

GENERATION OF GPS-RO CLIMATE DATA AT THE ROM SAF

Hans Gleisner

Danish Met. Institute (DMI)

&

ROM SAF

The EUMETSAT
Network of
Satellite
Application
Facilities



ROM SAF
Radio Occultation Meteorology

Outline

- ▶ ROM SAF consortium and objectives
- ▶ Climate processing: from excess-phases to monthly climatologies
- ▶ ROM SAF climate data provision & climate monitoring
- ▶ Ongoing studies



ROM SAF consortium



Partners: **DMI** (Copenhagen, Denmark)

*Kent B. Lauritsen, Hans Gleisner,
Stig Syndergaard, Johannes K. Nielsen,
Hallgeir Wilhelmsen, Helge Jønch-Sørensen*

ECMWF (Reading, UK)

Sean Healy

IEEC (Barcelona, Spain)

Estel Cardellach, Santi Oliveras

Met Office (Exeter, UK)

Ian Culverwell, Chris Burrows, Dave Offiler

ROM SAF objective and products

Main objective:

Operational processing and archiving of RO data from Metop and other RO missions.

Data products and software deliverables:

Near-real time RO data products

- operational products in NRT (refractivity, temperature, pressure, humidity,);

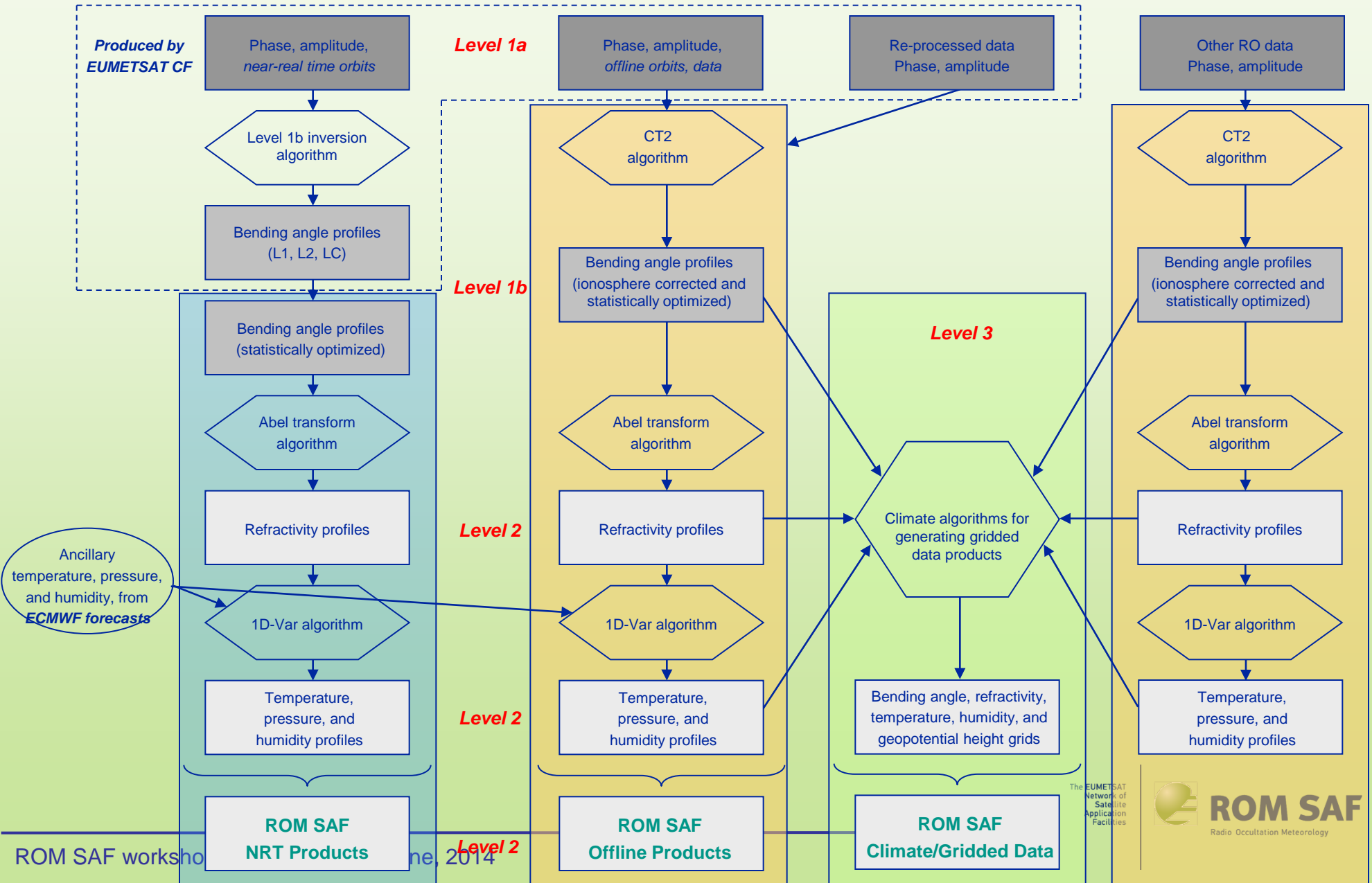
Offline RO data products

- profiles: bending angle, refractivity, temperature,;
- gridded: monthly-mean bending angle, refractivity, temperature,;
- reprocessed data sets;

Radio Occultation Processing Package (ROPP)

- routines for processing, assimilation, data handling, etc. of RO data;

NRT, Offline, and Climate processing overview



Main *profile* processing steps

1. From *phase & amplitude* to *bending angle*

$$L_1, L_2, A_1, A_2 \quad \Rightarrow \quad \begin{array}{l} GO (>25 \text{ km}) \\ CT2 (<25 \text{ km}) \end{array} \quad \Rightarrow \quad \alpha_1, \alpha_2$$

2. Ionospheric correction of *bending angles*

$$\alpha_{LC}(a) = \frac{f_1^2 \alpha_1(a) + f_2^2 \alpha_2(a)}{f_1^2 - f_2^2}$$

3. Statistical optimization of *bending angle*

$$\alpha = \alpha_b + \mathbf{K}(\alpha_{LC} - \alpha_b)$$

Steps 2 and 3 are combined according to *Optimal Linear Combination* algorithm devised by Gorbunov [2002].

Fit of background to data >40 km. dynamic estimation of obs. errors; global search of "best fitting" background profile.

Background: currently *MSIS-90* in future *BAROCLIM*.

Main *profile* processing steps

4. From *bending angle* to *refractive index* through Abel inversion

$$\ln[n(x)] = \frac{1}{\pi} \int_x^{\infty} \frac{\alpha(a)}{(a^2 - x^2)^{1/2}} da$$

Integral is solved by piecewise analytical integration and an asymptotic correction at the upper integration limit.

5. From *refractivity* to *pressure, temperature, humidity*

$$N = \kappa_1 \frac{p}{T} + \kappa_2 \frac{p_w}{T^2}$$

- Dry solution assuming $p_w=0$ and hydrostatic equilibrium.
- Wet solution through 1DVar using ECMWF short-term forecasts as *a priori*.

An alternative: *Average Profile Inversion*

Single-profile inversion

$$\alpha_{LC}(a), \alpha_{bgr}(a) \rightarrow \alpha_{SO}(a)$$

$$N(a) \approx \frac{10^6}{\pi} \int_a^\infty \frac{\alpha_{SO}(a')}{\sqrt{a'^2 - a^2}} da'$$

$$N(a) \rightarrow N(H)$$

$$\frac{d(\ln p)}{dH} = \frac{g}{R \cdot T(N, p)}$$

$$N^m(H) = \dots \textit{stat. analysis}$$

$$p^m(H) = \dots \textit{stat. analysis}$$

$$T^m(H) = \dots \textit{stat. analysis}$$

Average-profile inversion

$$\alpha_{LC}^m(H_a) = \dots \textit{stat. analysis}$$

$$\alpha_{LC}^m(H_a), \alpha_{top}^m(H_a) \rightarrow \alpha^m(a)$$

$$N^m(a) \approx \frac{10^6}{\pi} \int_a^\infty \frac{\alpha^m(a')}{\sqrt{a'^2 - a^2}} da'$$

$$N^m(a) \rightarrow N^m(H)$$

$$\frac{d(\ln p^m)}{dH} = \frac{g}{R \cdot T^m(N^m, p^m)}$$

use of a priori

Main *climate* processing steps

1. Quality control: reject profiles based on a set of QC tests
2. Vertical interpolation of profiles onto the climate height grid
3. Weighted averaging of profiles into monthly latitude bins
4. Estimation of errors, including sampling errors
5. Sampling error correction of monthly gridded data

Climate processing: QC

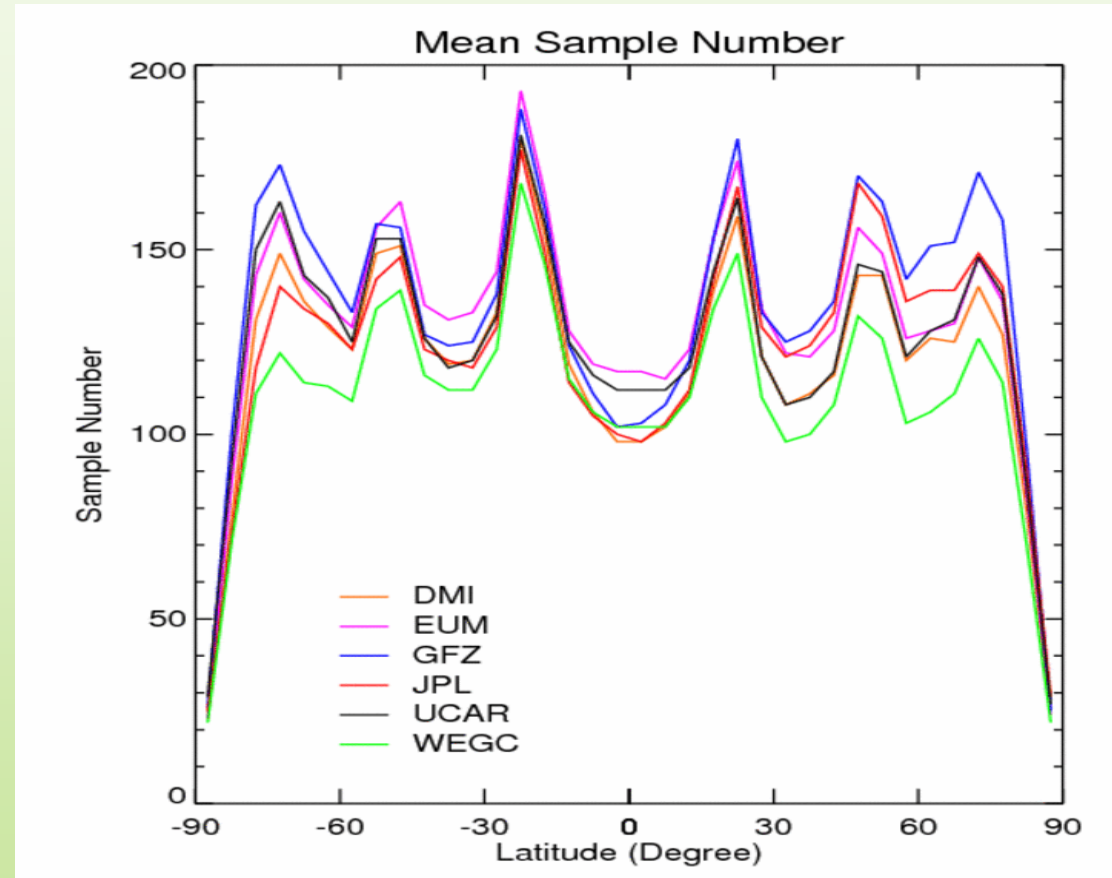
- Differences amongst processing centres –

Lessons from *ROtrends* working group:

QC procedures are a potential source of structural uncertainty.

After QC, there is a 5-20% difference in the number of data between processing centres. Of all available occultations, only 50% are common amongst all 6 centres.

The processing centres disagree strongly on which occultations to reject



Mean monthly CHAMP data number per 5 degree latitude bin.
From Ho et al., JGR, 2012.

Climate processing: QC

– ROM SAF QC screening –

QC0: basic sanity check

This screening step removes occultations with too few useful data points, and/or invalid data points.

- $\alpha(H_a)$ must reach below 30 km and above 60 km
- $\alpha(H_a)$ must contain more than 100 valid data points
- the impact altitude series H_a must be monotonous
- all $\alpha(H_a)$ values must be within valid range: $[-1,100]$ mrad
- $N(H)$ must reach below 30 km and above 60 km
- $N(H)$ must contain more than 100 valid data points
- the MSL altitude series H must be monotonous
- all $N(H)$ values must be within valid range: $[0,500]$ N-units

QC1: (not used)

QC2: bending angle quality

This screening step checks the quality of the bending angles, as quantified by the noise on the L2 impact parameter series and the fit of the raw LC bending angle to an a priori bending angle profile. The L2 score is the single most important quality indicator in the ROM SAF QC procedure, whereas the SO score currently is set to a value that only gives it a minor role.

- the L2 quality score must be less than 30.0
- the SO quality score must be less than 1000.0

QC3: removal of outliers

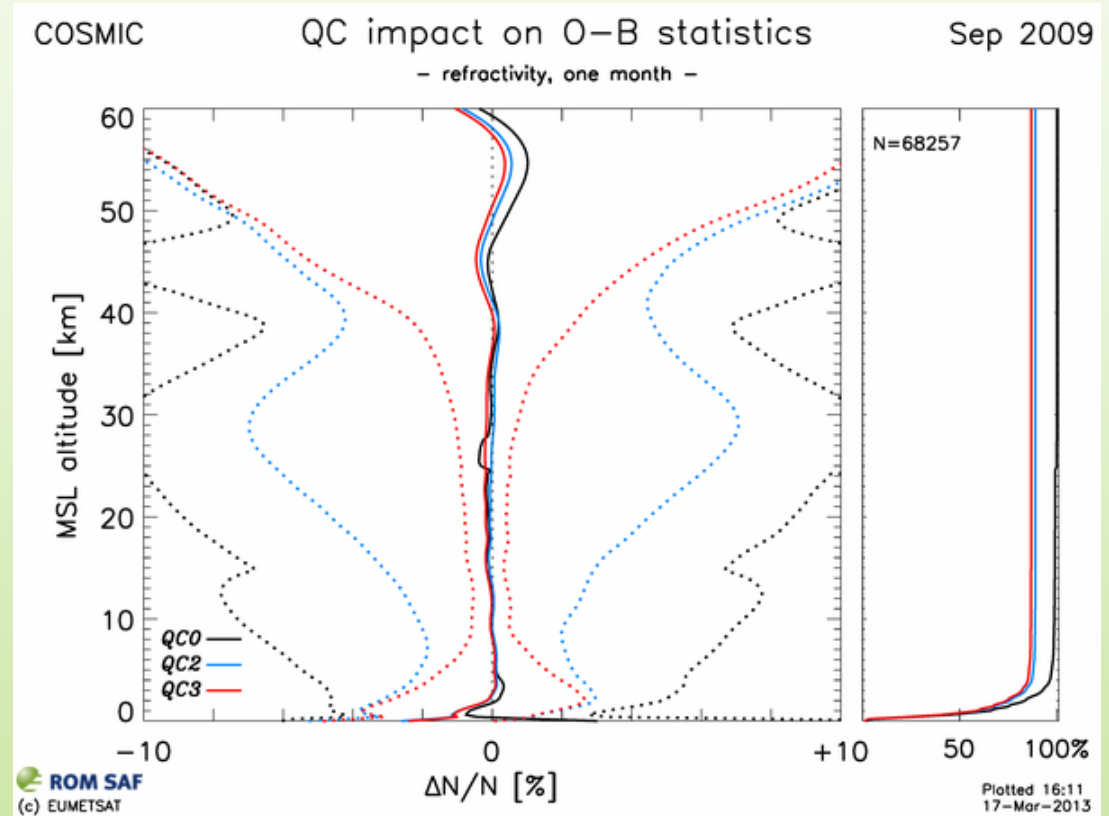
This screening step removes occultations that do not seem to belong to the distribution. This is currently done through comparison with ECMWF data mapped to refractivity and bending angle space. It is the refractivity criterion that dominates this screening step, while the bending angle criterion is less important.

- $N(H)$ must deviate from ECMWF by less than 10% between 10 – 35 km
- $\alpha(H_a)$ must deviate from ECMWF by less than 90% between 10 – 40 km

QC4: check on 1D-Var solution

This screening step removes profiles that have problems converging at an acceptable 1D-Var solution. It only affects the 1D-Var climate variables.

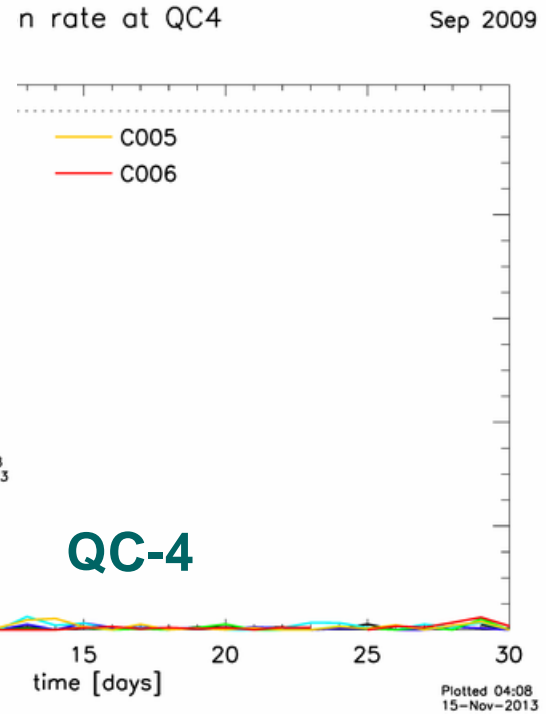
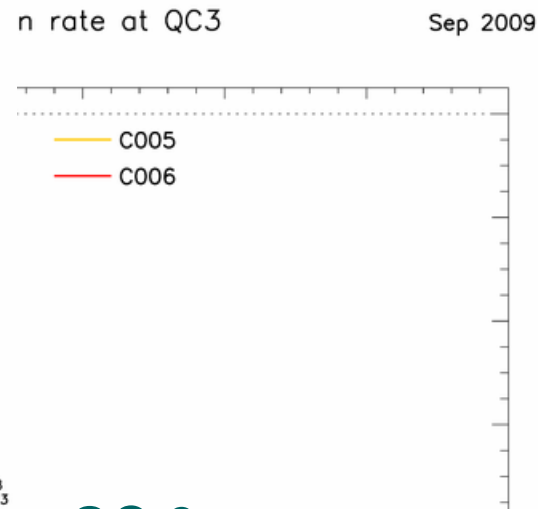
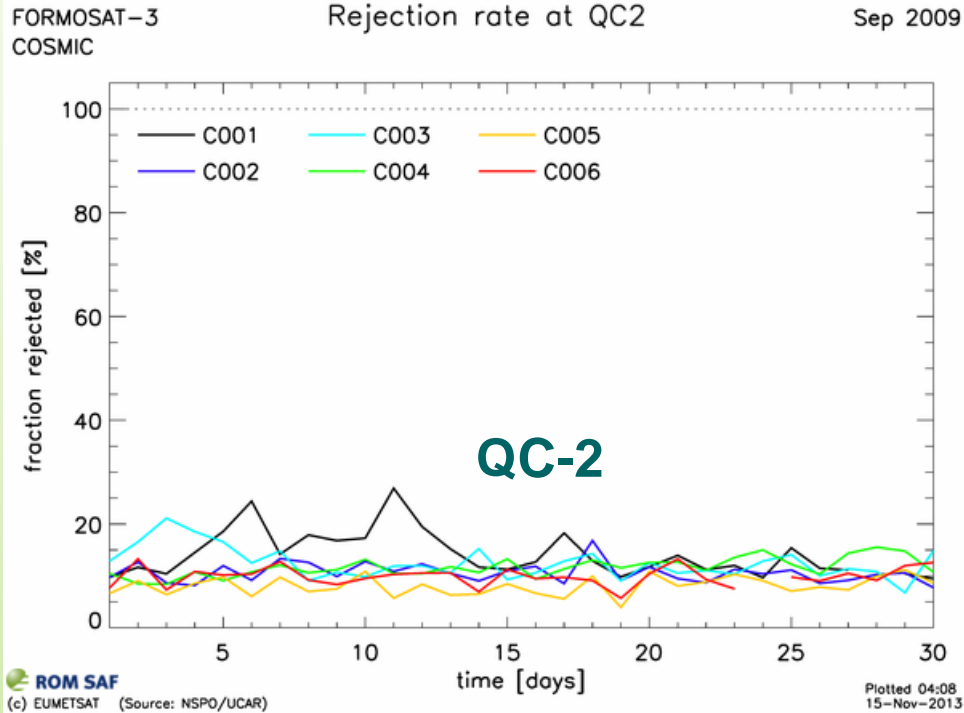
- the 1D-var algorithm must converge within 25 iterations
- the penalty function $2J/N_{\text{obs}}$ must be smaller than 5.0 at convergence



Standard deviations strongly affected by the QC.

Climate processing: QC

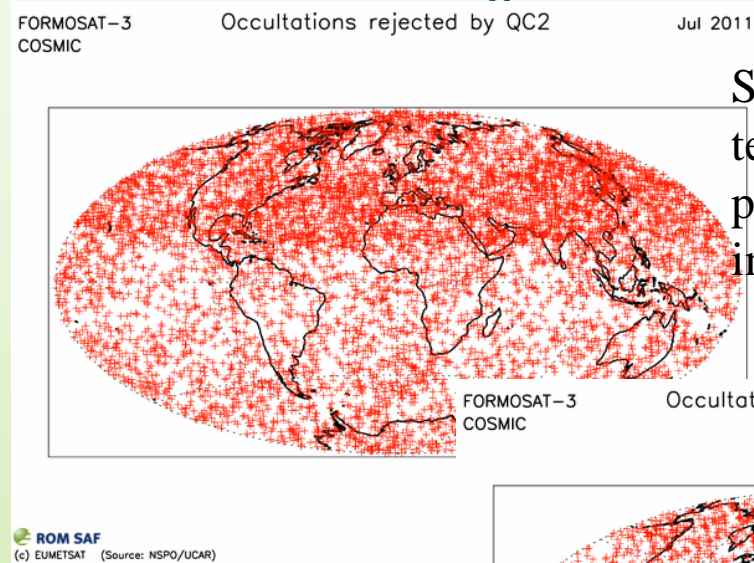
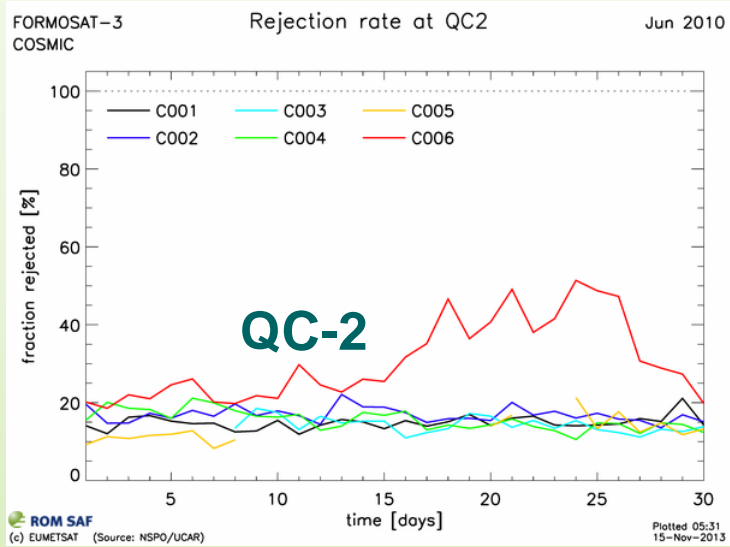
– ROM SAF QC screening –



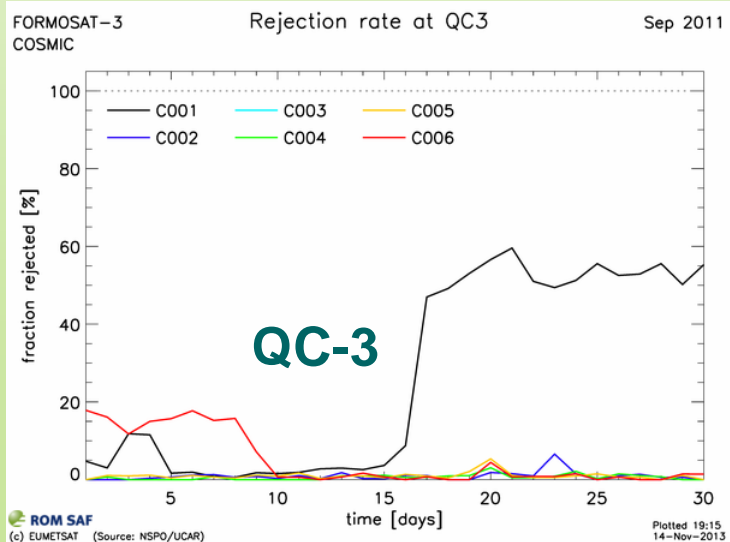
QC-2 is the dominating cause of rejection.
QC-3 less, and QC-4 very few.

Climate processing: QC

– ROM SAF QC screening –



Some years QC-2 has a tendency to a seasonal pattern: more rejections in summer hemisphere.



Odd QC-2/3 behaviour sometimes seen for individual satellites.

The EUMETSAT
Network of
Satellite
Application
Facilities

ROM SAF
Radio Occultation Meteorology

Climate processing: averaging

– binning and averaging –

Zonal binning-and-averaging in latitude bins.

Latitudinal bins are divided into two sub-bins.

Two means (N,S) are computed, followed by averaging weighted by the respective sub-bin areas A_N and A_S .

Alternative averaging: global fit of spherical harmonics to the data [e.g., Leroy, XXXX].

Alternative weighting: cosine weighting.

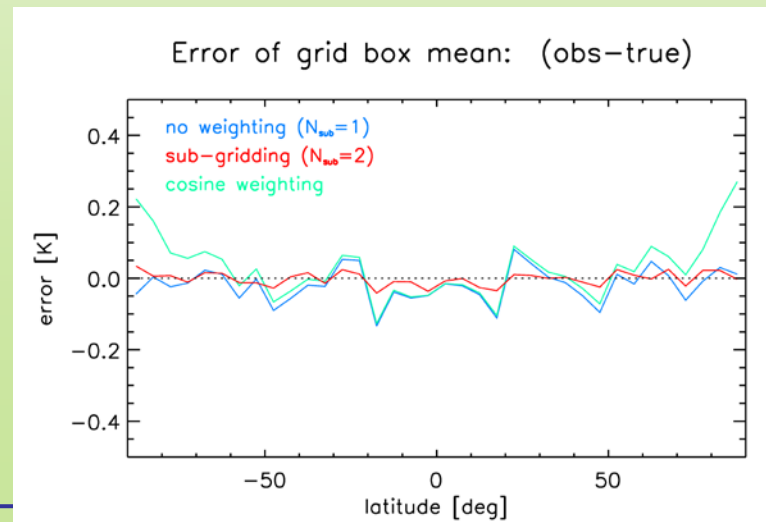
May introduce errors at the highest latitudes, due to assumption about distribution of occultations.

Plot shows errors when a temperature gradient of 0.6 K/lat.degree is sampled by actual Metop distribution.

$$\bar{X}_{S,i}(h) = \frac{1}{M_{S,i}} \sum_{j_S} X_{j_S}(h)$$

$$\bar{X}_{N,i}(h) = \frac{1}{M_{N,i}} \sum_{j_N} X_{j_N}(h)$$

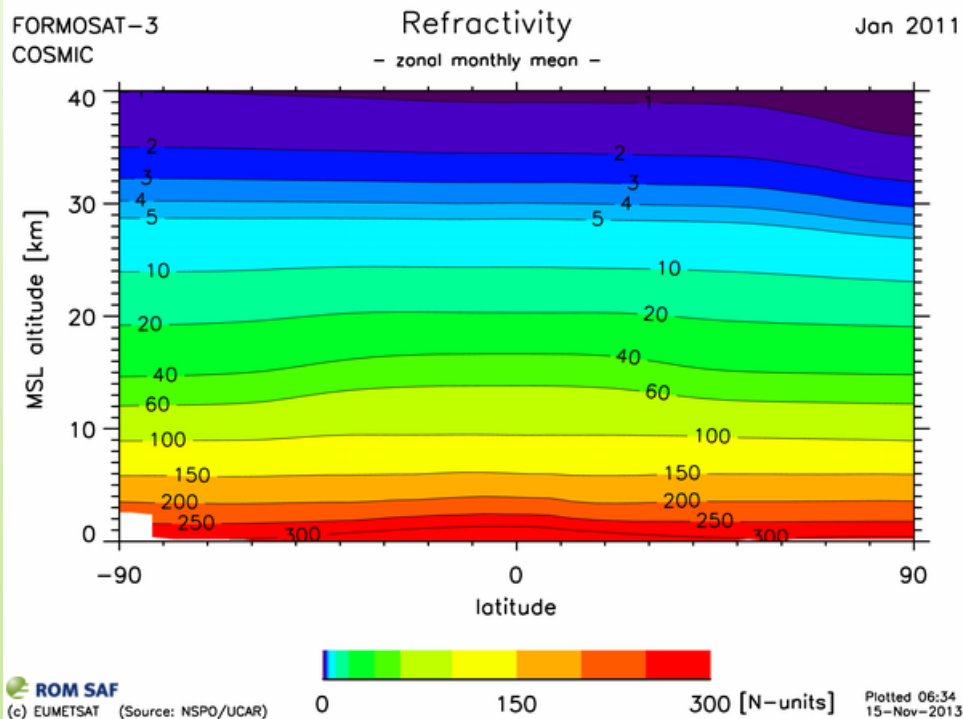
$$\bar{X}_i(h) = \frac{1}{A_{S,i} + A_{N,i}} \left[A_{S,i} \cdot \bar{X}_{S,i}(h) + A_{N,i} \cdot \bar{X}_{N,i}(h) \right]$$



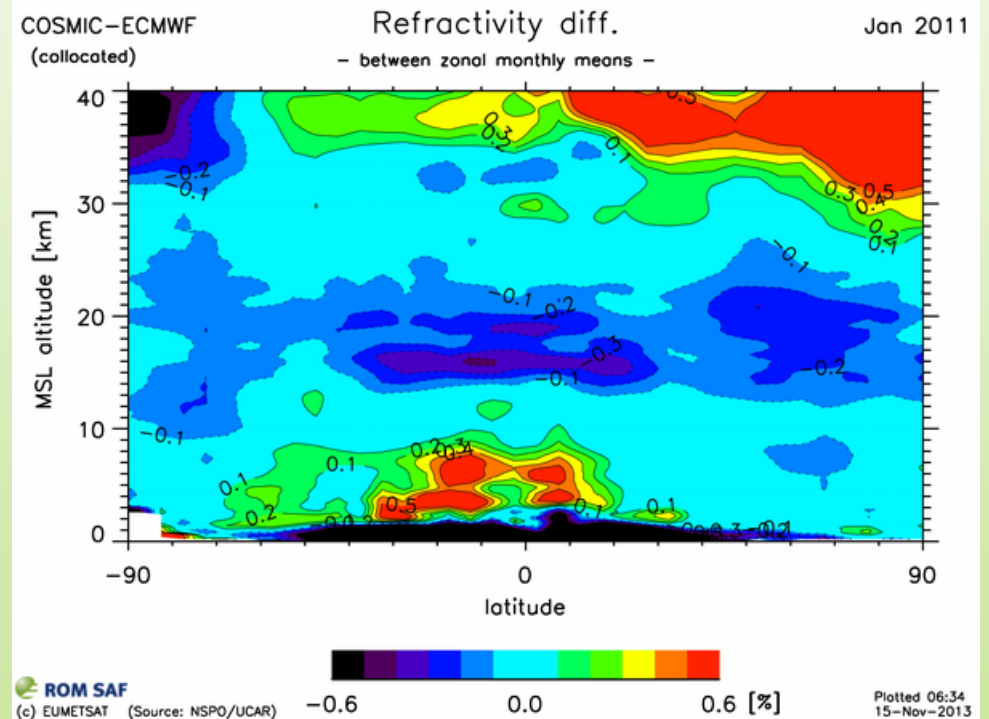
Climate processing: averaging

- binning and averaging -

COSMIC monthly mean refractivity



COSMIC, biases relative to ECMWF



Climate processing: error estimates

– observational errors –

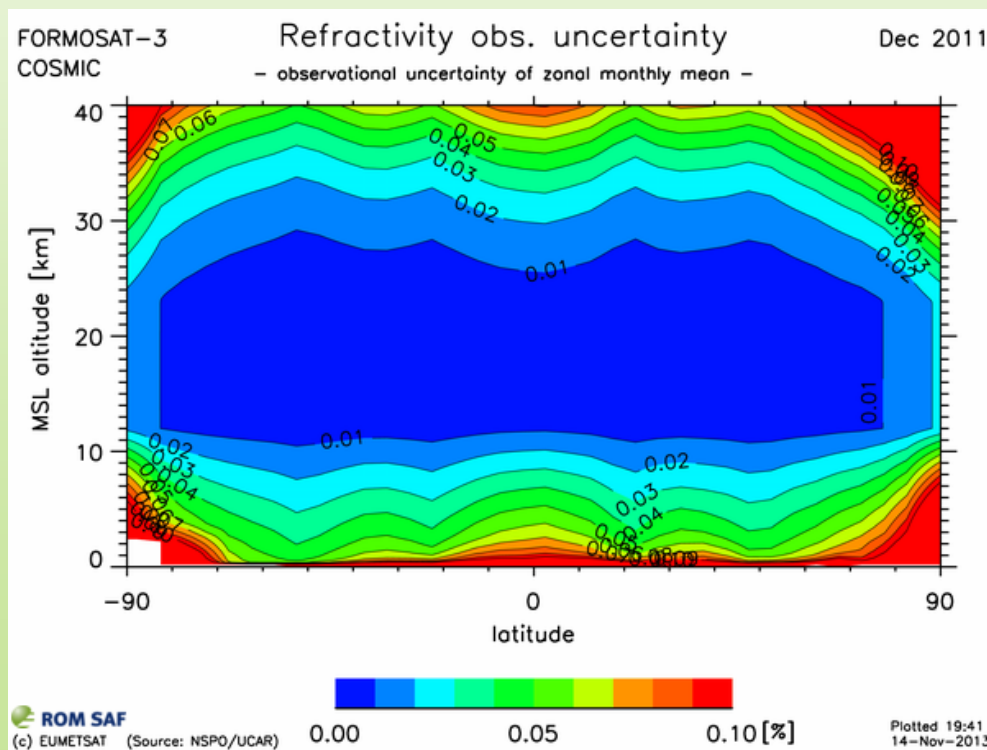
Observational error of the mean is obtained from the assumed observational errors for the profiles.
Random – can only be described by an uncertainty.

Weighted computation of errors.

$$\sigma_{S,obs}^2 = \frac{1}{N_S} \sum_{i=1}^{N_S} \sigma_{i,obs}^2$$

$$\sigma_{N,obs}^2 = \frac{1}{N_N} \sum_{i=1}^{N_N} \sigma_{i,obs}^2$$

$$\sigma_{obs}^2 = \frac{1}{A_S + A_N} (A_S \sigma_{S,obs}^2 + A_N \sigma_{N,obs}^2)$$



Climate processing: error estimates

– sampling errors –

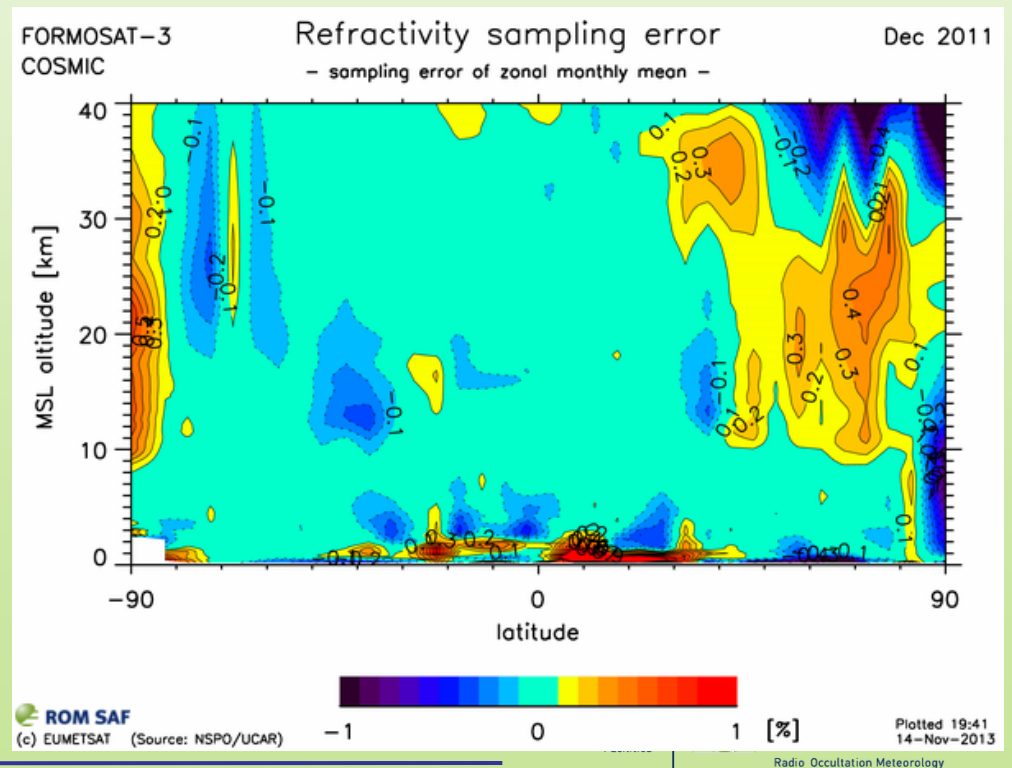
Sampling error of the mean is obtained from sampling a model at the nominal time and location of the observations.

Difference between mean from sampled data and full-grid mean gives an estimate of the sampling error.

This method reduces the sampling errors by around 70-80%, leaving a small *residual sampling error* [Scherllin-Pirscher et al, 2011].

We use operational ECMWF analysis at a 2.5x2.5 degrees resolution, roughly similar the RO measurements.

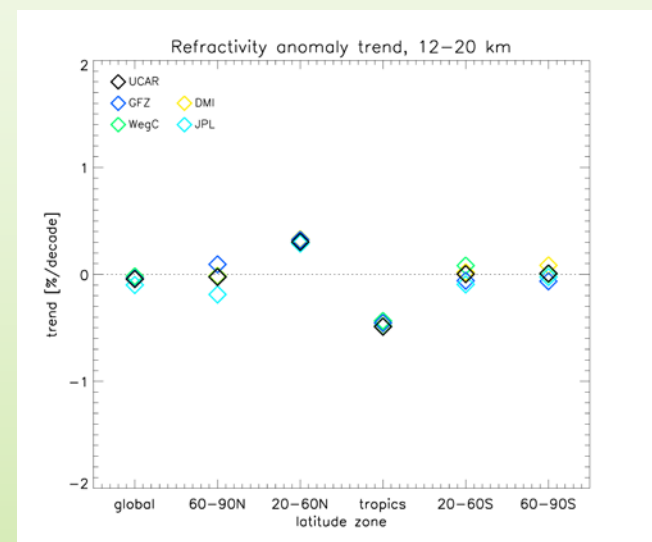
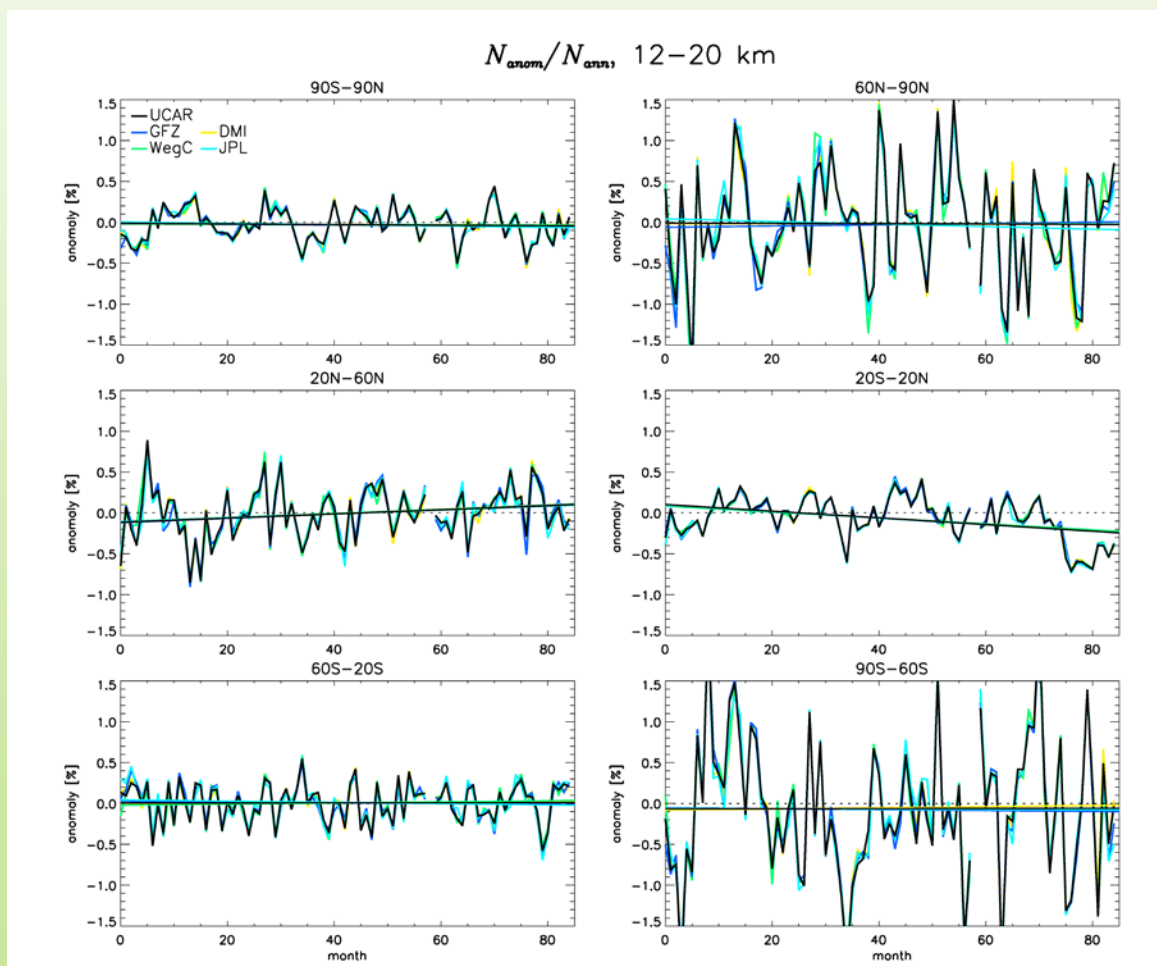
$$\Delta\bar{X} = \bar{X}_{samp} - \frac{1}{N_t N_\varphi N_\theta} \frac{1}{\sum \cos \varphi_k} \sum_{t=1}^{N_t} \sum_{k=1}^{N_\varphi} \sum_{l=1}^{N_\theta} X_{tkl} \cos \varphi_k$$



Climate processing: error estimates

– structural uncertainty –

Fractional anomalies in the 12-20 kilometer layer w.r.t. annual cycle.

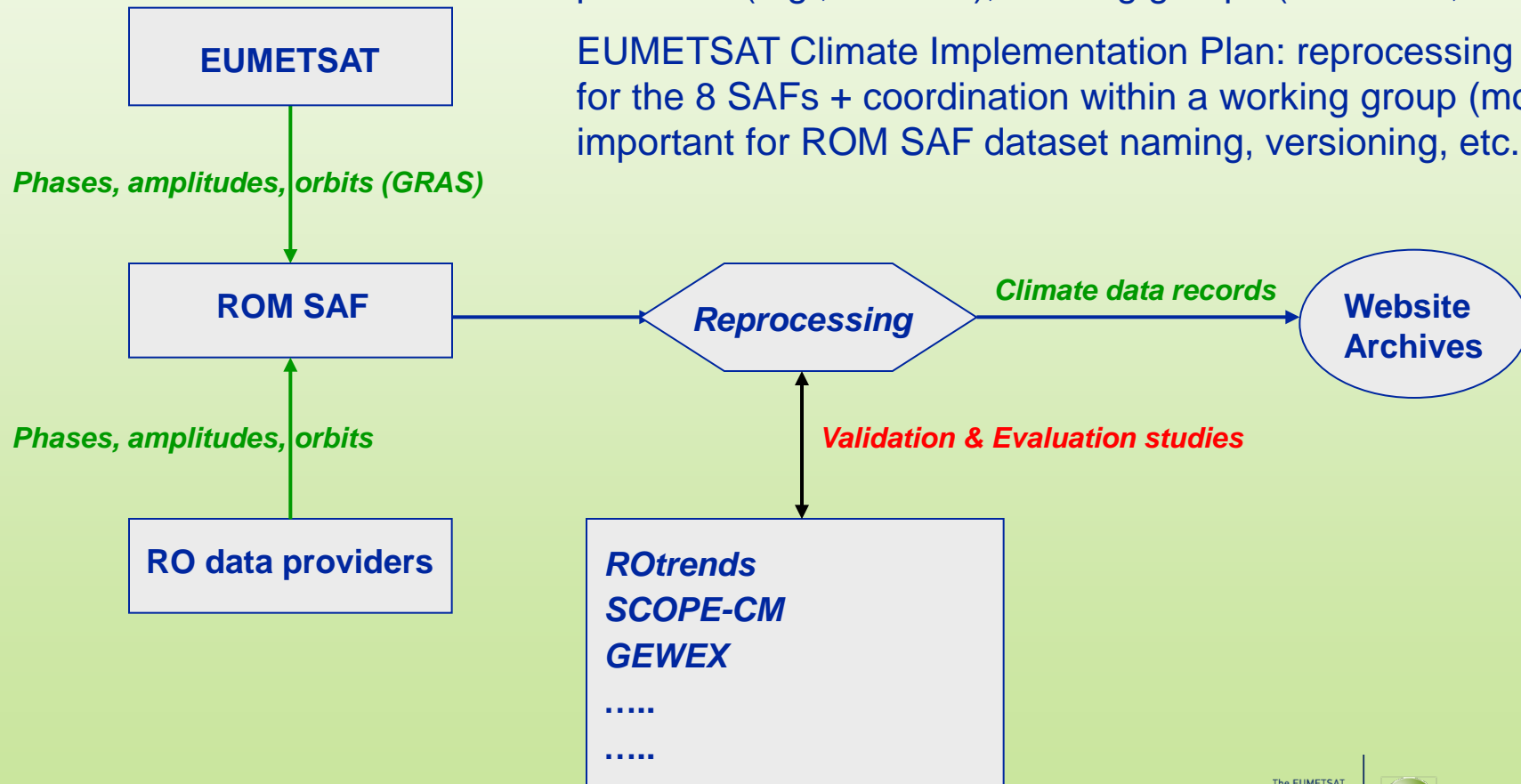


**Ho et al [JGR, 2009] conclude:
uncertainty of trend is 0.04% / 5yrs,
largely due to different subsets of
data being used by different centers.**

Climate data through reprocessing

ROM SAF generates climate data through reprocessing. Planned for every 2nd or 3rd year. Interfaces with EUMETSAT, RO data providers (e.g., CDAAC), working groups (ROtrends, SCOPE-CM)

EUMETSAT Climate Implementation Plan: reprocessing plan for the 8 SAFs + coordination within a working group (mostly important for ROM SAF dataset naming, versioning, etc.)



ROM SAF climate data

– climate monitoring & data provision –

Access to:

- ▶ Documentation
- ▶ Monitoring plots
- ▶ Data
- ▶ Software

ROM SAF - Climate Monitoring - Diagnostics 1 - Mozilla Firefox

www.romsaf.org/climate_monitoring/diagnostics1.php

The EUMETSAT Network of Satellite Application Facilities

ROM SAF
Radio Occultation Meteorology

Forgot your password? [User-login](#) [Print](#)

Climate Monitoring

This page provides monitoring of the offline Level 3 climate data generated at the ROM SAF. The basic data consist of zonally averaged monthly means on a latitude-height grid. Various quantities related to the climatologies are shown, such as standard deviation, data numbers, and error estimates. The *diagnostic plots* provide an assessment of the data numbers, the quality of the input profile data, and the impacts of the quality screening process, while the *service specs plots* demonstrate the compliance with a set of formal requirements.

The actual climate data products can be downloaded from the [Product Archive](#).

NOTE: JavaScript must be activated for this page to function properly.

Zonal grids | Time Series | **Diagnostics, monthly** | Diagnostics, multi-year | Service Specs

Mission / satellite:	Diagnostic variable:	Year - Month:
COSMIC	File numbers	2011 12

< > >| 1x << 1x >>

COSMIC	File numbers	2011 12
--------	--------------	---------

ROM SAF climate data

- data availability at ROM SAF product archive –

Data products:

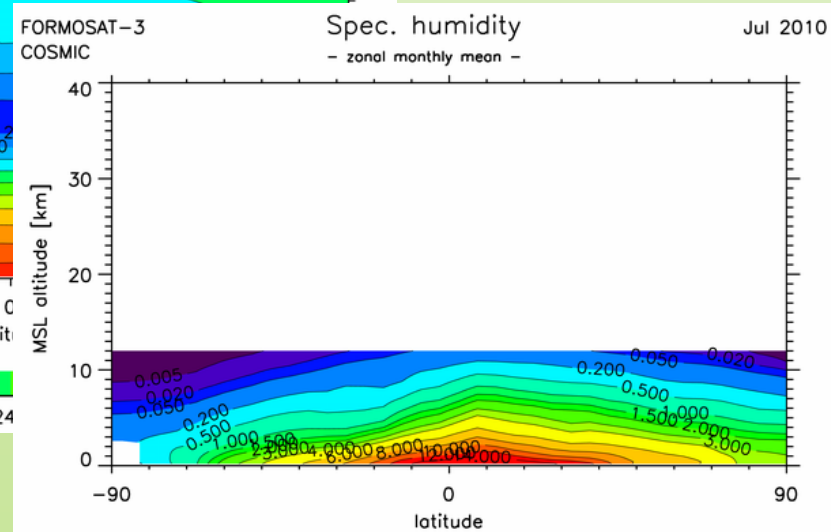
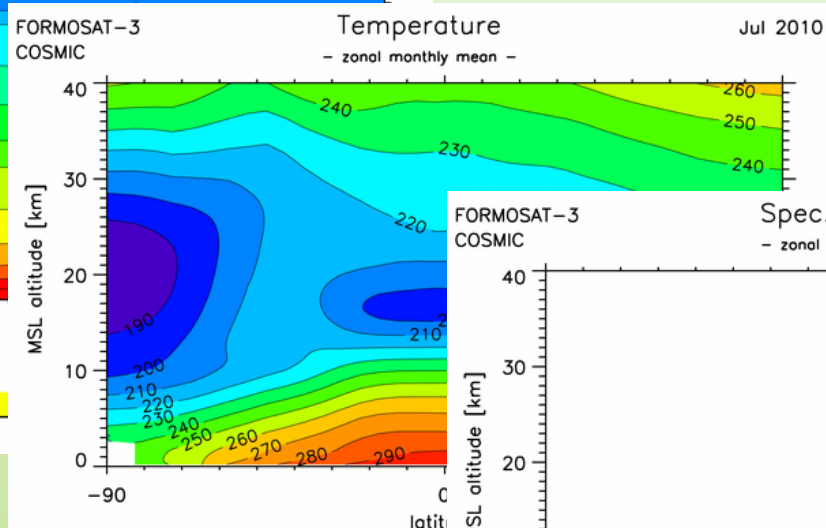
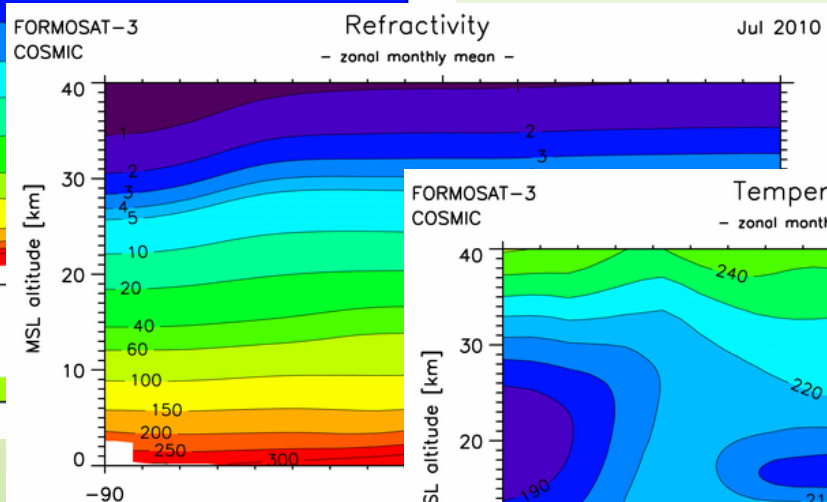
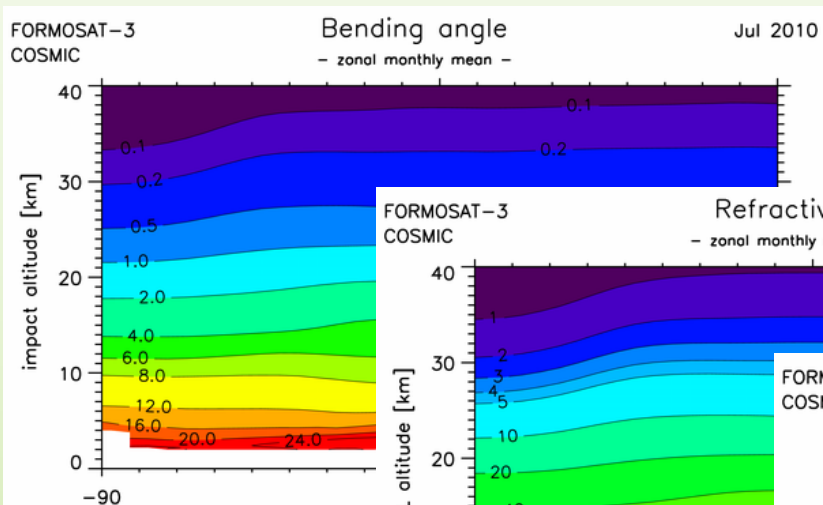
- ▶ data in netCDF format
- ▶ CF-1.5 compliant
- ▶ traceability to data used
- ▶ traceability to software used

The screenshot shows a Mozilla Firefox browser window displaying the ROM SAF website. The address bar shows the URL www.romsaf.org/priv/clm/cba/2010/. The page header includes the ROM SAF logo and a navigation menu. The main content area displays a directory listing for the path `/priv/clm/cba/2010/`. The listing includes a 'Parent Directory' and a series of files with their names, last modified dates, and sizes. The files are organized into two categories: 'trace_cbacol_cosmic' and 'zgrid_cbacol_cosmic', each with sub-files for years 201001 through 201011. The 'zgrid' files are consistently 145K in size, while the 'trace' files range from 2.9M to 4.1M.

Name	Last modified	Size
Parent Directory		-
trace_cbacol_cosmic_201001_0_2110_0010.nc	23-Aug-2013 12:11	4.6M
trace_cbacol_cosmic_201002_0_2110_0010.nc	23-Aug-2013 12:11	4.1M
trace_cbacol_cosmic_201003_0_2110_0010.nc	23-Aug-2013 12:11	4.0M
trace_cbacol_cosmic_201004_0_2110_0010.nc	23-Aug-2013 12:12	4.1M
trace_cbacol_cosmic_201005_0_2110_0010.nc	23-Aug-2013 12:12	3.3M
trace_cbacol_cosmic_201006_0_2110_0010.nc	23-Aug-2013 12:12	3.8M
trace_cbacol_cosmic_201007_0_2110_0010.nc	23-Aug-2013 12:12	3.8M
trace_cbacol_cosmic_201008_0_2110_0010.nc	23-Aug-2013 12:12	3.5M
trace_cbacol_cosmic_201009_0_2110_0010.nc	23-Aug-2013 12:12	2.9M
trace_cbacol_cosmic_201010_0_2110_0010.nc	23-Aug-2013 12:13	2.7M
trace_cbacol_cosmic_201011_0_2110_0010.nc	23-Aug-2013 12:13	1.8M
zgrid_cbacol_cosmic_201001_0_2110_0010.nc	23-Aug-2013 12:13	2.5M
zgrid_cbacol_cosmic_201001_0_2110_0010.nc	23-Aug-2013 12:11	145K
zgrid_cbacol_cosmic_201002_0_2110_0010.nc	23-Aug-2013 12:11	145K
zgrid_cbacol_cosmic_201003_0_2110_0010.nc	23-Aug-2013 12:11	145K
zgrid_cbacol_cosmic_201004_0_2110_0010.nc	23-Aug-2013 12:12	145K
zgrid_cbacol_cosmic_201005_0_2110_0010.nc	23-Aug-2013 12:12	145K
zgrid_cbacol_cosmic_201006_0_2110_0010.nc	23-Aug-2013 12:12	145K
zgrid_cbacol_cosmic_201007_0_2110_0010.nc	23-Aug-2013 12:12	145K
zgrid_cbacol_cosmic_201008_0_2110_0010.nc	23-Aug-2013 12:12	145K
zgrid_cbacol_cosmic_201009_0_2110_0010.nc	23-Aug-2013 12:12	145K
zgrid_cbacol_cosmic_201010_0_2110_0010.nc	23-Aug-2013 12:13	145K
zgrid_cbacol_cosmic_201011_0_2110_0010.nc	23-Aug-2013 12:13	145K

ROM SAF climate data

– zonal monthly means –



ROM SAF (c) EUMETSAT (Source: NSPO/UCAR)

ROM SAF (c) EUMETSAT (Source: NSPO/UCAR)

ROM SAF (c) EUMETSAT (Source: NSPO/UCAR)

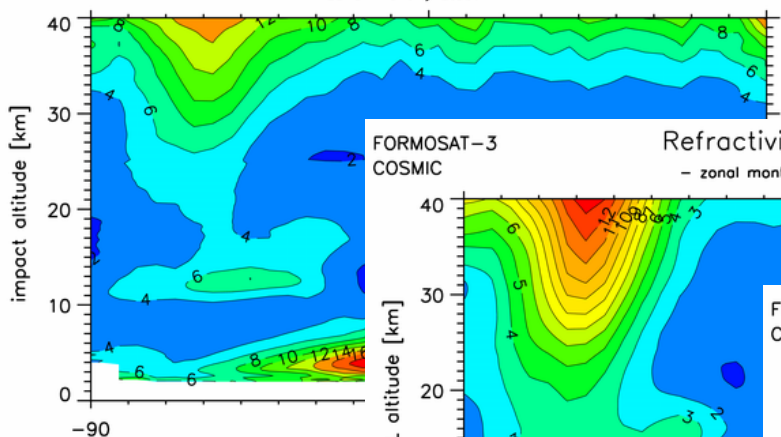
ROM SAF (c) EUMETSAT (Source: NSPO/UCAR)

Plotted 12:35 09-Jun-2013

ROM SAF climate data

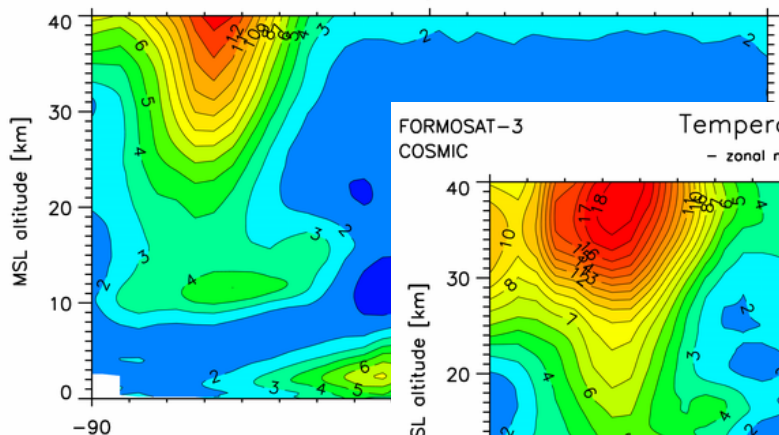
– monthly variability within grid boxes –

FORMOSAT-3
COSMIC
Bending angle stdev
- zonal monthly stdev -
Jul 2010



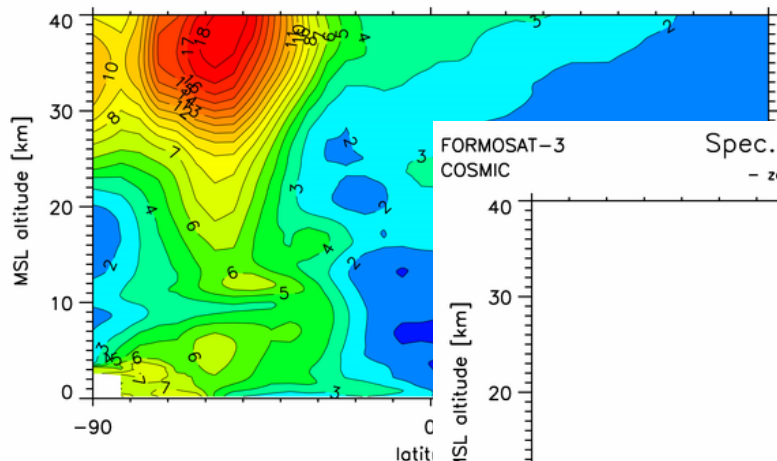
ROM SAF
(c) EUMETSAT (Source: NSPO/UCAR)

FORMOSAT-3
COSMIC
Refractivity stdev
- zonal monthly stdev -
Jul 2010



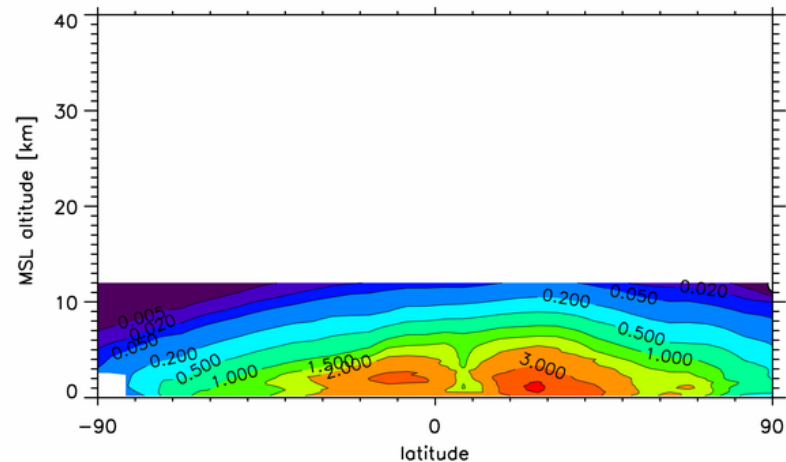
ROM SAF
(c) EUMETSAT (Source: NSPO/UCAR)

FORMOSAT-3
COSMIC
Temperature stdev
- zonal monthly stdev -
Jul 2010



ROM SAF
(c) EUMETSAT (Source: NSPO/UCAR)

FORMOSAT-3
COSMIC
Spec. humidity stdev
- zonal monthly stdev -
Jul 2010



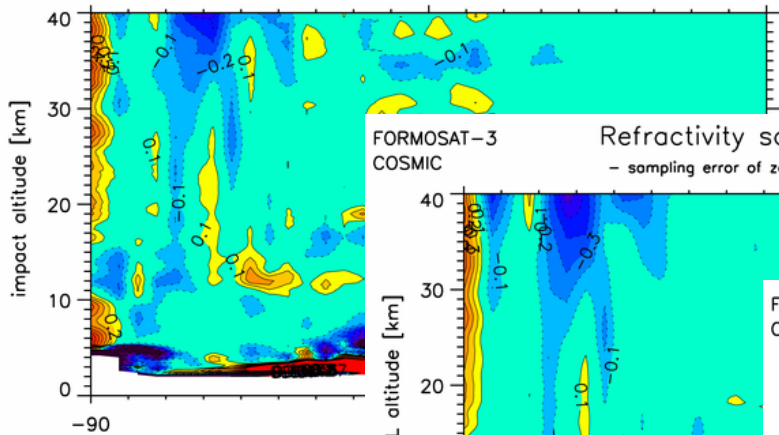
ROM SAF
(c) EUMETSAT (Source: NSPO/UCAR)

Plotted 12:35
09-Jun-2013

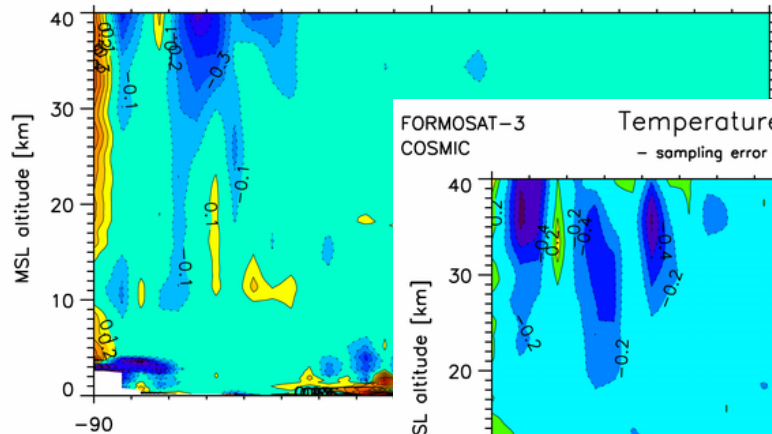
ROM SAF climate data

– estimation of sampling errors –

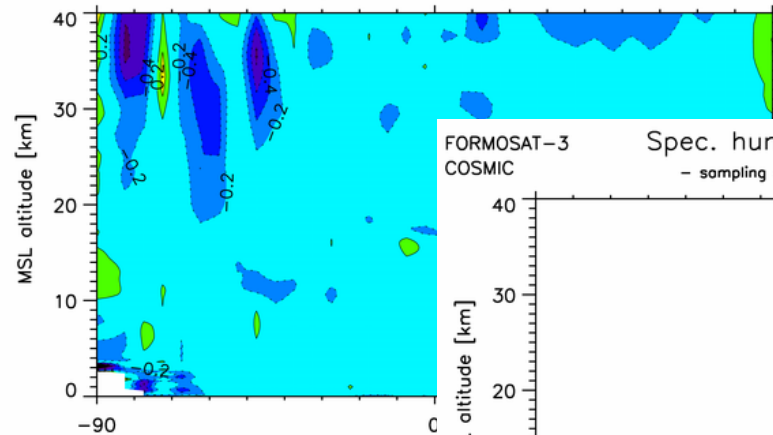
FORMOSAT-3
COSMIC
Bending angle sampling error
- sampling error of zonal monthly mean -
Jul 2010



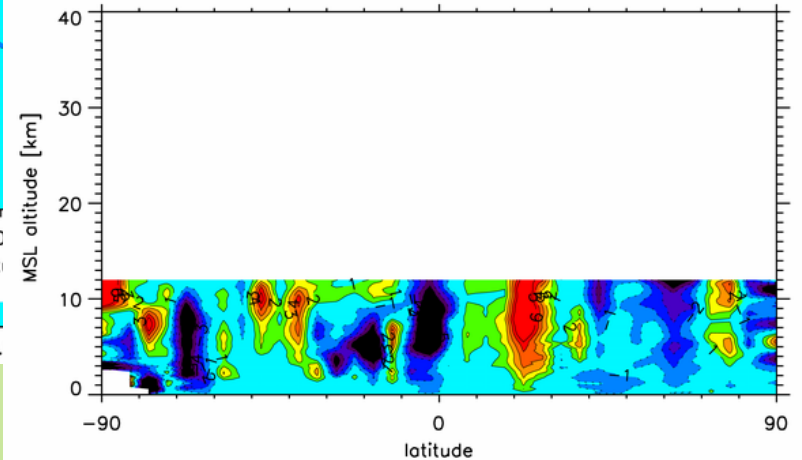
FORMOSAT-3
COSMIC
Refractivity sampling error
- sampling error of zonal monthly mean -
Jul 2010



FORMOSAT-3
COSMIC
Temperature sampling error
- sampling error of zonal monthly mean -
Jul 2010



FORMOSAT-3
COSMIC
Spec. humidity sampling error
- sampling error of zonal monthly mean -
Jul 2010



ROM SAF
(c) EUMETSAT (Source: NSPO/UCAR)

-1

ROM SAF
(c) EUMETSAT (Source: NSPO/UCAR)

-1

ROM SAF
(c) EUMETSAT (Source: NSPO/UCAR)

-1.2 0

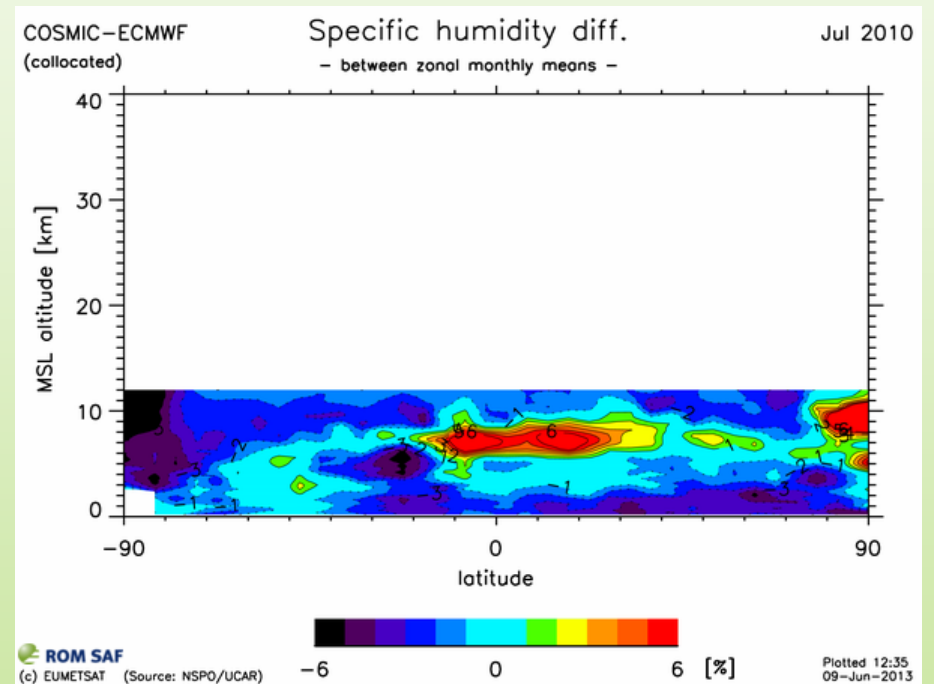
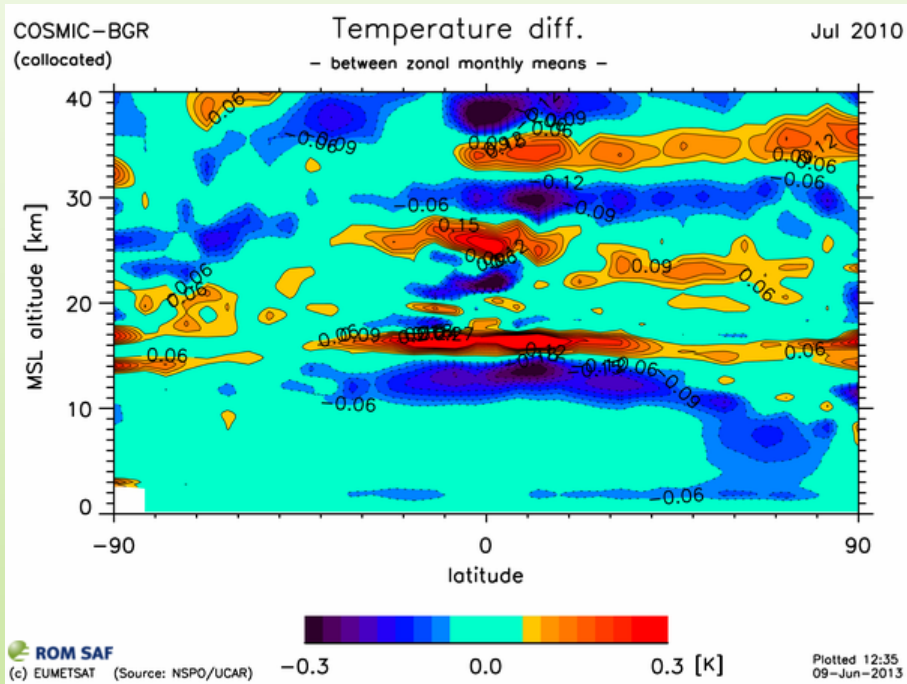
ROM SAF
(c) EUMETSAT (Source: NSPO/UCAR)

-6 0 6 [%]

Plotted 12:35
09-Jun-2013

ROM SAF climate data

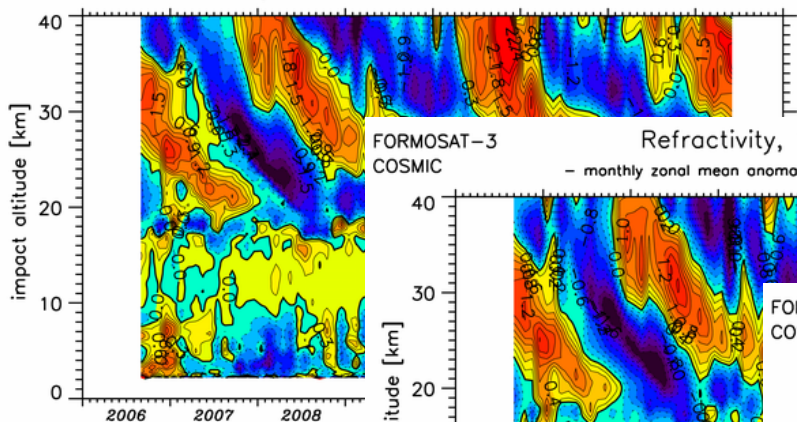
- characterization of differences w.r.t. ECMWF -



ROM SAF climate data

– time series data for the length of RO missions –

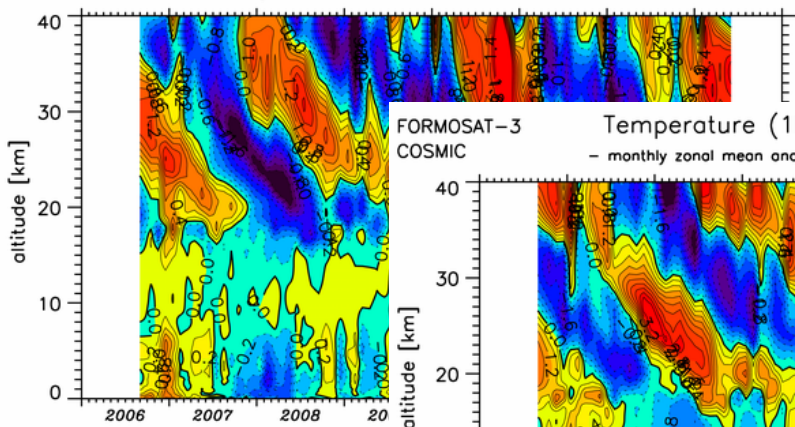
FORMOSAT-3
COSMIC
Bending angle, 10S–10N
– monthly zonal mean anomalies (de-seasonalized) –
2006–2013



ROM SAF
(c) EUMETSAT (Source: NSPO/UCAR)

-3

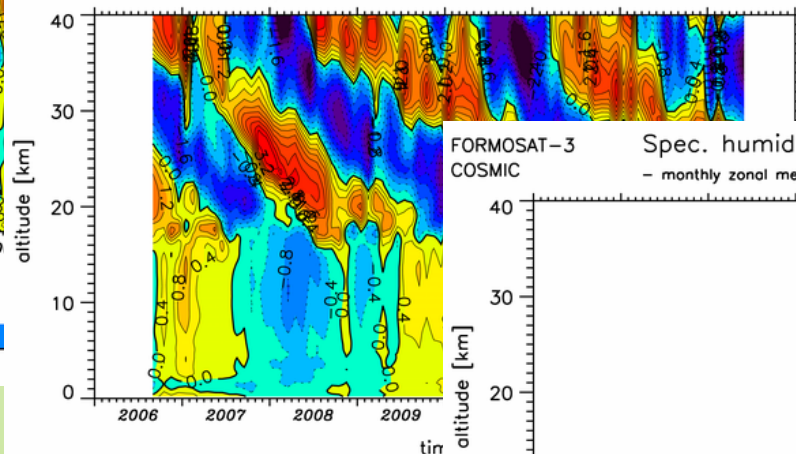
FORMOSAT-3
COSMIC
Refractivity, 10S–10N
– monthly zonal mean anomalies (de-seasonalized) –
2006–2013



ROM SAF
(c) EUMETSAT (Source: NSPO/UCAR)

-2

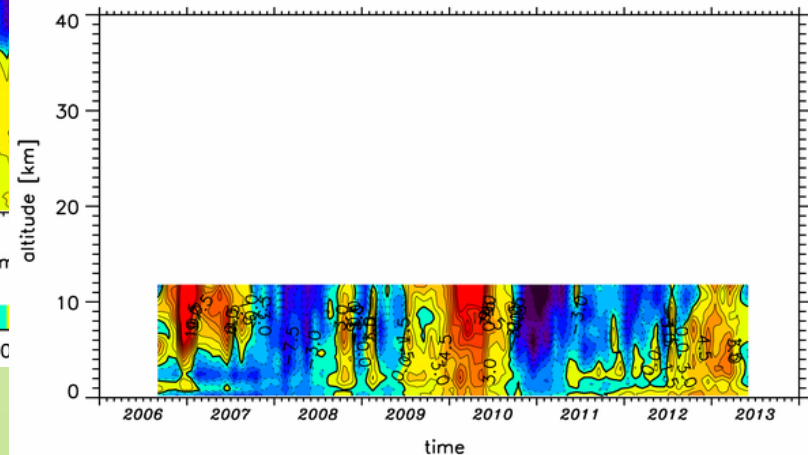
FORMOSAT-3
COSMIC
Temperature (1DVar), 10S–10N
– monthly zonal mean anomalies (de-seasonalized) –
2006–2013



ROM SAF
(c) EUMETSAT (Source: NSPO/UCAR)

-4

FORMOSAT-3
COSMIC
Spec. humidity (1DVar), 10S–10N
– monthly zonal mean anomalies (de-seasonalized) –
2006–2013



ROM SAF
(c) EUMETSAT (Source: NSPO/UCAR)

-15

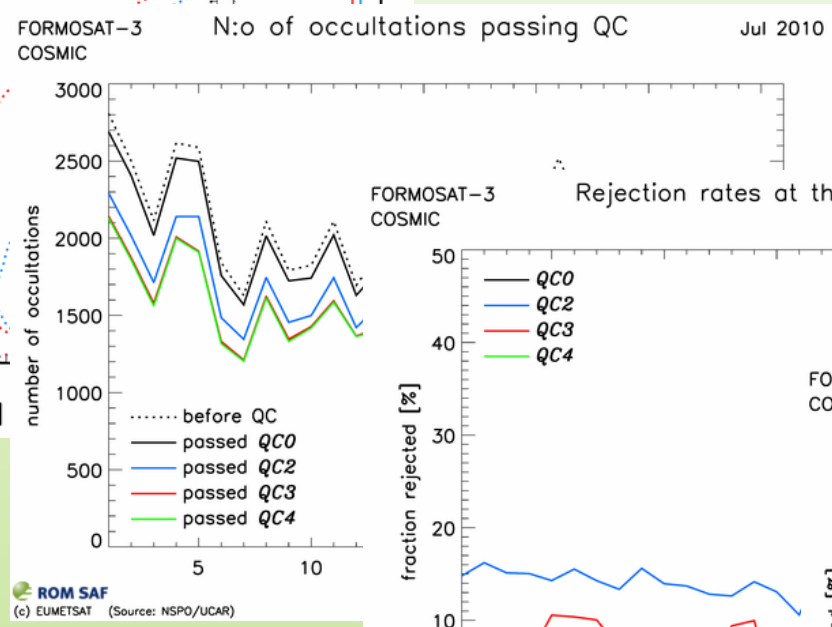
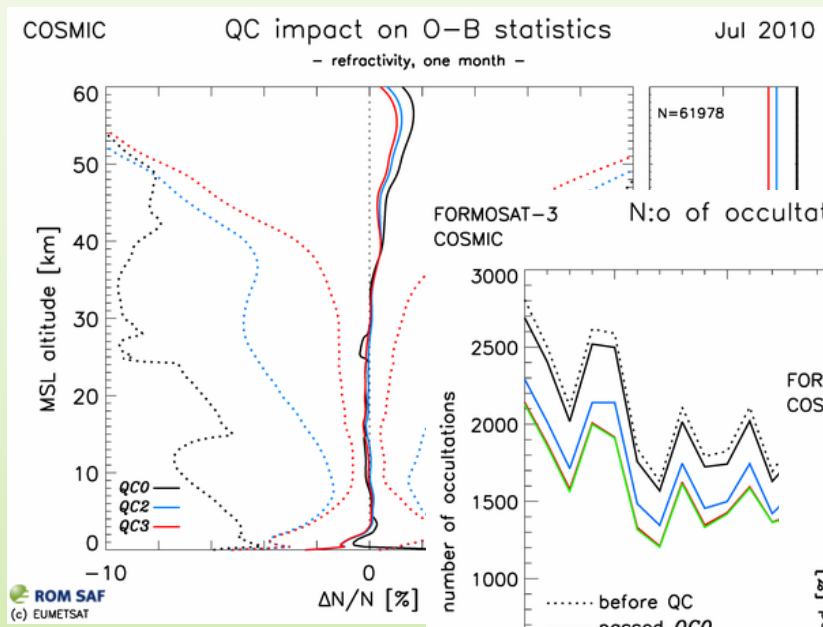
0

15 [%]

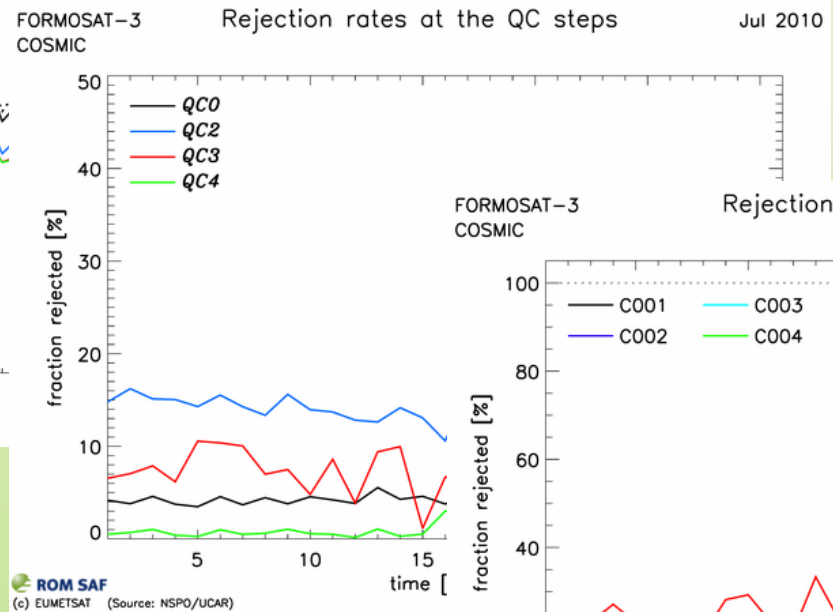
Plotted 14:53
14–Nov–2013

ROM SAF climate data

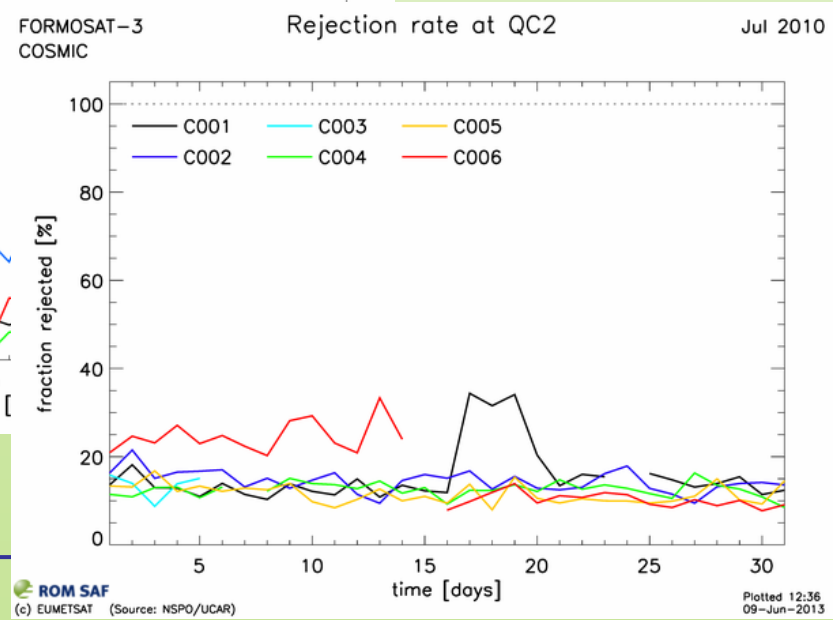
- monitoring of the QC screening on a monthly basis –



... per QC step



... per satellite

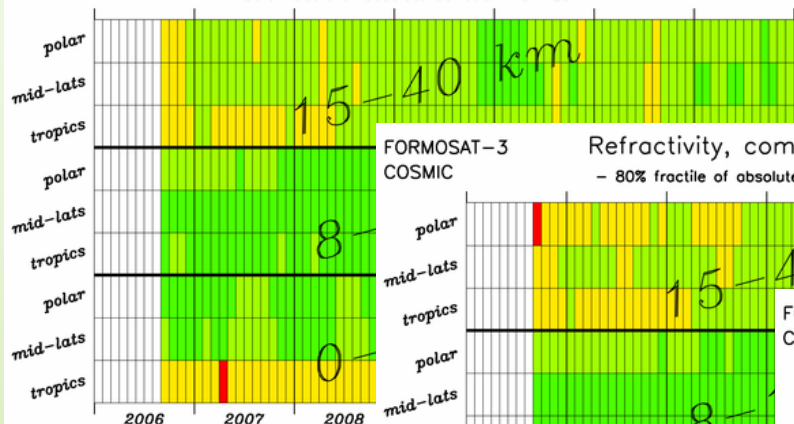


Plotted 12:36 09-Jun-2013

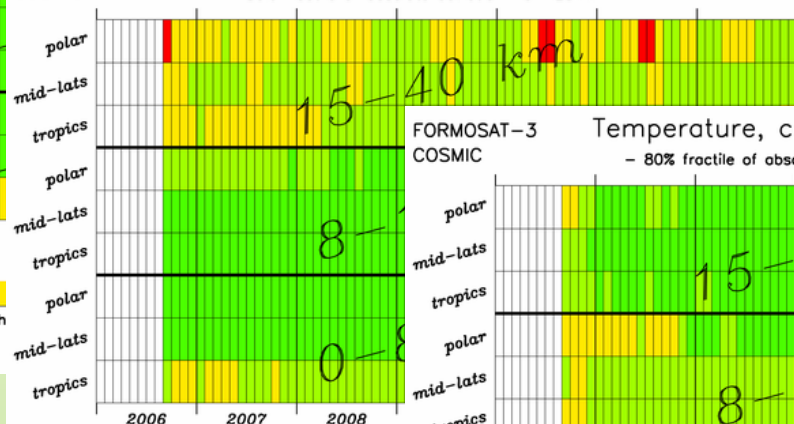
ROM SAF climate data

– validation statistics –

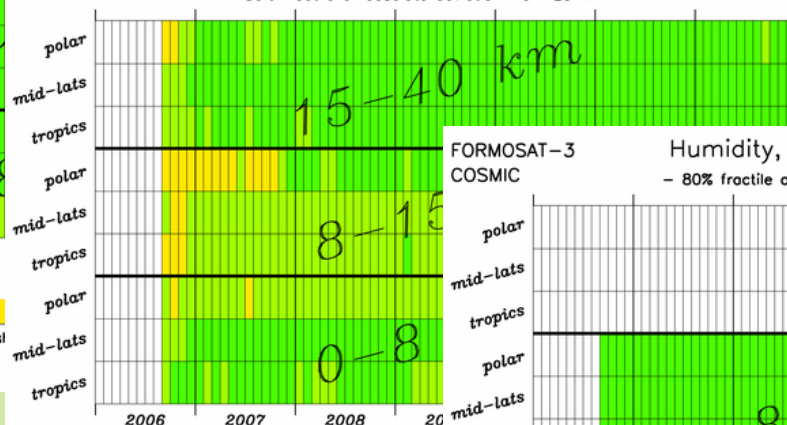
FORMOSAT-3 COSMIC Bending angle, compliance with PRD 2006-2012
 - 80% fractile of absolute deviation from ECMWF -



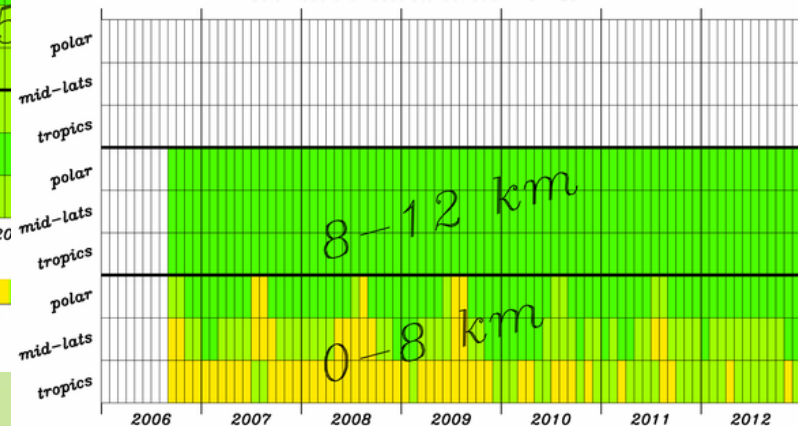
FORMOSAT-3 COSMIC Refractivity, compliance with PRD 2006-2012
 - 80% fractile of absolute deviation from ECMWF -



FORMOSAT-3 COSMIC Temperature, compliance with PRD 2006-2012
 - 80% fractile of absolute deviation from ECMWF -



FORMOSAT-3 COSMIC Humidity, compliance with PRD 2006-2012
 - 80% fractile of absolute deviation from ECMWF -



ROM SAF
 (c) EUMETSAT (Source: NSPO/UCAR)

ROM SAF
 (c) EUMETSAT (Source: NSPO/UCAR)

ROM SAF
 (c) EUMETSAT (Source: NSPO/UCAR)

ROM SAF
 (c) EUMETSAT (Source: NSPO/UCAR)

Plotted 10:13
 26-Aug-2013



Ongoing studies

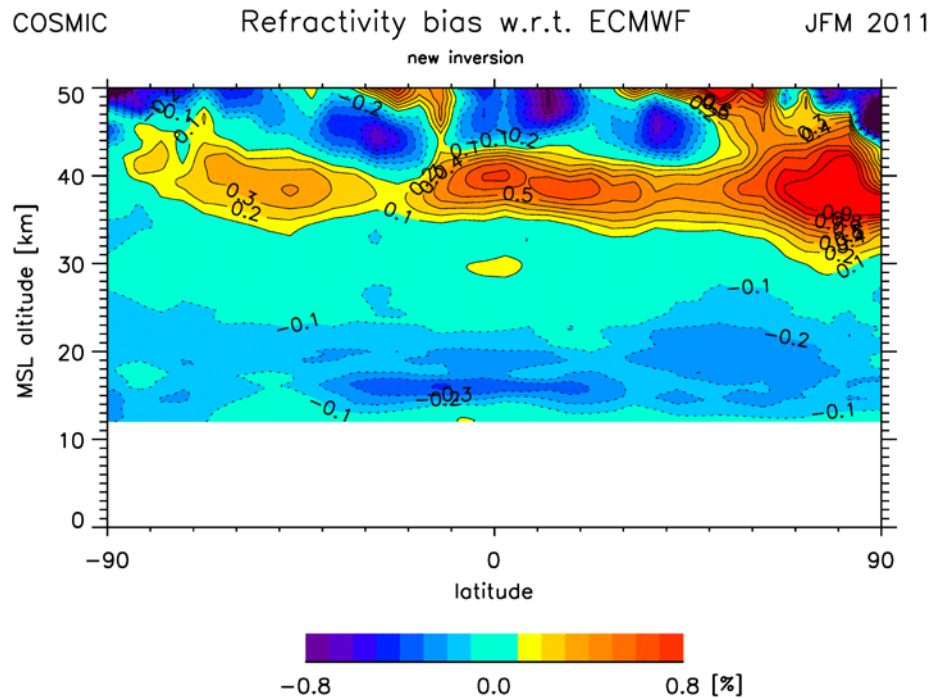
Studies:

- ▶ experiments with climate data generation using *API* inversion
- ▶ monitoring mean tropospheric temperatures using RO dry geopotential
- ▶

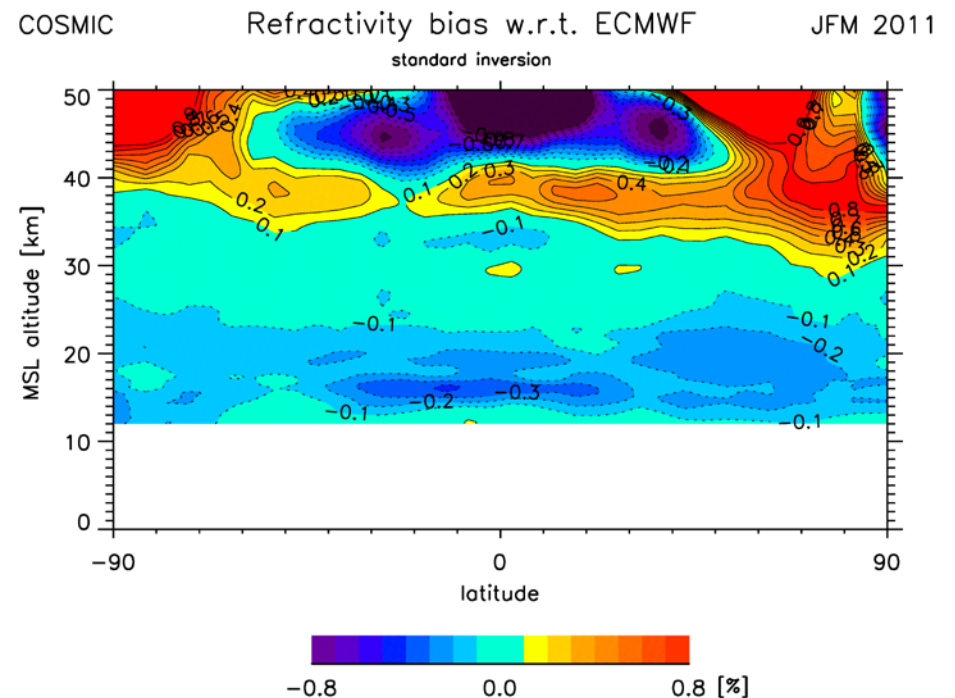
Climate processing using *API*

– COSMIC refractivity relative to ECMWF –

average-profile inversion – bias w.r.t. ECMWF

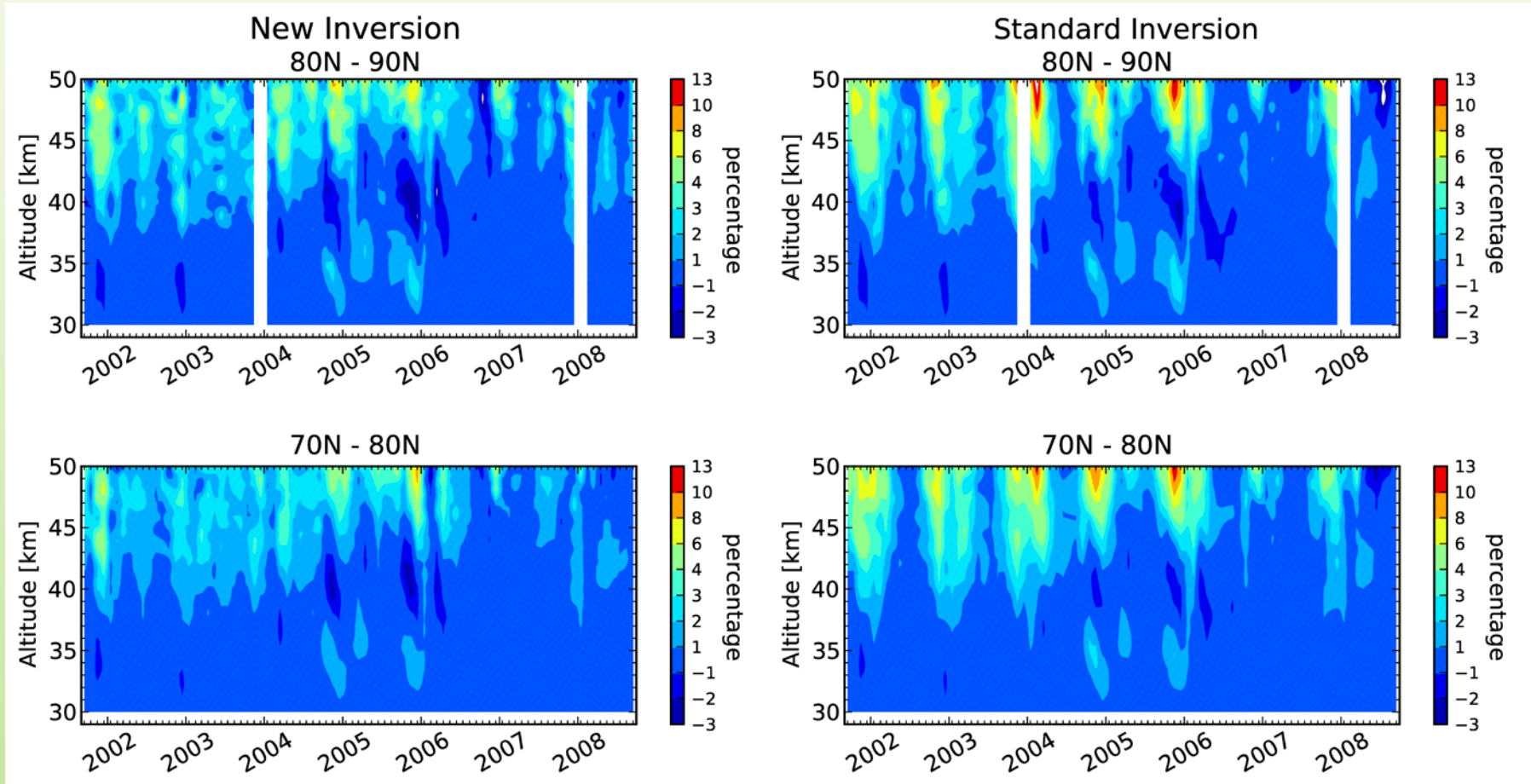


single-profile inversion – bias w.r.t. ECMWF



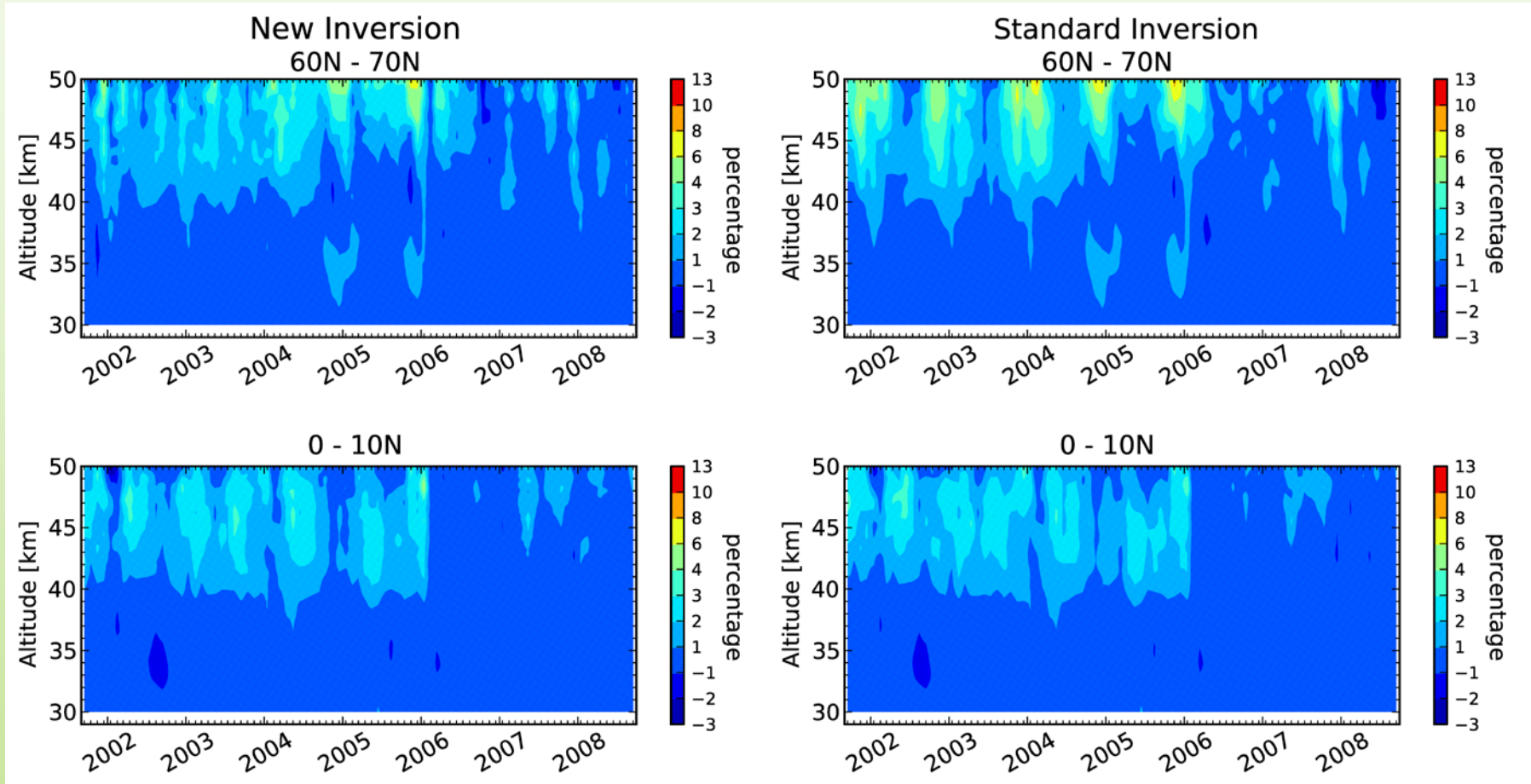
Climate processing using *API*

– CHAMP refractivity relative to ECMWF –



Climate processing using *API*

– CHAMP refractivity relative to ECMWF –



Monitoring mean tropospheric temperature

Integration of hydrostatic equation from pressure p down to surface:

$$\frac{dp}{dz} = -\frac{pg_0}{RT}$$
$$z(p) - z_s = \int_p^{p_s} \frac{RT(p')}{g_0} d\ln p'$$

observed dry geopotential

The gas constant, R , changes slightly with water vapour. Rewriting in terms of universal gas constant (R^*) and molar mass (μ_d) gives

$$z(p) - z_s = \frac{R^*}{\mu_d g_0} \int_p^{p_s} \frac{T(p')}{\left(1 - \frac{e}{p}(1 - \epsilon)\right)} d\ln p'$$

Geopotential height measures mean (virtual) temperature from the surface up to the given pressure level, approximately volume-weighted.

Monitoring mean tropospheric temperature

$$z(p) - z_s = \frac{R^* \overline{T}_v}{\mu_d g_0} \cdot \ln \frac{p}{p_s} \quad \text{where} \quad \overline{T}_v = \frac{\int_p^{p_s} T_v(p) d \ln p}{\int_p^{p_s} d \ln p}$$

=> 1 K mean temperature change raises the 300 hPa isobar by 36 meters

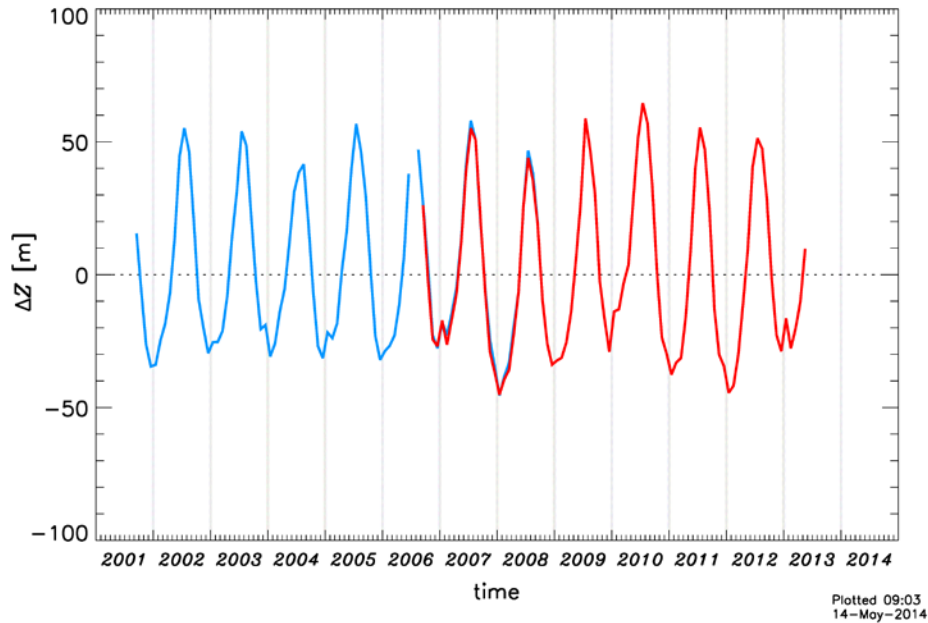
Assumptions made:

- ▶ dry atmosphere down to the selected isobar
- ▶ mean *virtual* temperature instead of mean temperature
- ▶ surface pressure do not change on spatial/temporal scales considered

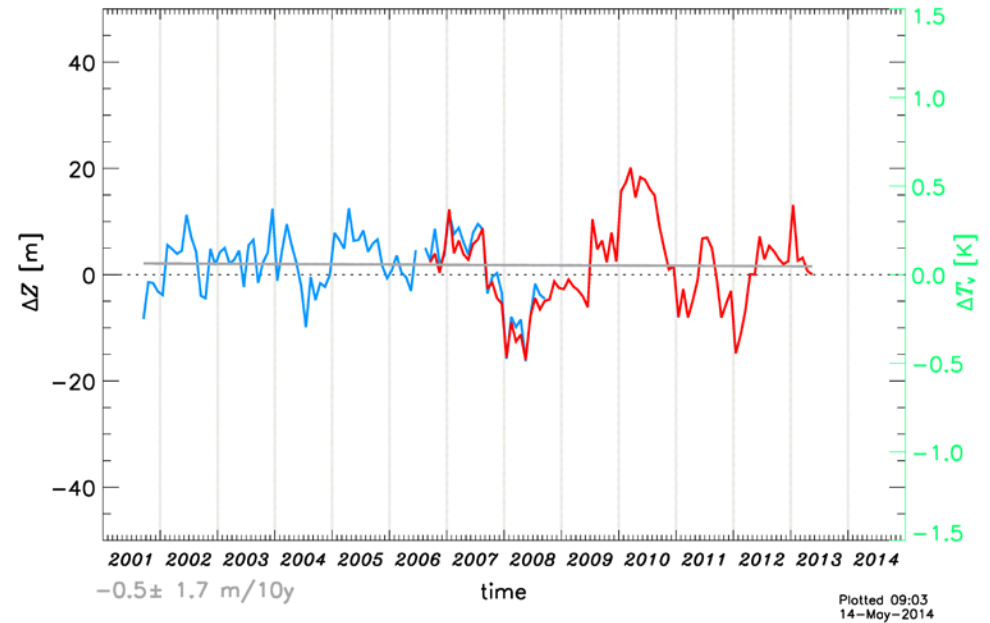
Monitoring mean tropospheric temperature

- 300 hPa geopotential, CHAMP/COSMIC, global -

CHAMP & COSMIC Geopotential height, 90S–90N, 300 hPa 2001–2013
- monthly mean anomalies -

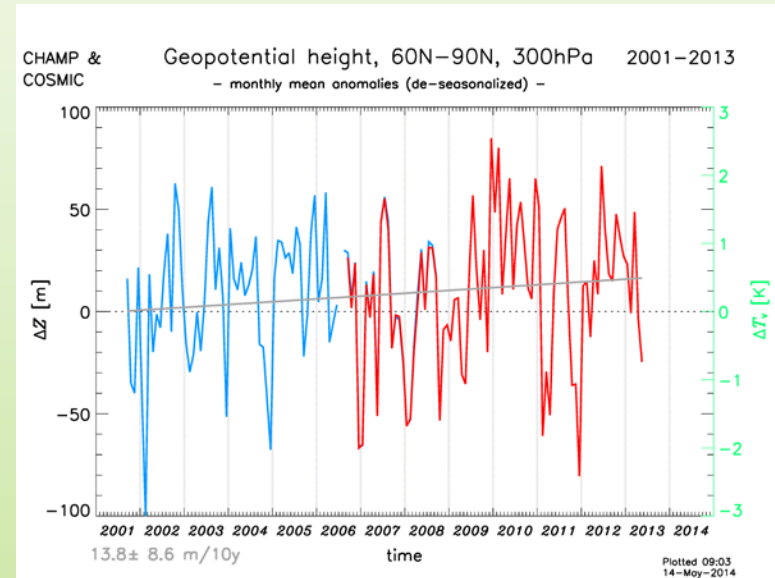
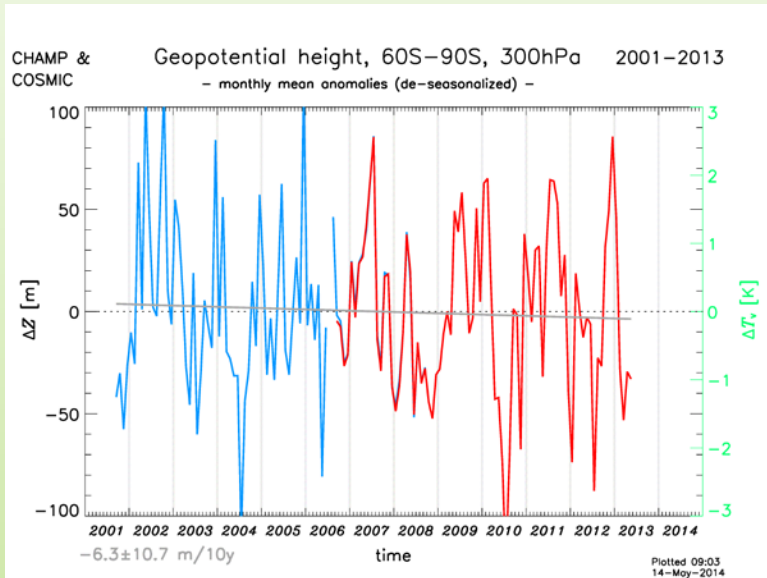


CHAMP & COSMIC Geopotential height, 90S–90N, 300hPa 2001–2013
- monthly mean anomalies (de-seasonalized) -



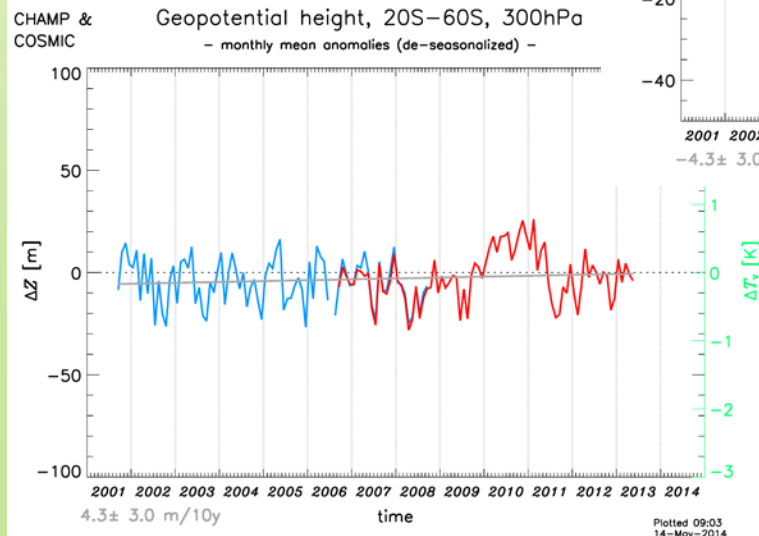
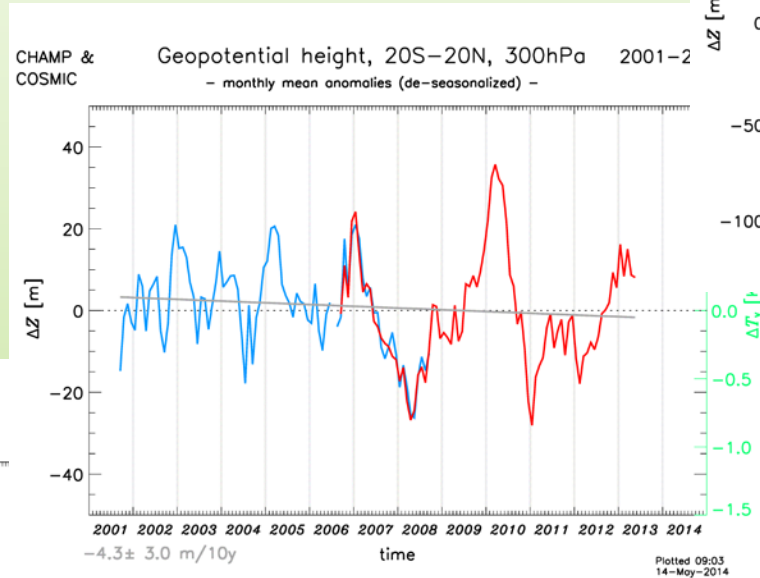
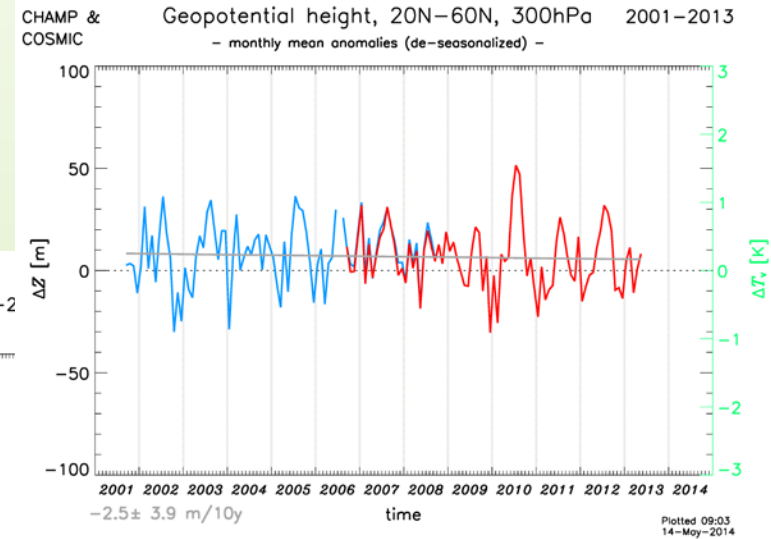
Monitoring mean tropospheric temperature

- 300 hPa geopotential, CHAMP/COSMIC, high latitudes –



Monitoring mean tropospheric temperature

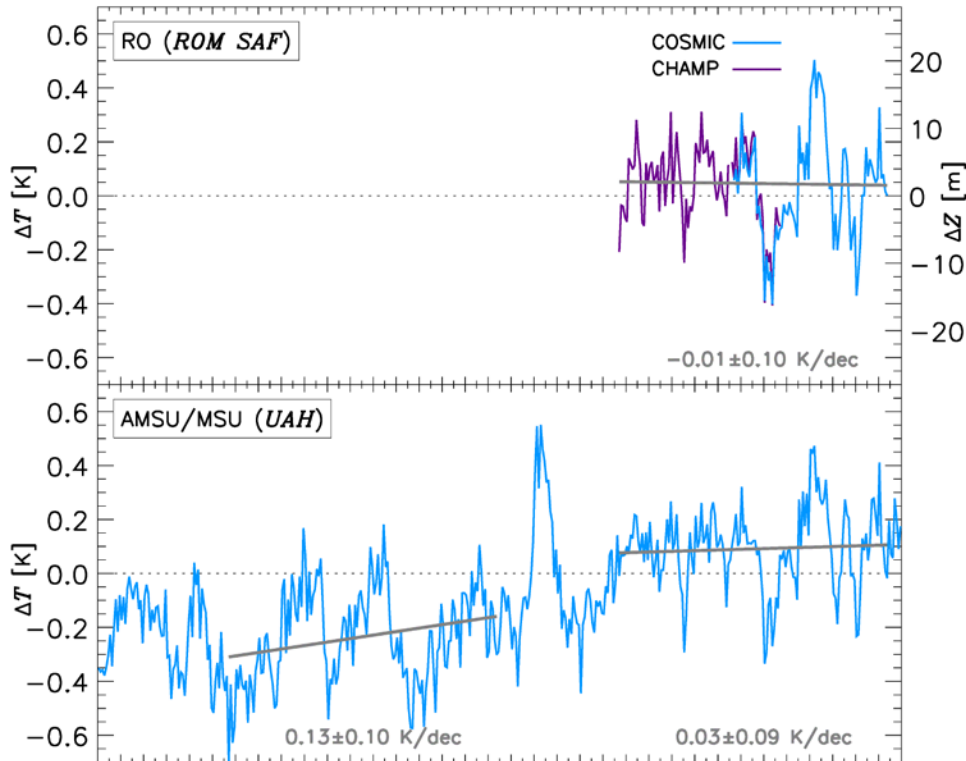
- 300 hPa geopotential, CHAMP/COSMIC, equatorial & midlats -



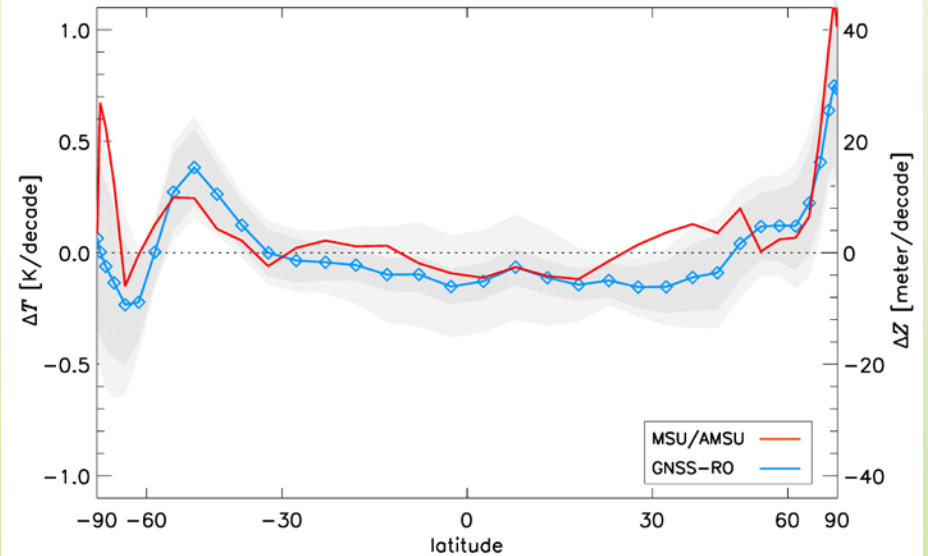
Monitoring mean tropospheric temperature

– RO and MSU/AMSU –

Global mean temperature records
– monthly mean anomalies –



Zonal mean troposphere temperature trends
2001–2013



STOP

—

The EUMETSAT
Network of
Satellite
Application
Facilities



ROM SAF
Radio Occultation Meteorology

Monitoring mean tropospheric temperature

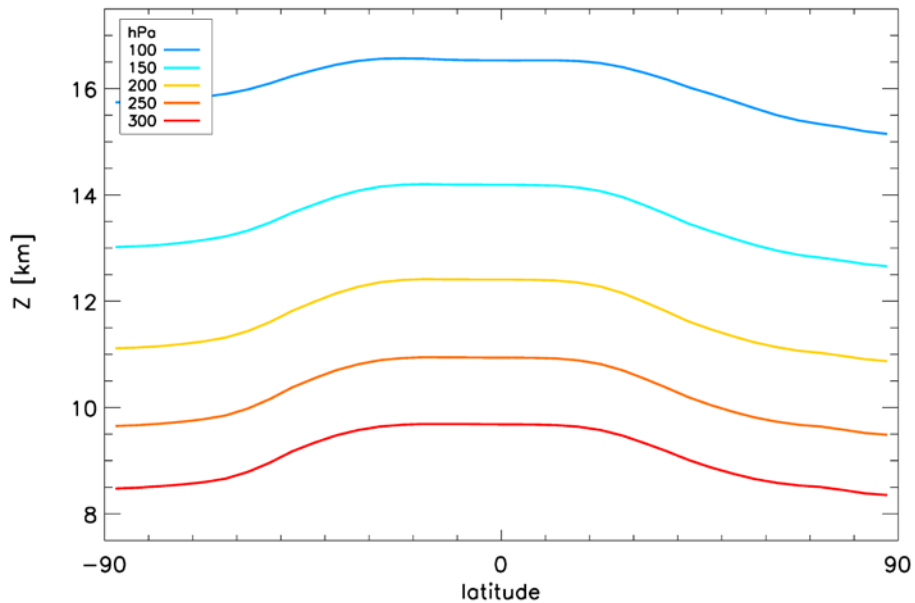
- ▶ COSMIC & CHAMP agree fairly well during overlap period
- ▶ sampling error correction required to combine missions
- ▶ CHAMP/COSMIC differences near equator – oscillations in CHAMP?
- ▶ dry geopotential at 300 hPa: what errors do we make?
- ▶ NCEP reanalysis agrees well with COSMIC, less well with CHAMP

- ▶ RO 300 hPa trend 2001-2013 only significant at high northern lats
- ▶ MSU *TLT* trends 2001-2013 agrees well with RO 300 hPa trends

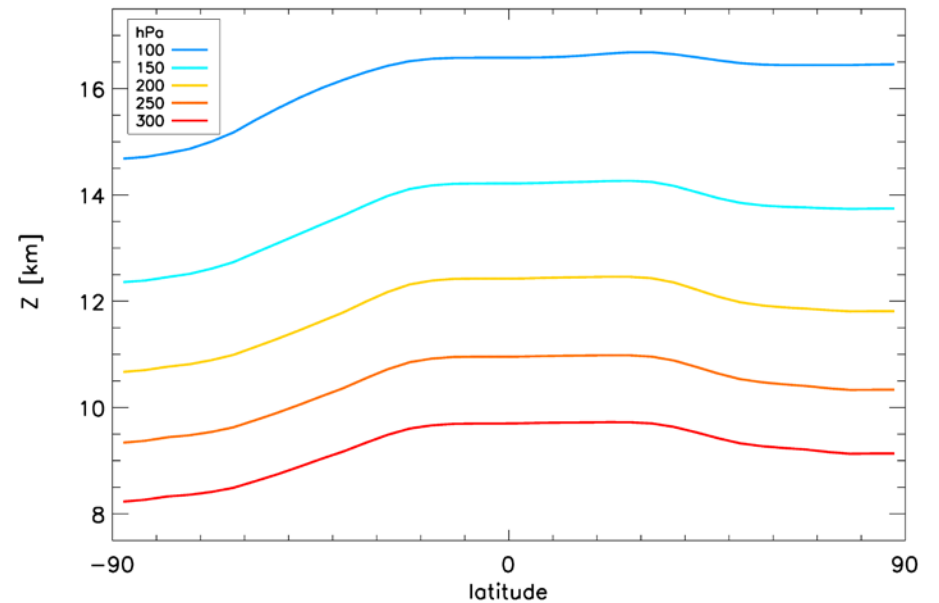
Monitoring mean tropospheric temperature

– geopotential of isobars, Jan/July 2009 –

FORMOSAT-3
COSMIC
Geopotential height
– zonal monthly mean –
Jan 2009



FORMOSAT-3
COSMIC
Geopotential height
– zonal monthly mean –
Jul 2009



Monitoring mean tropospheric temperature

- 300 hPa geopotential, observed RO and ERA-Interim –

