# Forecast Sensitivity to Observation Impacts and the U.S. Integrated Ocean Observing System

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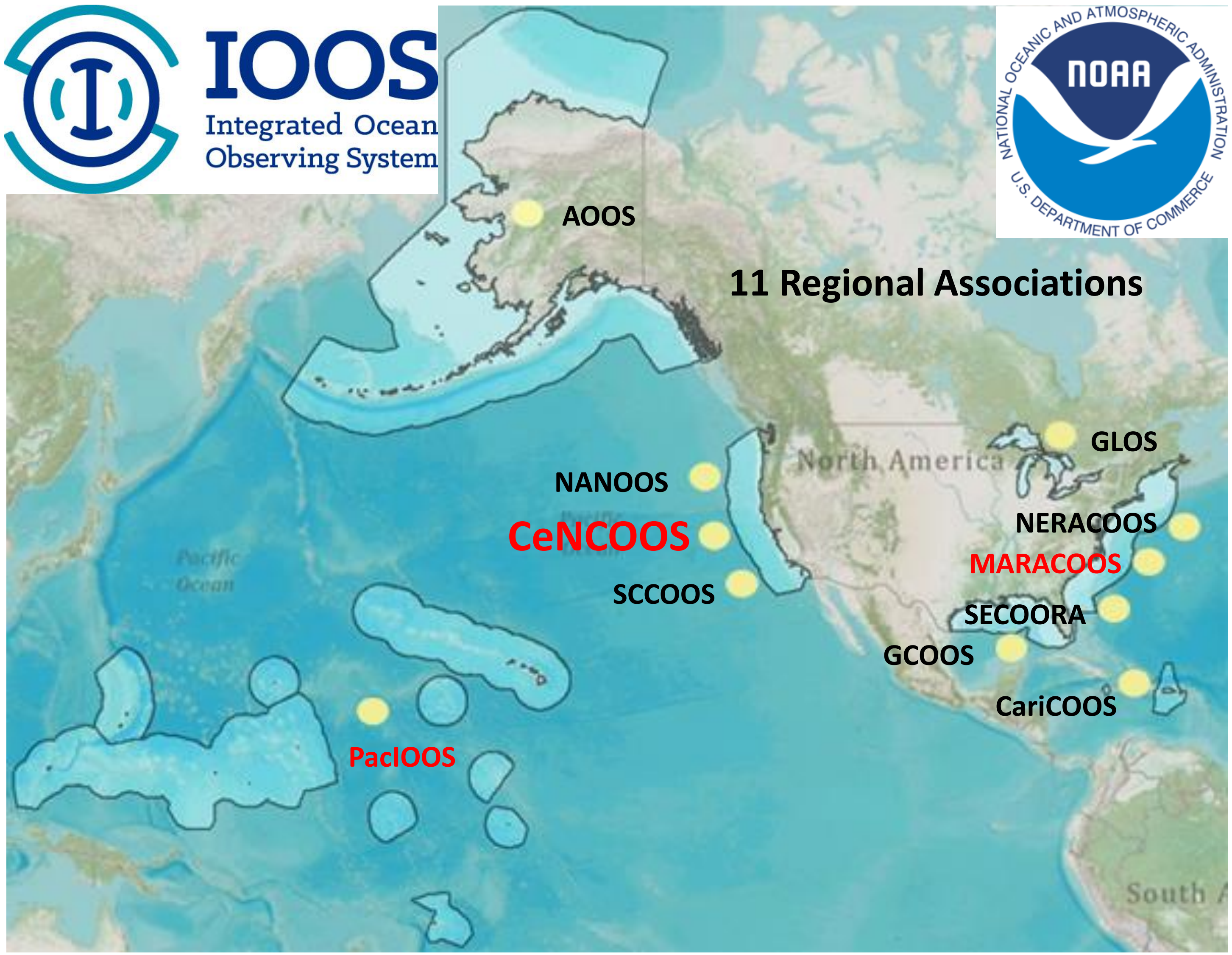



**CeNCOOS** = **Central and Northern California Ocean Observing System**
**MARACOOS** = **Mid-Atlantic Regional Association Ocean Observing System**
**PacIOOS** = **Pacific Island Ocean Observing System**

**CenCOOS, MARACOOS & PacIOOS near real-time analysis-forecast systems are all based on Regional Ocean Modeling System (ROMS) 4-dimensional variational (4D-Var) data assimilation.**

$$\boldsymbol{x}^a = \boldsymbol{x}^b + \boldsymbol{B}\boldsymbol{H}^T(\boldsymbol{H}\boldsymbol{B}\boldsymbol{H}^T + \boldsymbol{R})^{-1}\left(\boldsymbol{y} - H\left(\boldsymbol{x}^b\right)\right)$$

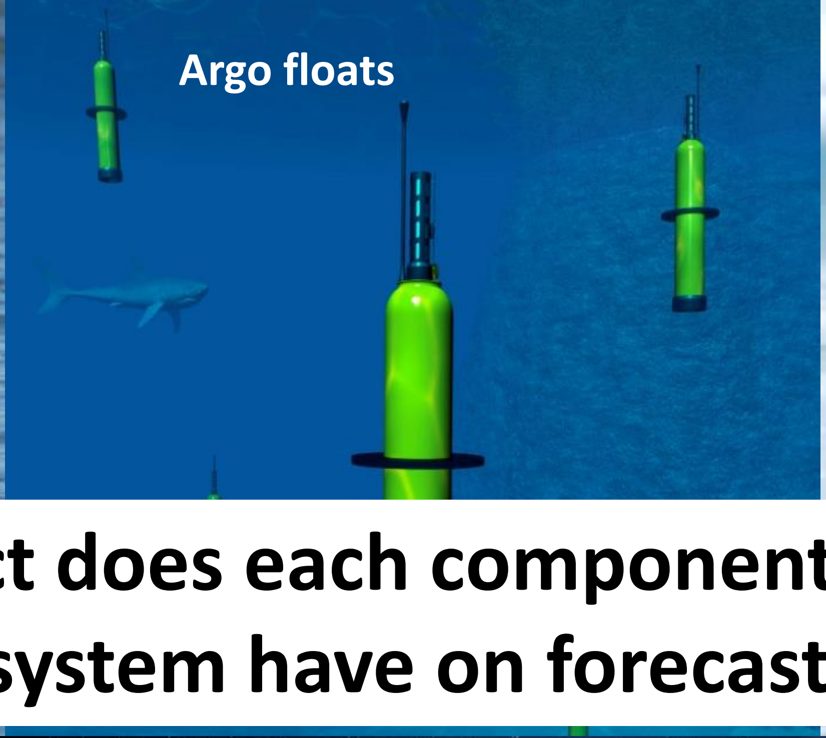
$\boldsymbol{x}^a$ = analysis state-vector
$\boldsymbol{x}^b$ = background state-vector
$\boldsymbol{y}$ = observation vector
$H$ = observation operator (NLROMS)
$\boldsymbol{H}$ = TL observation operator (TLROMS)
$\boldsymbol{H}^T$ = AD observation operator (ALROMS)
$\boldsymbol{B}$ = background error covariance
$\boldsymbol{R}$ = observation error covariance

Incremental, dual formulation, Lanczos formulation of restricted ***B***-preconditioned CG to minimize:

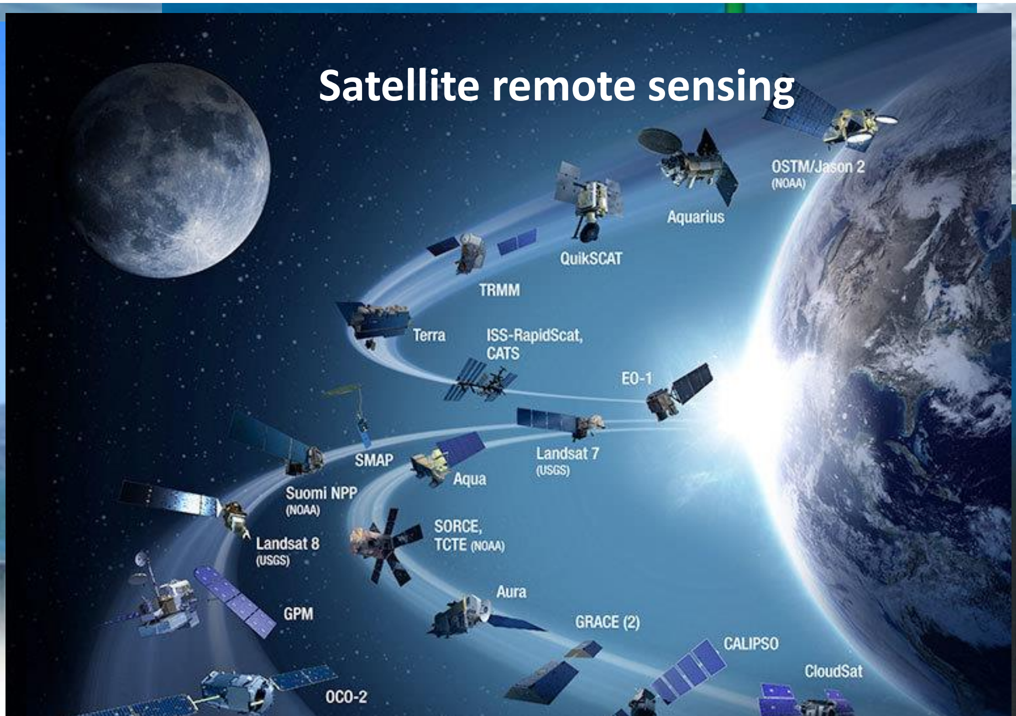
$$J = \delta\boldsymbol{x}^T\boldsymbol{B}^{-1}\delta\boldsymbol{x} + (\boldsymbol{d} - \boldsymbol{H}\delta\boldsymbol{x})^T\boldsymbol{R}^{-1}(\boldsymbol{d} - \boldsymbol{H}\delta\boldsymbol{x})$$

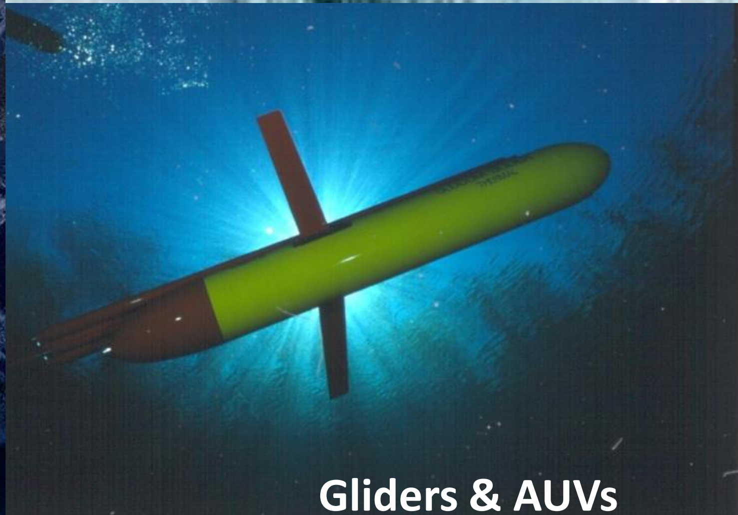
$\delta\boldsymbol{x} = \boldsymbol{x}^a - \boldsymbol{x}^b$ = increment
$\boldsymbol{d} = \left(\boldsymbol{y} - H\left(\boldsymbol{x}^b\right)\right)$ = innovation

# What impact does each component of the observing system have on forecast skill?

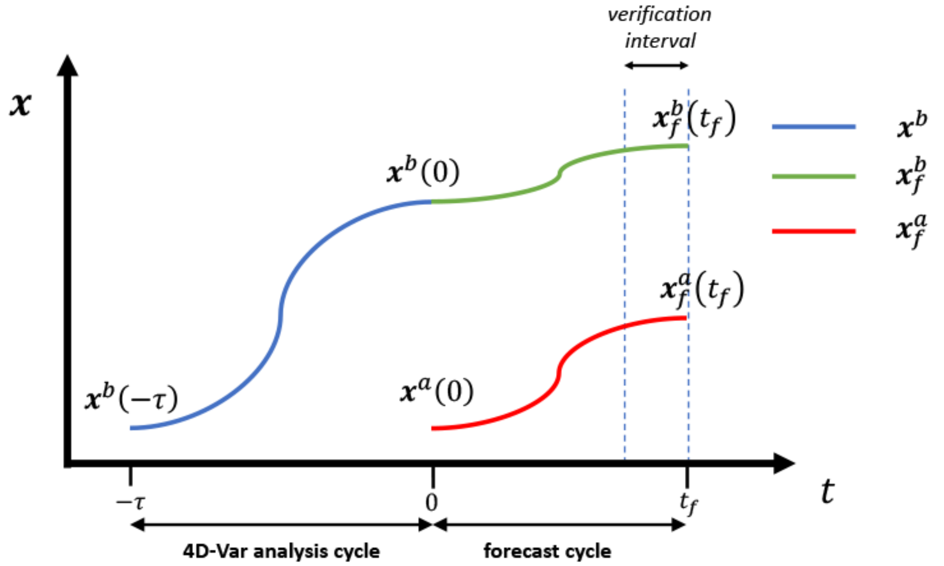


# Forecast Sensitivity to Observations

Baker & Daley (2000); Langland & Baker (2004); Errico (2007); Tremolet (2008); Zhu & Gelaro (2008)




**Forecast skill metric:**

$$e(t_f) = \left(\boldsymbol{x}_f(t_f) - \boldsymbol{x}^t(t_f)\right)^T \boldsymbol{C} \left(\boldsymbol{x}_f(t_f) - \boldsymbol{x}^t(t_f)\right)$$

**In practice $\boldsymbol{x}^t(t_f) \rightarrow \boldsymbol{x}^a(t_f)$, a *"verifying analysis."***
**Alternatively, we can use independent observations $\boldsymbol{y}_f$:**

$$e(t_f) = \left(\boldsymbol{y}_f(t_f) - \boldsymbol{y}(t_f)\right)^T \boldsymbol{C} \left(\boldsymbol{y}_f(t_f) - \boldsymbol{y}(t_f)\right)$$

**The change in forecast skill due to assimilating observations:**

$$\delta e = e^a(t_f) - e^b(t_f)$$

**To 3rd-order:**

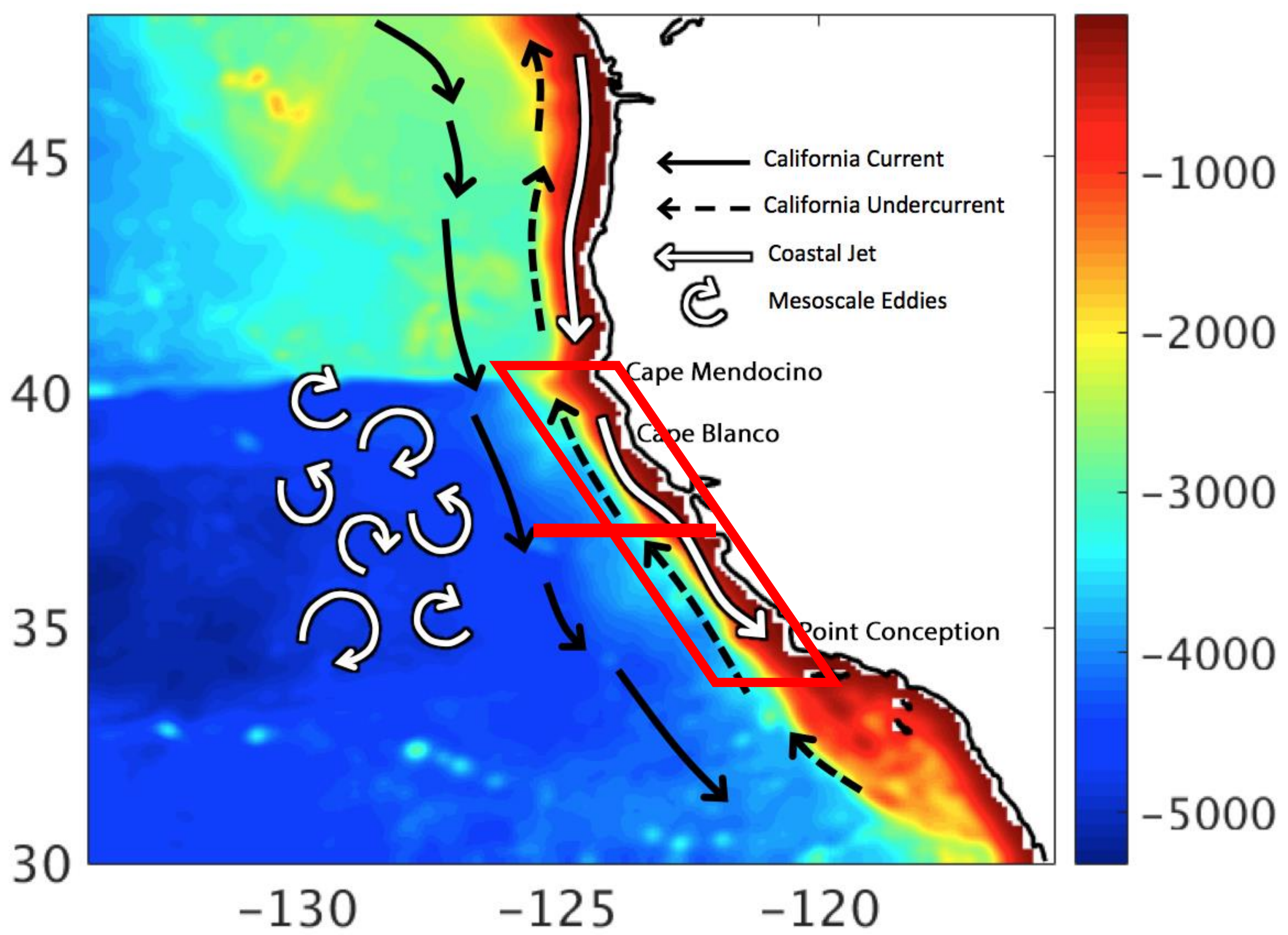
$$\delta e \approx \boldsymbol{d}^T(\boldsymbol{HBH}^T + \boldsymbol{R})^{-1}\boldsymbol{HB}\frac{1}{2}\left(\partial e^a/\partial \boldsymbol{x}^a|_{t=-\tau} + \partial e^b/\partial \boldsymbol{x}^b|_{t=-\tau}\right)$$

**Observation impacts:**

$$\delta e \approx \boldsymbol{d}^T \boldsymbol{g} = \sum_{i=1}^{N} d_i g_i$$

| | |
|---|---|
| $\delta e < 0$ | **Obs improve forecast skill** |
| $\delta e > 0$ | **Obs degrade forecast skill** |

# The California Current System




**ROMS**

- **1/10th degree resolution, 42 $\sigma$-levels**
- **COAMPS surface forcing**
- **Global HYCOM open boundary conditions**
- **Observations (2018 & 2019):**
  - **- satellite SST**
  - **- Aviso altimetry**
  - **- Argo profiling floats**
  - **- gliders**
  - **- HF radar surface radial currents**
- **Background quality control of obs**
- **4-day 4D-Var windows (1 outer-loop, 9 inner-loops)**
- **4-day forecasts ("*hindcasts*")**
- **Forecast metrics:**

**- central CA SST MSE $e_{SST}$**
**- central CA surface current MSE $e_V$**
**- central CA upwelling transport MSE $e_W$**

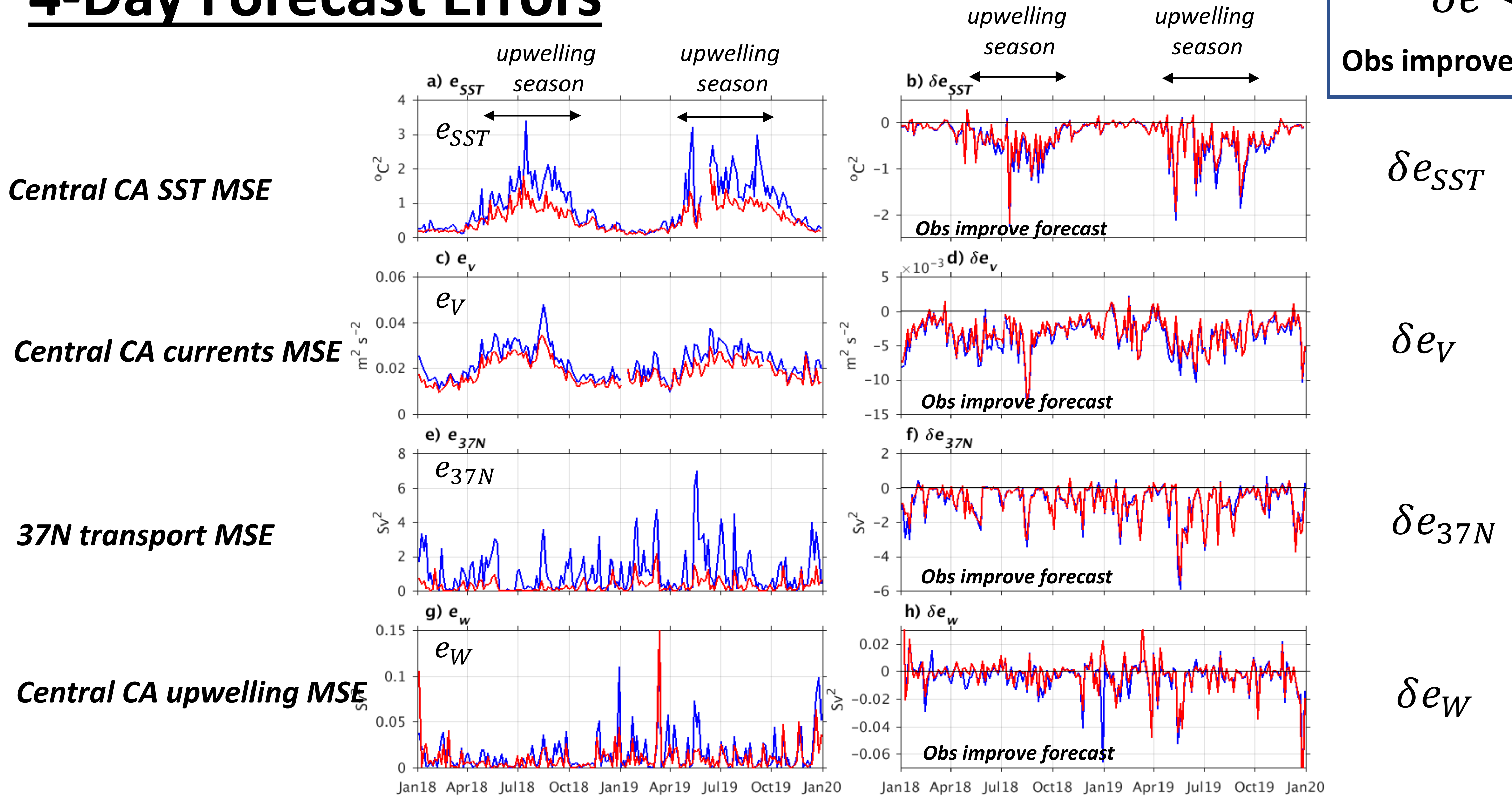
**- 37N transport MSE $e_{37N}$**

**Directly observed** **Indirectly observed**

# 4-Day Forecast Errors

$\delta e < 0$

**Obs improve forecast skill**



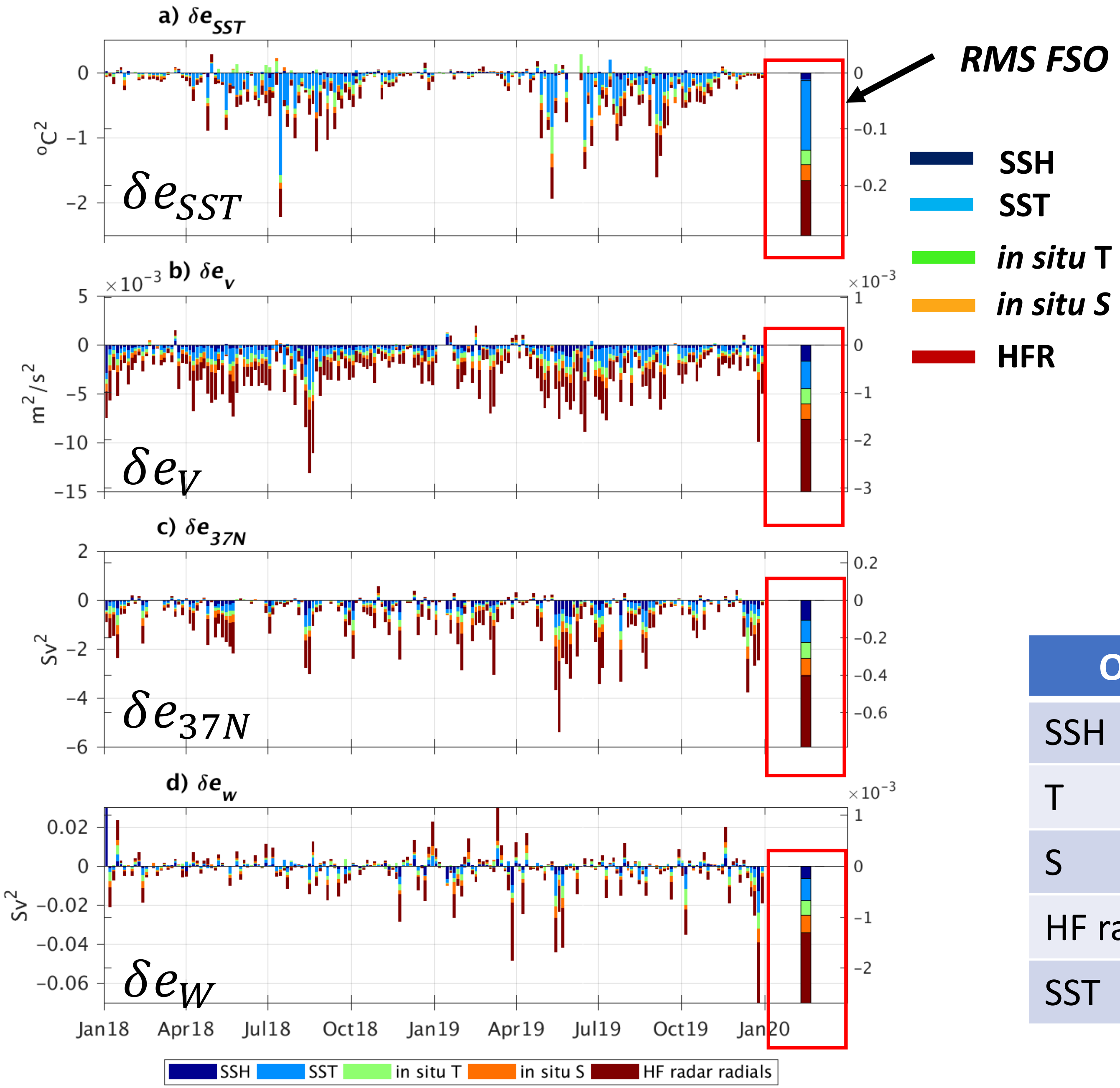

***background***

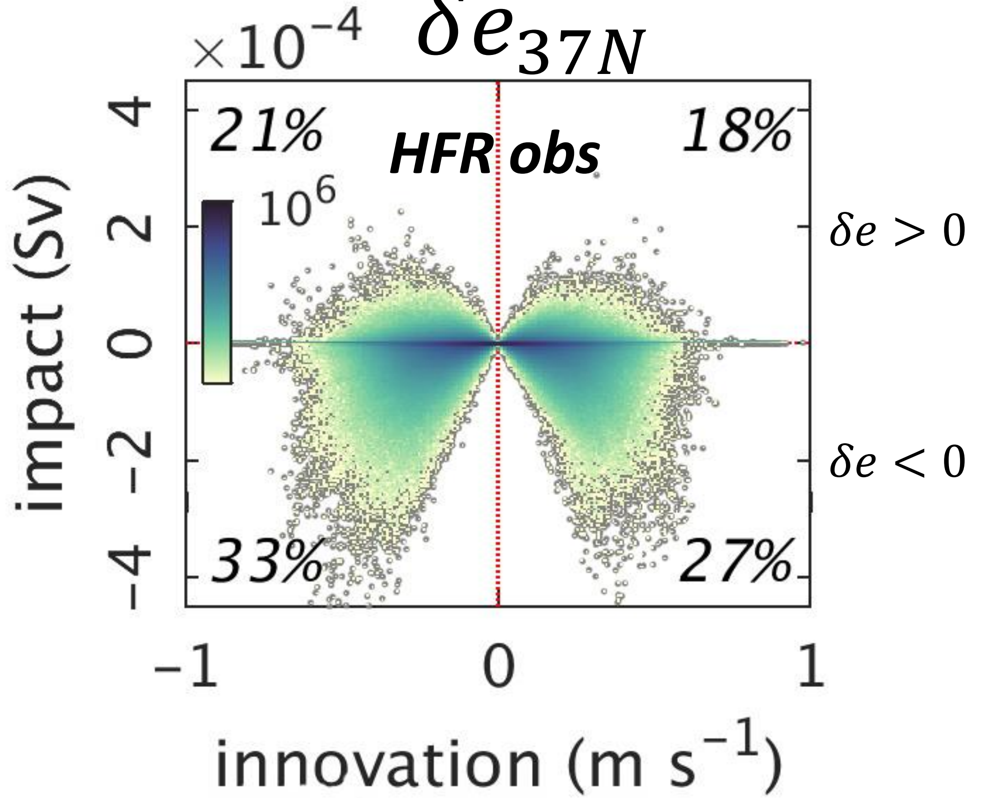
***analysis***

$\delta e = e^a - e^b$

$\delta e$ 3rd-order approx

# Forecast Sensitivity to Observations (FSO)

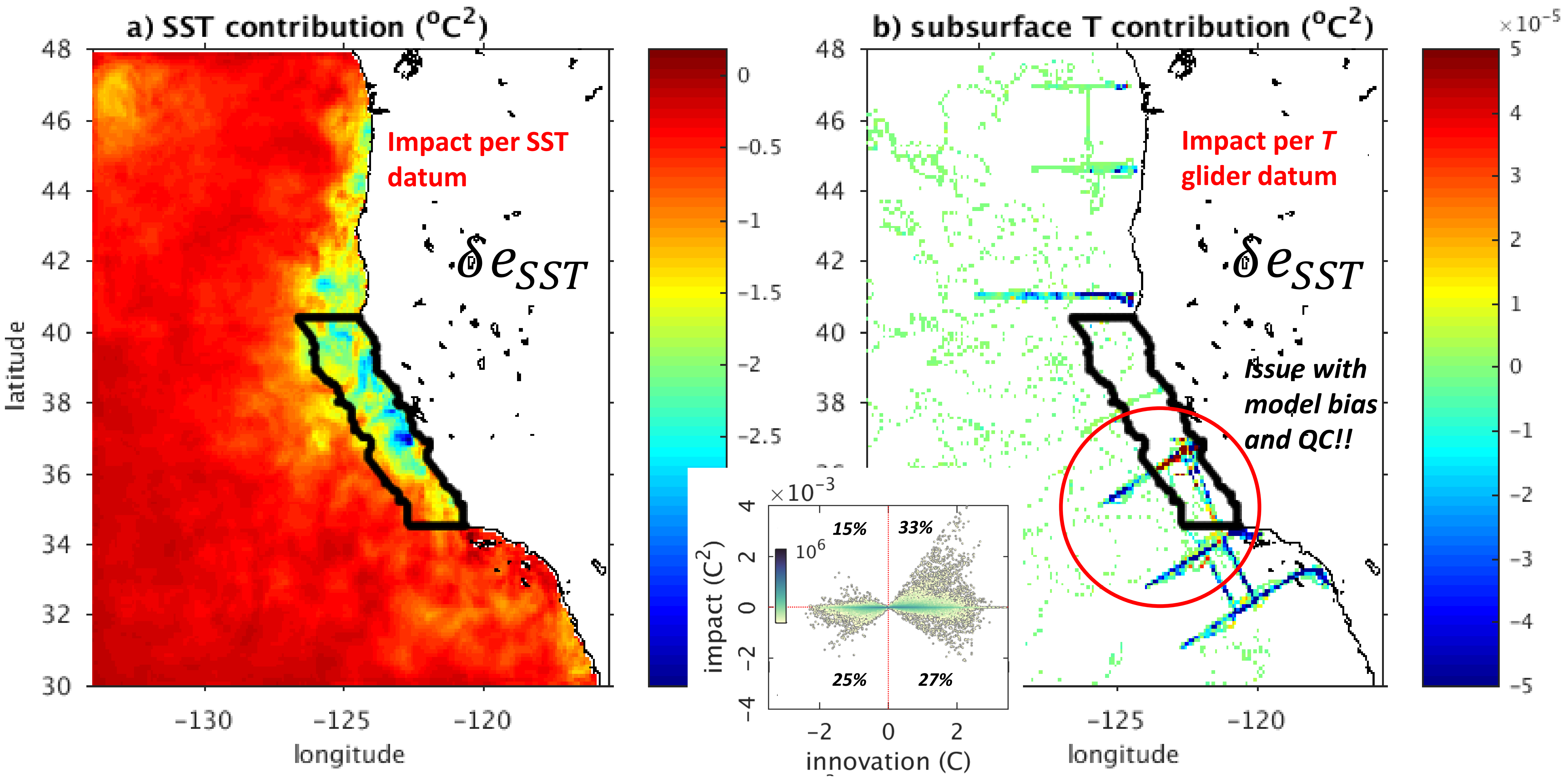


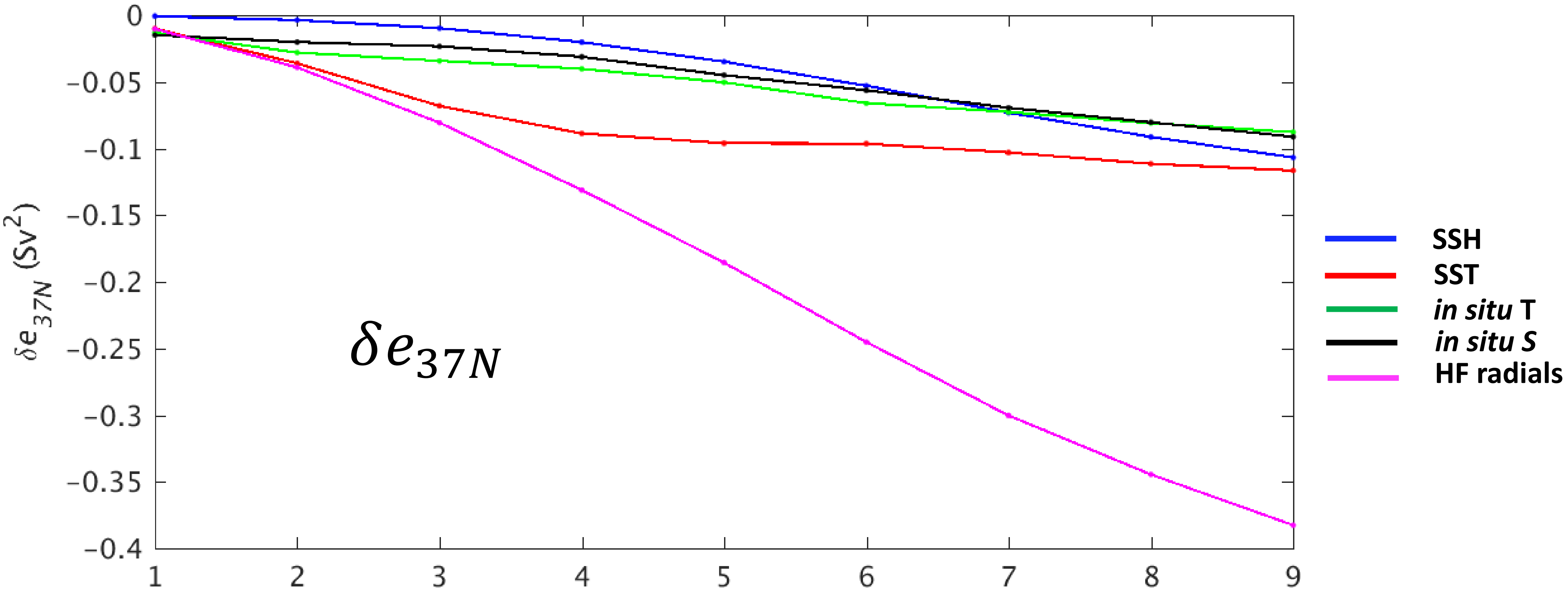

| Obs | $e_{SST}$ | $e_V$ | $e_{37N}$ | $e_W$ |
|---|---|---|---|---|
| SSH | 56% | 66% | 62% | 52% |
| T | 38% | 41% | 40% | 34% |
| S | 38% | 41% | 41% | 35% |
| HF radial | 58% | 65% | 61% | 51% |
| SST | 63% | 62% | 58% | 50% |

***Percentage obs that improve forecast skill***

## Observing System Monitoring



# System Performance




**Mean impact per datum versus inner-loop averaged over all analysis-forecast cycles**

# Summary

- Only ~50% of obs improve forecast (agrees with experience in NWP)
- Should more observations should be assimilated (*cf* Gelaro *et al.*, 2010)?
- Can better use made of existing observations (*i.e.* can more info be extracted from some obs)?
- Data thinning required to reduce relative impact of high volume obs (*e.g.* HF radar, SST – *work in progress*)
- FSO is useful for monitoring observing system and performance of 4D-Var system
- FSO can be applied to *highly targeted* forecast metrics (*e.g.* drifter trajectories in support of search-and-rescue)