A revised Ensemble Forecast Sensitivity to Observation Impact (EFSOI) method in hybrid data assimilation

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Forecast Sensitivity to Observation Impact (FSOI) & Ensemble FSOI (EFSOI)

- **OSEs: data denial experiments**
- provide the nonlinear impacts on the accuracy of the forecast w/ and w/o a certain set of observation

- **FSOI and EFSOI**
- Quantify how much each observation improves or degrades the analysis field in a linear sense by measuring errors of two forecast w/ DA (ana) and w/o DA (fg)
- **FSOI: Langland and Baker (2004)**
  - proposed an adjoint FSOI formulation for variational DA system
- **EFSOI: Kalnay et al. (2012)**
  - simplified the EFSOI from Liu and Kalnay (2008) for EnKF without using adjoint operators

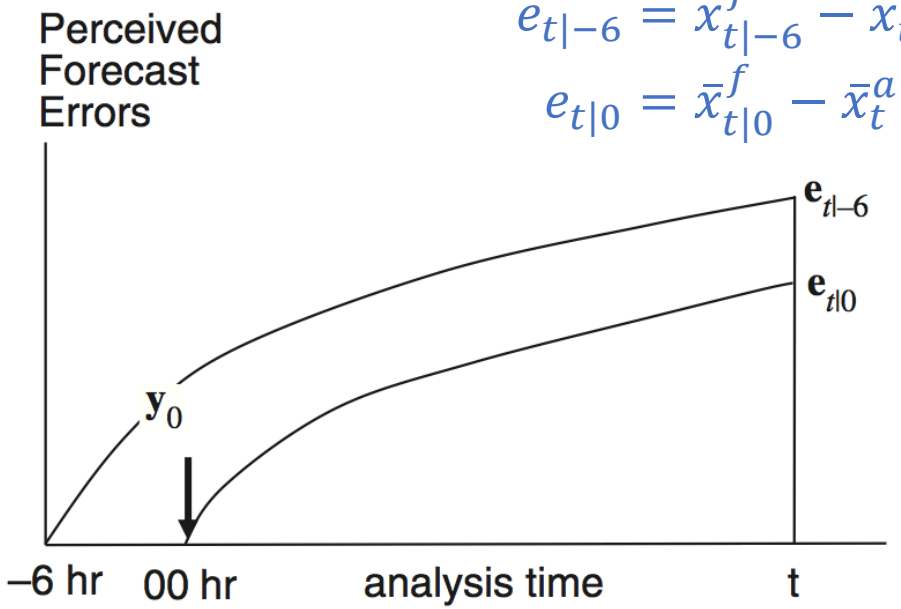
Ensemble FSOI (EFSOI)

- Quantifies contributions from each of the observations assimilated at 00 hr to the reduction(or increase) of the error of the forecast t hr

e: forecast error

$$e_{t|-6} = \bar{x}^f_{t|-6} - \bar{x}^a_t$$

$$e_{t|0} = \bar{x}^f_{t|0} - \bar{x}^a_t$$



- Forecast error reduction is defined as:

$$\Delta e_t^{f-g} \equiv \frac{1}{2} e_{t|0}^{\mathrm{T}} C e_{t|0} - \frac{1}{2} e_{t|-6}^{\mathrm{T}} C e_{t|-6} = \frac{1}{2} \left(e_{t|0} - e_{t|-6}\right)^{\mathrm{T}} C \left(e_{t|0} + e_{t|-6}\right)$$

C: norm operator, defining the measure of forecast error (dry/moist energy)

$$e^T C \mathrm{e} = \frac{1}{2}\frac{1}{S}\int_S \left[\int_0^1 \left(u'^2 + v'^2 + \frac{C_p}{T_r} T'^2 + \frac{L^2}{C_p T_r} q'^2\right) d\sigma + \frac{R_d T_r}{P_r^2} P_s'^2\right] dS$$

- Forecast error difference: $\mathbf{MK}\delta y_0$
- In EnKF system, Kalman gain: $\frac{1}{K-1} \boldsymbol{X_0^a} \mathbf{X_0^{a\,T}} \mathbf{H^T R^{-1}}$
- The equation can be approximated as:

$$\Delta e_t^{f-g} \approx \frac{1}{2(K-1)} \left[\mathbf{M X_0^a (H X_0^a)^T R^{-1}} \delta y_0\right]^{\mathrm{T}} \boldsymbol{C}\left(e_{t|0} + e_{t|-6}\right)$$

$$\approx \frac{1}{2(K-1)} \delta y_0^{\mathrm{T}} \mathbf{R^{-1} H X_0^a} \boldsymbol{X_{t|0}^{f\mathrm{T}}} \boldsymbol{C}\left(e_{t|0} + e_{t|-6}\right)$$

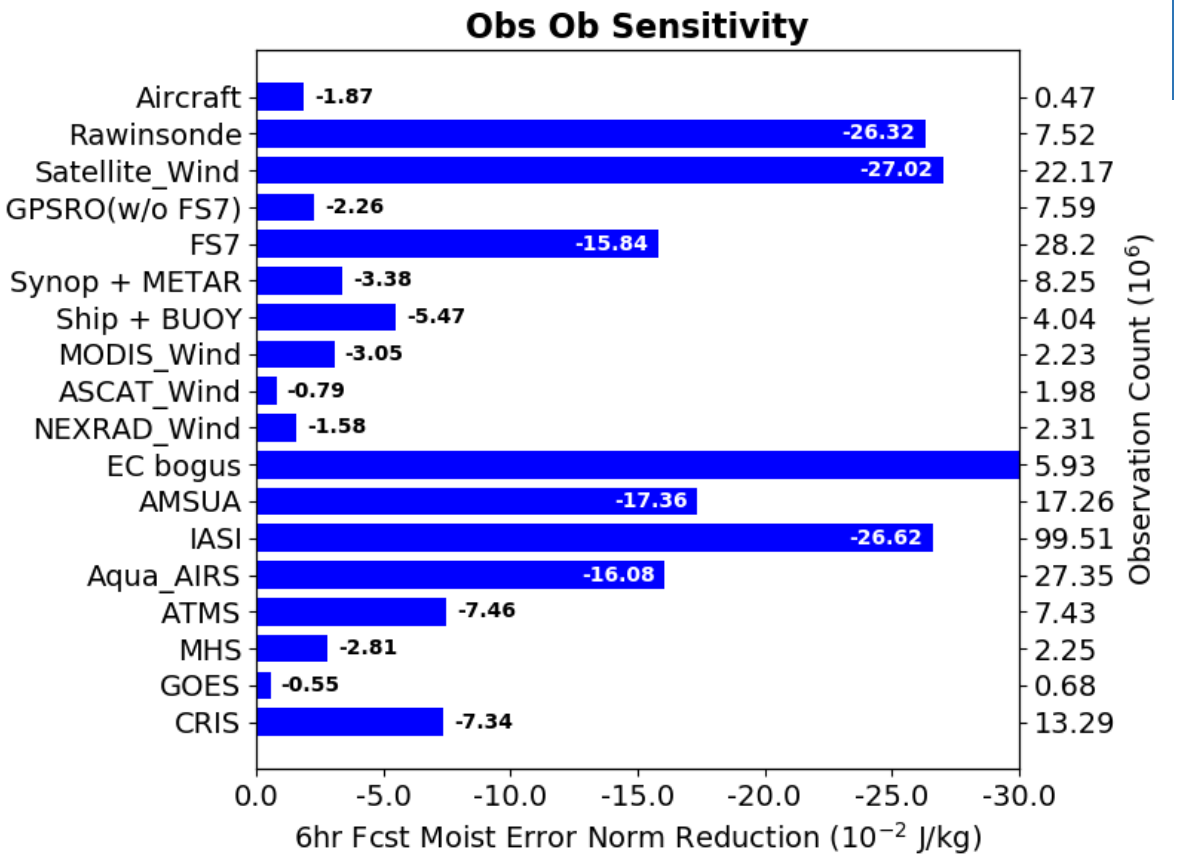
 # Forecast error reduction of one OBS.

Kalnay et al. (2012), Ota et al. (2013), Lien et al. (2018)

Ensemble FSOI (EFSOI) implementation in CWB GDAS

- Without too much modification, EFSOI method has been applied in both ensemble and hybrid systems (e.g., Ota et al. 2013; Hotta et al. 2017).

- This method has also been implemented (from NCEP) in CWB GDAS and proved to be useful in our FORMOSAT-7/COSMIC-2 operational evaluation.



2020 Jan-Feb average total impact

Ensemble FSOI (EFSOI) in hybrid EnVar system

- However, incompatible assimilation and other detail settings between EnVar and EnKF still cause some issues when directly using EFSOI in hybrid system:
  - Different analysis error covariance
  - The inconsistency of assimilated observation number (e.g. radiance data thinning)
  - Re-center and inflation should be considered
- Buehner at al. (2018) proposed a mixed approach of hybrid EFSOI:
  - The observation impact is solved by iterative minimization while the forecast propagation is from ensemble, providing more accurate estimates of observation impacts for the hybrid EnVar DA systems.
- A Revised-EFSOI is proposed with only slight modifications to better estimate observation impacts in hybrid DA w/o adjoint model.

Ensemble FSOI (EFSOI) in hybrid EnVar system

(o-g) obs. error Ensemble forecast t h perturbation

$$\Delta e_t^{f-g} \approx \frac{1}{2(K-1)} \delta y_0^T \mathbf{R}^{-1} (\mathbf{HX}_0^a) \boldsymbol{X}_{t|0}^{fT} \boldsymbol{C} \left(e_{t|0} + e_{t|-6} \right)$$

Ensemble size Ensemble analysis perturbation in obs. space

Error of forecast from analysis/first guess

Deterministic (EnVar) analysis and first guess forecast error

	$\mathbf{HX}_0^a$	$\boldsymbol{X}_{t|0}^{fT}$
Original- EFSOI (use available product)	1. directly get from **multiplicative-inflated ensemble w/o re-center** 2. EnKF **obs. number**	directly using multiplicative + additive **inflated ensemble forecast**
Revised- EFSOI (need additional product)	1. re-evaluate from **un-inflated ensemble w/ re-center** 2. near EnVar **obs. number**	redo the **un-inflated ensemble forecast**

Assimilated data number in Original-/Revised- EFSOI

Period: 20191001-2019110206
(dtg w/o TY bogus)

45-dtg average of
Total obs. Number & Average Impact

	Hybrid-Analysis
obs. type	Assimilated data number
Conventional data	18,548,190 (appr. 10.6%)
Radiance data	145,982,824 (appr. 83.5%)
GPS RO (w FS7)	10,225,531 (appr. 5.9%)
EC bogus	--- (---%)

EFT = 6h
Verification: self-analysis

	Original-EFSOI
obs. type	Estimate data number
Conventional data	16,320,833 (18.1%)
Radiance data	61,034,302 (67.9%)
GPS RO (w FS7)	10,417,967 (11.6%)
EC bogus	2,170,129 (2.4%)

Revised-EFSOI
Estimate data number
16,979,316 (10.2%)
136,913,608 (82.3%)
10,395,228 (6.2%)
2,169,986 (1.3%)

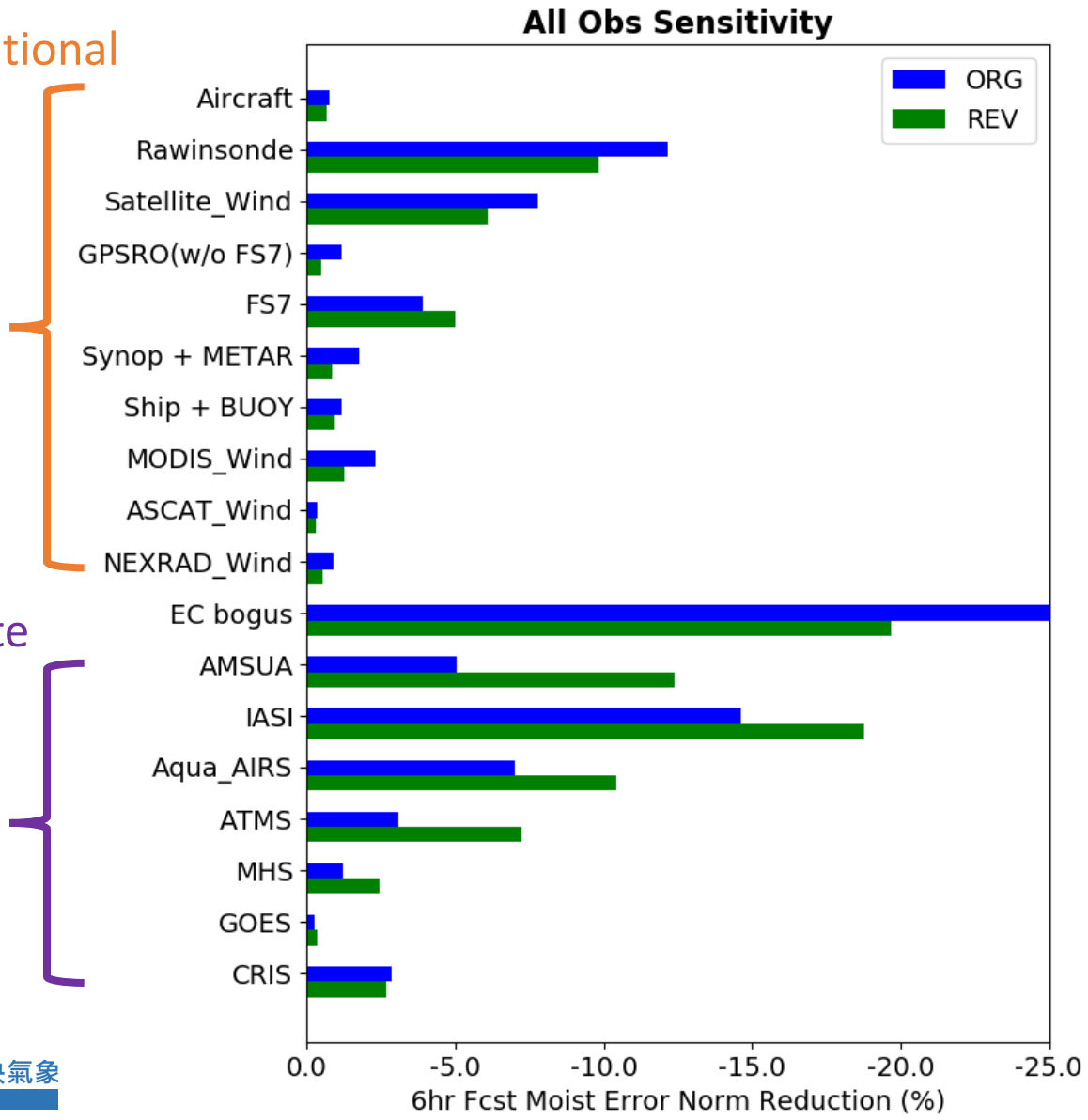
Observation Impact from EFSOI estimation

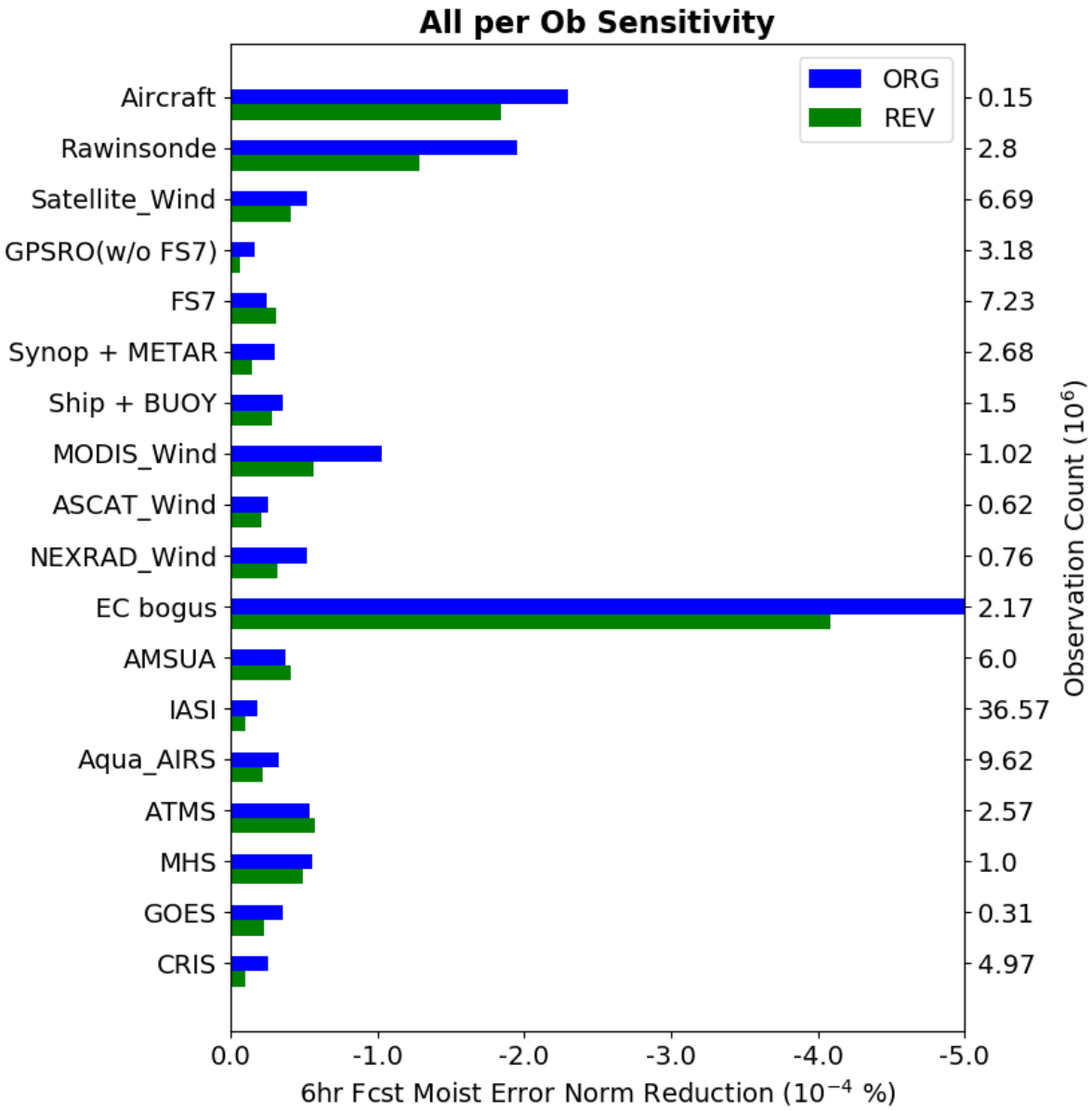
The average of 45-dtg in 2019 Oct. (w/o TY bogus)

Normalized results
Moist Energy(J/kg)

Conventional Data

Satellite Data





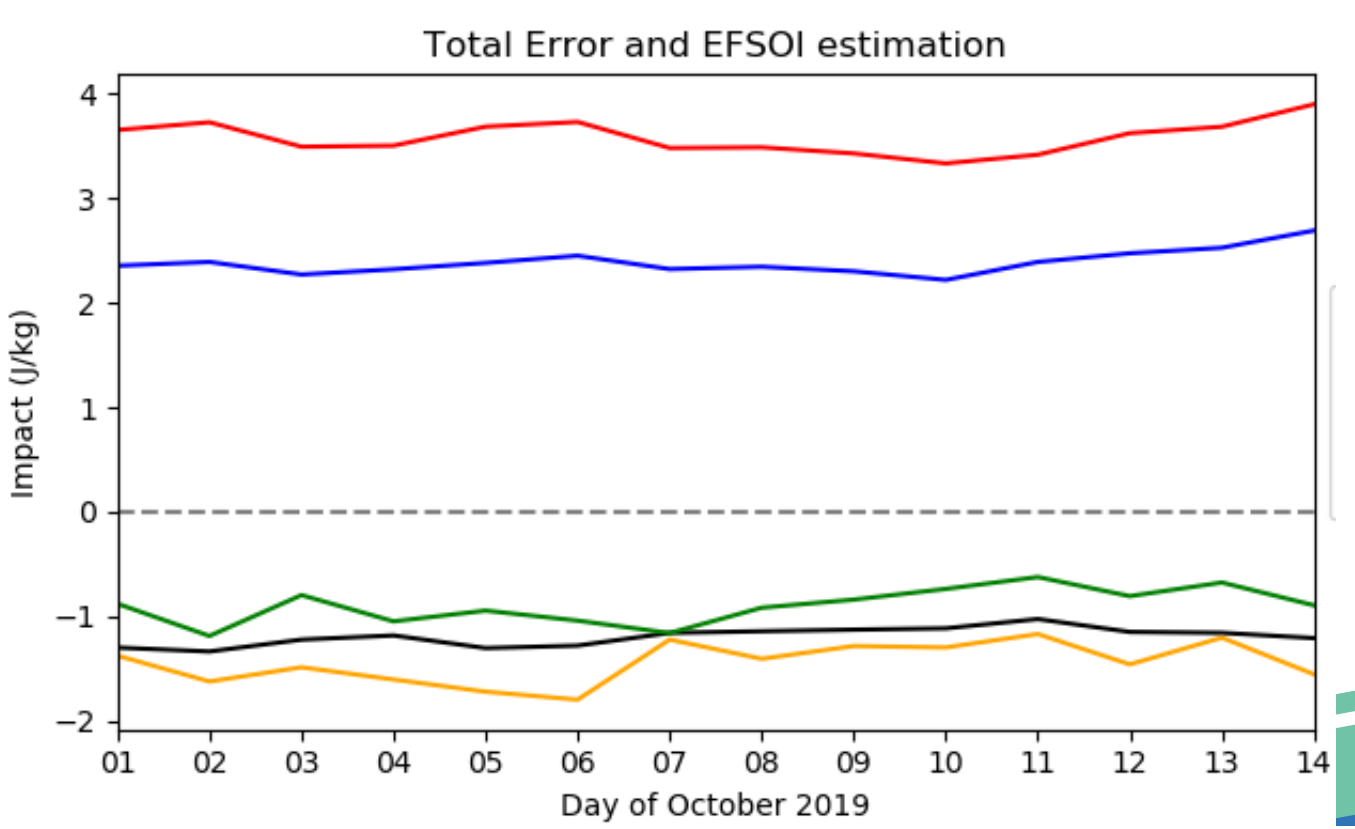
EFSOI Verified with OSEs results

- Issues:
  - OSE results include cycling effect of declining specific observation
  - EFSOI estimate each type of observation impact on the basis of assimilating all obs.

- **CTRL** and other data denial experiments:

Experiments (w/o)	Avg. obs. Number (%)
CTRL	100 (ALL obs.)
EC bogus	1.2
AMSUA	8.8
Satellite Wind	3.0
RO	4.4

- Period: 19100100 – 19101418
  - Dry Energy
  - Verified: CTRL-analysis
- CTRL
  - Compare 6hr Forecast error reduction with original-EFSOI and Revised-EFSOI estimation



Normalized fractional impact comparison

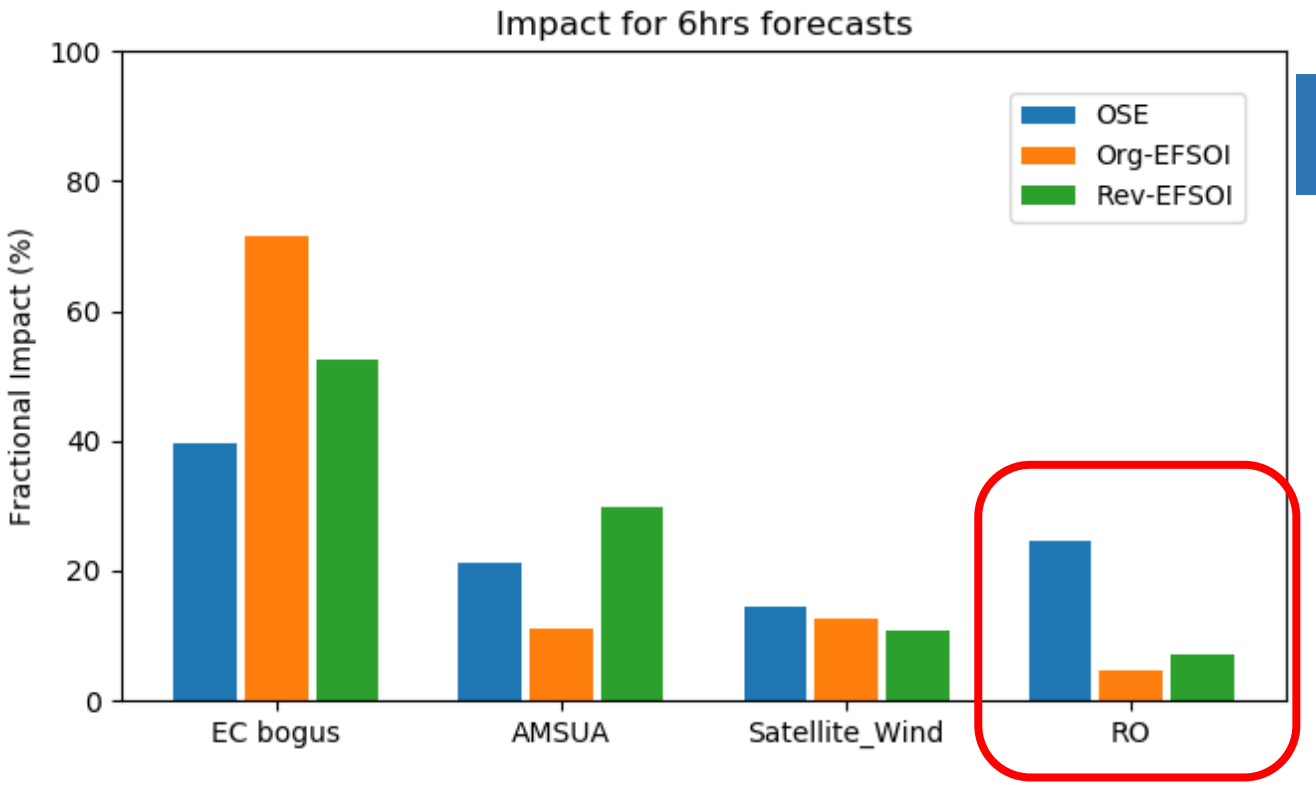
- Average of 19100100 to 19101418
- Measure the impact percentage (%) of a specific observation type for 6hr forecast error reduction estimated by EFSOI in CTRL.

$$F_{obs}(\mathrm{EFSOI}) = \delta e_{obs} / \delta e_{total}$$

- Measure the error reduction percentage (%) of OSEs compare to the first guess of CTRL and of total error reduction in CTRL.

$$F_{obs}(\mathrm{OSE}) = (\delta e_{ctl} - (e_{obs|0} - e_{ctl|\text{-}6})) / \delta e_{ctl}$$

- Relative impact become closer to the OSEs result when using Revised- EFSOI



EC bogus	AMSUA	Sat. Wind	RO (%)
39	**21**	**14**	**24**
71	11	12	4
52	29	10	7

Summary

- EFSOI has been implemented in CWBGFS system.
- A revised method is proposed to overcome the problem that the inconsistency of assimilated observation in EnVar and EnKF, also the use of more reasonable sources for EFSOI estimation.
- Results of the experiment in CWB GDAS (EnVar) show more reasonable impacts estimation in satellite data by using revised-EFSOI.
- Compare the relative impact of the subsets of observations from OSEs and EFSOI estimation, the revised method is also better except that RO impact is under estimated for both EFSOI methods.