wege entstehen, indem wir sie gehen
paths emerge in that we walk them

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Atmospheric Remote Sensing and Climate System Research Group
ARSCliSys

Climate Monitoring & Change Detection with GPS Radio Occultation

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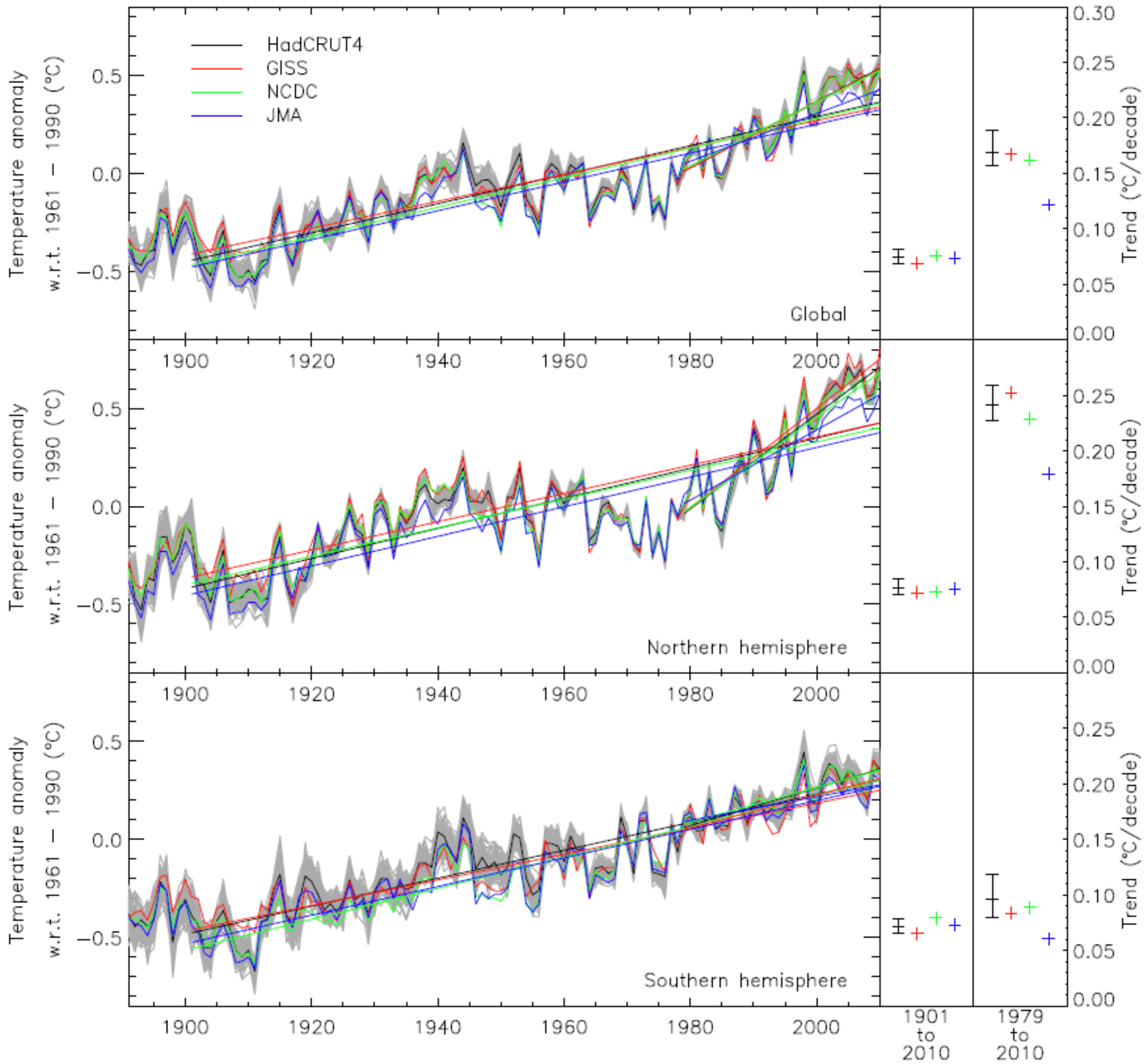
Thanks to all colleagues of the ARSCliSys research group/WEGC
and to all colleagues worldwide who contributed to work discussed here.

Outline

- Context and background
- Characteristics of RO data
- Accuracy and structural uncertainty
- Monitoring atmospheric variability
- Climate monitoring and trend detection
- Conclusions and outlook

Temperature change – surface observations

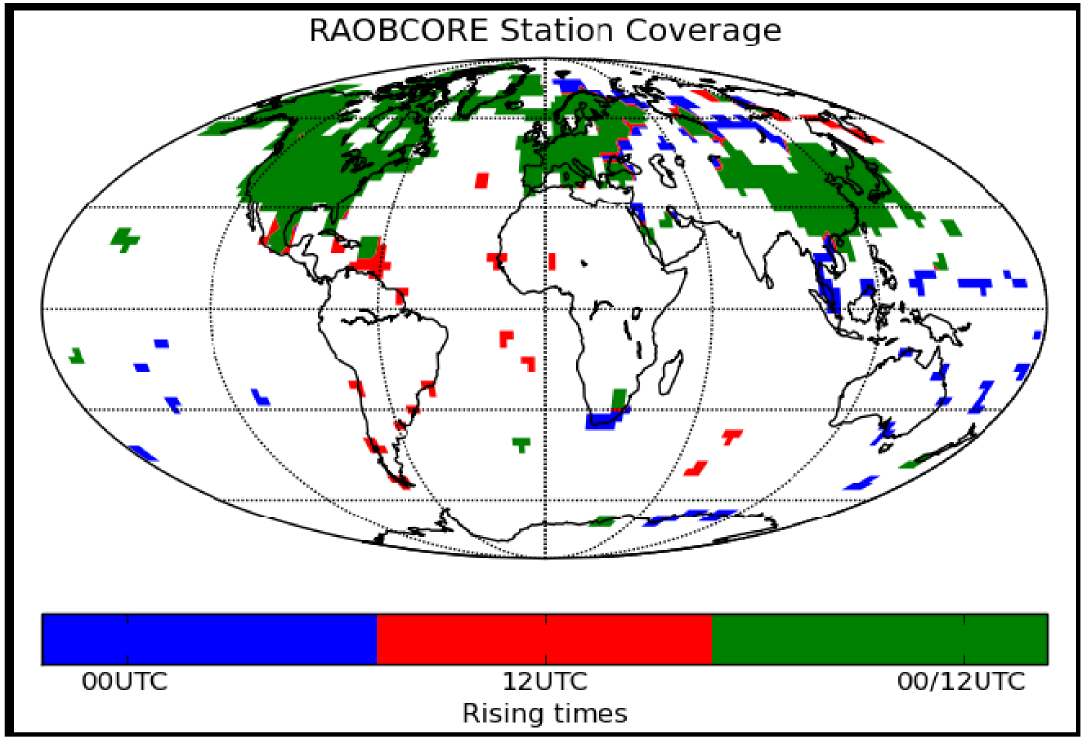


[Morice et al. 2012]

- **Global mean temperature**
- 1901 to 2010:
  Change: ~0.8 K
  Trend: ~0.07–0.075 K/decade
- 1979 to 2010:
  Increase in trendrate to
  ~0.12–0.18 K/decade
- "There has been no reduction in the global warming trend 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

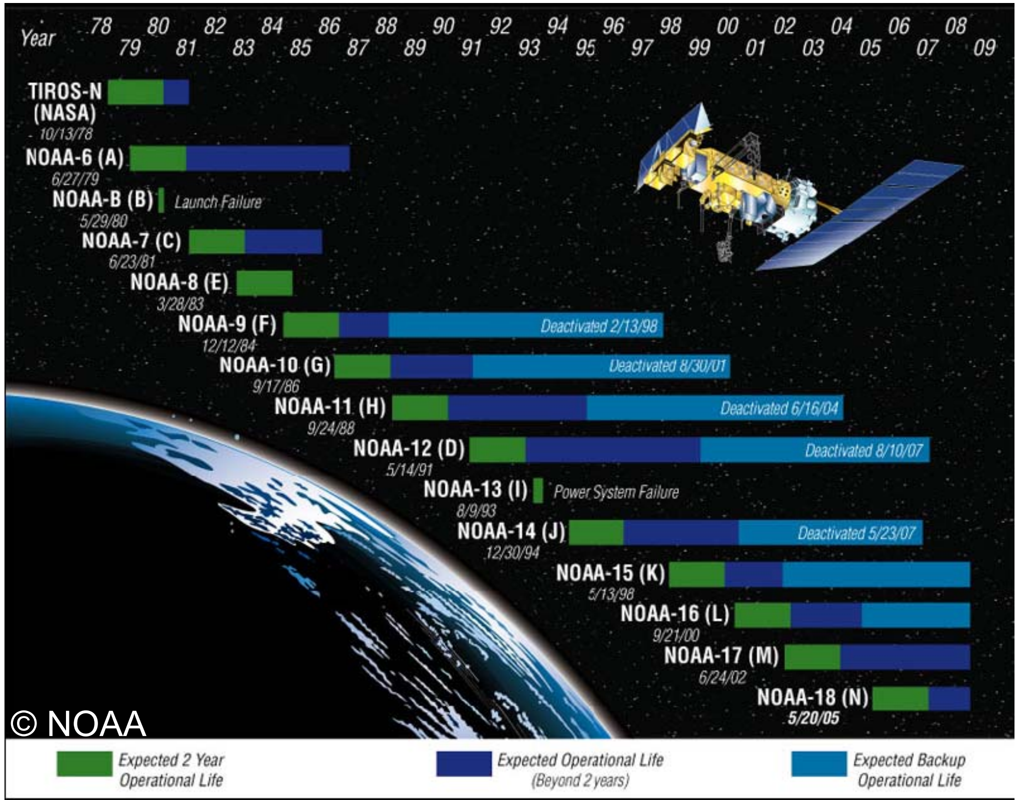


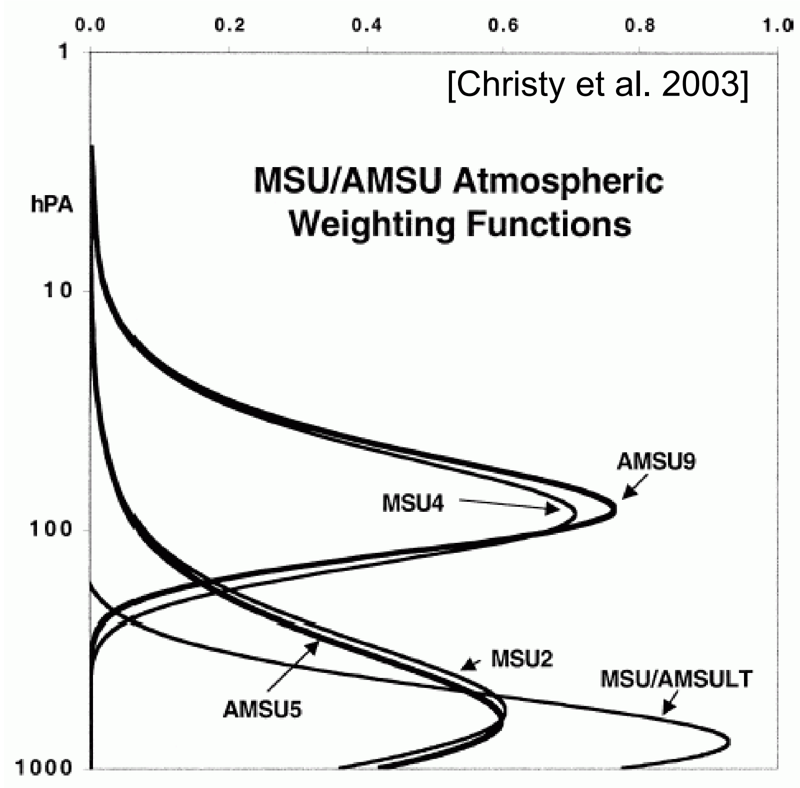
[Ladstädter et al. 2011]

[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 calibration/corrections to construct climate records





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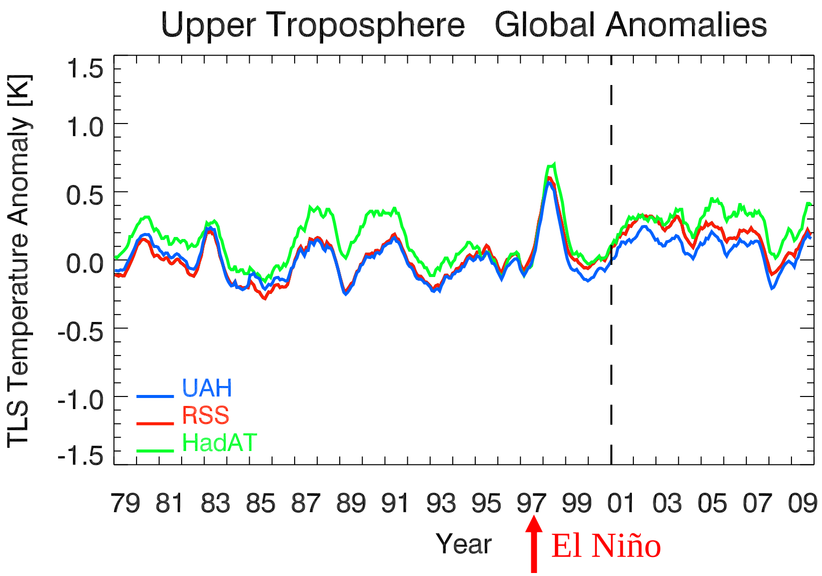
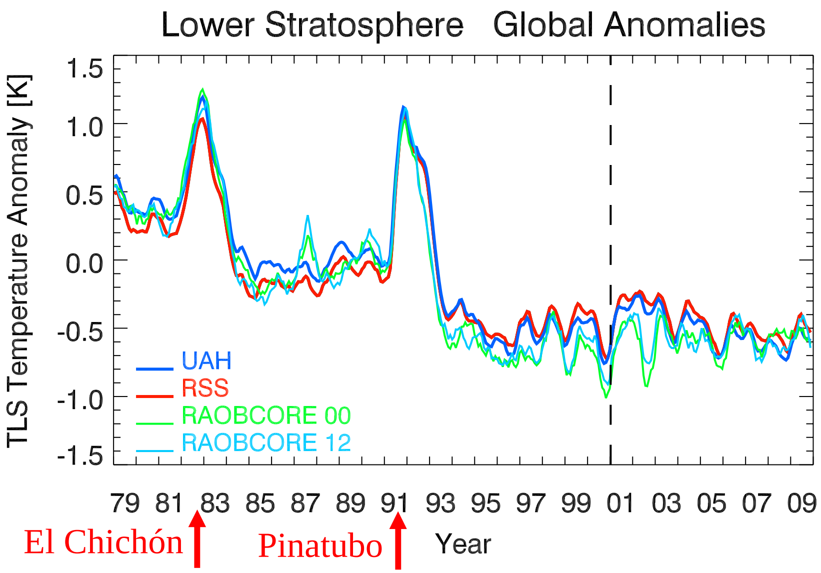
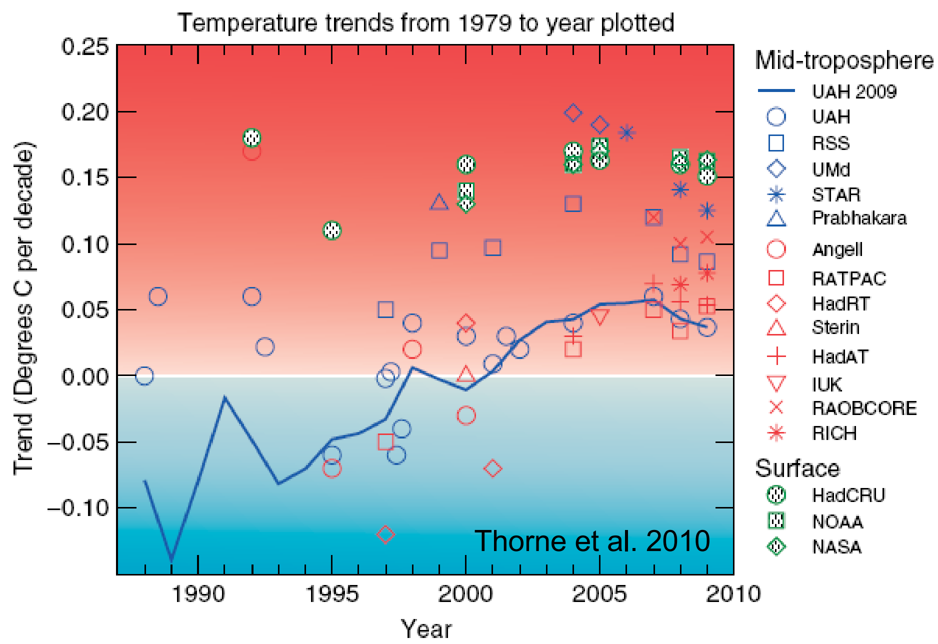
Tropopheric Warming



Stratospheric Cooling





- Construction of climate records requires intercalibration and homogenization
- Basic agreement in trends, but large uncertainties in rates and 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]

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
- Improve understanding, modelling, prediction of the climate system
- Assessing impacts of climate variability and change
- Climate information and prediction services
- Application to sustainable national economic development

<http://www.wmo.int/pages/prog/gcos>

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 standards of the international system of units (SI)

[GCOS-138 2010; GCOS-143 2010]

Fundamental Climate Data Record (FCDR)

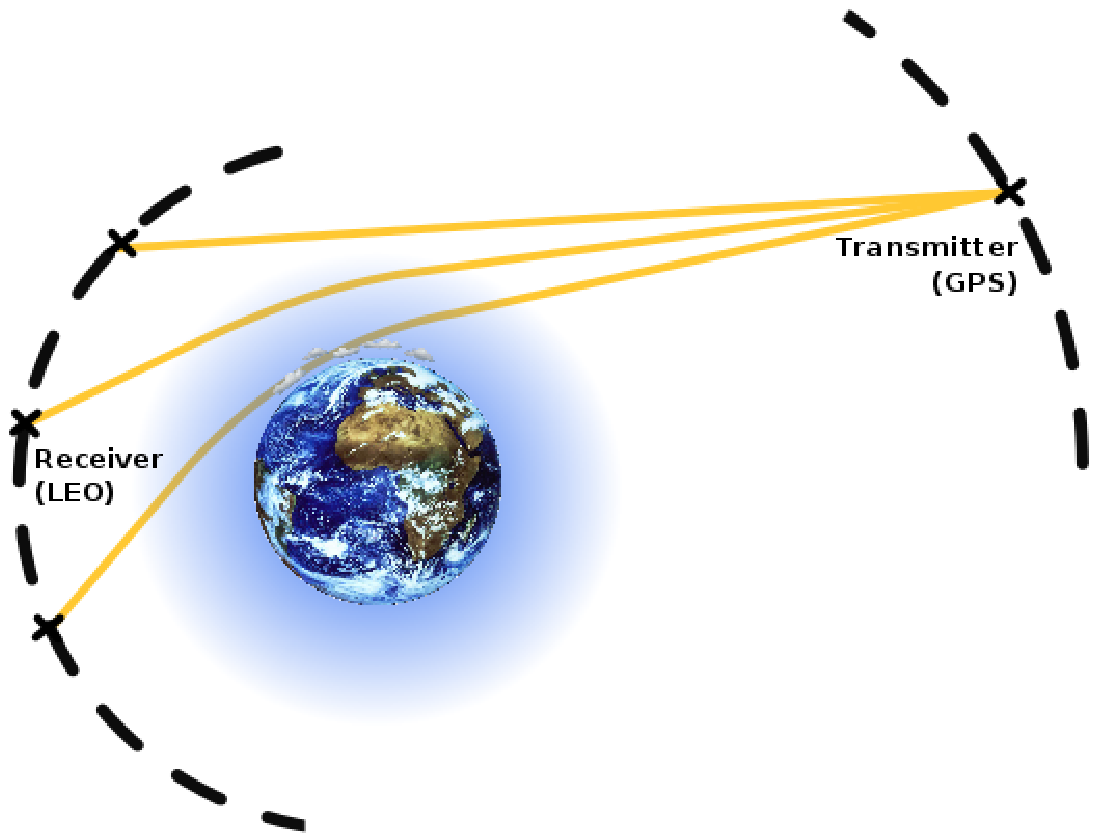
- long-term stability
- homogeneity
- reproducibility
- global coverage
- accuracy
- resolution in space and time
- product description and validation

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 (0.05 K) per decade LS

[GCOS-107, 2006; GCOS-143, 2010; GCOS-154, 2011]

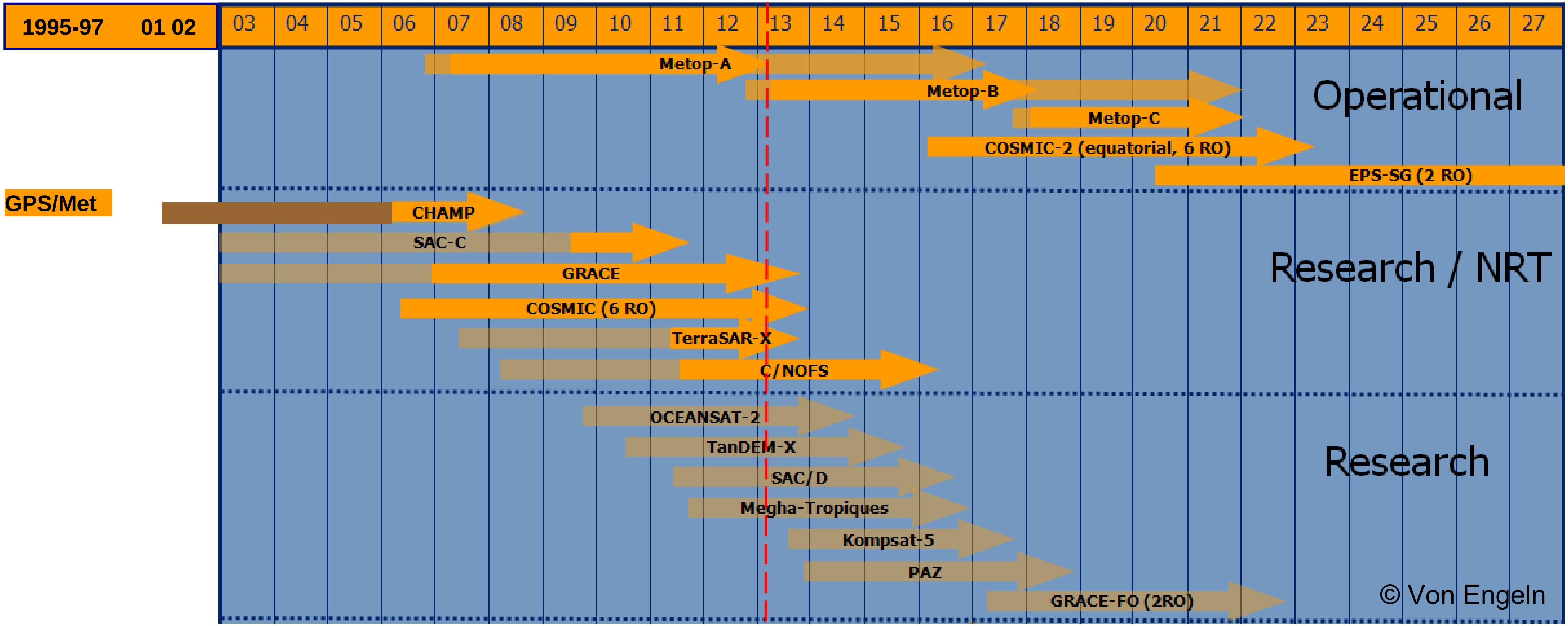
GNSS–LEO satellite constellations



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

Courtesy: T. Rieckh

Mission status



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**
  ~300 km, synoptic scales, climate
- **Long-term stability**
  measurements based on precise atomic clocks
- **No** need of **inter-satellite calibration**
- **Error characterization** of profiles and climatological fields
- **Structural uncertainty** estimates

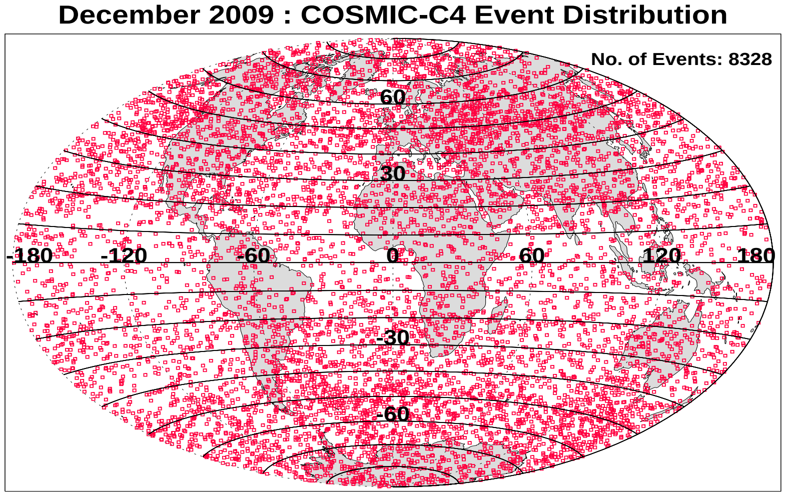
Error characterization important

- for evaluation of observational data
- for assimilation of observational data in numerical weather prediction models
- for use as climate data record

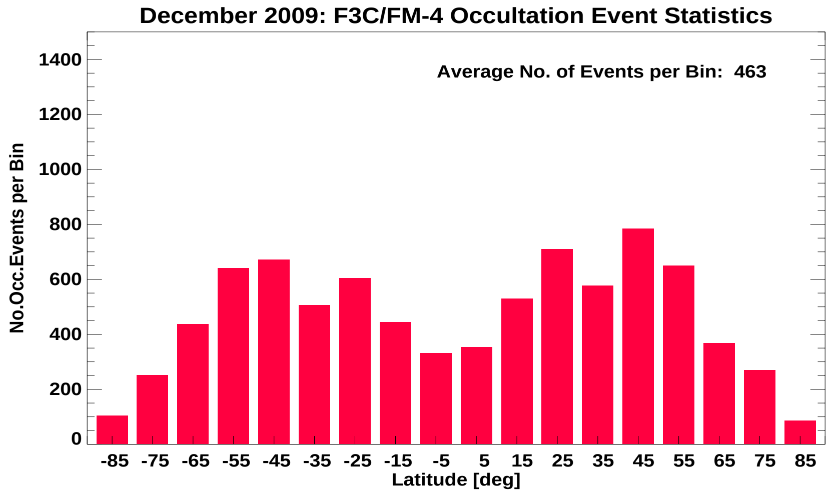
GPS RO data products

- Individual profiles of atmospheric variables
- Gridded climatological fields

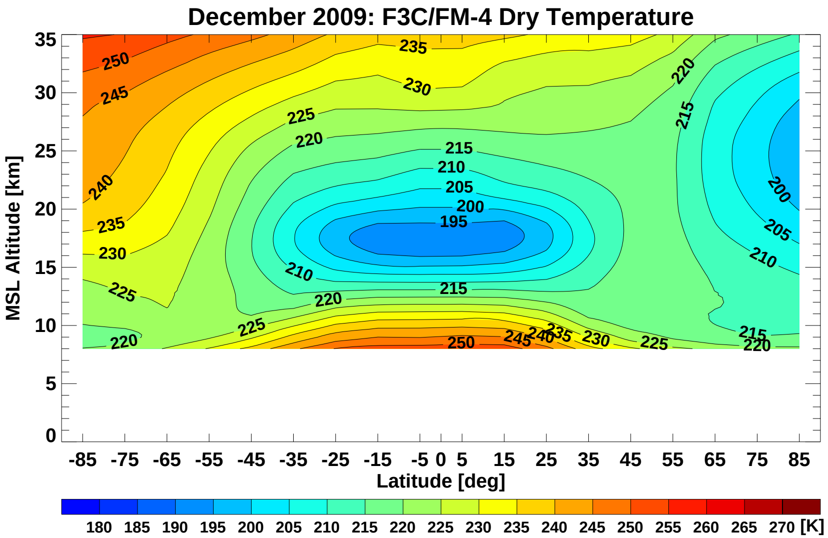
Distribution of occultation events

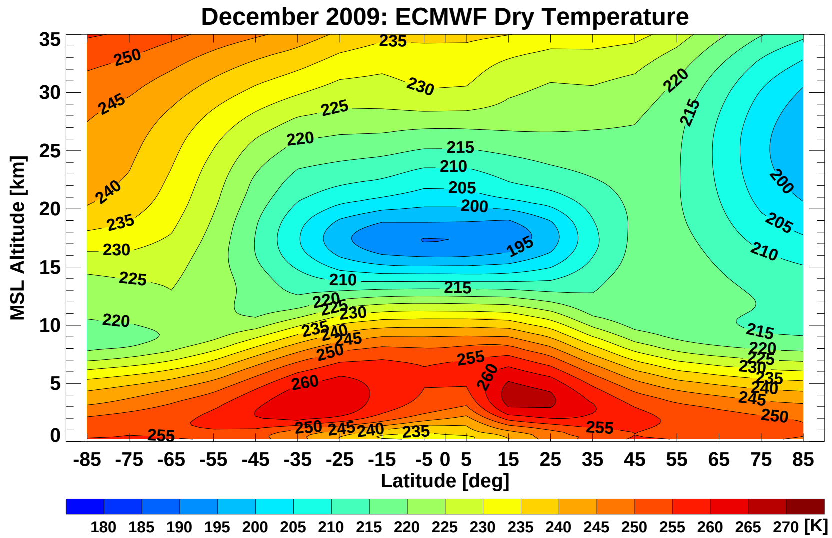


Number of profiles per 10°-bin

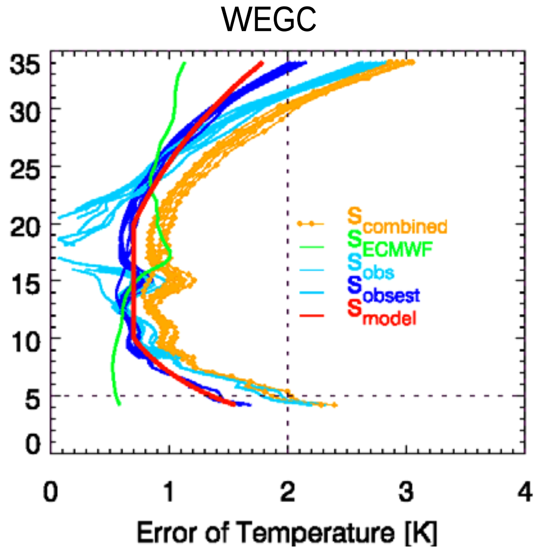


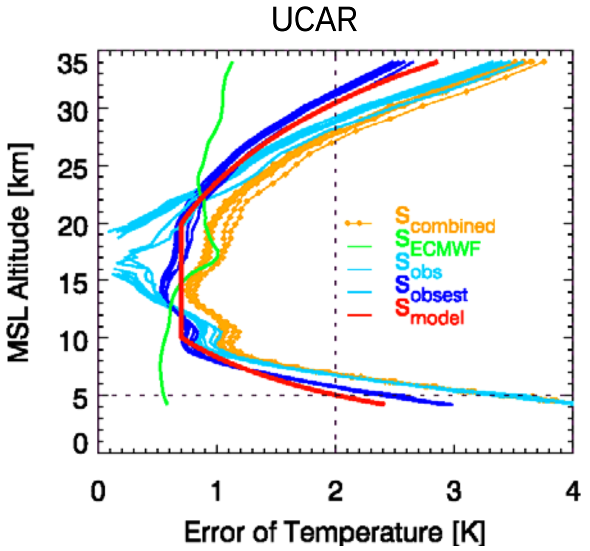
RO climatology **Dry Temperature** Reference ECMWF

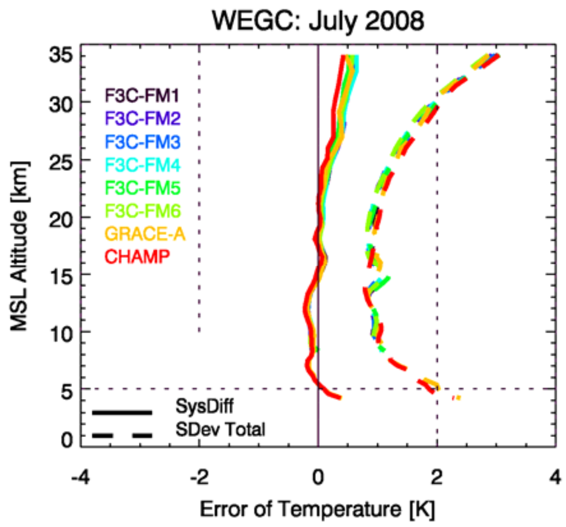




- **High accuracy (profiles):**
  Temperature < 0.7–1 K within ~8–25 km, <2 K outside
  α < 1%, N < 0.5%, p < 0.3%, Z < 15 m
- Agreement in error characteristics of different missions and centers
- Analytical error model based on empirical error estimates







[Scherllin-Pirscher et al. 2011a]

RO Climatologies – Error Characterization

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Statistical (observational) error

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

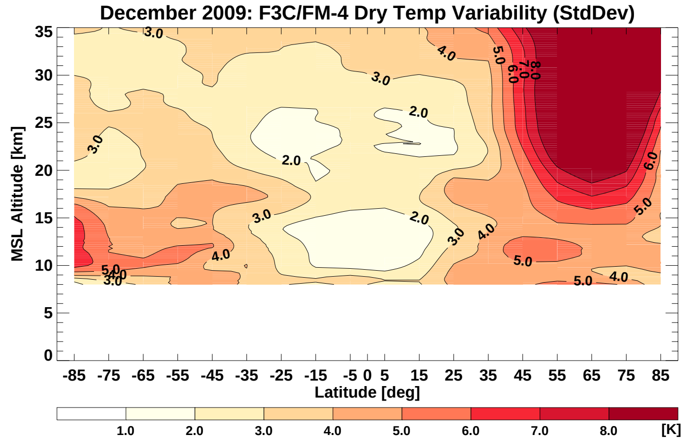
Sampling error

- **<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**

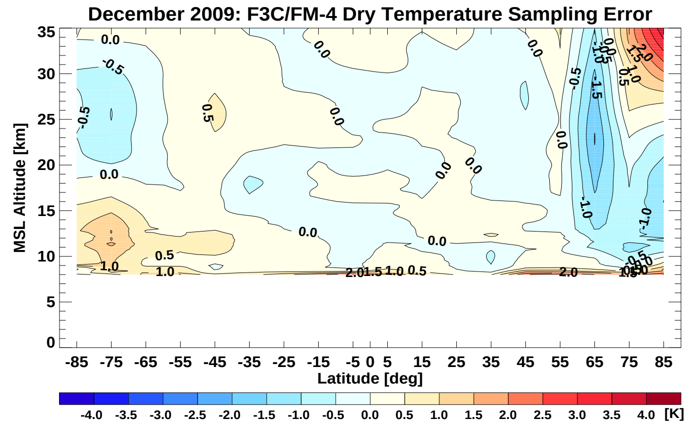
Potential systematic residual error

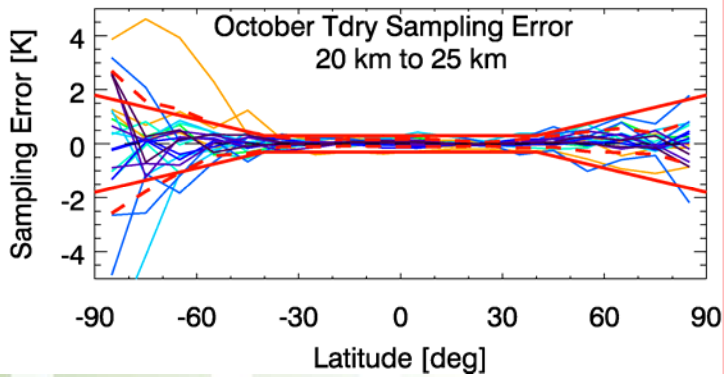
- Stratosphere: Ionospheric correction, Initialization of bending angle
- Troposphere: GPS L2 signal degraded, horizontal gradients

Variability



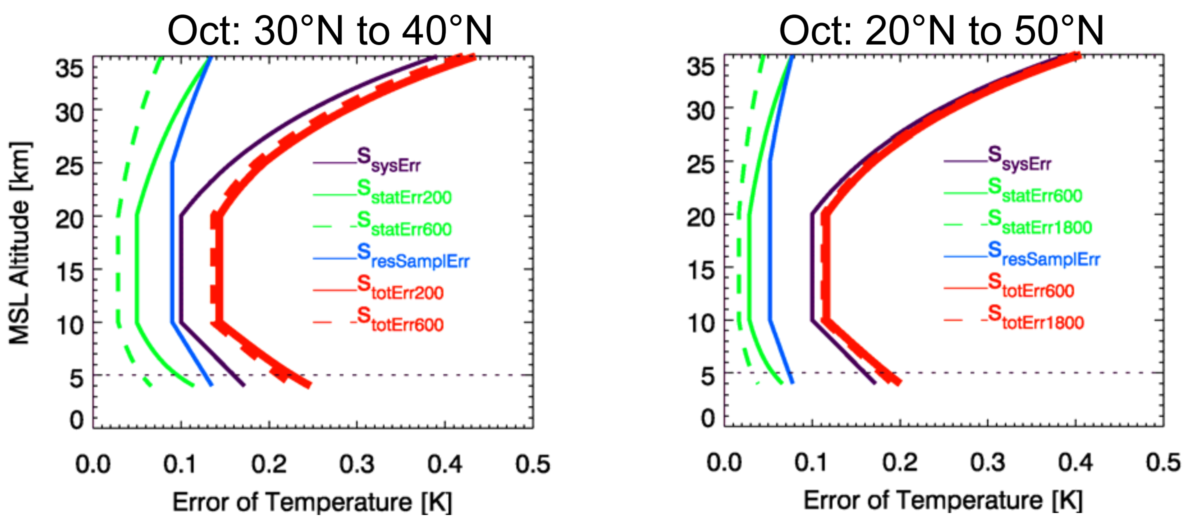
Sampling error





- **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)



Structural uncertainty in data sets

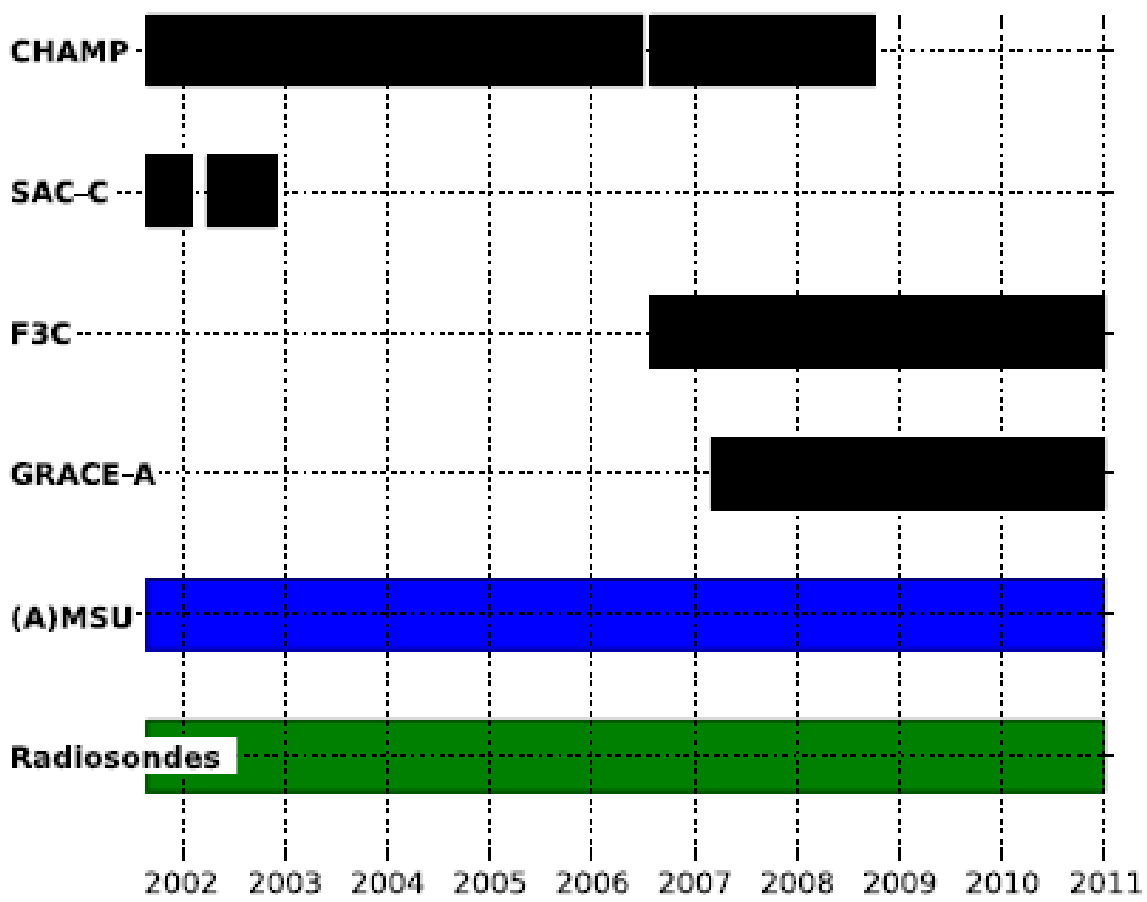
- Different methods in data processing and in the construction of climate records
- Differences in climate records from same basic measurements

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

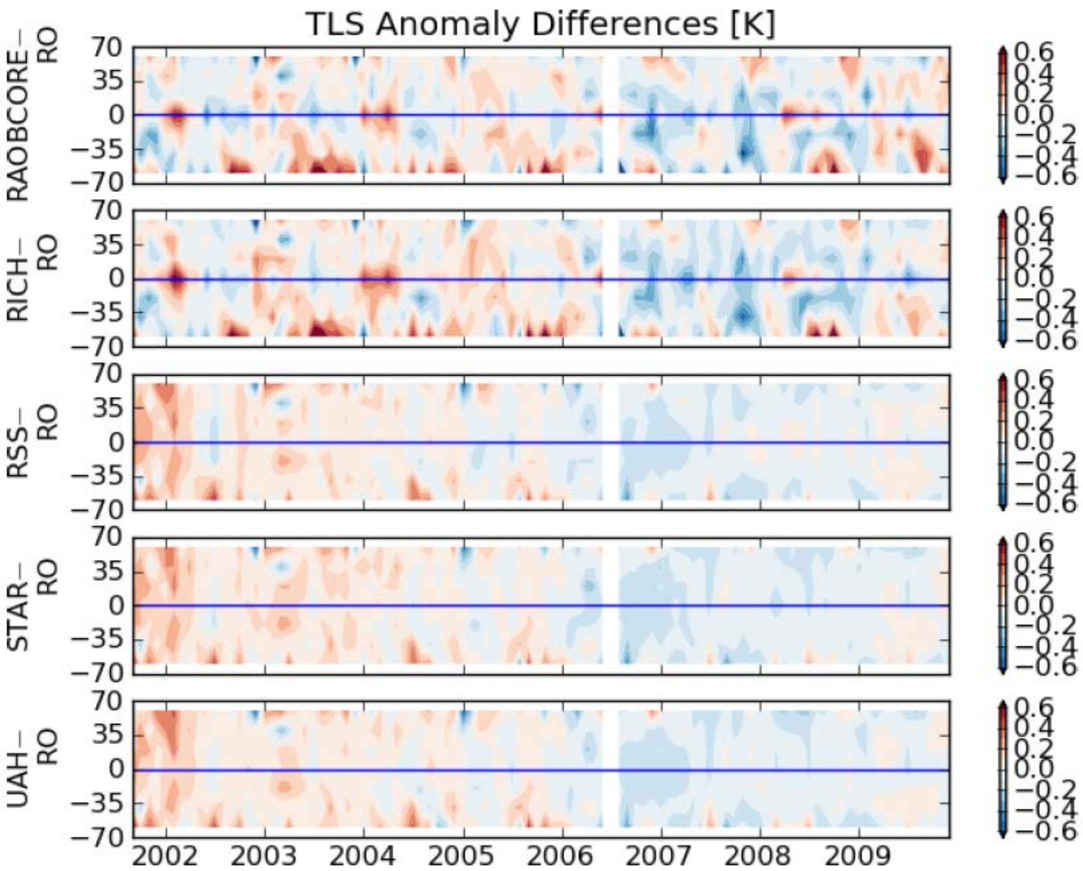
- Differencing removes climatological variability common to both data sets
- Remaining differences due to structural uncertainty

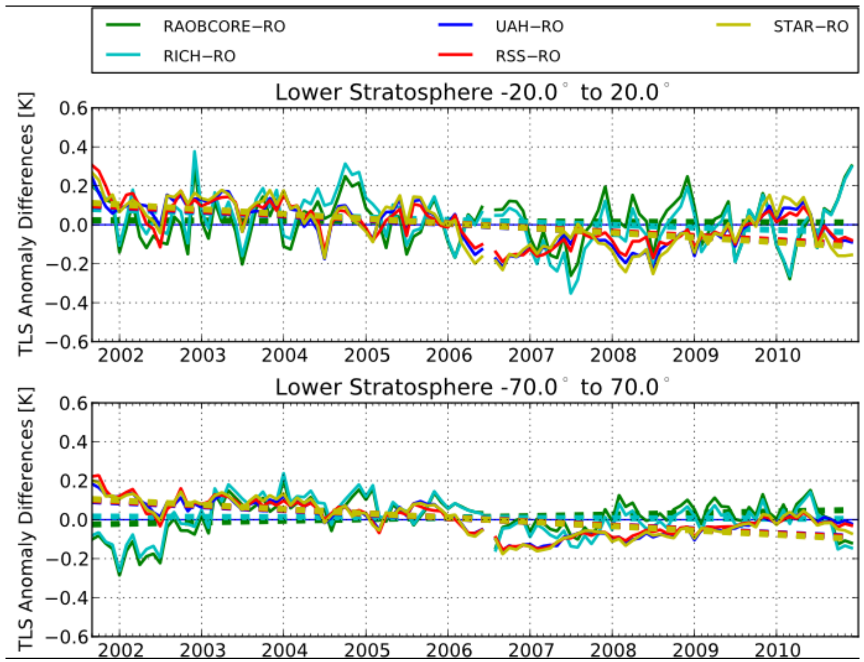


[Schroeder et al. 2003; Steiner et al. 2007; 2009, Ladstädter et al. 2011]

TLS anomaly differences and trends

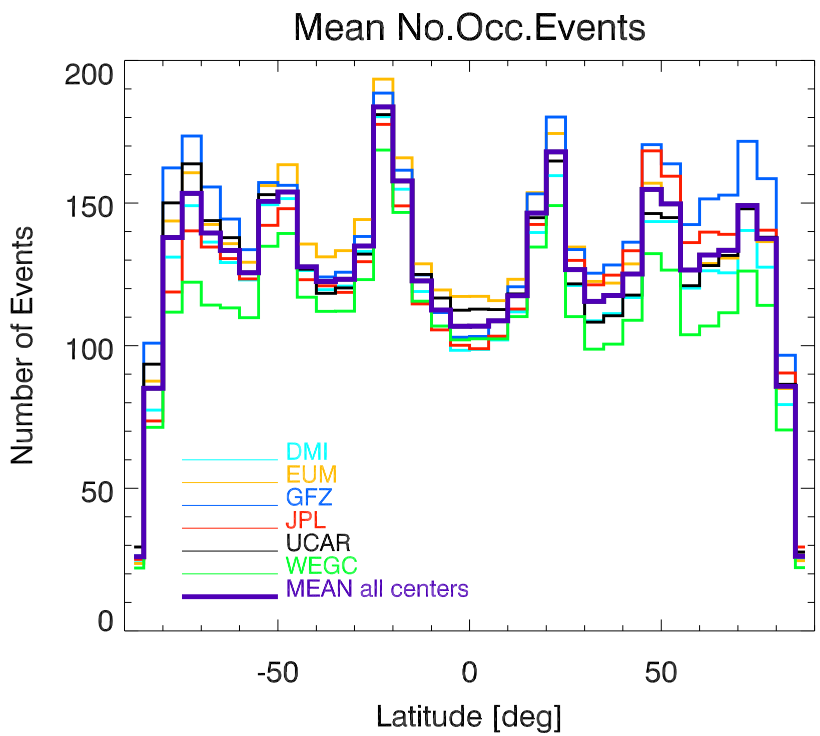
- Radiosondes–RO agree well, neglible trends in their difference
- (A)MSU–RO: show statistically significant difference trend (–0.2±0.06 K)/10 yrs
- Potential errors due to RO could be ruled out (sampling error, TLS computation,…)





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. 2012]
- Study using climatological data products different number of profiles due to quality control [Steiner et al. 2013]

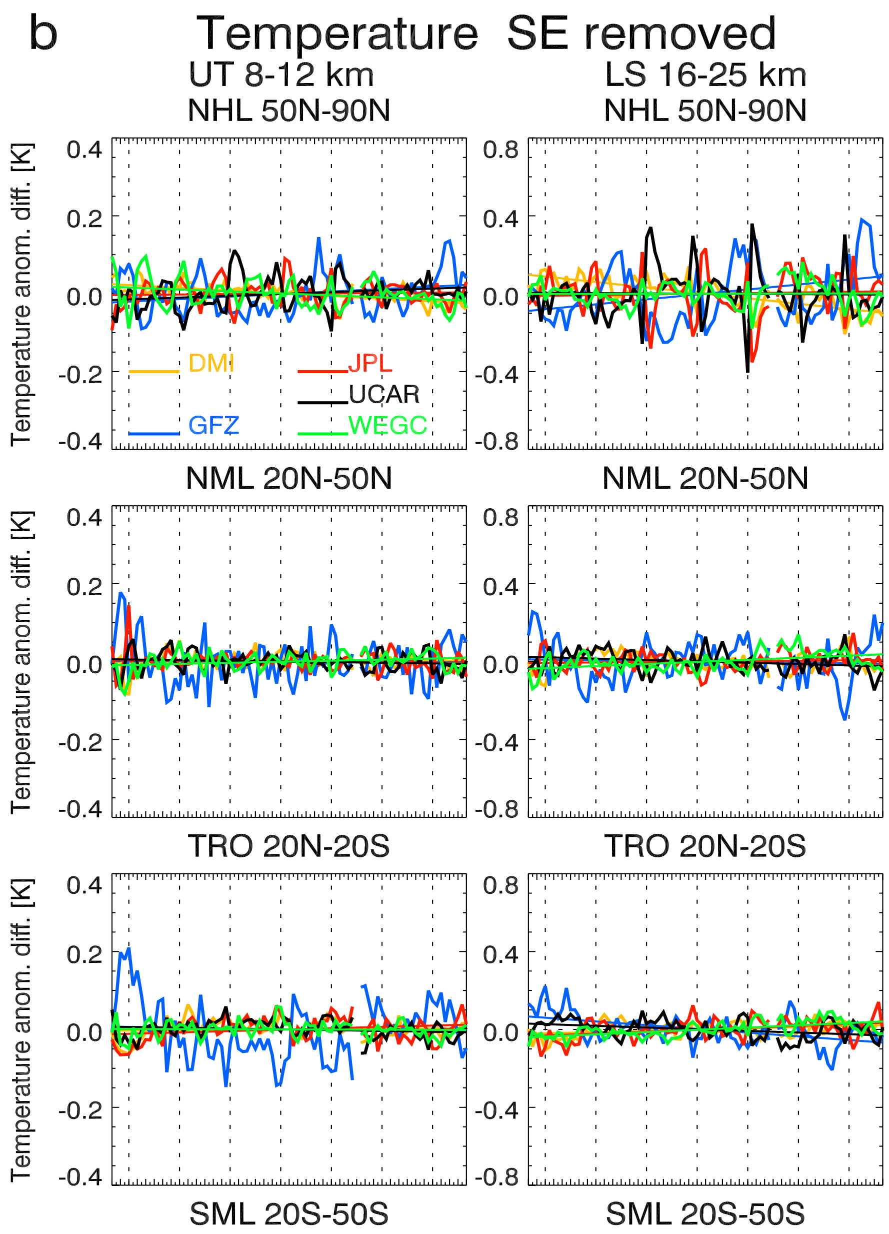


Structural uncertainty

- 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)
- <3 m for geop.height (10–20 m HL, LS)
- **0.05 K for temperature**
- **0.02 K in UT, 0.1 K in LS**
- **fulfills GCOS requirements**
- **trend independent of processing**

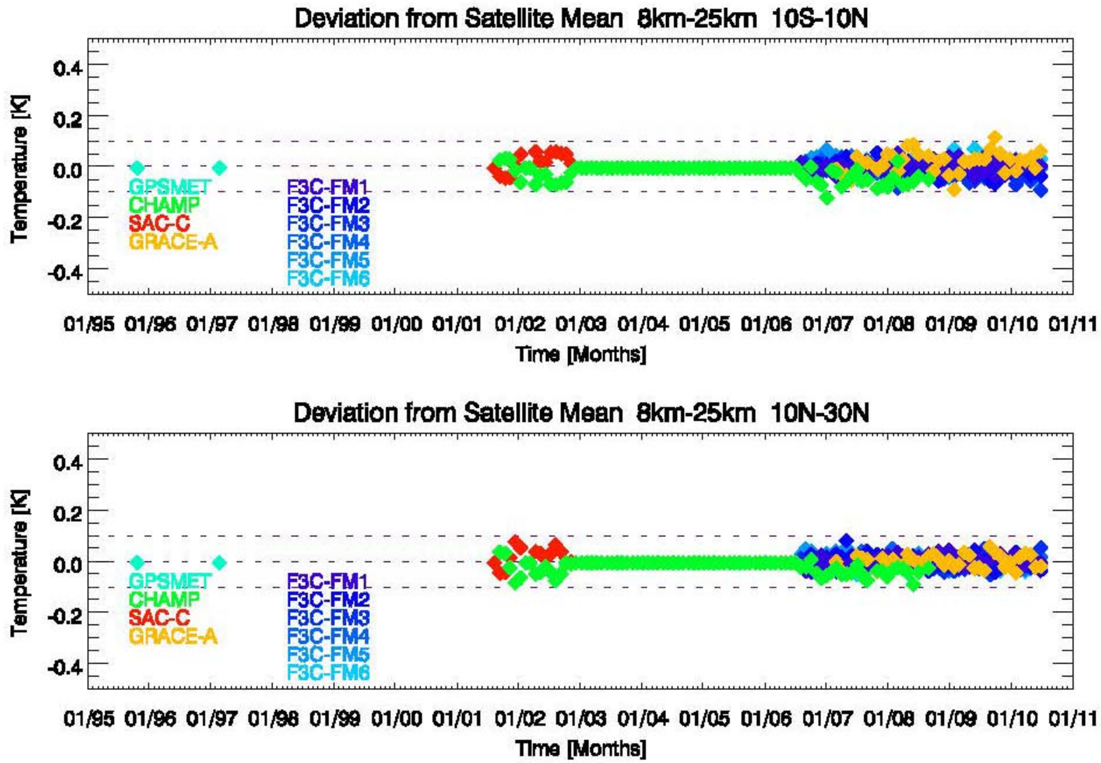
- larger above 25 km and high latitudes
- 0.2–0.7 K >25 km
- due to different BA initialization with different background data



[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 overall useful for investigating climate variability
- Low structural uncertainty within 50°S to 50°N and ~8 to 25 km
- RO data can be used for climate trend detection in this region

Consistency of data from different satellites



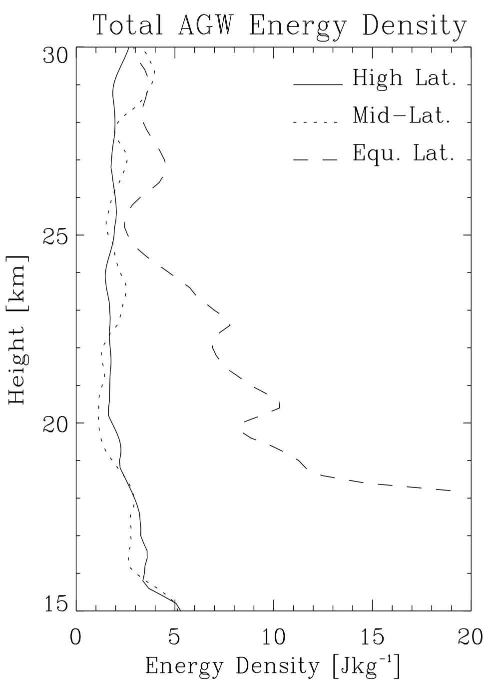
[Ho et al. *JGR* 2009; Steiner et al. *RS* 2009; Foelsche et al. *TAO* 2009, *AMT* 2011]

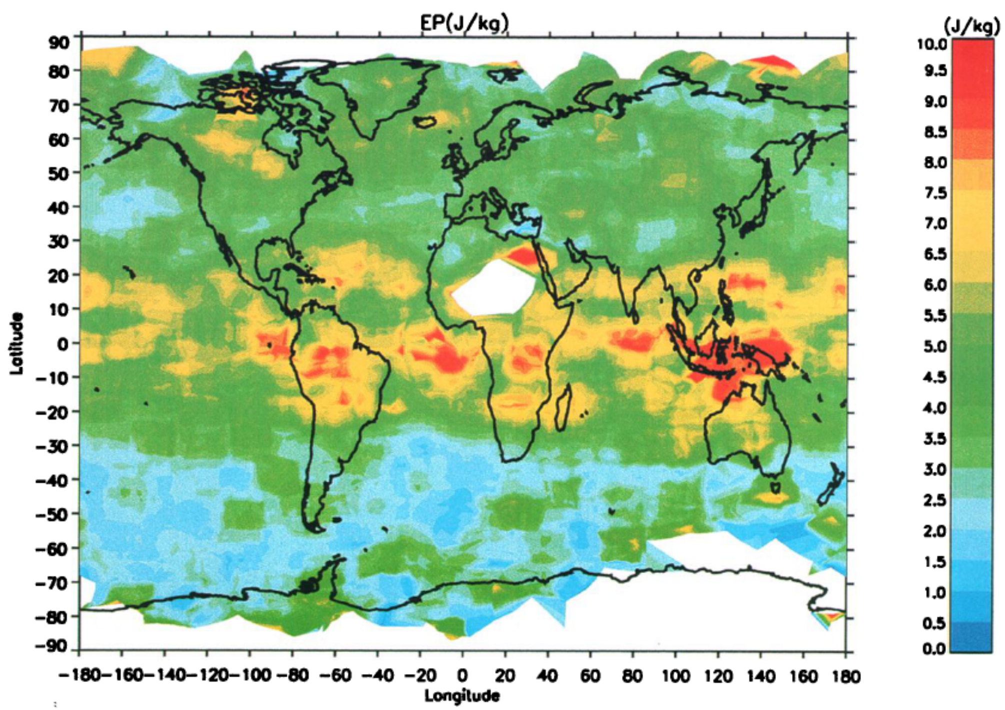
Monitoring UTLS variability and processes

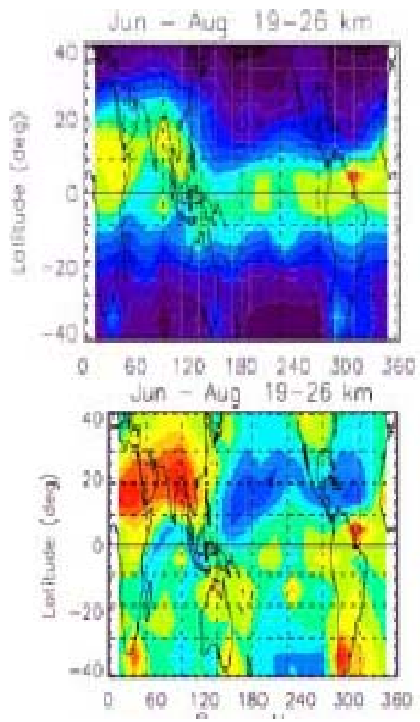
- Atmospheric gravity waves
- Kelvin waves
- Mountain waves
- Quasi-Biennial Oscillation
- El-Niño Southern Oscillation
- Madden-Julian Oscillation
- Diurnal tides

- Tropopause variability and structure
- Sudden stratospheric warmings
- Convective systems

- **Analysis of stratospheric gravity waves (GW)**
- First results using GPS/Met data – gravity wave energy density
- Climatologies of GW activity in the stratosphere, global, regional
- COSMIC data with more occultations provide a more detailed understanding of the GW activity on shorter time intervals

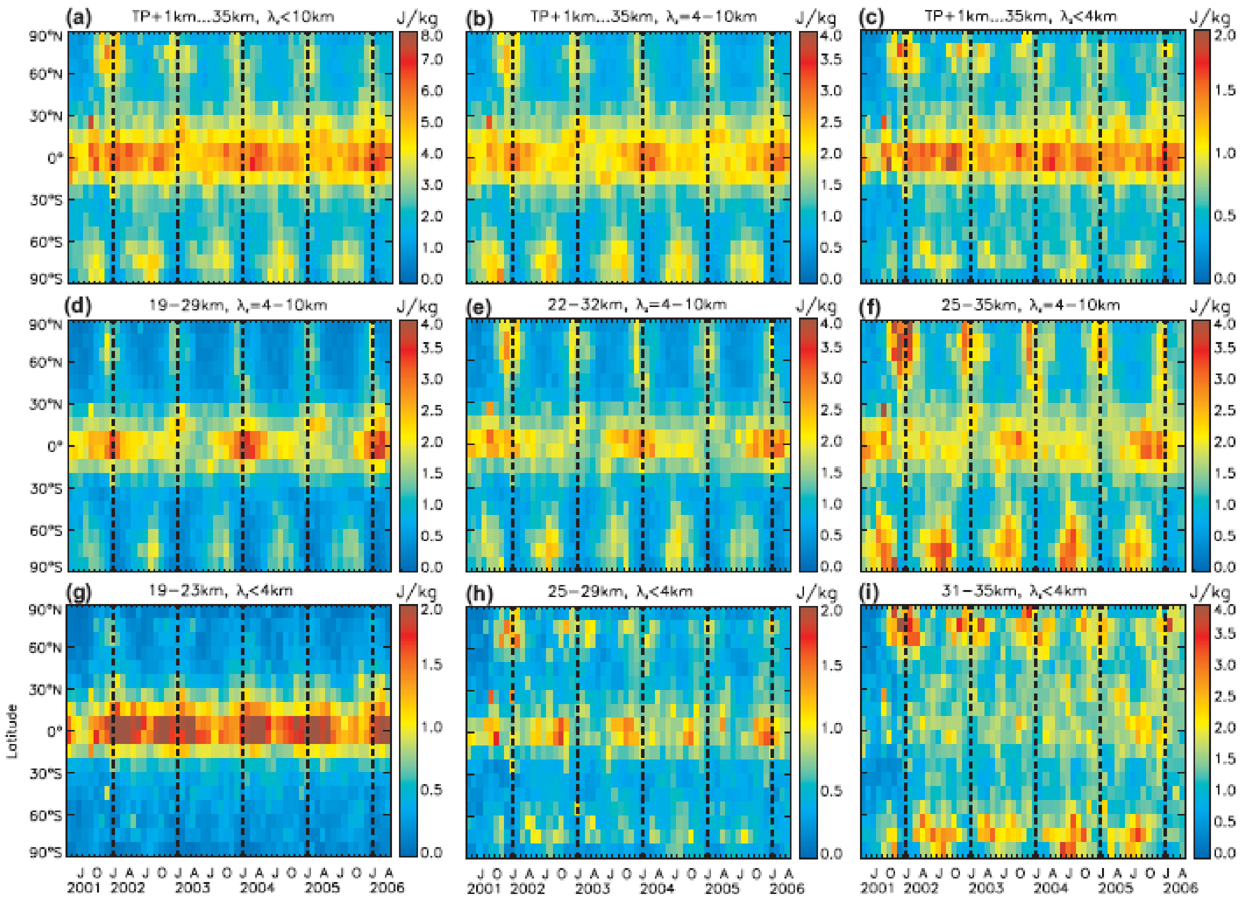






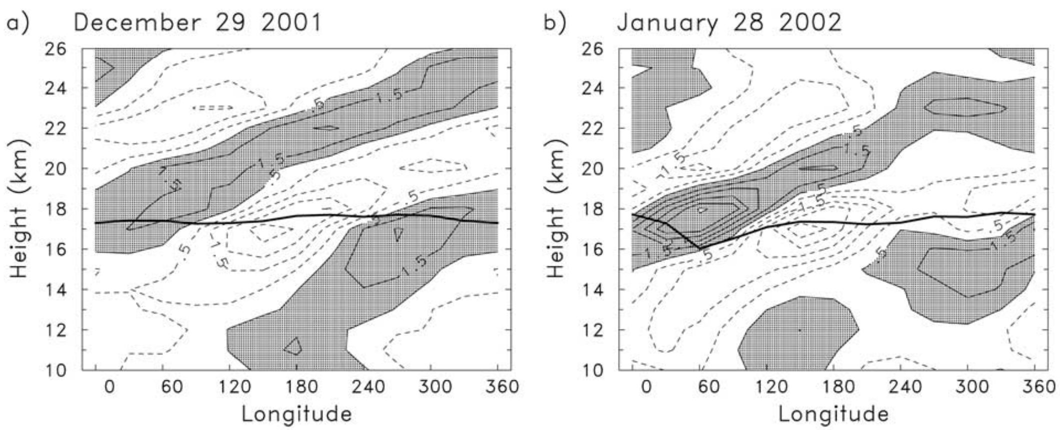
[Steiner and Kirchengast JAOT 2000; Tsuda et al. JGR 2000, OPAC 2010]

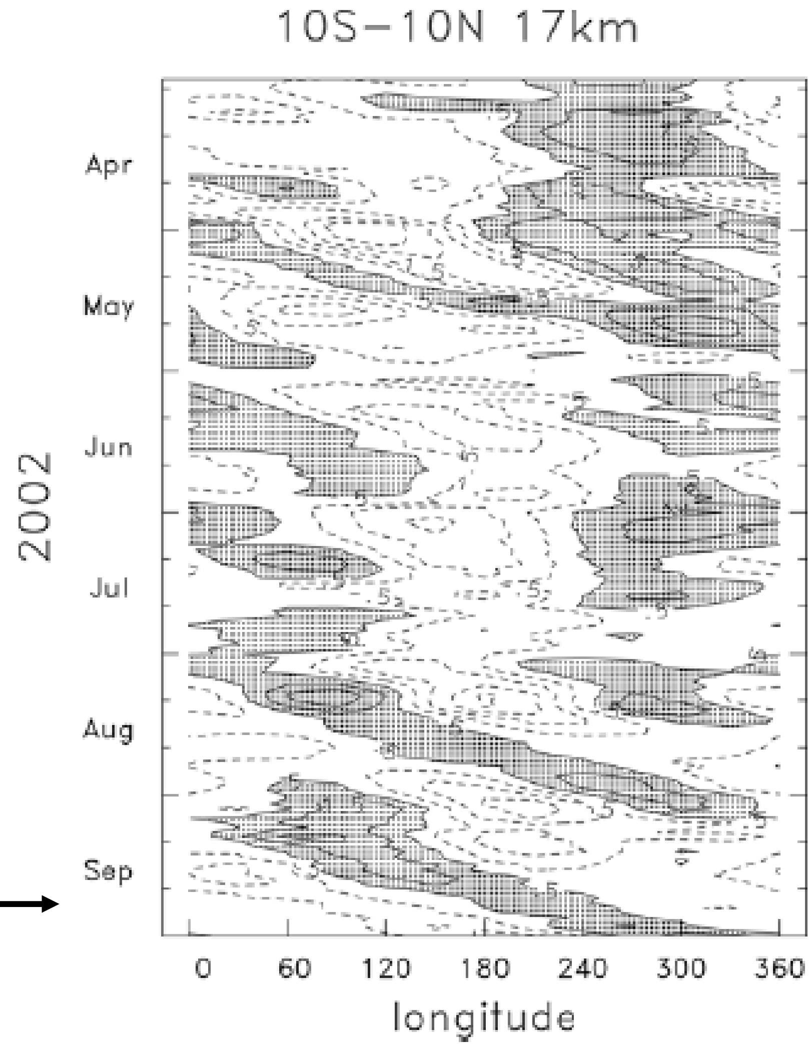
- **Global wave activity for different wavelengths and heights**
- For short λ_z, an equatorial annual enhanced WA observed within 19–23 km
- Enhancement of extratropical high latitude WA with increasing *z*.
- Mountain waves – limitations due to relative geometry of wave phase surfaces



[de la Torre and Alexander 2005; de la Torre et al. 2004; 2006]

Analysis of Kelvin waves



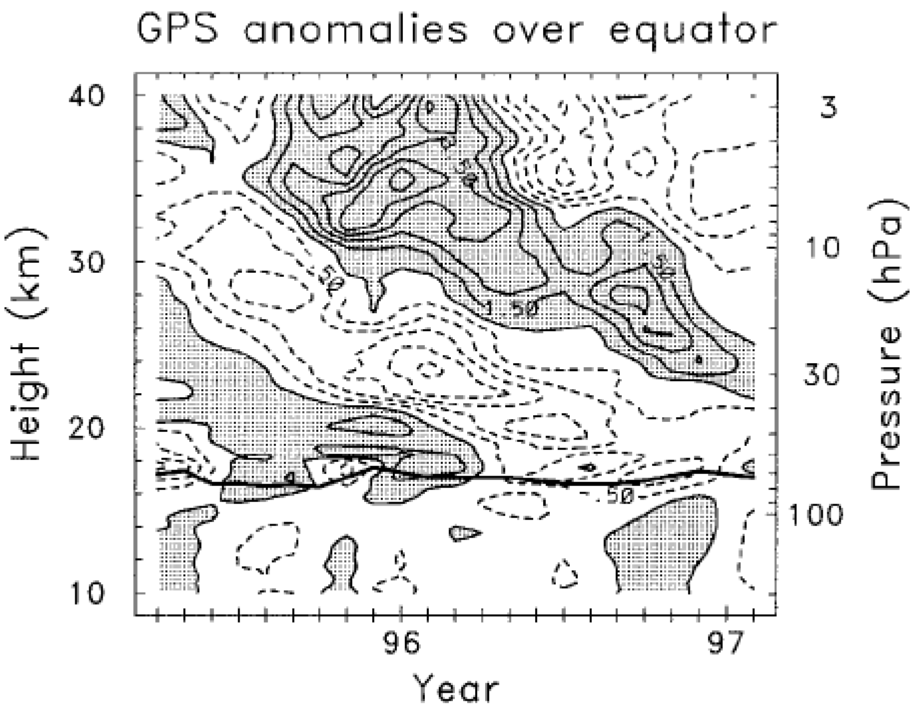


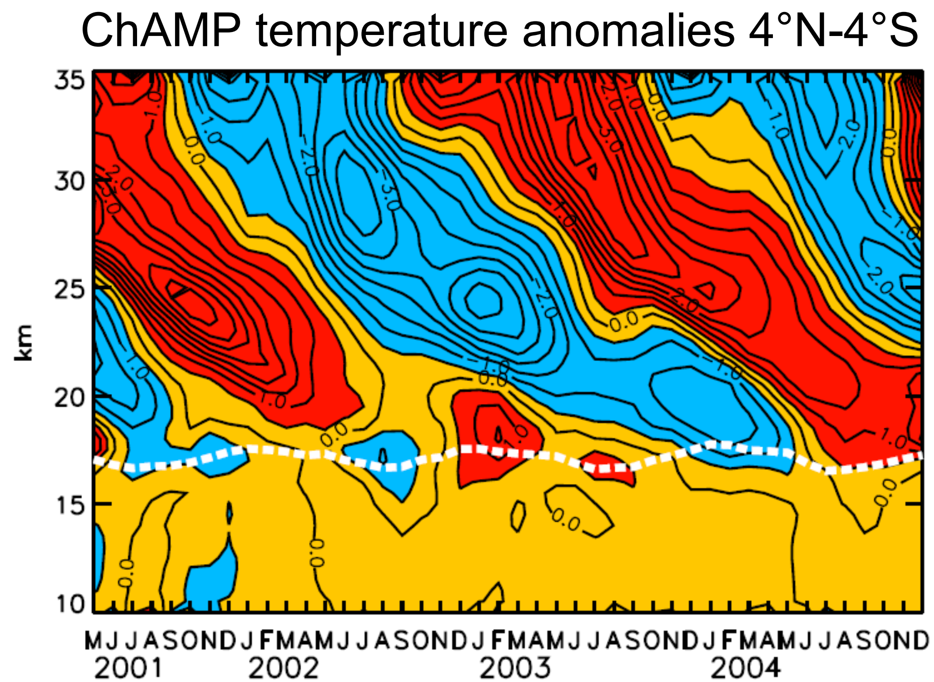
- Temperature anomalies at height vs longitude over 10°N–10°S show **Kelvin wave structure**
- characteristic **eastward phase tilt with height**
- vertical wavelengths of 4 km to 8 km
- max. amplitudes near tropical tropopause (17 km)
- longitude-time temperature anomalies at 17 km
- **eastward propagation** in May, Aug to Sep 2002

[Tsai et al. 2004; Randel and Wu 2000]

QBO pattern in RO anomalies

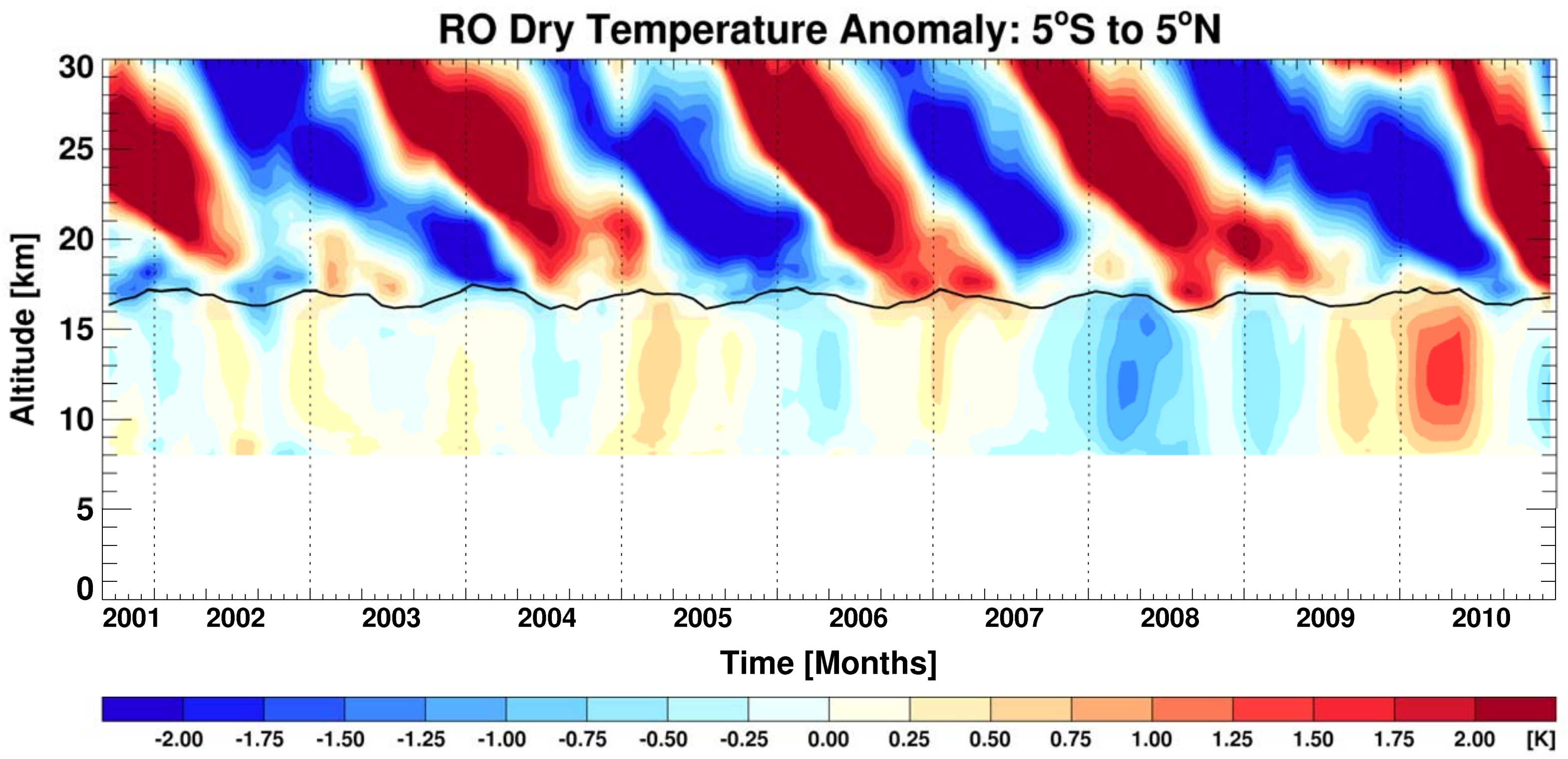
- Tropical lower stratosphere, ~5°N–5°S, ~28 months period
- Seasonal changes in radiative heating
- Downward propagating wind/temperature anomalies
- ±0.5 K to ±6 K at ~16–30 km





[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**

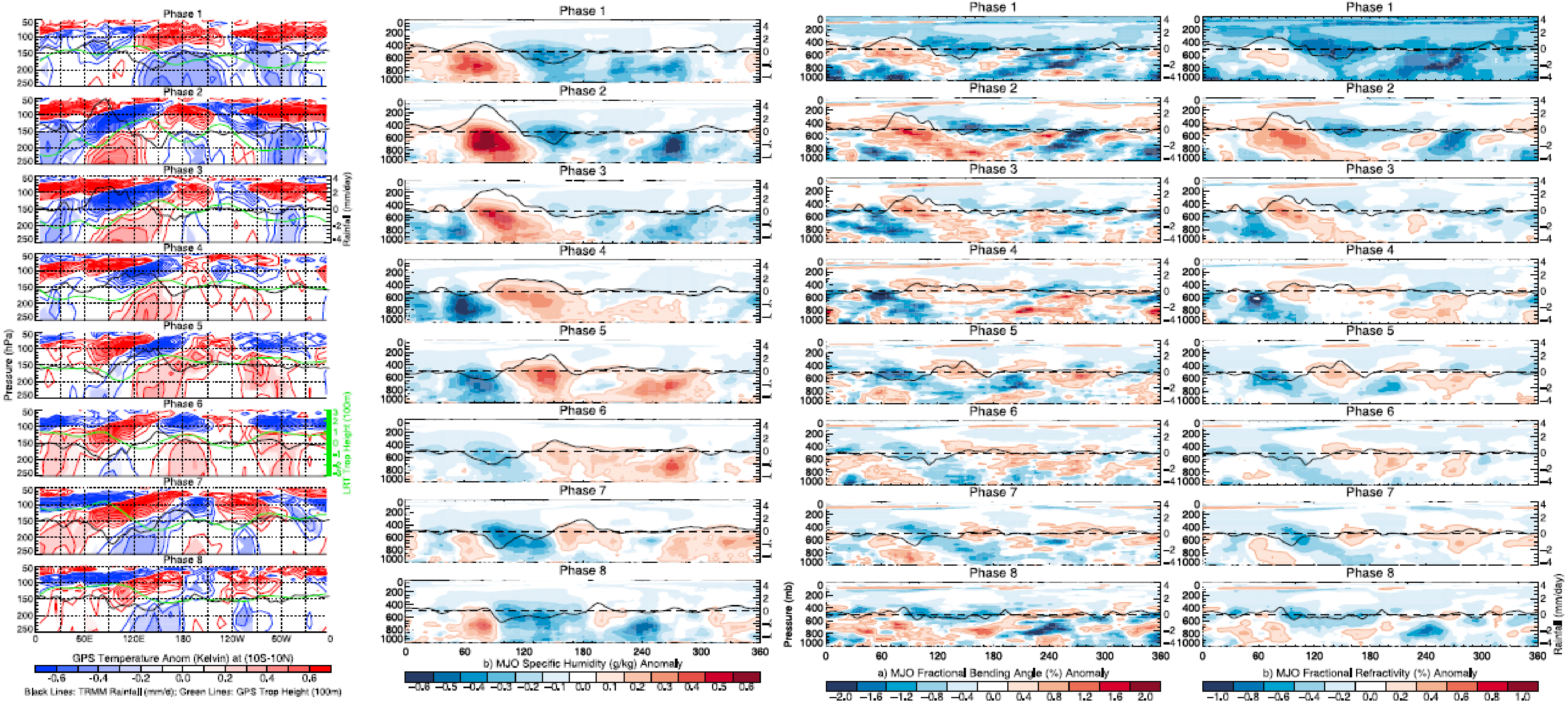


[Scherllin-Pirscher et al. 2012]

Madden-Julian Oscillation in RO Parameters

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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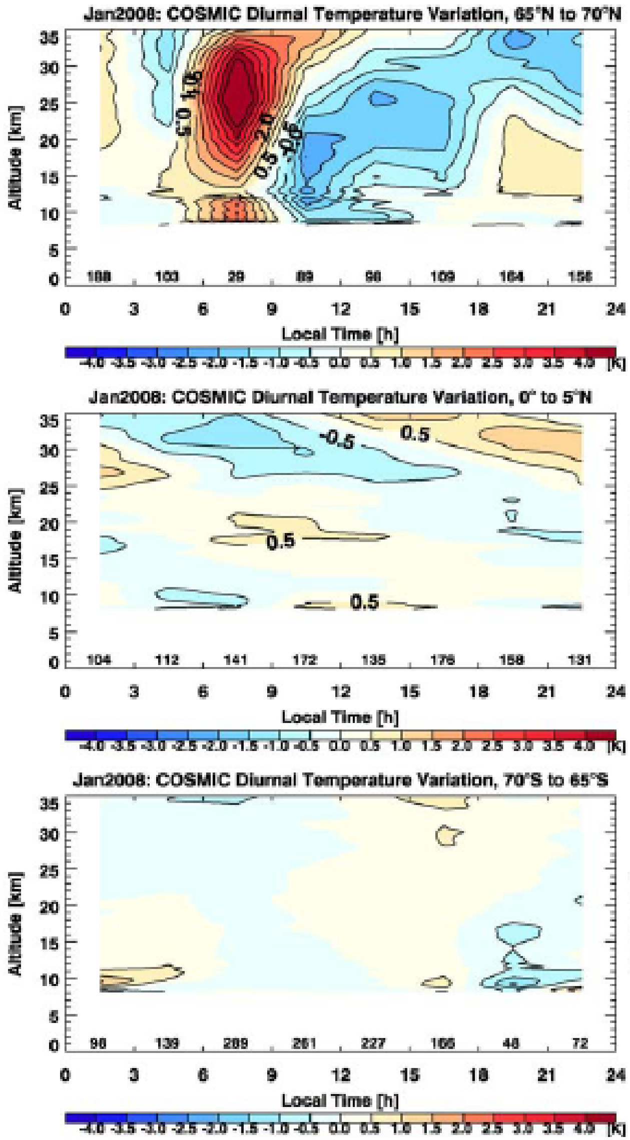
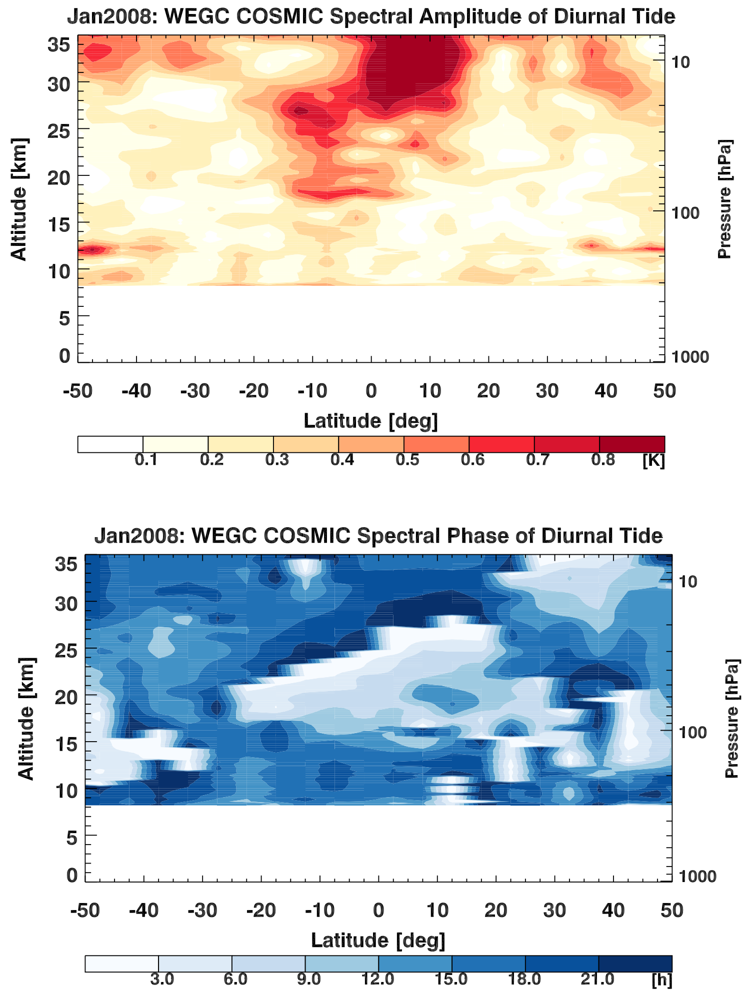
- **Utility of COSMIC RO data for monitoring diurnal tide dynamics**

Diurnal temperature variations



Spectral amplitude and phase of westward propagating diurnal tide

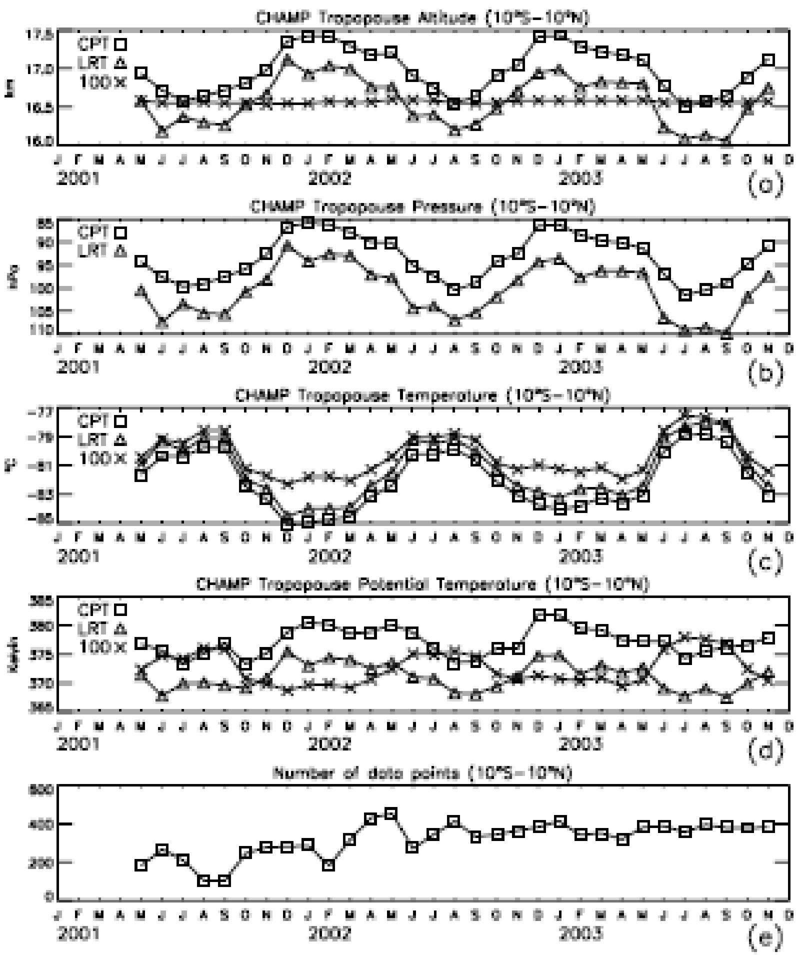


[Pirscher et al. JGR 2010]

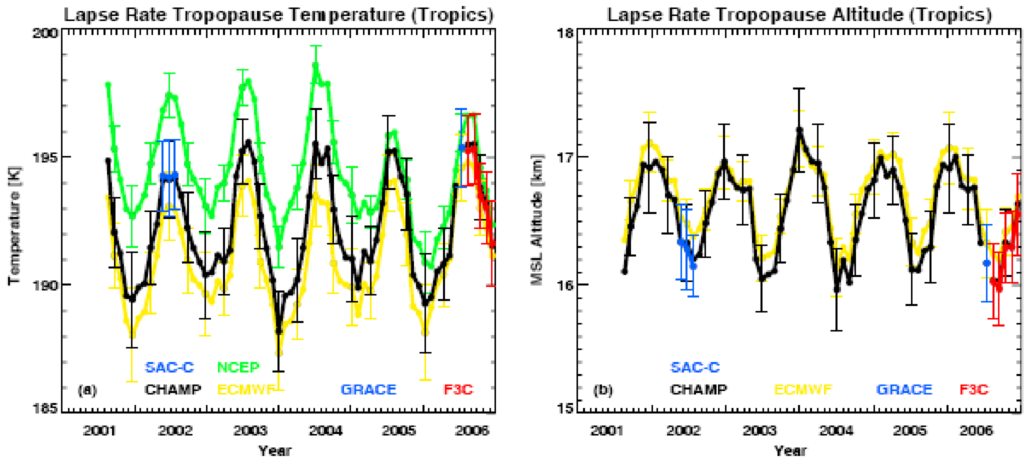
Insights into tropopause variability from RO

- monitoring of tropical tropopause variability
- tropopause parameters (CPT, LRT, height, temperature) and climatologies

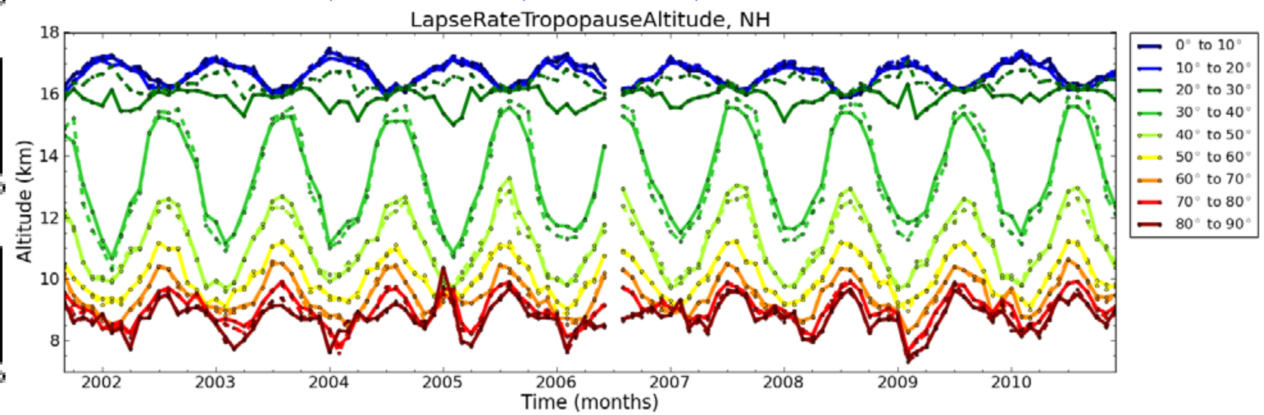
CHAMP 2001–2003



CHAMP, SAC-C, F3C 2001–2006



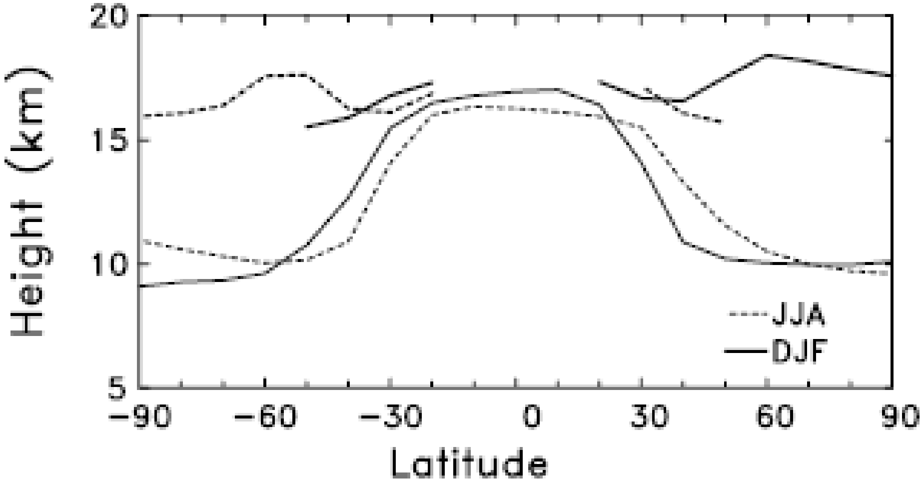
CHAMP, GRACE, SAC-C, F3C 2001–2010



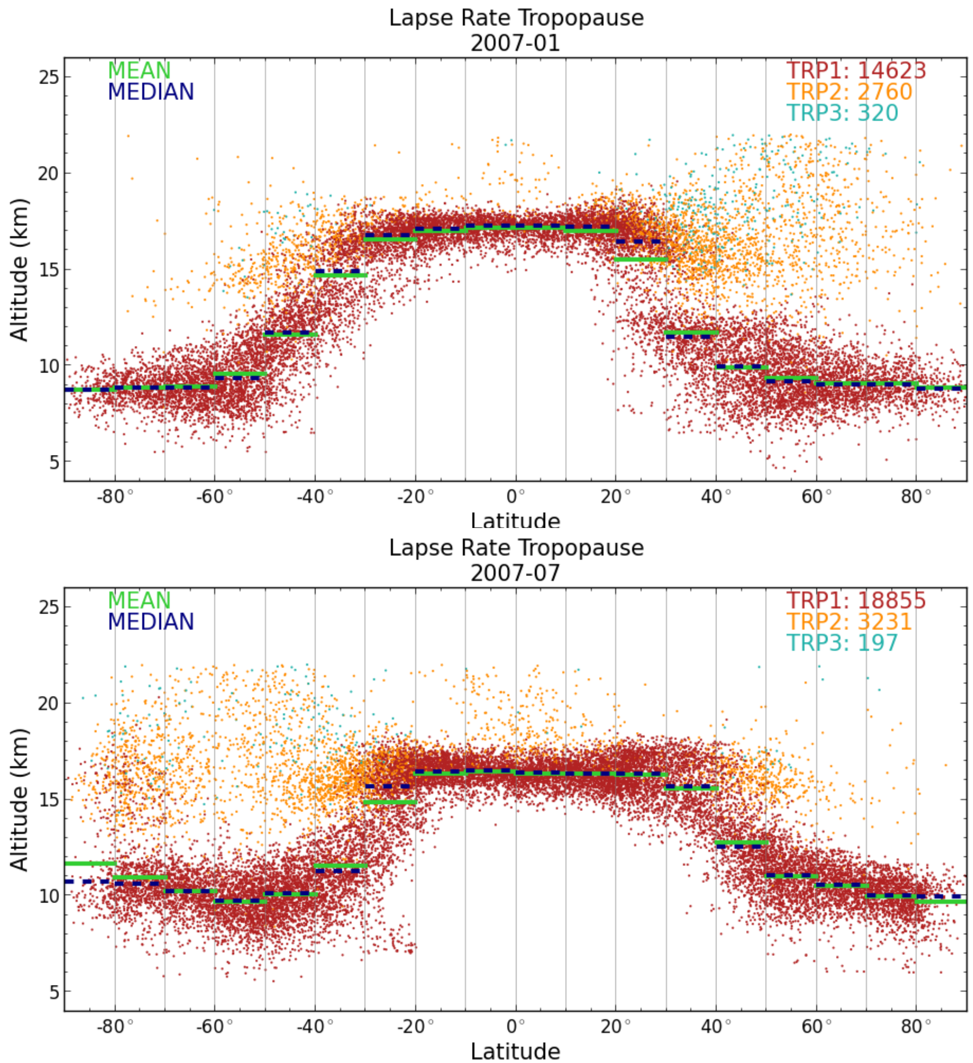
[Schmidt et al. 2004; Borsche et al. 2007; Foelsche et al. 2009; Rieckh et al. 2013]

Insights into tropopause structure

- double tropopause structures



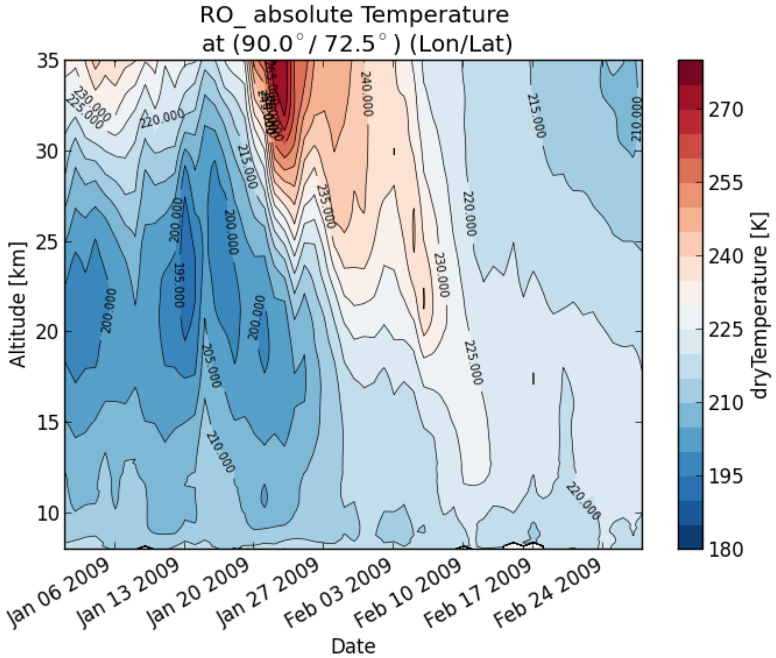
[Randel et al. 2007]

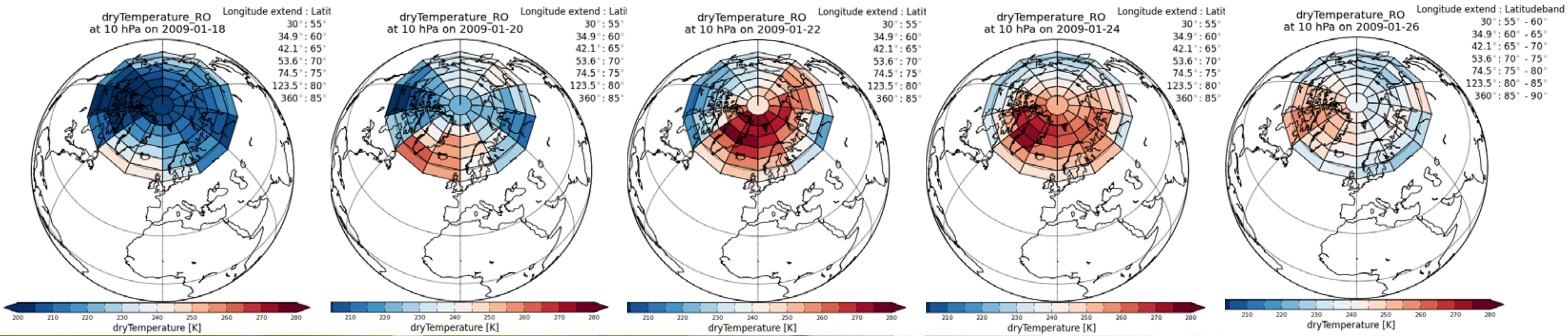


[Rieckh et al. EGU 2013]

Recent insights into sudden stratospheric warmings (SSW)

- Evolution and structure of SSW

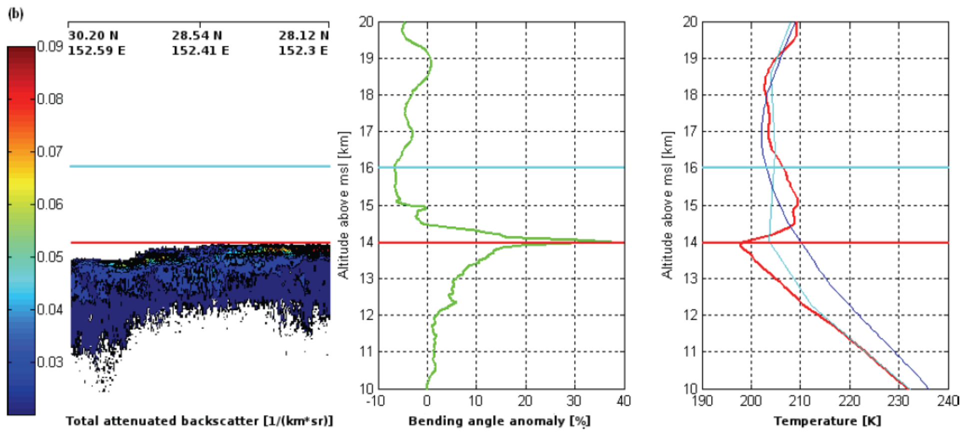


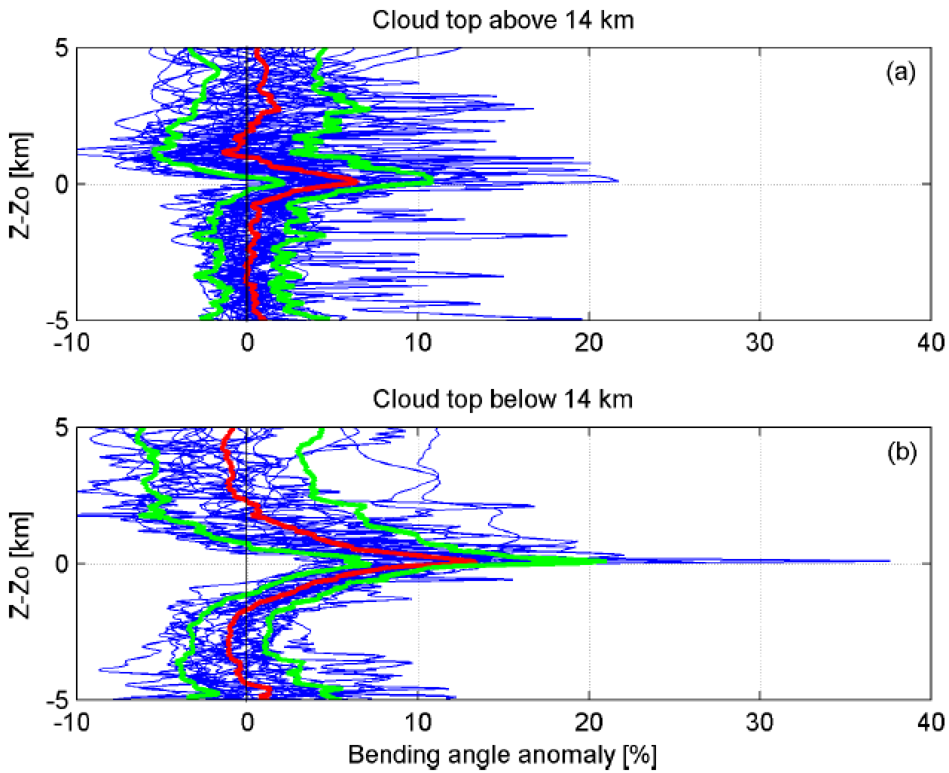


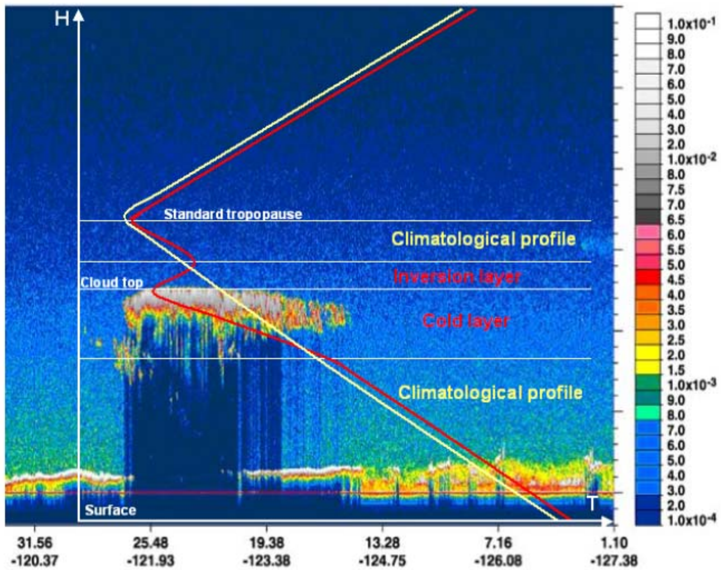
[Klingler, pers. comm. 2013]

Recent insights into thermal structure of convective clouds

- Detection of cloud top height using bending angle





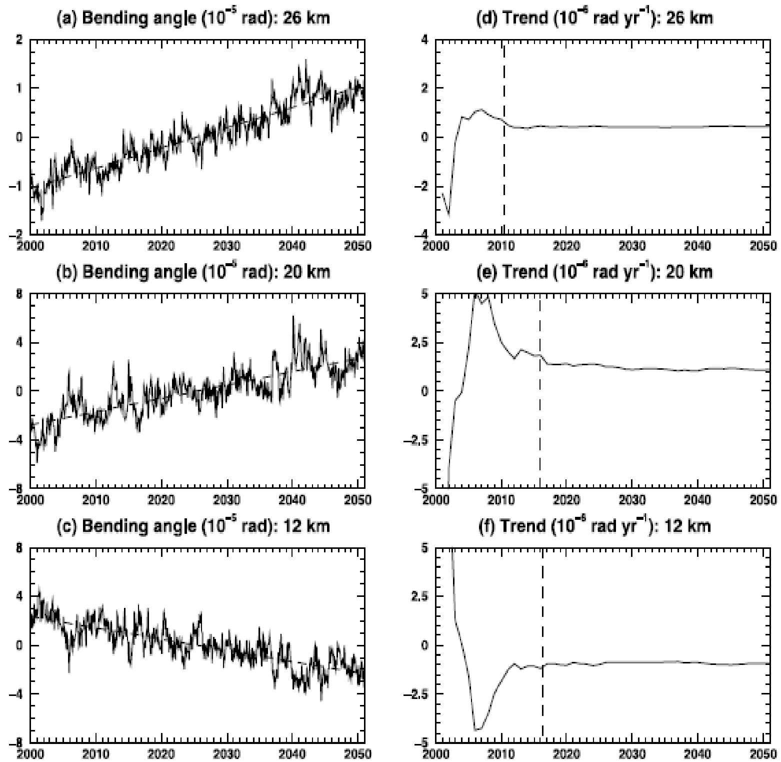


Climate change detection studies

- based on models
- based on simulations
- based on real observations

Climate change studies using models and simulations

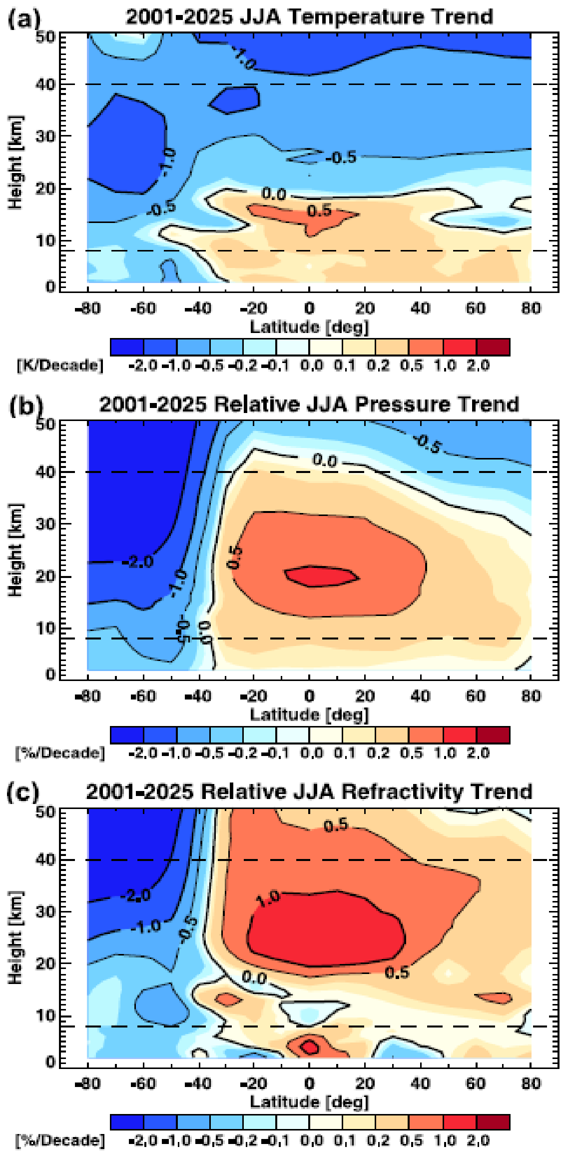
- *Yuan et al.* [1993]:
  "Simulations show the potential of GPS RO for the detection of climate change"
- *Leroy* [1997] :
  geopotential height useful for climate monitoring
- *Vedel and Stendel* [2003],
  Stendel et al. [2006]:
  Refractivity useful for climate monitoring
- *Leroy et al.* [2006]: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

Observing system simulation experiment (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 monitoring



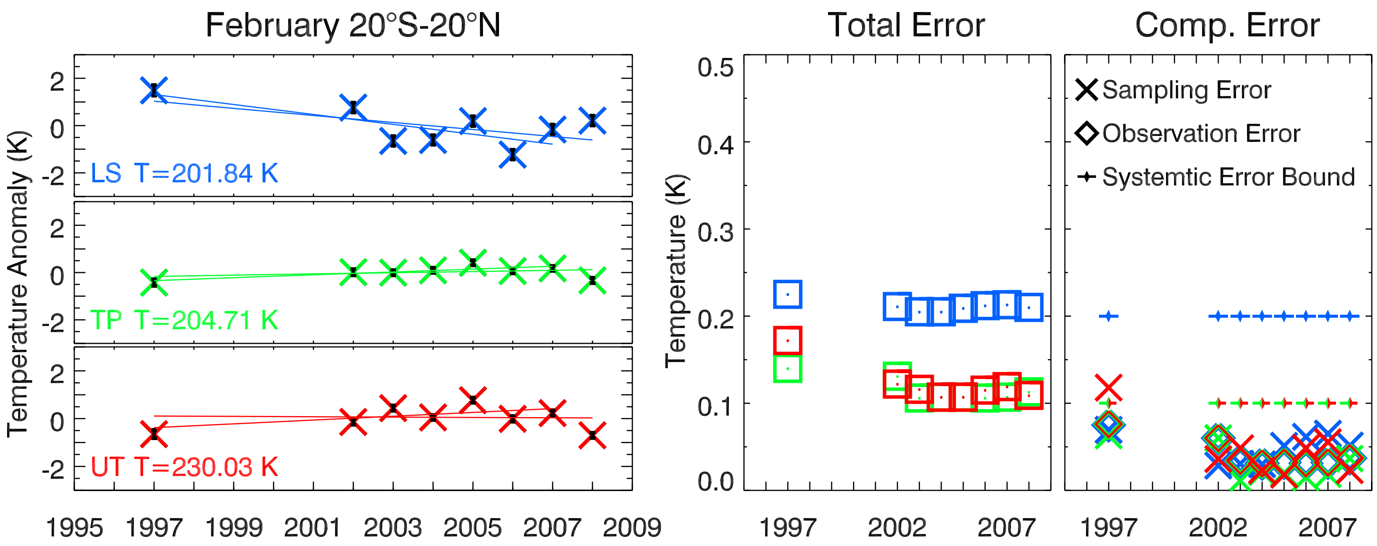
[*Steiner et al.* 2001; *Foelsche et al*. 2008; Lackner et al. 2011]

Trend detection using real RO observations

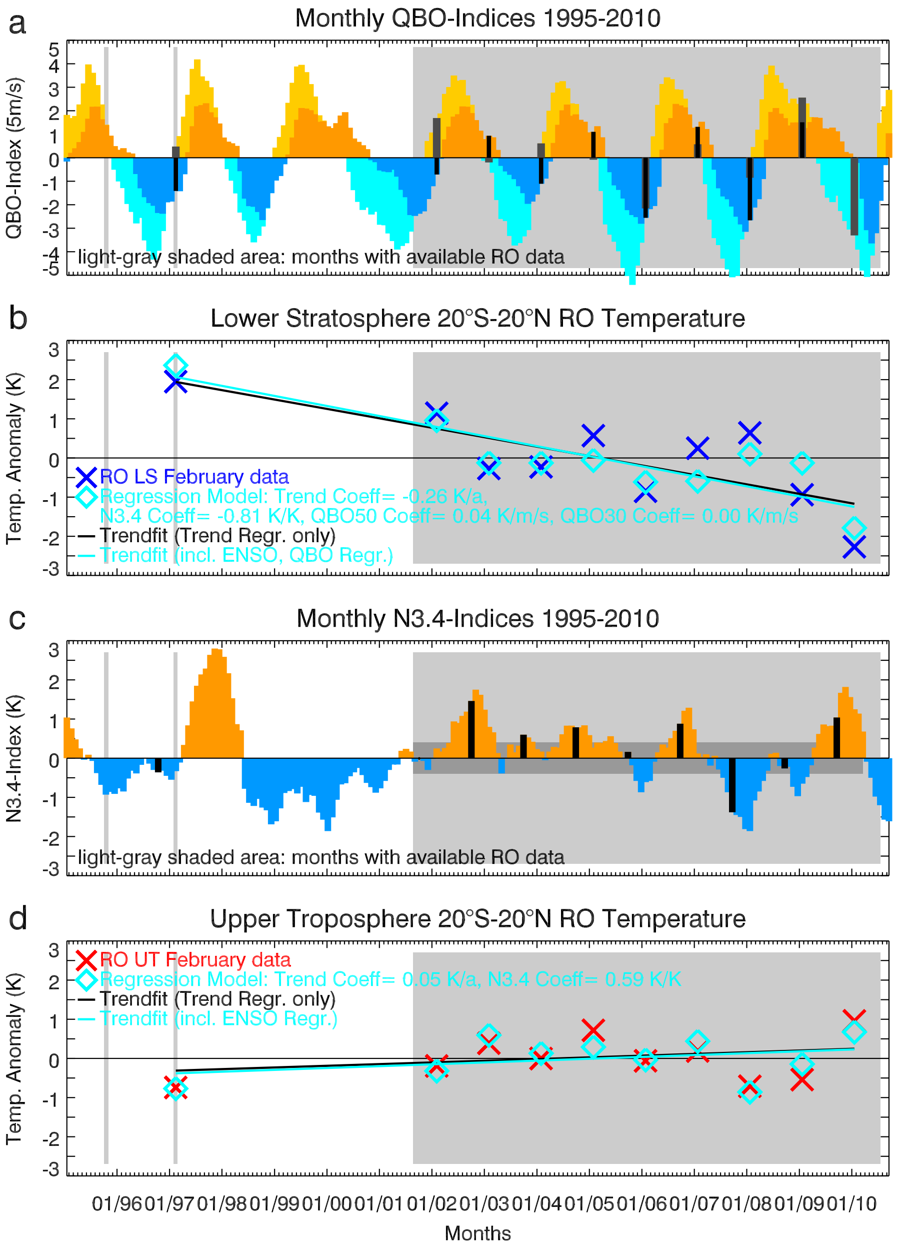
- **Region of best data quality:** 50°N–50°S, UTLS 300–30 hPa (~9–25 km)
- **GPS/Met**: 10/1995, 02/1997
  CHAMP: 09/2001–02/2008
  GRACE, F3C: 10/2006–07/2010

Demonstration study – RO temperature trends

- Tropics, February 1997, 2002 to 2008 (updated to 2010)
- Regression taking into account data quality



Wegener Center UNI GRAZ



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, 2001–2009.

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]

Variability and trends in UTLS

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

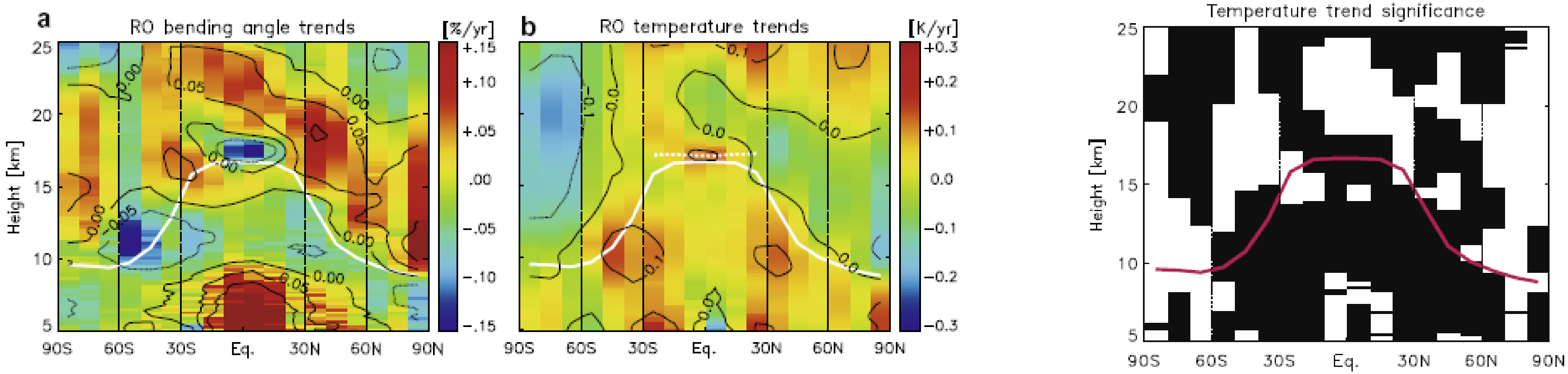


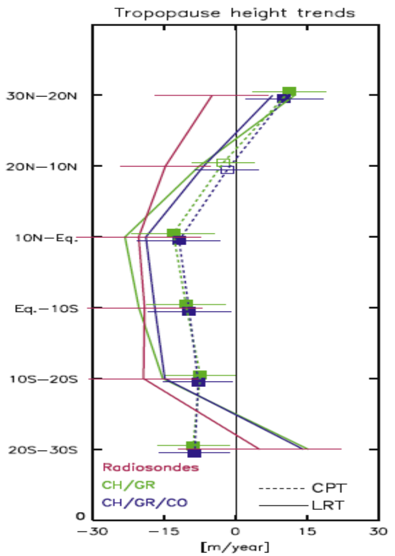
Fig. 10. Relative bending angle trends [%/yr] (a) and absolute temperature trends [K/yr] (b) from CHAMP and GRACE data (May 2001–August 2009).

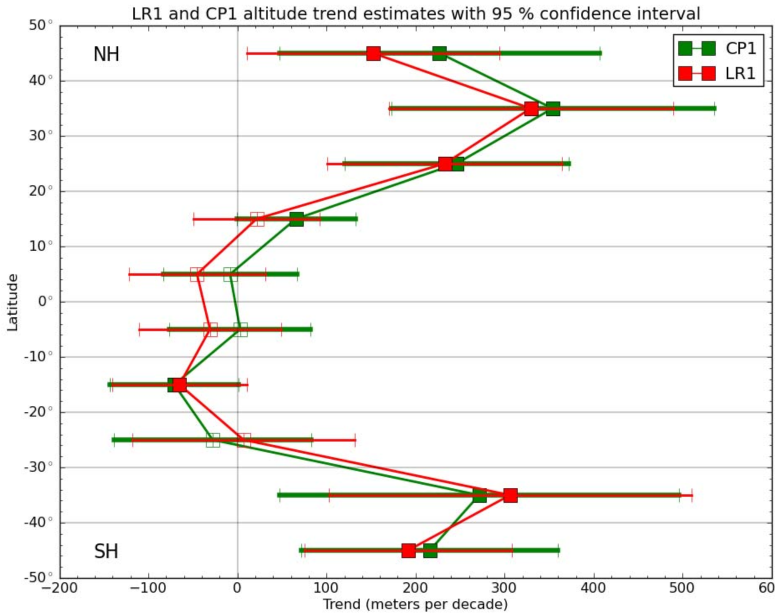
Fig. 11. Statistically significant temperature trends (C.I.=90%; *SIG* > 1.6

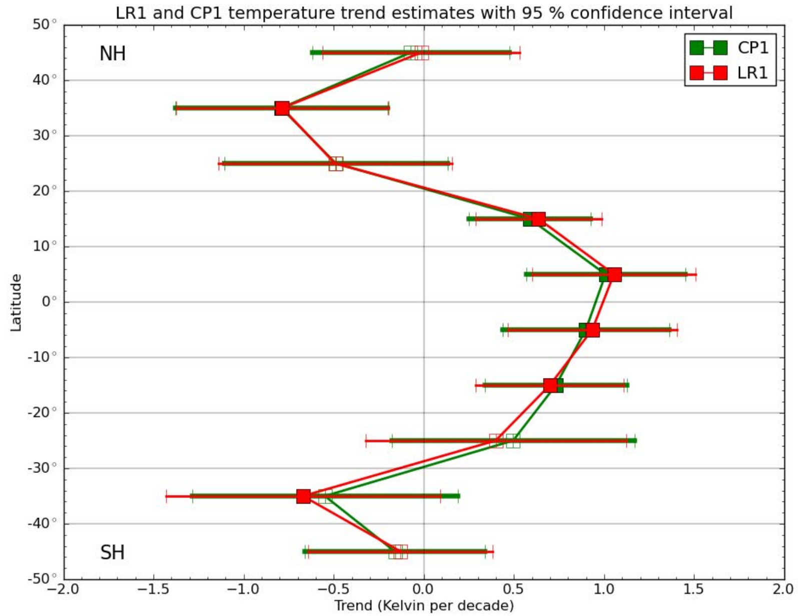
[Schmidt et al. 2010]

Recent insights into tropopause trends

- Tropopause height decrease in tropics of up to –80 m/decade and increase at mid-latitudes up to 300 m/decade
- Tropopause temperature increase in the tropics of up to 1 K/decade and decrease at mid-latitudes of up to about –0.75 K/decade



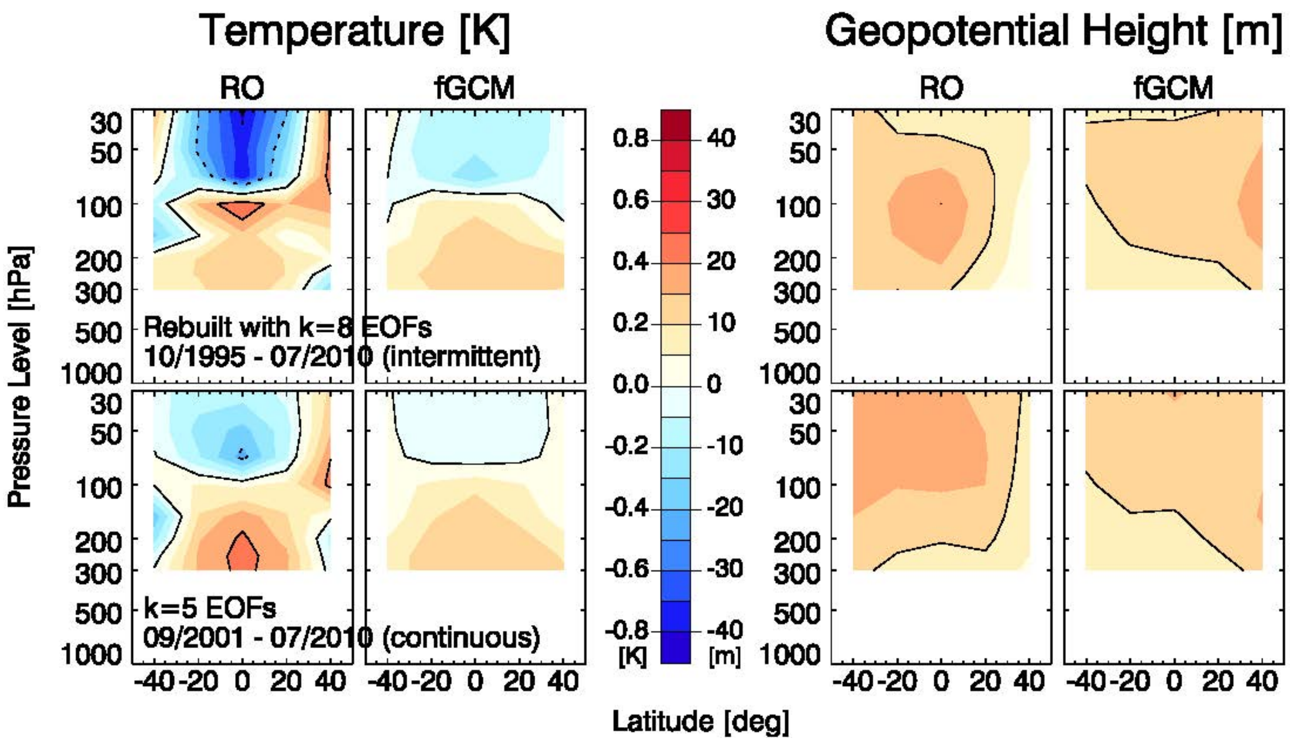




[Schmidt et al. 2010; Rieckh et al. 2013]

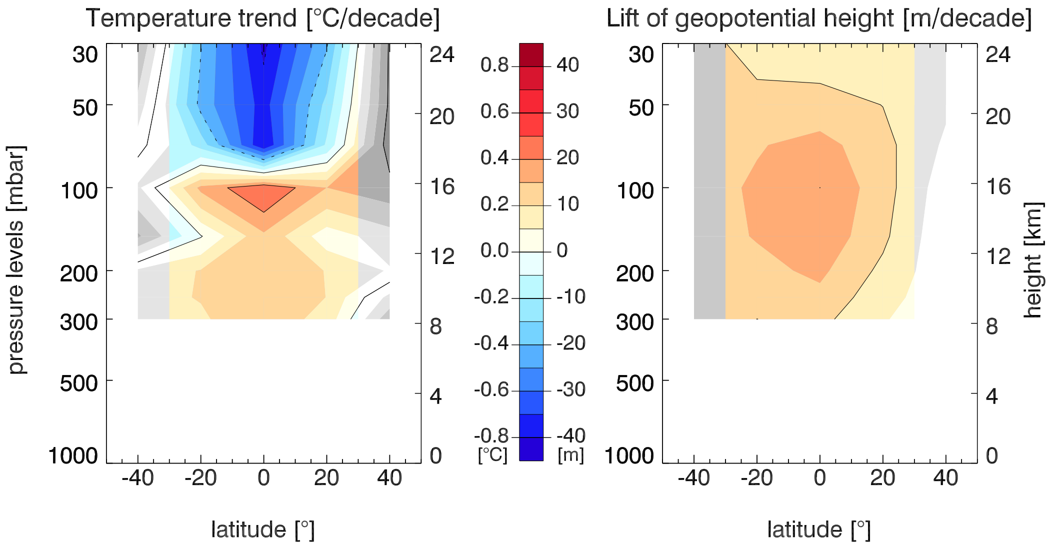
Optimal Fingerprinting

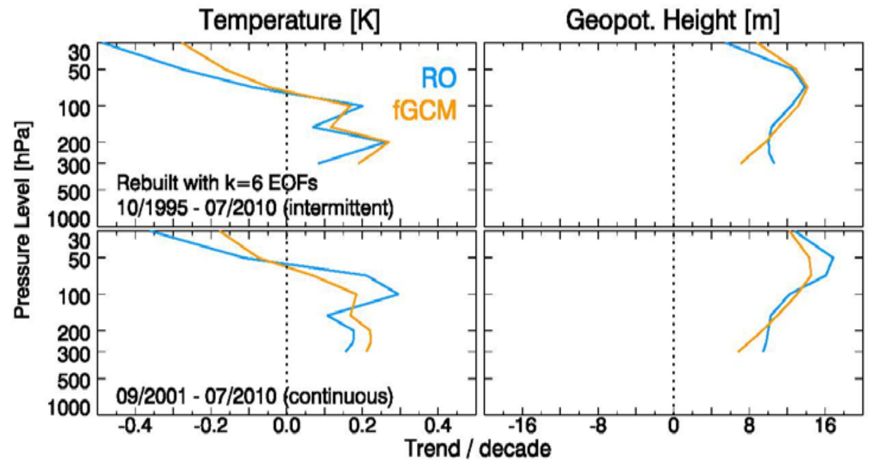
- Trend patterns (fingerprints) are different due to natural variability (e.g. El Niño) or due to anthropogenic trends
- Generalized multivariate regression of ***y***= **X*a*** + ***u*** with RO trends ***y***, forced climate model trends **X**, and climate noise ***u***
- Use of forced climate model runs (fGCM) and pre-industrial control runs



[Lackner et al. 2011]

Optimal fingerprinting – climate change signal





Mean Trend 50°S–50°N

- Emerging climate change signal in the RO record
- Signal in temperature (96% conf. level) and geopotential height (99% conf. level)
- Warming of the troposphere, Cooling of the stratosphere
- Uplift of geopotential height levels in upper troposphere
- Consistency with detection times of ~7–14 years, *Z(p)* first

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

[Lackner et al. 2011; Steiner et al. 2011]

GPS RO

- high accuracy and vertical resolution, consistency, long-term stability
- for monitoring atmospheric variability and climate
- potential for future global climate observing system
- **meets GCOS requirements for ECV air temperature**
- **early detection of climate trends**

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

- **reference standard** for
  validating and calibrating data from other observing systems
  and as absolute reference within assimilation systems

Outlook – GCOS Actions

- **Currently achievable performance**
  - 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 stability, meeting targets in upper troposphere and lower stratosphere (although not for spatial resolution)

- **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

- Processing advancements in lower troposphere and stratosphere to further lower structural uncertainties
- Improving the maturity of RO climate records
- Benchmark data with integrated uncertainties
- 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

THANK YOU !

Welcome!

International Workshop on
Occultations for Probing Atmosphere and Climate
Seggau Castle, Leibnitz near Graz, Austria
5 - 11 September 2013

OPAC-IROWG 2013