The Impact of different Radio Occultation Constellations on NWP and Climate Monitoring

András Horányi, Sean Healy (ECMWF)

and

Axel von Engeln, Yago Andres (EUMETSAT)

IROWG-4 workshop

© ECMWF

Some project details

– 18 month project financed by **EUMETSAT**

– Objectives:
  - Follow on the “Saturation Study” (F. Harnisch, 2012, random distribution of RO observations) taking into account **realistic future satellite orbits** (→ realistic RO distribution)
  - Assess best observation constellations to achieve **best RO observation distribution** in space and time (→ optimal data distribution)
  - Provide **guidance on RO instrument deployments** on future LEO satellites (→ e.g. COSMIC-2 Polar)

– **Ensemble of Data Assimilations** (EDA) impact assessment of simulated RO observations: 11 observation distribution *scenarios* committed; **only the results of a few scenarios will be shown here**. **More detail will be given at final report on June 30 @EUMETSAT**.

© ECMWF

METHODOLOGY: ENSEMBLE OF DATA ASSIMILATIONS (EDA)

© ECMWF

The EDA method (1)

- Goal: derive information on the analysis and short-term forecast error statistics (uncertainties) of the NWP model system

- Account properly for the main analysis error sources in the NWP system that come from the:

  (1) observations, (2) model background and (3) model

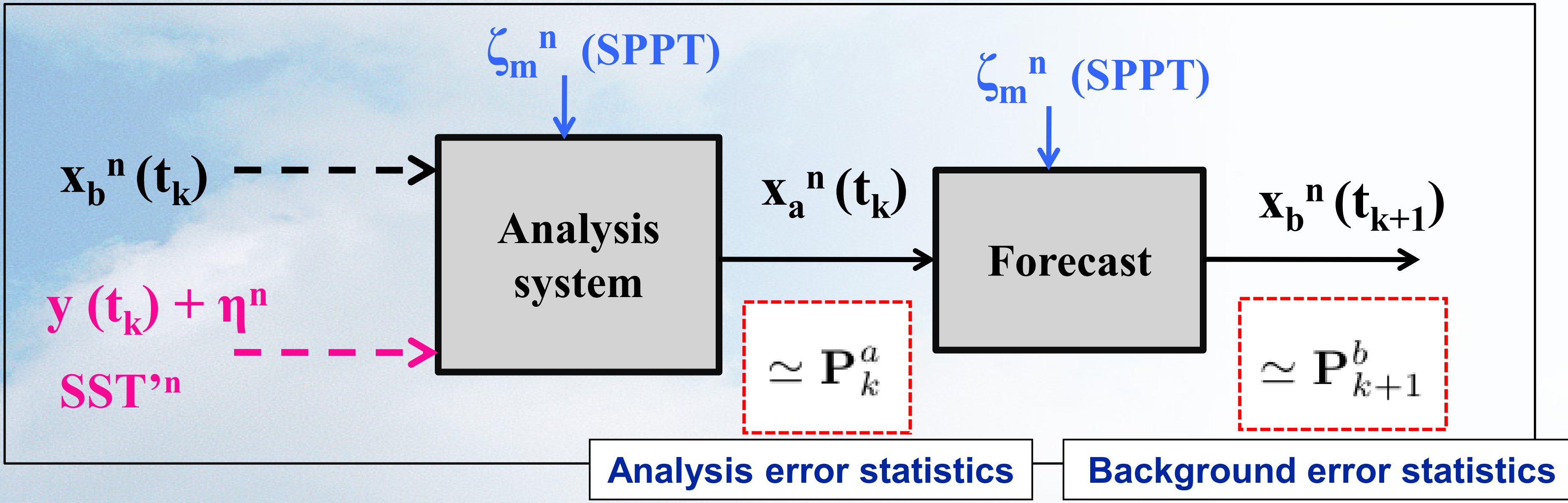
- Run an ensemble of independent 4D-Var data assimilation cycles

  → ensemble of analyses and forecasts provides information on analysis and forecast error statistics

(This is a well established method primarily used for data assimilation; see for instance Žagar et al. 2005; Isaksen et al. 2010, Bonavita et al. 2010, 2012)

© ECMWF
ECMWF

The EDA method (2)



Cycle of 10 4D-Var data assimilations in parallel using

- **perturbed observations** $\eta \sim \mathcal{N}(0, \mathbf{R})$
- **perturbed model physics (SPPT scheme)** $\zeta \sim \mathcal{N}(0, \mathbf{Q})$
- **assuming that** $\overline{\varepsilon_b^{k-1} \left(\varepsilon_b^{k-1}\right)^T} = \mathbf{P}_{k-1}^b$

→ **gives an ensemble estimate of <u>the error statistics of the analysis and short-range forecast</u>**

© ECMWF

The EDA method – EDA spread → impact

- The spread of the ensemble around the mean estimates the error variance of the analysis and short-range forecast

- The spread s (variance) of N-member ensemble for EDA experiments:

  for a given time d

$$s_d = \sqrt{\sigma_d^2} = \sqrt{\frac{1}{N-1} \sum_{n=1}^{N} (x^n - \overline{x})^2}$$

  for a period D (after spin up)

$$s = \sqrt{\mathbb{E}\left[\sigma_d^2\right]} = \sqrt{\frac{1}{D} \sum_{d=1}^{D} \left(\frac{1}{N-1} \sum_{n=1}^{N} (x^n - \overline{x})^2 \right)}$$

- EDA method: investigate how the EDA spread (the estimated variance of the analysis and forecast error PDF) is changing when additional observations are used → observation impact

© ECMWF

The EDA method: interpretation of EDA spread

Estimates the analysis (forecast) uncertainty, which is related to the error statistics and not the error itself.

$\mathbf{P}_k^a$ & $\mathbf{P}_{k+1}^b$

Depends on the assumed input error statistics and not the actual ones (→ R, B, Q)

Provides realistic estimate of uncertainty *if, and only if,* the assumed input error statistics are realistic.

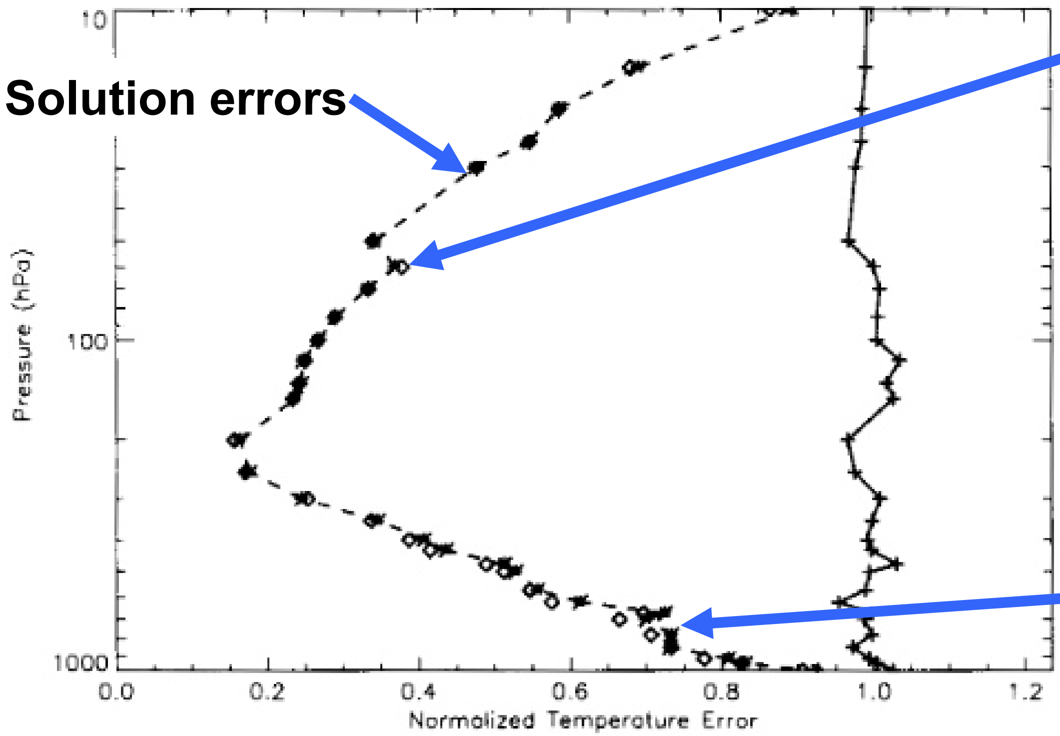
© ECMWF
ECMWF

Comparing EDA approach and OSSEs

- **OSSEs:** simulate all observations from a known truth - *the nature run*.
  - The simulated observations are assimilated into an NWP system, and **individual analysis and/or forecast errors**, ε, can computed because the truth is known.
  - The **statistics** of the analysis/forecast errors can be computed by averaging errors, **ε**, over the experiment.
- **EDA:** We estimate the analysis and forecast **error covariance matrices - not the forecast errors** - based on the assumed observation/model error statistics.
- Compare with old 1D-Var information content studies.

© ECMWF

Compare with 1D-Var information content



Diamonds: given by 1D-Var solution error cov. matrix (**EDA**)

$$\mathbf{A} = (\mathbf{B}^{-1} + \mathbf{H}^{T}\mathbf{R}^{-1}\mathbf{H})^{-1}$$

Crosses: computing the statistics of the retrieval errors (**OSSE**)

Figure 2. The normalized retrieved temperature errors (dashed line) calculated from 1000 simulated retrievals for (a) profile 1, (b) profile 2, (c) profile 3, and (d) profile 4 (see text). The normalized background errors (solid line) and theoretical error estimates derived from a solution covariance matrix (diamonds) are also shown for comparison in each case.

(Healy and Eyre, 2000)

© ECMWF
ECMWF

OBSERVATION PRE-PROCESSING (SIMULATION OF OBSERVATIONS)

© ECMWF

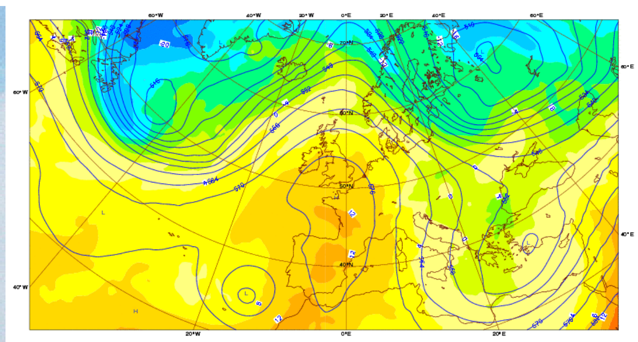
The EDA diagnostics: the spread

- The EDA spread is computed from the 00 and 12 UTC analyses.
- Mostly temperature spread is presented since the largest impact is in temperature
- Spread vertical profiles are plotted
- Time period for averaging: days July 11-25, 2008.
- Regions for averaging: NH extra-tropics (N20-N90), SH extra-tropics (S90-S20), tropics (S20-N20)

© ECMWF

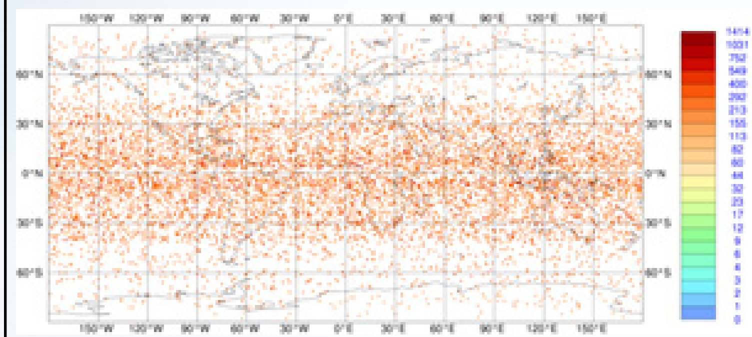
Simulation of GNSS RO observations

ECMWF NWP analysis
at T799 (~25 km) and L91
→ proxy for the ‘truth’



interpolate

EUMETSAT: Realistically distributed observation time and location (lat, lon, limb-azimuthal angle)



2D bending angle operator
(Healy et al. 2007)

add realistic observation errors

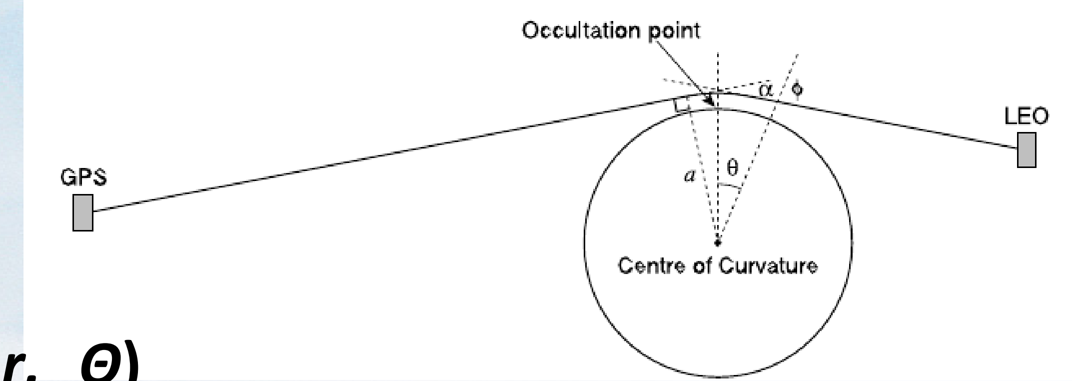
simulated bending angle profiles *α(a)*

bending angles on 247 fixed impact heights *h* (*a* - R_c)
similar to operationally used GRAS data

© ECMWF
Slide 12

Simulation of GNSS RO observations

- **2-D bending angle operator**



- **calculate the ray-path (*r*, *Θ*) and bending angle *α* by solving a set of differential equations (4-th order Runge-Kutta)**

$$\frac{dr}{ds} = \cos\phi$$

$$\frac{d\theta}{ds} = \frac{\sin\phi}{r}$$

$$\frac{d\phi}{ds} = -\sin\phi\left[\frac{1}{r} + \frac{1}{n}\left(\frac{\partial n}{\partial r}\right)_\theta\right] + \frac{\cos\phi}{nr}\left(\frac{\partial n}{\partial \theta}\right)_r$$

$$\frac{d\alpha}{ds} = -\frac{\sin\phi}{n}\left(\frac{\partial n}{\partial r}\right)_\theta + \frac{\cos\phi}{nr}\left(\frac{\partial n}{\partial \theta}\right)_r$$

- **Change in bending angle α along this ray-path**

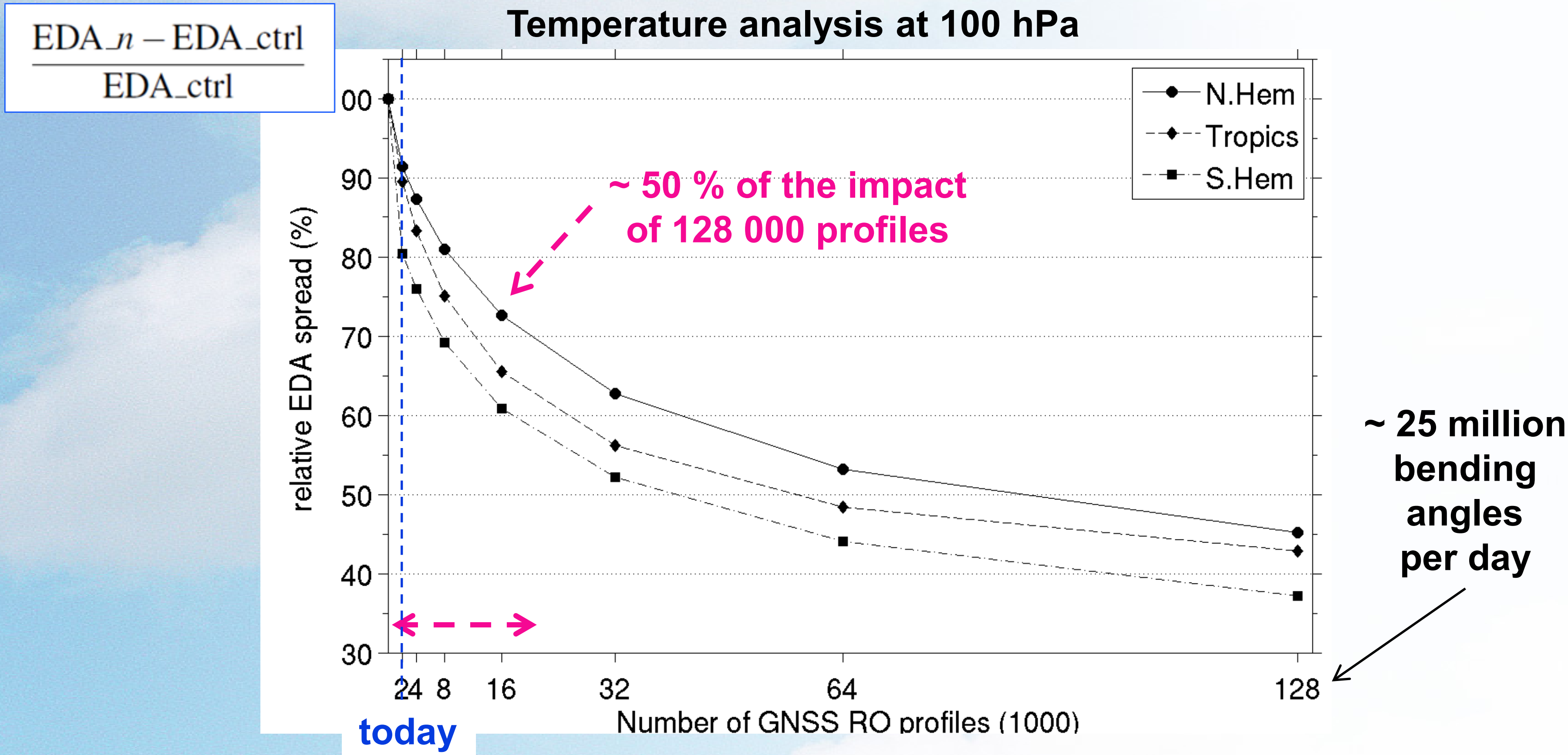
- **Included in ROM SAF ROPP package. Also used in OSSEs.**

© ECMWF

MAIN RESULTS OF THE "SATURATION STUDY" (REMINDER)

© ECMWF

Scaling of GNSS RO impact (F. Harnisch)



- **Large improvements up to 16 000 profiles per day**
- **Even with 32 000 – 128 000 profiles still improvements possible**

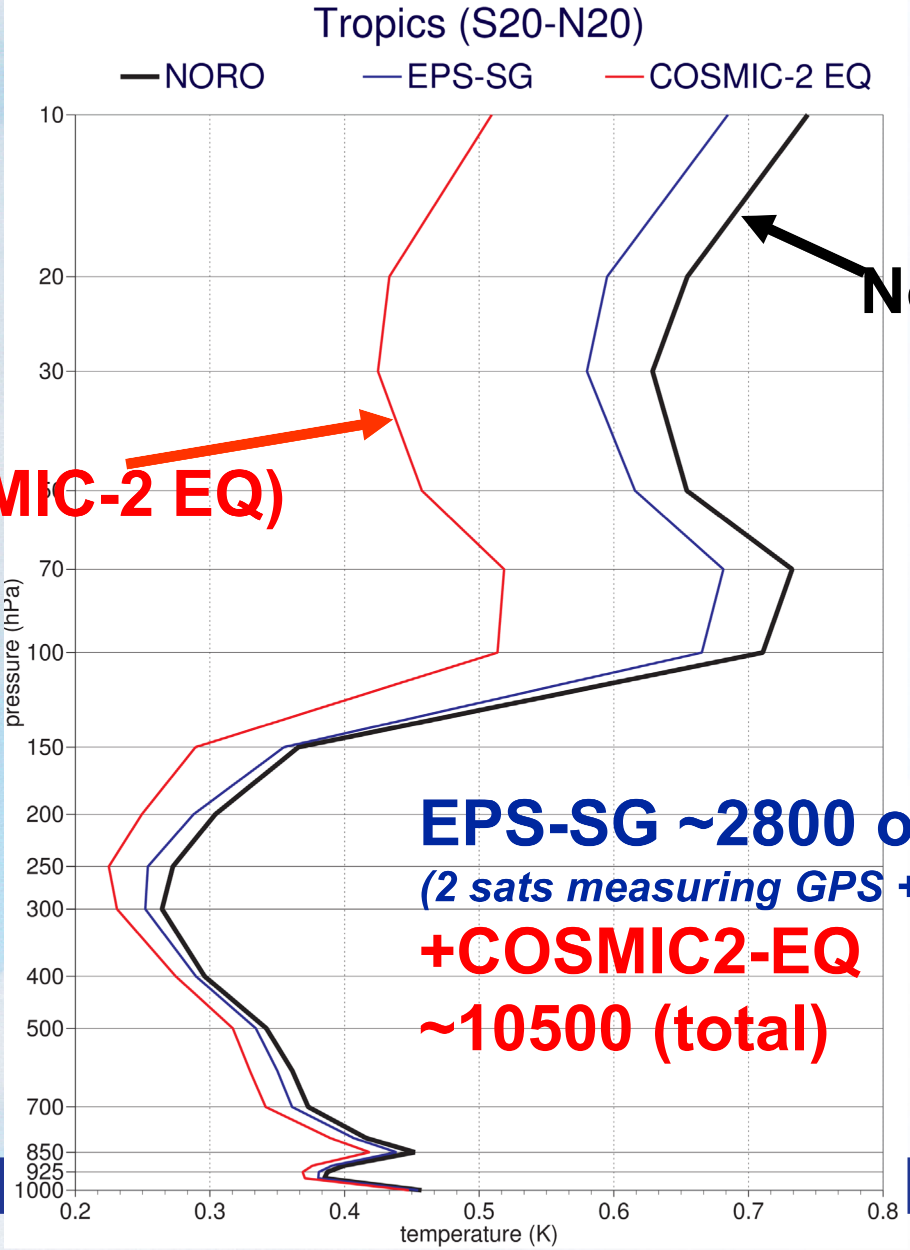
→ no evidence of saturated impact up to 128 000 profiles
(although the additional impact per observation is decreasing)

© ECMWF

RESULTS: COSMIC-2

© ECMWF

The impact of COSMIC-2 Equator (tropics) - TEMPERATURE



No RO

(EPS-SG+COSMIC-2 EQ)

EPS-SG ~2800 occs per day

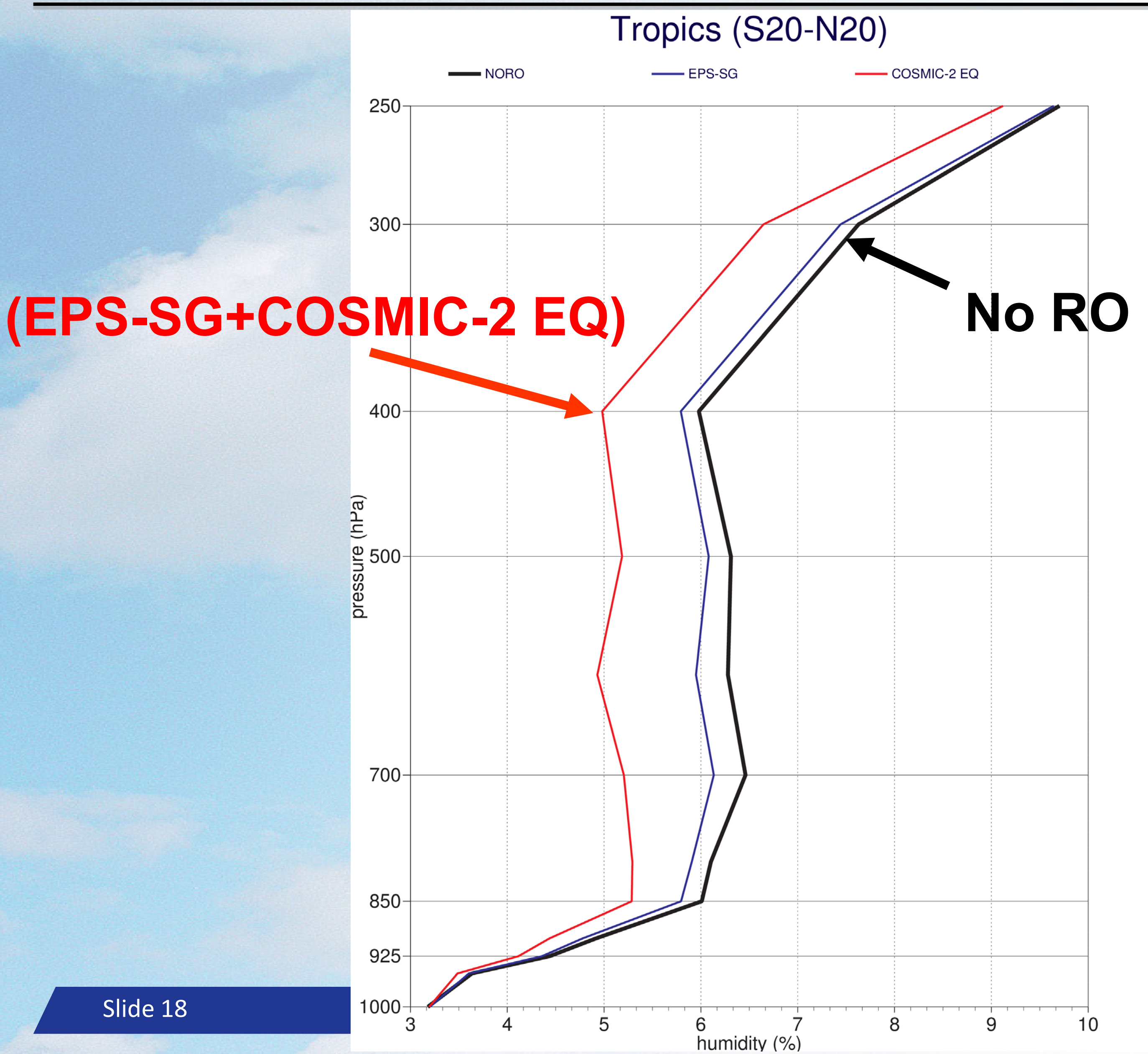
(2 sats measuring GPS + Galileo)

+COSMIC2-EQ

~10500 (total)

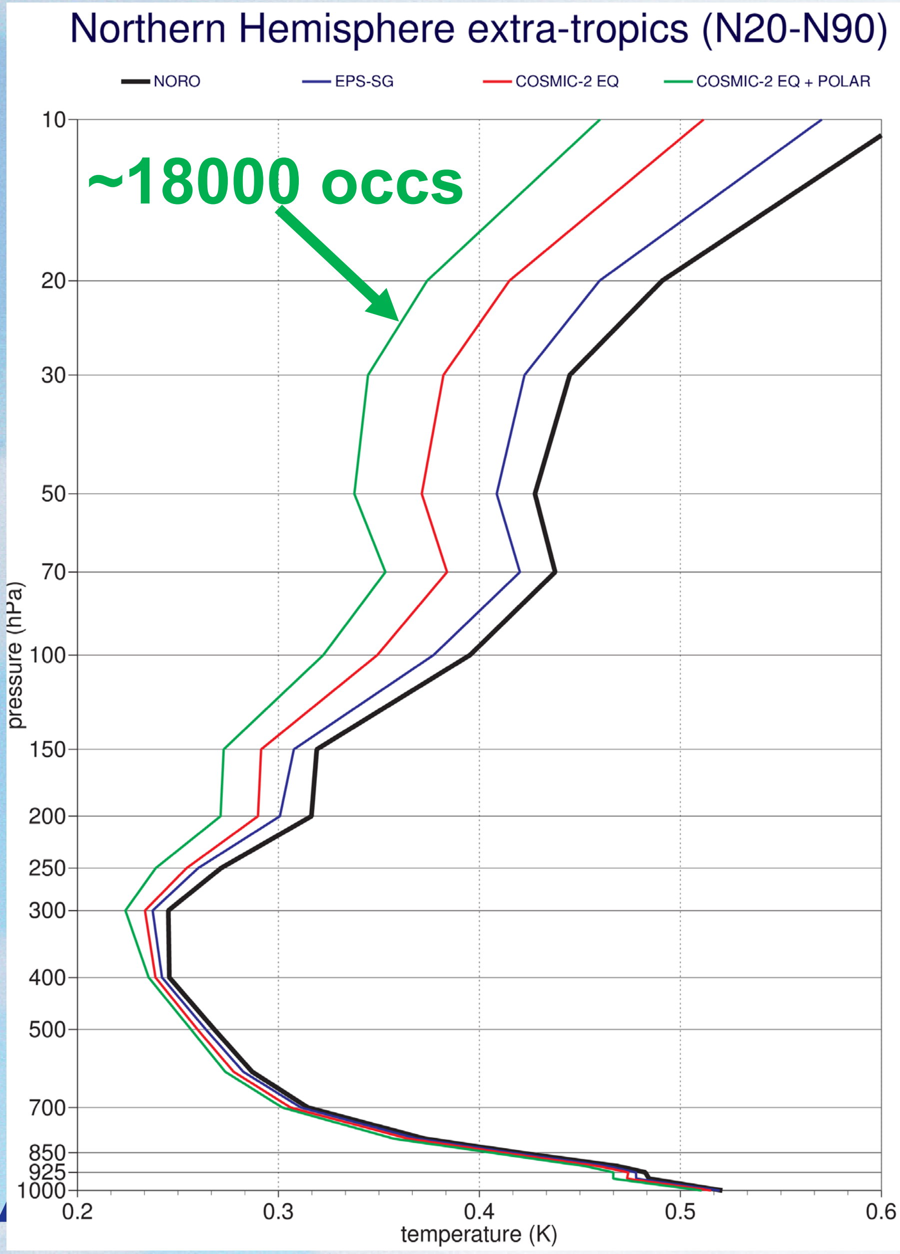
ECMWF

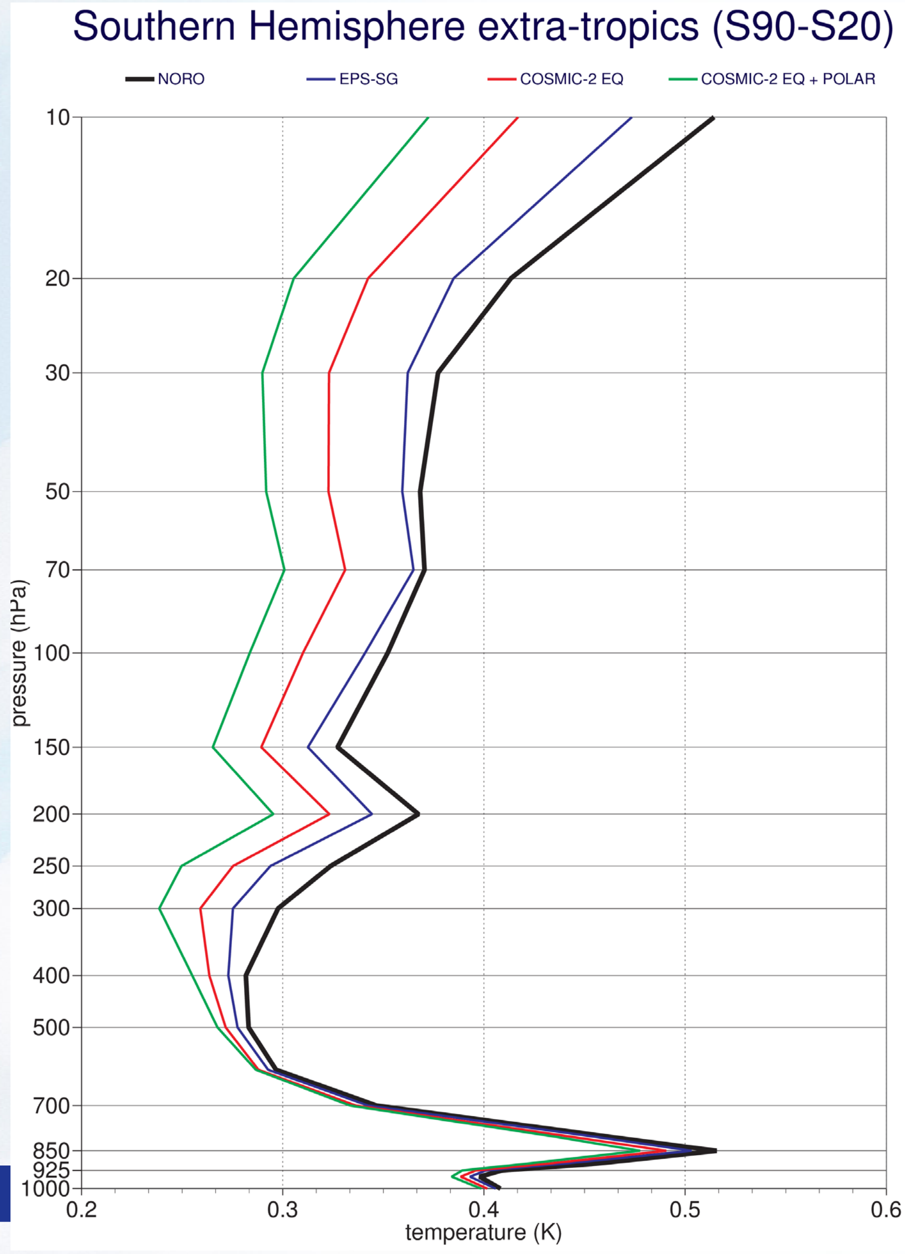
The impact of COSMIC-2 Equator (tropics) – RELATIVE HUMIDITY



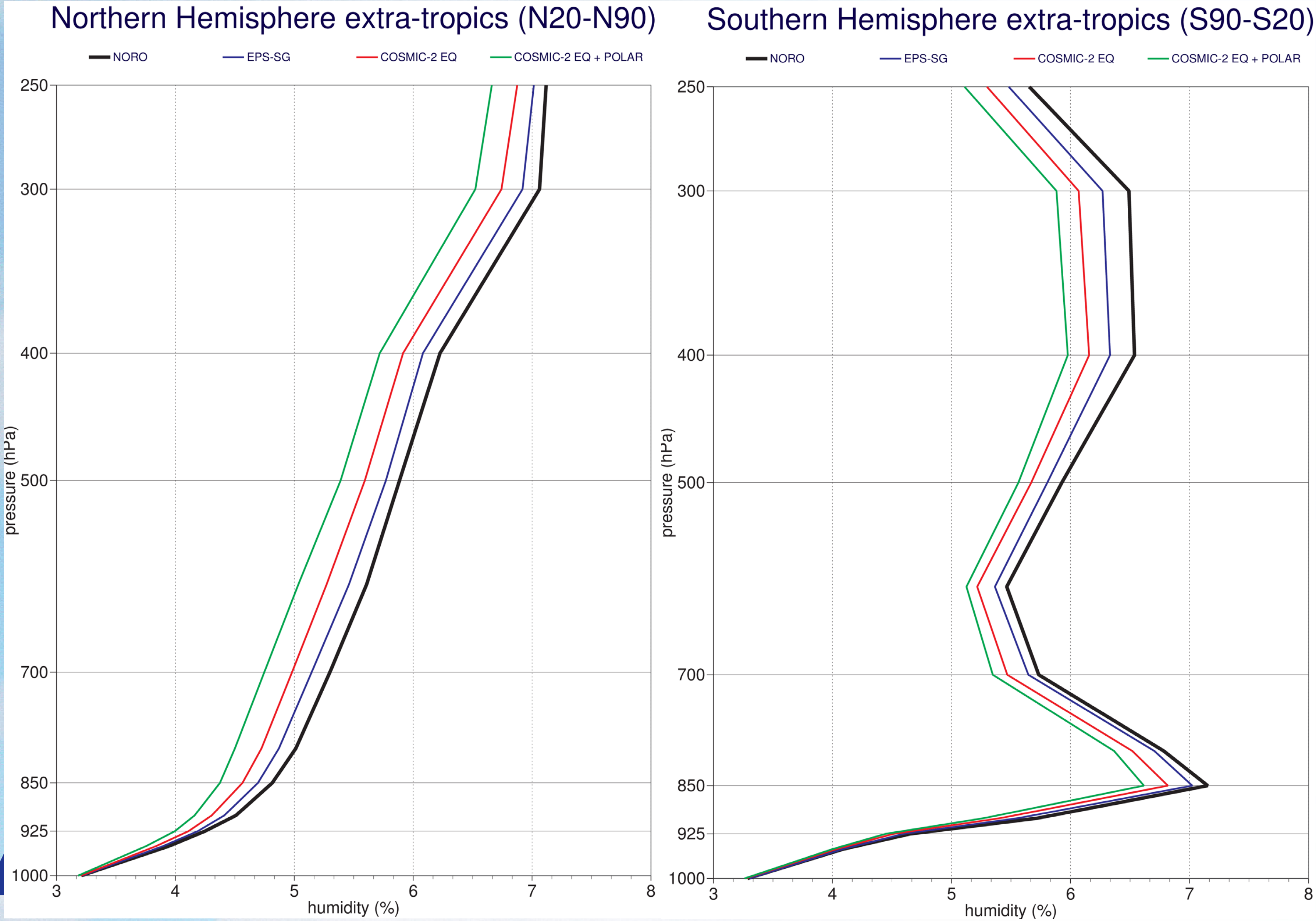
ECMWF

COSMIC-2 Polar + (EPS-SG +COS2-EQ, extra-tropics) - TEMPERATURE





COSMIC-2 Polar + (EPS-SG +COS2-EQ; extra-tropics) – RELATIVE HUMIDITY



COSMIC-2 Polar mitigation strategy

Can 4 sun-synchronous RO satellites compensate for the loss of COSMIC2 Polar?

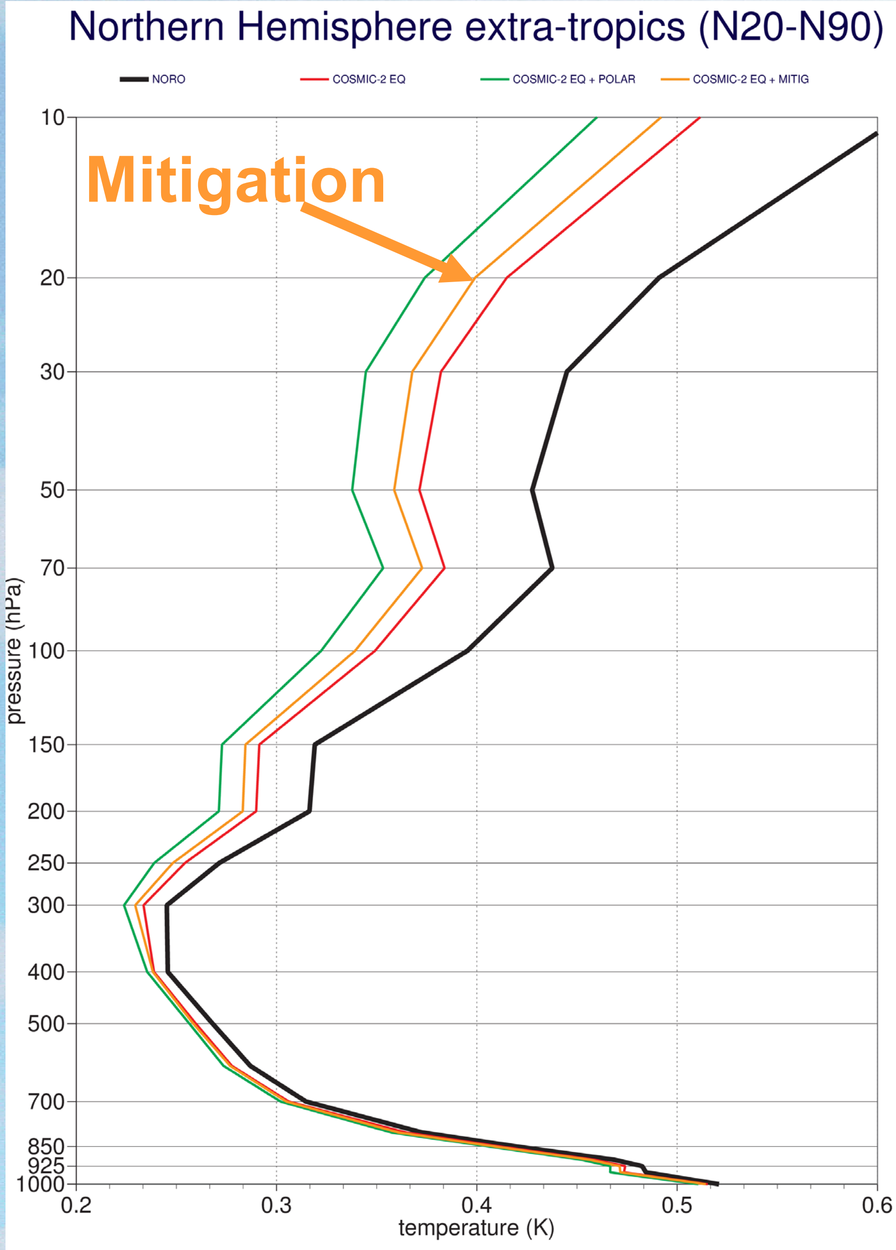
COSMIC-2 EQ + EPS-SG

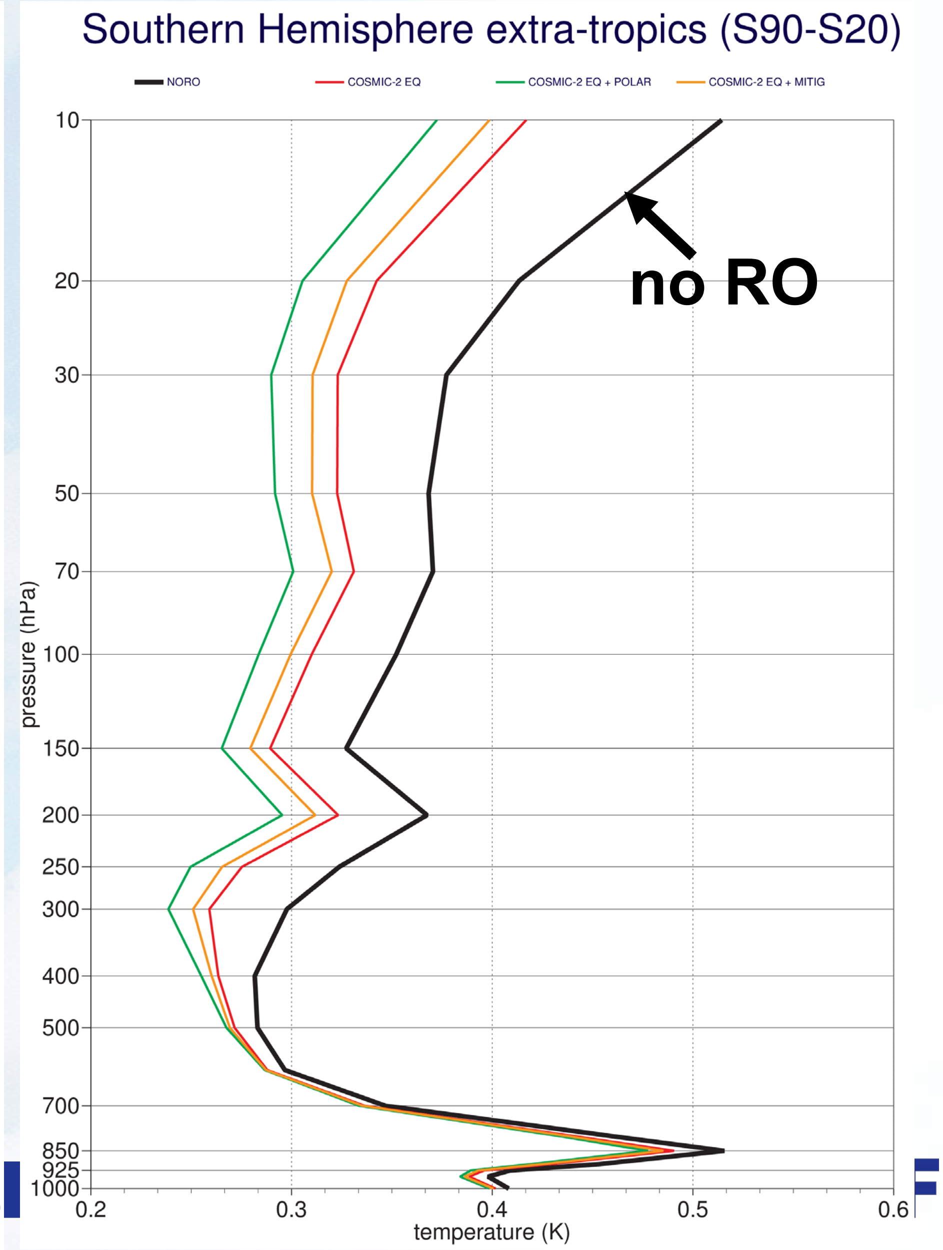
+ RO night + RO Early Morn

(~13300 per day)

© ECMWF

The possible mitigation of the lack of COSMIC-2 Polar (extra-tropics)



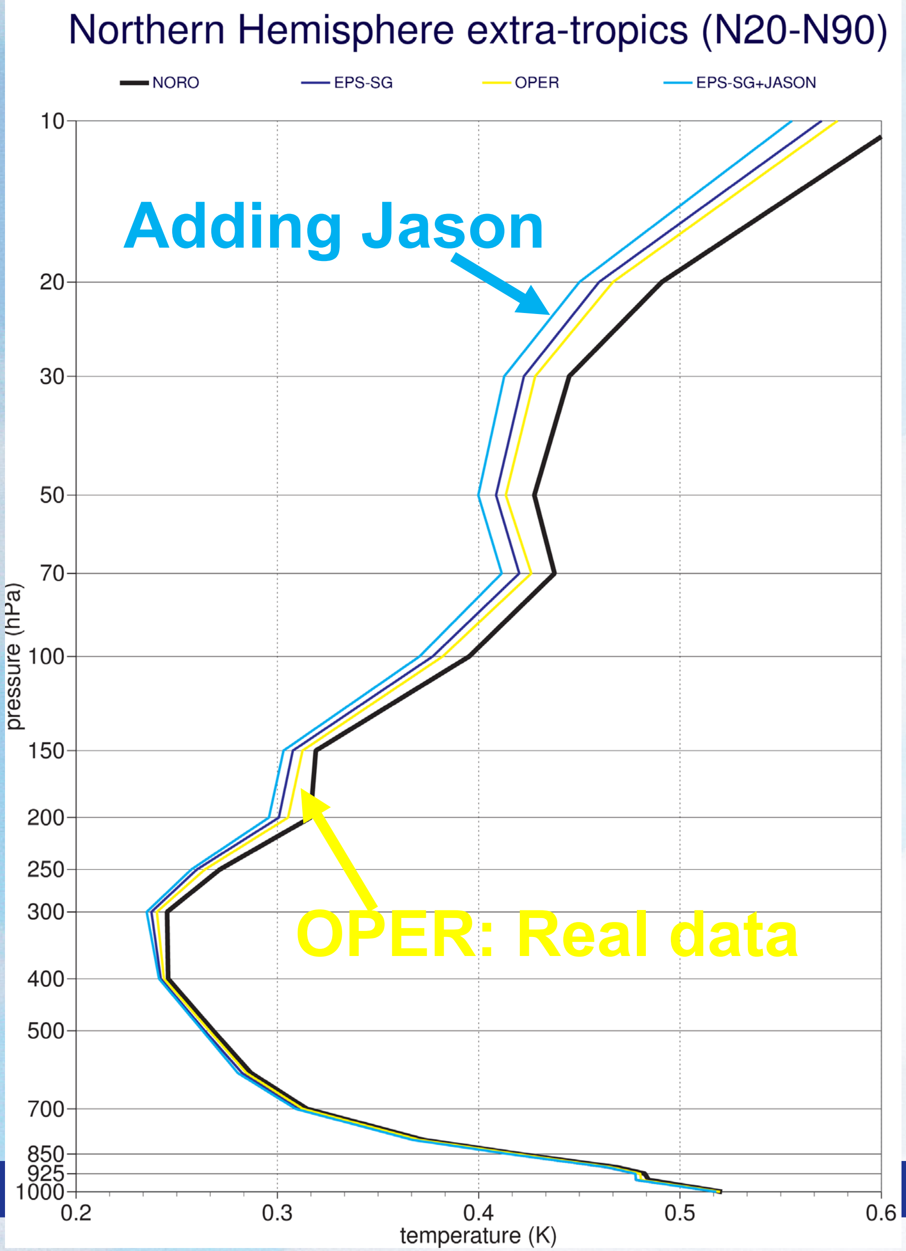


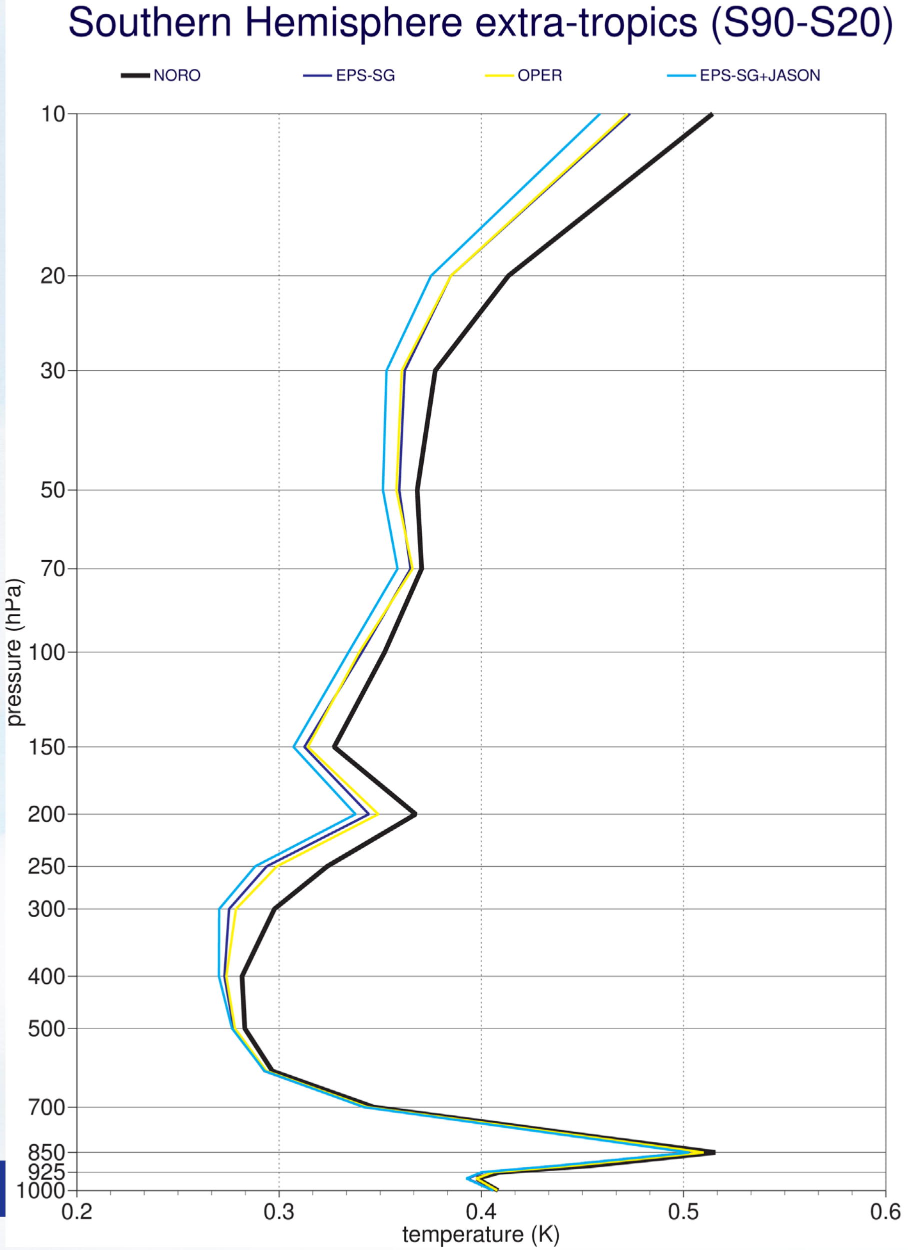
RESULTS: JASON

(Provides about ~1000 per day)

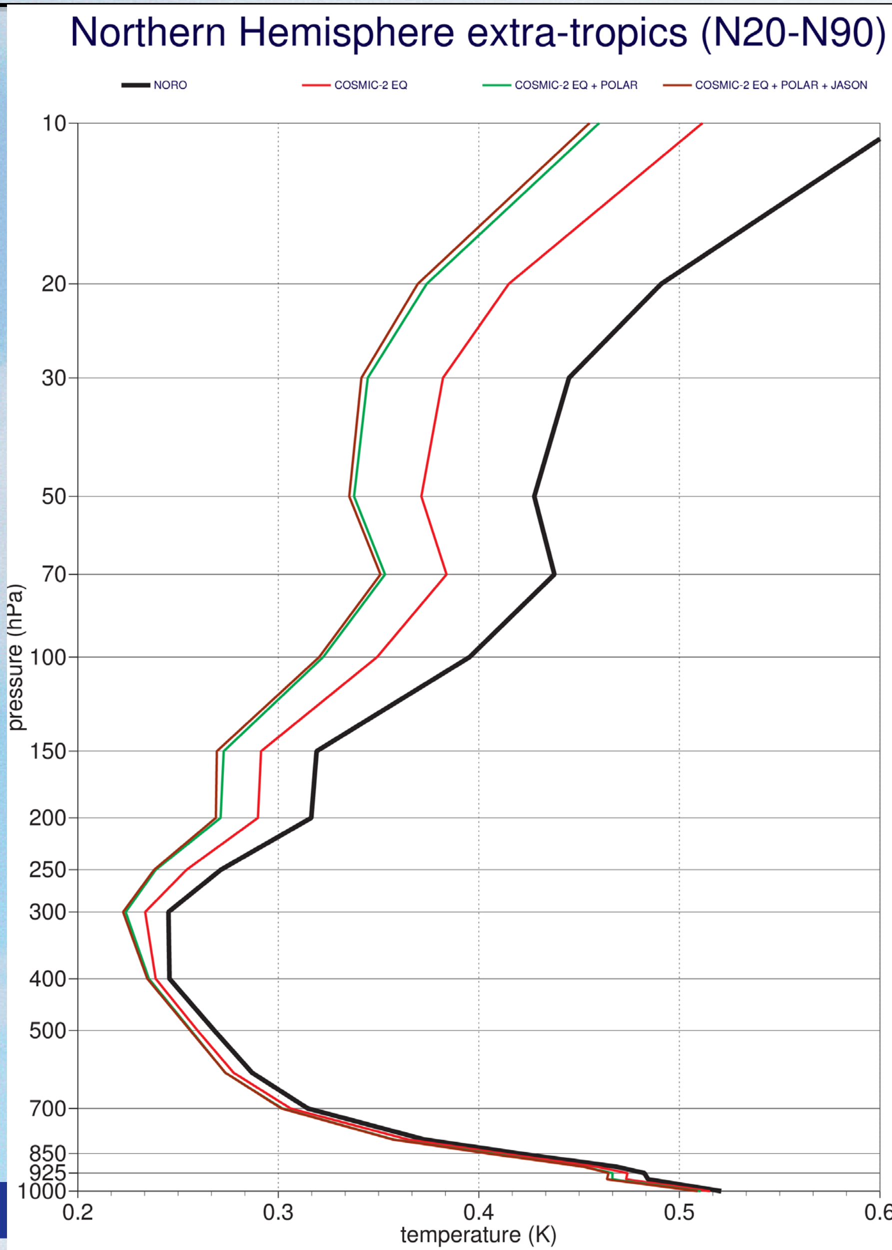
© ECMWF

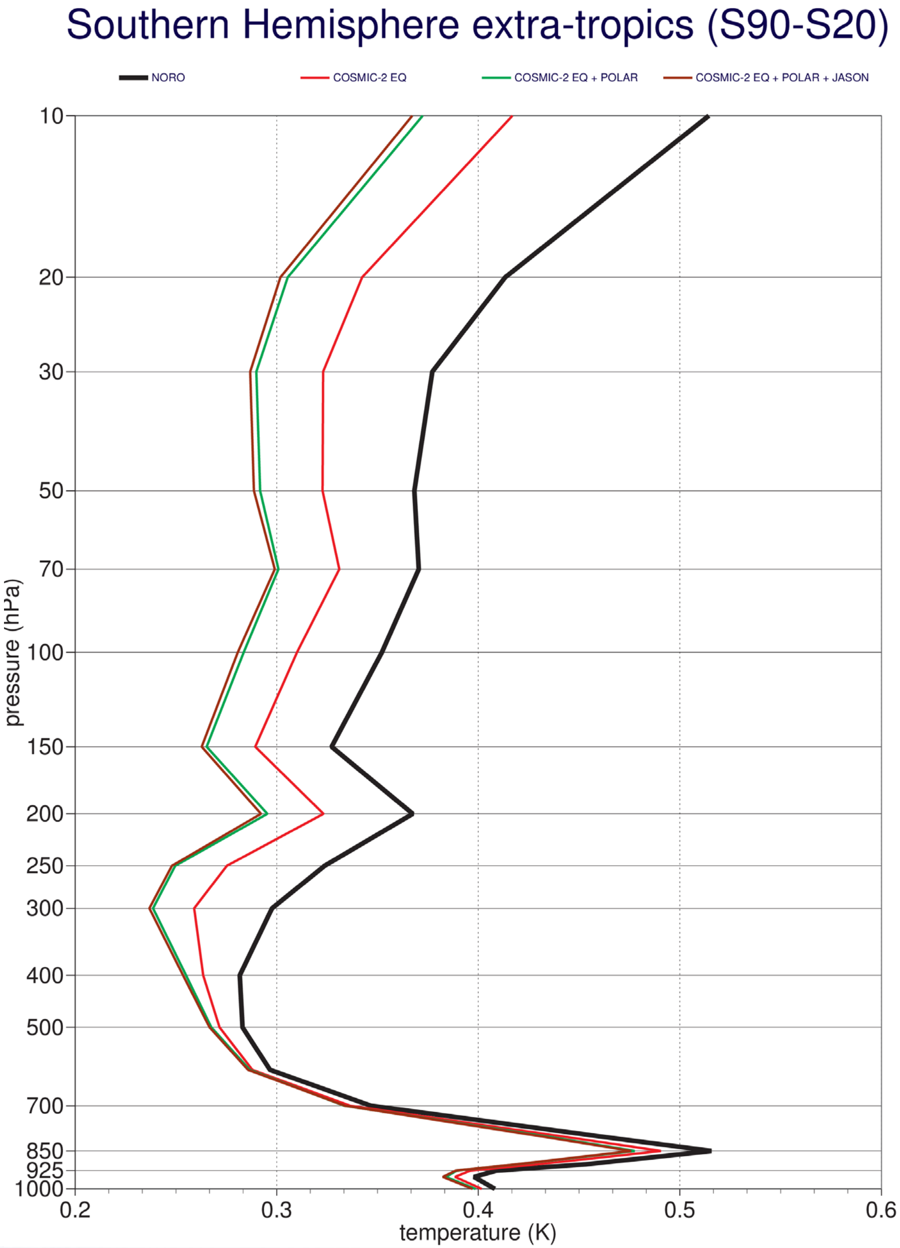
JASON with respect to EPS-SG and OPER (extra-tropics)





Adding JASON to COSMIC-2 (EQ+POL) +EPS-SG





SUMMARY, CONCLUSIONS

© ECMWF

Summary

- EDA approach has been outlined and differences with respect to OSSEs have been noted.
- Investigated 2000-19000 observations per day. EDA spread values are determined mainly by observation numbers, rather than orbits etc.
- We can quantify impact of both COSMIC-2 EQ and COSMIC-2 polar relative EPS-SG.
- 4 sun-synchronous RO satellites cannot compensate for the loss of COSMIC-2 Polar.
- Jason-CS and EPS-SG together has greater impact than the current operational data.
- Jason-CS is particularly important in the absence of COSMIC-2 polar

© ECMWF

Working groups

- **I have not looked at the new COSMIC-1 data**. I would appreciate the NWP sub-group group to give a view on:
  - NWP impact
  - if the change should be made, do we need more time, ….
- Status of COSMIC-2 Polar.
- Recommend New Project to CGMS: to compare EDA approach with OSSE approach?
- I'm still unsure whether we need refractivity measurements.
- Space weather/NWP: Convergence of observation operators. 2D neutral bending angle operators and slant TEC operator have many similarities. Opportunities to work together.

© ECMWF