GENERATION OF GPS-RO CLIMATE DATA AT THE ROM SAF

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&
ROM SAF

The EUMETSAT Network of Satellite Application Facilities

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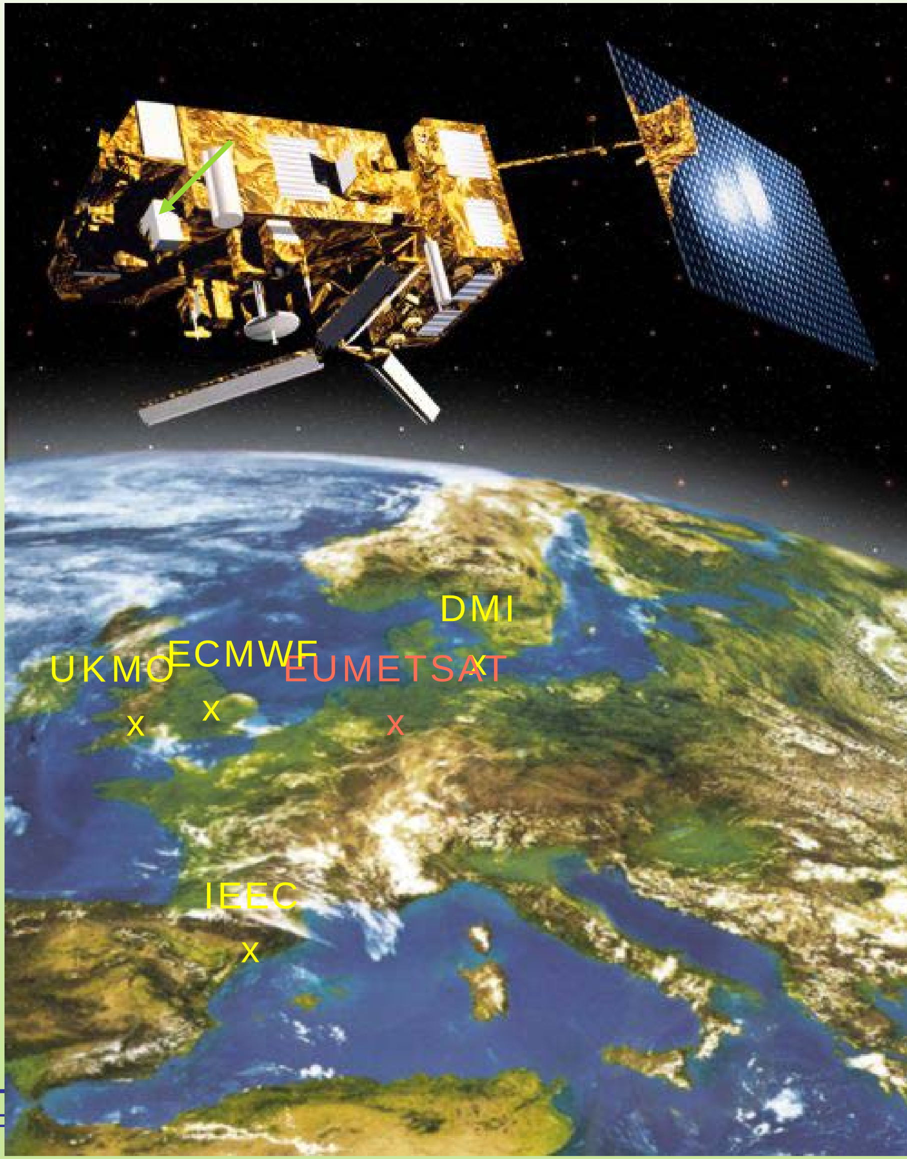
Outline

- 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,
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ECMWF (Reading, UK)

Sean Healy

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Estel Cardellach, Santi Oliveras

Met Office (Exeter, UK)

Ian Culverwell, Chris Burrows, Dave Offiler

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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, ...);

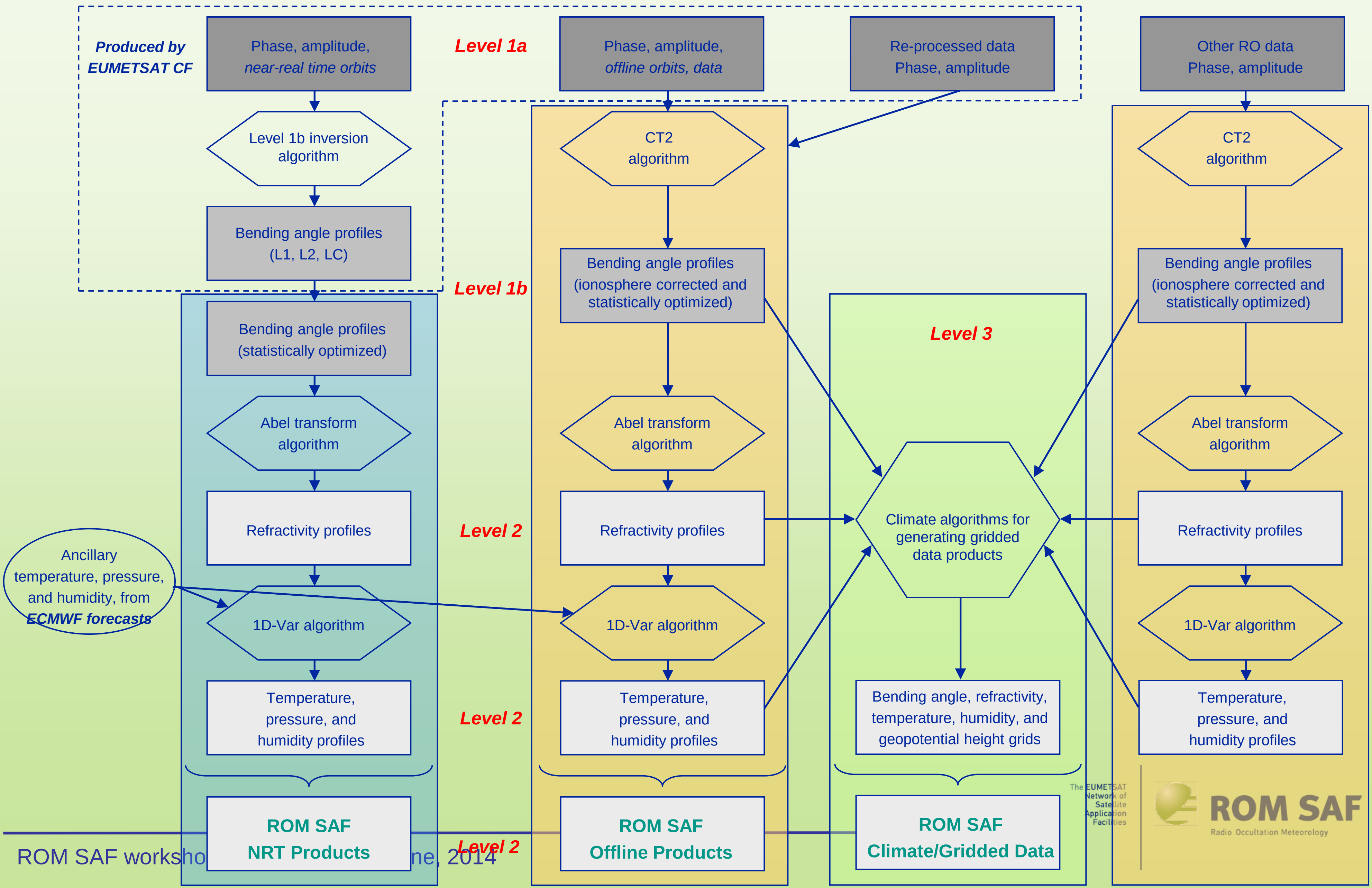
Offline RO data products

- 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*

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

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*

$$\boldsymbol{\alpha} = \boldsymbol{\alpha}_b + \mathbf{K}(\boldsymbol{\alpha}_{LC} - \boldsymbol{\alpha}_b)$$

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

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

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

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

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

$$N^m(H) = \ldots \textbf{\textit{stat. analysis}}$$
$$p^m(H) = \ldots \textbf{\textit{stat. analysis}}$$
$$T^m(H) = \ldots \textbf{\textit{stat. analysis}}$$

use of *a priori*

Average-profile inversion

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

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

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

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

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

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

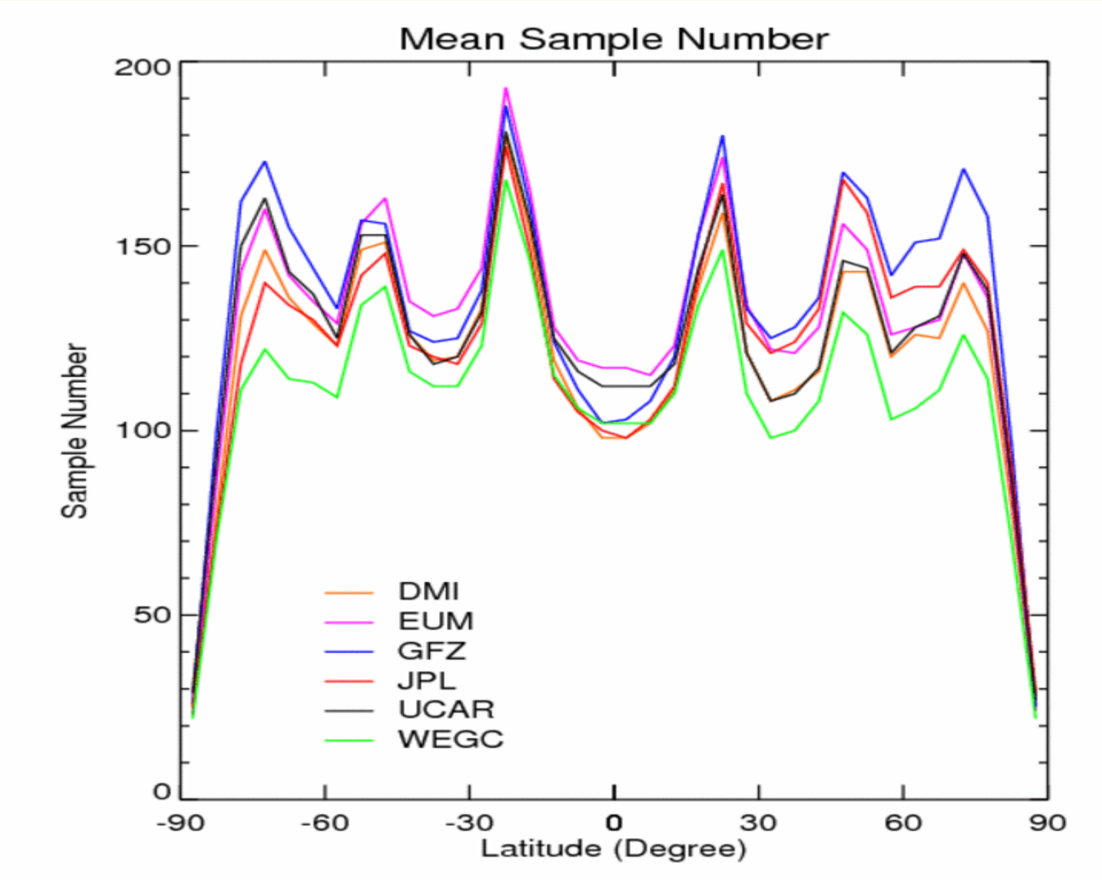
Climate processing: QC

– 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

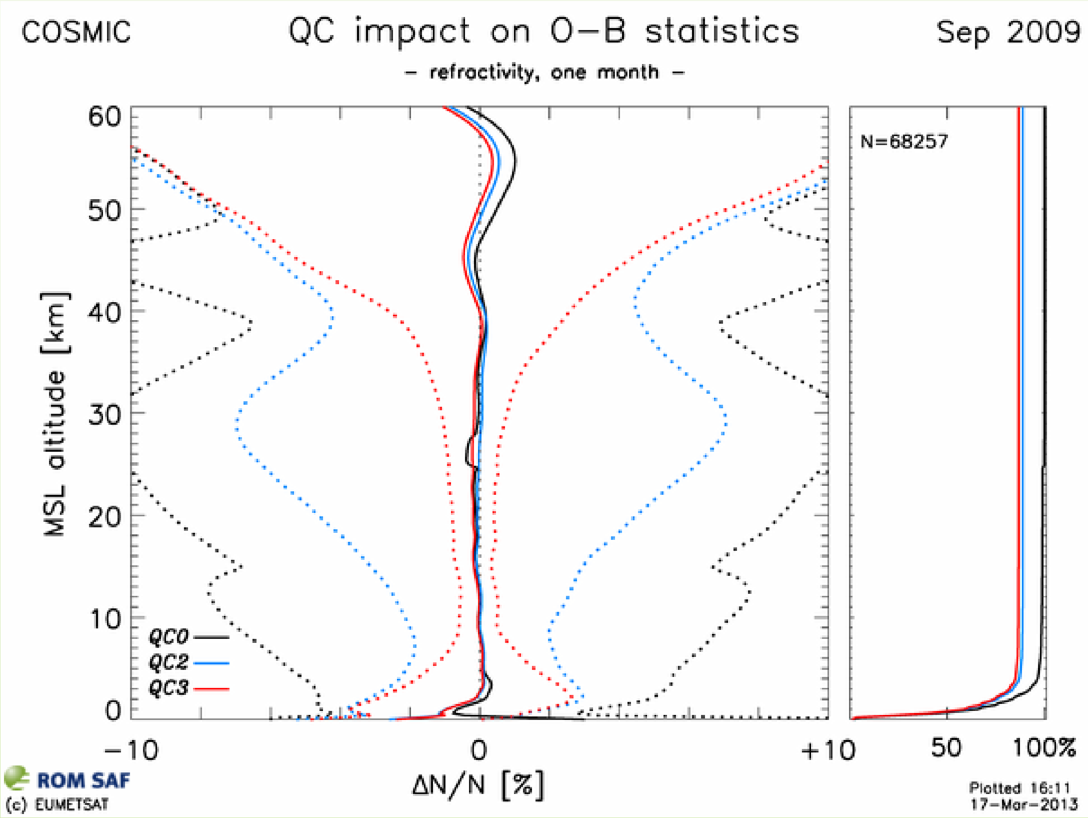


Mean monthly CHAMP data number per 5 degree latitude bin. From Ho et al., JGR, 2012.

Climate processing: QC

– ROM SAF QC screening –

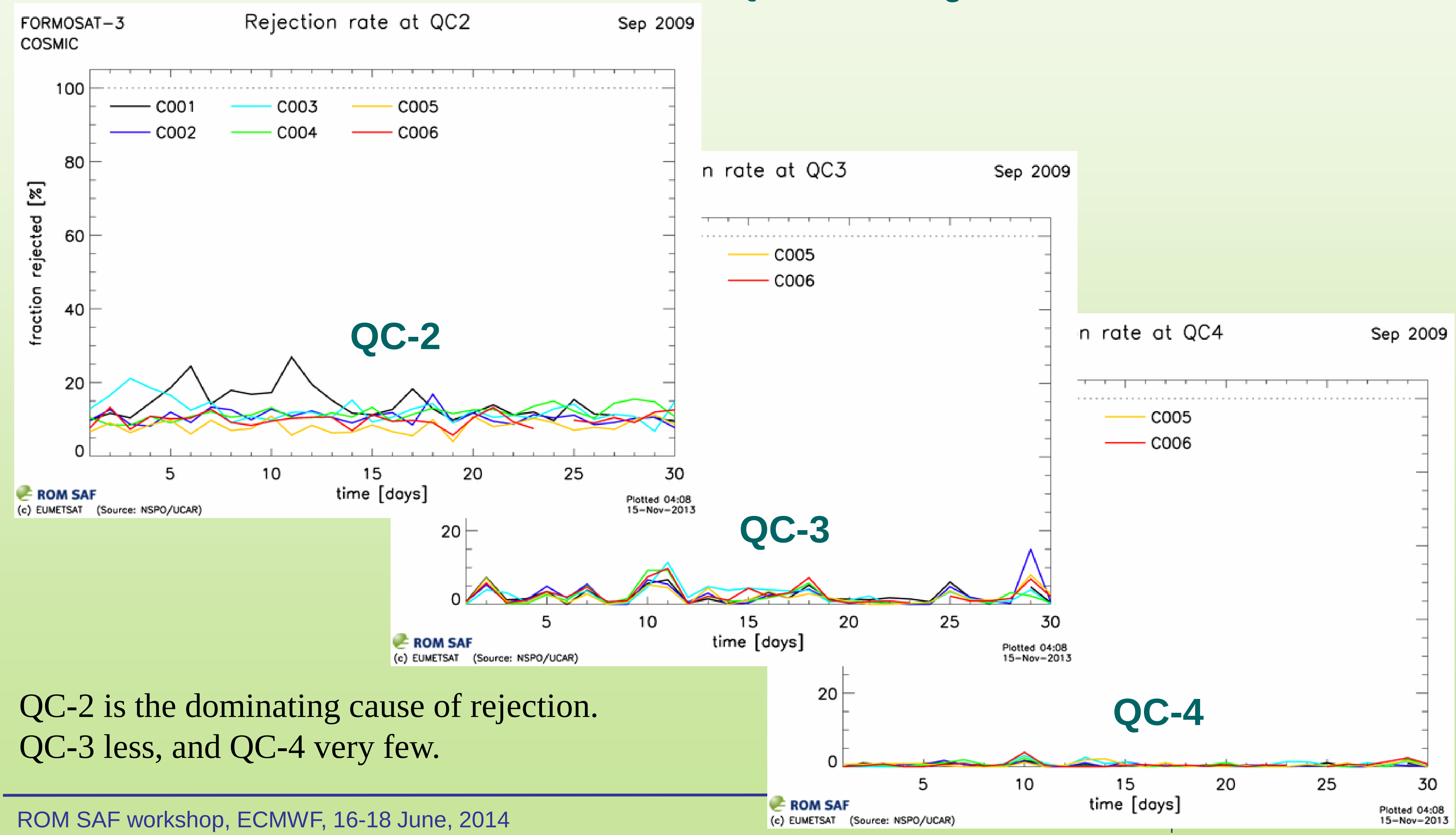
QC0: basic sanity check
This screening step removes occultations with too few useful data points, and/or invalid data points.
– $\alpha(H_a)$ must reach below 30 km and above 60 km – $\alpha(H_a)$ must contain more than 100 valid data points – the impact altitude series H_a must be monotonous – all $\alpha(H_a)$ 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 $2J/N_{obs}$ must be smaller than 5.0 at convergence



Standard deviations strongly affected by the QC.

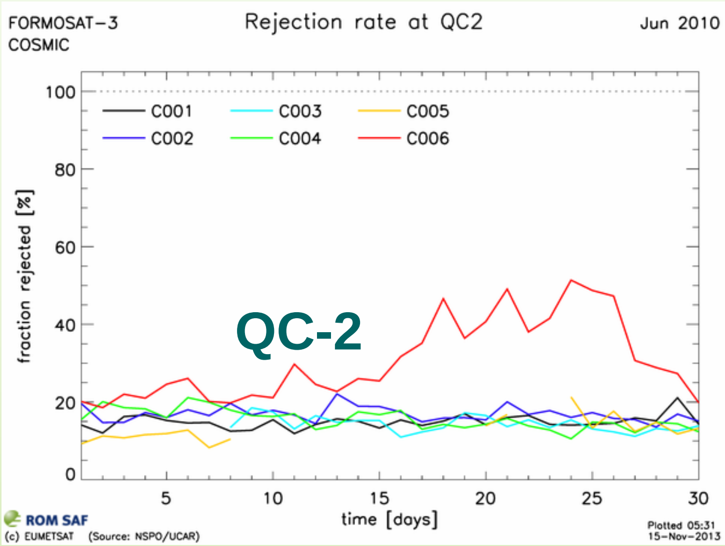
Climate processing: QC

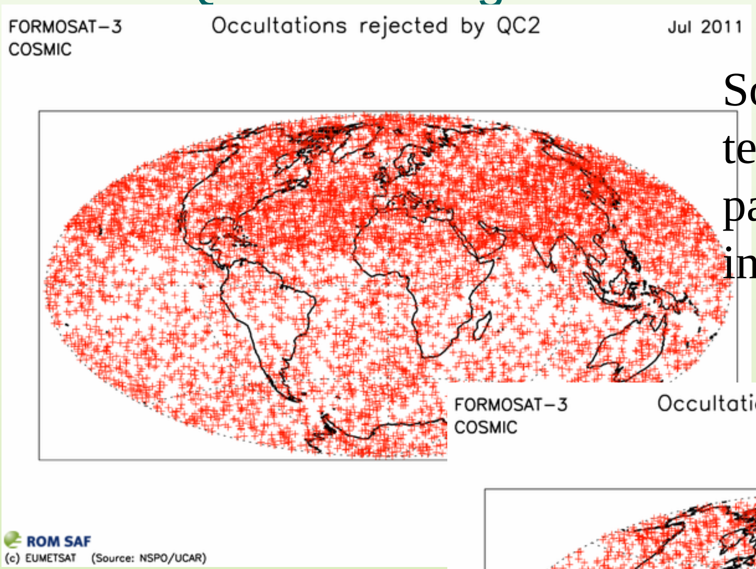
– ROM SAF QC screening –



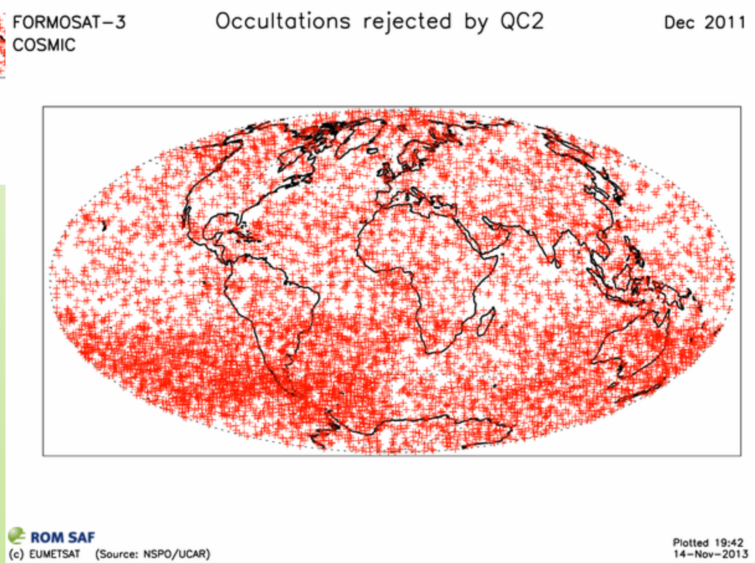
QC-2 is the dominating cause of rejection.
QC-3 less, and QC-4 very few.

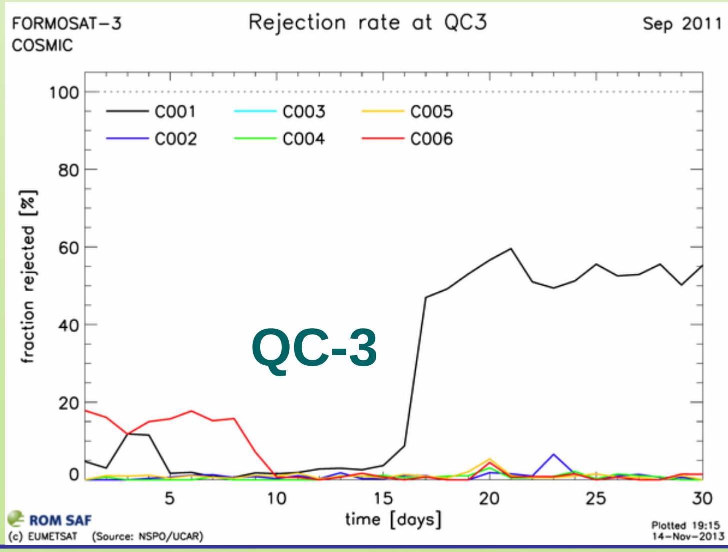
Climate processing: QC
– ROM SAF QC screening –





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.

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.

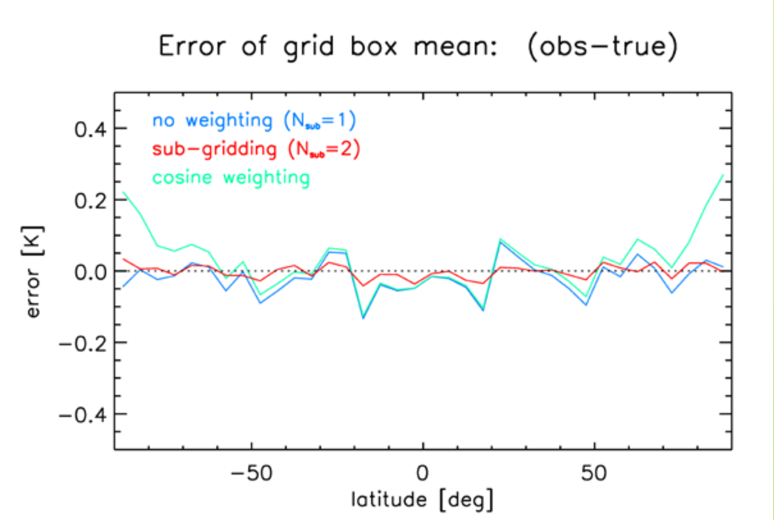
Alternative averaging: global fit of spherical harmonics to the data [e.g., Leroy, XXXX].

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.

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

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

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



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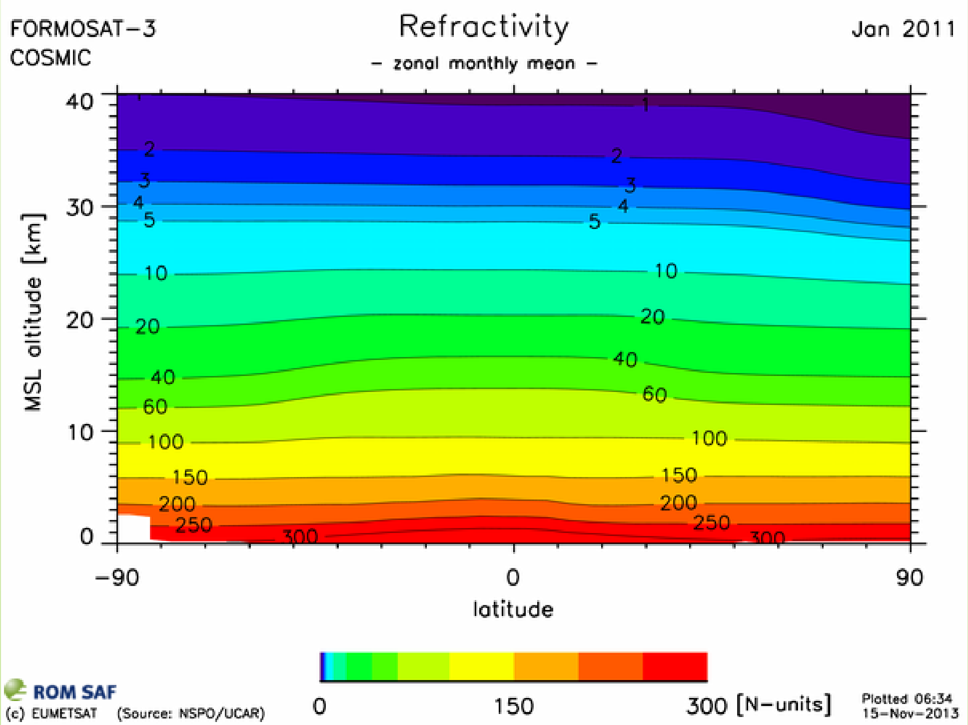
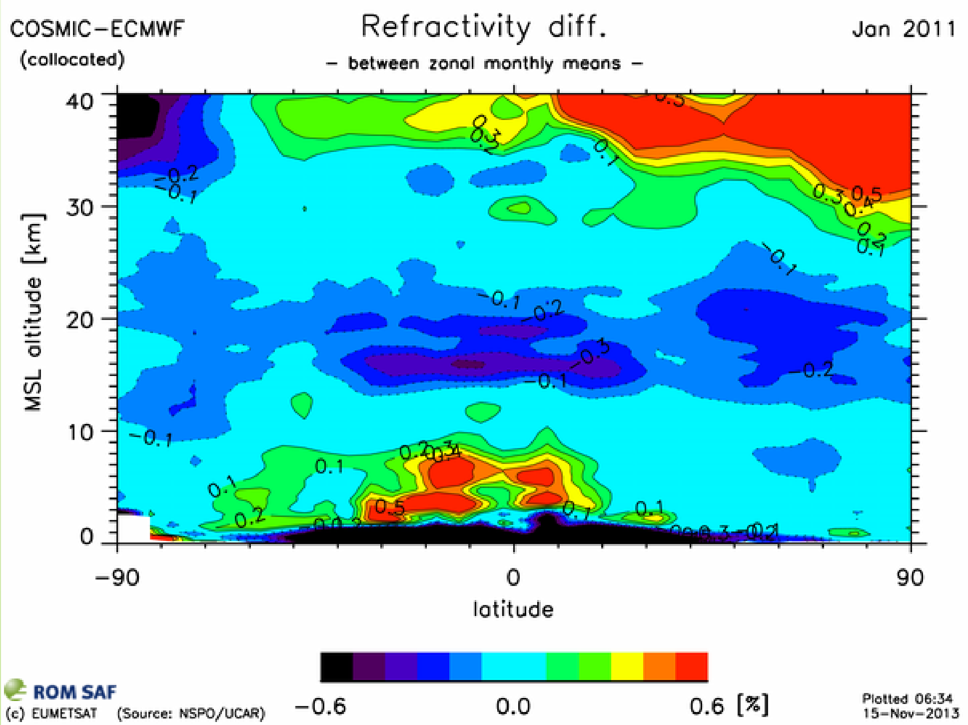
Climate processing: averaging

– binning and averaging –

COSMIC monthly mean refractivity



COSMIC, biases relative to ECMWF



Climate processing: error estimates

– observational errors –

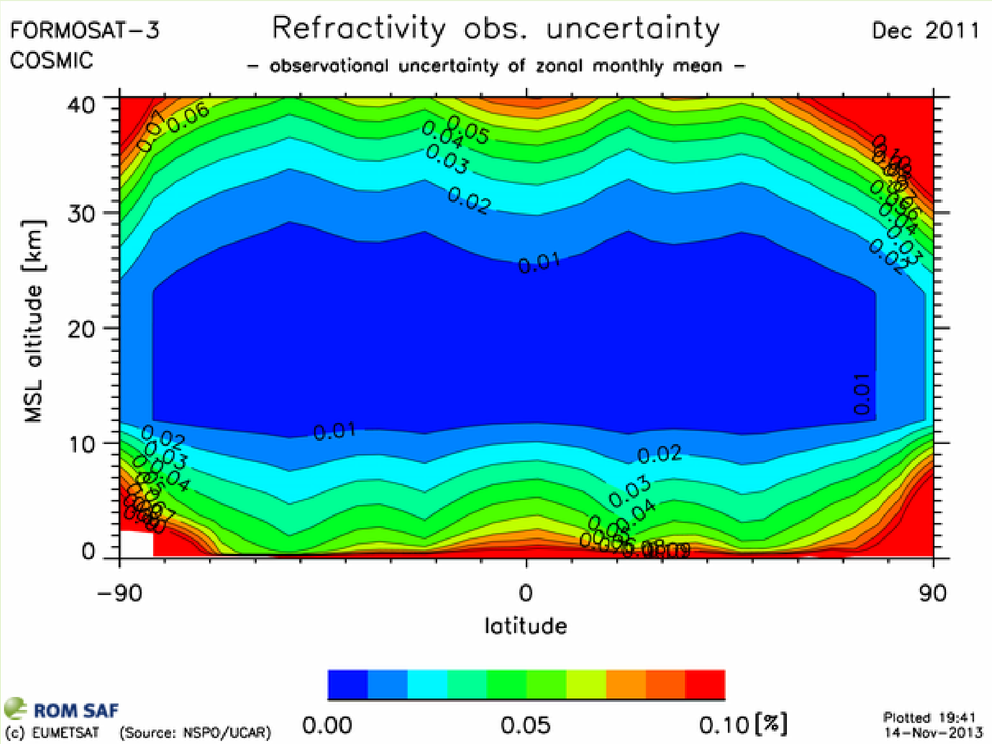
Observational error of the mean is obtained from the assumed observational errors for the profiles. Random – can only be described by an uncertainty.

Weighted computation of errors.

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

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

$$\sigma^2_{obs} = \frac{1}{A_S + A_N}\left(A_S\sigma^2_{S,obs} + A_N\sigma^2_{N,obs}\right)$$



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Climate processing: error estimates
– sampling errors –

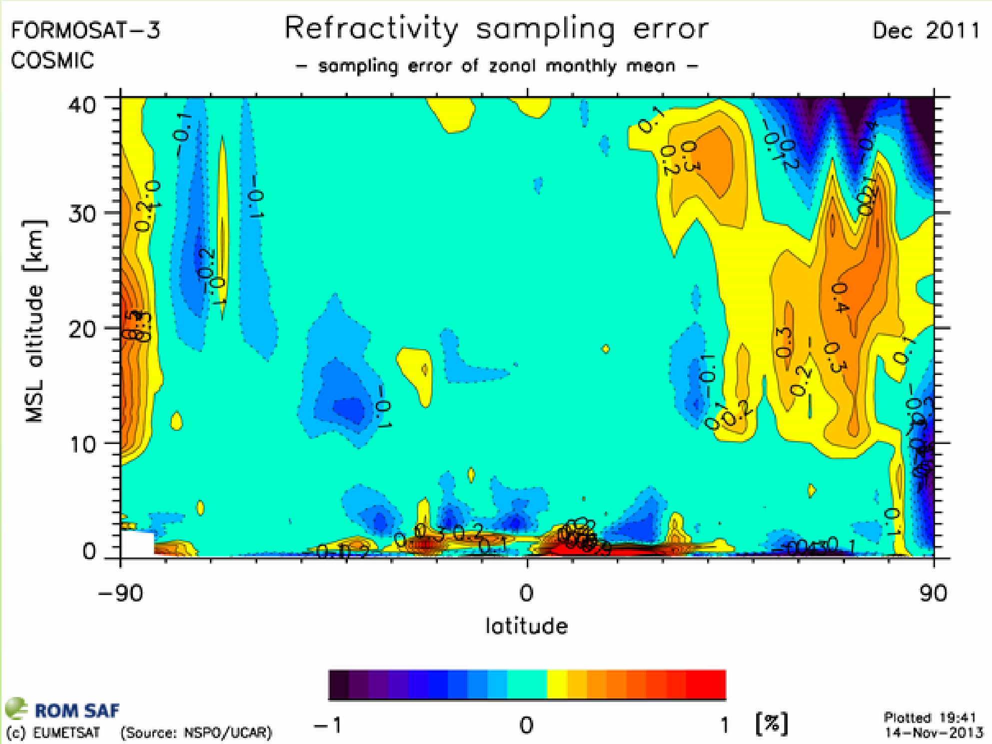
Sampling error of the mean is obtained from sampling a model at the nominal time and location of the observations.

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

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 etal, 2011].

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



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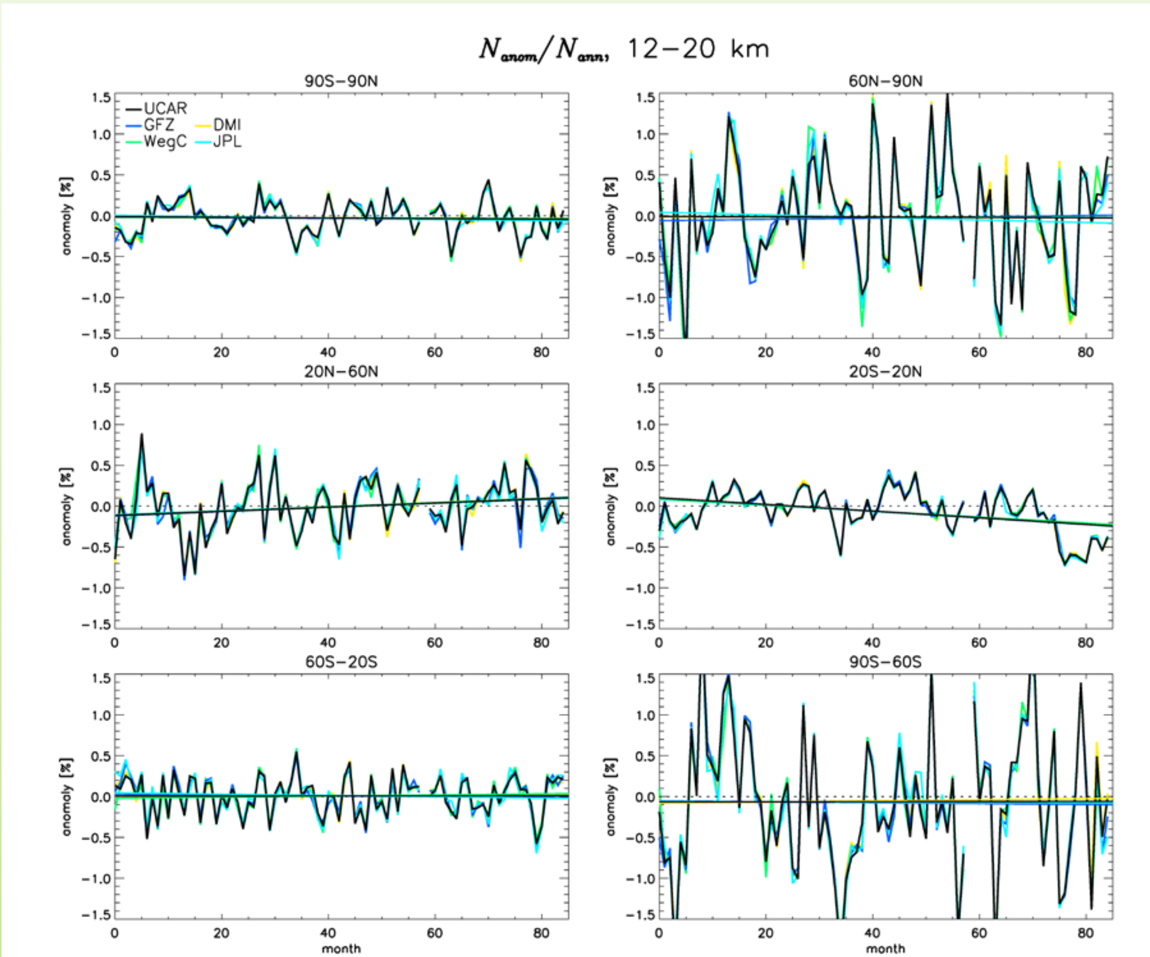
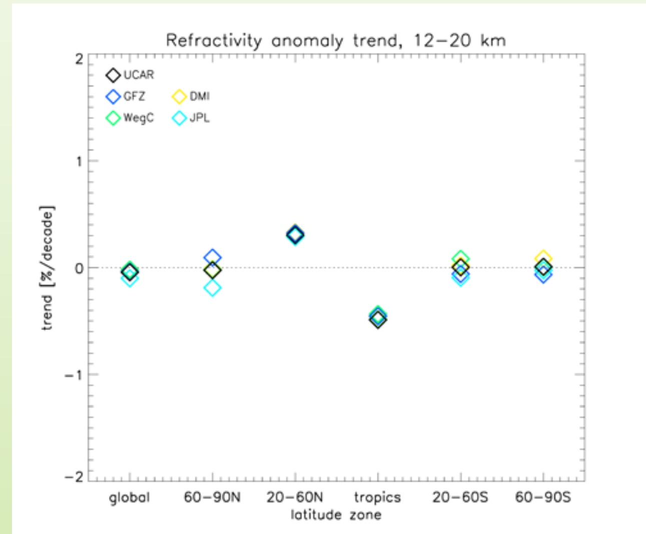
Climate processing: error estimates

– 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.

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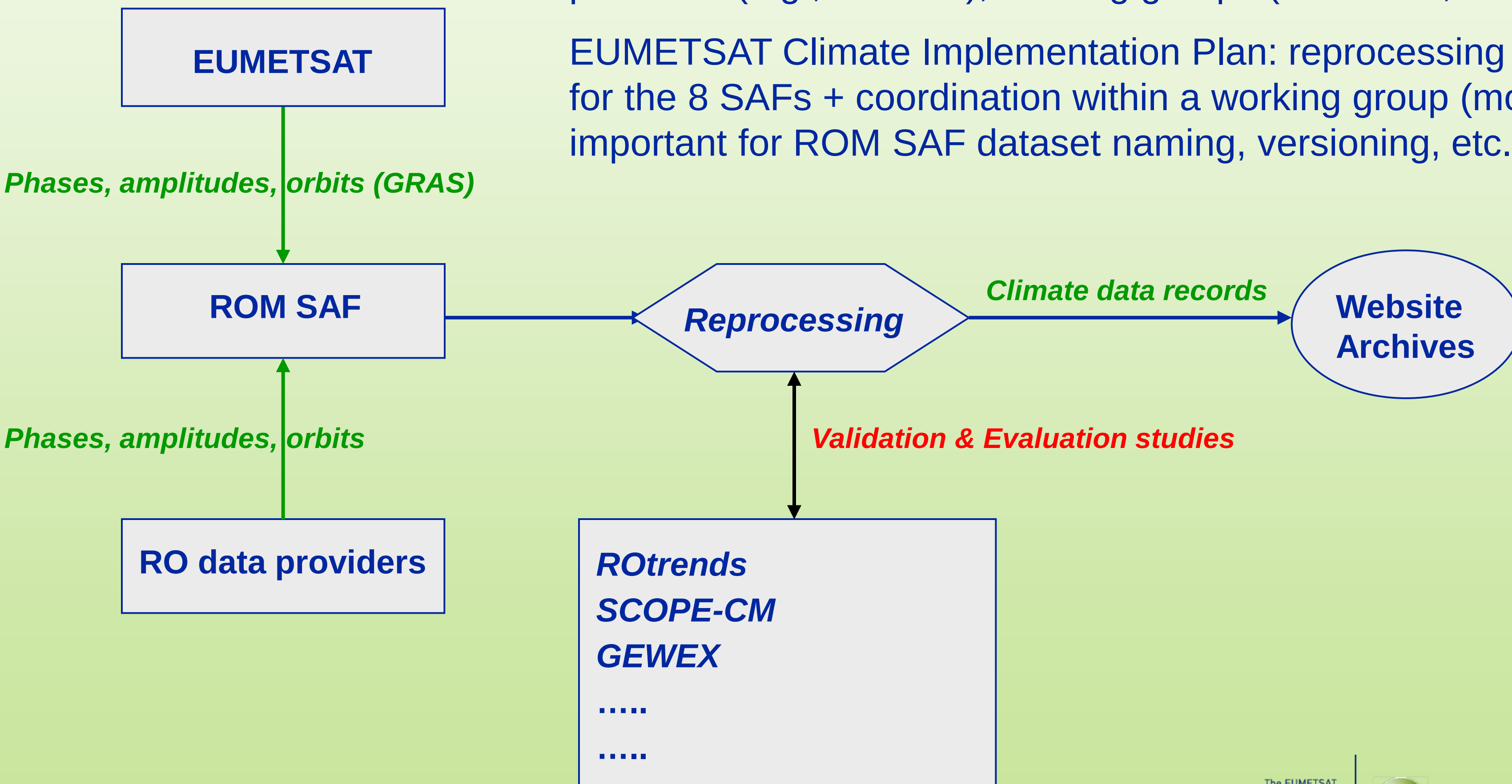
Climate data through reprocessing

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.)



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ROM SAF climate data

– climate monitoring & data provision –

Access to:

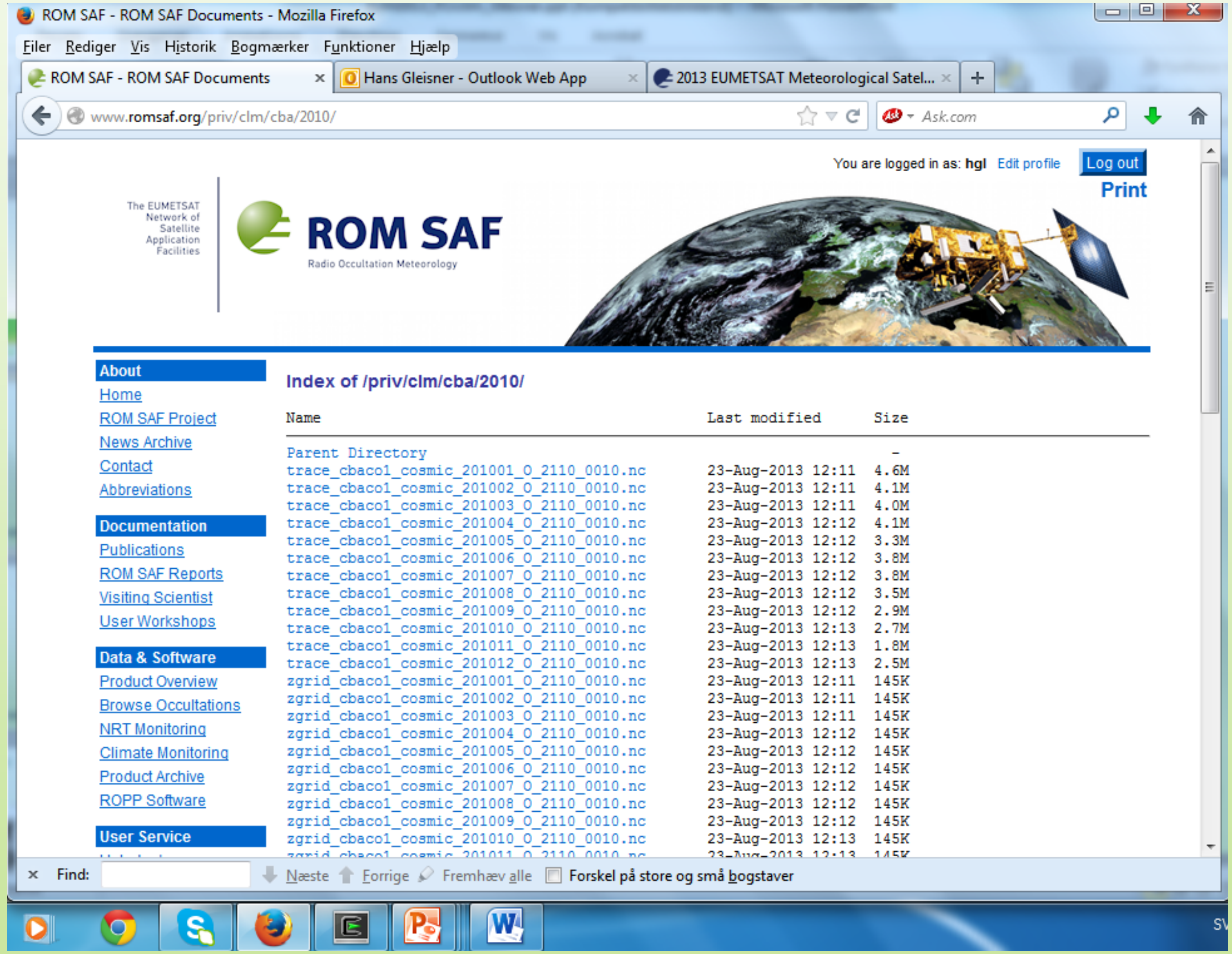
- Documentation
- Monitoring plots
- Data
- Software

ROM SAF climate data

– data availability at ROM SAF product archive –

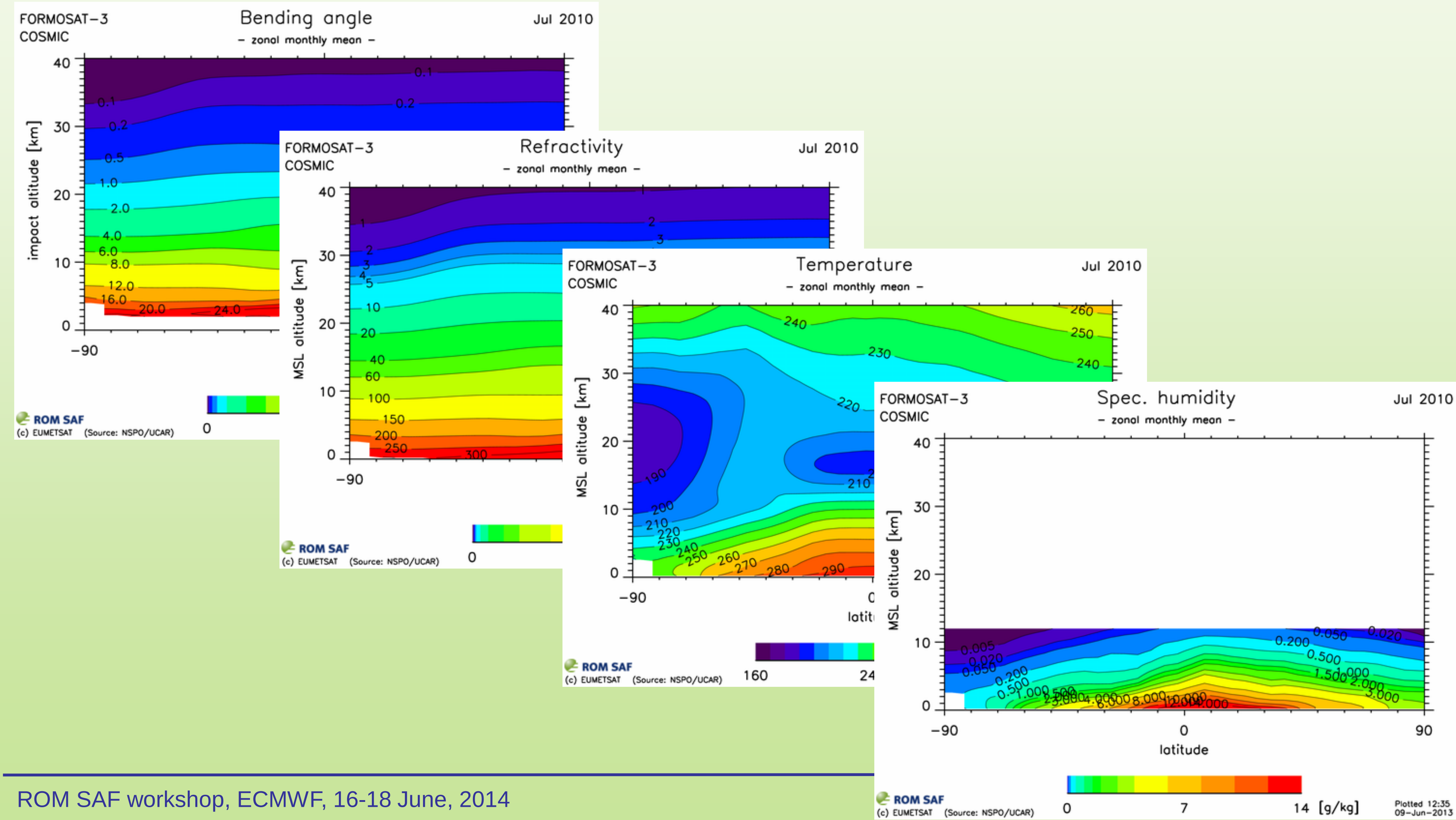
Data products:

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



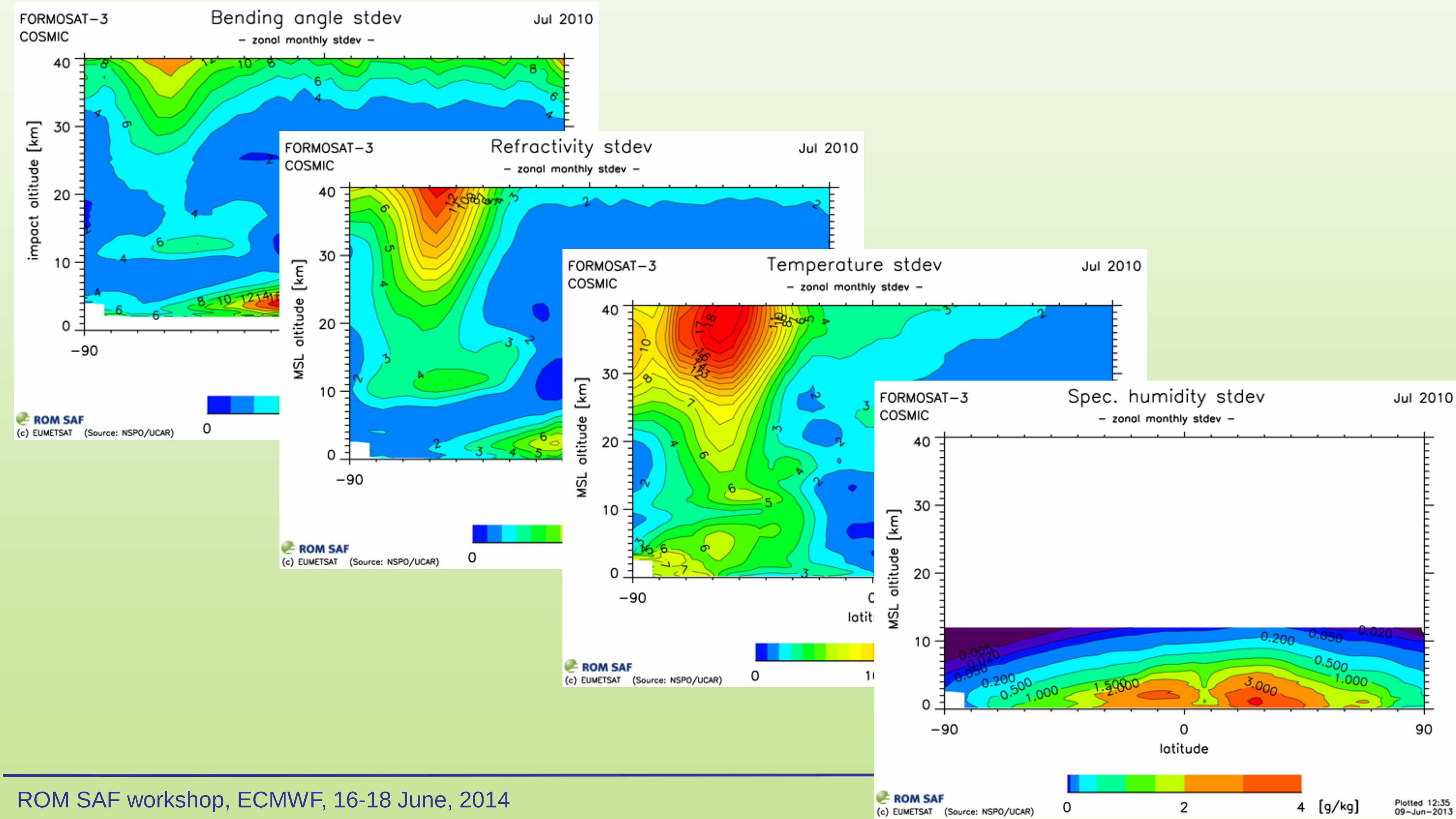
ROM SAF climate data

– zonal monthly means –



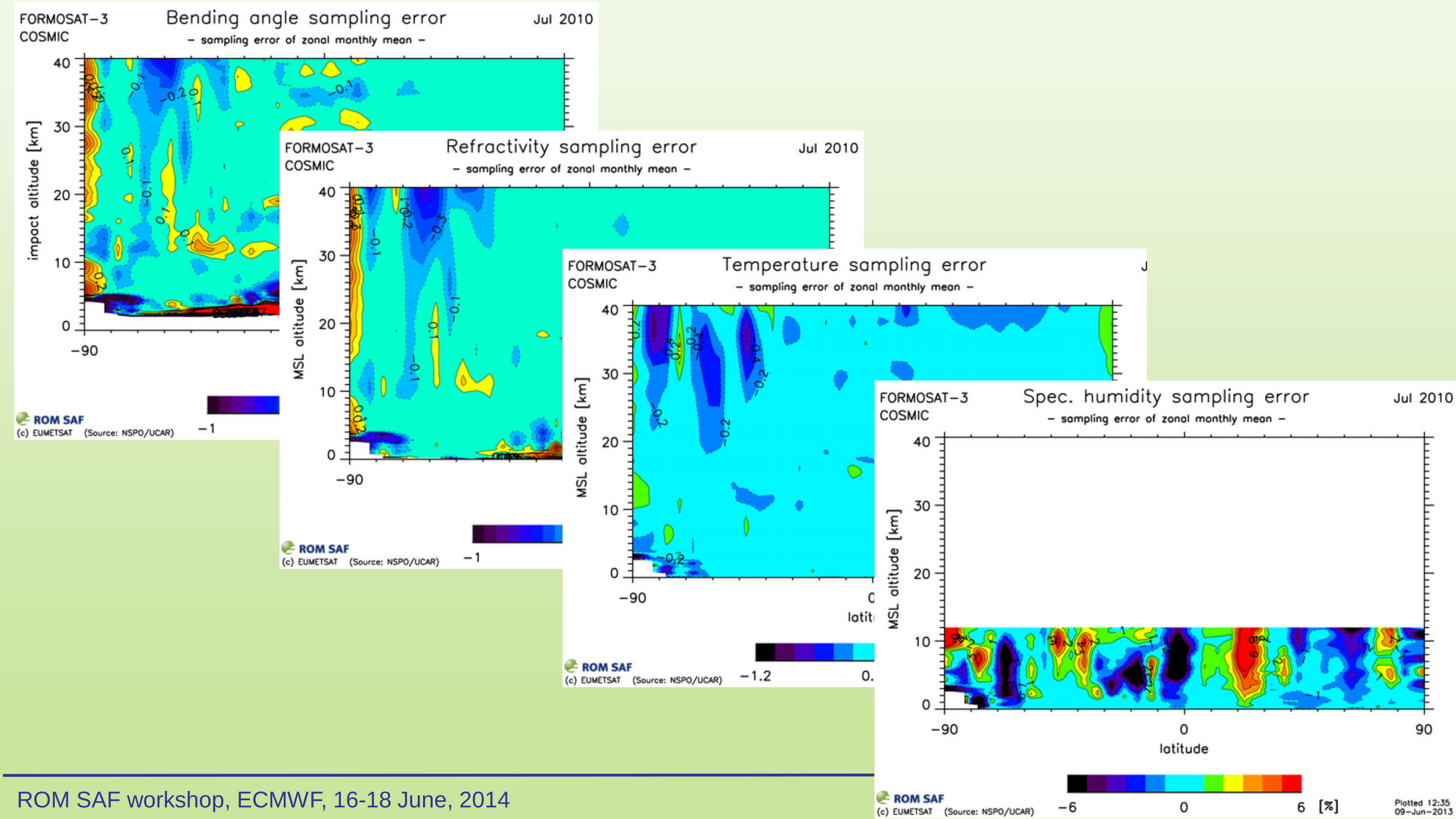
ROM SAF climate data

– monthly variability within grid boxes –



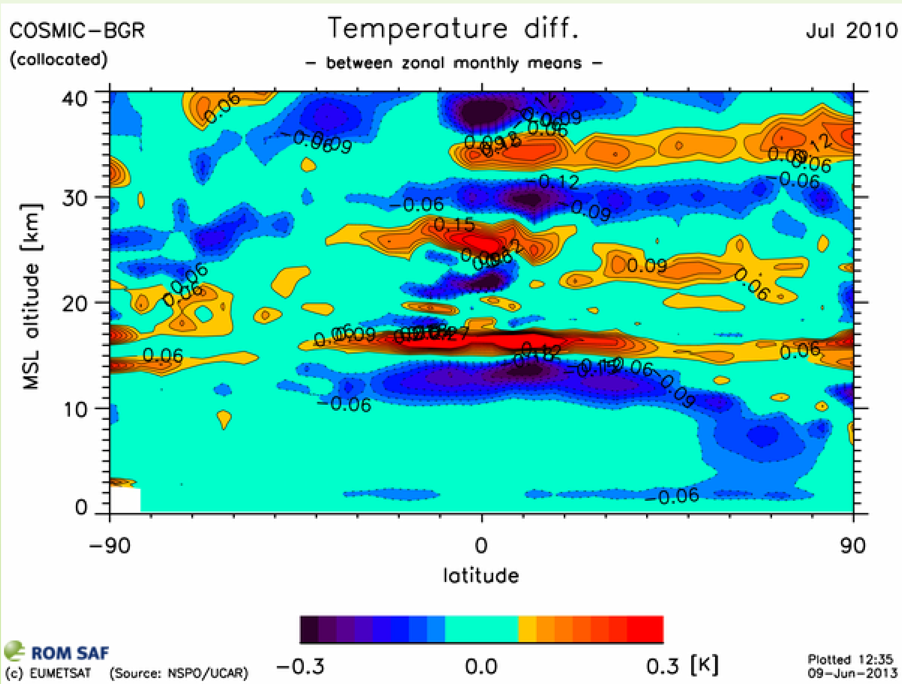
ROM SAF climate data

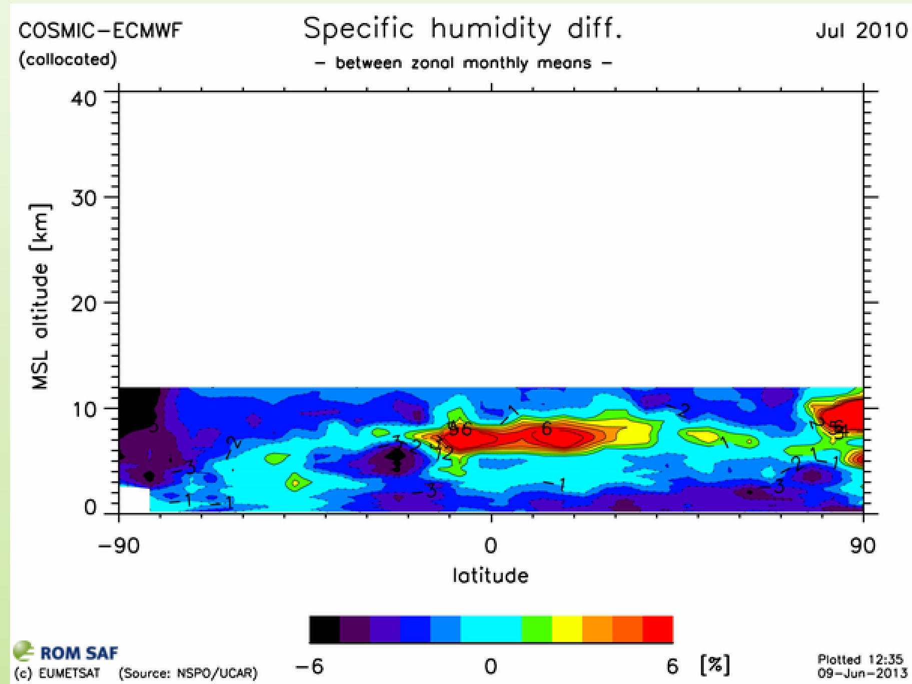
– estimation of sampling errors –



ROM SAF climate data

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





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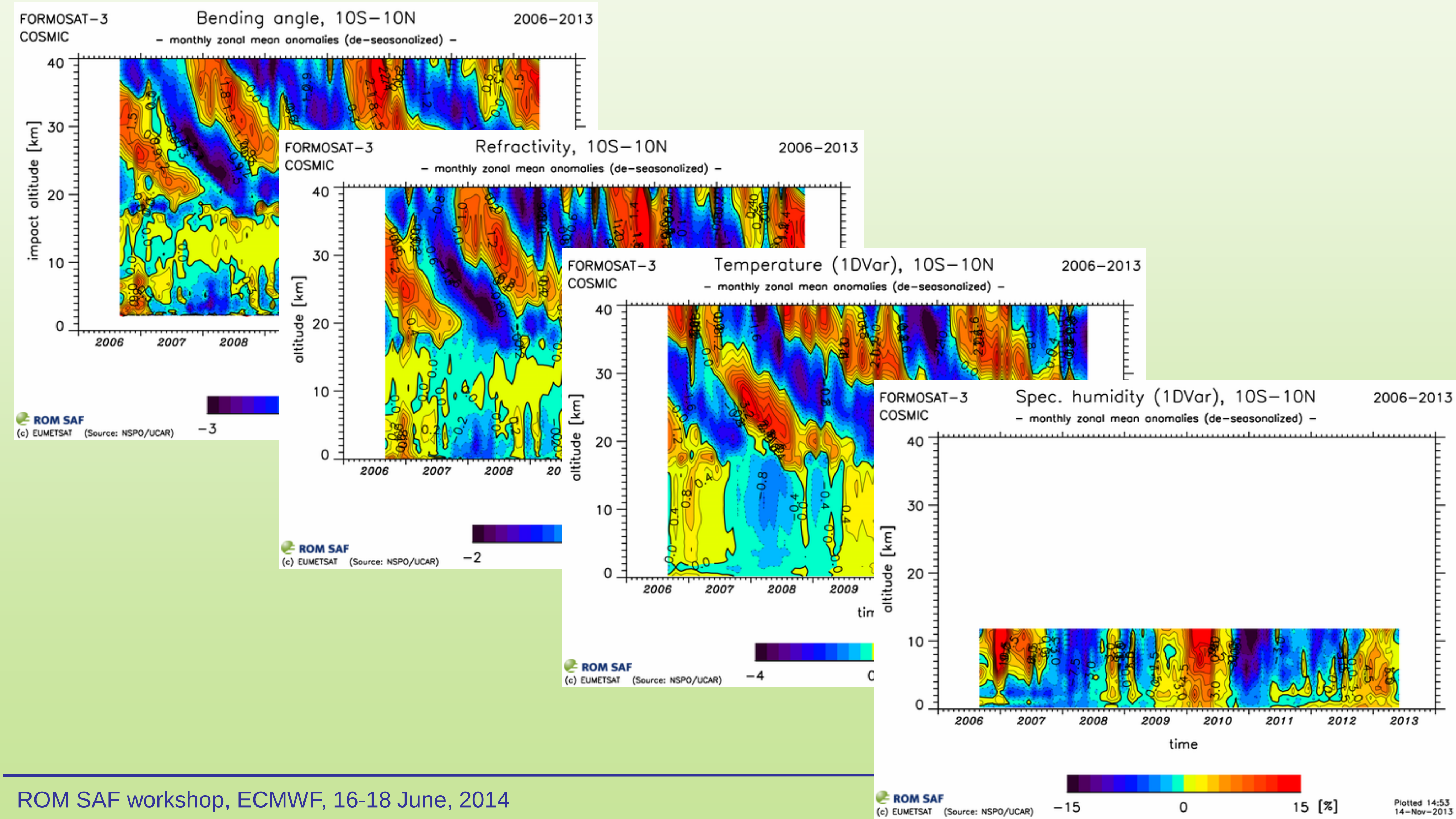
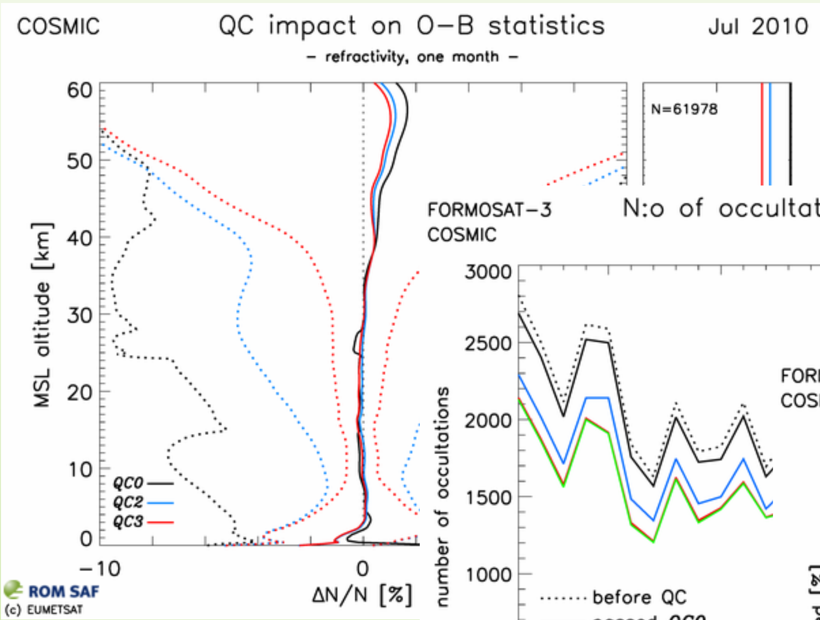
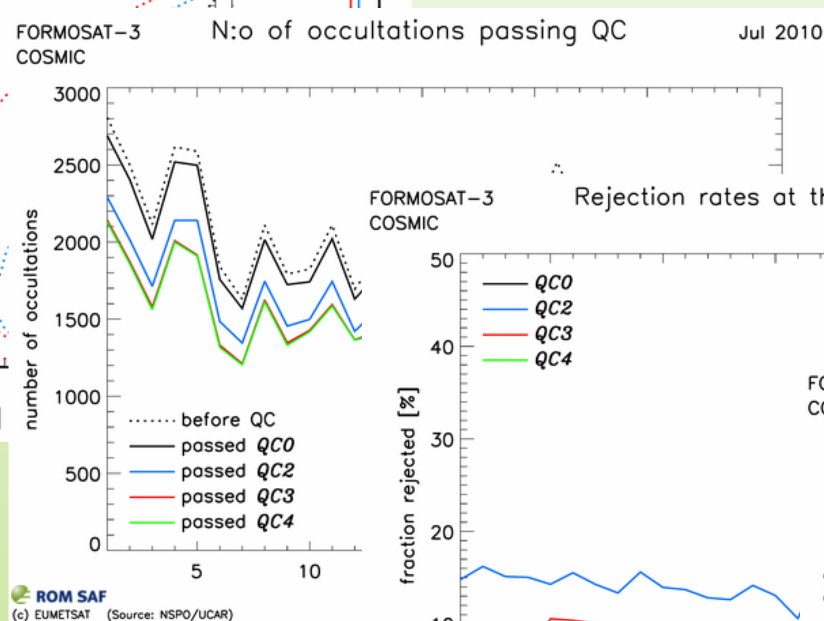
– time series data for the length of RO missions –



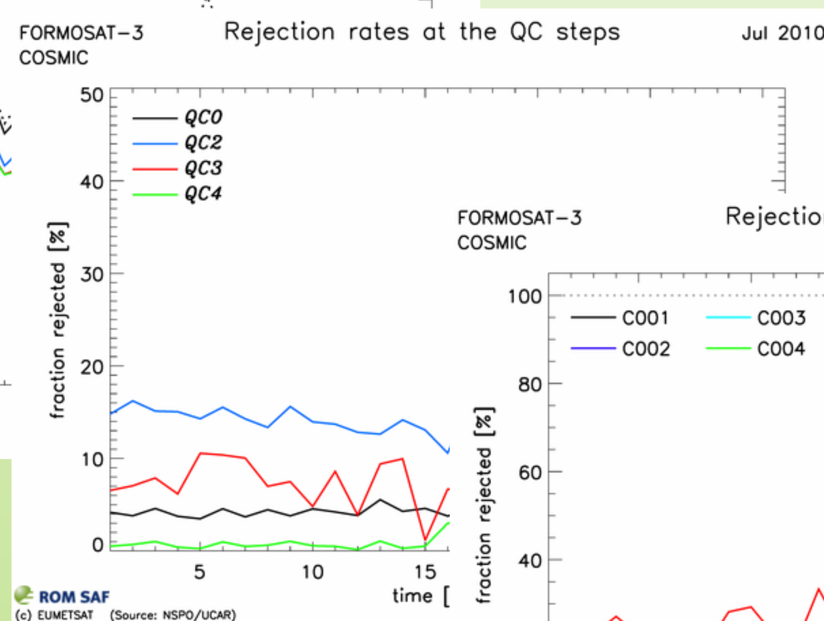
ROM SAF climate data

– monitoring of the QC screening on a monthly basis –

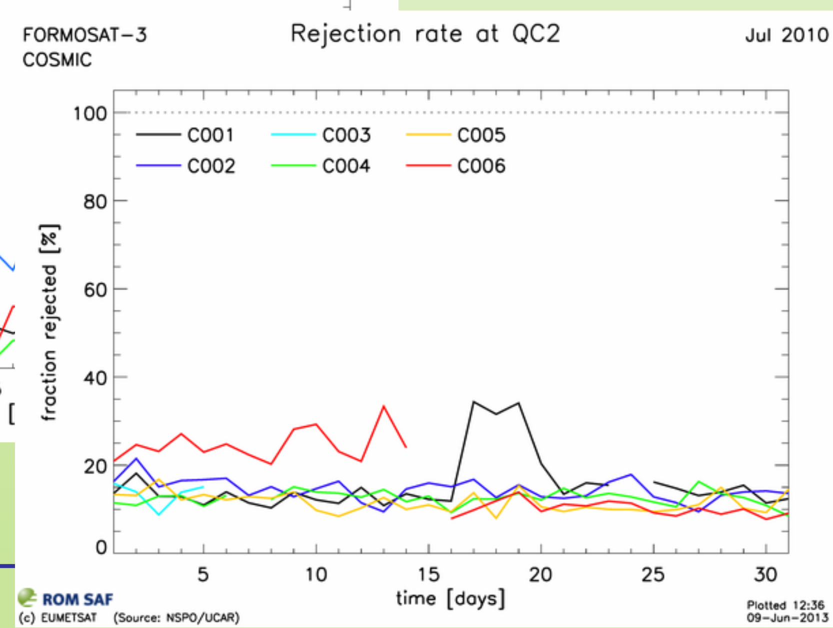




… per QC step

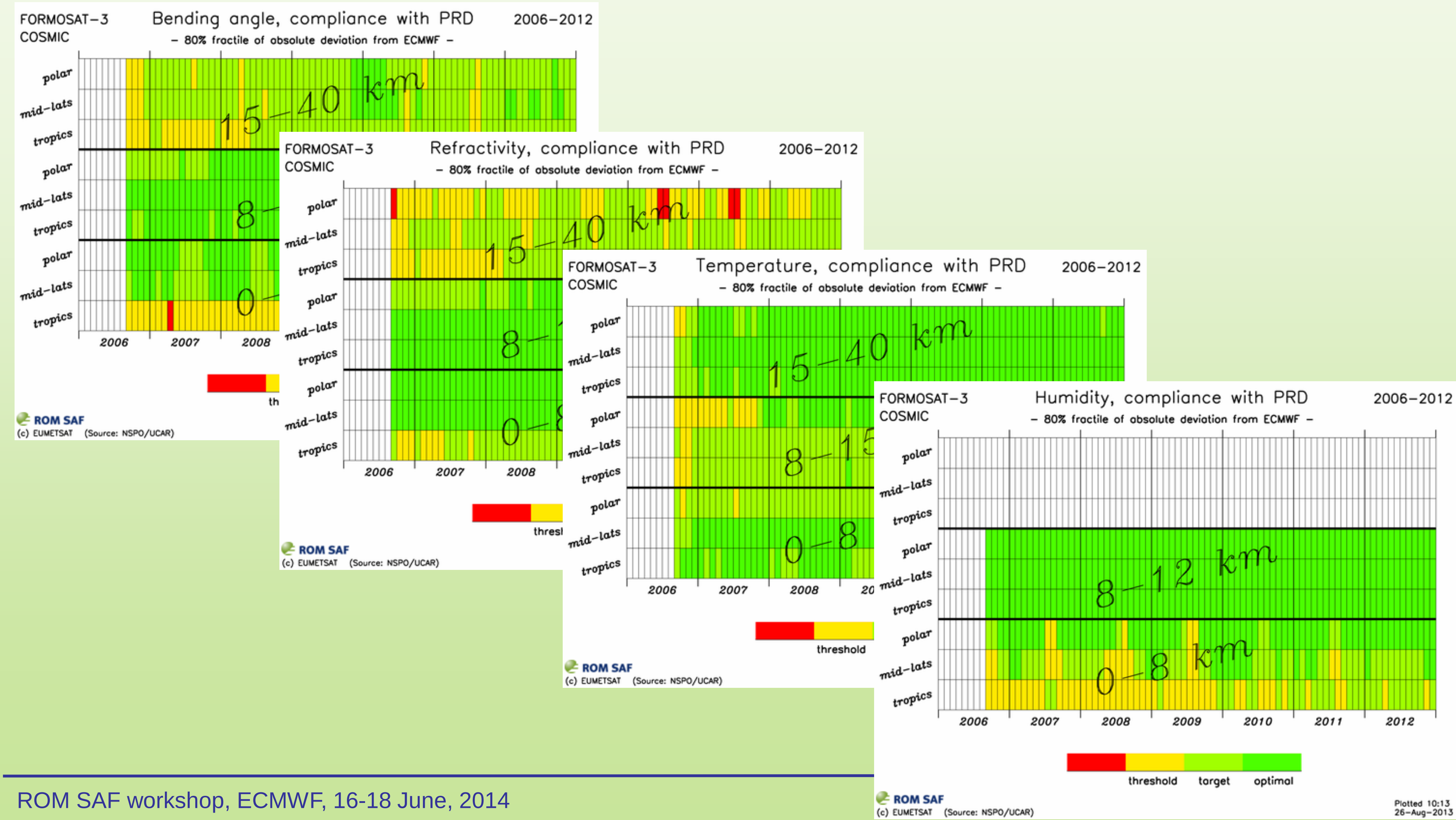


… per satellite



ROM SAF climate data

– validation statistics –



Ongoing studies

Studies:

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

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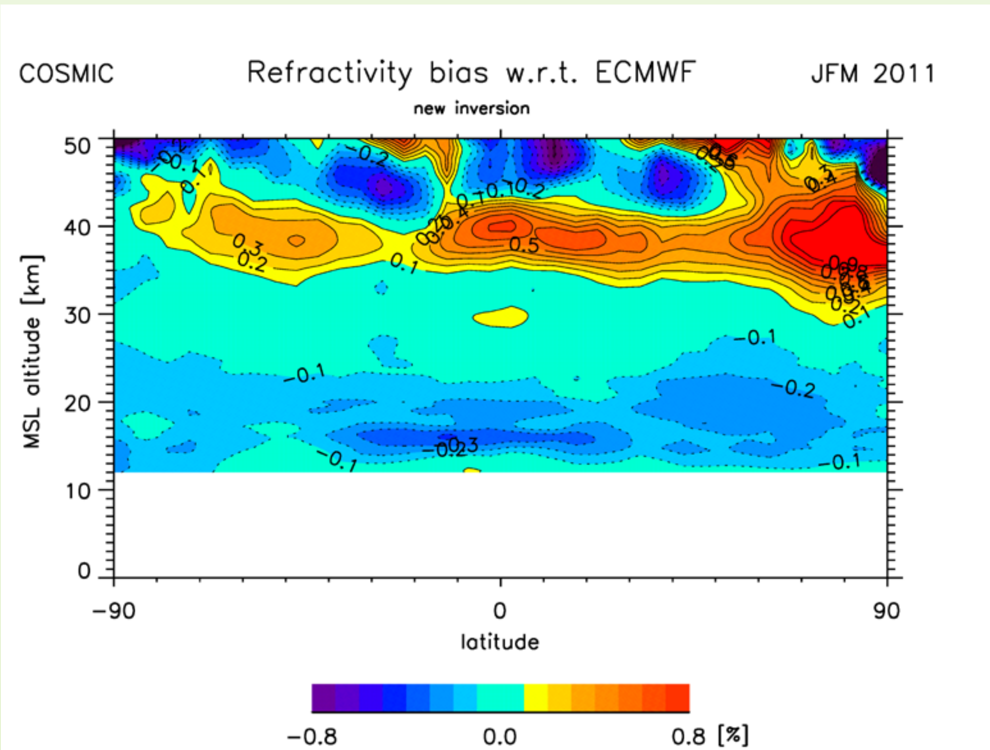
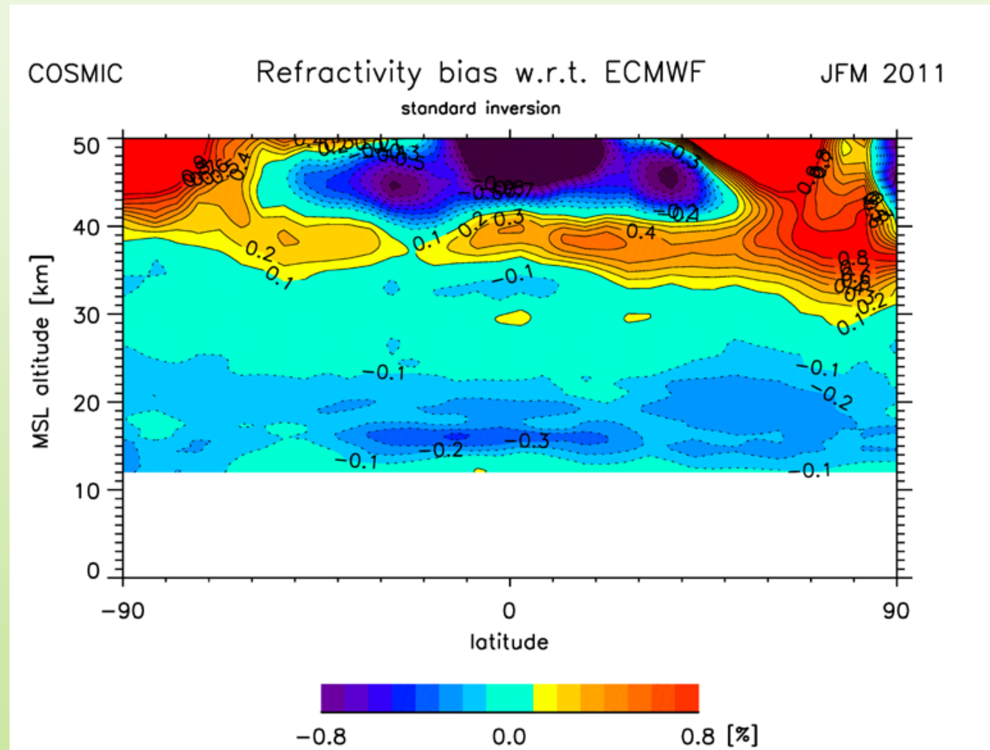
Climate processing using *API*

– COSMIC refractivity relative to ECMWF –

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



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



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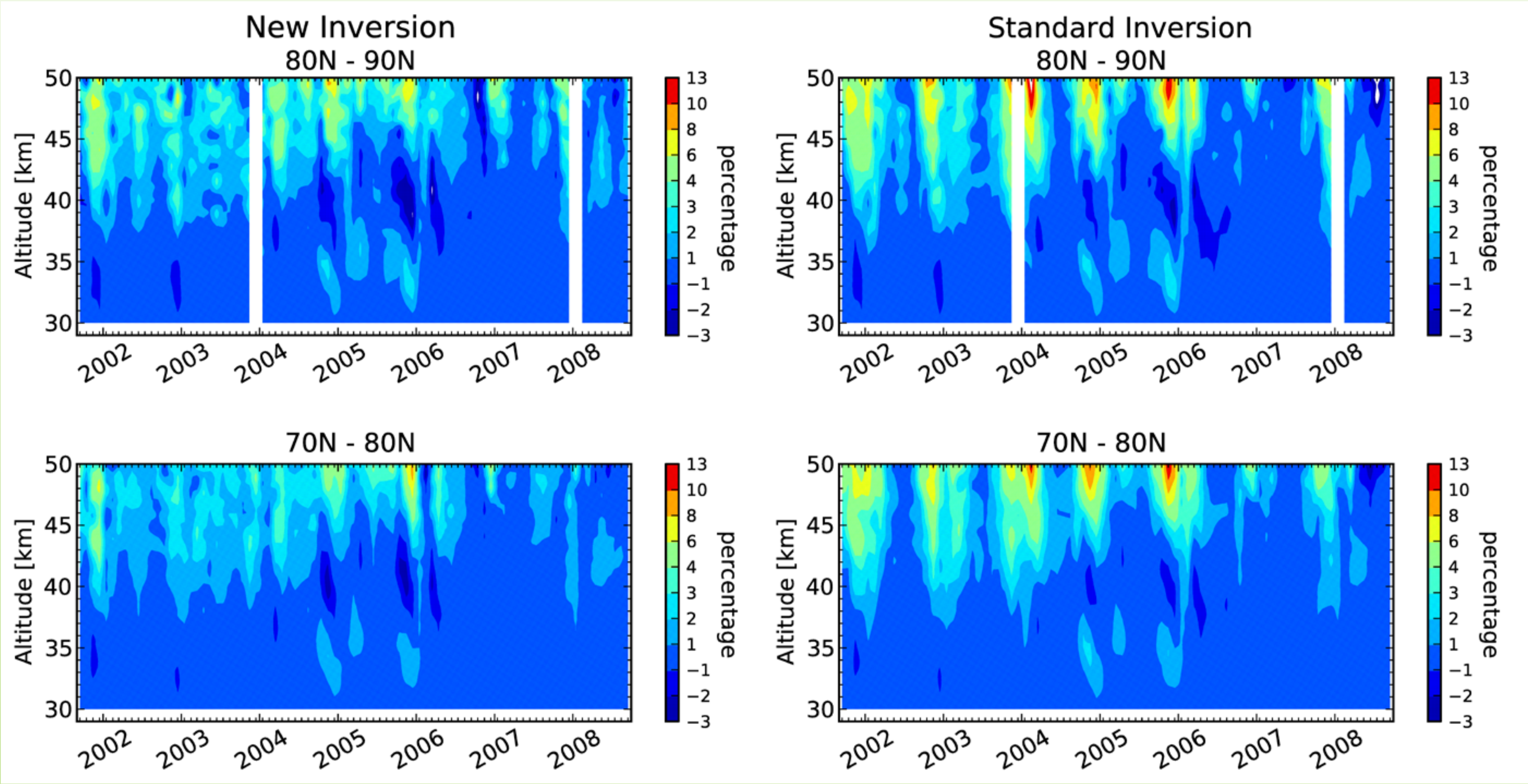
Climate processing using *API*

– CHAMP refractivity relative to ECMWF –



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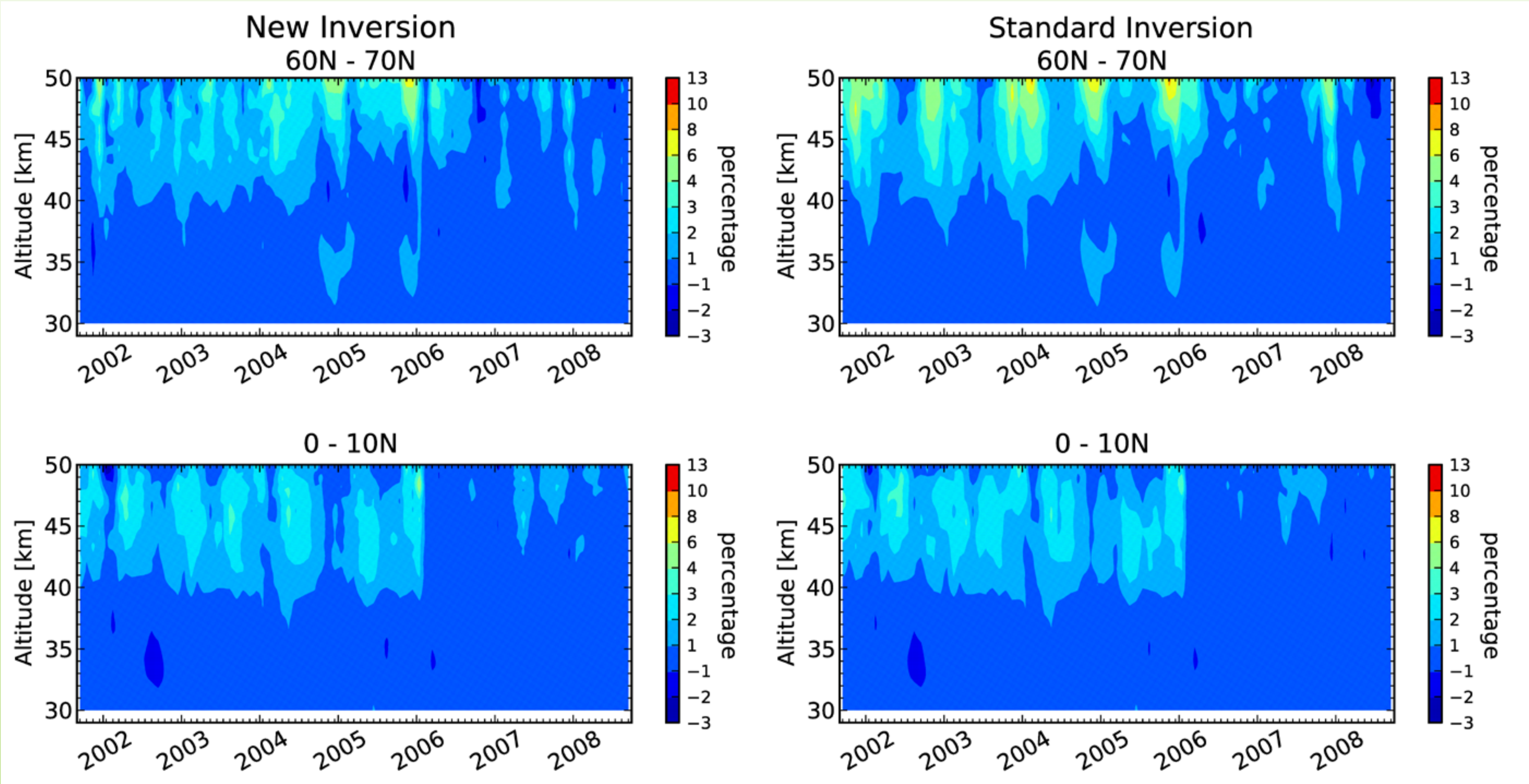
Climate processing using *API*

– CHAMP refractivity relative to ECMWF –



Monitoring mean tropospheric temperature

Integration of hydrostatic equation from pressure *p* down to surface:

$$\frac{dp}{dz} = -\frac{p g_0}{RT}$$

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

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.

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Monitoring mean tropospheric temperature

$$z(p) - z_s = \frac{R^* \overline{T_v}}{\mu_d g_0} \cdot \ln \frac{p}{p_s}$$

where

$$\overline{T_v} = \frac{\int_p^{p_s} T_v(\acute{p}) d\ln\acute{p}}{\int_p^{p_s} d\ln\acute{p}}$$

=> 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

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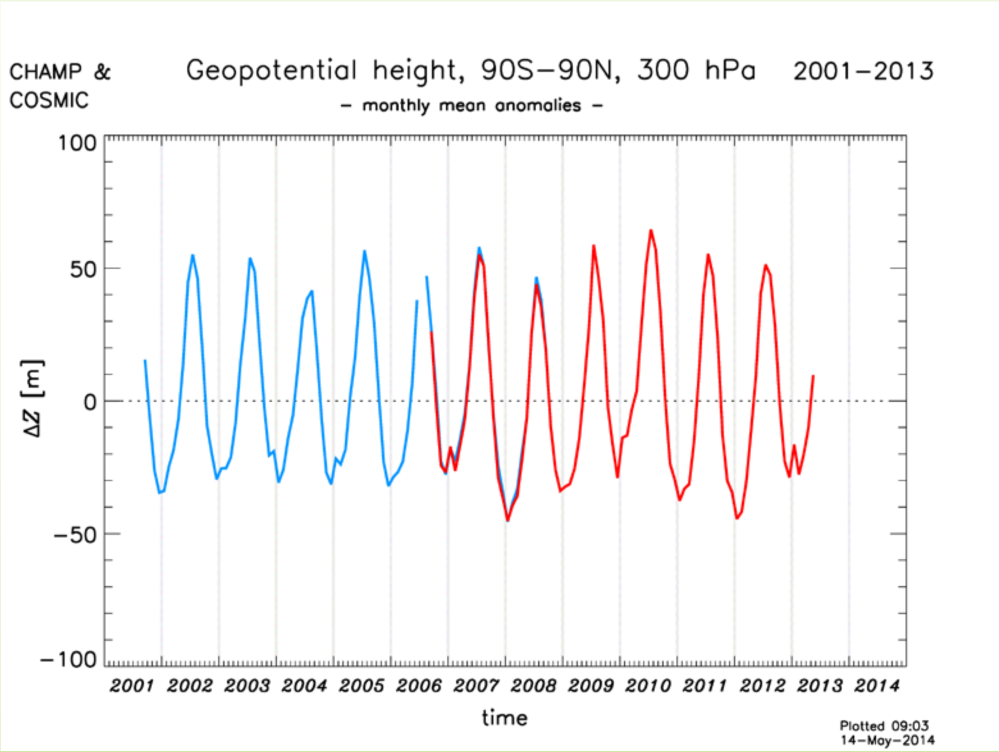
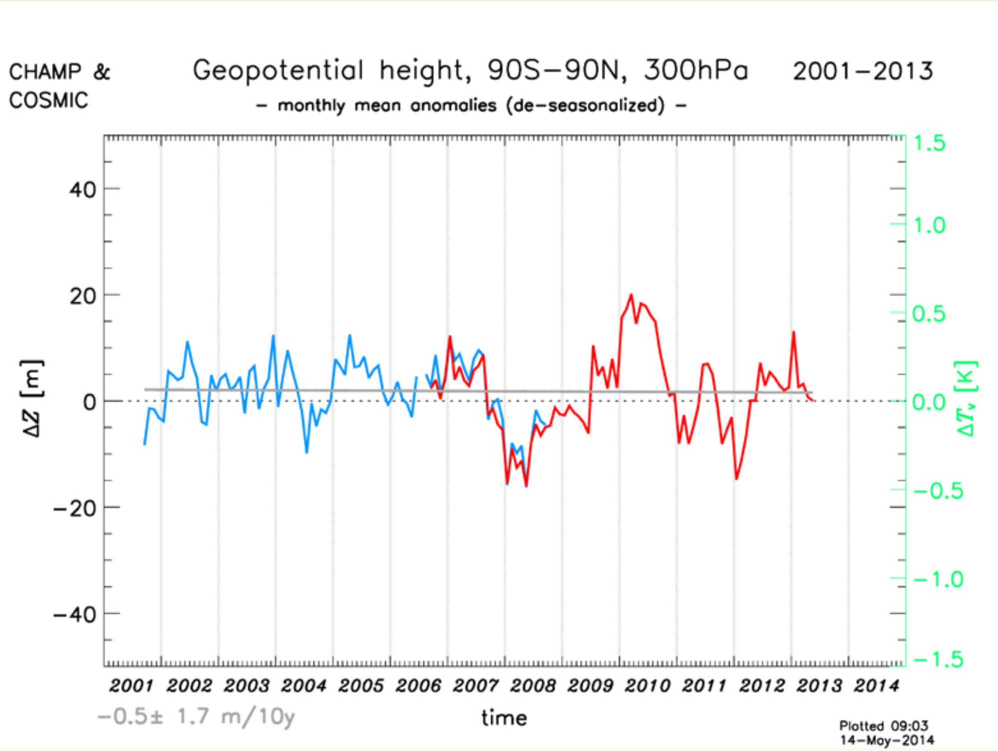
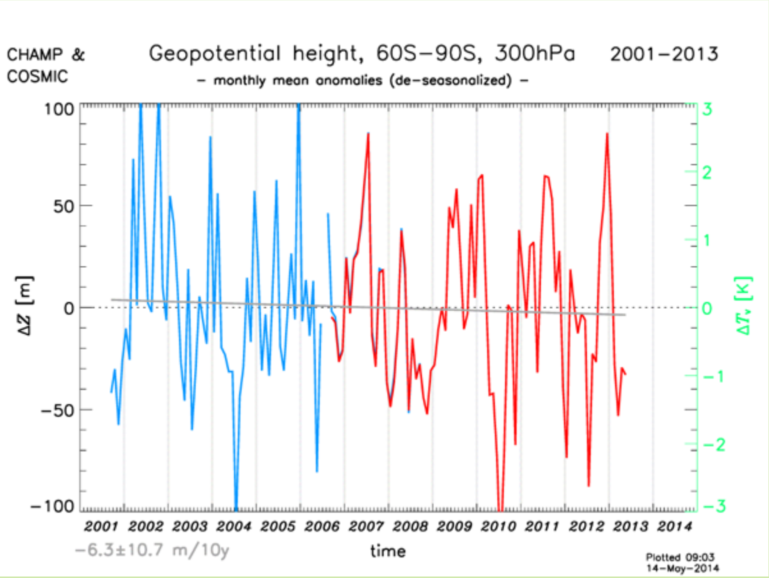
Monitoring mean tropospheric temperature
– 300 hPa geopotential, CHAMP/COSMIC, global –

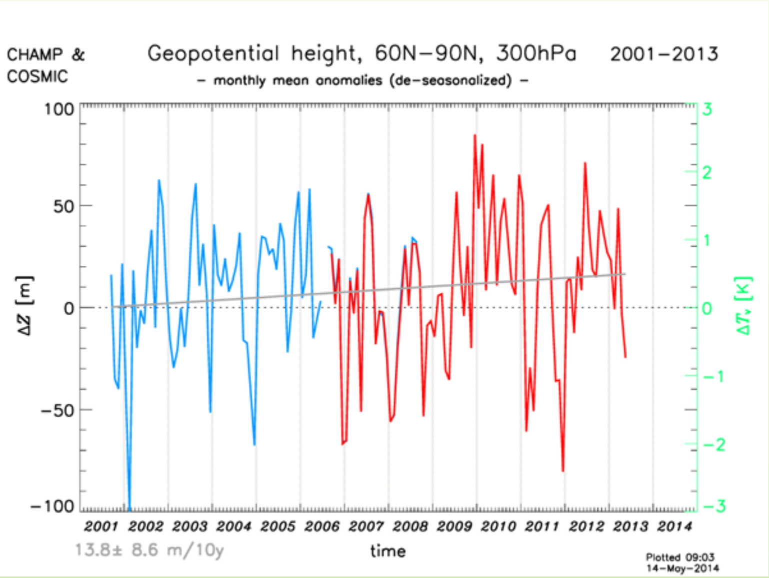




Monitoring mean tropospheric temperature

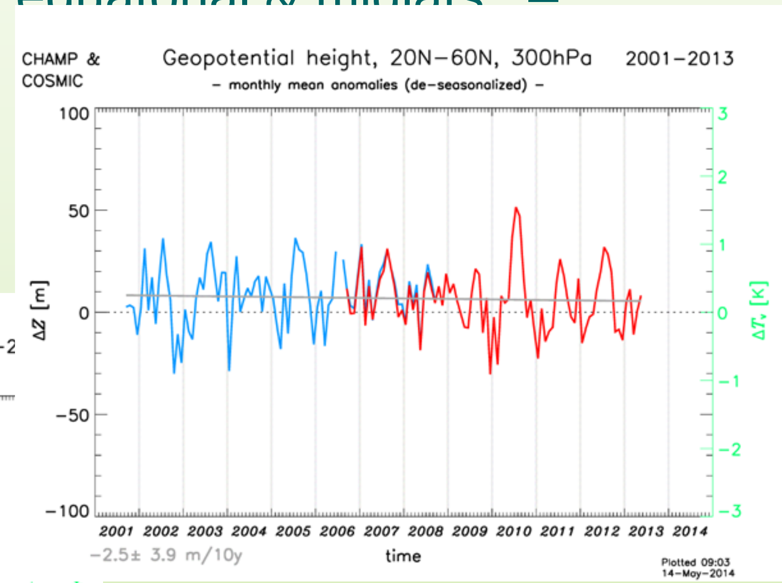
–   300 hPa geopotential, CHAMP/COSMIC, high latitudes   –

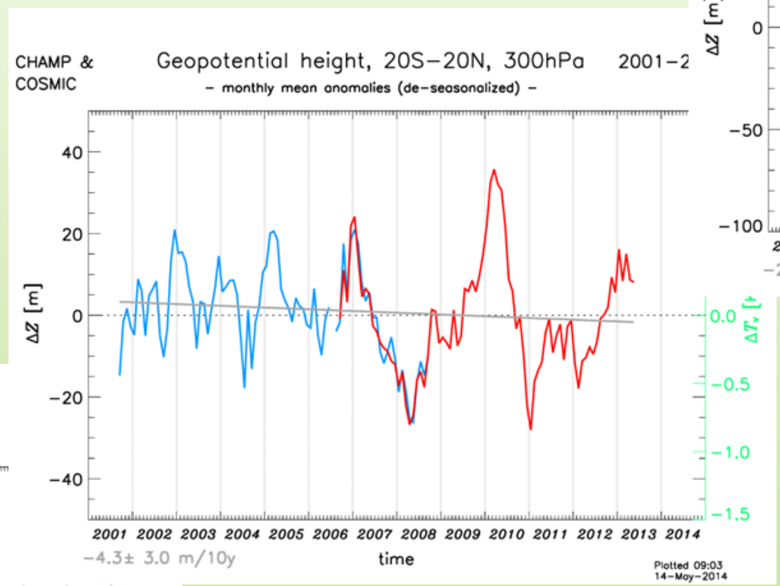


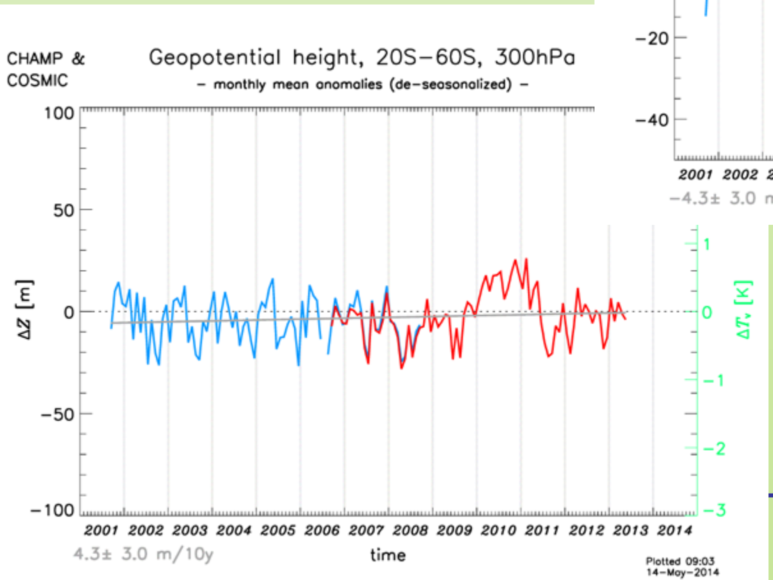


Monitoring mean tropospheric temperature

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







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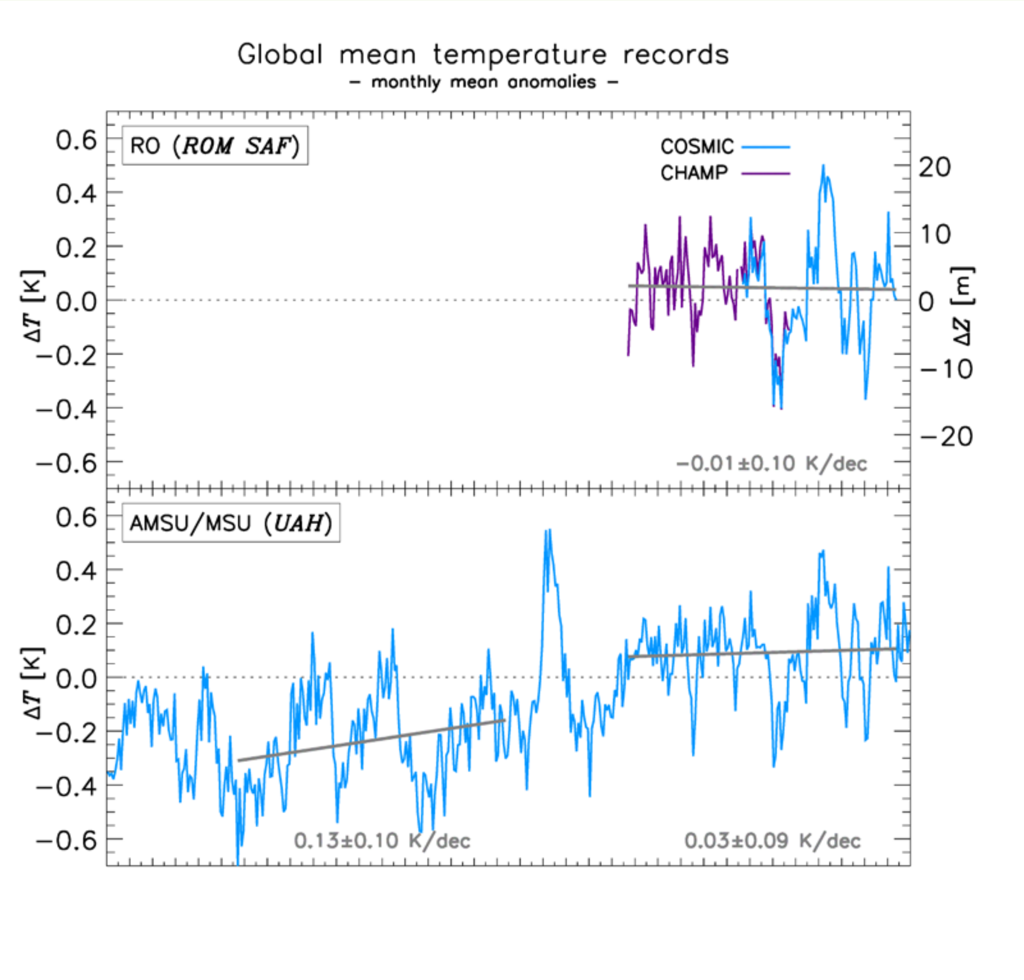
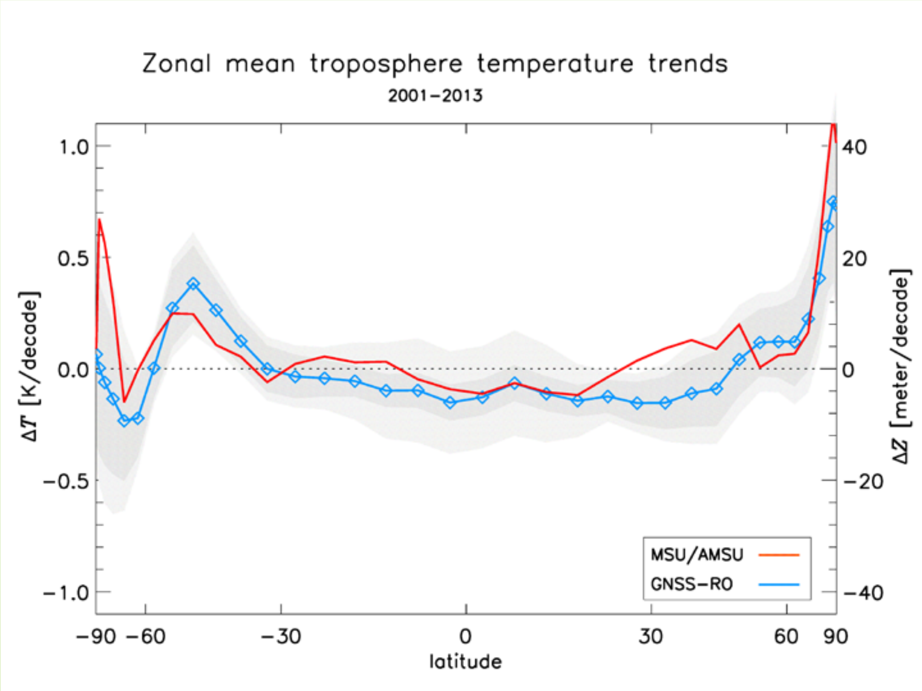
Radio Occultation Meteorology

Monitoring mean tropospheric temperature

– RO and MSU/AMSU –





STOP

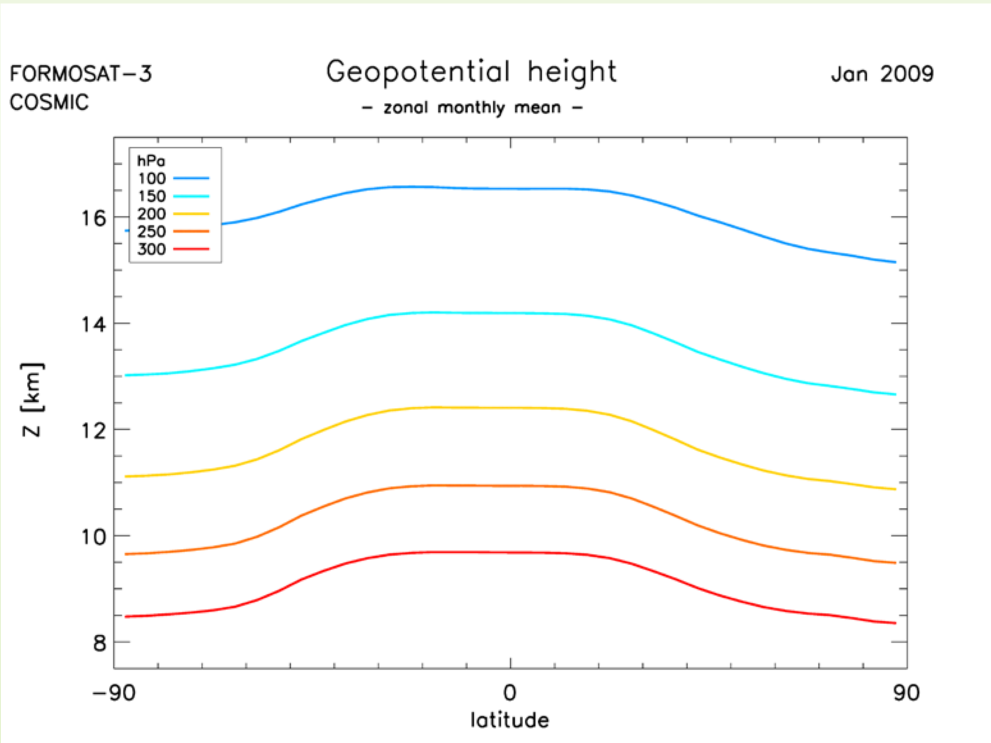
Monitoring mean tropospheric temperature

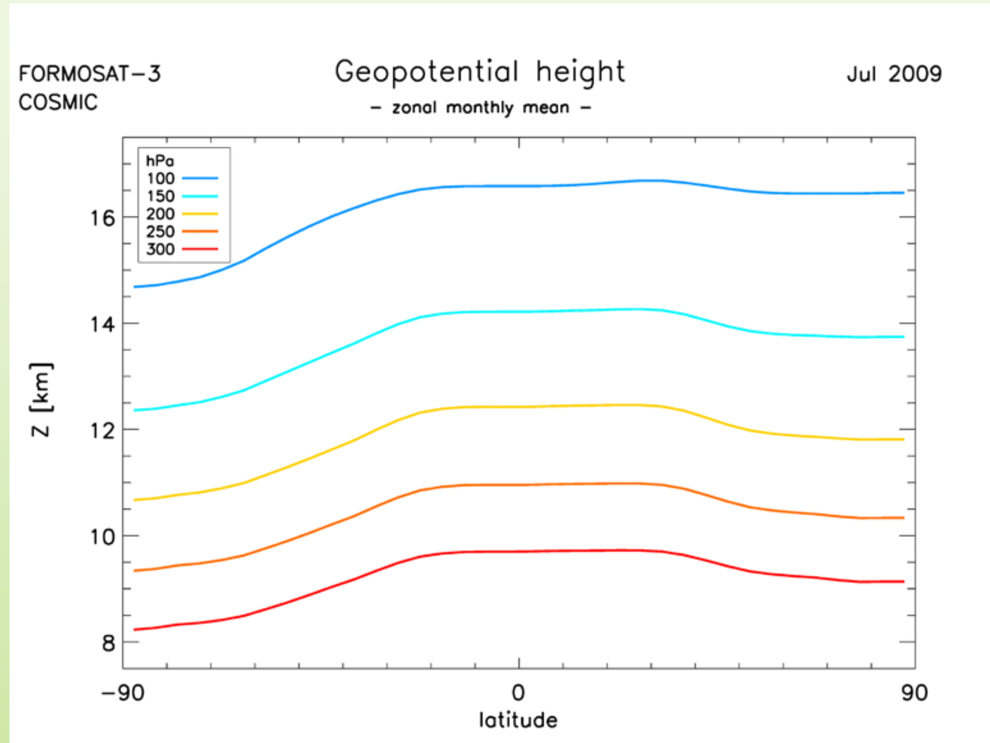
- COSMIC & CHAMP agree fairly well during overlap period
- sampling error correction required to combine missions
- CHAMP/COSMIC differences near equator – oscillations in CHAMP?
- dry geopotential at 300 hPa: what errors do we make?
- NCEP reanalysis agrees well with COSMIC, less well with CHAMP

- 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 –





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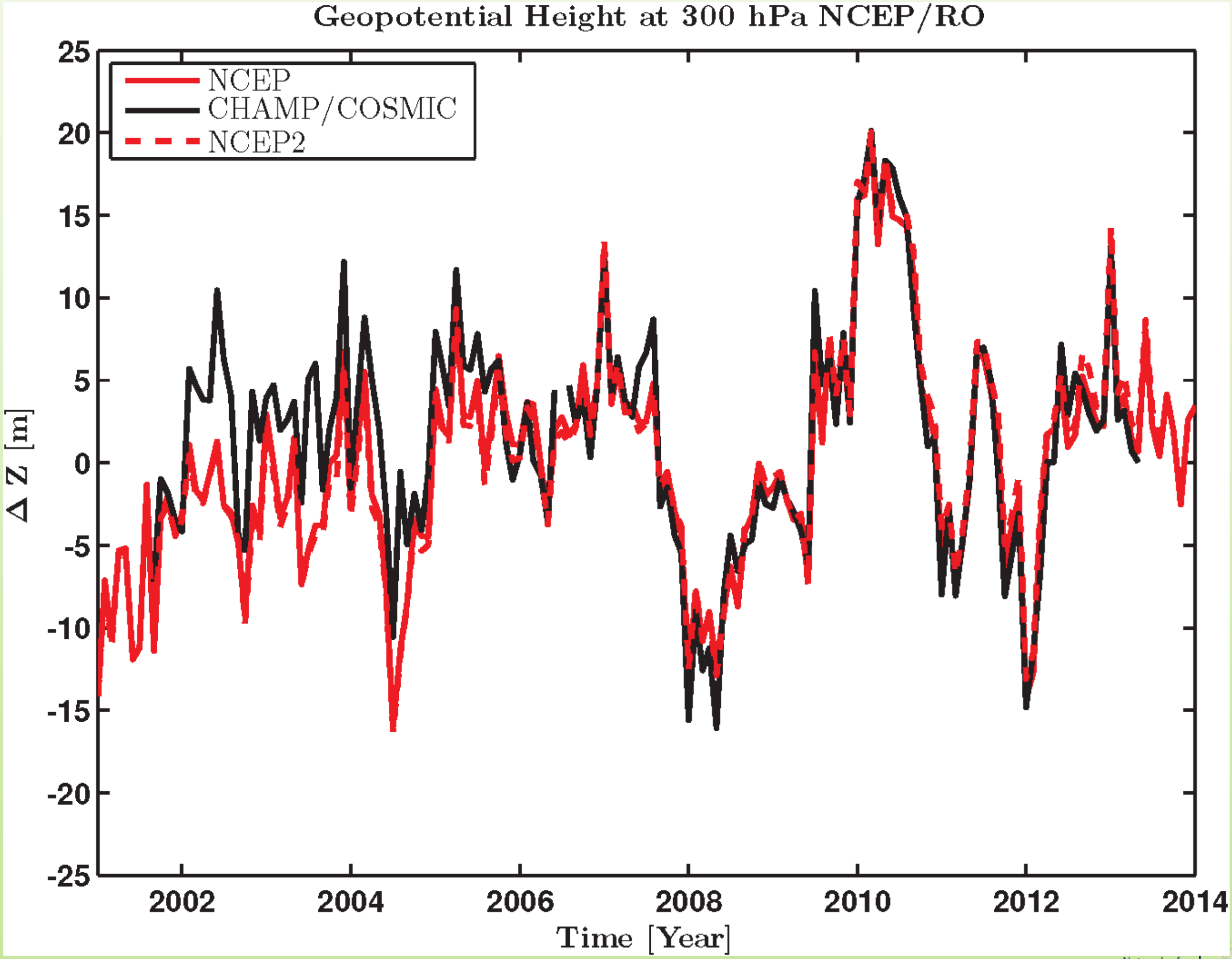
Monitoring mean tropospheric temperature

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



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