OPAC-3 Workshop
September 2007, Graz, Austria

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

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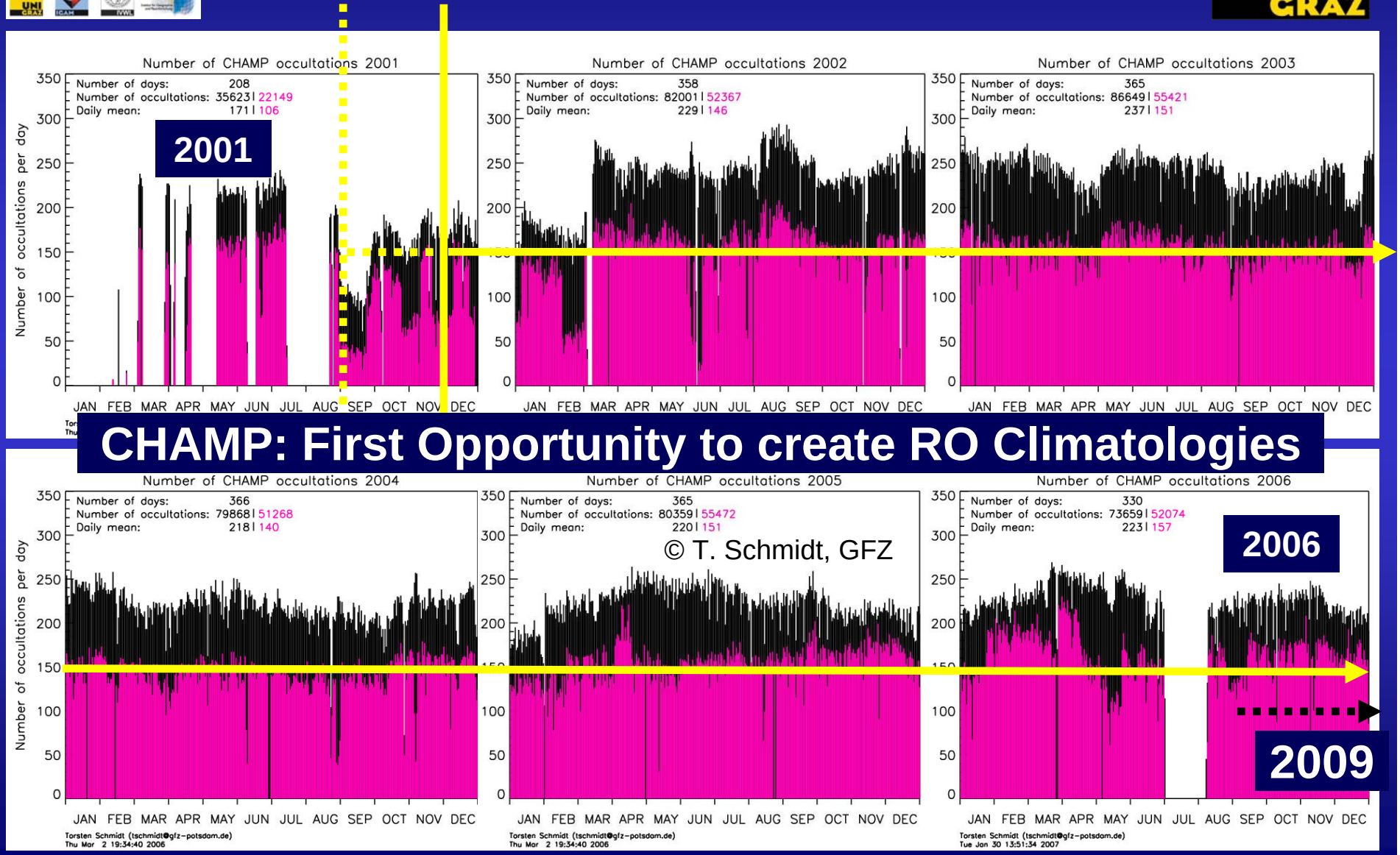
Radio Occultation with CHAMP

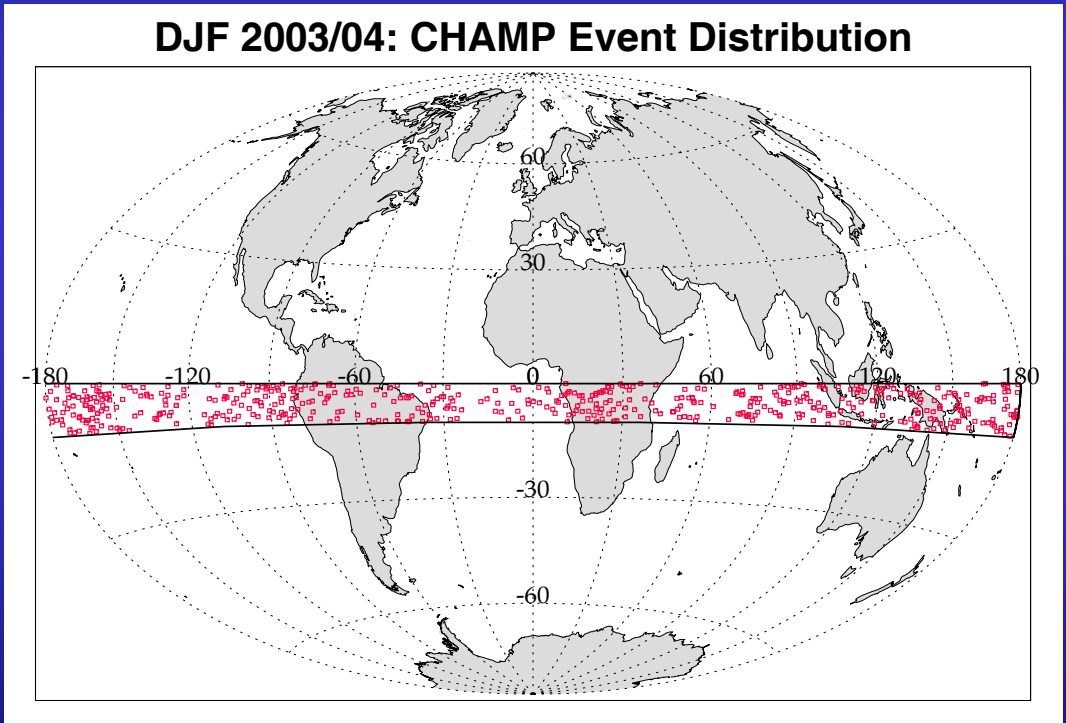


Observing Climate

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

WegCenter Retrieval (1)

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).

WegCenter Retrieval (2)

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).

External quality control (for outlier profiles): Refractivity 5 km–35 km: $\Delta N/N<10\%$; Temperature 8 km–25 km: $\Delta T<20$ K. Reference: collocated ECMWF operational analysis profiles (T42L60 resp. T42L91 as of 01/02/2006).

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:

$$\overline{T_{\mathrm{dry}}(z)} = \frac{1}{\sum_{i=1}^{N_{\mathrm{prof}}(z)} \cos(\varphi_i)} \sum_{i=1}^{N_{\mathrm{prof}}(z)} T_{\mathrm{dry}\,i}(z, \varphi_i) \cos(\varphi_i)$$

- **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

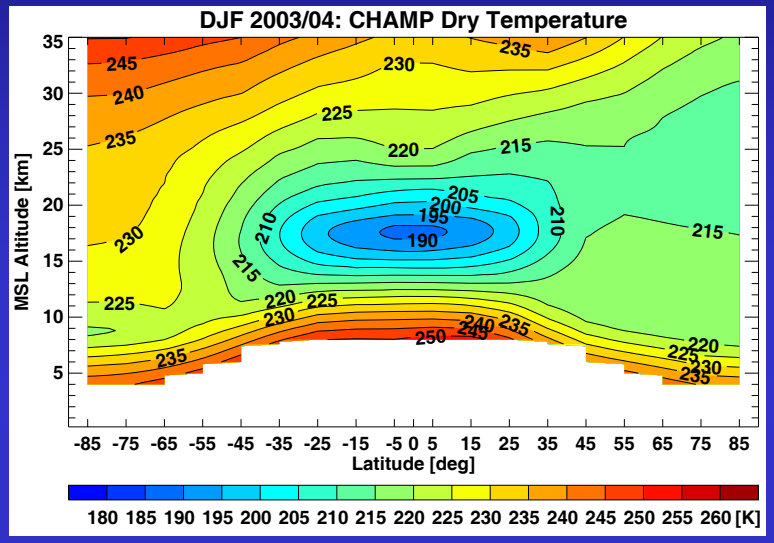
Estimation of Sampling Error

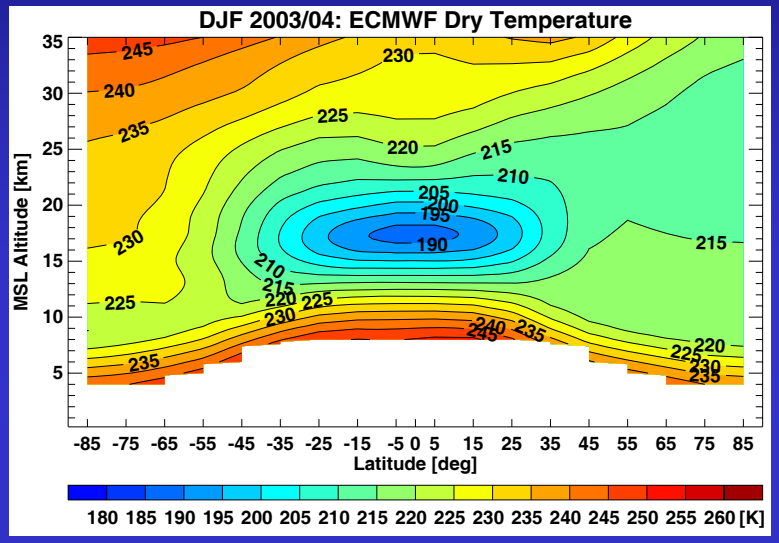
Based on ECMWF fields – 4 time layers/day
ECMWF is taken as a proxy for the "true" temporal and spatial evolution

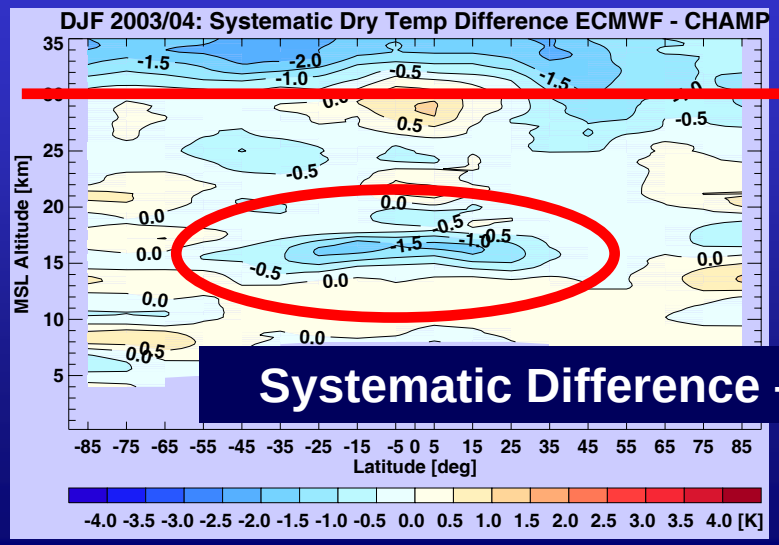
Sampling Error:

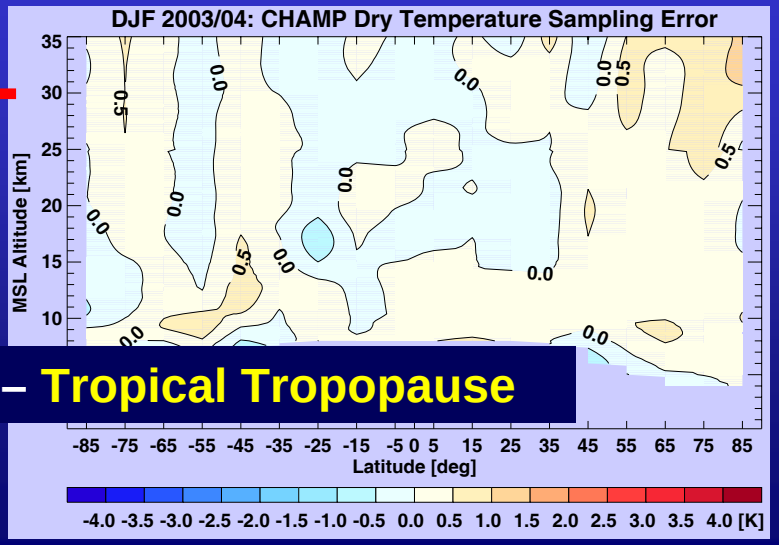
"True" profiles at the RO locations
minus
"True" mean field

Dry Temperature – DJF 2003/04





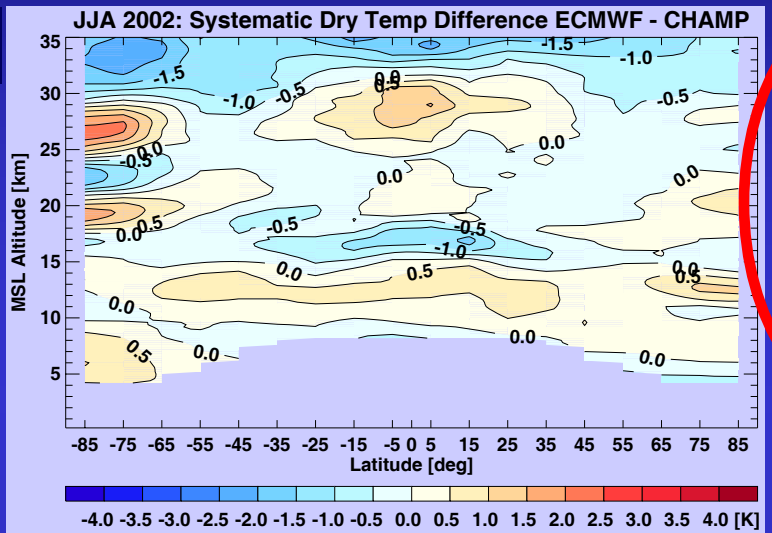




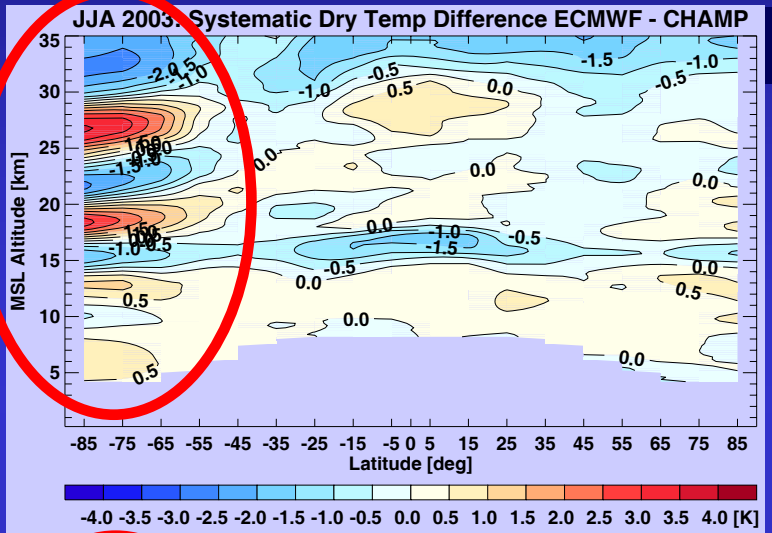
Systematic Difference – Tropical Tropopause

Systematic Difference – Summer

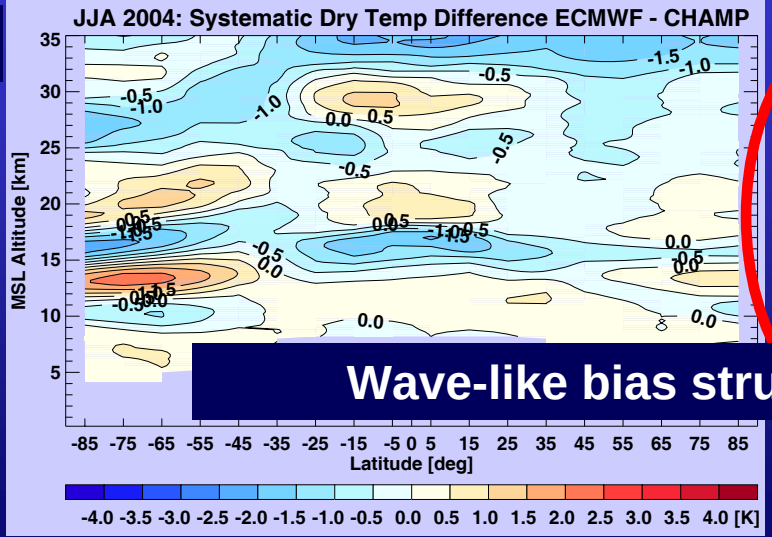
2002



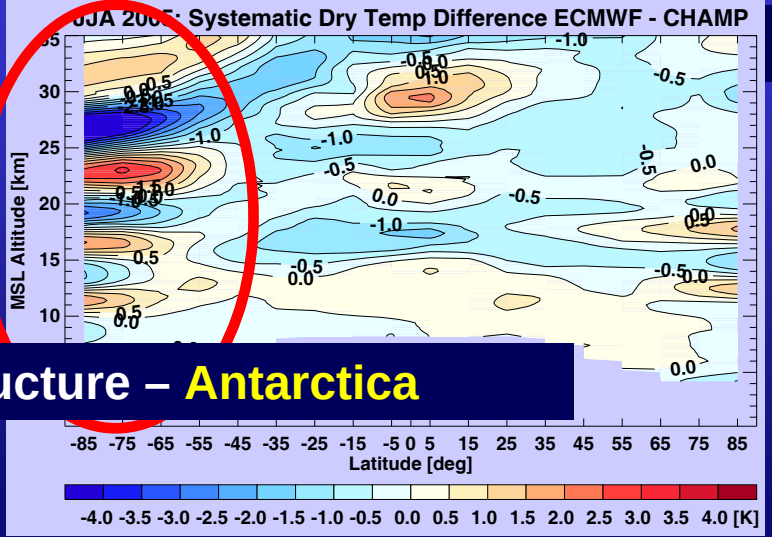
2003



2004

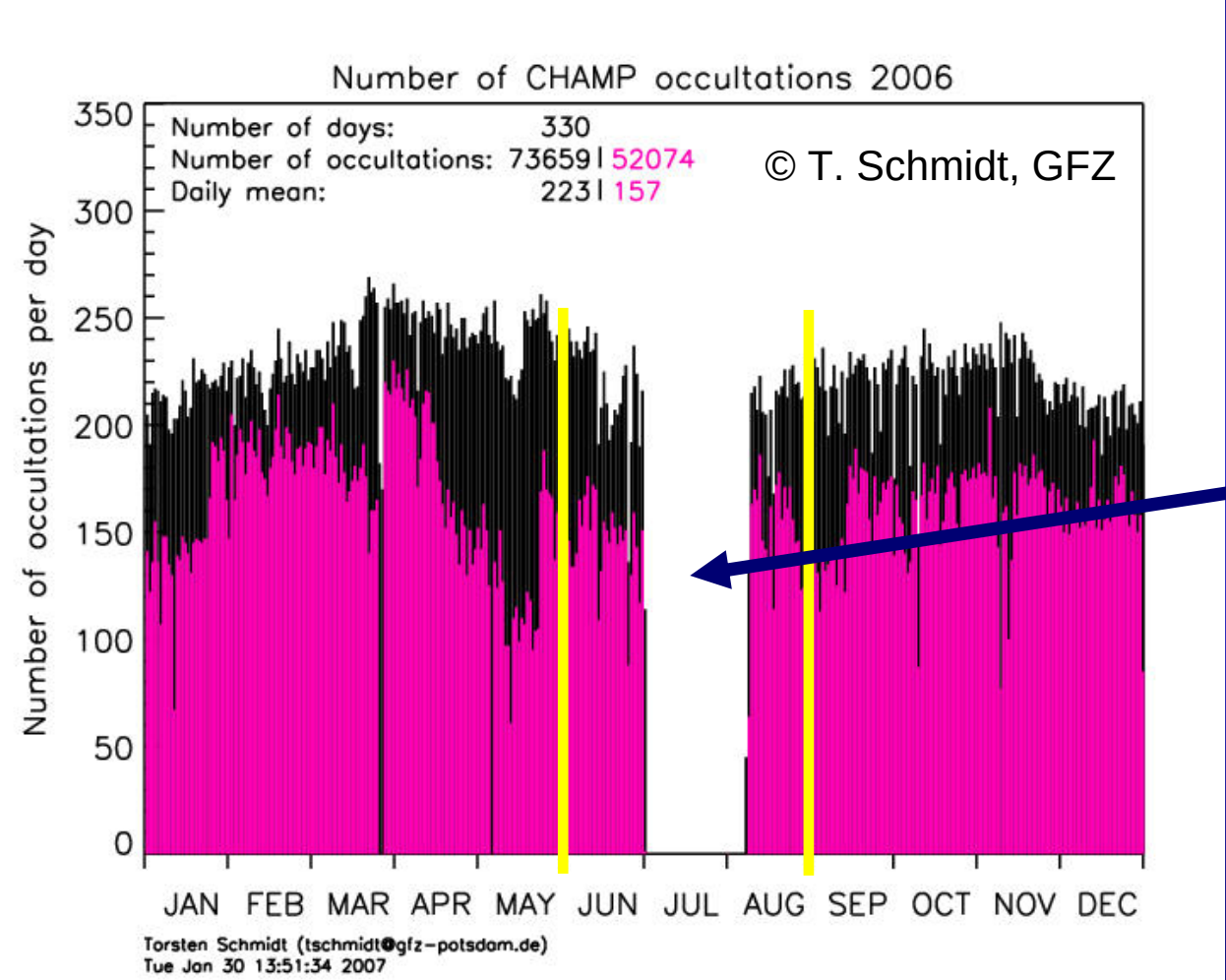


2005



Wave-like bias structure – Antarctica

Sampling Problem – JJA2006



Summer 2006

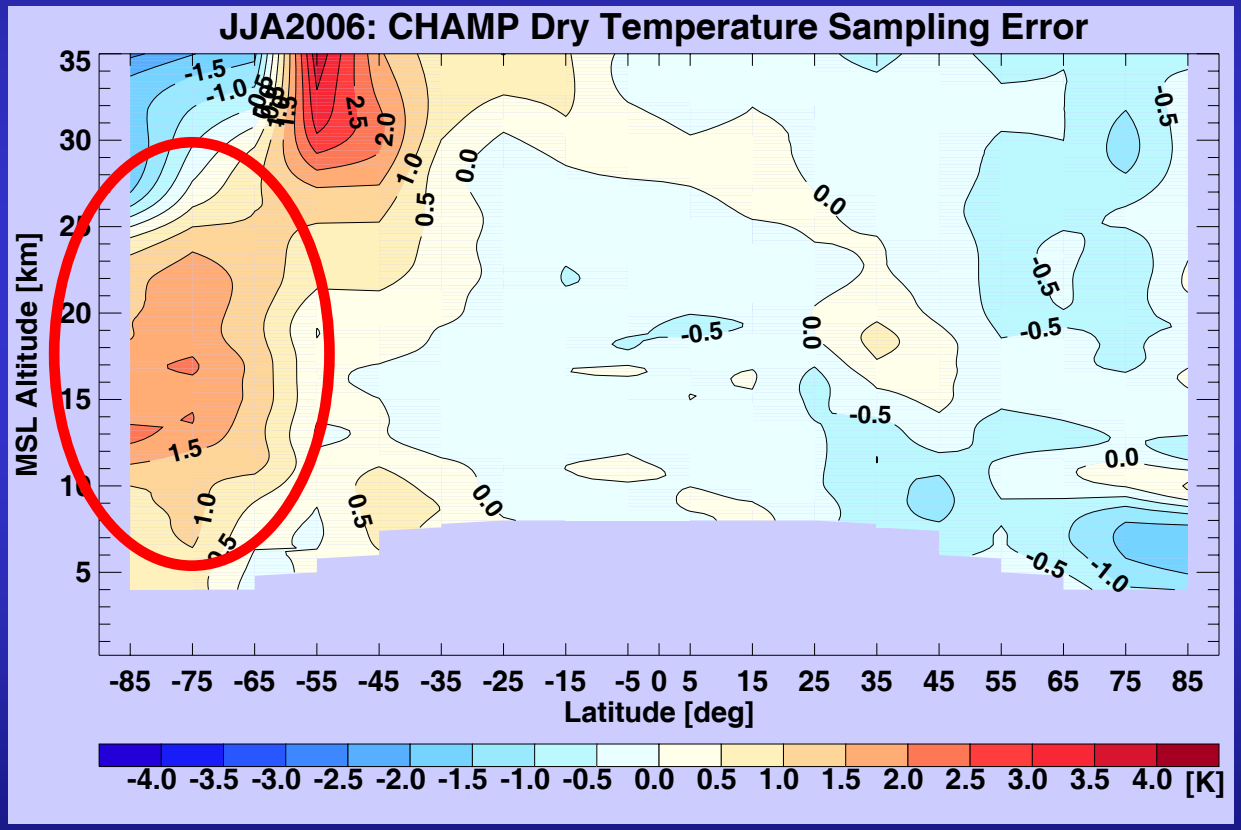
Lack of CHAMP data

~5 weeks

“Gap” can be filled

With GRACE data

Sampling Error – JJA2006



Summer 2006

Lack of CHAMP data

~5 weeks

Sampling error

amazingly small

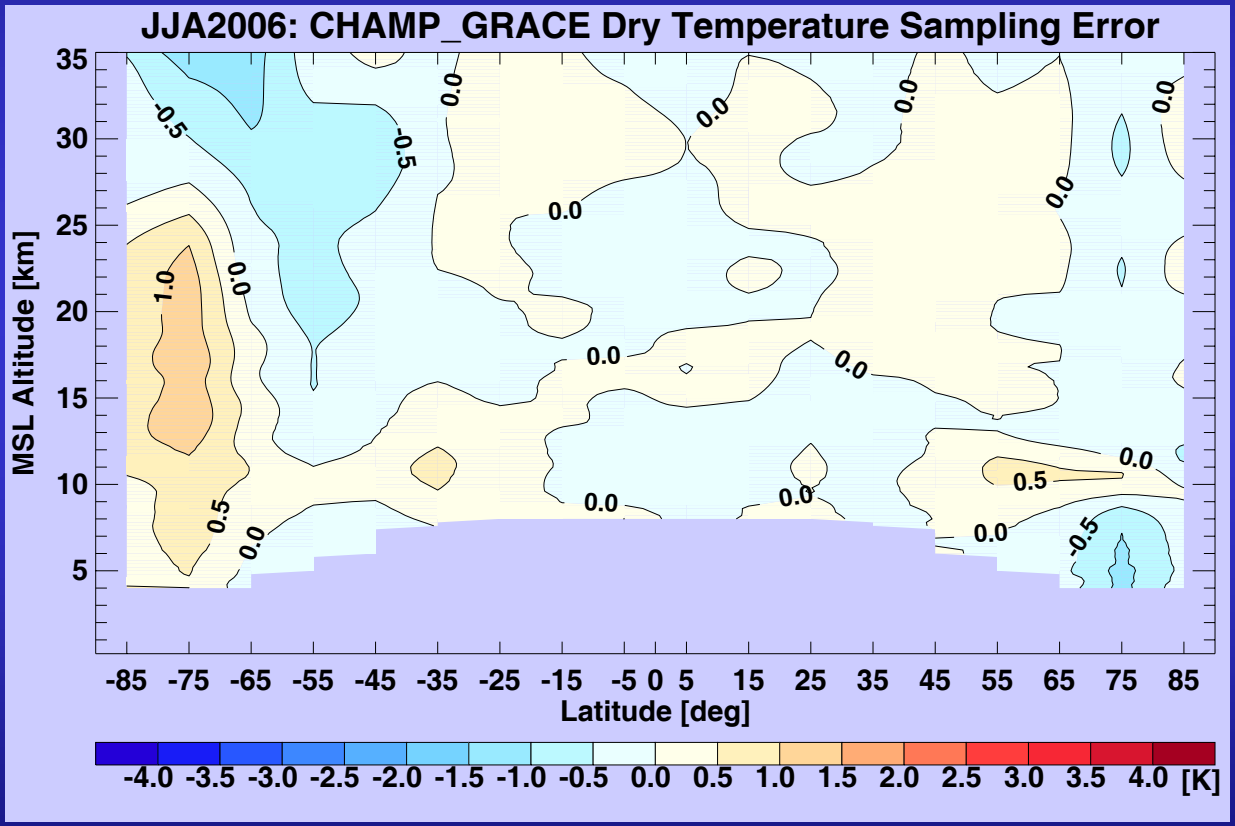
(for zonal means)

But southern (winter)

polar vortex

clearly too warm

Sampling Error – JJA2006



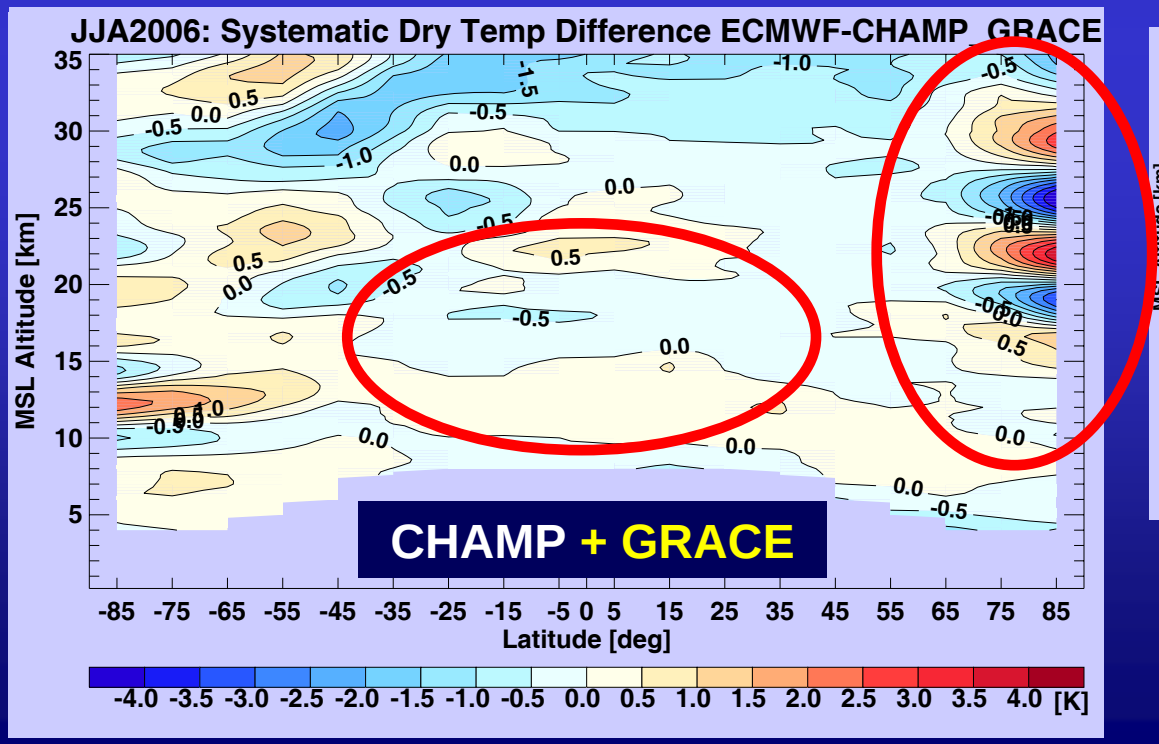
Summer 2006

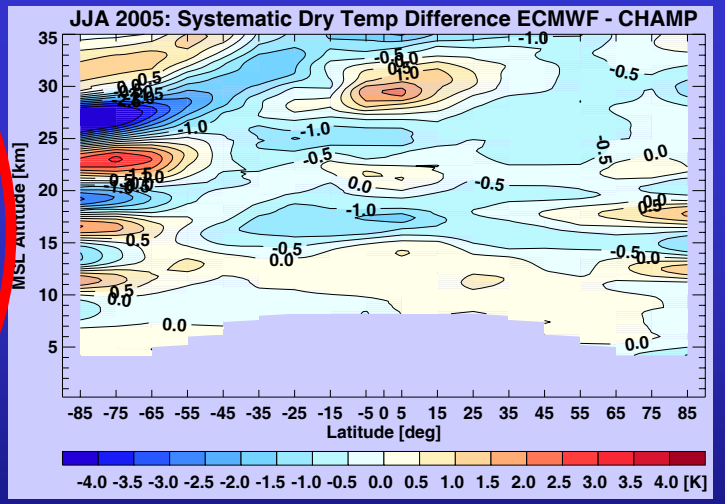
CHAMP + GRACE data

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

Tropical Tropopause

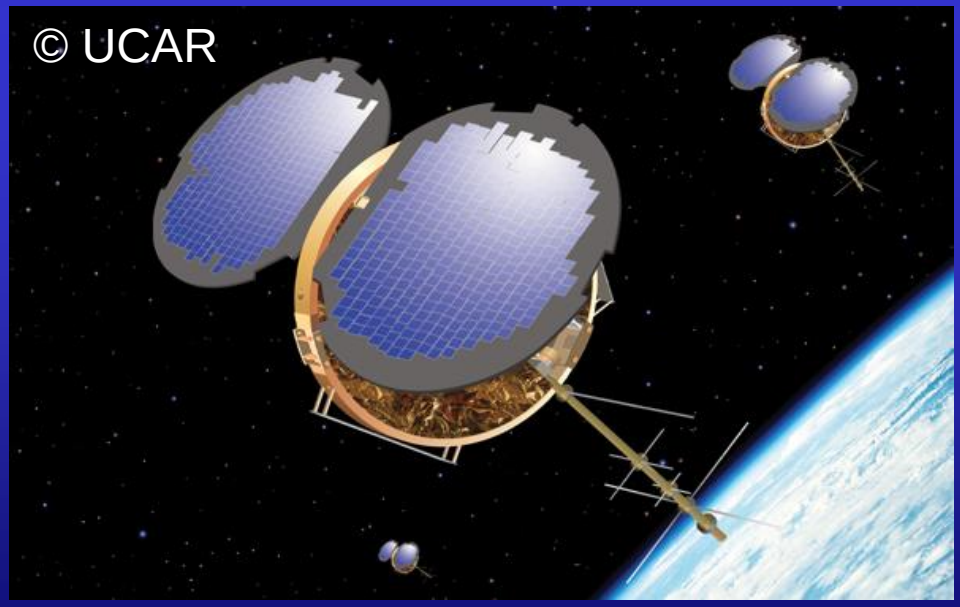
Systematic Difference in Tropical Tropopause Region essentially disappeared with new ECMWF scheme

Borsche et al. 2007, *Geophys. Res. Lett.*

More on the Tropical Tropopause at 9:50

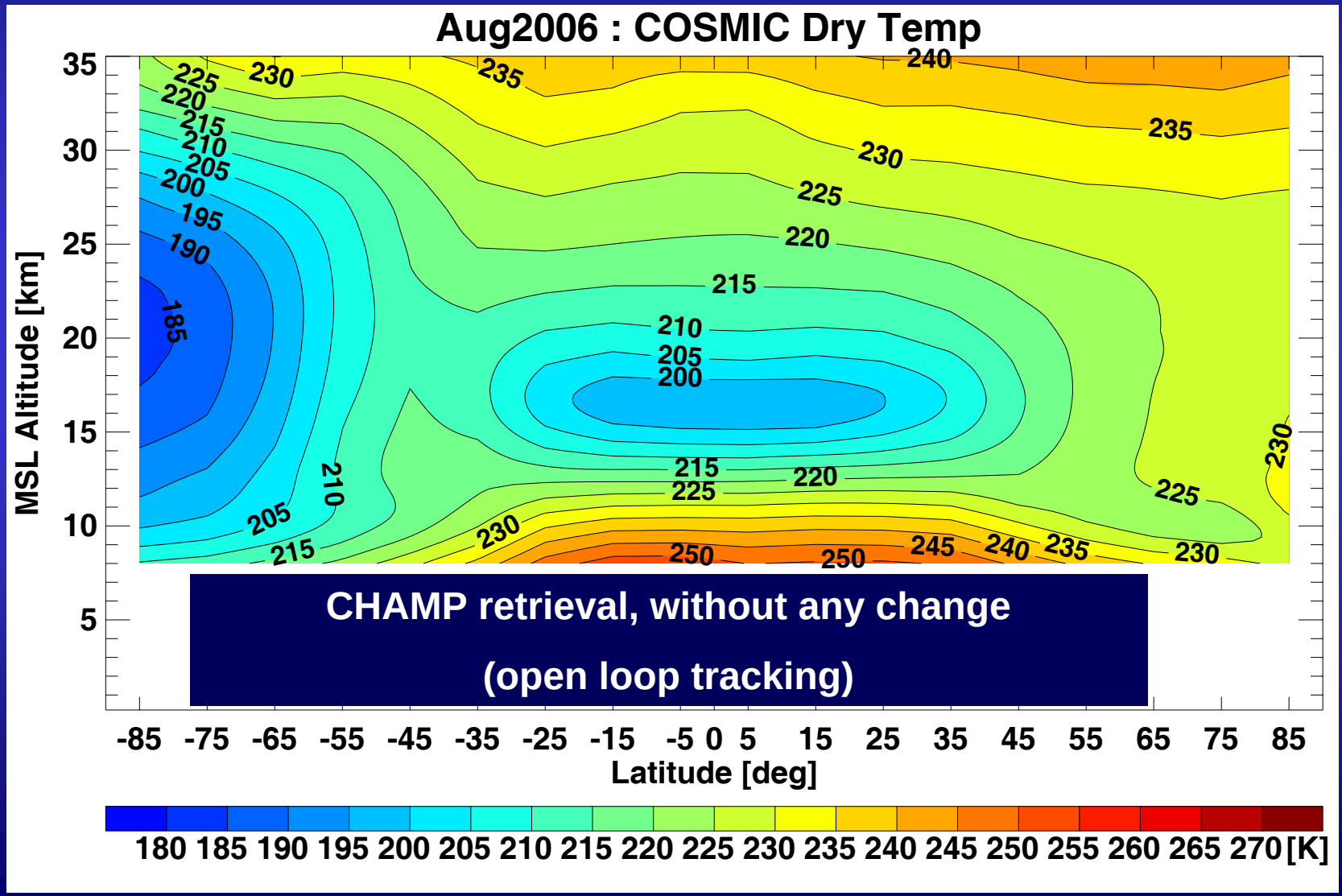
Observing Climate

Preliminary Results for FORMOSAT-3/COSMIC



Foelsche et al. 2007, *TAO,* submitted

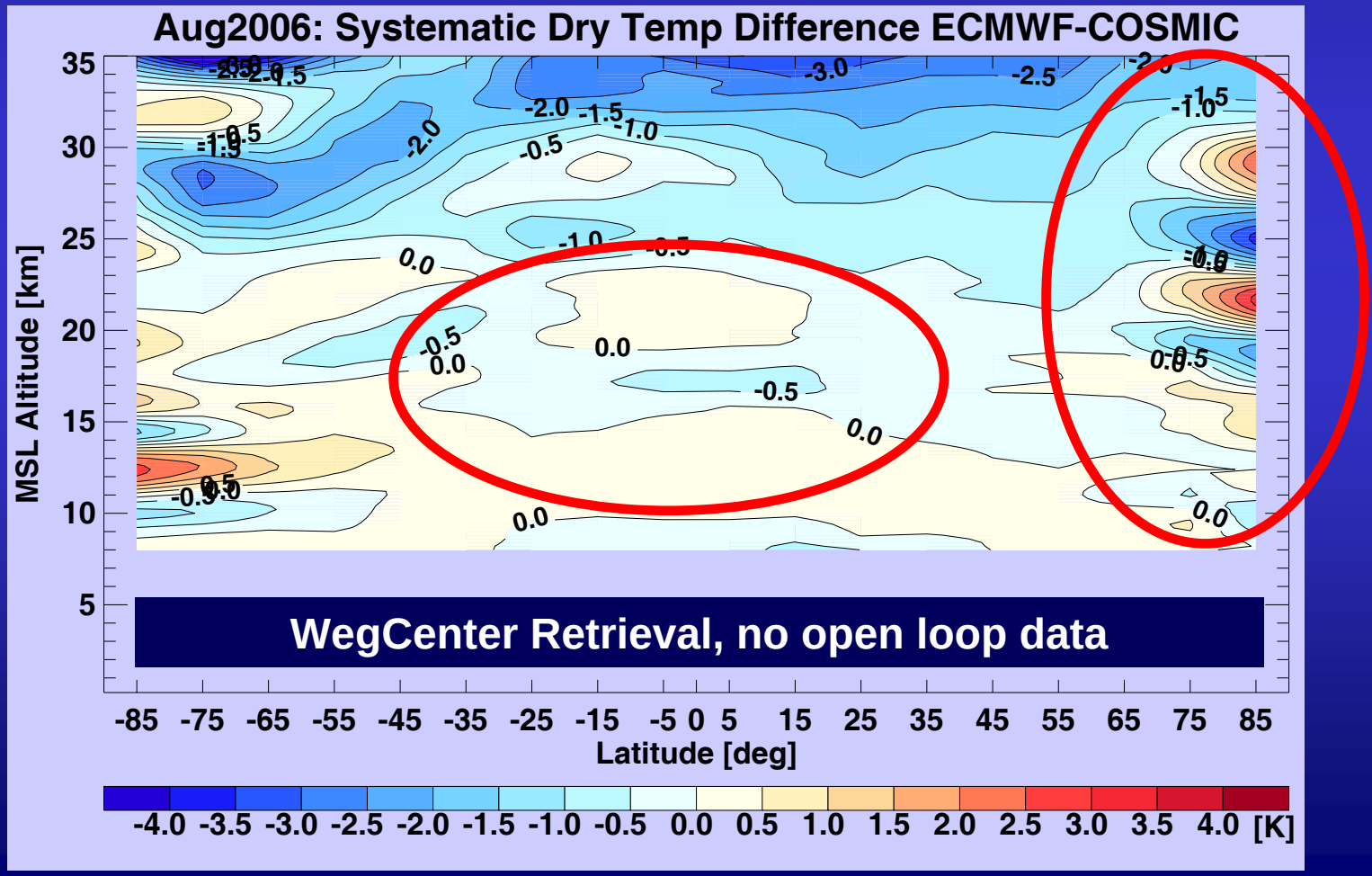
Monthly Mean Dry Temperature



Monthly Mean Dry Temperature

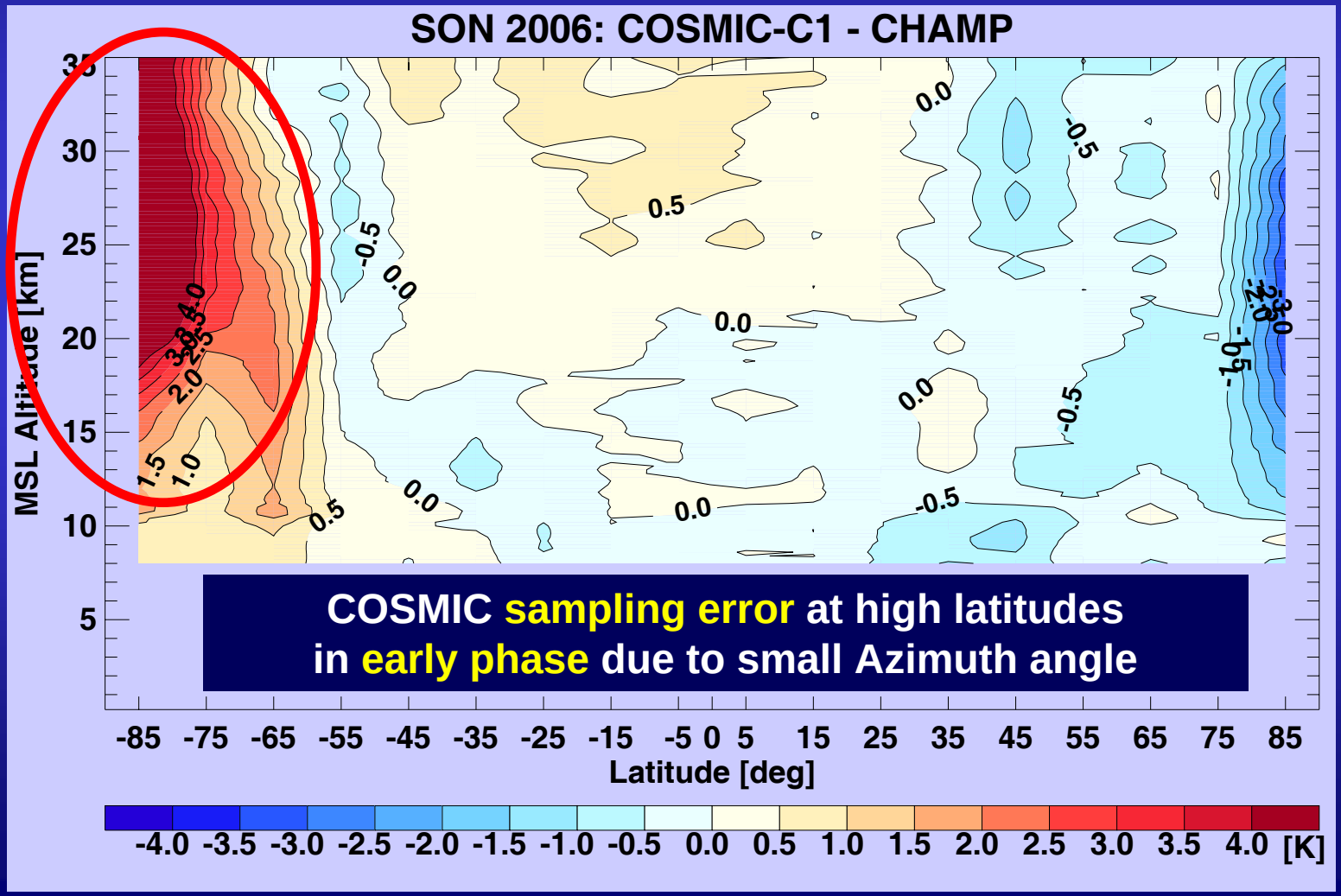
FORMOSAT-3/COSMIC August 2006

All satellites



Seasonal Mean Dry Temperature

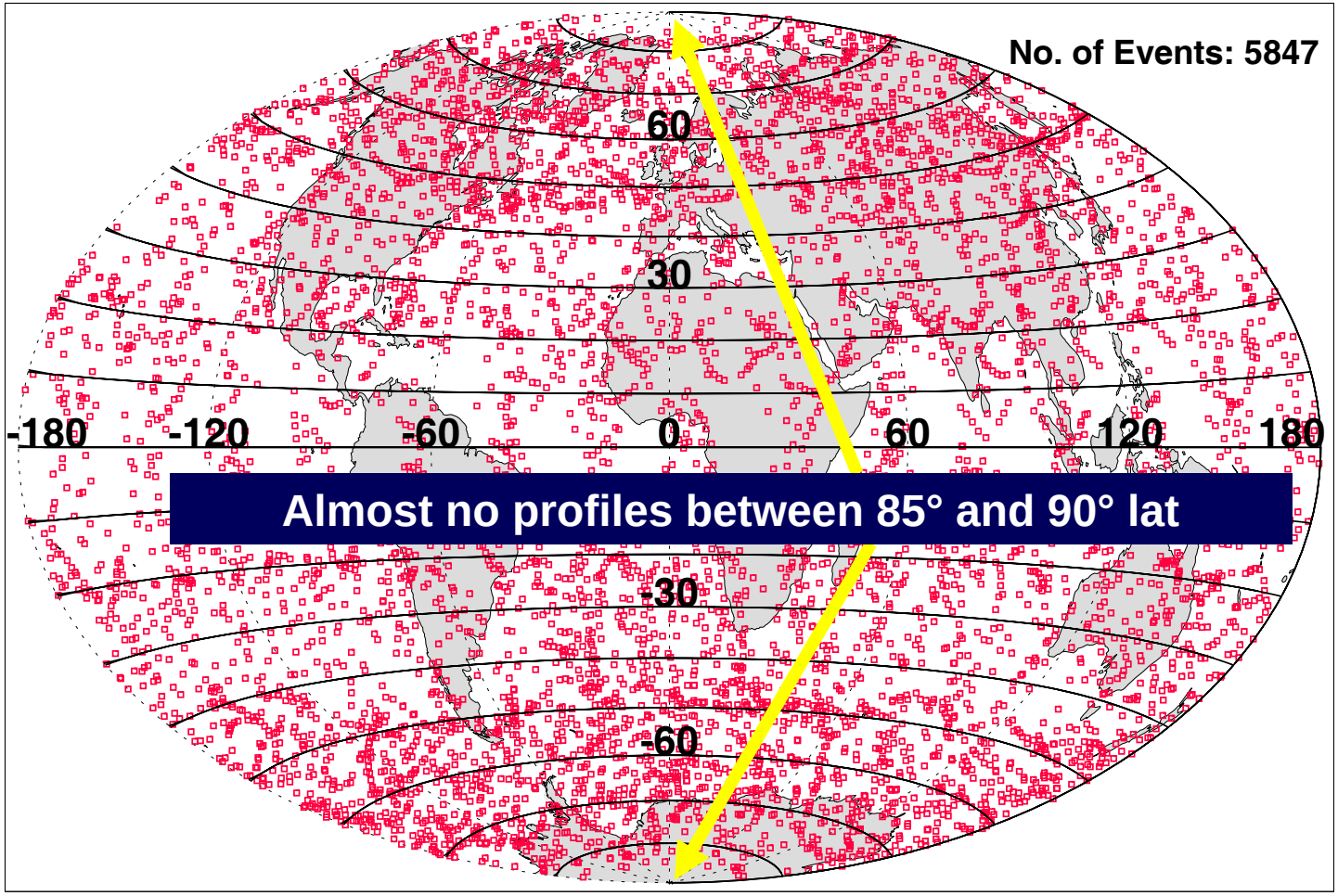
SON 2006 COSMIC-FM1 **minus** CHAMP



COSMIC sampling error at high latitudes in early phase due to small Azimuth angle

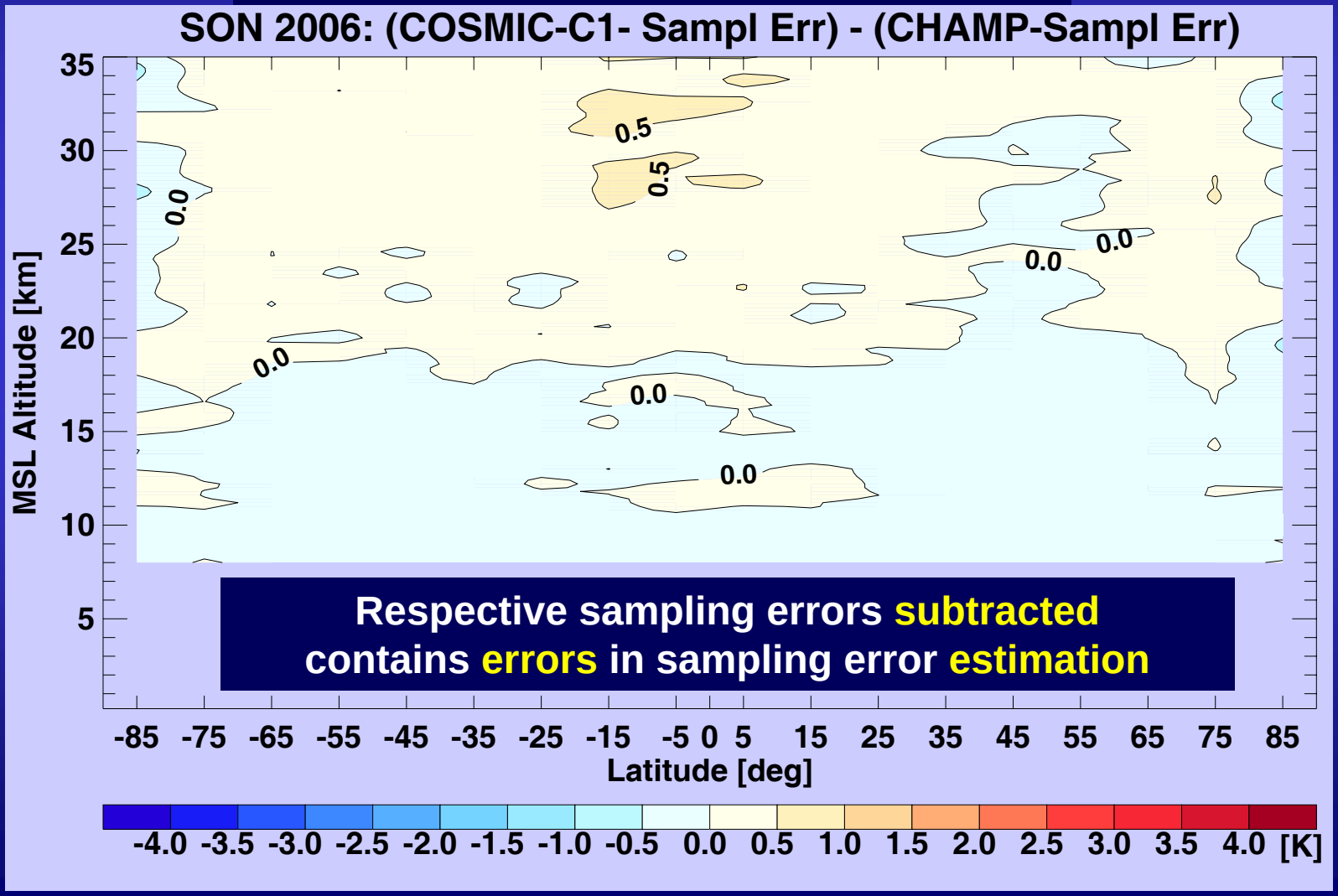
COSMIC Sampling

Sep 2006 : COSMIC-C1 Event Distribution



Seasonal Mean Dry Temperature

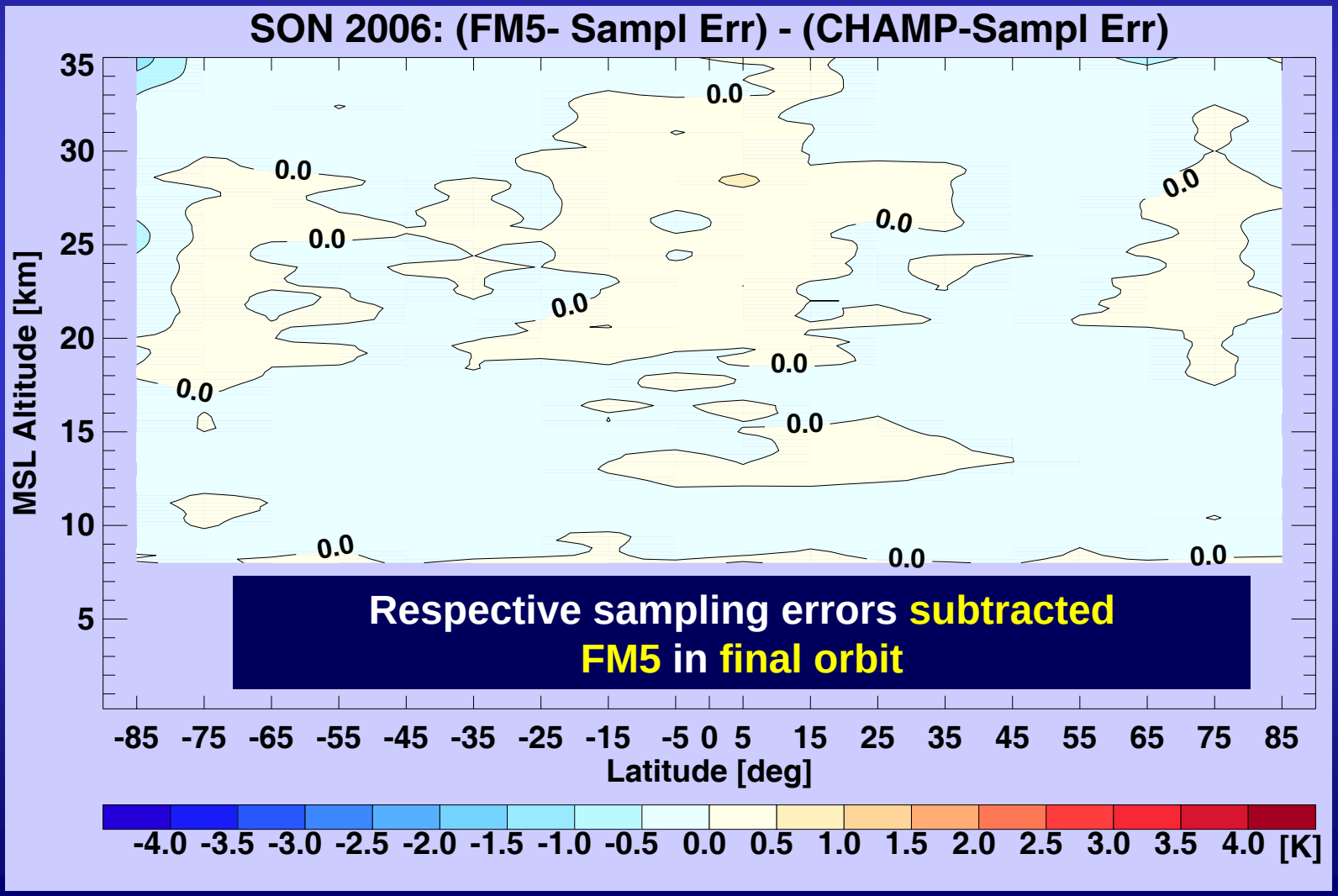
SON 2006 COSMIC-FM1 **minus** CHAMP



Respective sampling errors **subtracted**
contains **errors** in sampling error **estimation**

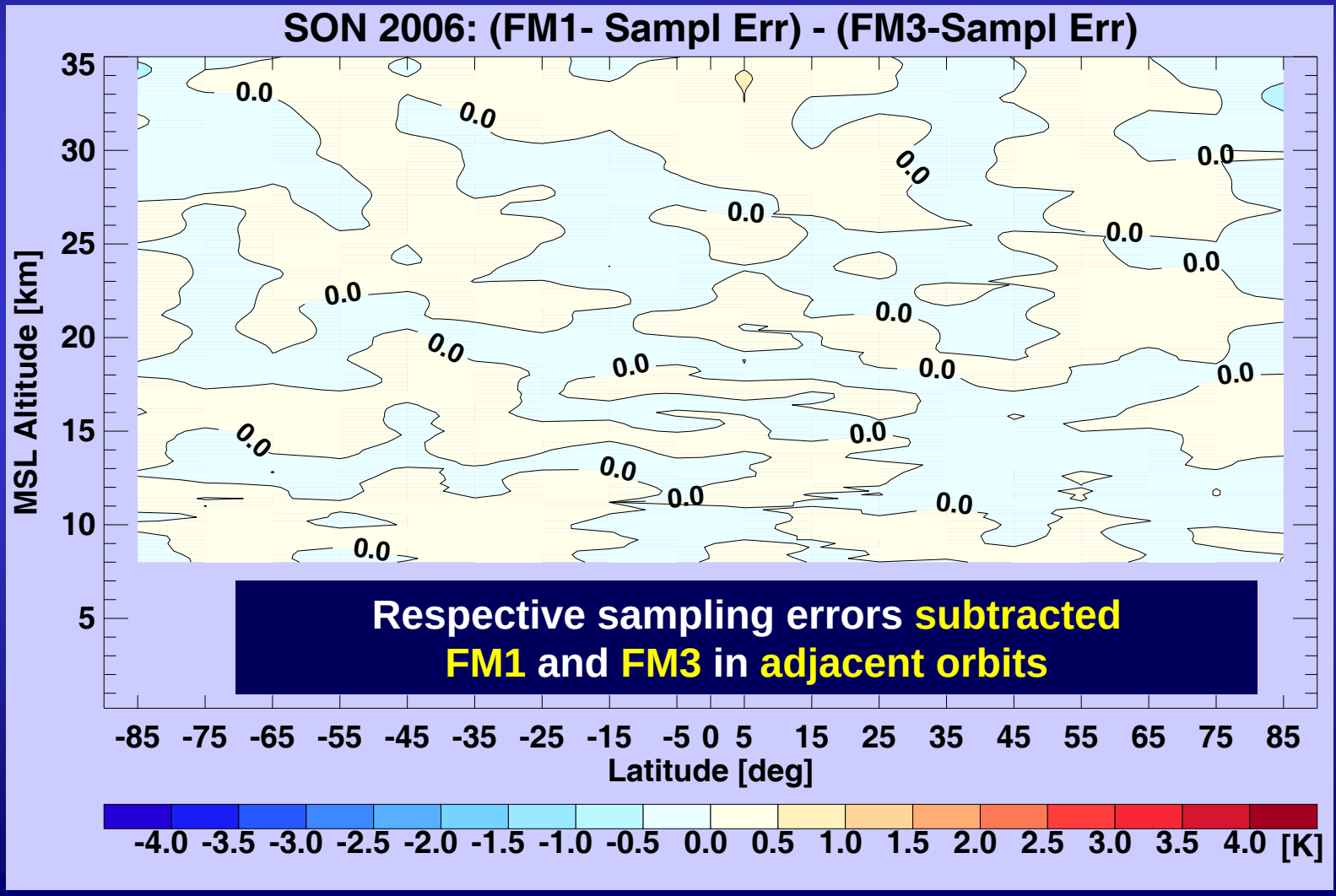
Consistency of RO Data

SON 2006 COSMIC-FM5 minus CHAMP



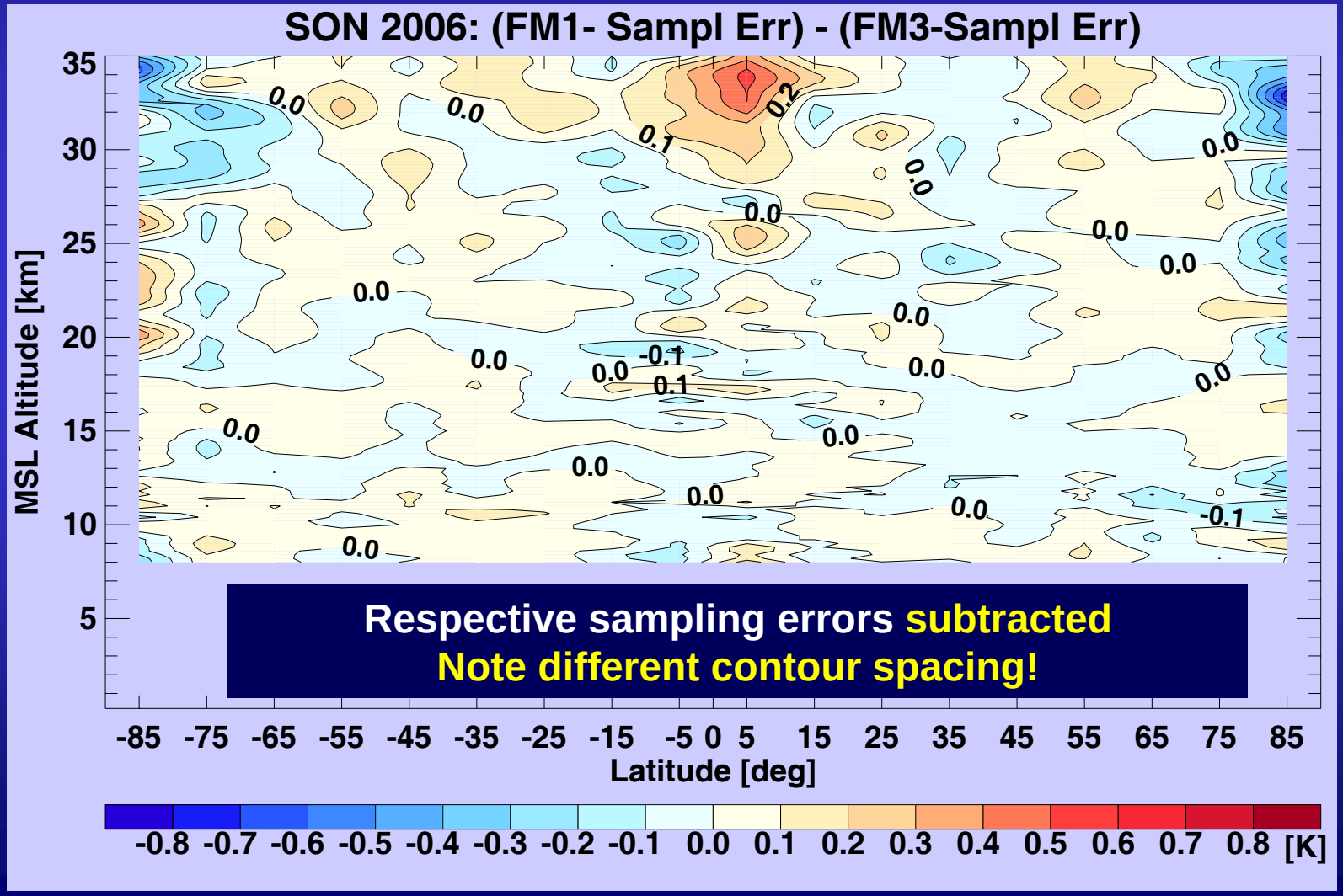
Consistency of RO Data

SON 2006 COSMIC-FM1 **minus** COSMIC-FM3



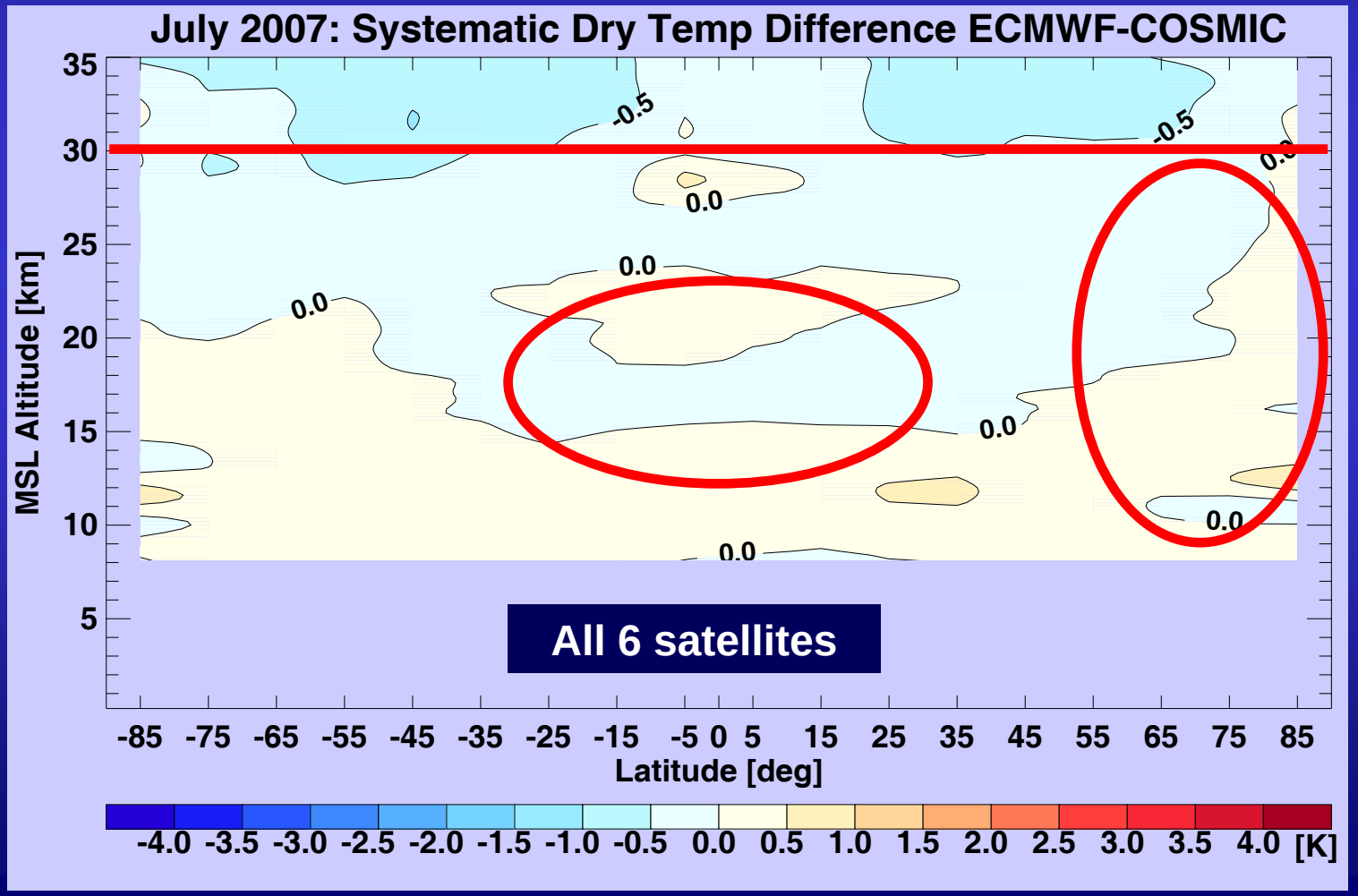
Consistency of RO Data

SON 2006 COSMIC-FM1 minus COSMIC-FM3



System. Difference – July 2007

December 2006: Assimilation of RO data at ECMWF



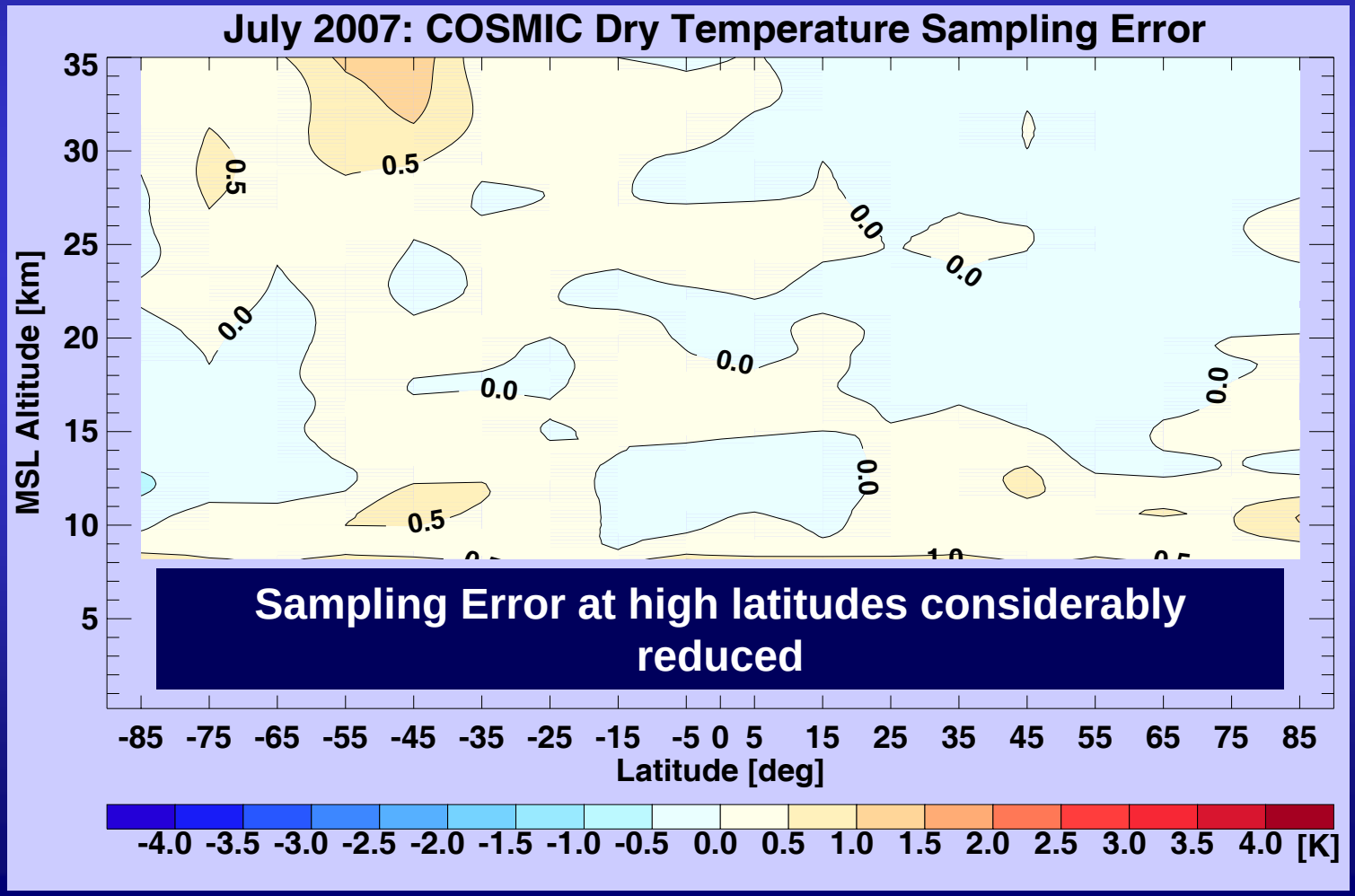
System. Difference – July 2007

Wavelike bias disappeared with assimilation of RO data

Systematic differences above 30 km considerably reduced

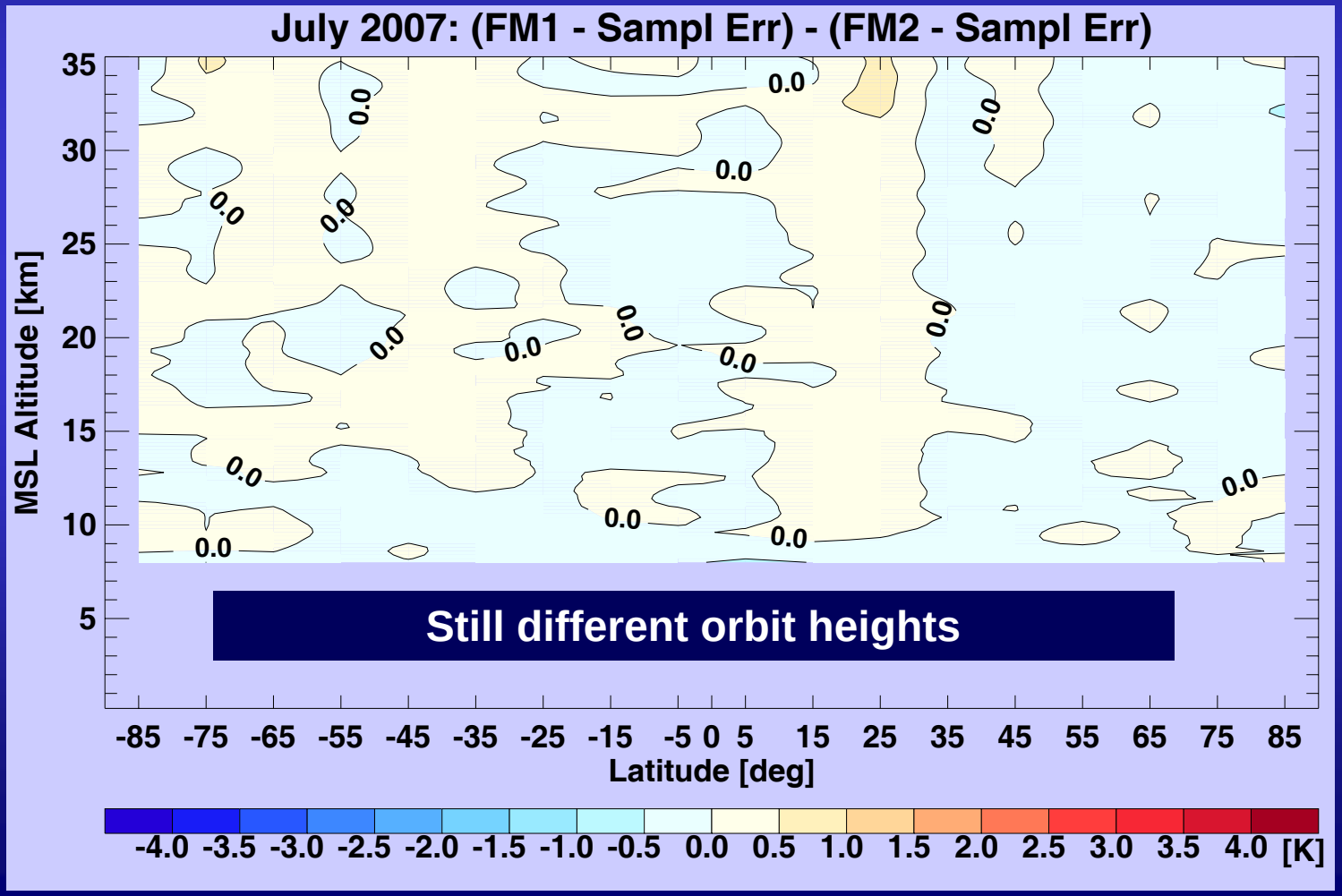
Sampling Error – July 2007

Azimuth angle further opened



Consistency – July 2007

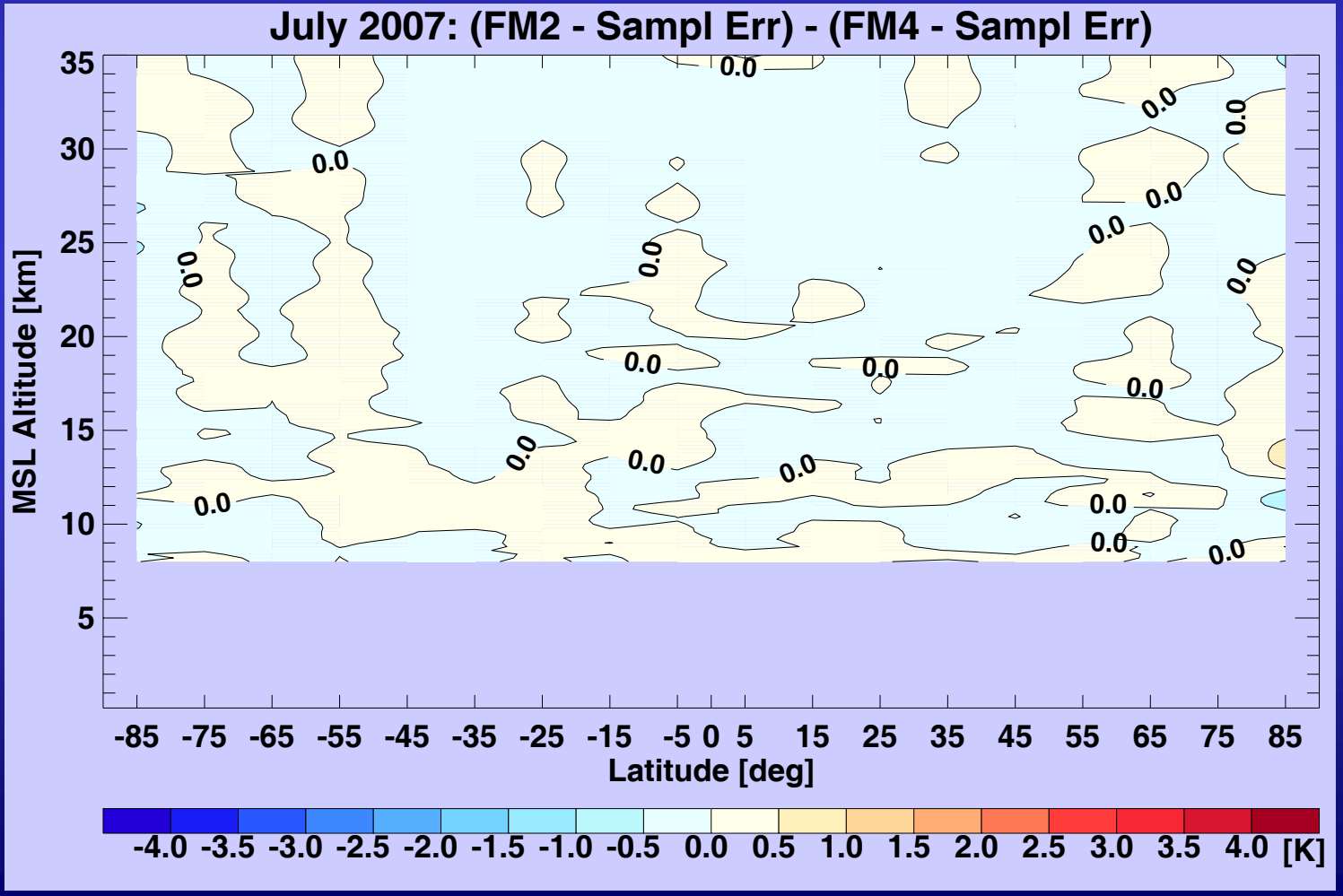
COSMIC-FM1 minus COSMIC-FM2



Still different orbit heights

Consistency – July 2007

COSMIC-FM2 minus COSMIC-FM4



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!

Outlook

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!