GRAS SAF Workshop on Applications of
GPS Radio Occultation Measurements

ECMWF Reading, UK; 16-18 June 2008

Climate Signal Detection with GPS Radio Occultation Measurements

(focus trend signal detection, mainly based on GPS/Met and CHAMP radio occultation records 1995-1997 and 2001-2008)

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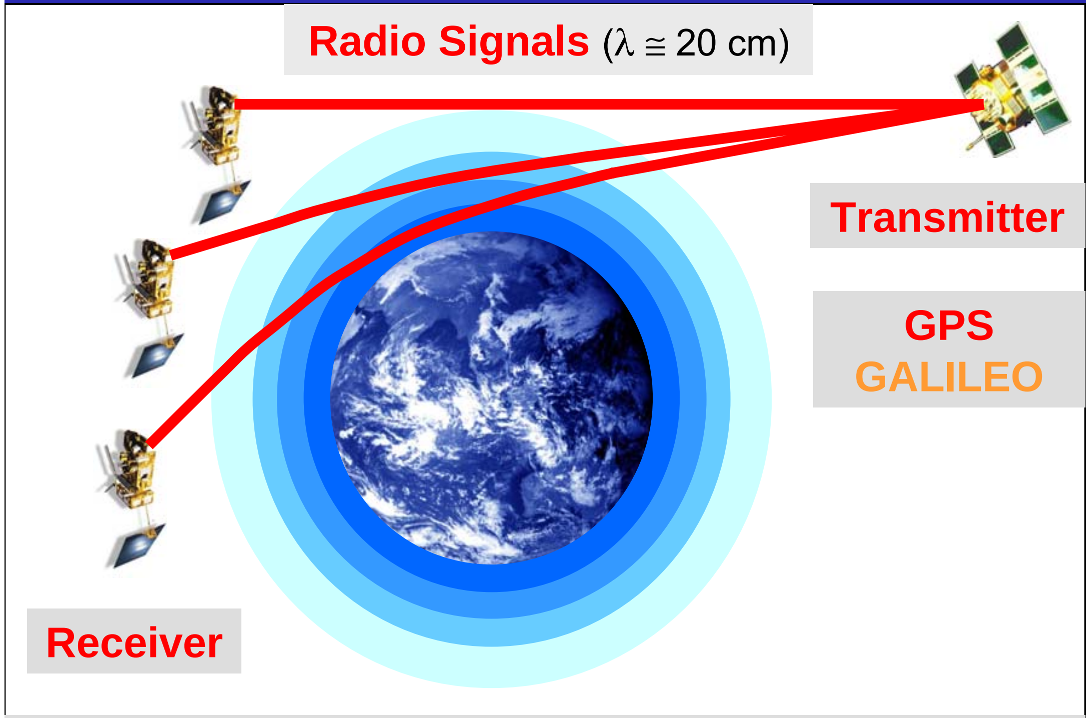
Thanks for funds to FWF, esa, asap FFG

Outline

- Radio Occultation (RO) method and properties
  (just to have an intro included, essentially skipped in the talk)
- RO data set and climatologies
- On uncertainties and consistency of climatologies
- Climate trend signal detection study design
- Trend, error, and uncertainty calculations
- Results and discussion
- Conclusions and outlook

Radio Occultation Principle



Satellite in Low Earth Orbit:

GPS/MET, CHAMP,

SAC-C, GRACE, COSMIC, MetOp, Oceansat-2 …

GNSS–LEO satellite constellations

allow

- radio occultation observations in an active limb sounding mode exploiting the
- atmospheric refraction of GNSS signals providing
- measurements of phase path delay for the retrieval of
- key atmospheric/climate parameters

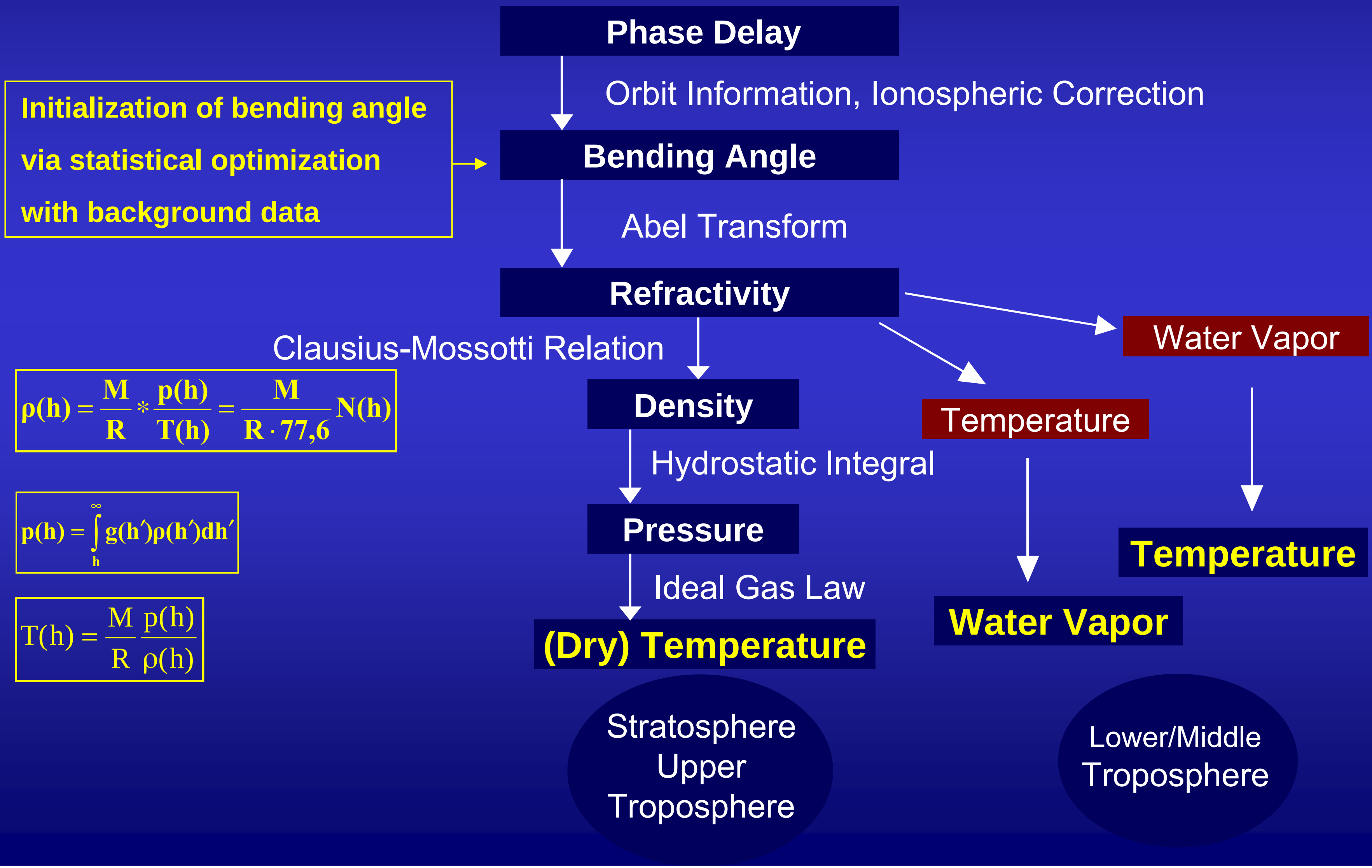
  e.g., refractivity *N*,

  geopotential height *Z*,

  temperature *T*, humidity *q*

Courtesy: U. Foelsche

Retrieval of Atmospheric Variables

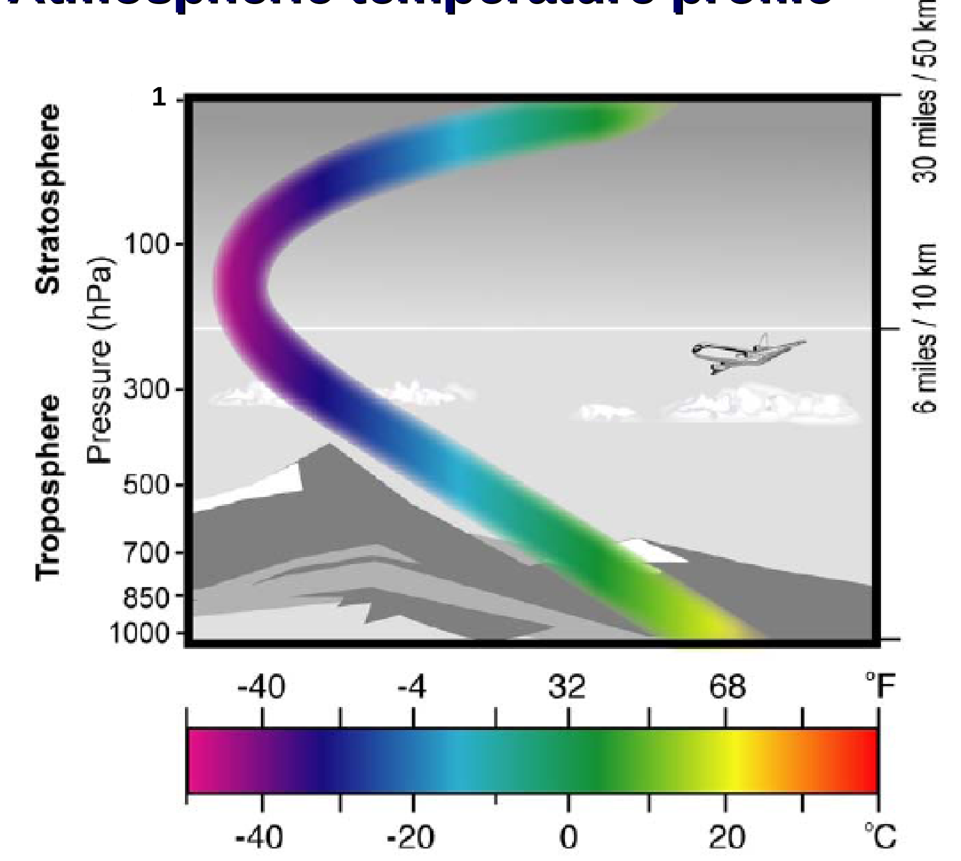


RO Data Characteristics

Properties

- Global coverage
  ~250 RO events/day →
  130–180 atmospheric profiles/day
- Essentially all weather capability
- High accuracy and
  high vertical resolution
  in the Upper Troposphere and
  Lower Stratosphere (UTLS)
  (~8−30 km)
- Long-term stability
  due to intrinsic self-calibration,
  precise timing with atomic clocks
- Homogeneity and consistency
  despite very different orbits, different
  instruments & raw processing chains

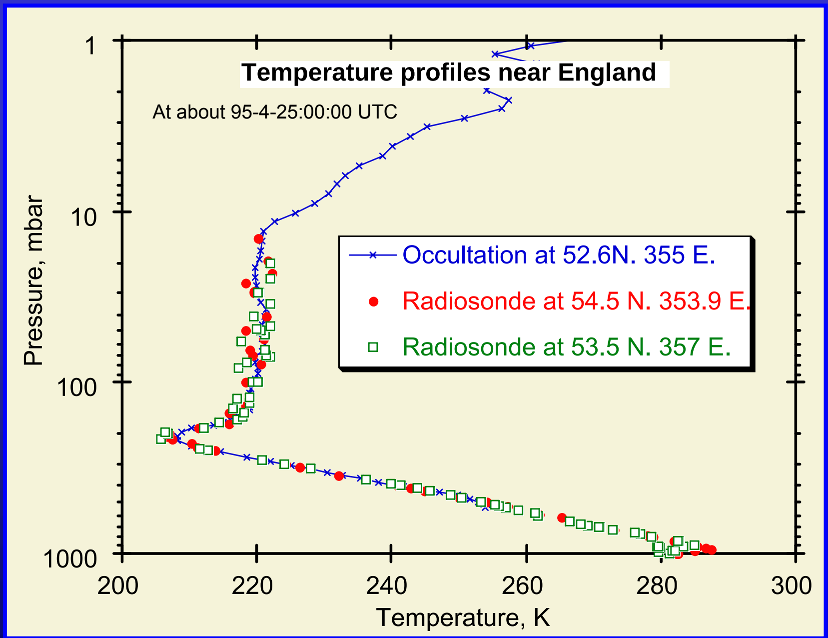
Atmospheric temperature profile

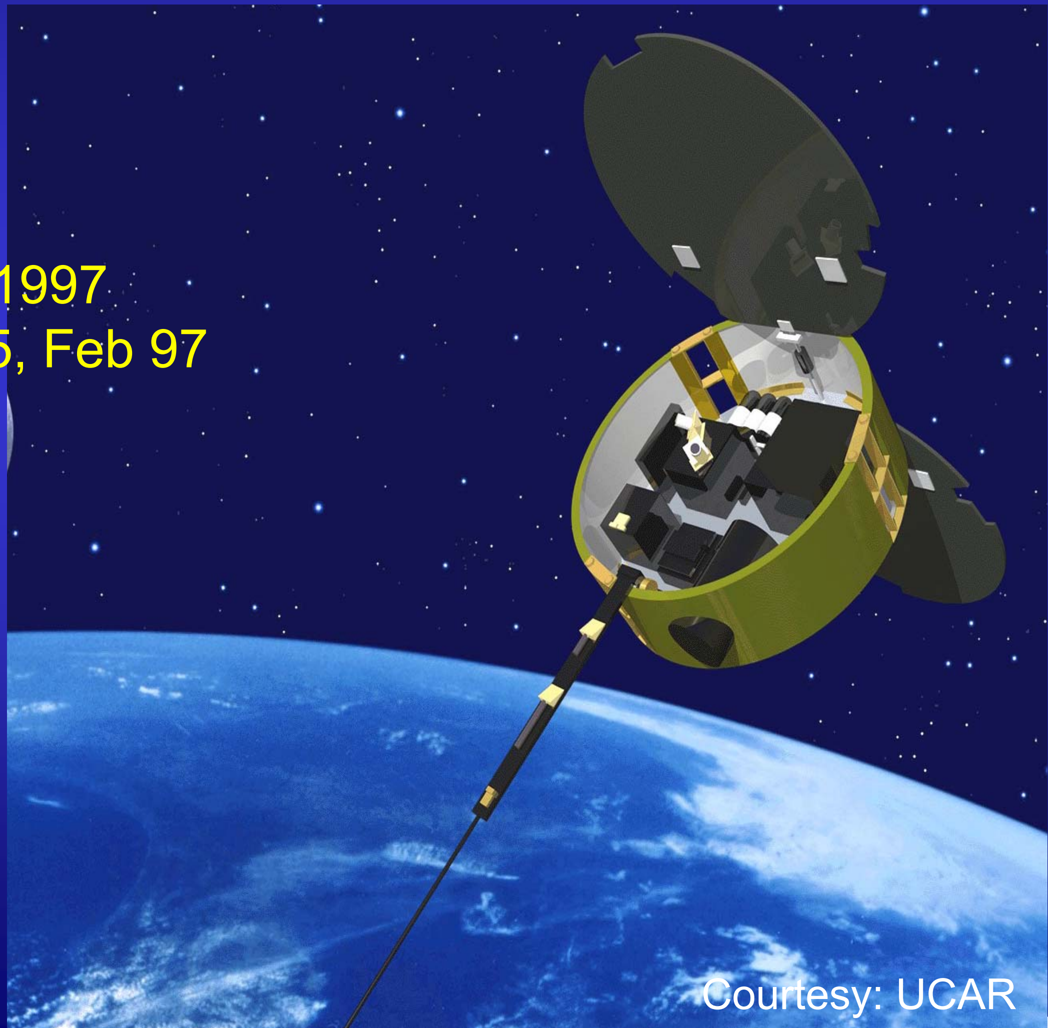


RO Mission GPS/Met

Proof of concept on MicroLab-I 1995

Intermittent Measurements 1995–1997
‘Prime time’ data used from Oct 95, Feb 97





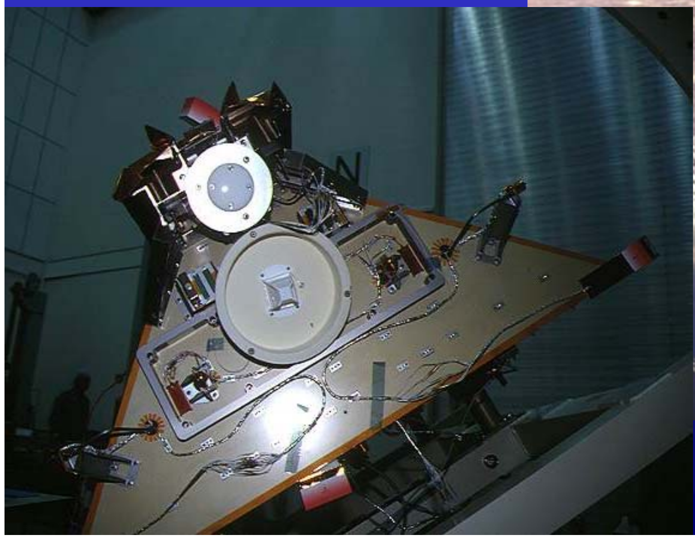
RO Mission CHAMP

CHAMP in orbit since July 15, 2000

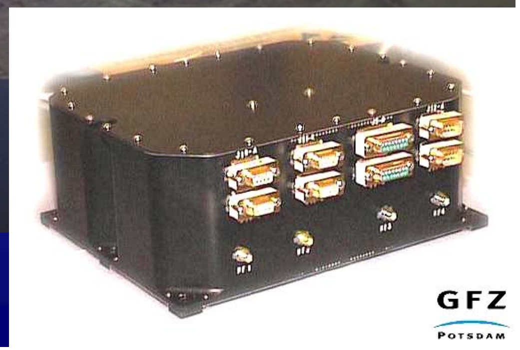
Continuous RO measurements since Sep 2001

Courtesy: J. Wickert (GFZ)

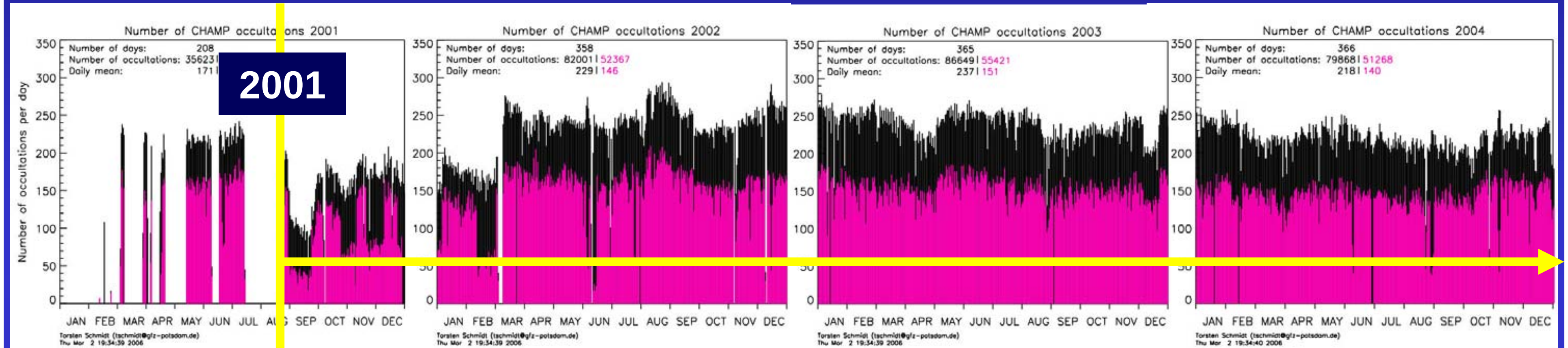
Occultation antenna



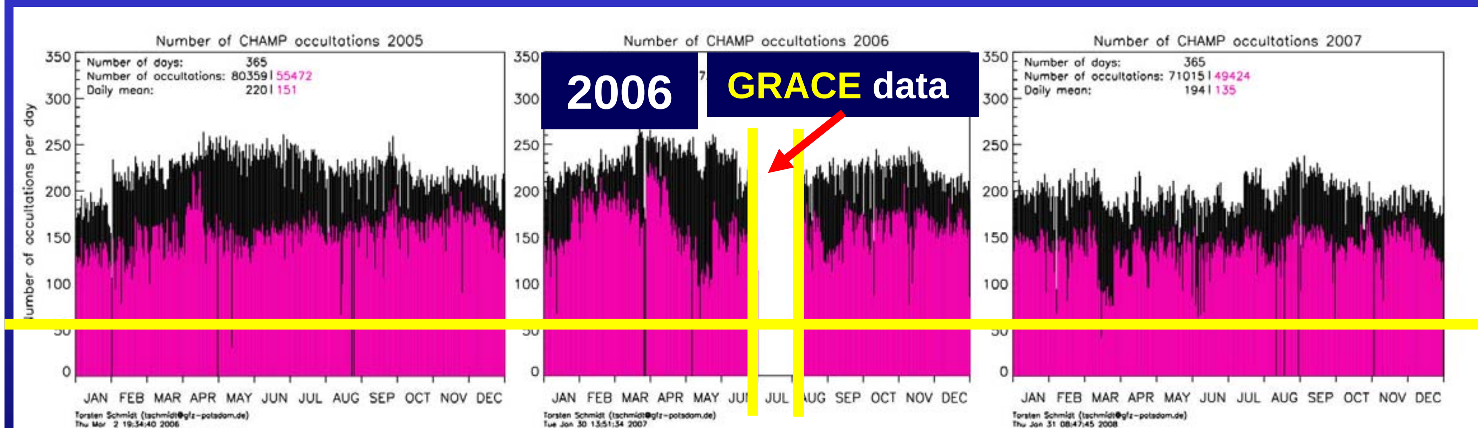
GPS Receiver onboard CHAMP



CHAMP RO data record



© T. Schmidt, GFZ



~130 − 180 RO atm.profiles/day

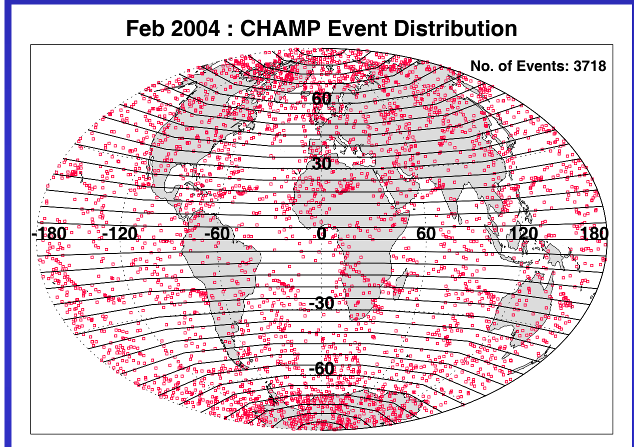
2009

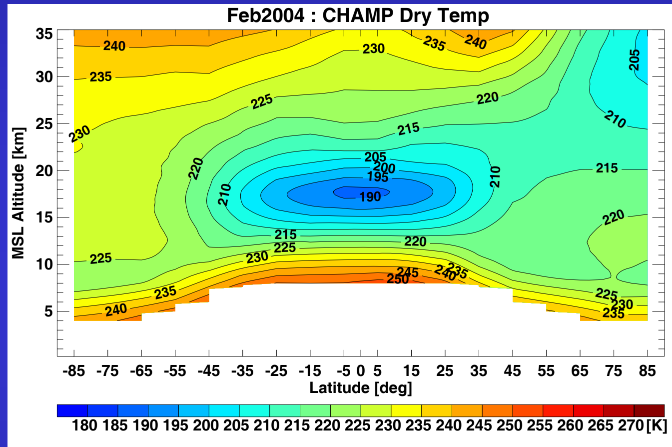
CHAMP: First opportunity for multi-year RO climatologies

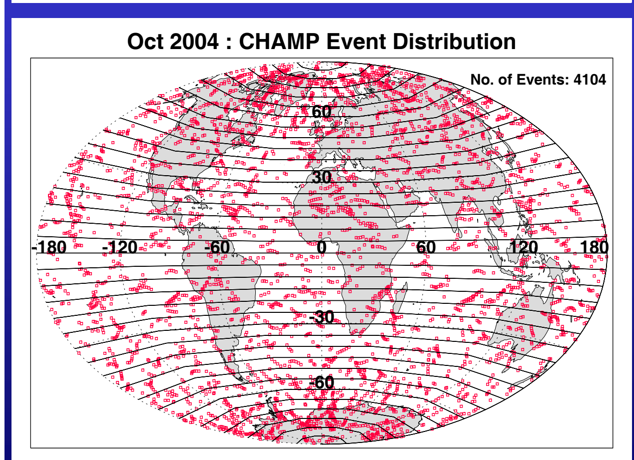
RO based Climatologies

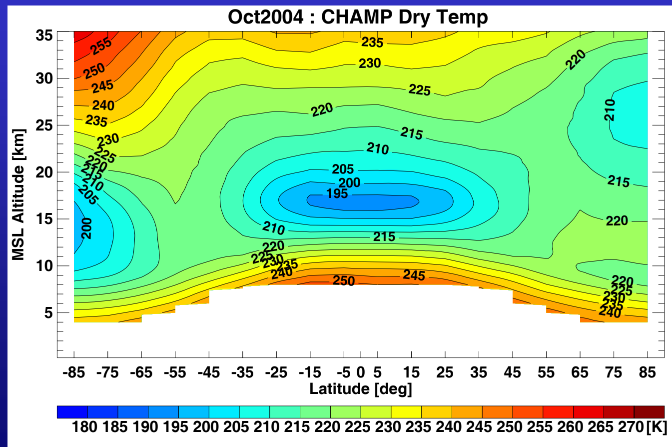
Event Distribution and Dry Temperature Climatologies

Example Months – February/October 2004









- WegCenter Retrieval
  CCRv2.3, OPSv5.2/v5.3
- Phase & orbit data from GFZ Potsdam
- Monthly mean fields
- Zonal mean fields
- Binning and Averaging
  36 latitude bands
  5° latitudinal width
- Background bending angle data for statistical optimization:
  ECMWF analyses for CHAMP (T42L60, T42L91)
  ERA-40 for GPS/Met (T42L60)

(on uncertainties and consistency of climatologies…)

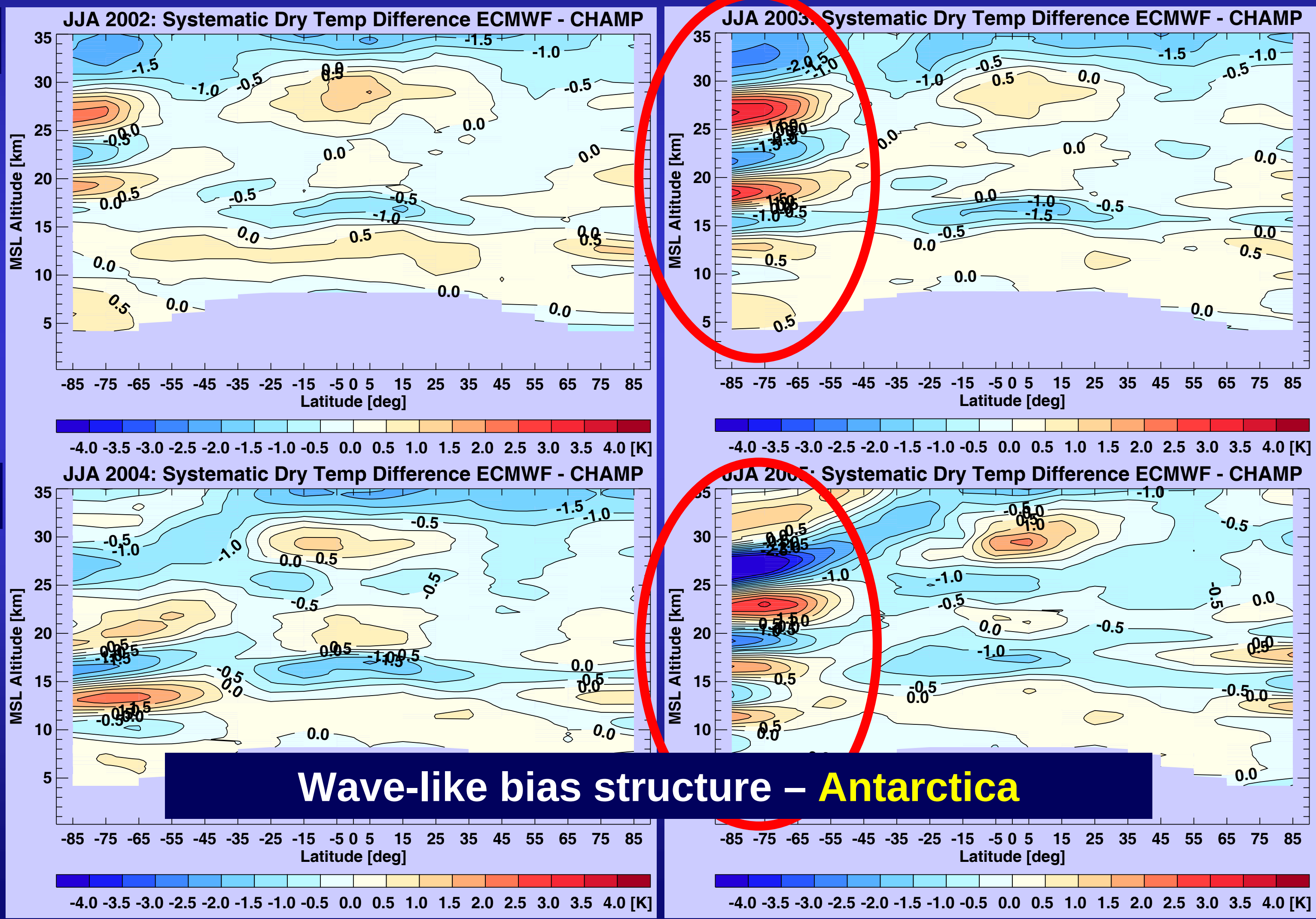
Systematic Difference – Summer

2002

2003

2004

2005



Wave-like bias structure – Antarctica

Gobiet et al., GRL 2005, *Foelsche et al.*, ClimDyn 2007

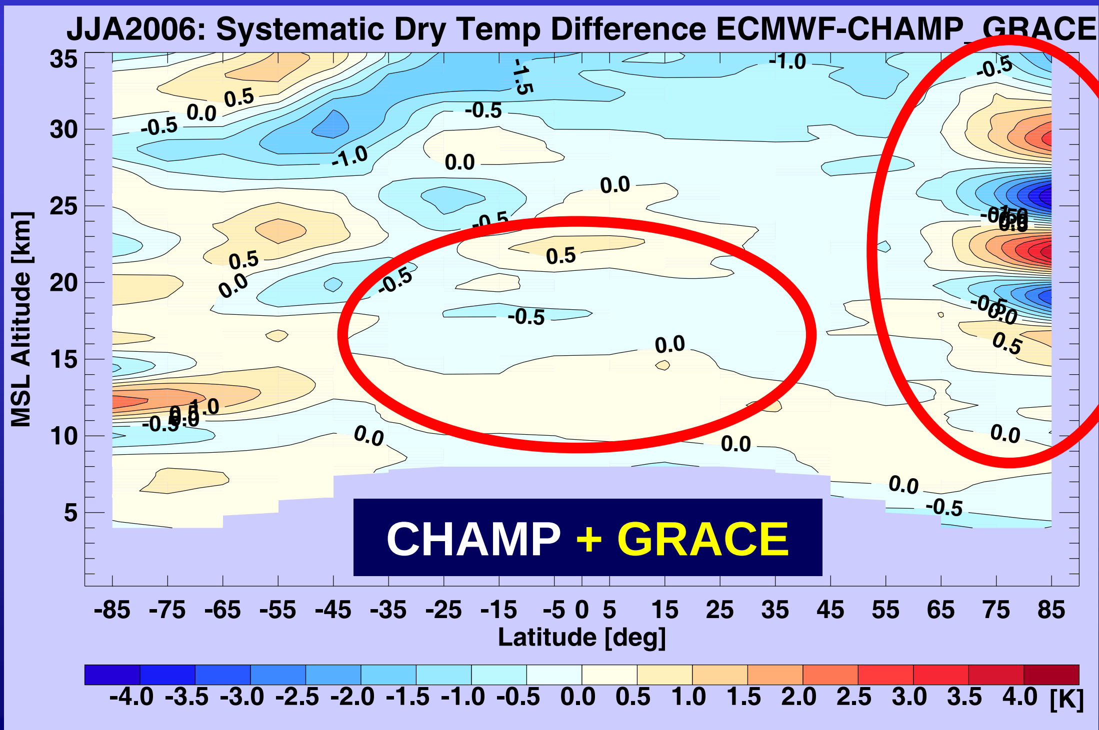
Systematic Difference – JJA2006

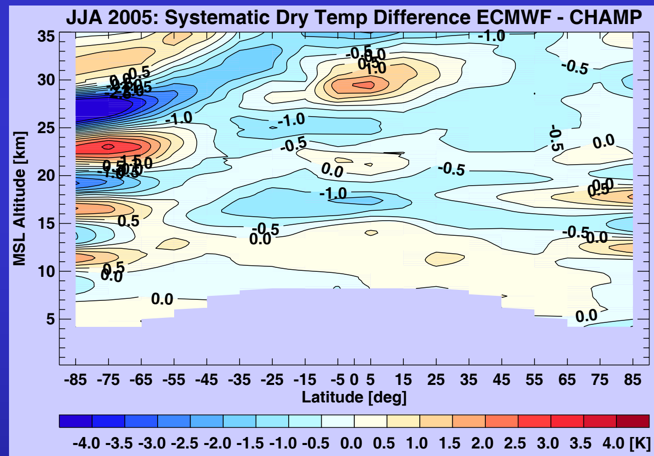
Wegener Center
www.wegcenter.at

IGAM
UNI GRAZ

February 2006: Major change at ECMWF

Horizontal Resolution:	T511 → T799
Vertical Resolution:	L60 → L91
Top model level:	0.1 hPa → 0.01 hPa





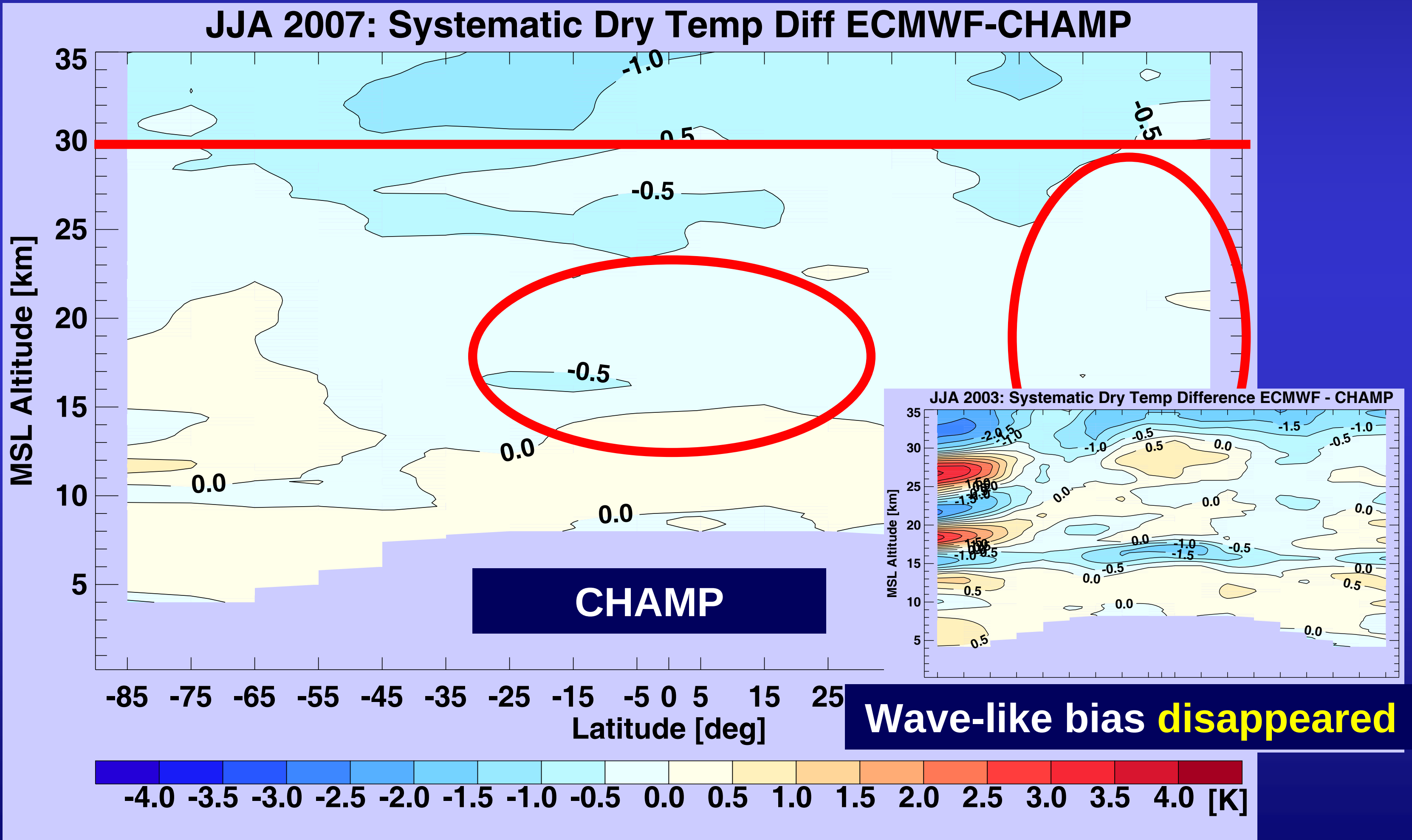
Tropical Tropopause differences disappeared

Wave-like bias structure now over the Arctic

Foelsche et al., ClimDyn 2007

Systematic Difference – JJA 2007

as of December 2006: Assimilation of RO data at ECMWF

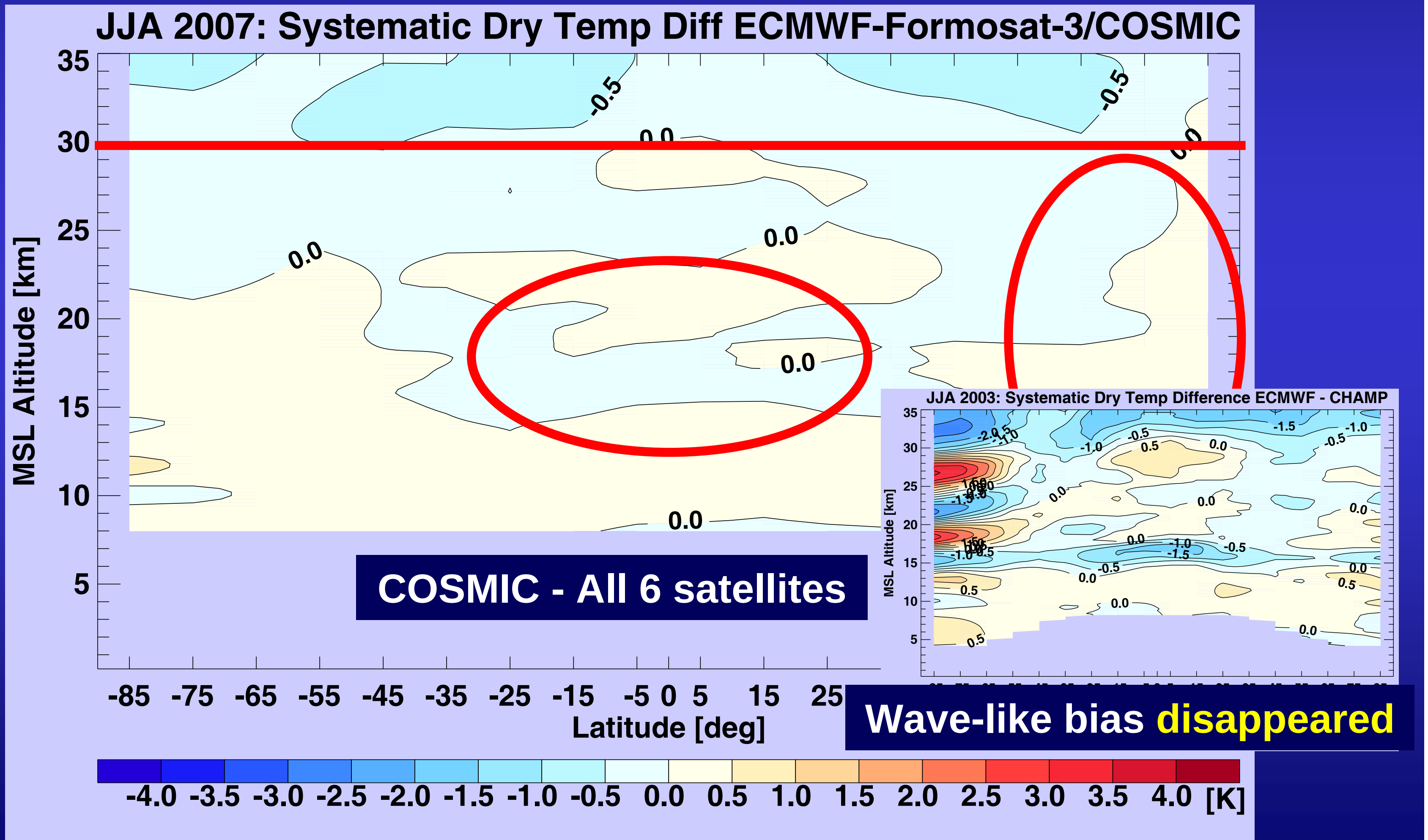


Wave-like bias disappeared

Foelsche et al., OPAC 2008

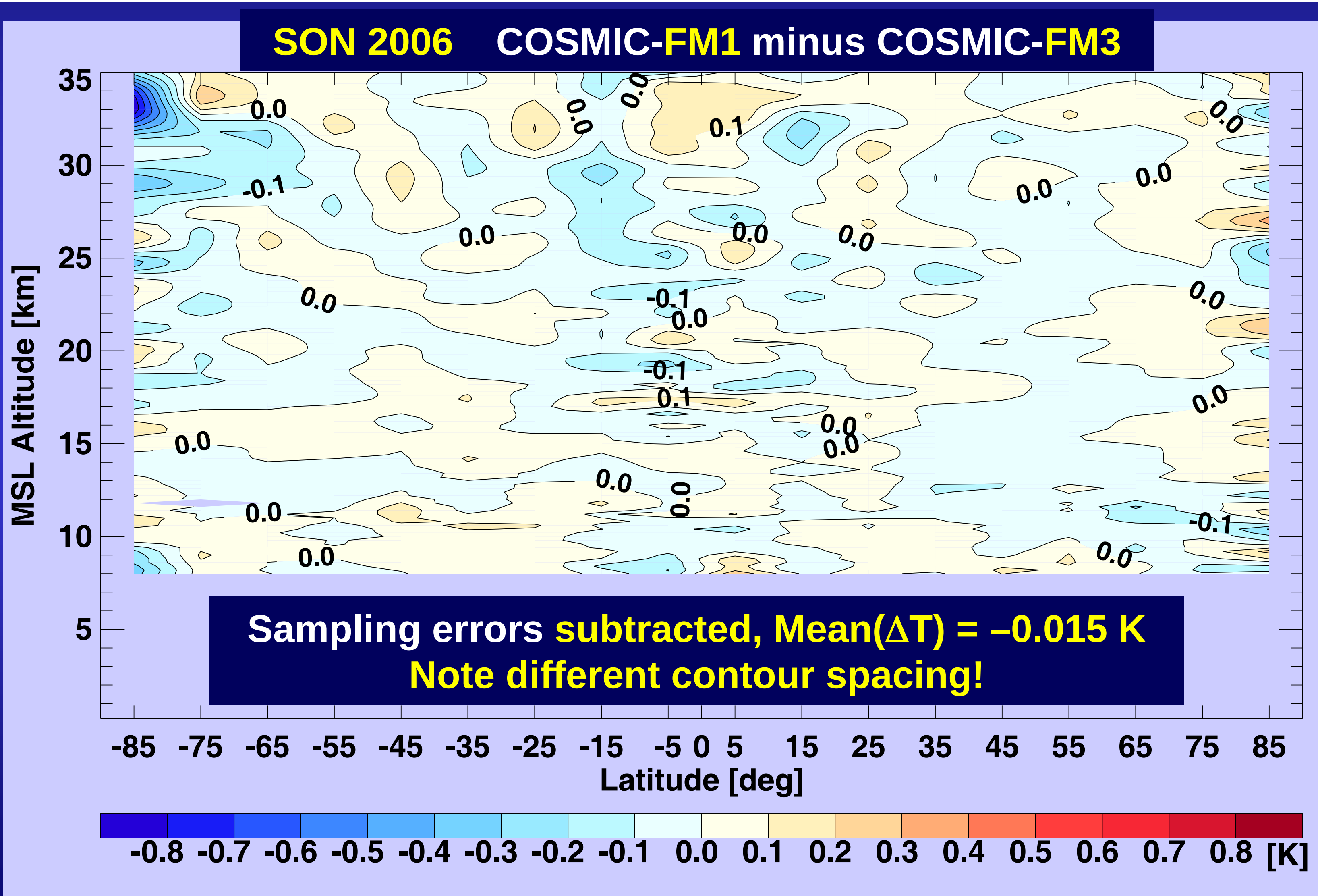
Systematic Difference – JJA 2007

as of December 2006: Assimilation of RO data at ECMWF



Foelsche et al., OPAC 2008

Consistency of RO Data



Foelsche et al., TAO 2008

Consistency of RO Data

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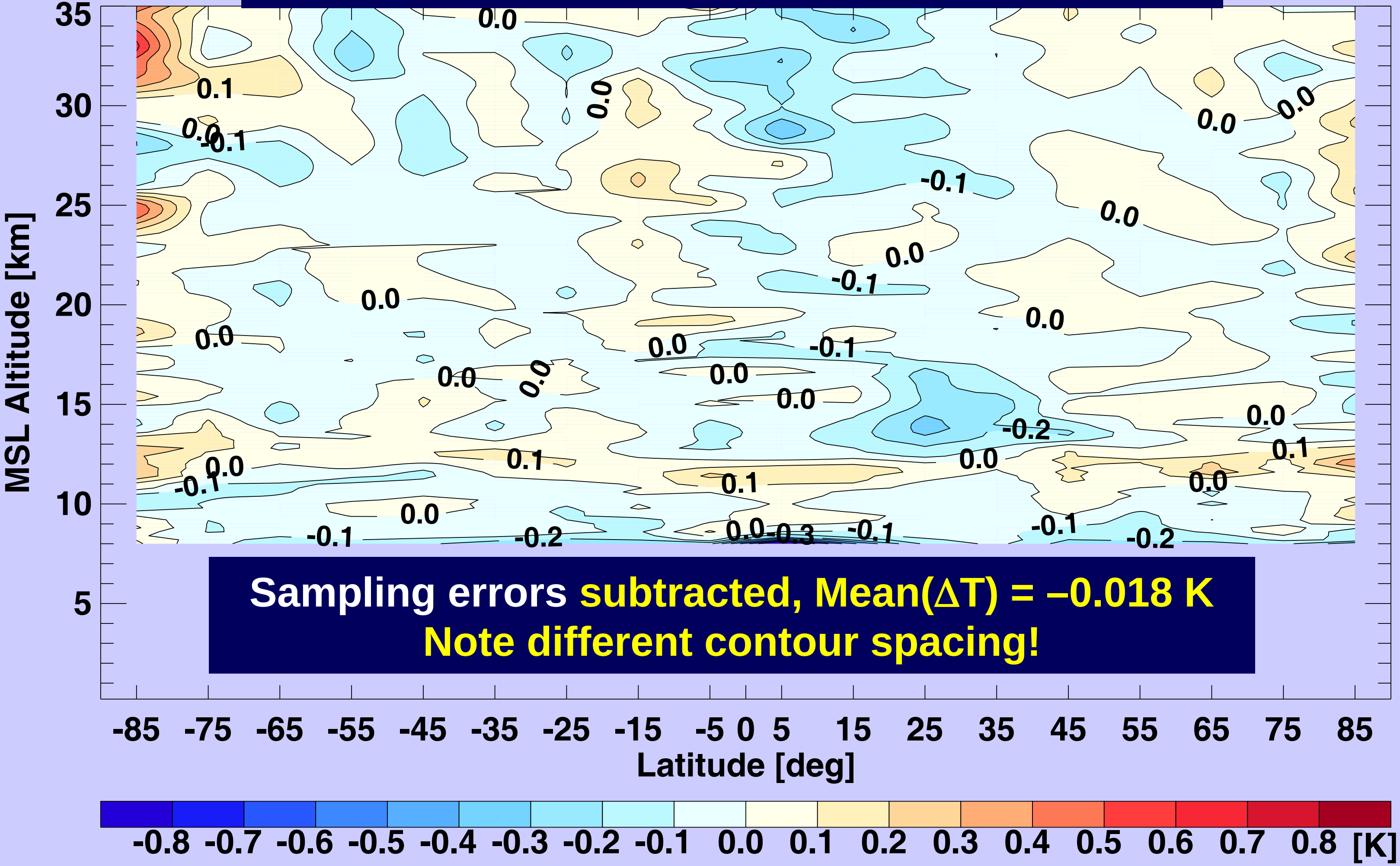
COSMIC

IGAM
UNI GRAZ

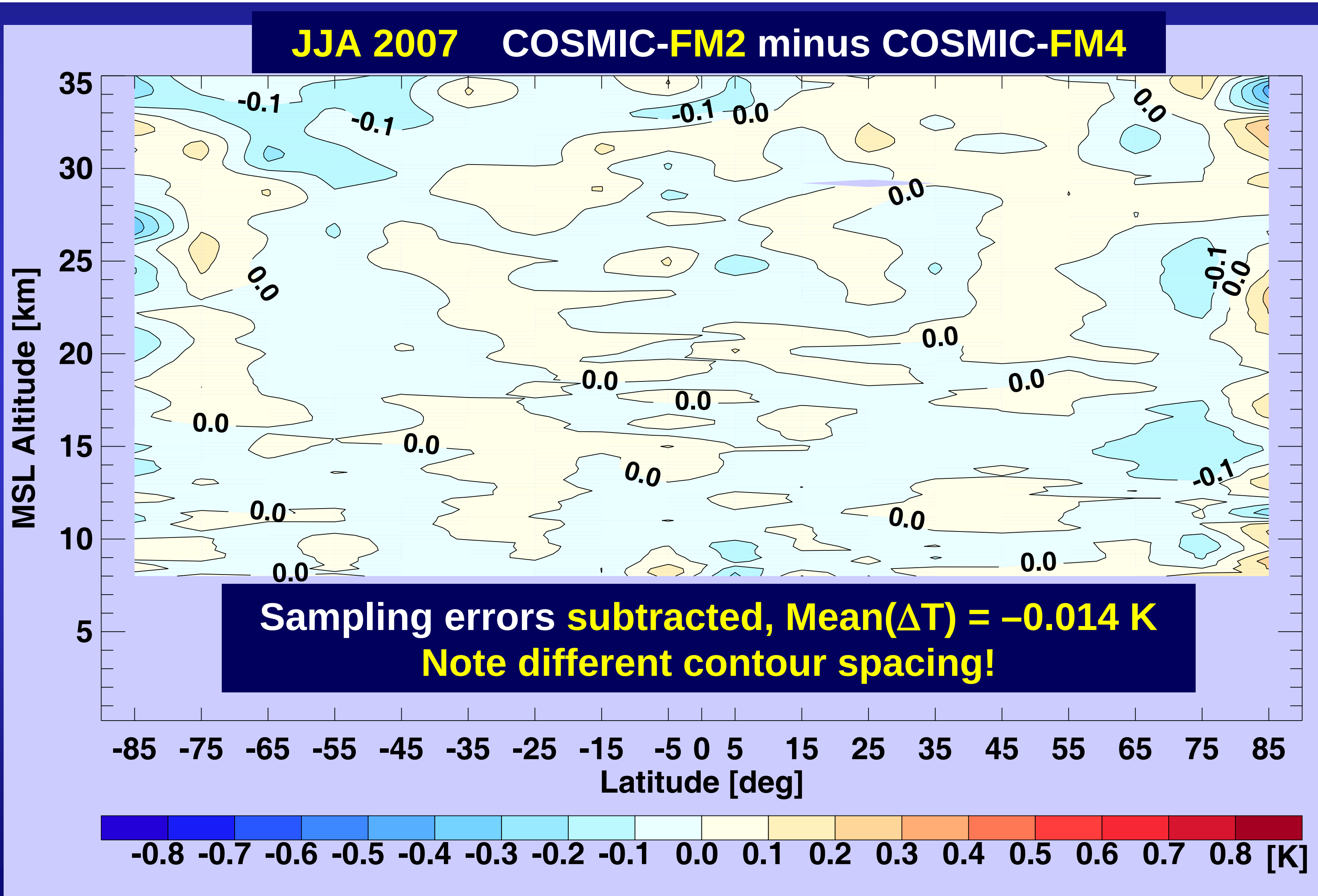
SON 2006 COSMIC-FM3 minus COSMIC-FM5



Sampling errors subtracted, Mean(ΔT) = –0.018 K
Note different contour spacing!

Foelsche et al., TAO 2008

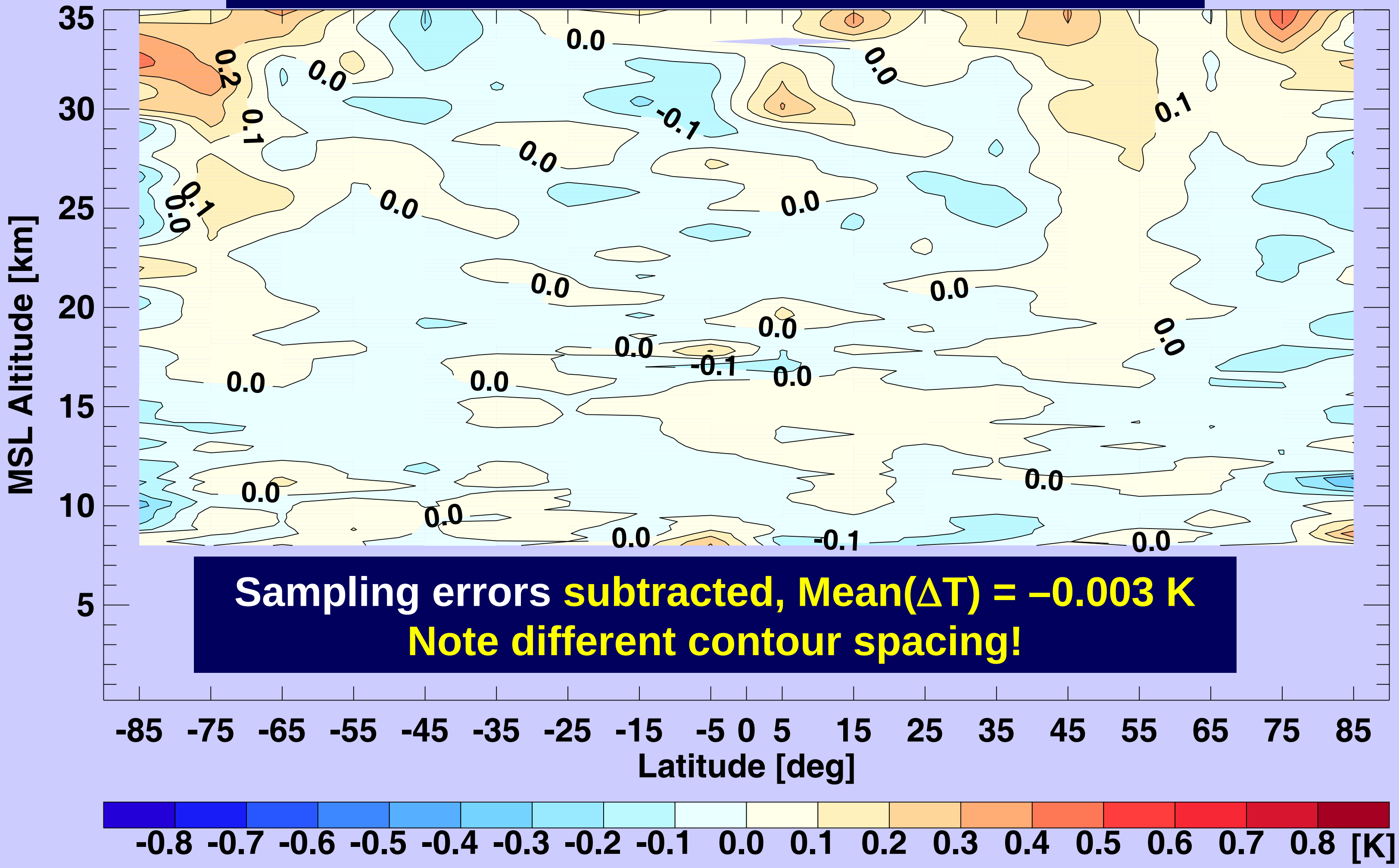
Consistency of RO Data



Foelsche et al., OPAC 2008

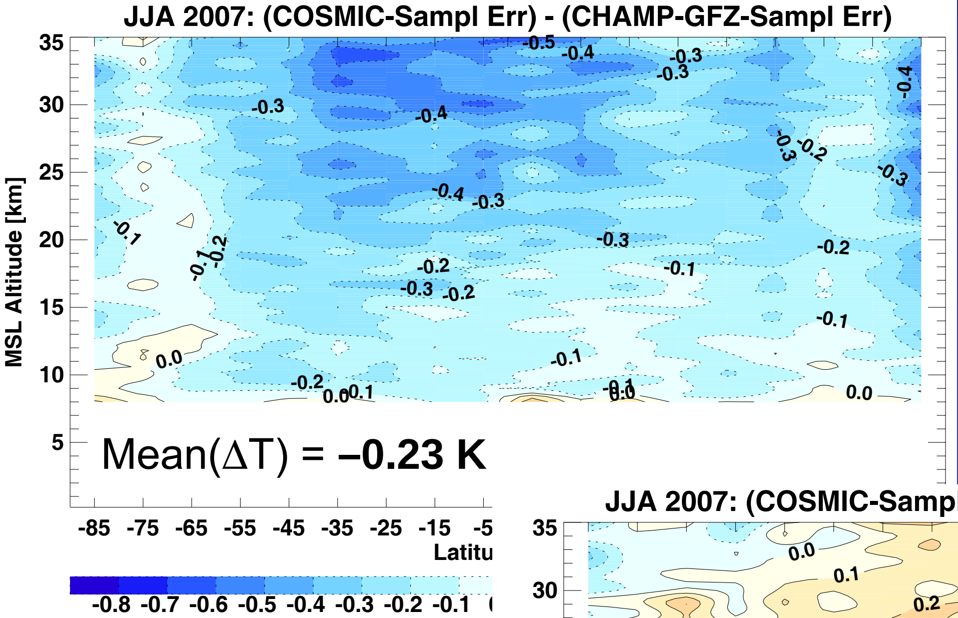
Consistency of RO Data

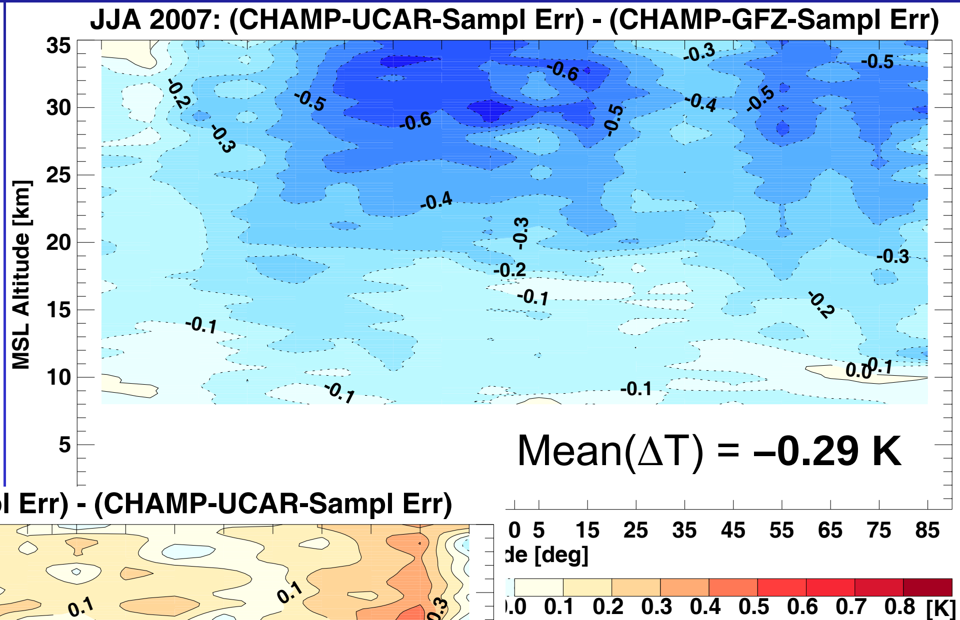
JJA 2007 COSMIC-FM2 minus COSMIC-FM6

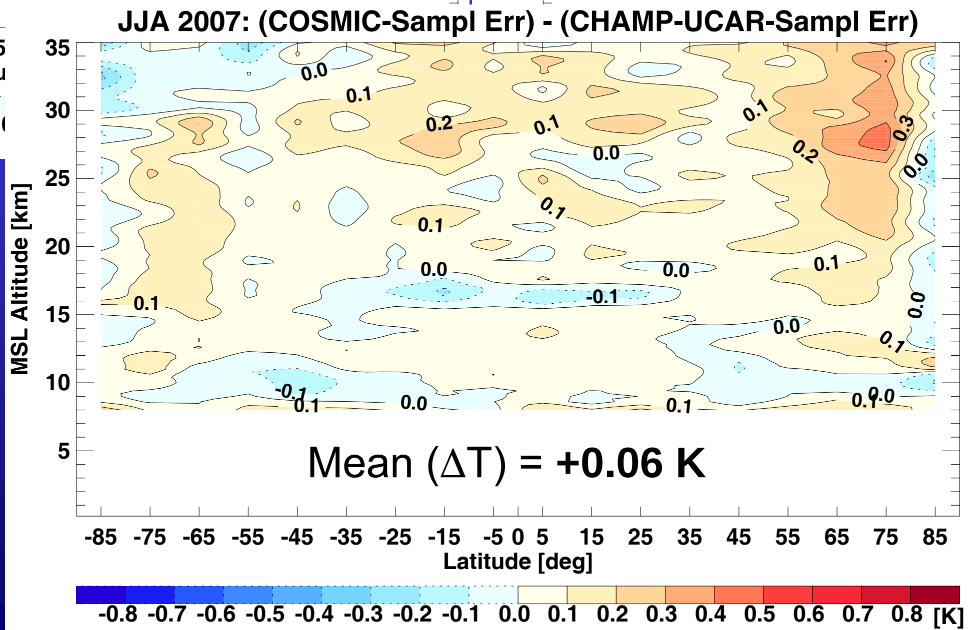


Sampling errors subtracted, Mean(ΔT) = –0.003 K
Note different contour spacing!

Difference – RO Climatologies





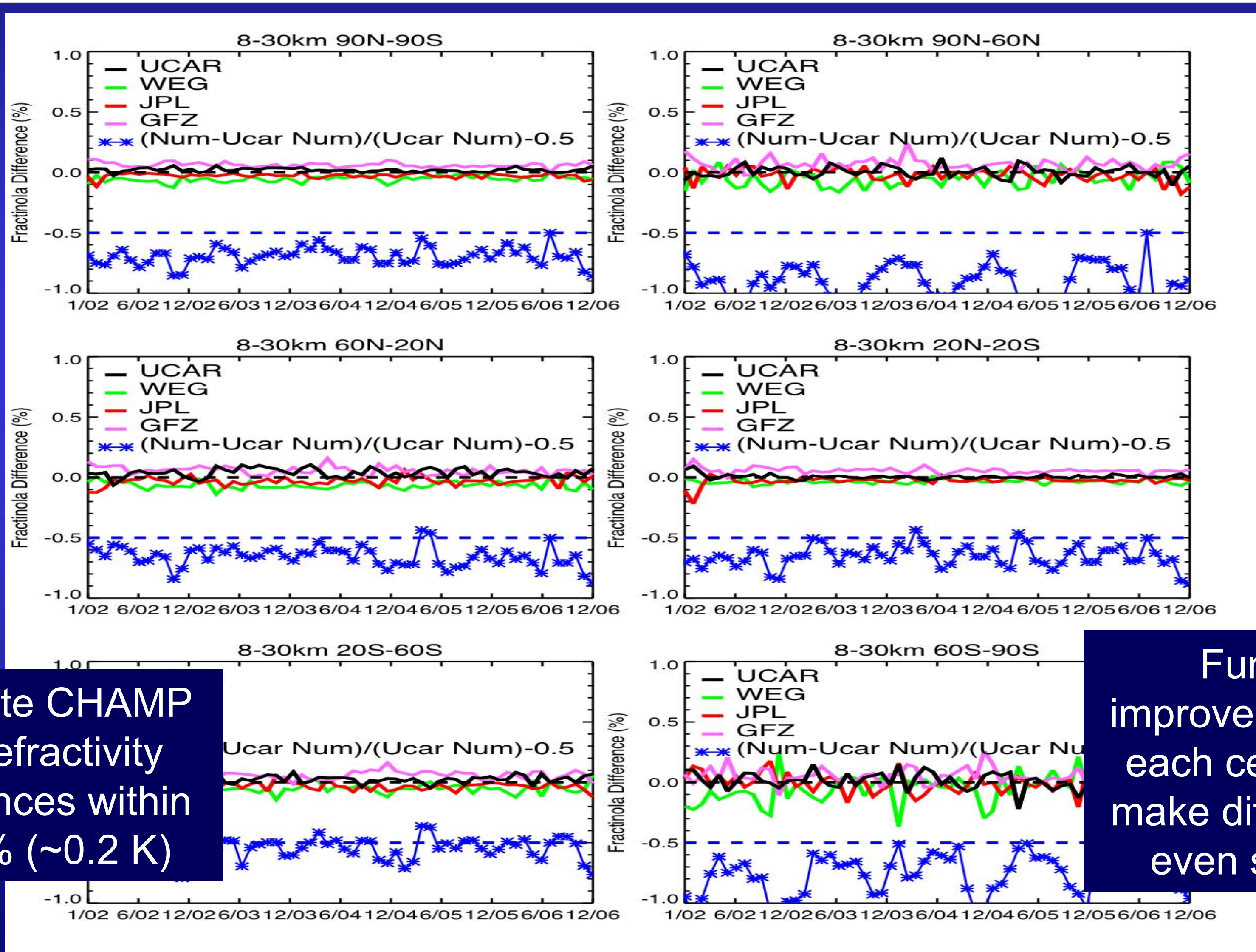


Small systematic difference between GFZ and UCAR phase delay& orbital data

Reason currently studied; very similar for SON 2006 and April 2002

Foelsche et al., OPAC 2008

Still consistency amongst GFZ, JPL, UCAR, WEGC

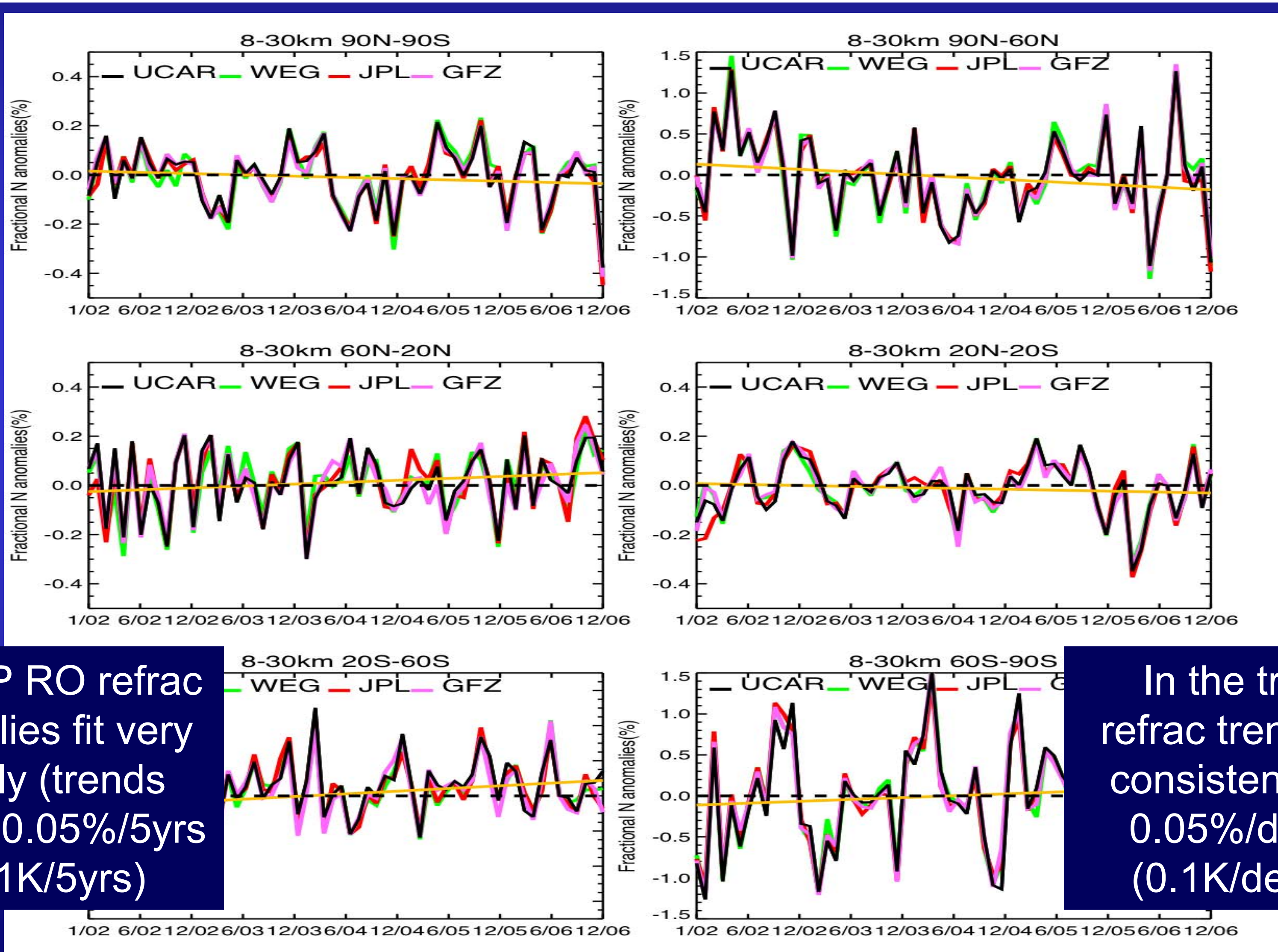


Absolute CHAMP RO refractivity differences within ~0.1% (~0.2 K)

Further improvements at each center will make differences even smaller

Ho et al., RO *N* Trends Intercomp Study, 2008

Still consistency amongst GFZ, JPL, UCAR, WEGC



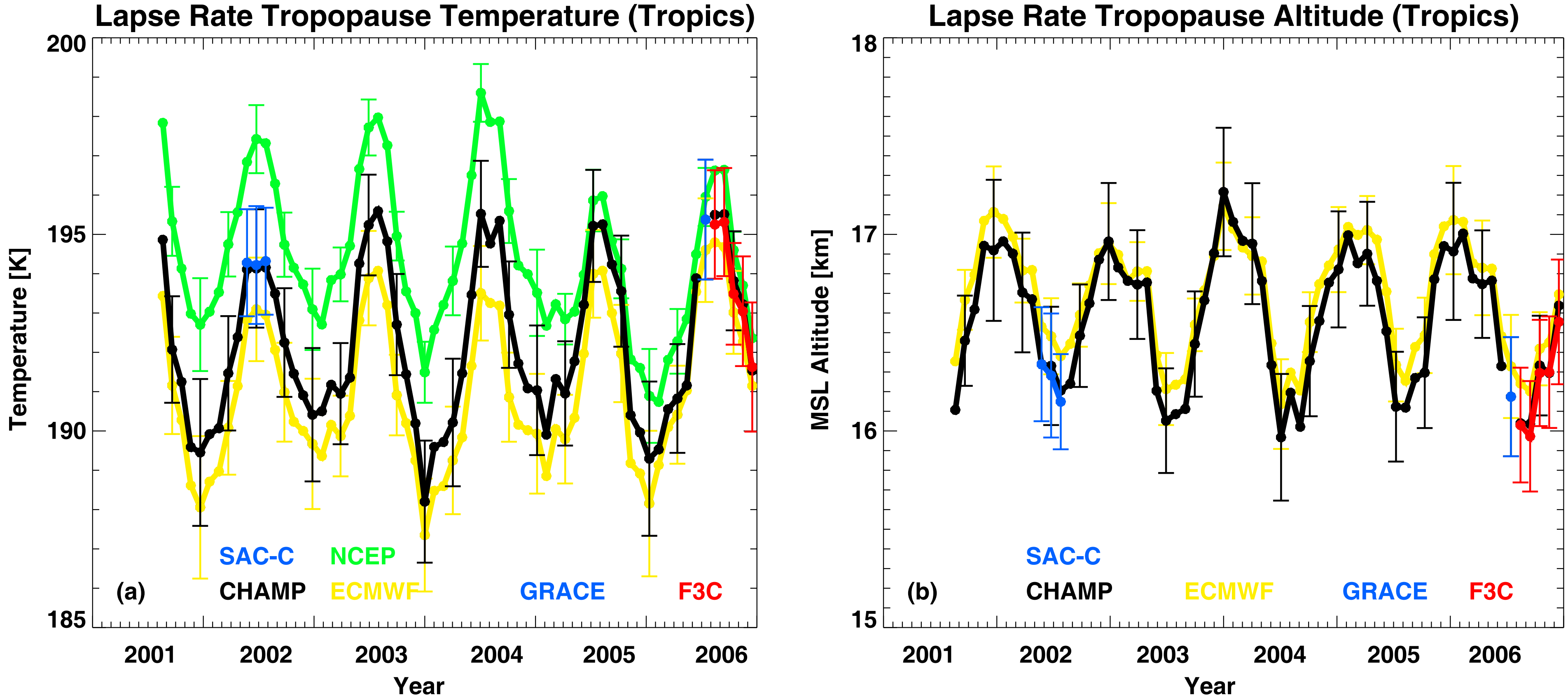
CHAMP RO refrac anomalies fit very closely (trends within ~0.05%/5yrs (~0.1K/5yrs)

In the tropics refrac trends even consistent within 0.05%/decade (0.1K/decade)

Ho et al., RO *N* Trends Intercomp Study, 2008

Consistency Example Derived Parameters

Tropical Lapse Rate Tropopause

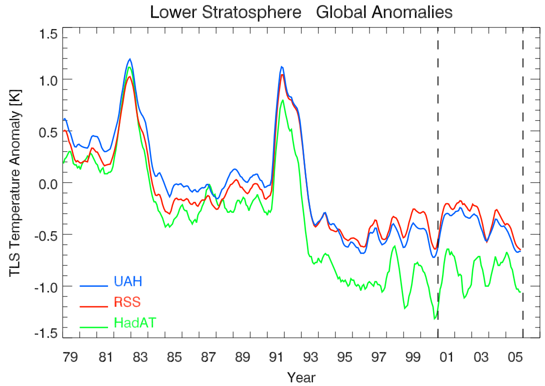


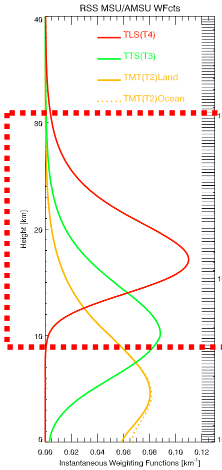
Excellent agreement between data from different RO mission (CHAMP and COSMIC). "Anchor points" from SAC-C and GRACE.

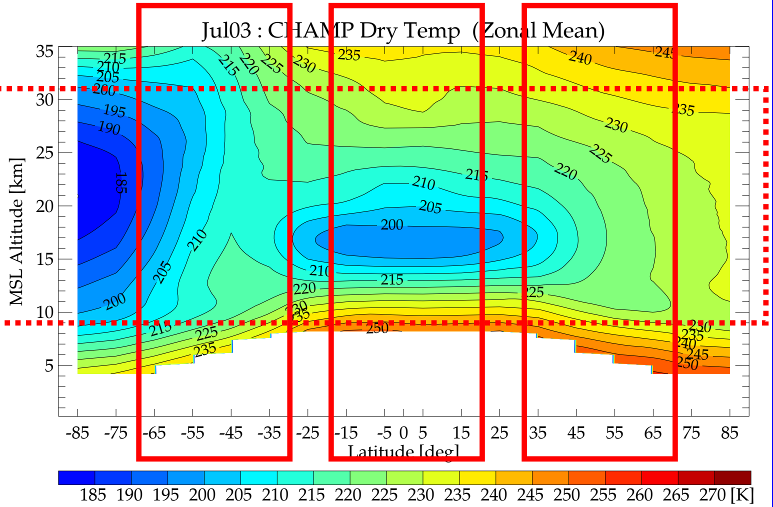
Borsche et al., GRL 2007, Foelsche et al., TAO 2008

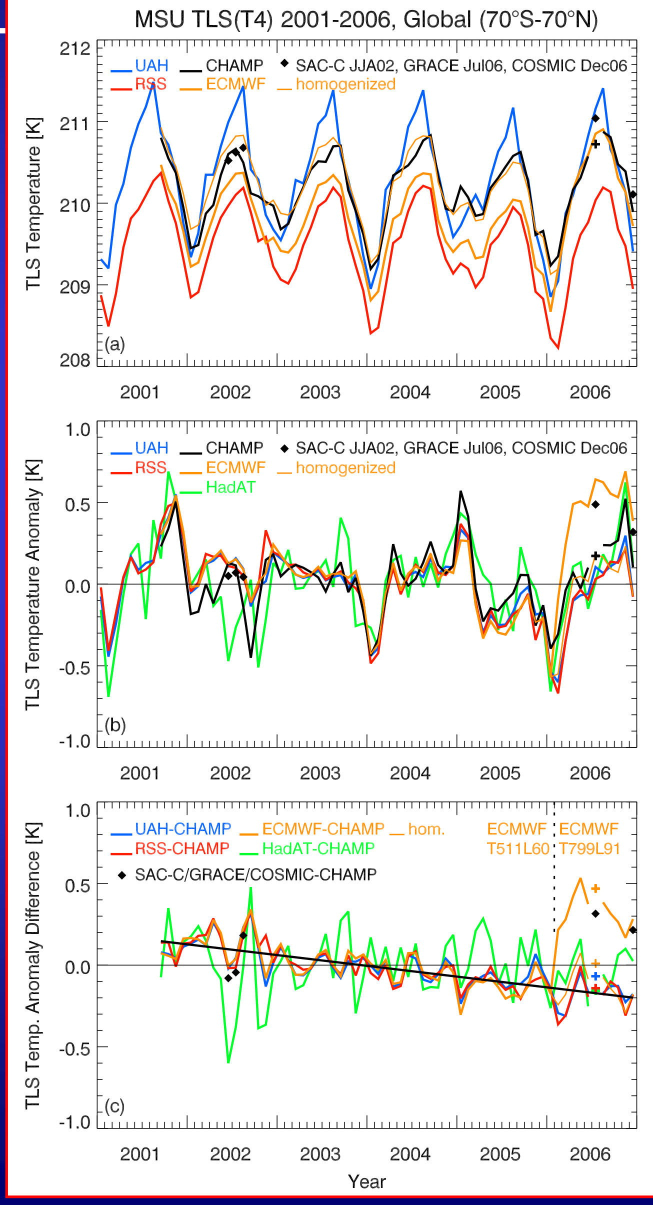
Consistency Example
Derived Parameters

RO-based Synthetic MSU/AMSU Records





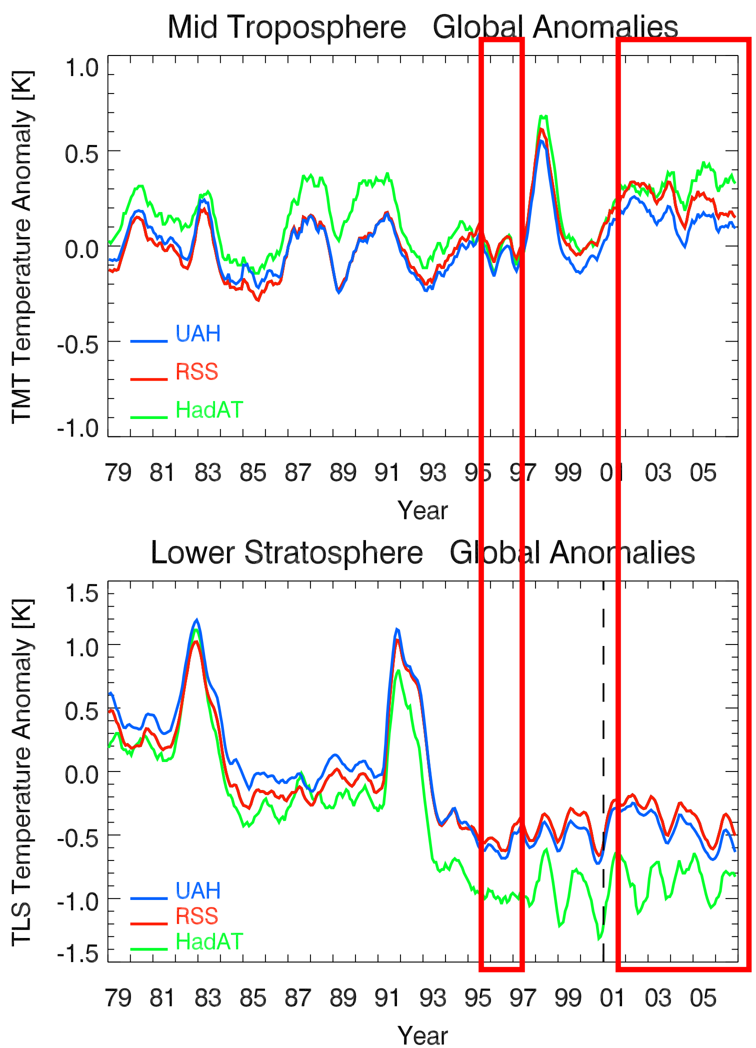




Steiner et al., JGR 2007

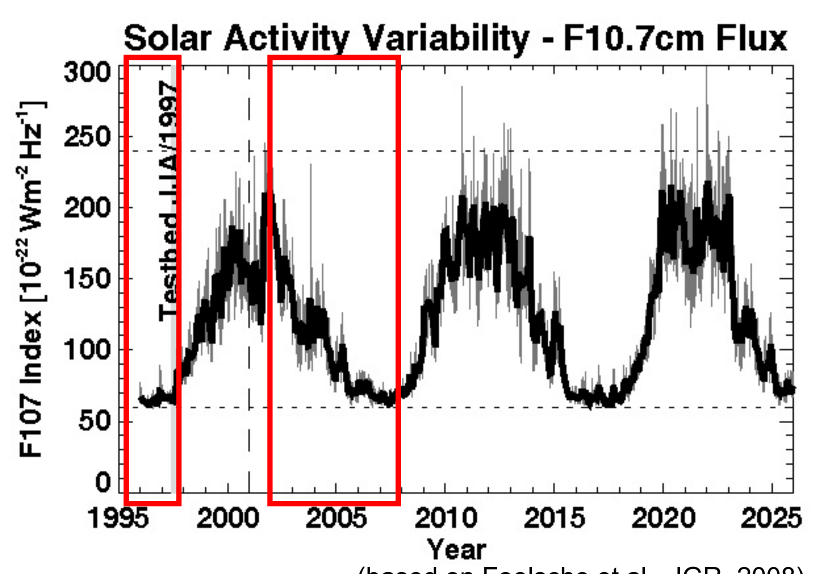
Signal Detection Setting the Scene: 1995–2007 Atmospheric Variability

Internal climate variability



(Steiner et al., JGR, 2007; after Karl et al., CCSP Report, 2006)

Solar variability



(based on Foelsche et al., JGR, 2008)

Within data-covered time periods:

- No relevant volcanic eruption
- No major El Niño/La Niña events
- No high solar activity; F10.7 indices ~60–160, wrt ionospheric variability

Climate Trend Signal Detection
Study Design

- Questions: Is a significant trend detectable in available RO data?
  Does the observed trend exceed inter-annual variability?
  Does the observed trend exceed natural trend variability?
- GPS/Met and CHAMP dry temperature climatologies: *T*dry(*p*)
  zonal monthly means for February and October
- Timeframe: October 1995 and 2001−2006 (7 yrs with data, 12 yrs in total)
  February 1997 and 2002–2007 (7 yrs with data, 11 yrs in total)
- Regions: Tropics (20°S−20°N)
  NH Extratropics (20°N−50°N)
  SH Extratropics (20°S−50°S)
- Pressure/Altitude Layers: UTLS within 300–30 hPa (~9–25 km)
  Lower Stratosphere LS (100–30 hPa)
  Tropopause TP (200–100 hPa)
  Upper Troposphere UT (300−200 hPa)
- Additional analysis for finer resolution: 5 regions and
  5 pressure levels (300, 200, 100, 50, 30 hPa)

Currently record extended to 2008

Calculations of Measurement Errors, Trends, and Uncertainties

- **RO measurement errors**:

  Sampling error: e_{samp} (estimated using ECMWF analyses "True" profiles at the RO locations minus "True" mean field)

  Observation error: e_{obs} = 1K/sqrt(N), N…Number of RO profiles, 1K for individual profile

  Systematic error: e_{sys} = 0.2 K ≤100 hPa, 0.1 K >100 hPa (Gobiet et al., 2007)

  Total error: $e_{ROtotal}$ $$e_{ROtotal} = \sqrt{(e_{samp})^2 + (e_{sys})^2 + (e_{obs})^2}$$

- **Linear Trend:** *δT* least-squares fit considering $s_{ROtotal}$ for each individual month
- **Uncertainties:** Uncertainty of the trend: $s_{\delta T}$

  Inter-annual variability of inspected period – de-trended StDev: $s_{97\text{-}07}$, $s_{95\text{-}06}$

  Natural climate trend variability: s_{NatVar} $$s_{NatVar} = \frac{1}{N}\sum_{i=1}^{N} s_i^{gcm}$$ estimated based on multi-century pre-industrial control runs of 3 representative global climate models for IPCC AR4 (ECHAM5+HadCM+CCSM3)

- **Signal-to-Noise Ratio SNR:**

  Signal/ Interannual Variability:
  $$SNR_{(s_{\delta T}+s_{97-07})} = \frac{\delta T}{\sqrt{s_{\delta T}^2 + s_{97-07}^2}}$$

  Signal/ Natural Trend Variability:
  $$SNR_{(s_{\delta T}+s_{NatVar})} = \frac{\delta T}{\sqrt{s_{\delta T}^2 + s_{NatVar}^2}}$$

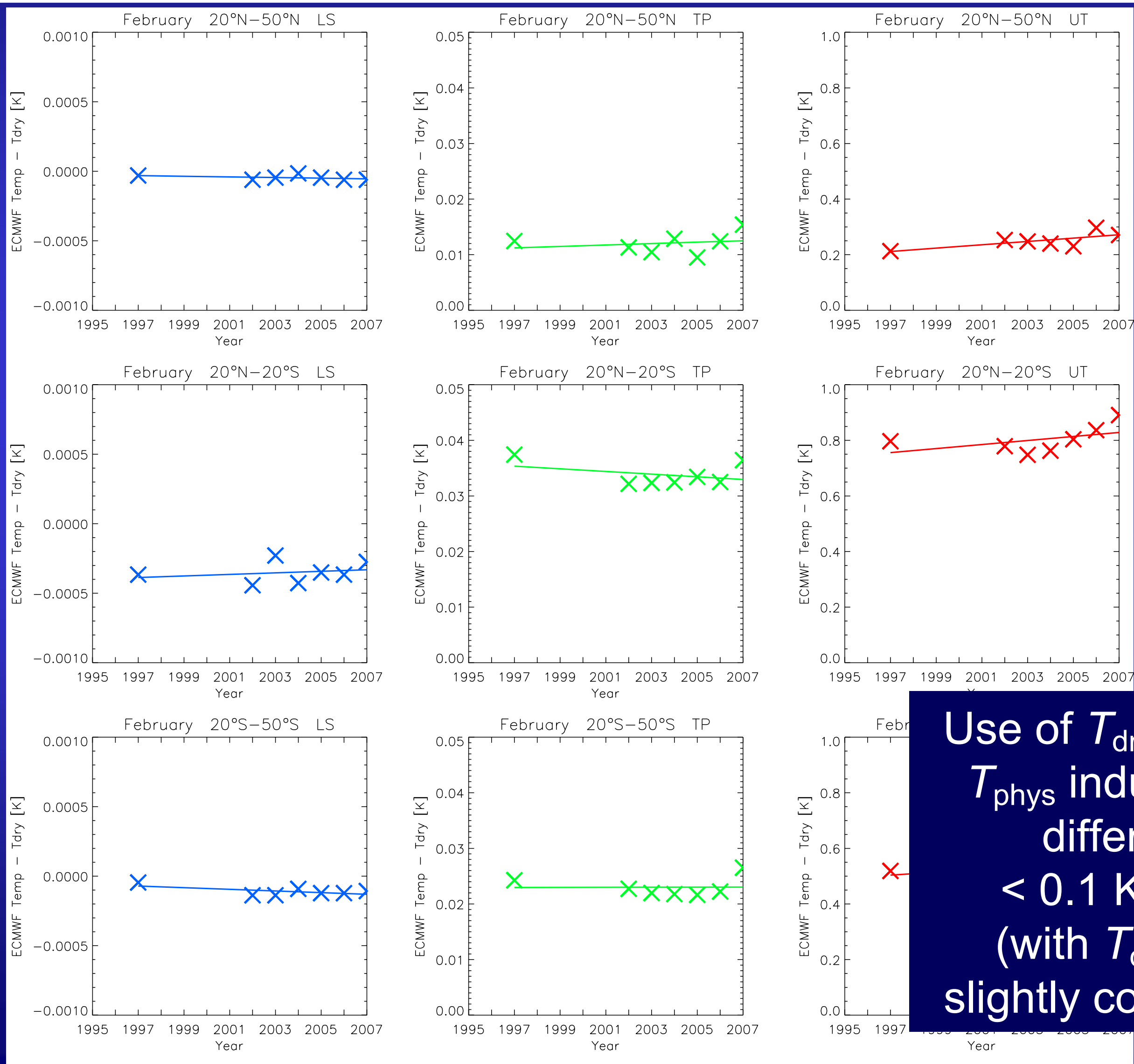
- **Significance:** Students *t*-test

Trend Differences T_{phys}–minus–T_{dry}, Feb 1997-2007 (estimated based on ECMWF analyses)

NHE20-50

Tropics

SHE20-50



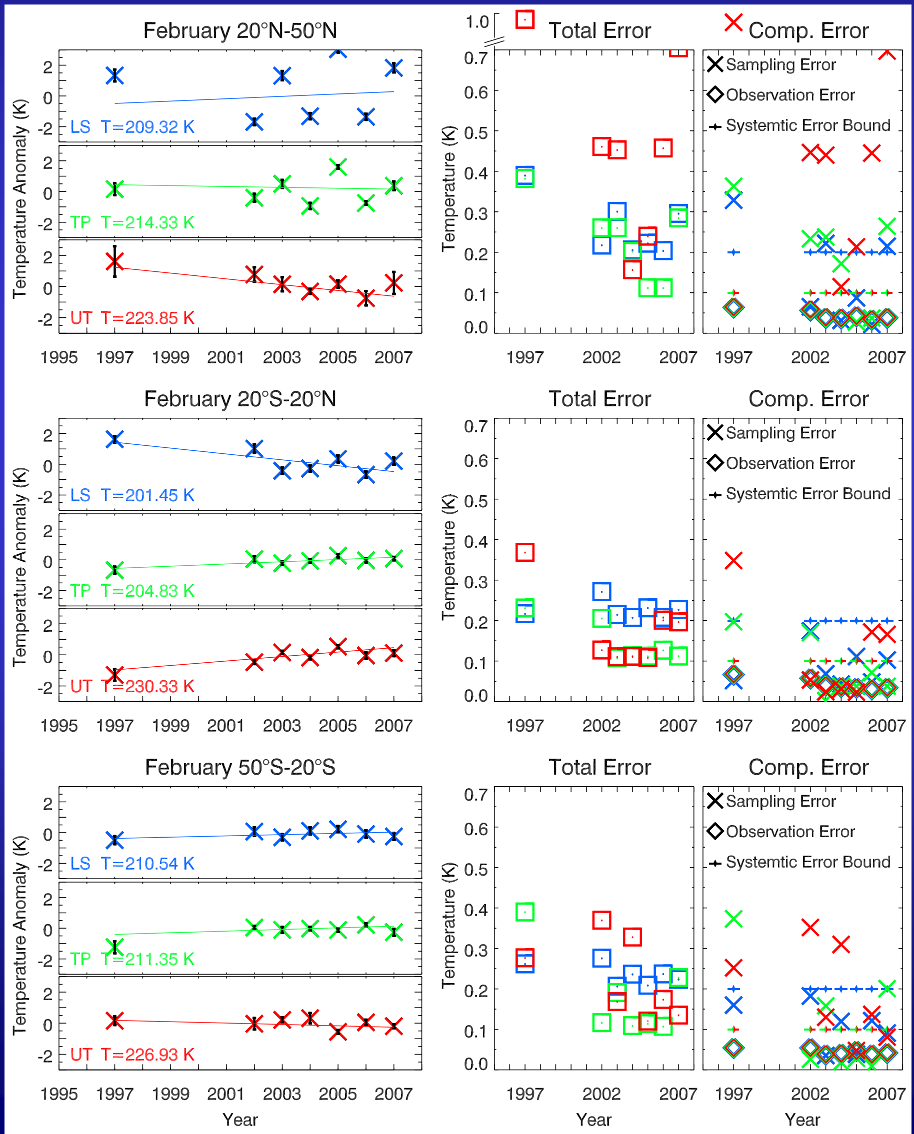
Use of T_{dry} instead of T_{phys} induces trend differences < 0.1 K/decade (with T_{dry} trends slightly conservative)

RO Temperature Trends and RO Data Errors February

NHE 20–50

Tropics

SHE 20–50



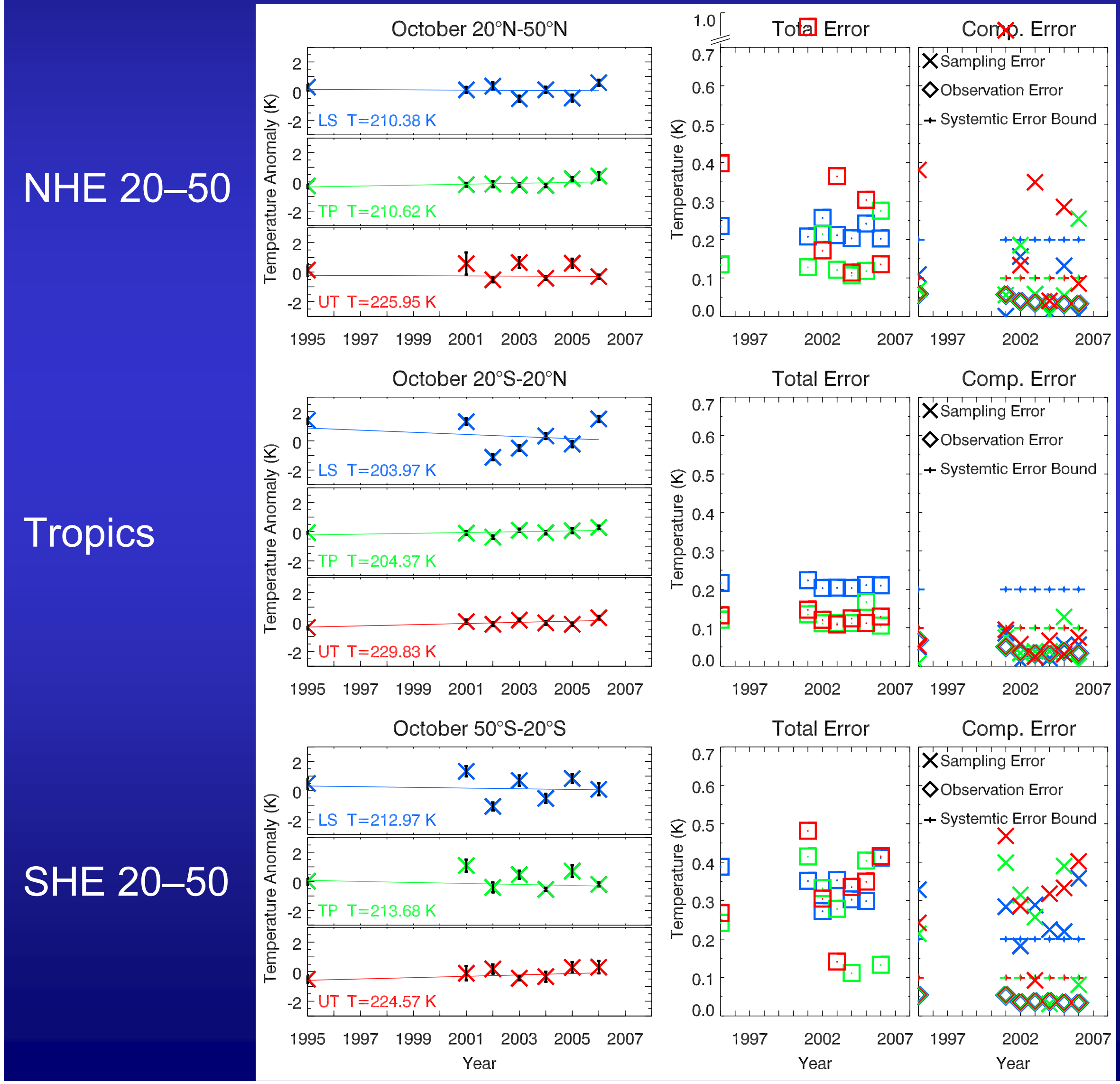
Temperature anomalies (left) wrt 2002–2006 mean with individual total RO error

Max Total RO error: 0.98K Feb97

Component errors (right):

- Sampling error: max 0.97 K Feb97 dominant for GPS/Met and in NHE
- Observation error: ~0.05 K
- Systematic error:
  0.2 K in LS
  0.1 K in UT, TP
  dominant error source in tropics

RO Temperature Trends and RO Data Errors October



Temperature anomalies (left) wrt 2002–2006 mean with individual total RO error

Max Total RO error: ~0.8K Oct01

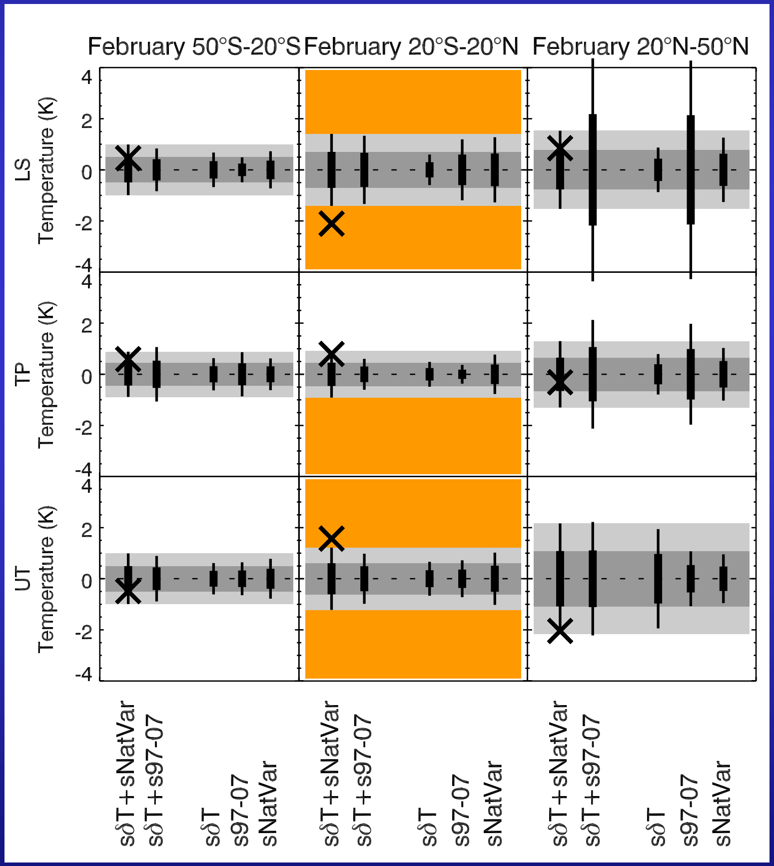
Component errors (right):

- Sampling error: max ~0.8 K Oct01 dominant for GPS/Met in NHE/SHE and for CHAMP in SHE
- Observation error: ~0.05 K
- Systematic error:
  0.2 K in LS
  0.1 K in UT, TP
  dominant error in tropics, NHE LS

RO Temperature Trends vs Key Uncertainties
δtrend, interann.var, nat.var

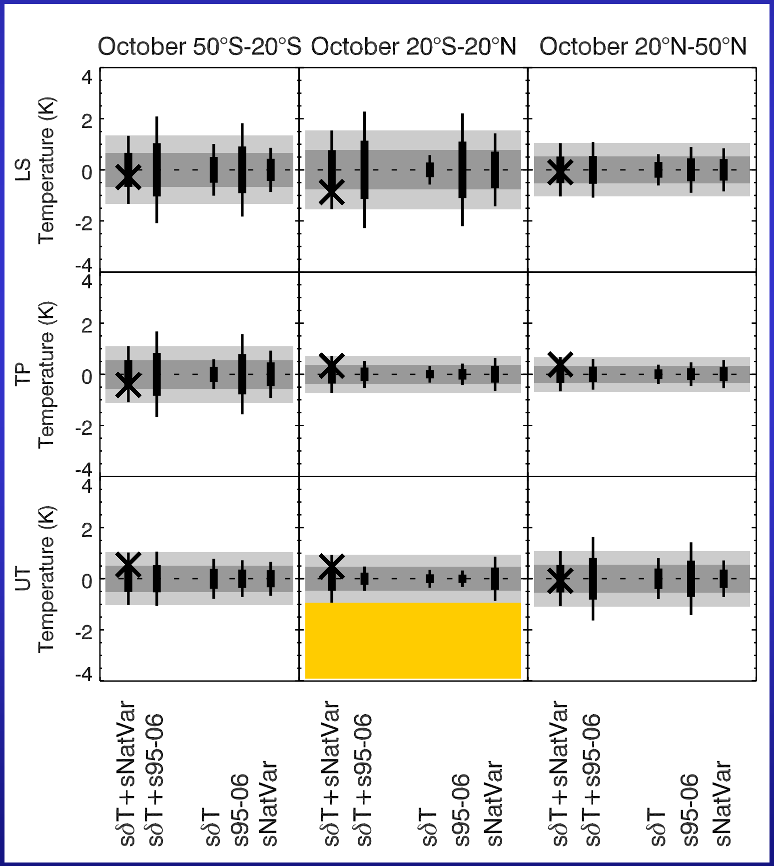
Feb 1997-2007

SHE20-50 Tropics NHE20-50



Oct 1995-2007

SHE20-50 Tropics NHE20-50

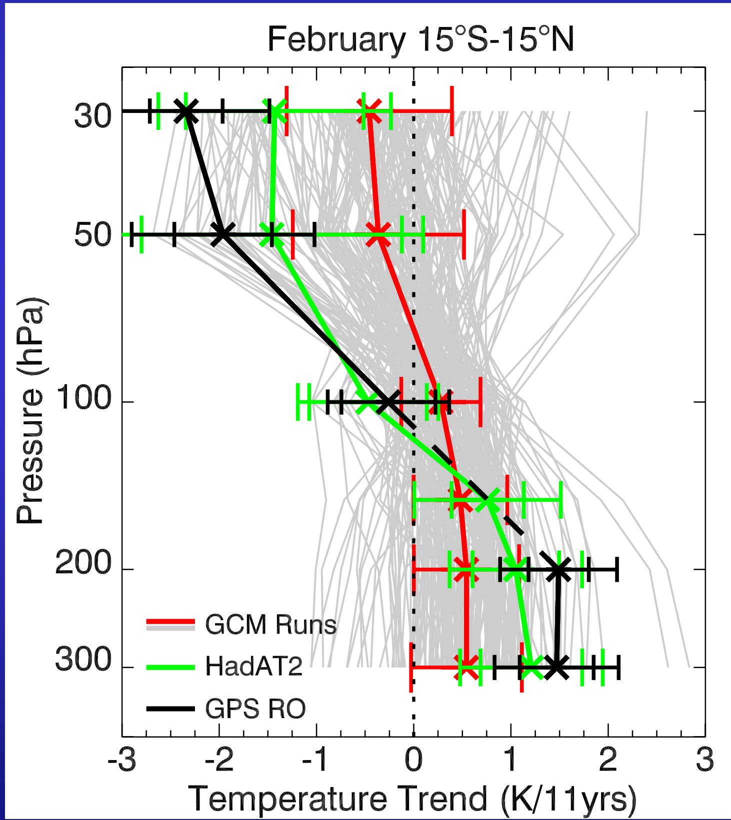


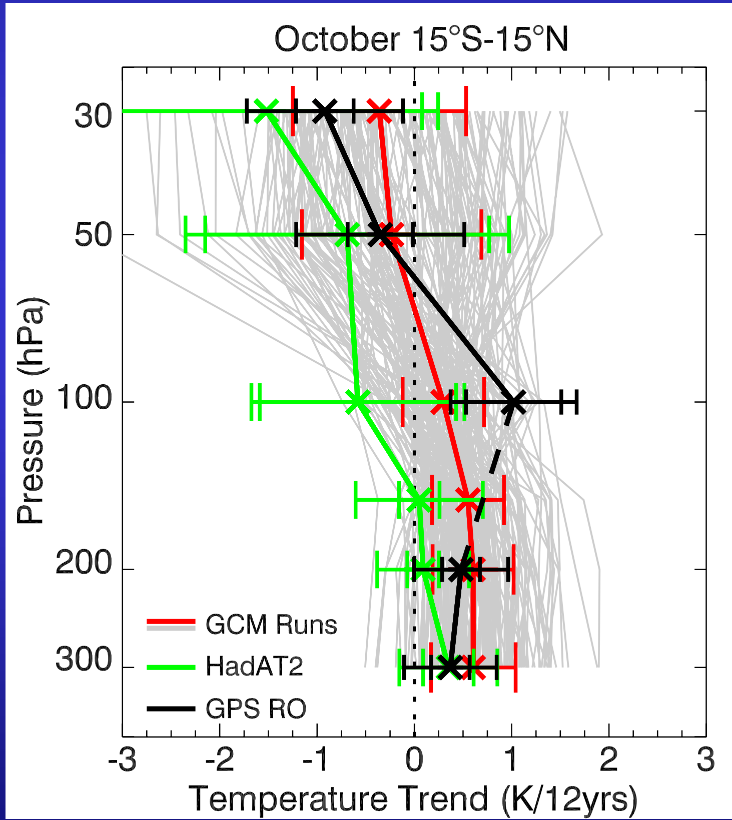
Significant 11-yr trend in Feb in UT & LS over natural and inter-annual variability

orange: > 95% significance level
yellow: > 90% significance level

Discussion: Comparison to Trends from GCM runs and Radiosonde Data

RO: 1995/97 GPS/Met, 01/02-06/07 CHAMP; HadAT2: Raobs climate dataset/ same years; GCM runs: IPCC AR4 A2 and B1 scenario runs of ECHAM5+HadCM+CCSM3, 11-yr trends sampled from 2001-2020 period





Agreement within uncertainty estimates in February between RO, Raobs, GCMs

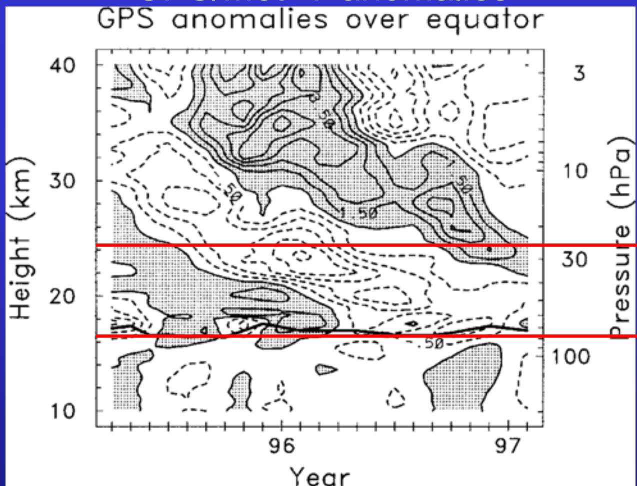
Agreement within uncertainty estimates in October in UTLS

Discussion: QBO

Quasi-Biennial Oscillation QBO

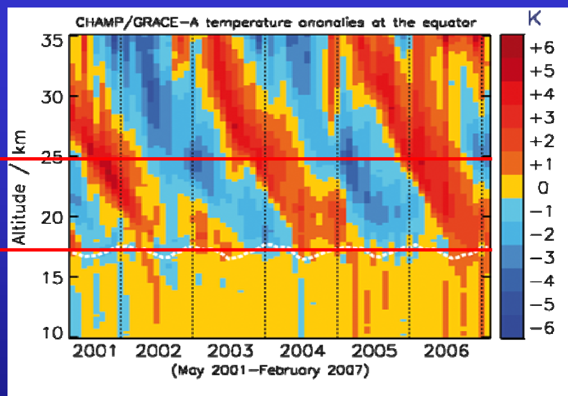
- pattern in tropical lower stratosphere with a period of ~28 months
- seasonal changes in radiative heating due to dissipation of vertically prop. waves
- downward propagating wind/temperature anomalies
- constrained to 5°N–5°S and to vertical layer of ~16–22 km
- T-anomalies of up to ±6 K at ~16–30 km, at tropopause decrease to < ±0.5 K

GPS/Met T-anomalies



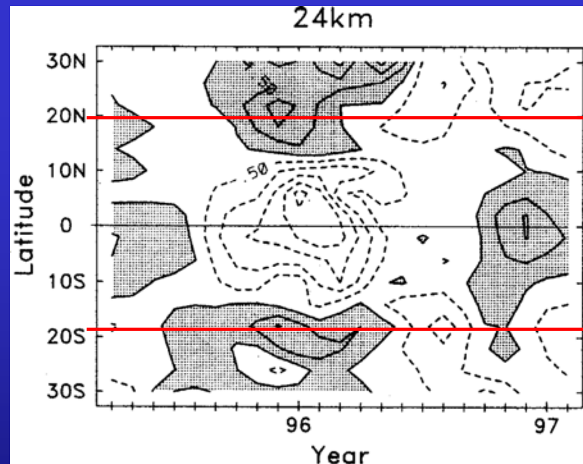
(Randel et al., JGR, 2003, Fig. 16)

CHAMP/GRACE



(Schmidt et al., ACP, 2005, updated)

GPS/Met at 24 km



(Randel et al., JGR, 2003, Fig. 18)

Estimated contribution from QBO – mean over tropical region (20°N–20°S) and over vertical layer of ~16–25 km: < 0.5 K in standard deviation (LS Trend still significant)

Conclusions and Outlook

- Given available monthly GPS/Met and CHAMP RO records within October 1995 and 2001-2006 / February 1997 and 2002-2007 we addressed the following signal detection questions:
  Is a trend detectable exceeding inter-annual variability in Oct95-06 or Feb97-07?
  Is a trend detectable exceeding natural trend variability estimated from preind.ctrl.?
- A significant warming/cooling trend, relative to noise and to natural variability, was found in February in the tropical UT/LS.
- Comparison with trends from HadAT2 RAOBs climate data showed agreement within uncertainty estimates in February; GCMs agree in envelope as well (though the bulk shows less warming/cooling contrast across the tropical tropopause)
- Discussion of QBO contribution estimate suggests minor influence to trend significance in LS
- Ongoing work includes the quantitative estimation of the QBO contribution from RO data, the extension of the trend estimates to Oct07 and Feb08, respectively, the re-check of GPS/Met data processing, the cross-check of use of either GFZ or UCAR phase delay and orbital data, the consistency with COSMIC, and more…

Conclusions and Outlook

- Given available monthly GPS/Met and CHAMP RO records
  within October 1995 and 2001-2006 / February 1997 and 2002-2007
  we addressed the following signal detection questions:
  Is a trend detectable exceeding inter-annual variability in Oct95-06 or Feb97-07?
  Is a trend detectable exceeding natural trend variability estimated from preind.ctrl.?
- A significant v ... ariability, was found in Febr ...
- Comparison v ... agreement within uncerta ... s well (though the bulk show ... opause)
- Discussion of ... trend significance i ...
- Ongoing work ... ution from RO data, the ... espectively, the re-check of GPS/Met data processing, the cross-check of use of either GFZ or UCAR phase delay and orbital data, the consistency with COSMIC, and more…

With more than a decade of time now spanned by RO data it is exciting times that have recently started for climate signal detection based on this unique data source in terms of accuracy, consistency, and long-term stability; promises of around twenty years ago are more and more confirmed by real data…

Thank You!