Environment and Climate Change Canada

Forecast Sensitivity to R matrix (FSR) Implemented on ECCC's Global Prediction System

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1. Introduction

Motivation:

- Observation error statistics (**R**) strongly influence analysis quality, but remain difficult to estimate.
- Most existing methods assume that the analysis gain is already optimal, requiring accurate specification of both **B** and **R**.
- Forecast Sensitivity to Observations (**FSO**) avoids this assumption. It requires only the validity of the forecast-model tangent linearization (adjoint FSO) or the correlations in the ensemble perturbations (ensemble FSO) and the validity of the verifying truth.
- Daescu (2008, 2013) extended the FSO framework to diagnose Forecast Sensitivity to the observation-error specification (**FSR**).
- FSO was subsequently adapted from adjoint-based DA to ensemble DA (Kalnay et al. 2012) and hybrid ensemble-variational DA (Buehner et al. 2018).
- FSR was later extended to ensemble DA (Hotta et al. 2017), but has not yet been implemented in a hybrid ensemble-variational framework.

Objectives:

- Assess the value of **FSR** as a complementary tool for estimating/optimizing **R**.
- Develop and implement a hybrid ensemble-variational FSR formulation within ECCC's global data assimilation system.

2. Formulation

Forecast error metric: As in FSO, define the forecast error by the quadratic norm

$$e^f = \mathbf{e}^T\mathbf{C}\mathbf{e}, \quad \mathbf{e} = \mathbf{x}^f - \mathbf{x}^v$$

where $\mathbf{x}^f$ is the forecast, $\mathbf{x}^v$ is the verifying truth, and $\mathbf{C}$ defines the error metric.

Forecast sensitivity to scaling factors:

- Observations partitioned into subgroups i
- Scale subgroup covariance: $\mathbf{R}_i \rightarrow s_i^o \mathbf{R}_i$
- Sensitivity of forecast error [following Daescu (2008)]

$$\frac{\partial e^f}{\partial s_i^o} = -(\mathbf{\Pi}_i \delta \mathbf{y}^{O-A})^T \mathbf{\Pi}_i \frac{\partial e^f}{\partial \mathbf{y}^o}$$

$$\frac{\partial e^f}{\partial \mathbf{y}^o} = 2\mathbf{K}^T\mathbf{M}^T\mathbf{C}\mathbf{e}$$

Hybrid Ensemble-Variational implementation (Buehner et al. 2018):

- $\mathbf{M}^T$: ensemble-space approximation
- $\mathbf{K}^T$: variational minimization
- Consistent with hybrid EnVar assumptions
- **No assumption on optimality of K nor correctness of B and R.**

3. Experimental Set-up

System:

- **ECCC** operational Global Deterministic Prediction System (**GDPS**)
- 4DEnVar data assimilation
- Flow-dependent **B** from 256 member LETKF ensemble

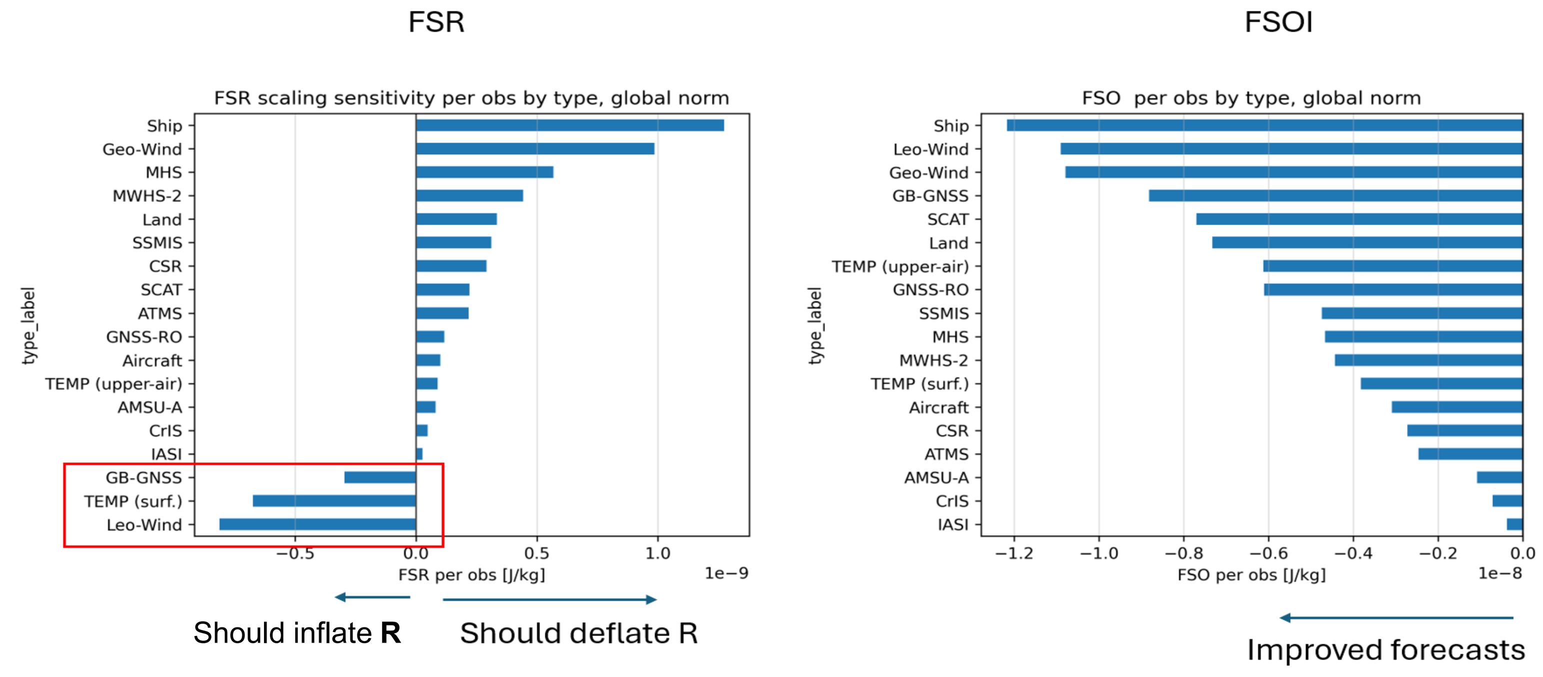
Period:

- June-August 2022 (3 months)
- One cycle every 18 h
- Uniform sampling of 00, 06, 12 and 18 UTC initializations

FSO and FSR specifications:

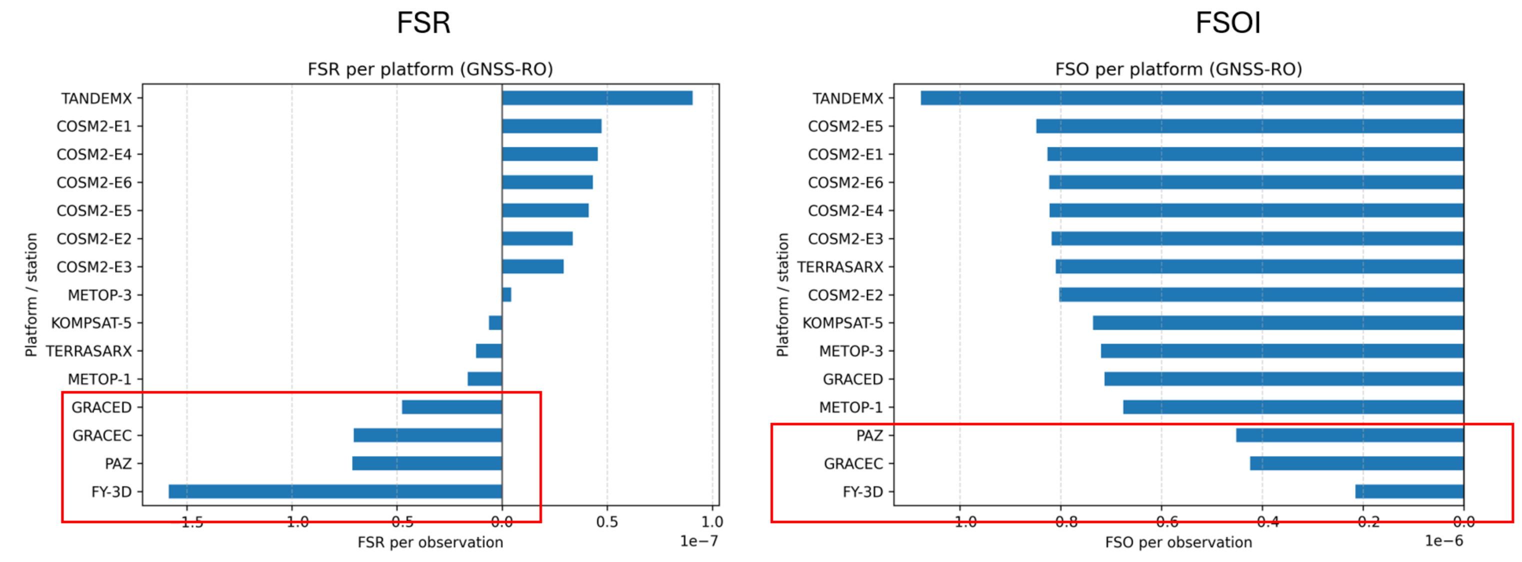
- Error norm: Global, tropospheric (surface to 100hPa) moist total energy
- Lead time: 24 h
- Verifying truth: GDPS analysis (own-analysis)

4.1 Results: By types (per obs)



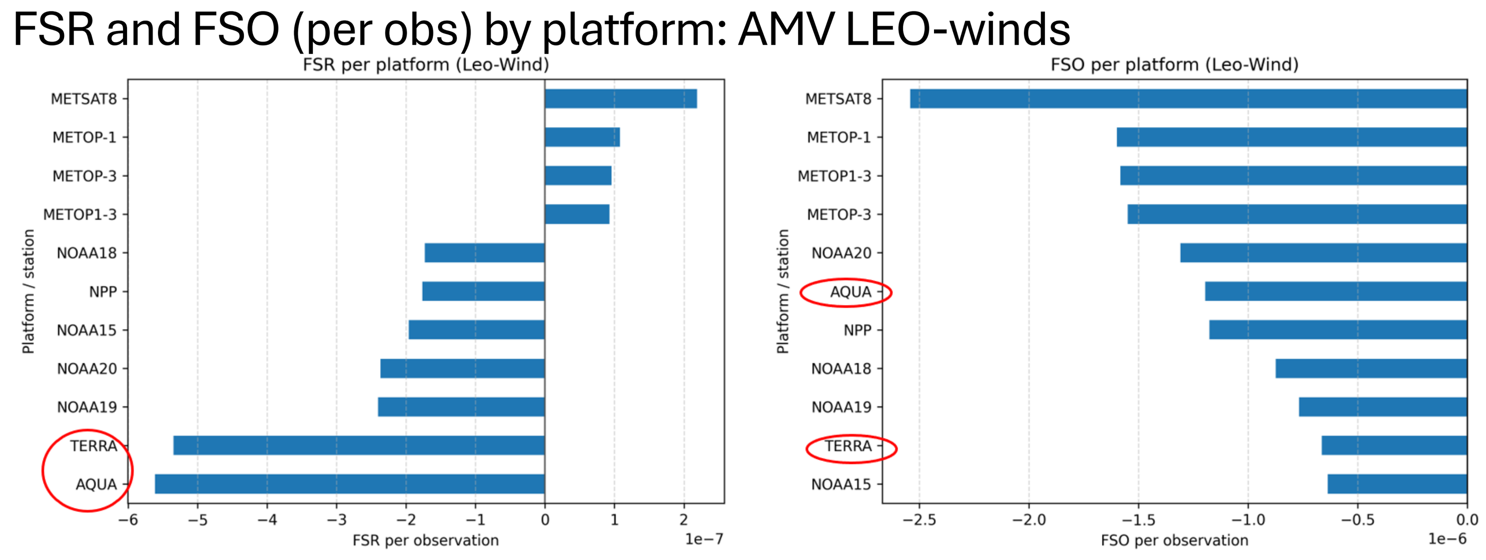
4.2 Results: By platform

FSR and FSO (per obs) by platform: GNSS-RO



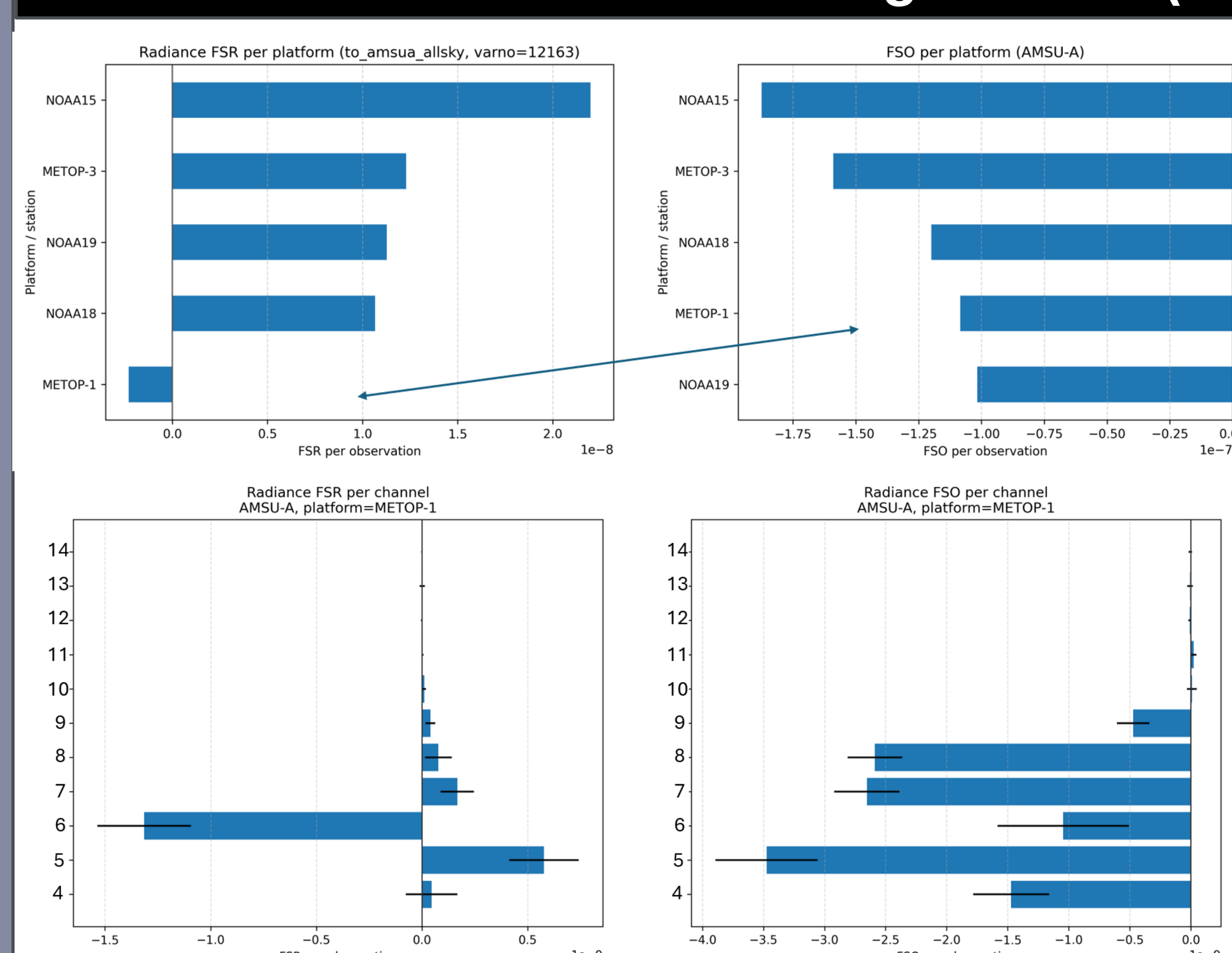
- **GRACE-C, GRACE-D, PAZ, and FY-3D** have beneficial impacts (FSO < 0), yet FSR suggests that their prescribed observation errors may be too small.
- FSR therefore provides information beyond observation impact alone and can guide refinement of the **R** specification.

FSR and FSO (per obs) by platform: AMV LEO-winds

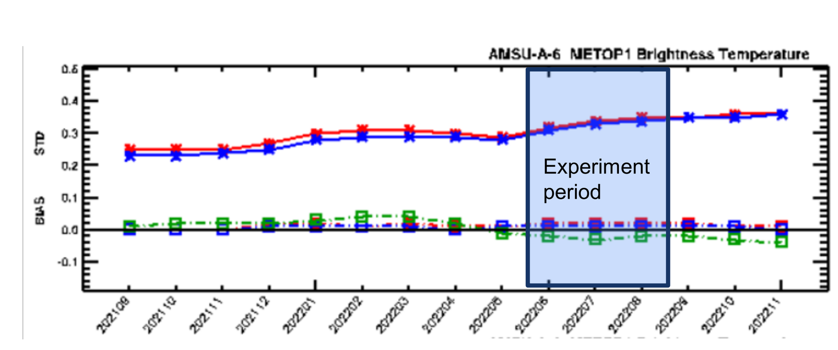


- **Terra** and **Aqua** produce highly consistent FSR signals despite being separate platforms, consistent with their common MODIS wind retrieval algorithm.

5. Interesting case: AMSU-A Channel 6 Degradation (MetOp-1)



- AMSU-A/MetOp-1 had beneficial FSO impacts but **anomalous FSR sensitivities**.
- Channel-level FSR diagnostics identified **Channel 6** as the source of the signal.



- O-B monitoring independently confirmed degradation of Channel 6 during the study period.
- Channel 6 was subsequently removed from operations (November 2022).
- FSO remained largely positive, whereas **FSR exposed the emerging problem**.

Take-home message: FSR can reveal observation-quality issues that are not evident from FSO alone.

6. CONCLUSIONS & FUTURE WORK

- First implementation of hybrid EnVar FSR in ECCC's GDPS.

Key Findings

- FSR helps identify whether σ^o should be inflated or deflated.
- FSR complements FSO with actionable guidance for **R** tuning.
- The AMSU-A/MetOp-1 Channel 6 case demonstrates the potential diagnostic value of FSR for operational monitoring.

Short term goals:

- Discuss results with instrument and observation experts.
- Explore the use of external analyses as the verifying truth.

Long-term goal:

Use FSR-guided tuning of the operational **R** matrix.

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