Status on the operational assimilation of GNSS-RO data at ECMWF

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Thanks to Noureddine Semane

EUMETSAT ROM SAF RADIO OCCULTATION METEOROLOGY

ECMWF

Outline

1. Usage of GNSS RO observations
2. How do we assimilate the data?
3. Impact of data (FSOI)
4. ROMEX
5. Summary

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1. Usage of GNSS RO observations

Operational assimilation	# daily profiles	since
Spire	5500	2020 & 2022
Metop B/C	2 x 550	05/2013 & 03/2019
COSMIC-2	6000	03/2020
TanDEM-X	75	06/2015
TerrSAR-X	240	06/2015
Sentinel-6A	650	01/2022
KompSat-5	100	07/2019
GRACE C	100	01/2022

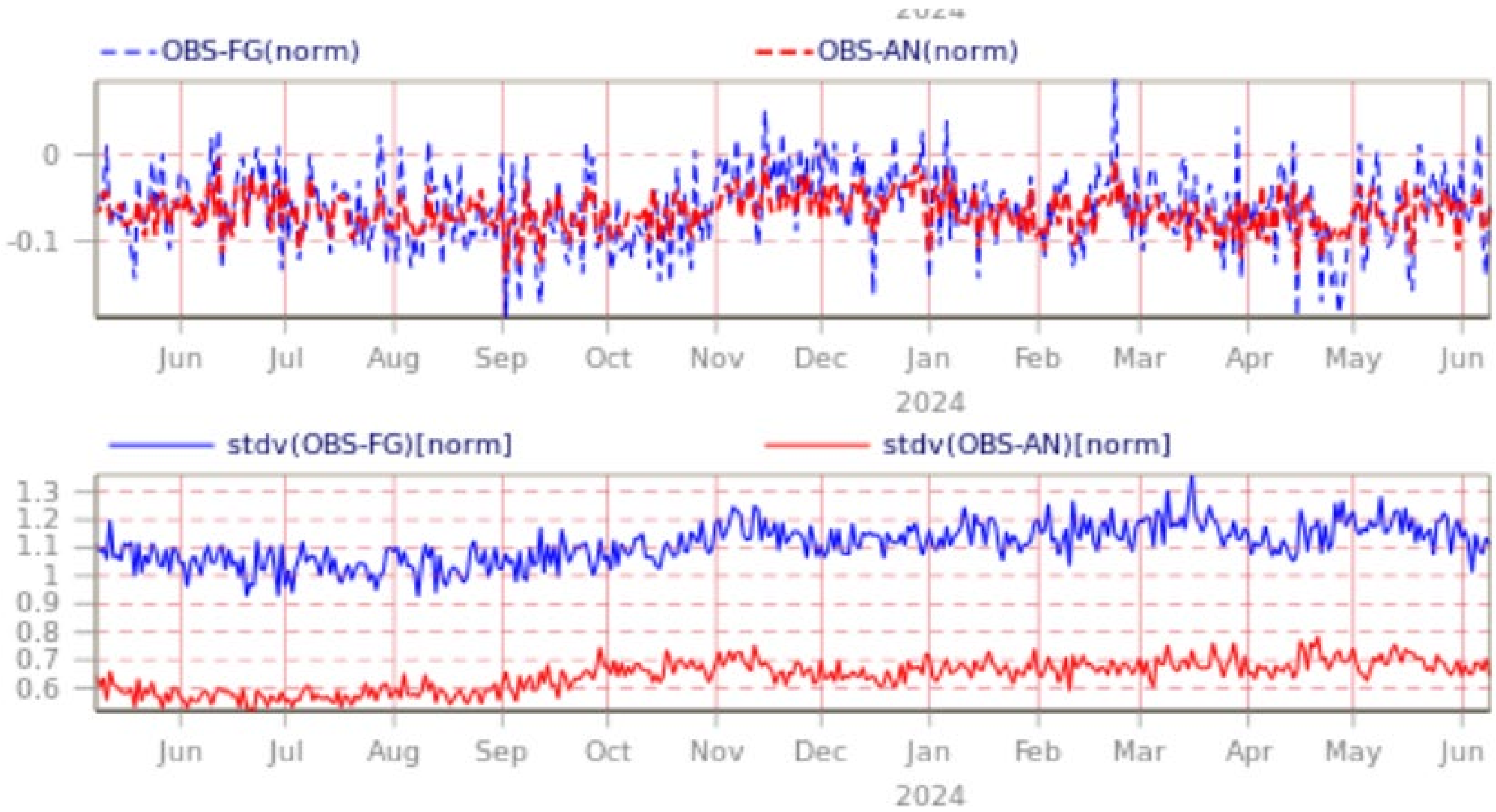
Monitoring
Fengyun 3 D
GRACE D
PAZ

Blocklisting
Sentinal-6A and GRACE C above 30 km
All GNSS-RO data above 50 km

Timeseries Spire

20km impact height

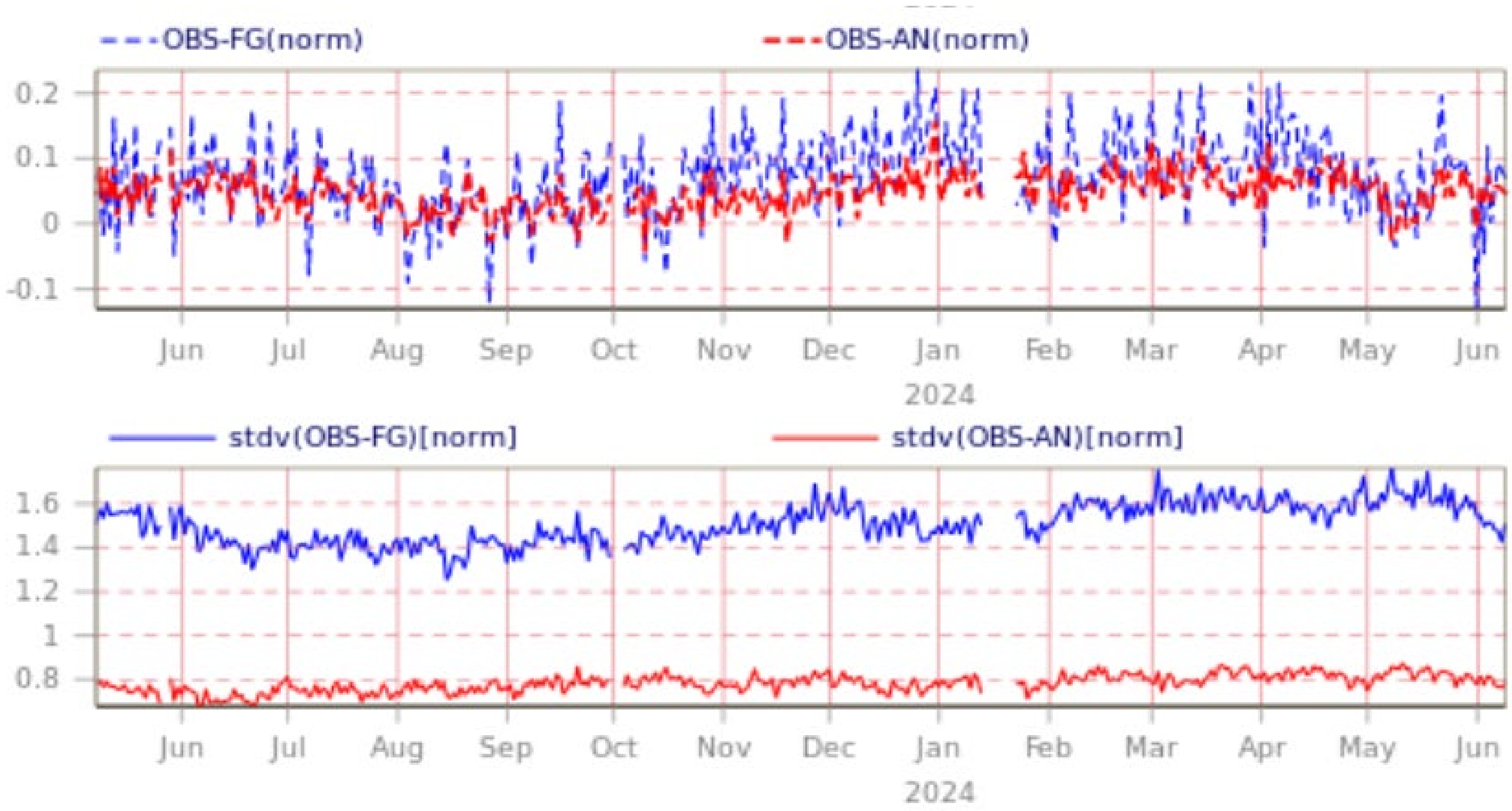
globally



Timeseries COSMIC2-E6

20km impact height

globally



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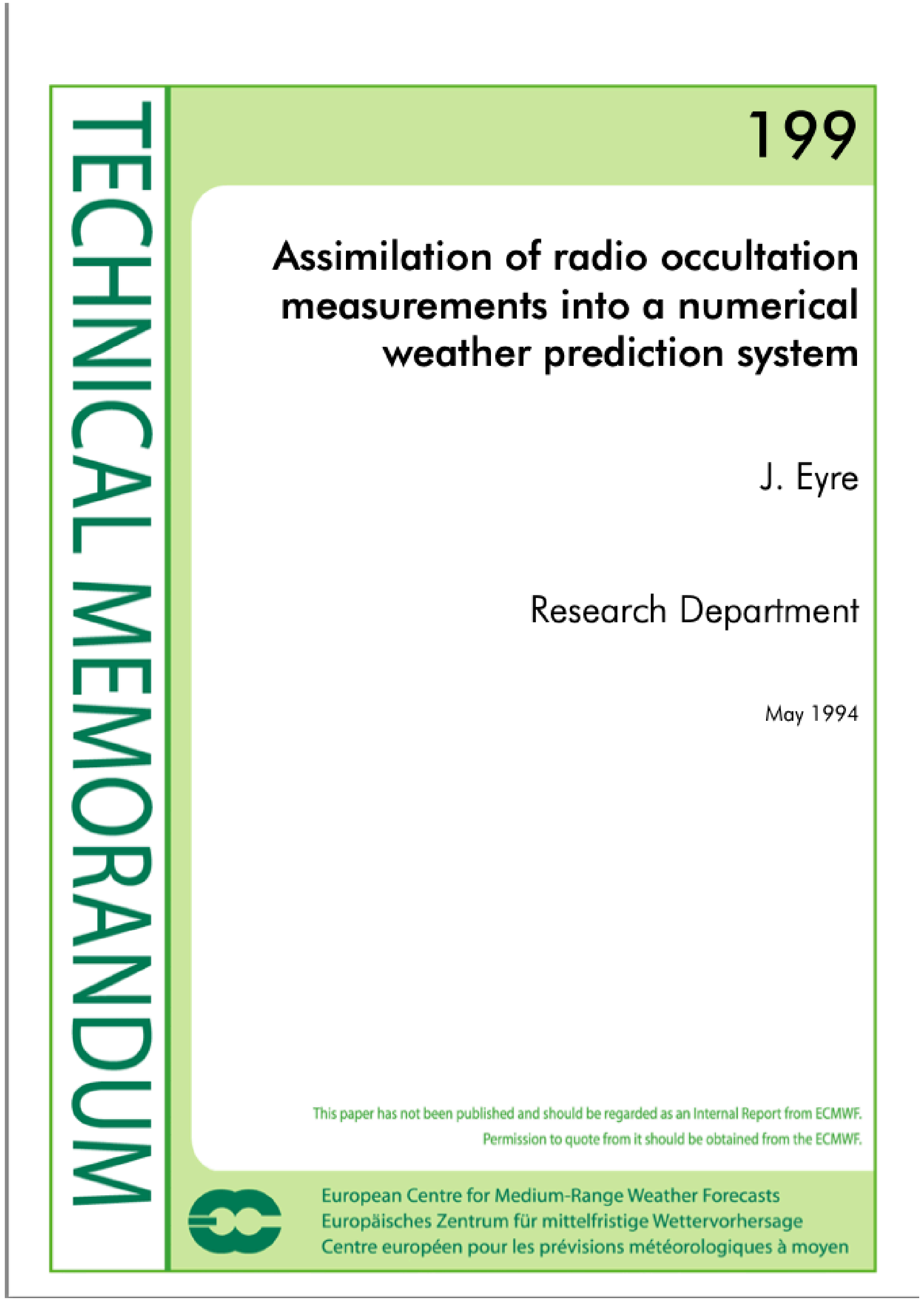
2. How do we assimilate GNSS-RO data

- ECMWF assimilates bending angles
- John Eyre suggested following options are reasonable
  - Refractivity profiles
  - Bending angle with a 1D or 2D operator

- GNSS-RO temperature and humidity **retrievals** not an optimal use of the measurement information.

- Most global NWP centers now assimilate **bending angle**.
- Comprehensive comparison of refractivity vs bending angle assimilation by Mike Rennie
  - Rennie, M.P. (2010), The impact of GPS radio occultation assimilation at the Met Office. Q.J.R. Meteorol. Soc., 136: 116-131. https://doi.org/10.1002/qj.521


TECHNICAL MEMORANDUM

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Assimilation of radio occultation measurements into a numerical weather prediction system

J. Eyre

Research Department

May 1994

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Permission to quote from it should be obtained from the ECMWF.

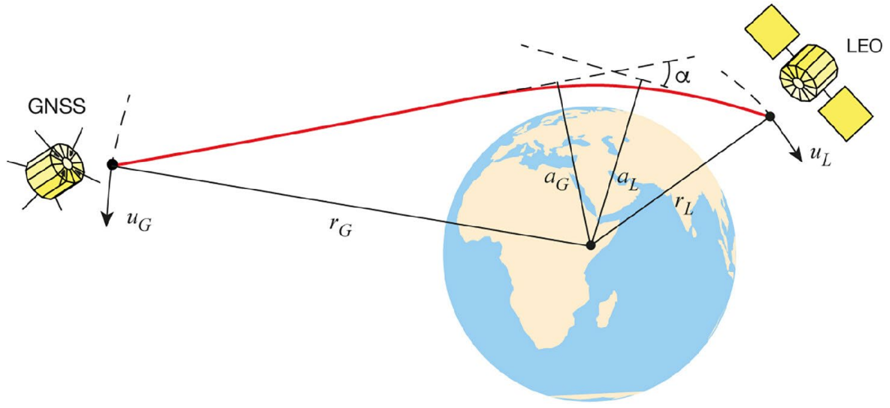
European Centre for Medium-Range Weather Forecasts
Europäisches Zentrum für mittelfristige Wettervorhersage
Centre européen pour les prévisions météorologiques à moyen

2. How do we assimilate GNSS-RO data

- ECMWF assimilates bending angles
- **Assimilating the data using a 2D Forward Operator**

Assimilating GNSS-RO with 2D Operators

- GNSS-RO is a limb measurement and the ray bending takes place over 100's of km in the horizontal
- The 2D operators take account of the real limb nature of the measurement, and this should reduce the forward model errors defined as



$$H(\mathbf{x_t}) - \mathbf{y_t} = \boldsymbol{\varepsilon}_\mathbf{f}$$

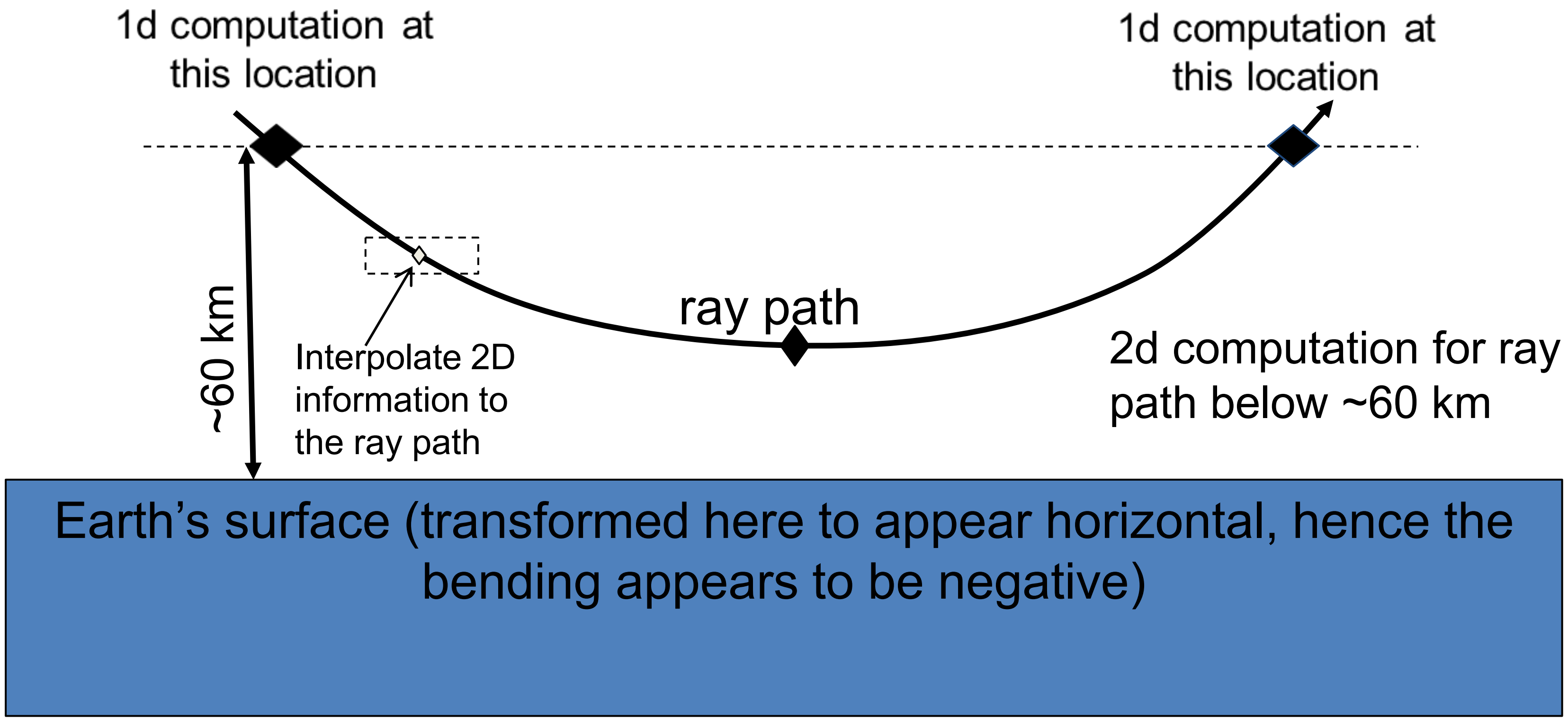
Forward model error

Noise free observation

Discrete representation of true state from model

- Reducing the forward model errors should improve our ability to retrieve information from the observation, but this must be balanced:
- **Extra Information versus Additional Computing Costs**.

2D assimilation approach



Computational cost

Occultation plane described by 31 profiles with 40 km separation, spanning 1200 km

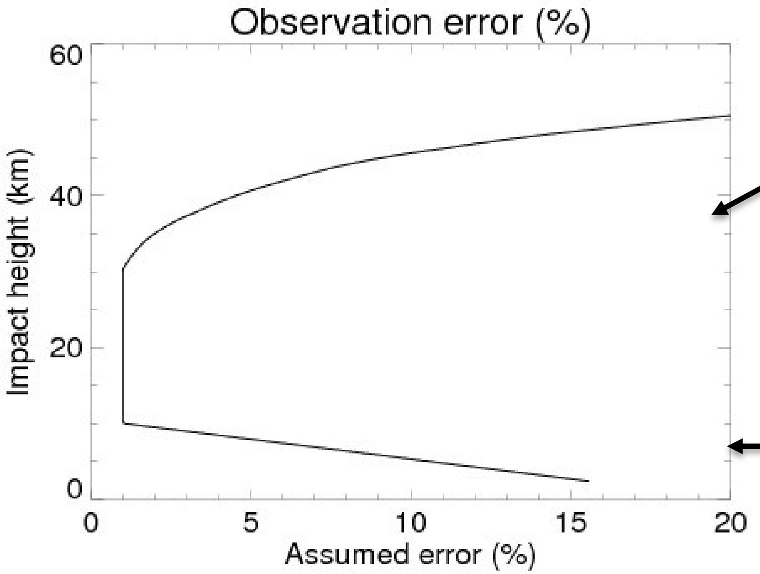
2. How do we assimilate GNSS-RO data

- ECMWF assimilates bending angles
- Assimilating the data using a 2D Forward Operator
- **Assignment of Observation errors**

Assumed covariance matrix, $\mathbf{R}$

$$J(\mathbf{x}) = \frac{1}{2}(\mathbf{x}-\mathbf{x}_b)^T \mathbf{B}^{-1}(\mathbf{x}-\mathbf{x}_b) + \frac{1}{2}(\mathbf{y}_m - H(\mathbf{x}))^T \mathbf{R}^{-1}(\mathbf{y}_m - H(\mathbf{x}))$$

- The $\mathbf{R}$ determines the weight we give to the GNSS-RO in the 4D-Var. We use a relatively crude global model at ECMWF. It is the same for all GNSS-RO instruments, and it ignores vertical error correlations

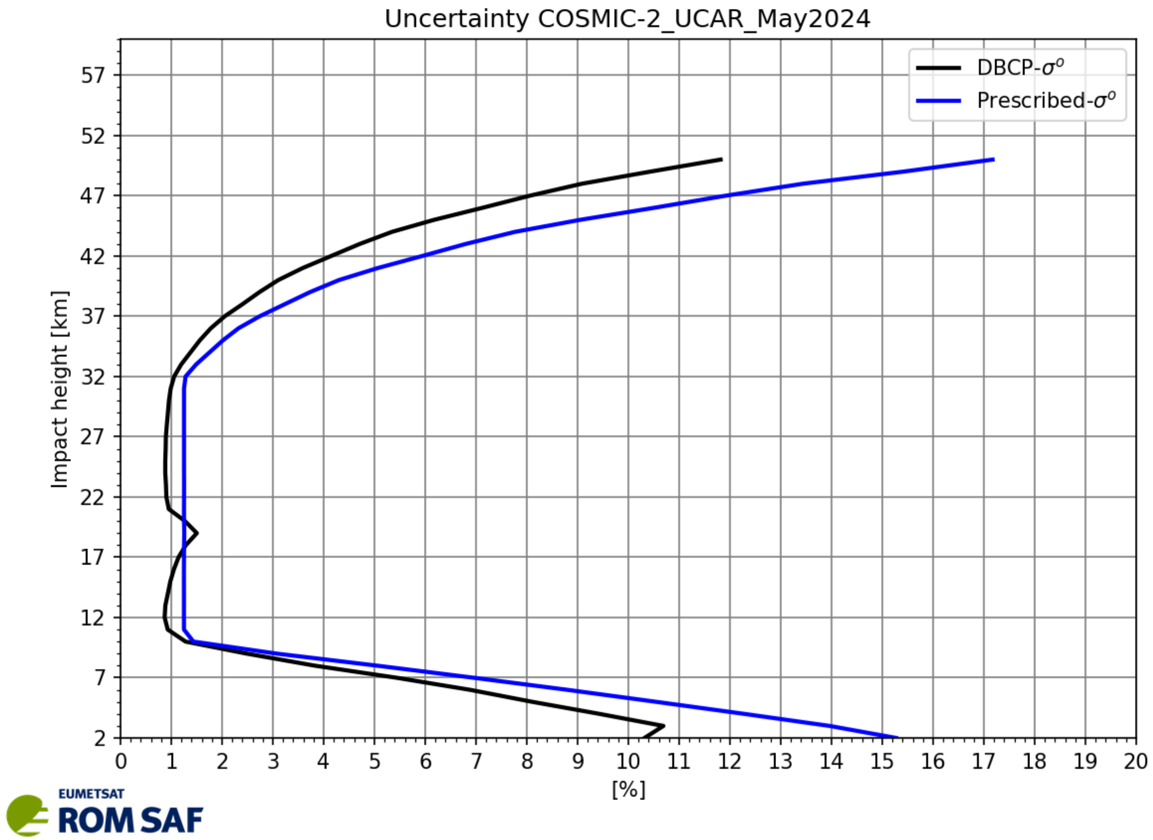


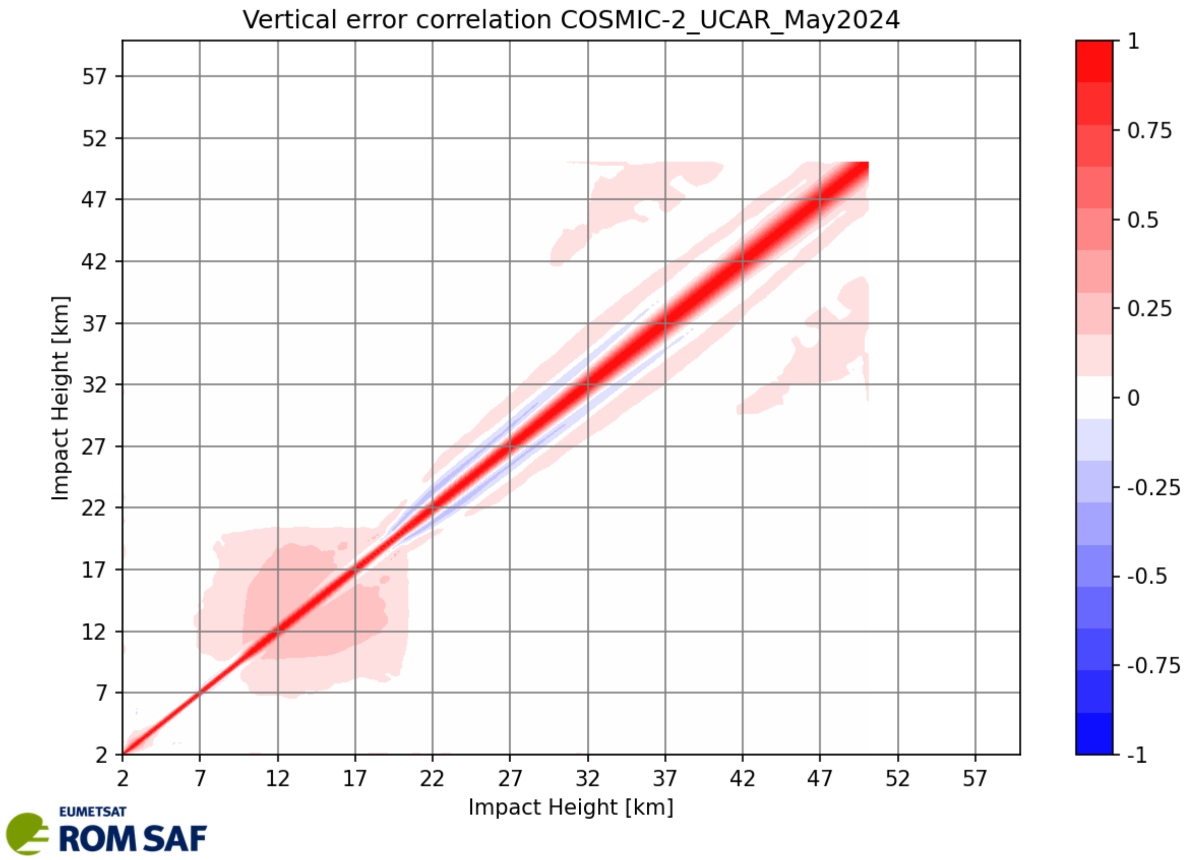
Above 10 km, 1.25% is used until this reaches the 3 microradian lower limit

Uncertainty is assumed to be 20% of the observed bending angle value at an impact height of 0 km, with the percentage falling linearly with impact height to 1.25% at 10 km.

- We can compare the ECMWF uncertainty model with a “diagnosed” $\mathbf{R}$ matrix – Desroziers, Three Cornered Hat. See, *for example*,
  - Todling, R, Semane, N, Anthes, R and S Healy (2022). The Relationship Between Two Methods for Estimating Uncertainties in Data Assimilation, QJRMS, available from: https://doi.org/10.1002/qj.4343

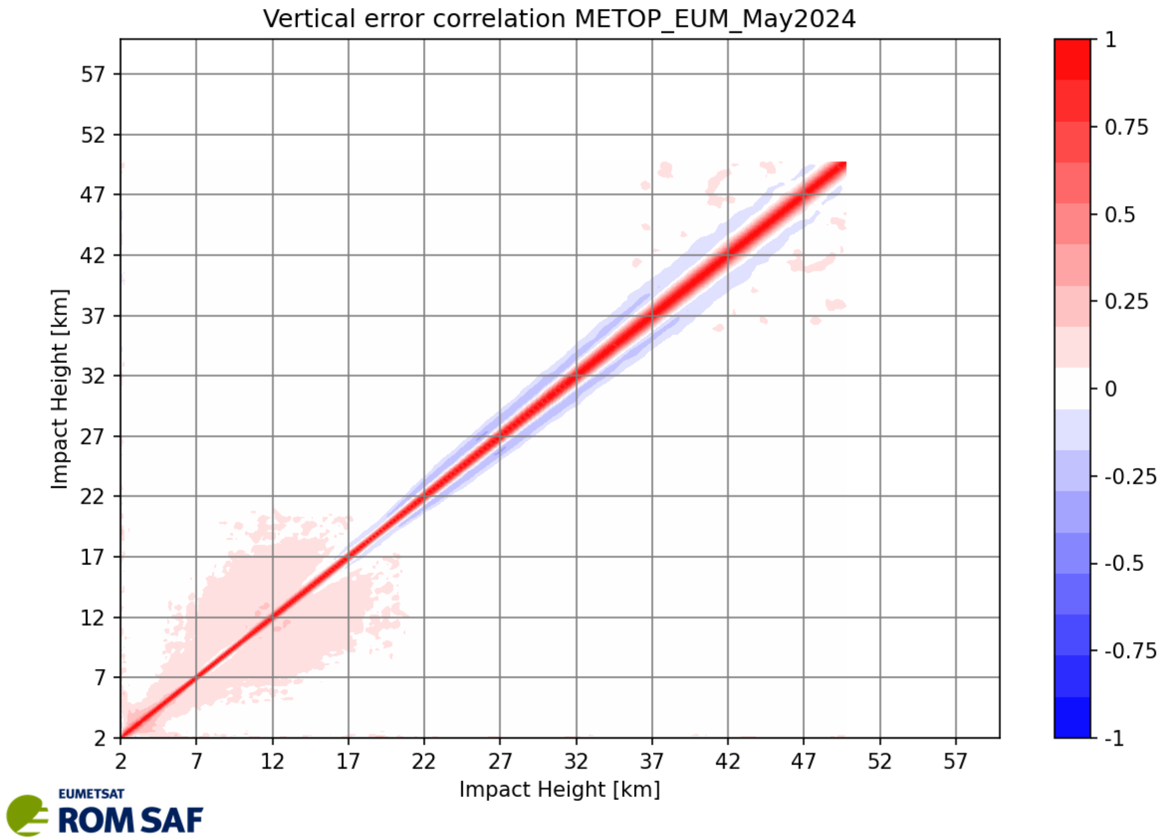
Comparing with diagnosed R matrix

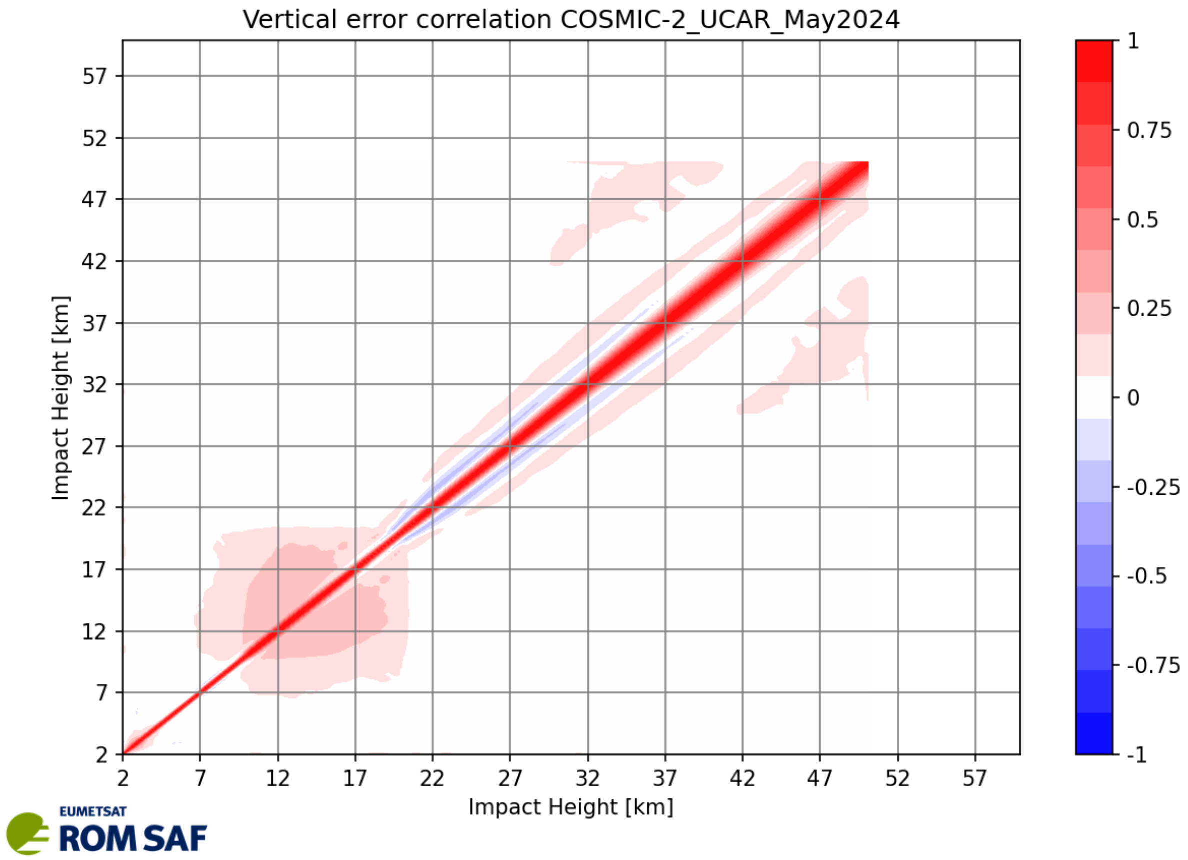




Diagnosed correlation matrix for GRAS and COSMIC-2

GRAS





2. How do we assimilate GNSS-RO data

- ECMWF assimilates bending angles
- Assimilating the data using a 2D Forward Operator
- Assignment of Observation errors
- **Updates in new operational IFS cycle 49R1**

Switch on stratospheric **balance above 20 km**

- Balance constraint above 20 km means that the stratospheric sounding instruments can generate geostrophical-balanced increments from the start of the assimilation window, instead of relying on just the model to develop them from univariate increments during the window integration.

- Multivariate balances add variance to the background errors and observations can be fit more closely.

Extending GNSS-RO assimilation in the vertical from **50 km to 60 km.** Improving the GRAS and COSMIC-2 uncertainty model in the stratosphere

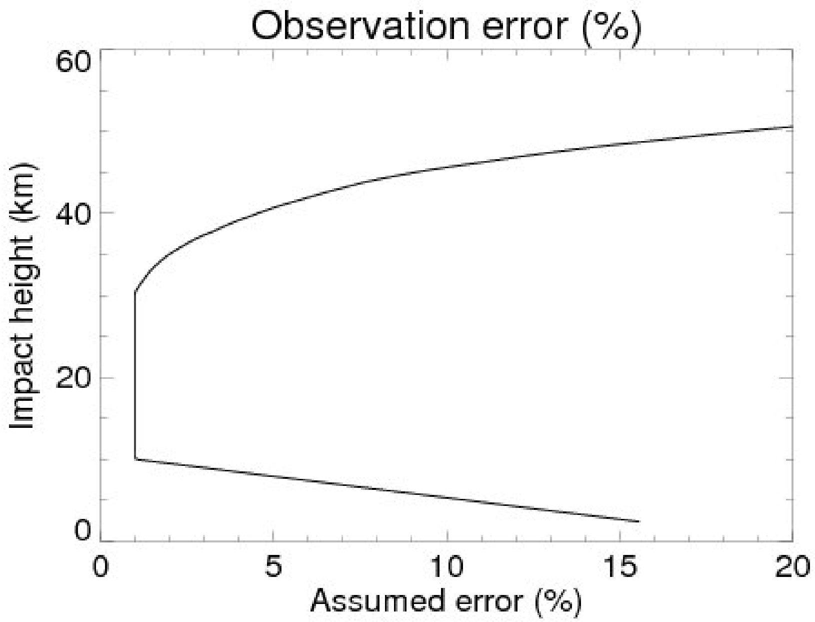
- Increasing GNSS-RO observation usage and weight improves their efficacy as anchor observations in the stratosphere (Only GNSS-RO, AMSUA and ATMS are currently sensitive to the 50-60 km layer).

- **New scaling of GNSS-RO observation error statistics** is based on a tuneable GNSS-RO observation uncertainty model (specifically developed for 49R1).

New scaling of GNSS-RO observation errors

- Scaling is applied only for GRAS/COSMIC-2
- Reducing the σ_o lower limit by 25% from 3 to 2.25 microradians

Global observation error model: only includes a variation in the vertical as function of impact height



2. How do we assimilate GNSS-RO data

- ECMWF assimilates bending angles
- Assimilating the data using a 2D Forward Operator
- Assignment of Observation errors
- Updates in new operational IFS cycle 49R1
- **Quality control**

Quality control

- The corrections to the atmospheric state by the DA system are driven by the (o-b) departures = $\mathbf{y_m} - H(\mathbf{x})$

- We would expect these departures to be comparable to the standard deviation of the observation error, σ_o (=square root of the diagonal of the $\mathbf{R}$ matrix).

- But in some cases the departures are much bigger because of gross errors on the observation, so $|\mathbf{y_m} - H(\mathbf{x})| > k\sigma_o$ where k is large (>5)

- We use VarQC to remove gross observation errors

2. How do we assimilate GNSS-RO data

- ECMWF assimilates bending angles
- Assimilating the data using a 2D Forward Operator
- Assignment of Observation errors
- Updates in new operational IFS cycle 49R1
- Quality control
- **Tangent point drift included**

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Running OSE experiments

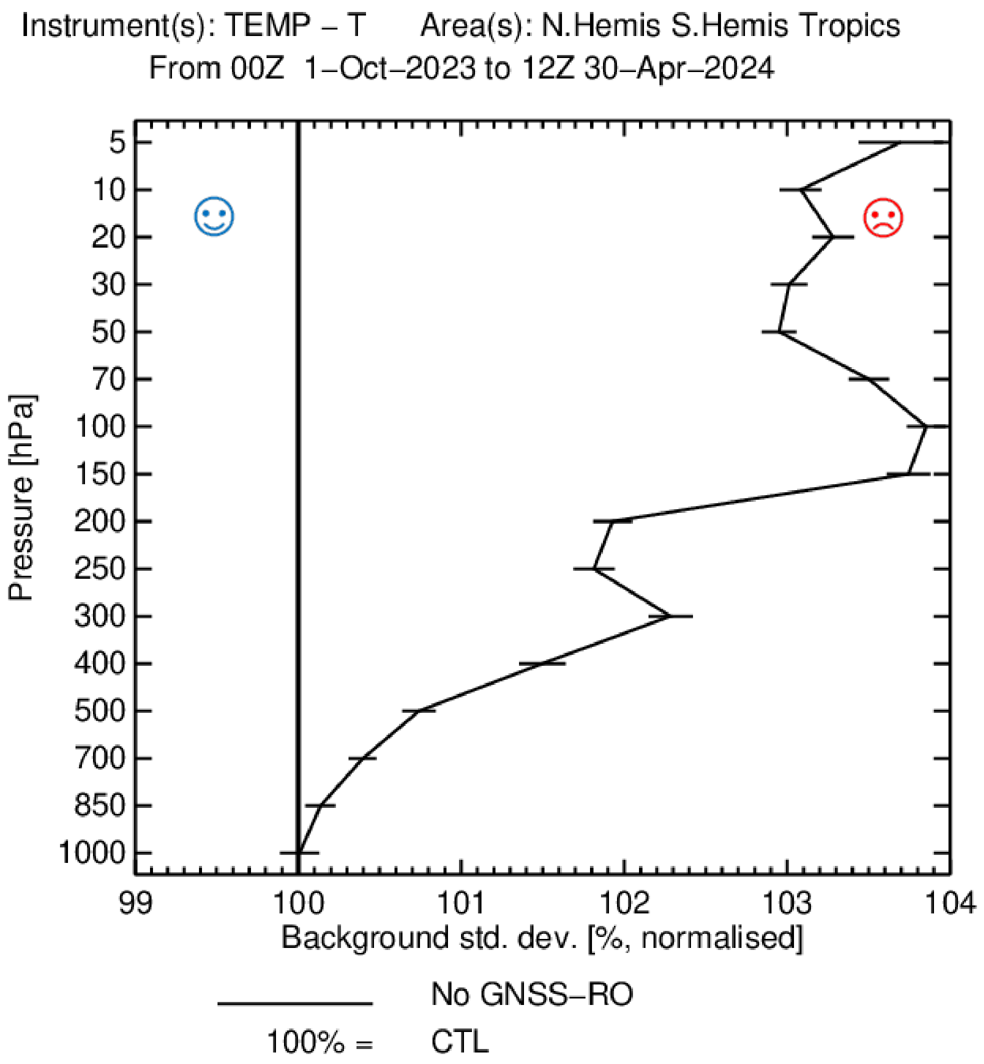
Sean Healy

- Removing GNSS-RO observations

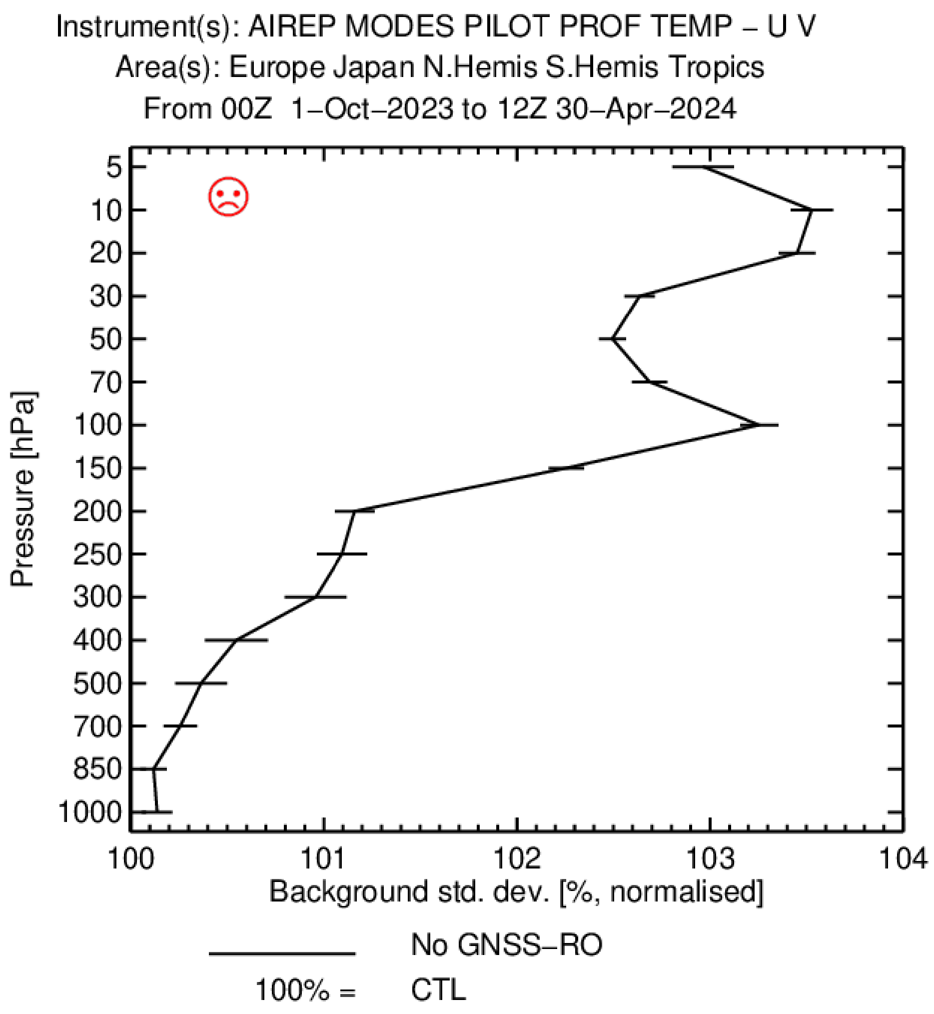
Impact on short-range forecasts (12 hours)

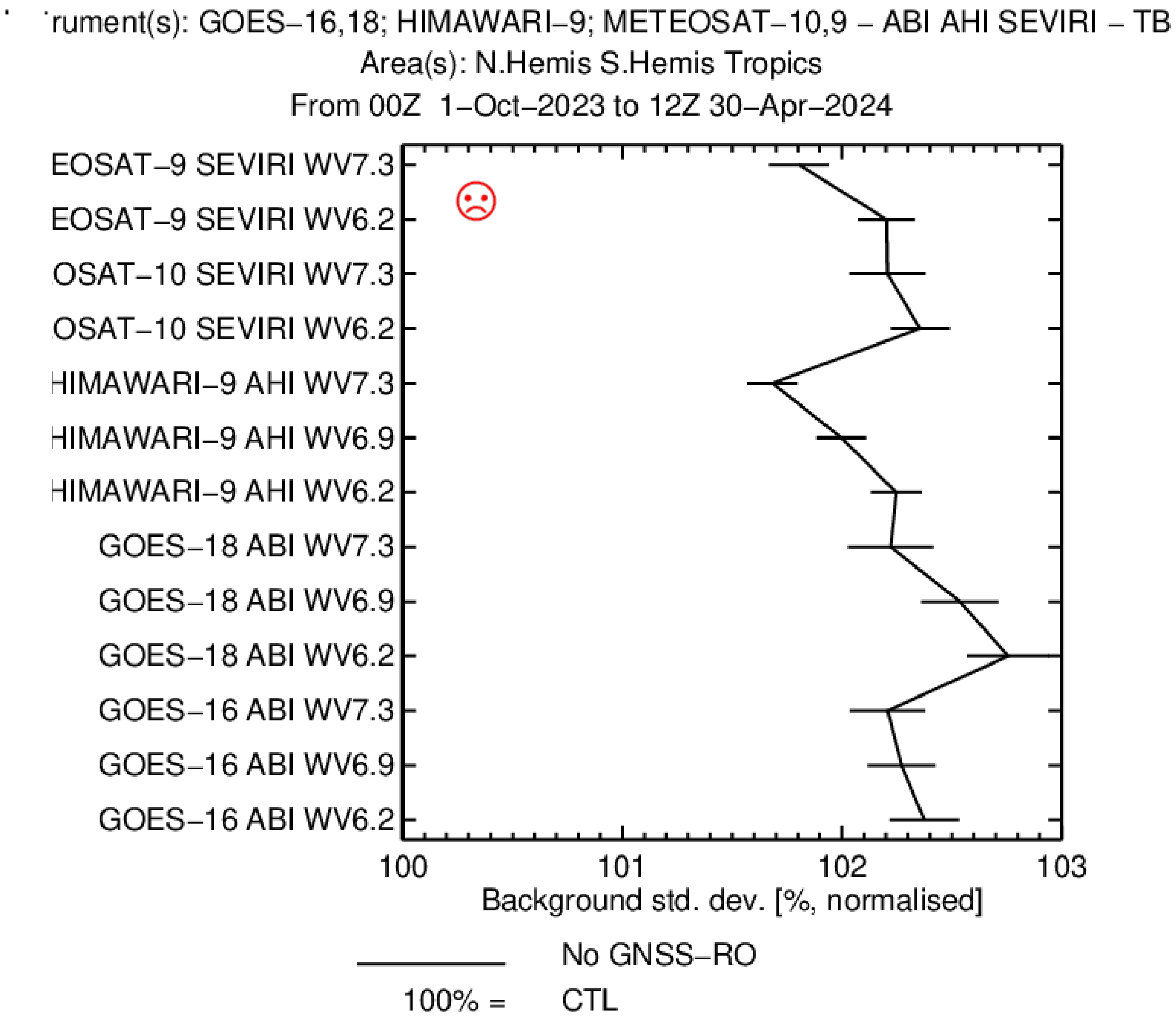
- If the forecasts are improved with GNSS-RO, the **departure statistics** of other observation types should be improved. For example, we should fit radiosondes temperatures more closely

- **Globally averaged statistics**
  - 100 % = neutral impact
  - < 100 % = positive impact ☺
  - > 100 % = degradation ☹

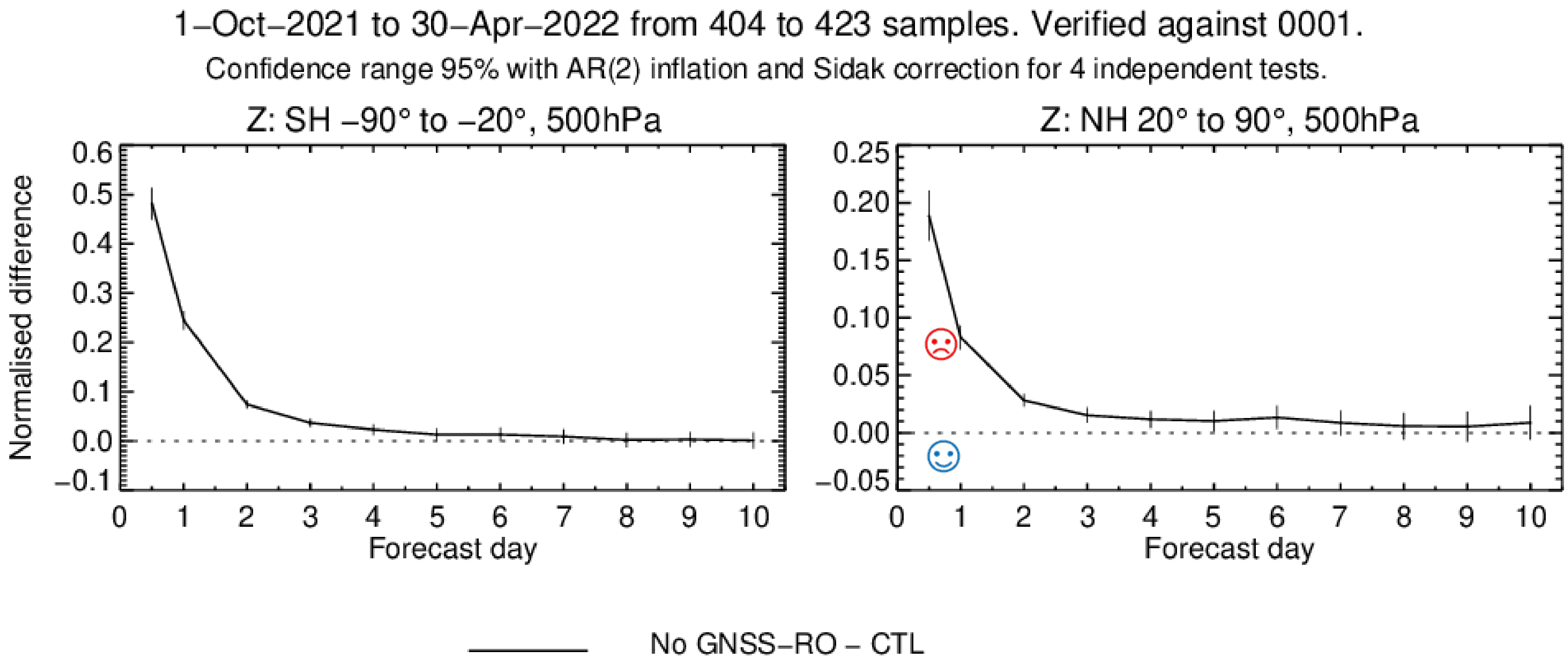


Impact on wind and humidity





Impact on medium-range forecasts – Geopotential @ 500 hPa



Running extended experiments including RO observations

- Work done together with Frederic Vitart (ECMWF) and Qiang Fu (University of Washington)

Overview

- GNSS-RO has a significant impact on both random and systematic analysis and forecast errors in the stratosphere

- **Qiang Fu**: Qu. *What is the GNSS-RO impact on extended-range forecasts?*

- New set of experiments now running at ECMWF designed to explore this question
  - Run the extended-range forecasting system with different initial conditions, generated both with and without GNSS-RO being assimilated
  - Consider NH hemisphere winters since 2020 – the year when GNSS-RO observation numbers increased with COSMIC-2, Spire, …
  - Period 1, October 1, 2020 to April 30, 2021
  - Period 2, October 1, 2021 to April 30, 2022
  - Period 3, October 1, 2022 to April 30, 2023

- Run one extended-range experiment per week for each period

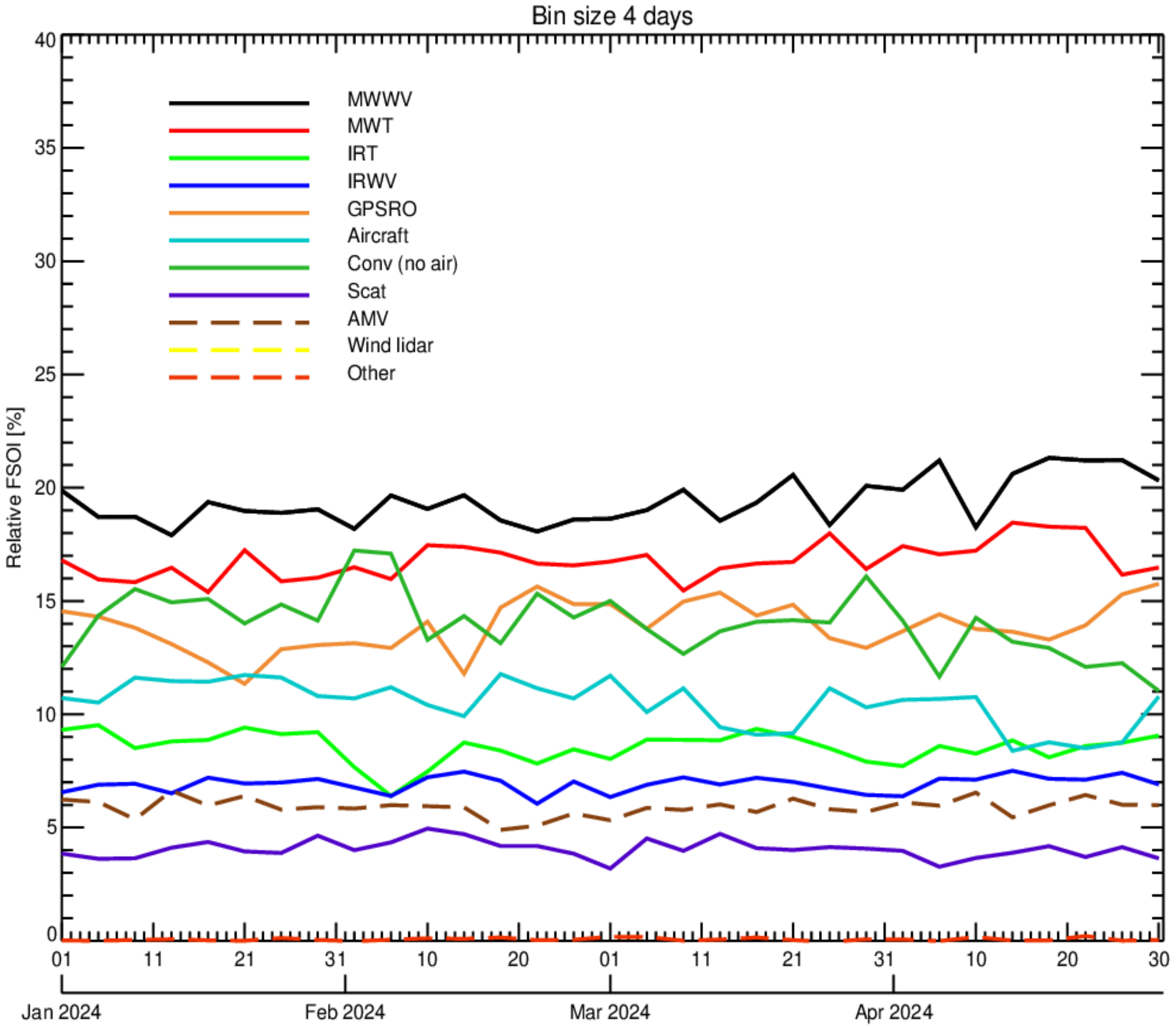
Forecast sensitivity to observation impact (FSOI)

- This is a **globally integrated scaler** quantity that sumarises how observing systems contributed to the reduction of 24 hour forecast errors (surface pressure, wind, temperature). Theory outlined here
  - LANGLAND, R.H. and BAKER, N.L. (2004), Estimation of observation impact using the NRL atmospheric variational data assimilation adjoint system. Tellus A, 56: 189-201. https://doi.org/10.1111/j.1600-0870.2004.00056.x
  - Cardinali, C., 2009: Monitoring the observation impact on the short-range forecast. *Q. J. R. Meteorol. Soc.*, 135, 239-250, doi:10.1002/qj.366
  - Eyre, J.R., 2021: Observation impact metrics in NWP: A theoretical study. Part I: Optimal systems. *Q. J. R. Meteorol. Soc.*, 147, 3180-3200, doi:10.1002/qj.4123

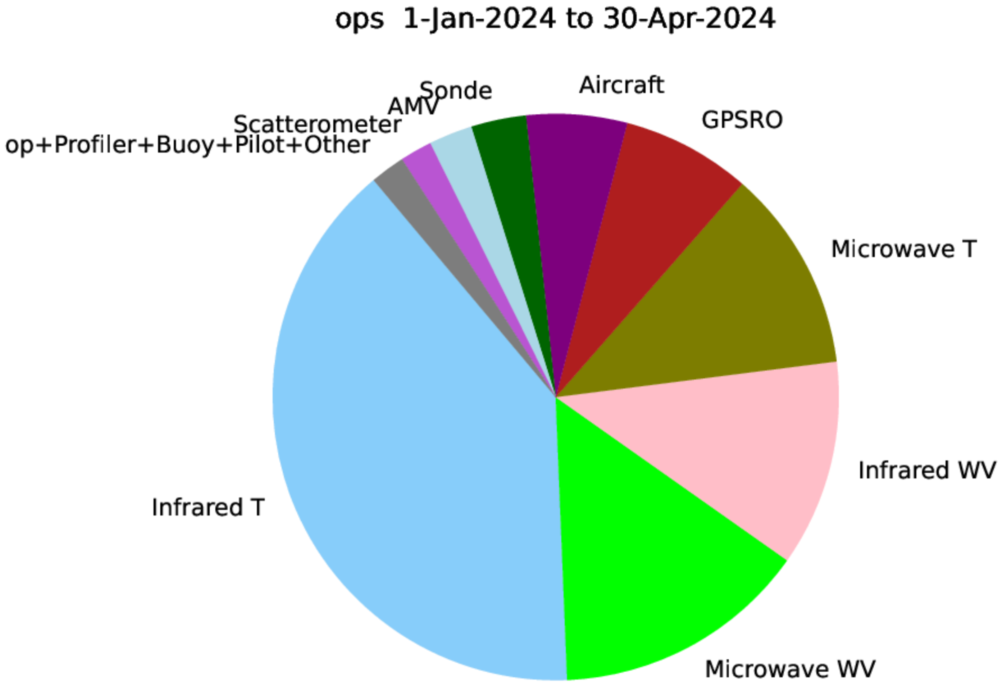
- Usually provides information that is consistent with OSEs, but can produce inconsistent results, where the FSOI of an observation type increases, but the quality of forecasts is degraded

- Best to use FSOI alongside impact experiments

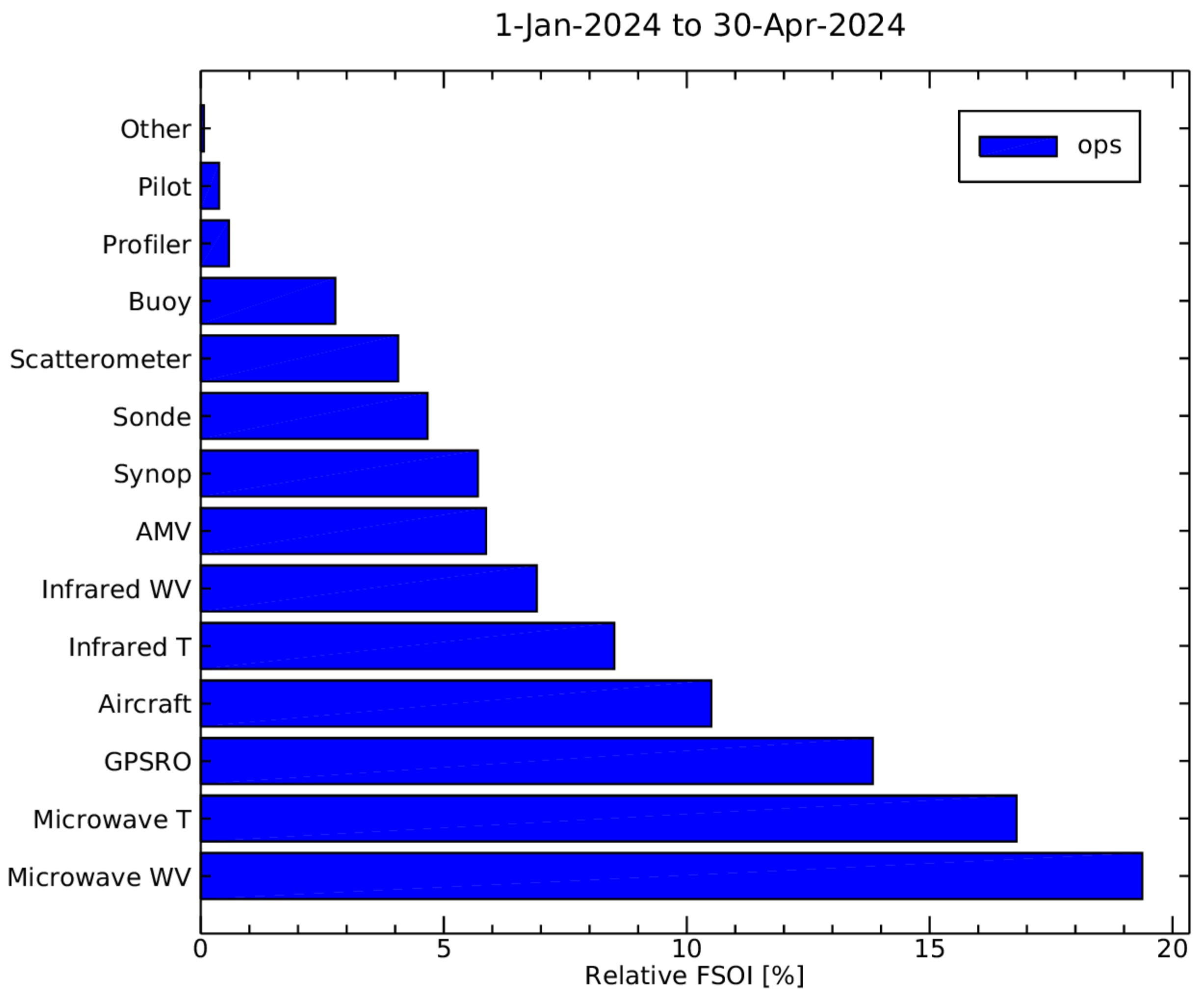
FSOI time series



FSOI in 2024



number



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4. Radio Occultation Modeling Experiment (ROMEX)

- Initiative coordinated through IROWG, started in 2023
- RO data providers have sent their Level 1-2 data (excess phase, bending angle) to EUMETSAT.
- ROMEX collected 30,000-40,000 RO profiles per day for September-November 2022.
- EUMETSAT has processed all the data and submitted the bending angle data to ROM-SAF.
- Availability of data since mid-February to NWP community

First results of data assimilation experiments

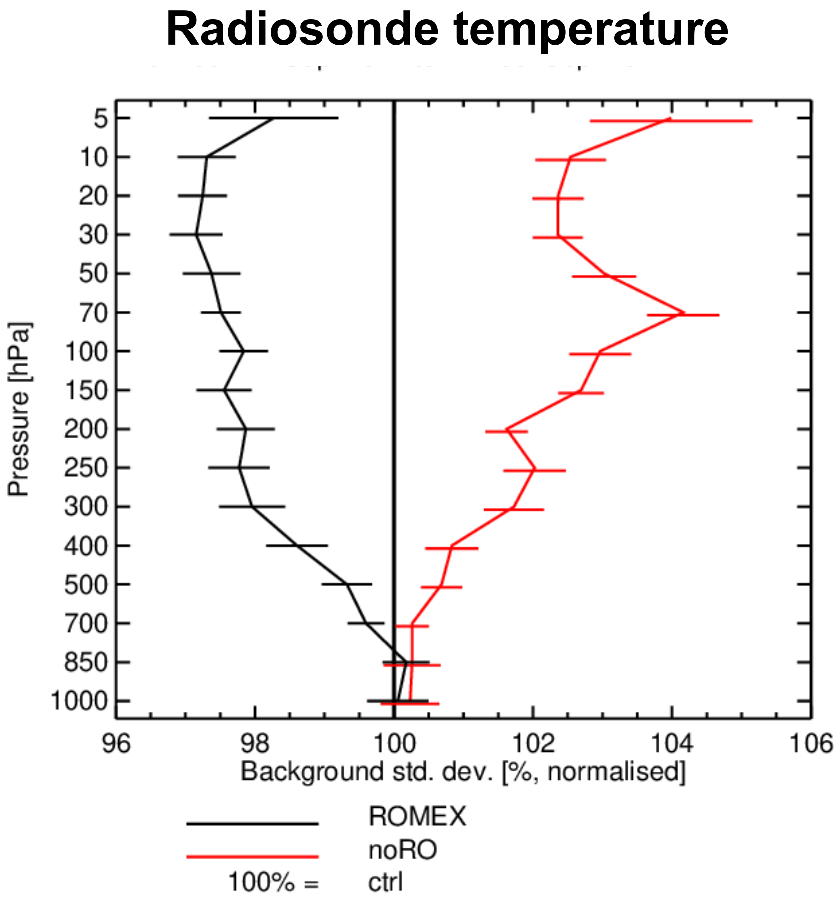
Setup

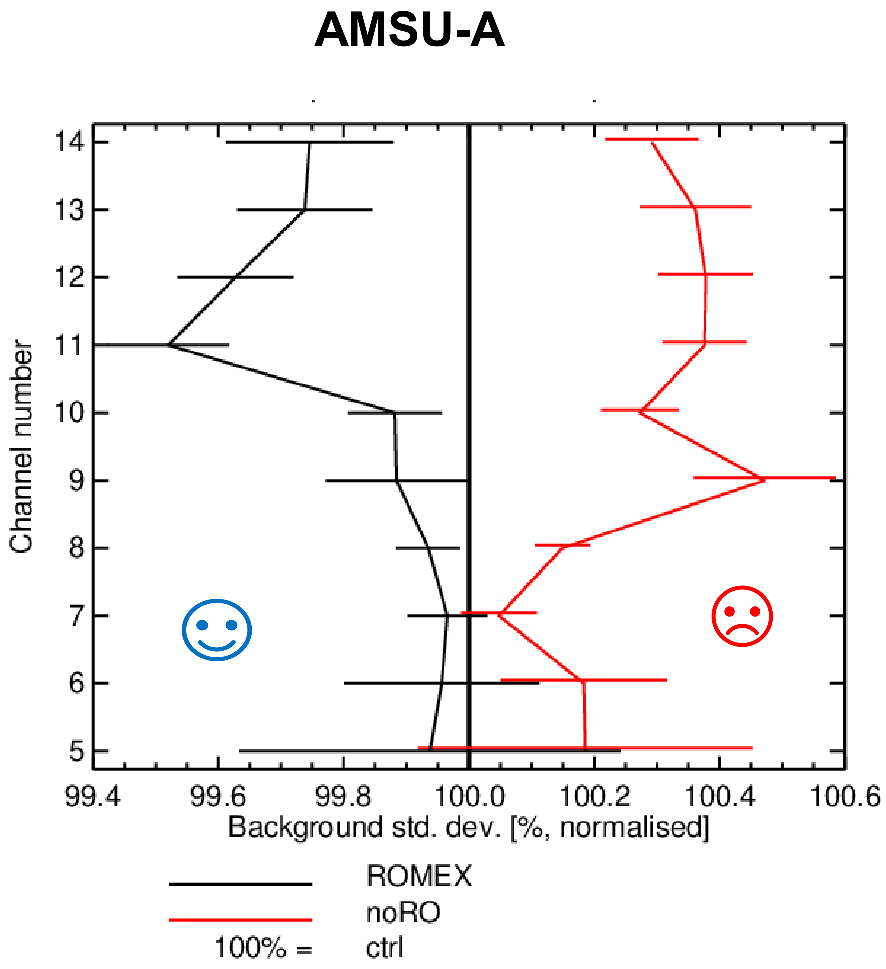
- Using operational model cycle of the IFS
- Run data assimilation experiments for Sept 2022

Verification against operational analysis and observations

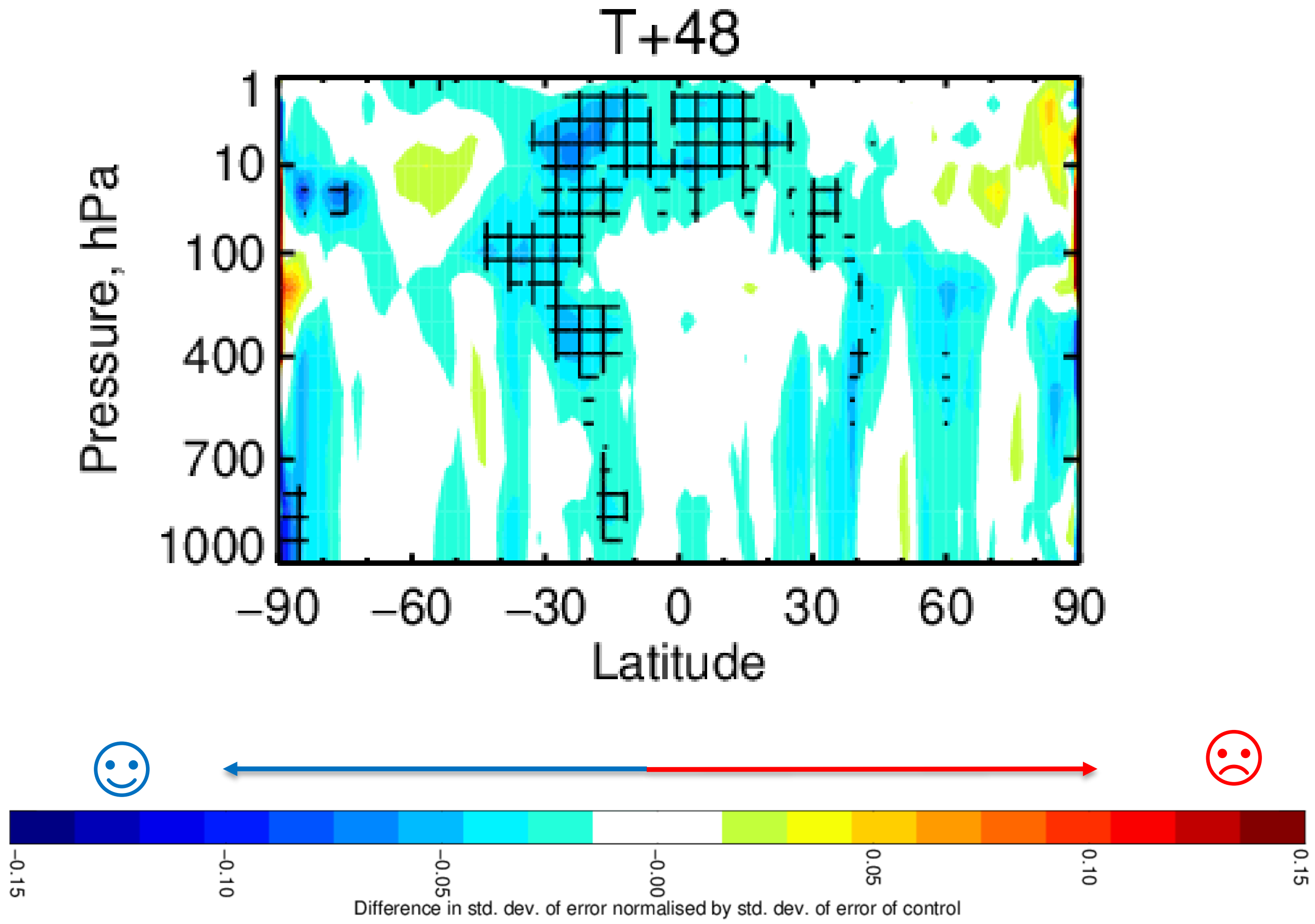
- Fits to independent observations (globally)
- Forecast scores

Impact on short-range forecasts (12h):
Change in std dev in First Guess departures (globally)





Impact on medium-range forecasts:
Difference in Std dev of forecast error for Geopotential
ROMEX - control



ROMEX: Summary

- Good impact on temperature, geopotential and wind in short-range and medium-range forecast scores in terms of std dev.
- Slight increase in mean error for Geopotential height (2- 5 m), caused by cooler background
- Ongoing investigation of cause and assessment of the meaning of this change
  - Doing sensitivity studies of forward operator (refractivity coefficient)

Setup EDA experiments

Aim

Test if the addition of real GNSS-RO data reduces the EDA spread as discussed in Harnisch et al 2013 using simulated data.

Experiments

control:

Operational data available for the period, including the GNSS-RO data

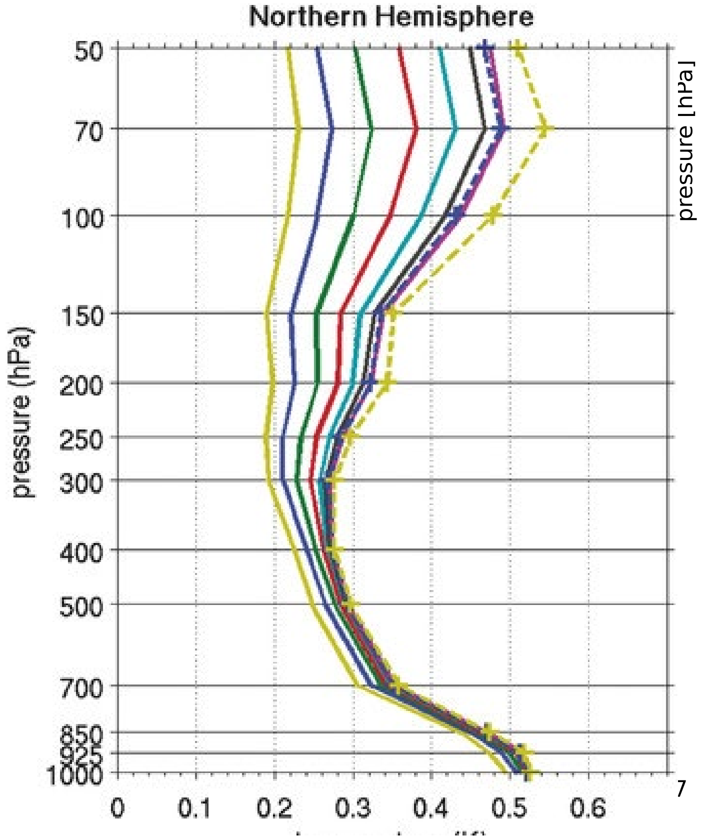
ROMEX:

control + commerical and Chinese GNSS-RO data

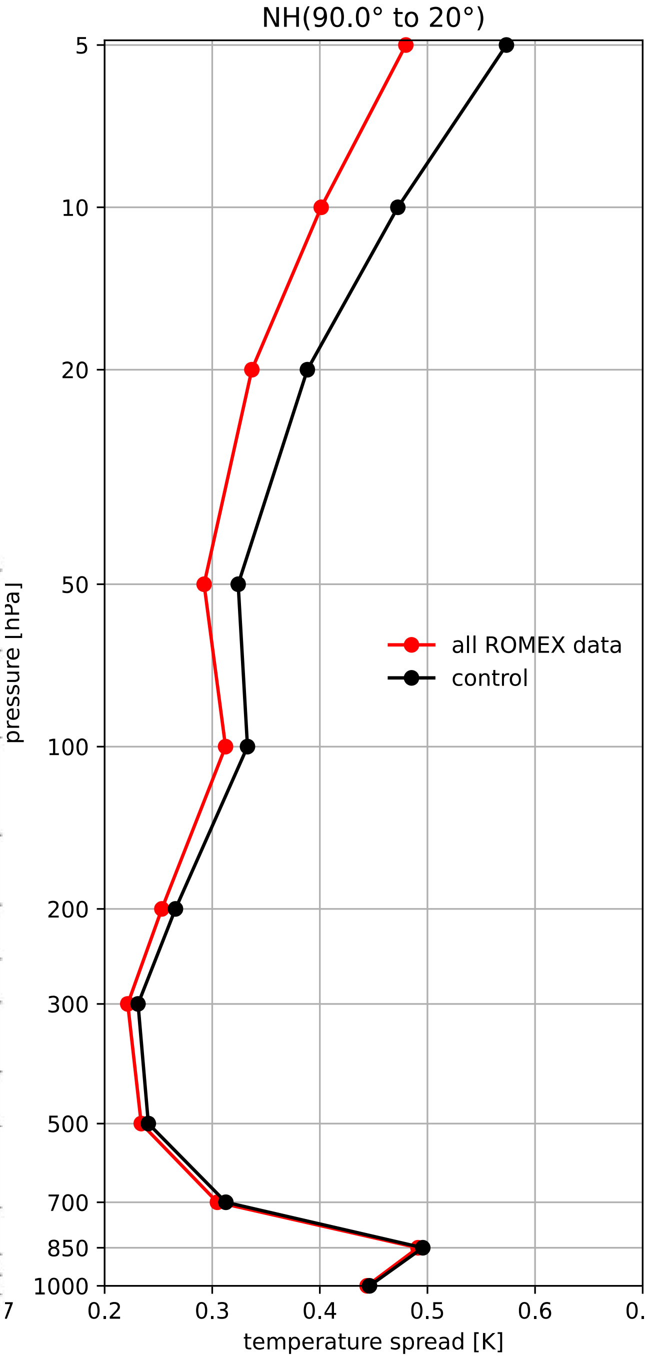
Findings

Decrease in EDA spread with the addition of more GNSS-RO data.

ECMWF



Harnisch et al 2013



ROMEX: Summary

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- Slight increase in mean error for Geopotential height (2- 5 m), caused by cooler background
- Ongoing investigation of cause and assessment of the meaning of this change
  - Doing sensitivity studies of forward operator (refractivity coefficient)
- Extend EDA analysis to look into which scaler are affected
  - Additional radio occultation observations help reduce stratospheric uncertainty at useful scales
- Extend running OSEs

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- Good and strong impact from assimilating GNSS-RO data in NWP
- Started investigation of GNSS RO impact on extended range forecasts
- Running sensitivity experiments for forward model (triggered by ROMEX)
- Looking into impact of GNSS RO on different scales

Questions

- What possible GNSS-RO forward operator improvements need to be tested?
- Shall we study extreme weather events to test sensitivities of the RO forward operator?
- Focus also on investigating impact on various spatial scales?

Backup

Assimilation with a 2D observation operator

Integrate these differential equations to determine the ray path in polar co-ordinates:

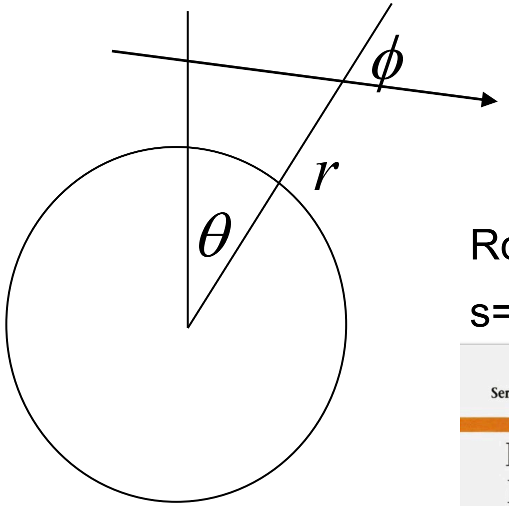
$$\frac{dr}{ds} = \cos\phi$$

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

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

They may look a bit daunting, but set $(\partial n/\partial r)_\theta = 0$ and they define a straight line!

1D: $$\alpha(a) = -2a\int_a^\infty \frac{d\ln n/dx}{\sqrt{x^2 - a^2}}\,dx$$



Rodgers, page 149

s= distance along ray path