



Comparing the adjoint- and ensemble-based approaches to observation impact on short-range forecasts

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Outline



Introduction

Recap of FSOI Basics

Preliminary Results

Closing Remarks



FSOI at GMAO: from Adjoint- to Ensemble-based?

Evolution of Forecast Sensitivity and Observation Impact (FSOI) at GMAO:

- GMAO has been calculating FSOI in its **Forward Processing (FP)** system for several years.
- FP has evolved from **3dVar** to **Hybrid-3dVar** to what is presently **Hybrid-4dEnVar**.
- Our strategy follows the Langland & Baker (2004) approach and relies on the availability of an **adjoint model**.
- Along the years the GMAO forward model has gone from FV to FV³; accordingly, the adjoint model has gone from **AD-FV** to **AD-FV³**.
- **Linearized physics**, and corresponding adjoint, has evolved from simple diffusion and vertical drag to more elaborate accountability of convection (Holdaway, Errico, Gelaro & Kim).

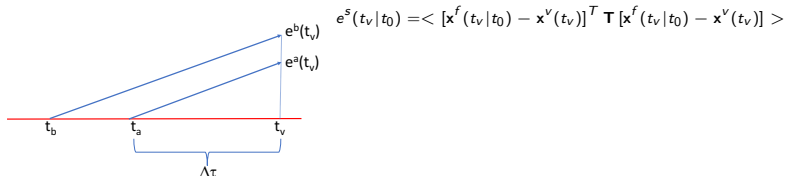
Ensemble DA opens the door to bypass the Adjoint Model:

- ▶ In a dual-analysis system (Var & Ens) the possibility exists to **base FSOI fully on the ensemble** - this has its caveats (see what follows).
- ▶ Alternatively:
 - Method I** The **AD-Var-analysis** can be adapted to make use of an ensemble forecast to implicitly estimate forecast sensitivities;
 - Method II** Or, similarly, but not identically, the ensemble might be used to explicitly estimate forecast sensitivities required by the **AD-Var-analysis**.

This presentation provides insights from preliminary evaluation of these possibilities.

Error reduction measure and FSOI

Forecast error:



The impact of observations is typically evaluated by studying how the error measure above changes as a consequence of assimilating observations. Whether based on adjoint or ensemble techniques, these methods require evaluation of expressions of the form:

$$\delta e \approx \langle \mathbf{d}^T \mathbf{K}^T \mathbf{g}_0 \rangle$$

with \mathbf{d} and \mathbf{K} being the background residual vector and the analysis gain matrix, and \mathbf{g} amounting to a forecast sensitivity vector whose approximation leads to all kinds of formula.

	AD-Solver (\mathbf{K}^T)	Forecast Sensitivity (\mathbf{g}_0)	This Talk
VA-FSOI	Var	ADM	done
EE-FSOI	En	En	done
VE-FSOI	Var	En	done
EA-FSOI	En	ADM	—



VA-FSOI vs EE-FSOI in a Dual-Analysis Hybrid System



Adjoint- and Ensemble-based FSOI

Variational-Adjoint-FSOI (VA-FSOI)

Second-order Approximation (Trapezoidal rule; Langland & Baker 2004; Tellus):

$$\mathbf{g}_0^A \equiv \frac{1}{2}(\mathbf{M}_a^T \mathbf{T} \mathbf{e}^a + \mathbf{M}_b^T \mathbf{T} \mathbf{e}^b).$$

And in a system such as [GSI](#), the calculation of δe can be done as in:

$$\delta e \approx \langle \mathbf{d}^T \mathbf{R}^{-1} \mathbf{H} \tilde{\mathbf{g}} \rangle,$$

where $\tilde{\mathbf{g}}$ is derived from the GSI-hybrid solver as in (double-CG or Bi-CG):

$$\begin{aligned} (\mathbf{B} + \mathbf{B} \mathbf{H}^T \mathbf{R}^{-1} \mathbf{H} \mathbf{B}) \mathbf{z} &= \mathbf{B} \mathbf{g}_0^A \\ \tilde{\mathbf{g}} &= \mathbf{B} \mathbf{z} \end{aligned}$$

for $\mathbf{B} = \beta_c \mathbf{B}_c + \beta_e \mathbf{B}_e$.

Ensemble-Ensemble-FSOI (EE-FSOI)

In Ensemble systems, the gradient is defined with respect to the ensemble mean:

$$\mathbf{g}_0^E \equiv \frac{1}{2} \mathbf{X}_a^{fT} \mathbf{T} (\bar{\mathbf{e}}^a + \bar{\mathbf{e}}^b),$$

where $\mathbf{X}_a^f \equiv \mathbf{X}^f(t_v | t_a)$ is a matrix created from the ensemble perturbation of forecasts issued from t_a and valid at t_v , and the over-bar represents ensemble average.

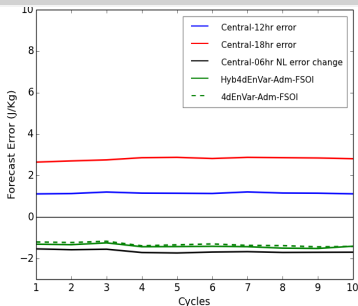
And in a system such as the [EnSRF](#), calculation of δe amount to:

$$\delta e \approx \frac{1}{2} \langle \mathbf{d}^T \mathbf{R}^{-1} \mathbf{H} (\mathbf{L} \bullet \mathbf{X}^a \mathbf{X}^{fT}) \mathbf{T} (\bar{\mathbf{e}}^a + \bar{\mathbf{e}}^b) \rangle,$$

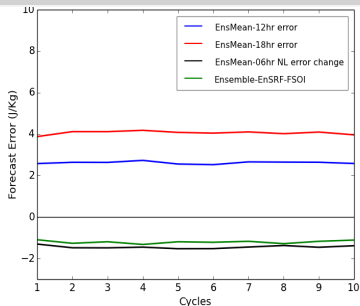
where $\mathbf{X}_a \equiv \mathbf{X}_a(t_a)$ is a matrix formed from ensemble analysis perturbations (Kalnay *et al.*, 2012, Tellus; Ota *et al.*, 2013, Tellus). An argument has been made to have \mathbf{L} above as an advected form of the \mathbf{L} used in the forward ensemble analysis.

VA-FSOI vs EE-FSOI

From Central Forecasts



From Ensemble Forecasts



- ▶ Error reductions are similar between central and ensemble forecasts, though latter is slightly smaller in absolute value for 12-hour forecasts.
- ▶ Left: compares FSOI when backward Var changed from Hyb-4dEnVar to 4dEnVar.
- ▶ Right: presents EE-FSOI.



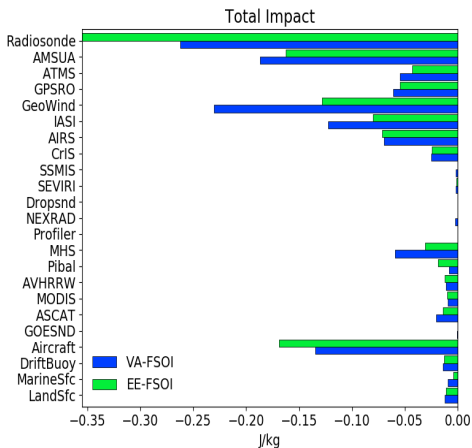
VA-FSOI vs EE-FSOI

Total Impact

- ▶ To render a fair comparison, we calculate Adjoint-based impacts for a changed Adjoint analysis integration where the climatological term is shut off, thus converting the backward run into a 4dEnVar instead of its default (FP-like) Hybrid-4dEnVar.
- ▶ At first glance, impact rankings are similar.
- ▶ Closer examination reveals considerable differences (e.g., radiosondes and satellite winds).
- ▶ Differences are also non-negligible for MW and IR satellite radiances (AMSU-A, ATMS, IASI).

Overall this comparison reflects that:

- ▶ Ensemble mean forecasts are unrelated to the central forecast.
- ▶ But more importantly, the ensemble analysis handles observations largely differently to how the hybrid analysis does.



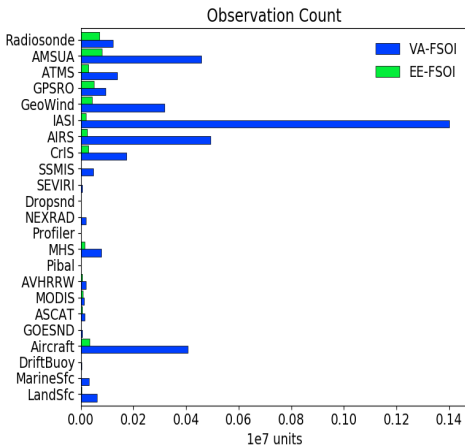


VA-FSOI vs EE-FSOI

Observation Counts

- ▶ The difference in treatment of observations between ensemble and central analyses is **evidenced in the observation count**.
- ▶ The GSI and EnSRF solvers have considerably **different convergence criteria**.
- ▶ Even with the ideal **DFS-based criterium** (chosen here), the EnSRF ignores a very large percentage of the observations.

All-in-all we don't think observation impacts derived from the EnSRF solver represent well how the deterministic (central) analysis system uses observations.





VA-FSOI vs VE-FSOI in a Dual-Analysis Hybrid System



VA-FSOI vs VE-FSOI

Variational-Ensemble-FSOI (VE-FSOI) Method I

As in Buehner *et al.* (2018, MWR), in a EnVar, such that $\mathbf{B} = \mathbf{B}_e$, the ensemble background covariance allows for the following to be written

$$\begin{aligned} \mathbf{B}_e \mathbf{g}_0^A &= \mathbf{L} \bullet \mathbf{X}_b (\mathbf{X}_b)^T \mathbf{g}_0^A \\ &\approx \mathbf{L} \bullet \mathbf{X}_b \mathbf{X}_a^T \mathbf{M}^T (t_a, t_b) \mathbf{g}_0^A \end{aligned}$$

We can replace \mathbf{g}_0^A with \mathbf{g}_0^E (using central forecast errors) in the RHS to get

$$\begin{aligned} \mathbf{B}_e \mathbf{g}_0^A &\approx \mathbf{B}_e \mathbf{g}_0^E \\ &\approx \frac{1}{2} \mathbf{L} \bullet \mathbf{X}_b \mathbf{X}_a^T \mathbf{M}^T (t_a, t_b) \mathbf{X}_a^{fT} \mathbf{T} (\mathbf{e}^a + \mathbf{e}^b) \\ &= \frac{1}{2} \mathbf{L} \bullet \mathbf{X}_b \mathbf{X}_b^{fT} \mathbf{T} (\mathbf{e}^a + \mathbf{e}^b) \end{aligned}$$

which amounts to a simple change to the RHS of the minimization problem solved for calculation of observation impacts in the Var system.

Note: $\mathbf{e}^a (\mathbf{e}^b)$ replaces $\bar{\mathbf{e}}^a (\bar{\mathbf{e}}^b)$

Variational-Ensemble-FSOI (VE-FSOI) Method II

Alternatively, we can try to use the approach of Ancell & Hakim (2007; MWR) to estimate forecast sensitivities using an ensemble of forecasts.

In this case, the forecast sensitivity is estimated as in:

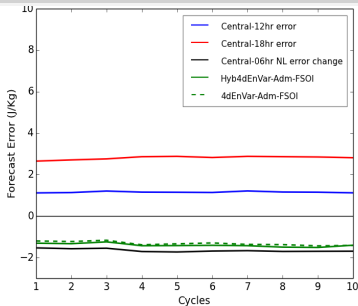
$$\frac{\partial f}{\partial \mathbf{x}} = \mathbf{D}^{-1} \begin{bmatrix} \delta \mathbf{x}_1 \delta \mathbf{e}_1^T \\ \delta \mathbf{x}_2 \delta \mathbf{e}_2^T \\ \vdots \\ \delta \mathbf{x}_n \delta \mathbf{e}_n^T \end{bmatrix}$$

where $\mathbf{D} = \text{diag}(\|\delta \mathbf{x}_1\|^2, \|\delta \mathbf{x}_2\|^2, \dots, \|\delta \mathbf{x}_n\|^2)$, $\text{dim}(\mathbf{x}_i) = \text{dim}(\mathbf{e}_i) = M \times 1$, and n is the state-space dimension.

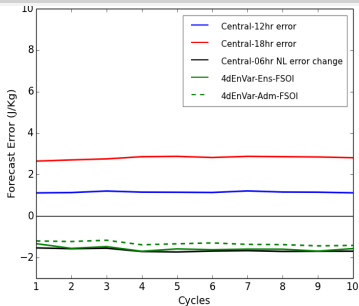
This presentation will not present results for Method II.

VA-FSOI vs VE-FSOI Method I

From Central Forecasts



From Central Forecasts



- ▶ Lack of **advection of localization scales** in the RHS of the Var impact expression motivates following Buehner *et al.* (2018; MWR) and evaluating 12-hr instead of 24-hr FSOI.
- ▶ **Left:** compares FSOI when backward Var changed from Hyb-4dEnVar to 4dEnVar.
- ▶ **Right:** compares VA-FSOI with VE-FSOI Method I.

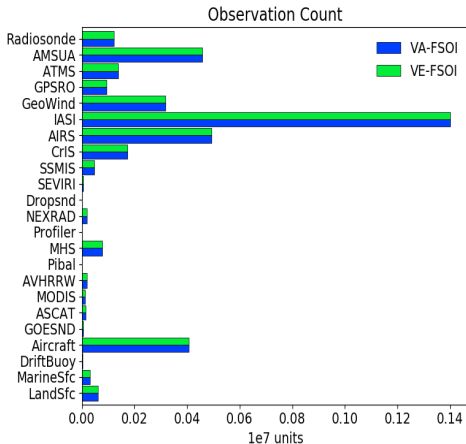
Remark: 32-member ensemble perturbations seem rather reasonable replacement for ADM for 12-hr sensitivity calculation in 4dEnVar context.



VA-FSOI vs VE-FSOI Method I

Observation Counts

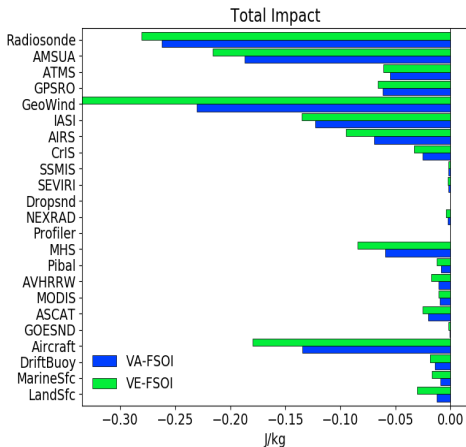
- ▶ The two approaches **treat the observations in exactly the same way**, and fully consistent with how the forward (Hyb-4dEnVar) solver treats them.
- ▶ Replacing the Adjoint Model with Ensemble perturbations to estimate forecast sensitivities leaves the **analysis solver untouched wrt each other**.
- ▶ The figure on the right shows observation counts between the VA-FSOI and VE-FSOI Method I techniques, for backward integrations of 4dEnVar, covering a 10-day period.



VA-FSOI vs VE-FSOI Method I

Total Impact

- Overall, impacts don't seem to change much and are largely comparable when ADM is replaced with Ensemble perturbations.
- Closer look reveals satellite winds (GeoWind), MW sensors (MHS, AMSU-A), aircrafts and near surface observations to have larger impact when Ens-Perts are used compared to when ADM is used to estimate forecast sensitivity.
- The above seems to be consistent with the fact that the simply parameterized adjoint physics is expected to mis-represent water and near surface fields as compared to the full GCM.





Closing Remarks

- ▶ More importantly, though the observation operators in the hybrid GSI and EnSRF are shared, **GSI and EnSRF treat observations rather differently.**
- ▶ In a **dual hybrid DA** system, when a (low resolution) ensemble analysis filter is used to provide flow dependence to a (high resolution) hybrid analysis, certain configurations of the ensemble filter might **discourage assessing observation impact using the EE-FSOI** based on the EnDA part of system.
- ▶ The comment above applies particularly to **GSI-EnSRF-based** systems.
- ▶ As in Buehner *et al.*, we have shown that it is possible to **enable the Var system** to derive observation impacts with forecast sensitivities calculated from the ensemble thus **avoiding the adjoint model.**