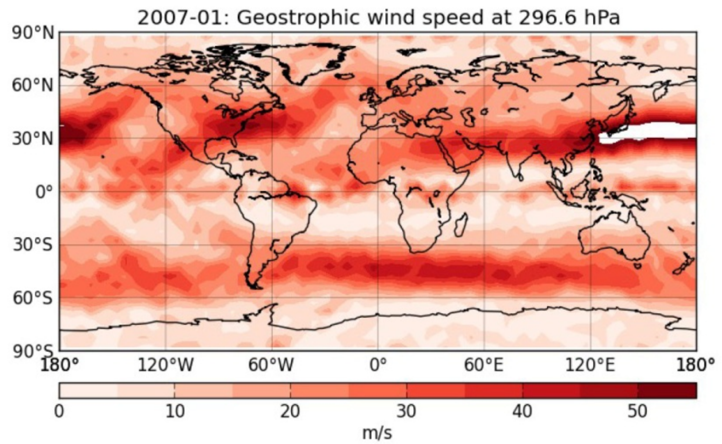
[Klingler et al. *MSc thesis* 2014]

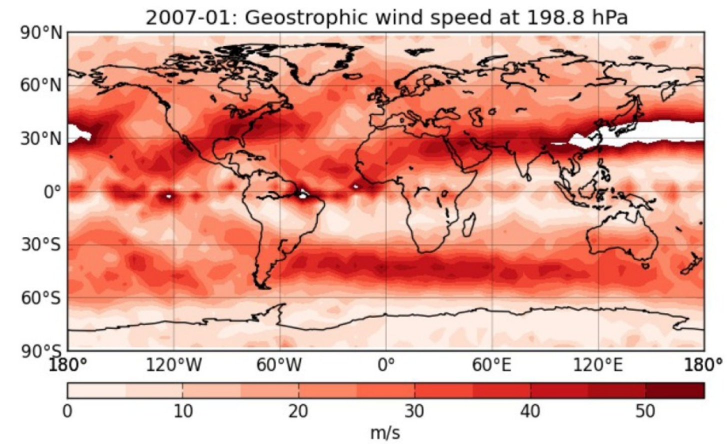
Recent insights into the characteristics of geostrophic winds

- Estimation of geostrophic wind fields from RO geopot.height field gradients (just a few indicative draft-figs of Sep and Jan example months here)









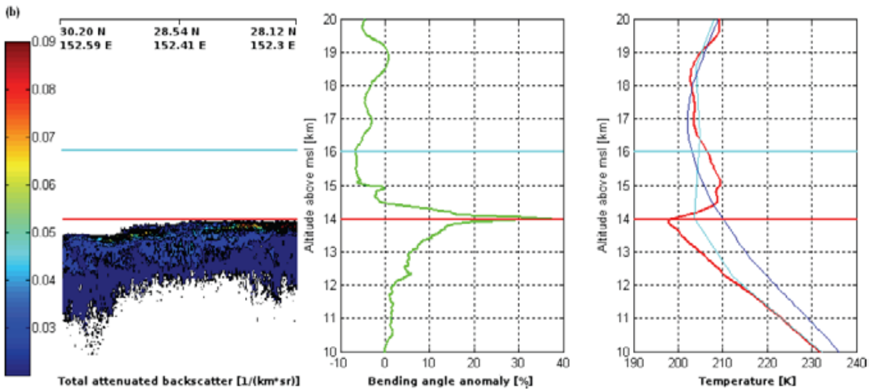
[Scherllin-Pirscher et al. 2014]

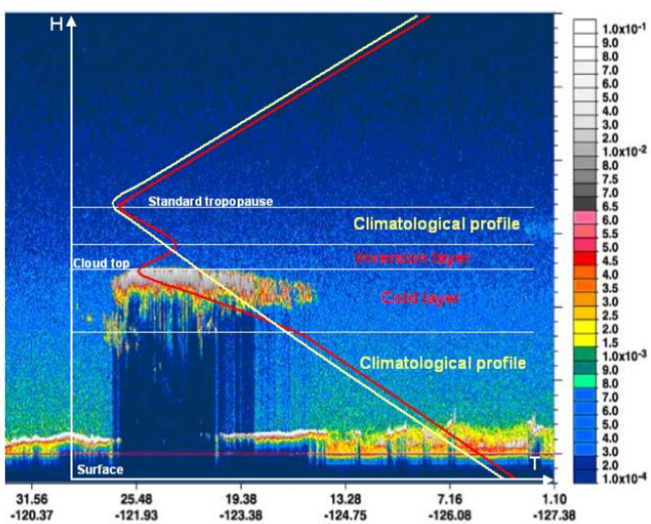
Wegener Center

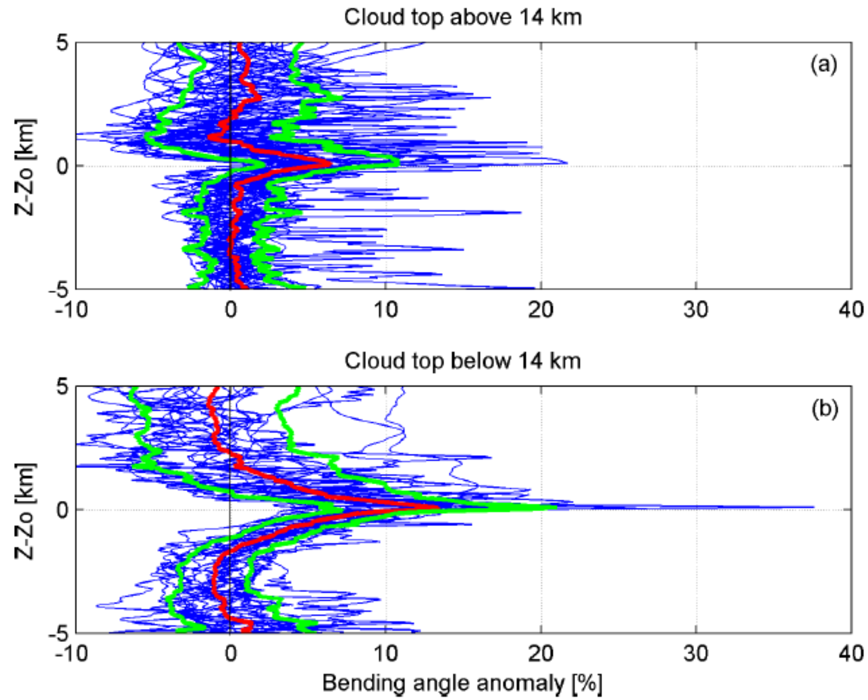
UNI GRAZ

Recent insights into thermal structure of convective cloud systems

- For example, detection of cloud top height using RO bending angle anomalies



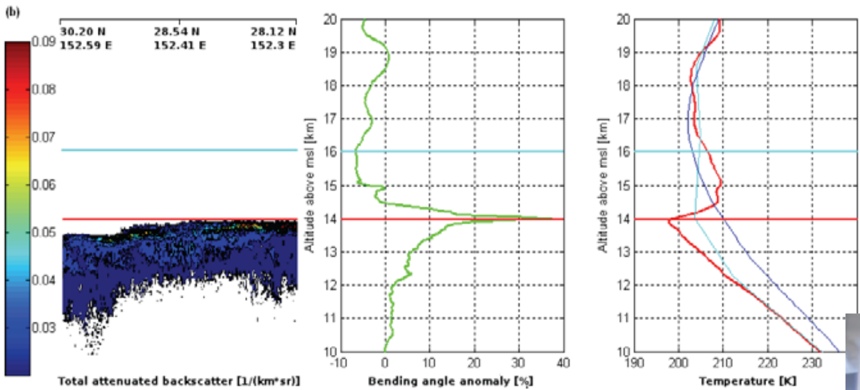


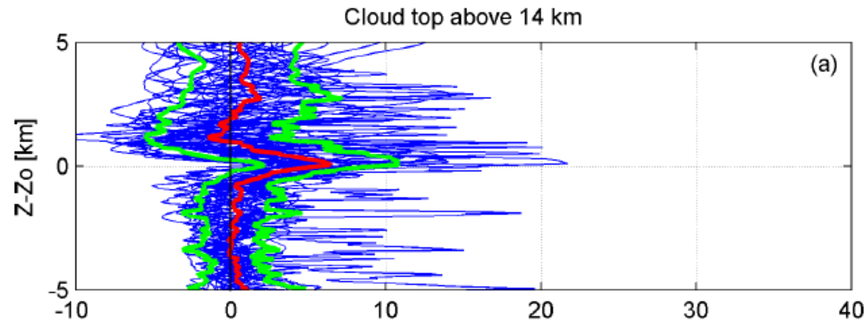


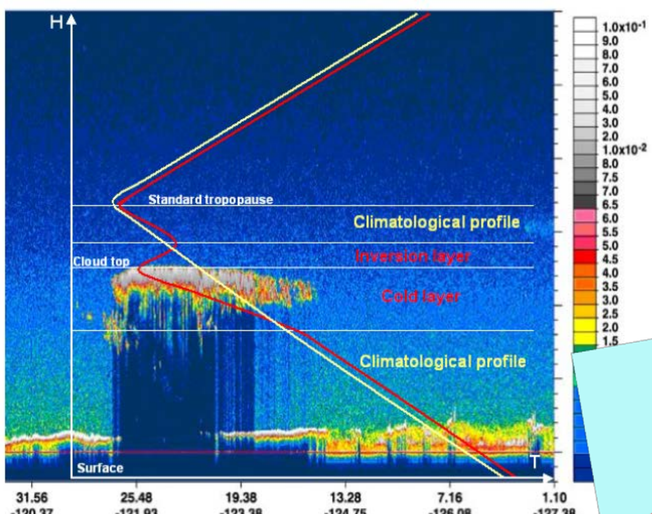
[Biondi et al. 2010, 2011, 2014]

Recent insights into thermal structure of convective cloud systems

- For example, detection of cloud top height using RO bending angle anomalies







Most recent and MOST CUTE detected little "system":
top height observed: 53 cm
WELCOME Next Gen RO Scientist
Noah Biondi, borne 11 June 2014! ☺

[Biondi et al. 2010, 2011, 2014]

Presentation Outline

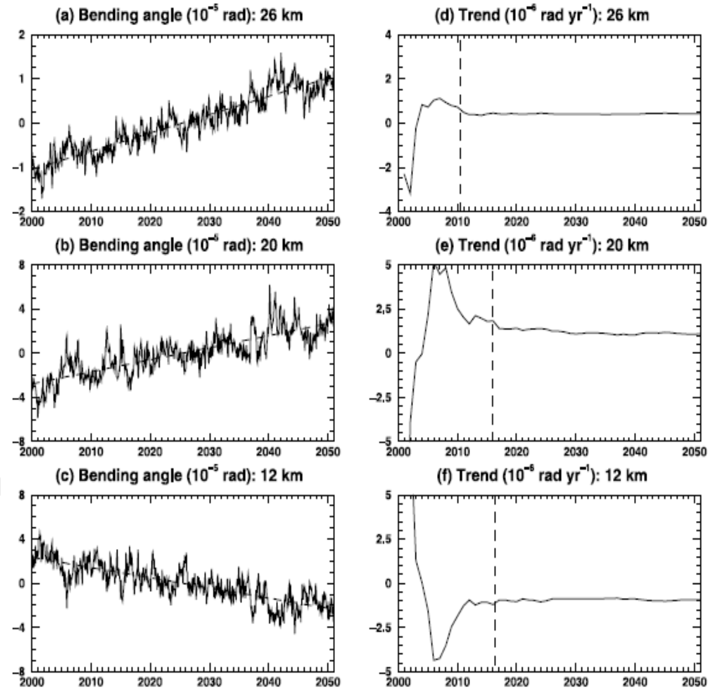
- Context and background
- Characteristics of RO data
- Accuracy and structural uncertainty
- Monitoring climate variability
- **Climate change monitoring and trend detection**
- Conclusions and outlook–towards SI-traceable records

Climate change and trend detection studies

- based on models and simulations
- based on real observations

Climate change studies using models and simulations

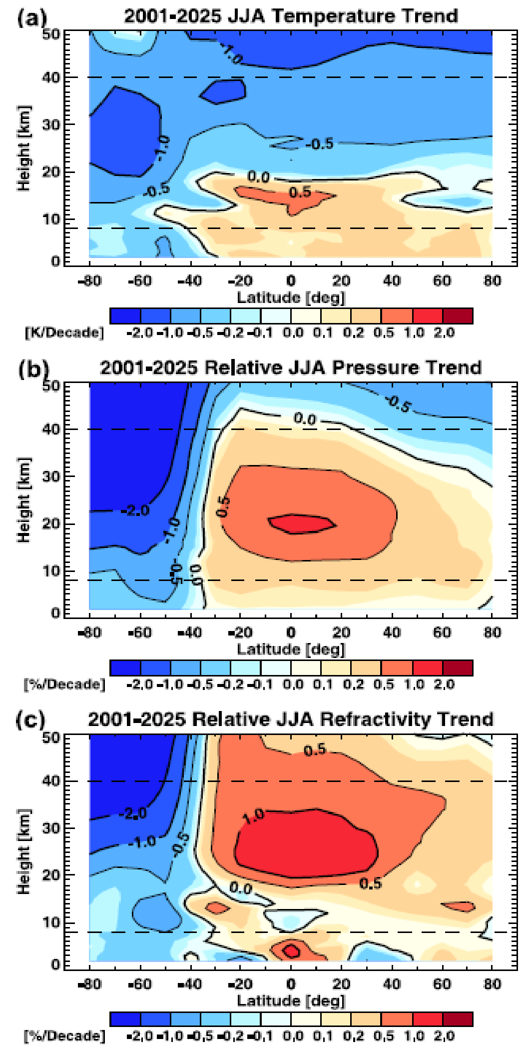
- *Yuan et al.* [1993]:
  "Simulations show the potential of GPS RO for the detection of climate change"
- *Leroy* [1997] :
  geopotential height useful for climate monitoring
- *Vedel and Stendel* [2003],
  Stendel et al. [2006]:
  Refractivity useful for climate monitoring
- *Leroy et al.* [2006]:
  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.



[Ringer and Healy 2008]

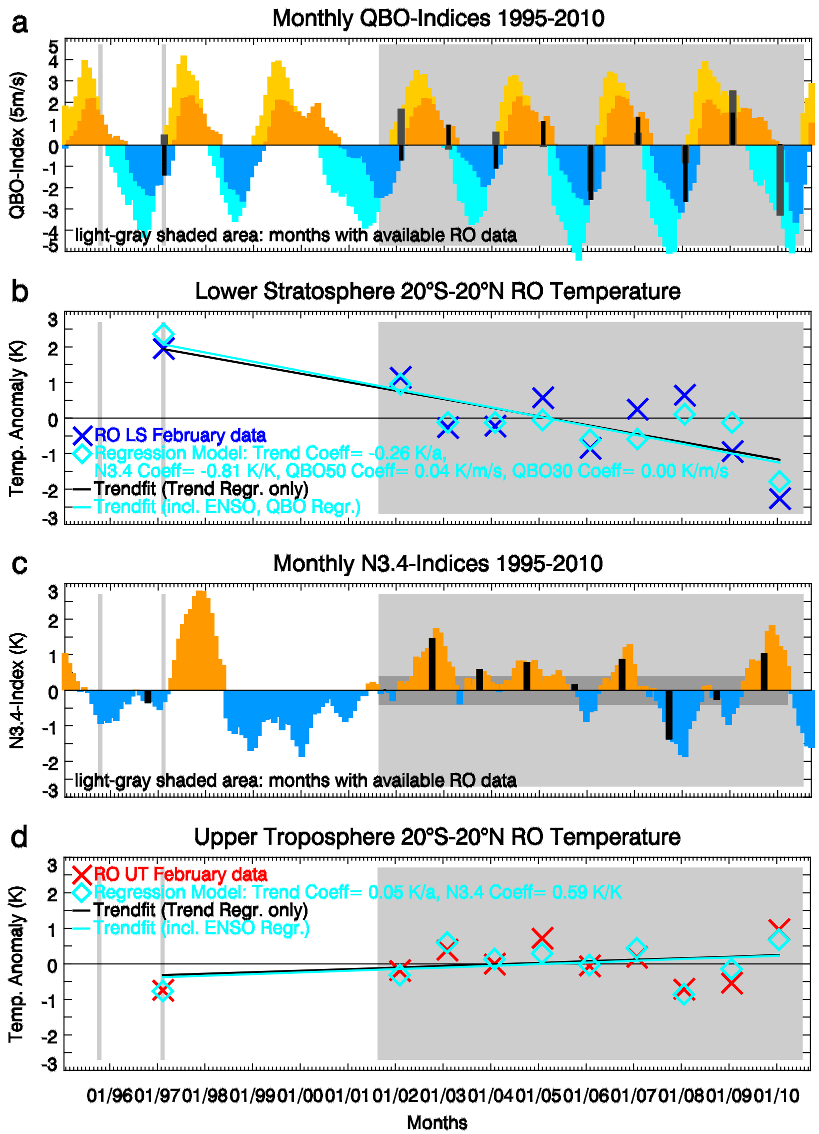
Climate observing system simulation experiment (Clim.OSSE)

- test climate change monitoring capability of RO
- RO-accessible parameters
  refractivity, pressure/geop. height, temperature
- show complementary climate change sensitivity in different regions of the UTLS
- combined information of RO parameters is of high value for UTLS climate change monitoring



[Steiner et al. 2001; Foelsche et al. 2008; Lackner et al. 2011]

Trend Detection with RO Data – Multiple Regression



QBO Index: 50 hPa & 30 hPa winds

- Shows no appreciable influence

Lower stratosphere, tropics

- A significant cooling trend, relative to inter-annual and to natural variability, was found in *February* 1997, 2002–2010.

ENSO Nino3.4 index

- Explains most of UT variability and 50 % variability in LS

Upper troposphere, tropics

- no detectable trend so far

[Steiner et al. *GRL* 2009; Steiner et al. *Radio Sci*. 2011]

Trend Detection with RO Bending Angle Data

Variability and trends in UTLS

- Bending angle and temperature trends
- Upper tropospheric warming – bending angle decrease
- Lower stratospheric cooling – bending angle increase

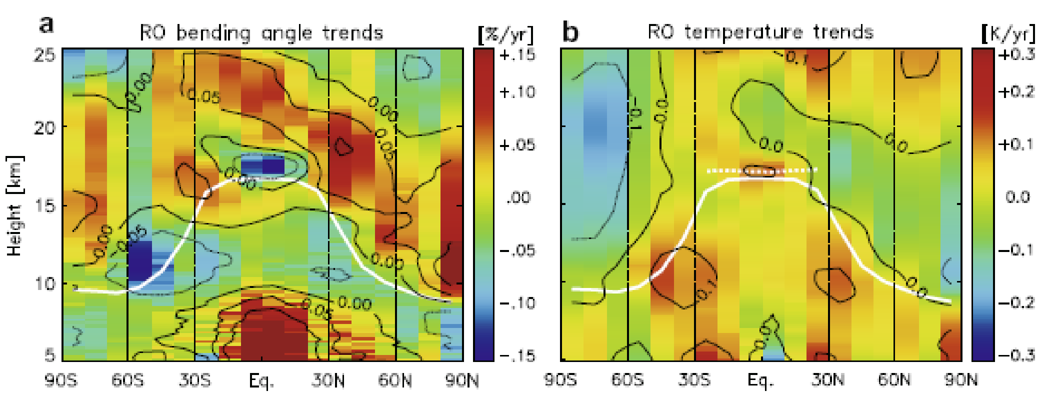


Fig. 10. Relative bending angle trends [%/yr] (a) and absolute temperature trends [K/yr] (b) from CHAMP and GRACE data (May 2001–August 2009).

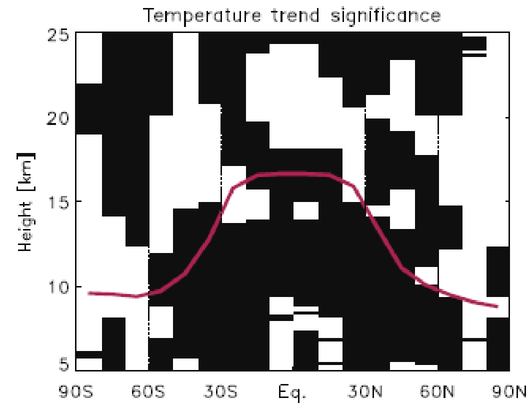


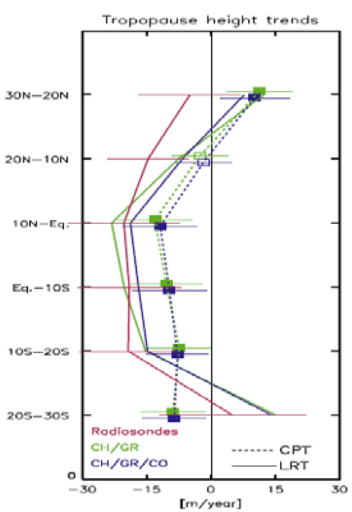
Fig. 11. Statistically significant temperature trends (C.I.=90%; *SIG* > 1.6

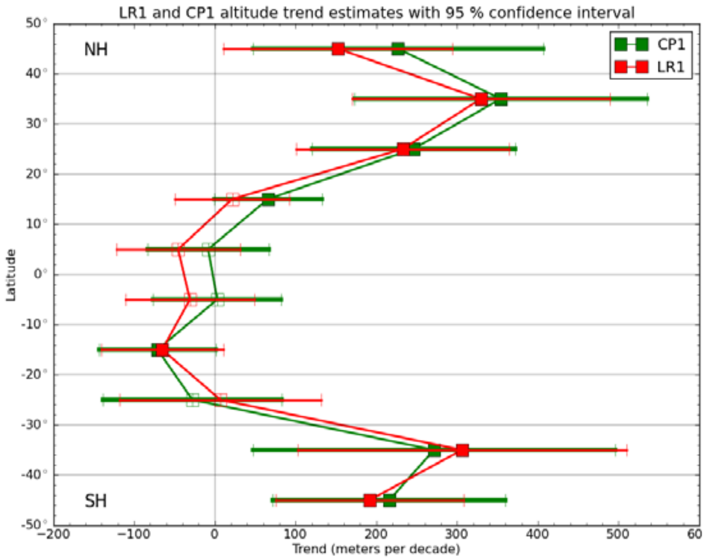
[Schmidt et al. 2010]

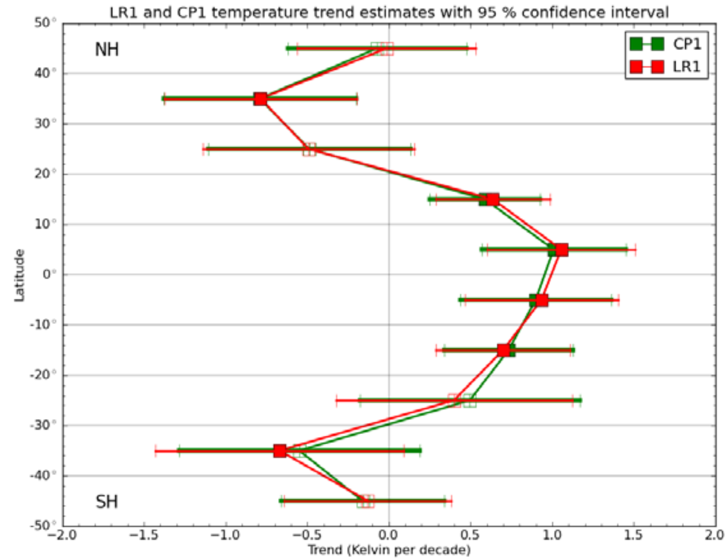
Insights into (emerging) tropopause trends over the recent decade

- Tropopause height decrease in tropics of down to around –70 m/decade and increase at mid-latitudes of up to around 300 m/decade (not stable yet, though)
- Tropopause temperature increase in the tropics of up to around 1 K/decade and decrease at mid-lats of down to around –0.7 K/decade (also not yet stable)

(large uncertainty ranges still, increasingly longer record will help further stabilize)

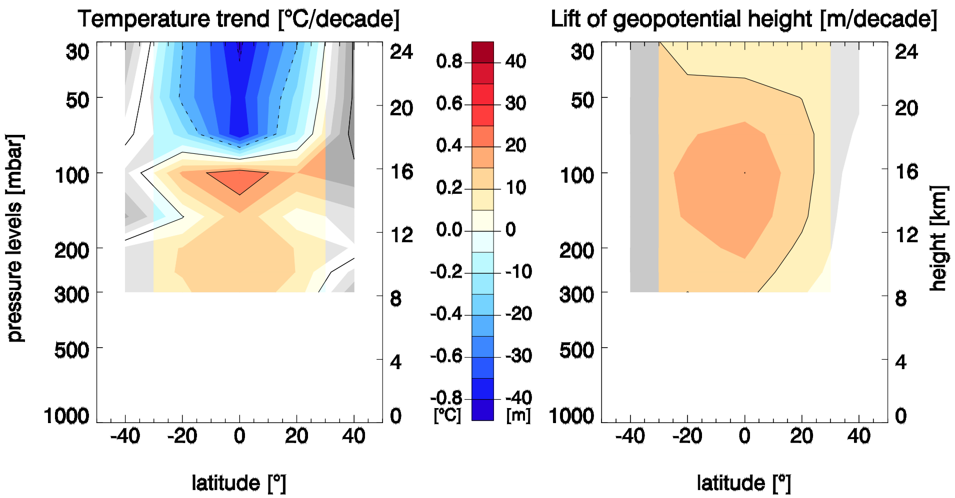


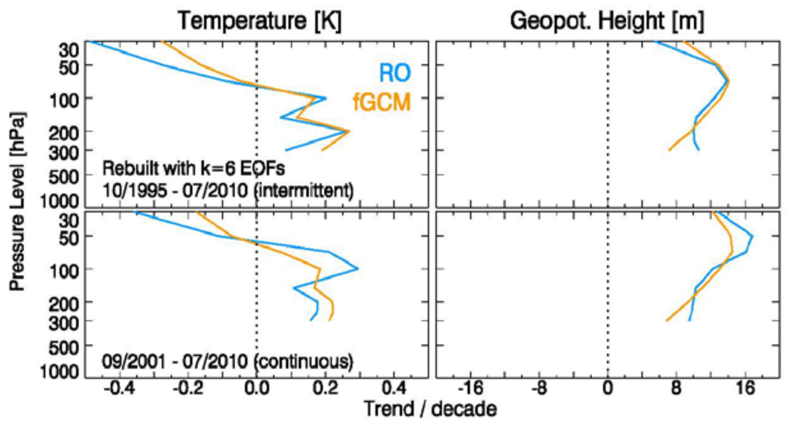




[Schmidt et al. 2010; Rieckh et al. 2013]

Optimal fingerprinting – climate change signal detected





Mean Trend 50°S–50°N

- 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

  [Leroy et al. JGR 2006, Foelsche et al. JGR 2008, Ringer and Healy GRL 2008].

[Lackner et al. *JCLIM* 2011; Steiner et al. *Radio Sci.* 2011]

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GNSS RO & Climate – a unique resource for science and applications:

- high accuracy and vertical resolution, consistency, long-term stability
- for monitoring climate variability and climate change
- potential for benchmark-quality global climate observing system
- **meets GCOS requirements for ECV upper-air temperature**
- **early detection of (emerging) climate trends demonstrated**

  ~15 m/decade geop.height increase >> ~1.5–3 m/decade UTLS **struct.Uncert.**
  ~0.3 K/decade warming in UT >> ~0.02 K/decade UT **struct.Uncert.**
  ~0.6 K/decade cooling in LS tropics >> ~0.07 K/decade LS **struct.Uncert.**

- **authoritative reference standard in the free atmosphere** for validating and calibrating thermodynamic data from other observing systems, and as absolute reference within assimilation systems

- **Currently achievable performance**
  - (A)MSU trends in the troposphere show differences between different data products, but are generally in closer agreement with trends from newly homogenized radiosonde data than with former ones
  - Middle and upper stratospheric trends derived from SSU data show substantial differences between the two currently available data records
  - GPS RO accuracy is within ~0.1 K and has exceptional long-term stability, meeting GCOS climate monitoring targets in the UTLS (although not for horizontal target resolution <100 km, and not yet globally)
- **Action A21** *[A20 IP-04]*
  - "*Ensure the continuity of the constellation of GNSS RO satellites.*"
  - "*Replacement for current COSMIC constellation needs to be approved urgently to avoid or minimize a data gap.*"

[GCOS-154, 2011]

Outlook – Next Steps – Towards SI-traceable Records

- Processing advancements in lower troposphere and upper stratosphere to further reduce structural uncertainties
- Improving the maturity of RO climate data records
- Benchmark records (SI-traceable) with integrated uncertainty estimates (rOPS, WEGC's reference occultation processing system)
- Exploitation of water vapor information
- Evaluation of climate models
- Applications in support of WCRP grand challenges: clouds and climate sensitivity, water availability, regional information
- Next-generation missions (Multi-GNSS, LMIO…LEO-LEO microwave and IR-laser occultation,…)

Thank You! ☺

Note: WEGC publications available at
www.wegcenter.at/en/arsclisys-publ