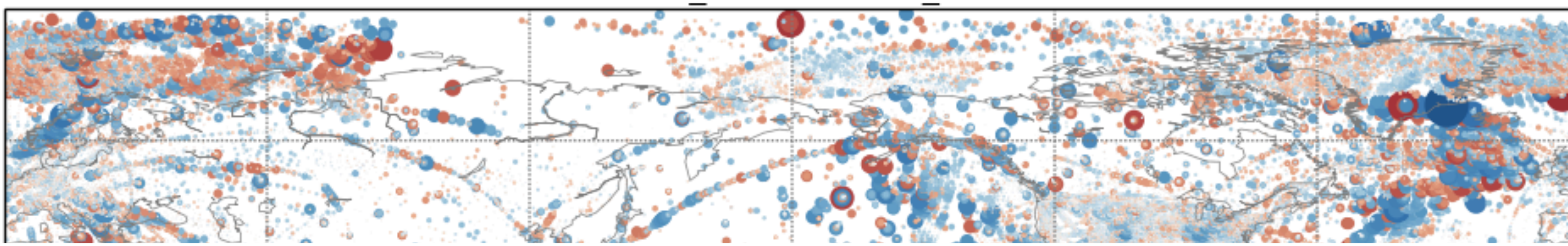
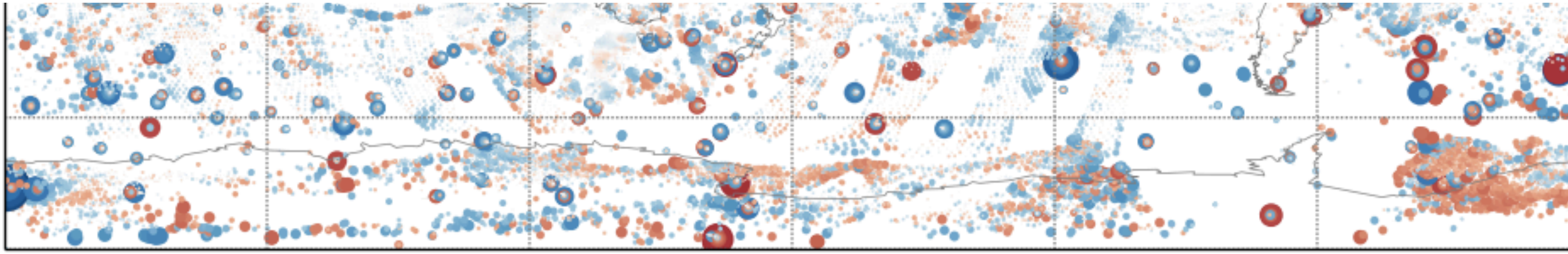


Efficient Estimation of the Impact of Observing Systems using Ensemble Forecast Sensitivity to Observations (EFSO)



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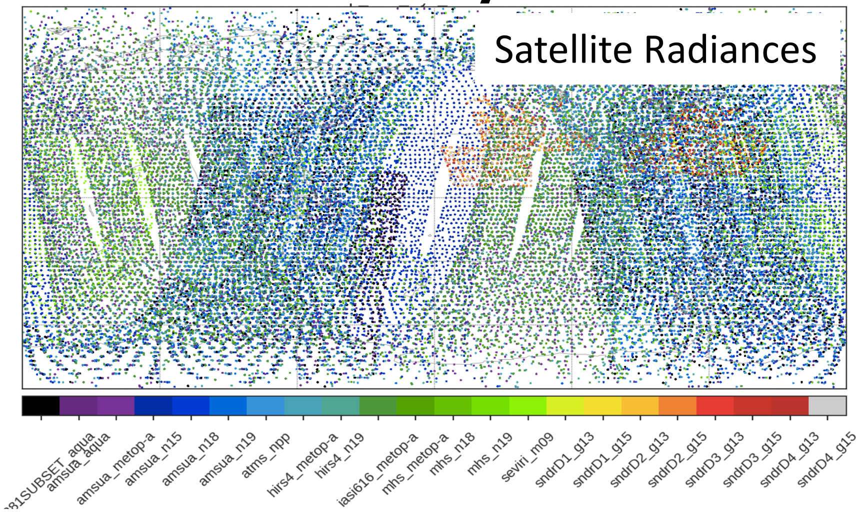
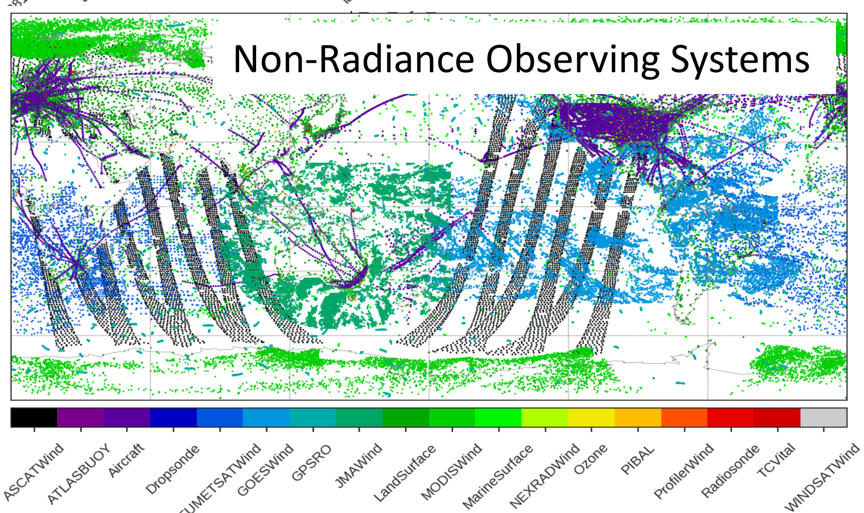
University of Maryland

Acknowledgements to Daisuke Hotta, Jim Jung, Daryl Kleist, Guo-Yuan Lien, Yoichiro Ota, Cheng Da, Shinji Kotsuki, Takemasa Miyoshi, David Santek, Brett Hoover, Jordan Alpert and Krishna Kumar.

Massive Amount of Observations

More than 10^6 of observations assimilated every 6 hours





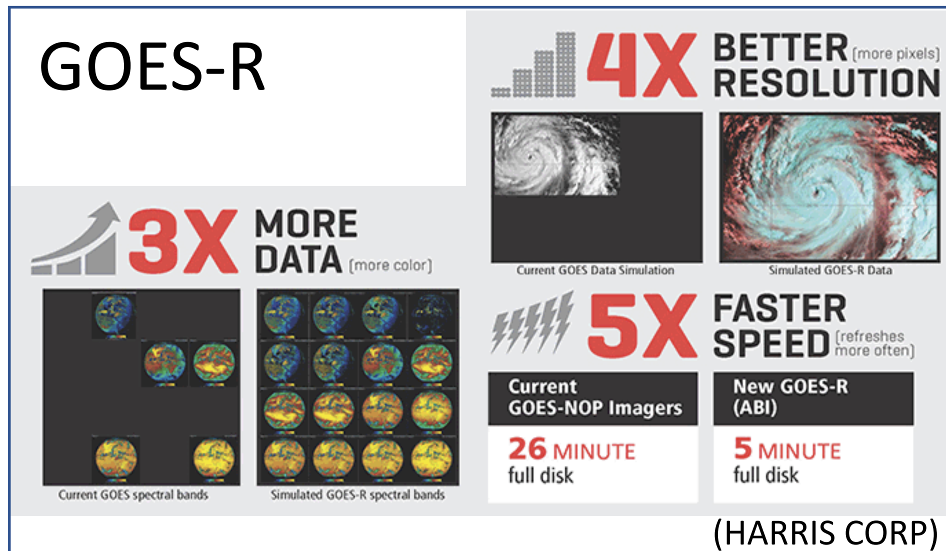
and more on the way….

Next generation satellites

- **50X** more data
- GOES R, S, T, U and Himawari 8, 9

Phase array radar

- **60X** more data
- USA, Japan



How to efficiently evaluate the impacts of all of them?

Evaluating Observation Impact

Observing System Experiments (OSEs):

- Comparing forecasts w/ and w/o a set of observations
- Direct approach to evaluate the observational impact
- Low discernibility, Computationally expensive

Forecast Sensitivity to Observations (FSO):

- Langland and Baker (2004)
- Computationally economical
- Requires adjoint model (inconsistent in representing moist processes.)

Ensemble FSO (EFSO):

- Kalnay et al. (2012)
- Estimates impact of each observation all at once
- Computationally **economical**, Free of adjoint model
- Requires advection of localization

EFSO Formulation

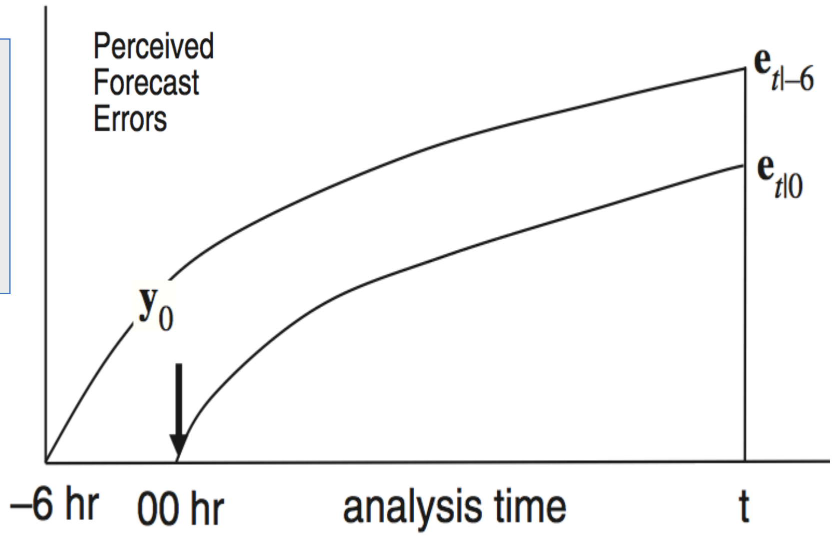
$$\Delta e^2 = \mathbf{e}_{t|0}^T C \mathbf{e}_{t|0} - \mathbf{e}_{t|-6}^T C \mathbf{e}_{t|-6}$$
$$\approx \frac{1}{K-1} \delta \mathbf{y}_0^T \mathbf{R}^{-1} \mathbf{Y}_0^a \mathbf{X}_{t|0}^{fT} C(\mathbf{e}_{t|0} + \mathbf{e}_{t|-6})$$

O-B of the ens. mean

Analysis perturbation in obs. space

Forecast perturbation

(Kalnay et al., 2012)

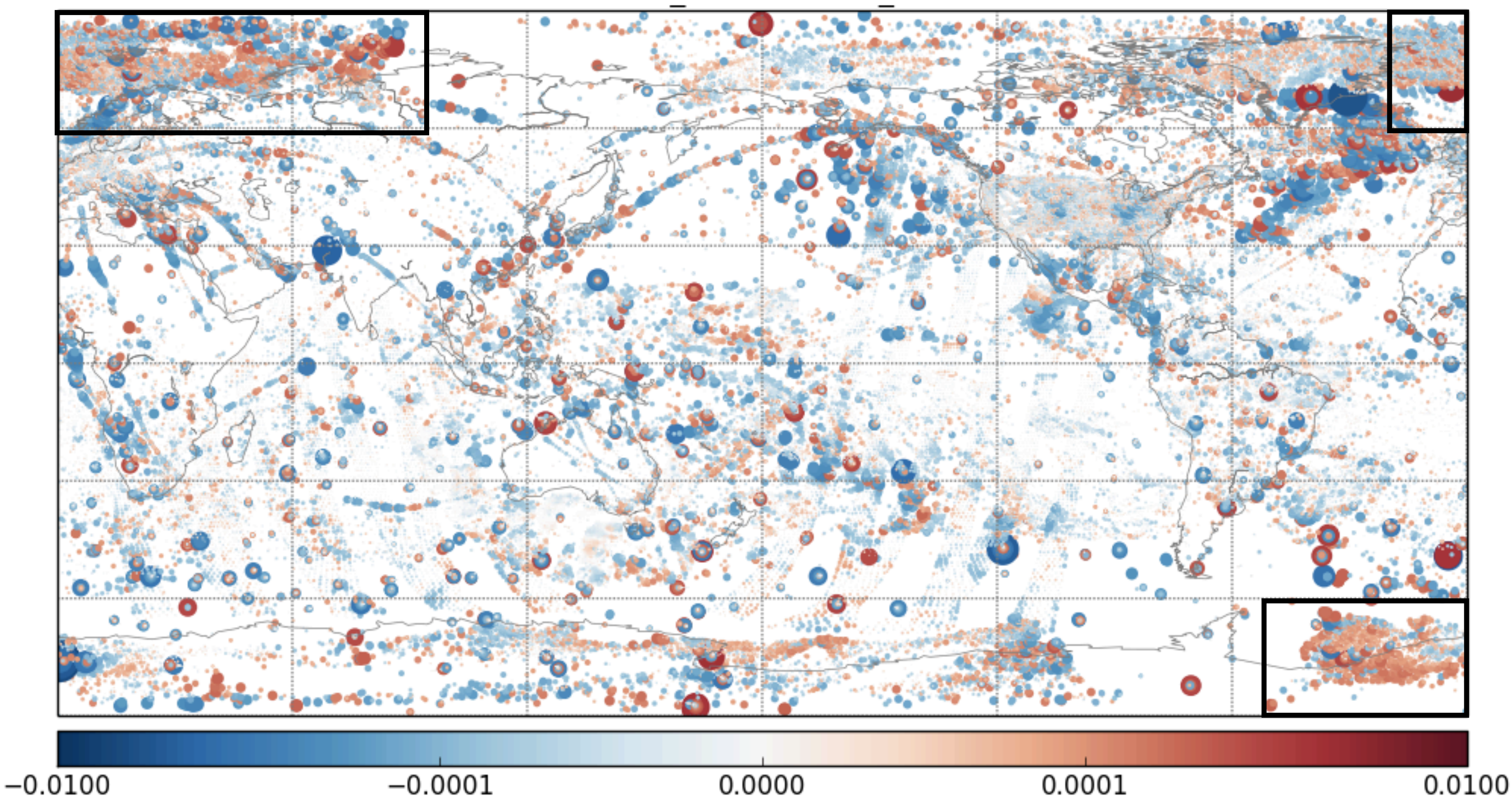


- **Quantifies** how much **each observation** improves or degrades model forecasts.
- A **linear mapping** from error changes to each observations.
- **Negative value**: error reduction/ **beneficial** observation
- **Positive value**: error growth/ **detrimental** observation

Experimental Setup

Period (1 month)	Jan/10/2012 00Z – Feb/09/2012 18Z
Model	GFS T254/T126 L64
DA	LETKF/3D-Var Hybrid GSI v2012
Localization cut-off length	2000 km/ 2 scale heights
Error norm	Moist total energy (MTE) $MTE = \frac{1}{2}\frac{1}{\lvert S\rvert}\int_S \int_0^1 \{(u'^2 + v'^2) + \frac{C_p}{T_r}T'^2 + \frac{R_d T_r}{P_r^2}p_s'^2 + w_q \frac{L^2}{C_p T_r}q'^2\} d\sigma dS$

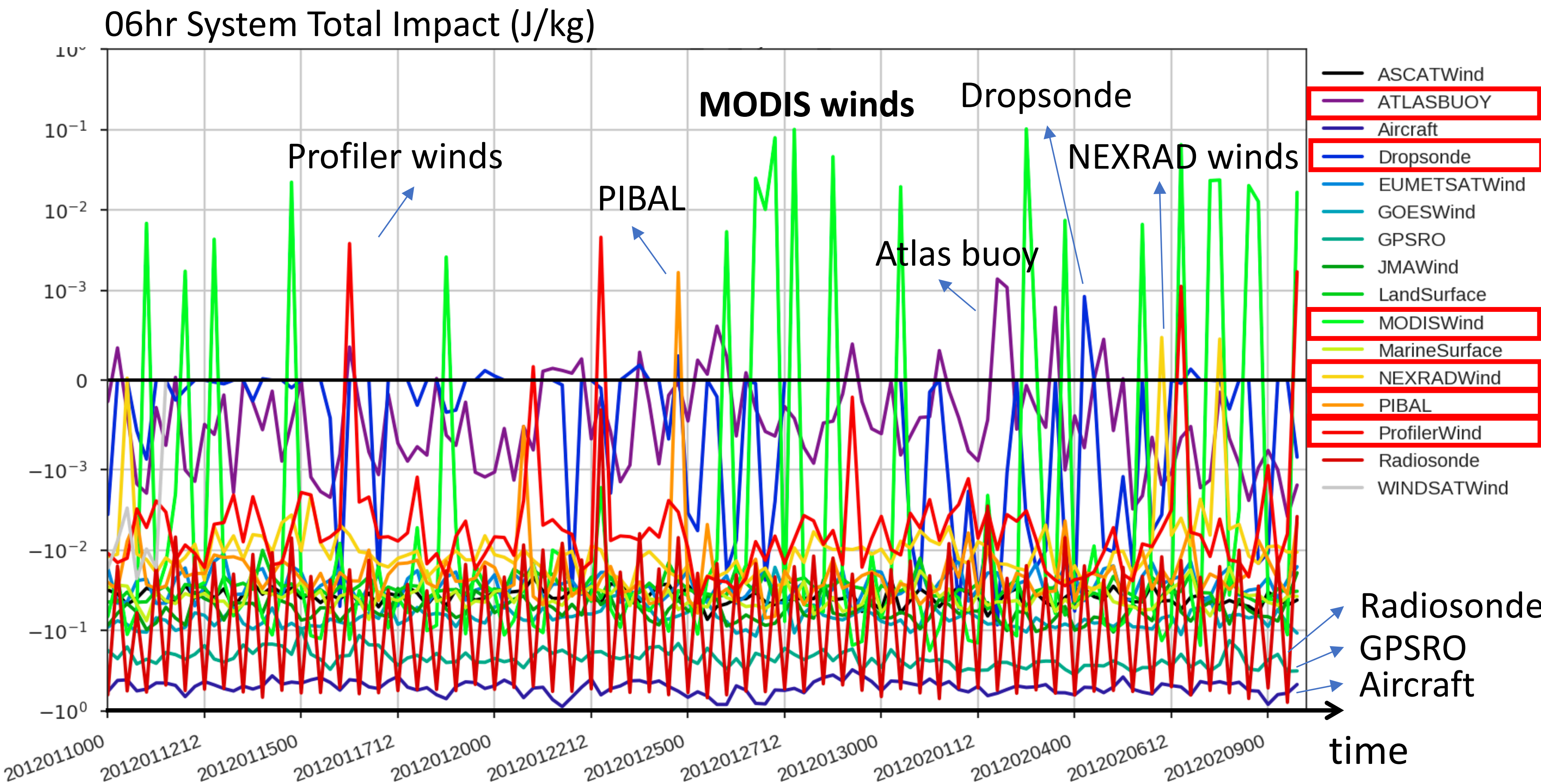
Clustered Detrimental Observations



Regions (black boxes) with clusters of **detrimental (red)** observations.

Case: Feb/06/2012 18Z
Color: 06hr MTE impact (J/kg)
Size: Magnitude of impact

Detrimental episodes can be monitored

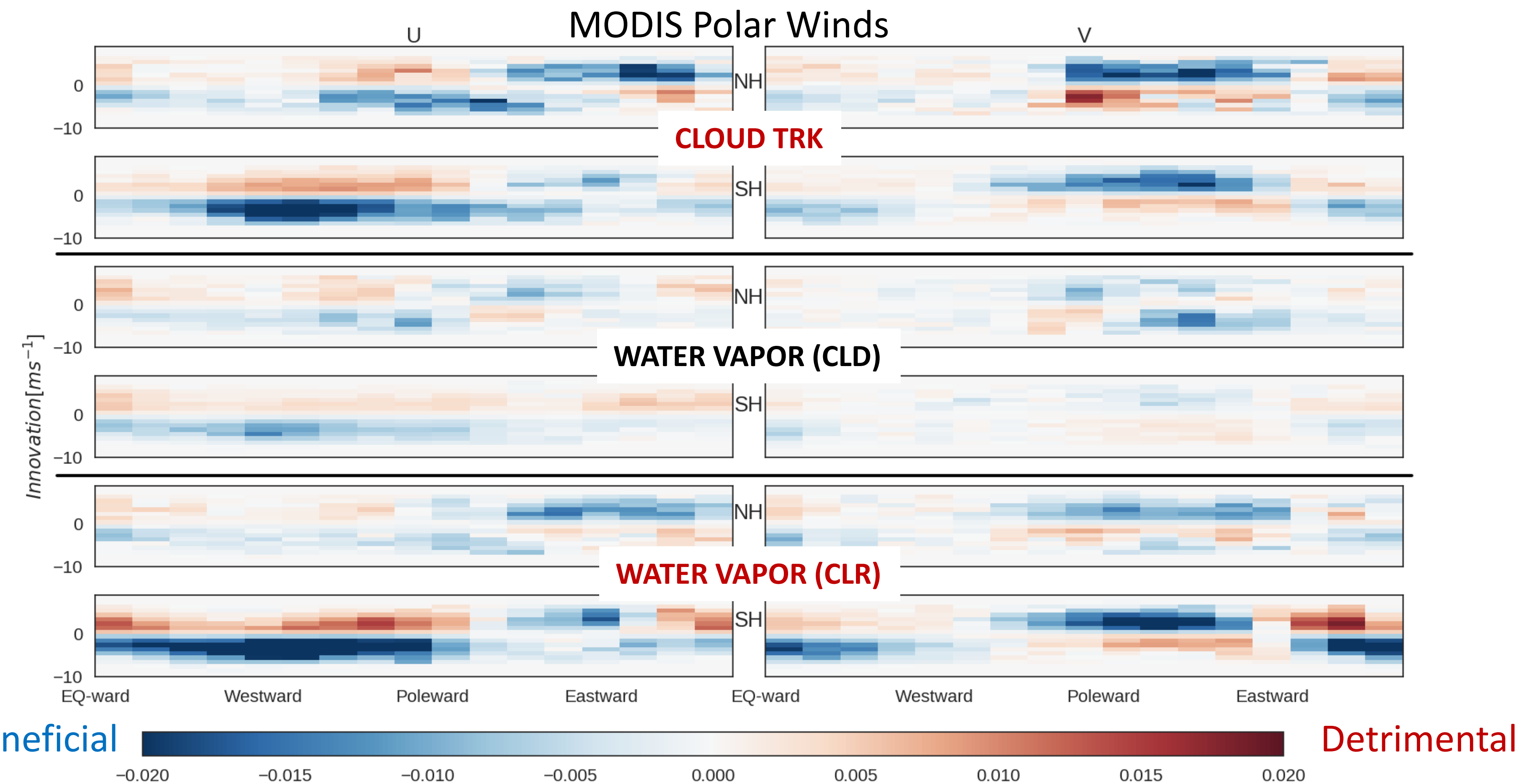


Detrimental episodes in some observing systems.

MODIS polar winds is one of the contributors.

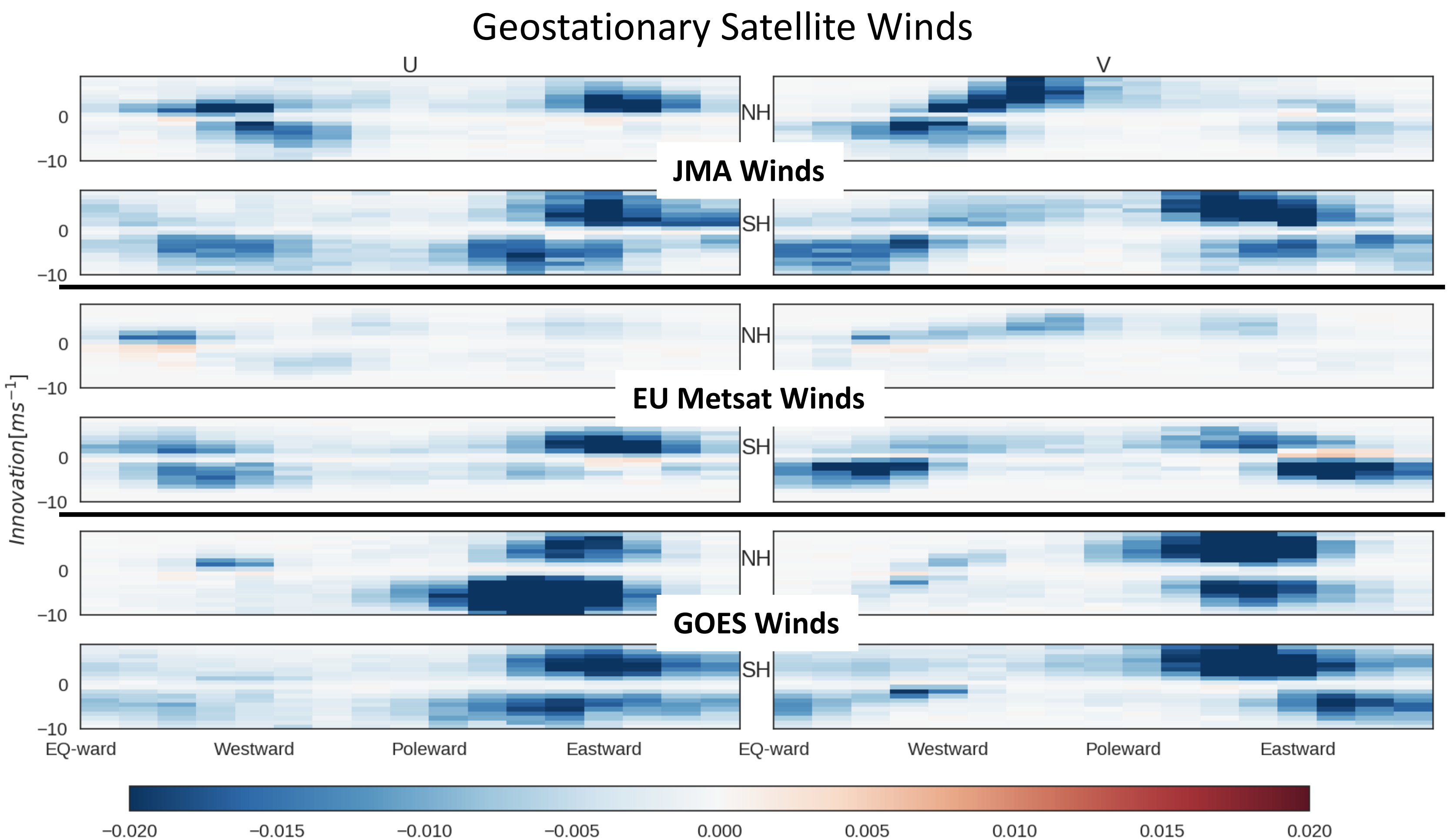
Powerful QC monitoring for every system!

Biases: Innovation and Wind Direction



- Prevailing **positive innovation bias** in U comp. of MODIS wind
- Cloud tracking winds (top) and Water vapor tracking (bottom) resemble each other in both hemisphere
- Good for fixed state-dependent QC

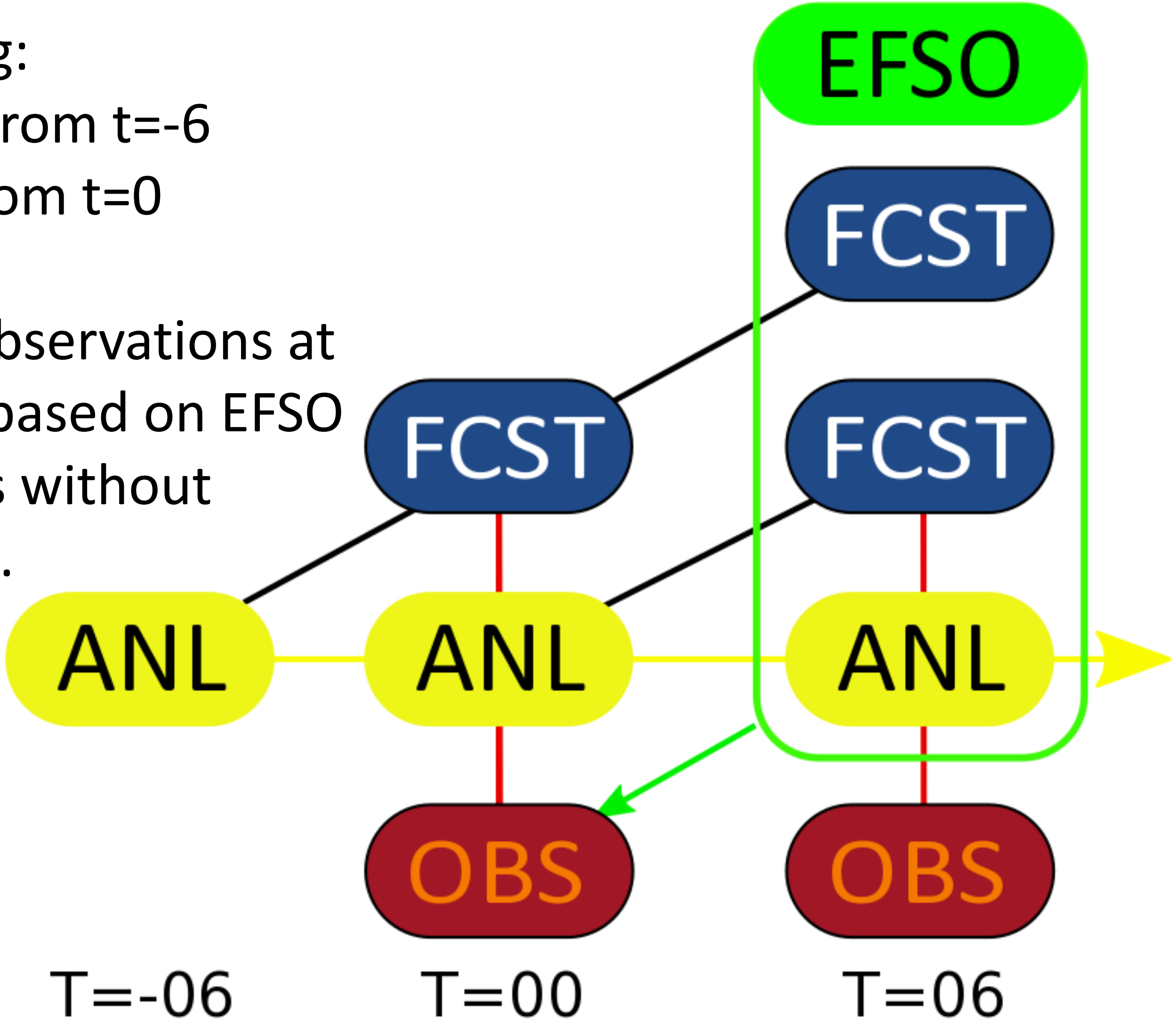
Biases: Innovation and Wind Direction



- No such biases for Geostationary Satellite Winds

Proactive QC Algorithm

1. Perform EFSO using:
    1. 12-hr forecast from t=-6
    2. 6-hr forecast from t=0
    3. analysis at t=6
2. Determine set of observations at t=0 to be rejected based on EFSO
3. Repeat the analysis without those observations.



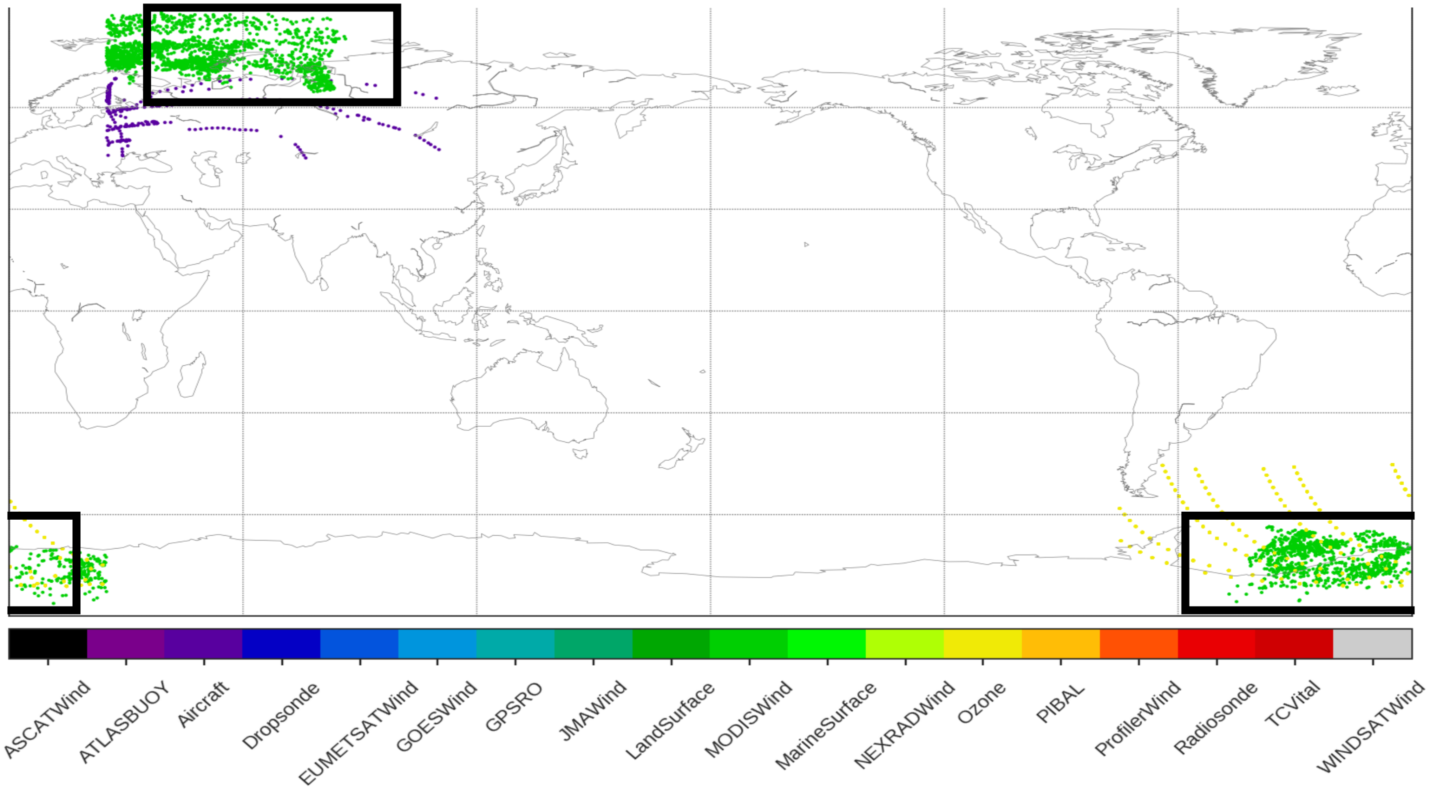
Adapted from Hotta (2017)

Three Data Denial Experiment Methods

1. Hotta (from Hotta 2017 and Ota 2013)

- Identify **forecast error degradation regions**
- Perform EFSO w.r.t. those regions for 6-hr impact
- Reject detrimental observations only from the systems that have net detrimental impact.

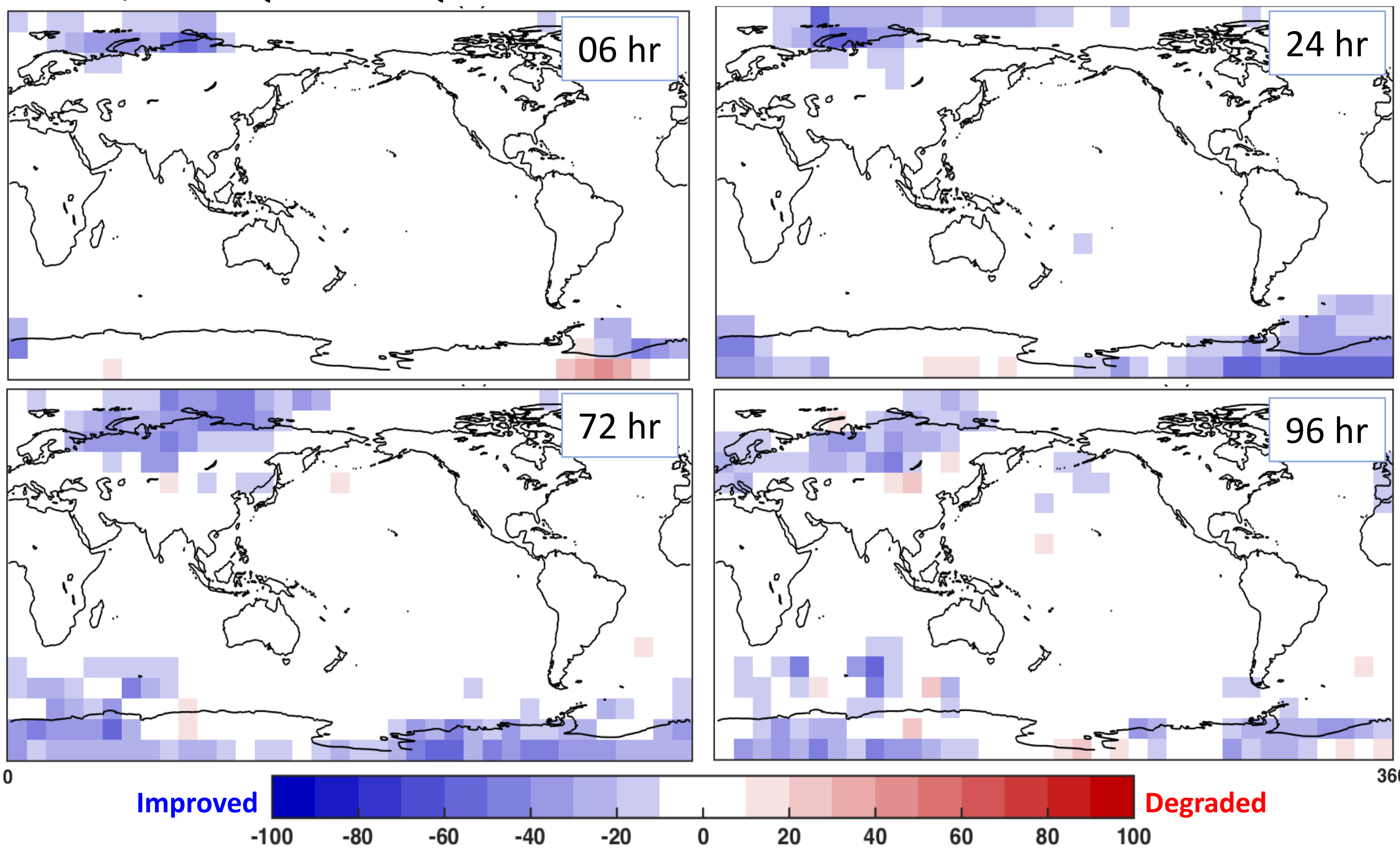
Case: Feb/06/2012 18Z



1. Hotta Method: Impact on the Forecasts

$(e^f_{beforeQC} - e^f_{afterQC}) / e^f_{beforeQC} \times 100$ [%]

Feb/06/2012 18Z



Improved regions **strengthen** and **propagate** with weather system

Three Data Denial Experiment Methods

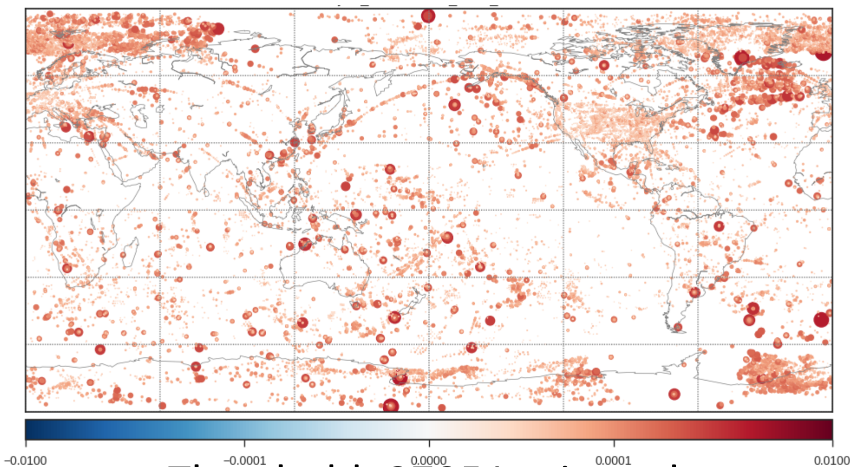
2. Threshold (THR)

- Compute global EFSO for 06-hr impact of each observation
- Reject detrimental observations with a positive (detrimental) impact larger than a 10^-5 (J/kg) threshold.

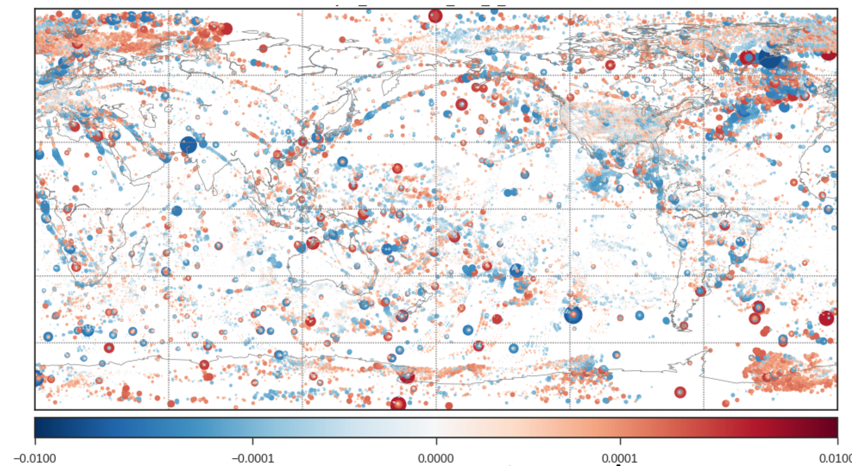
3. Beneficial Growing Mode (BGM; **reanalysis**)

- Inspired by Trevisan (2010):
  Assimilation in Unstable Subspace (AUS)
- Compute the global EFSO for 06, 24-hr impact
- Assimilate only when: $\Delta e^2_{24|0} < \Delta e^2_{6|0} < 0$

Case: Feb/06/2012 18Z
Color: 06hr MTE impact (J/kg)
Size: Magnitude of impact



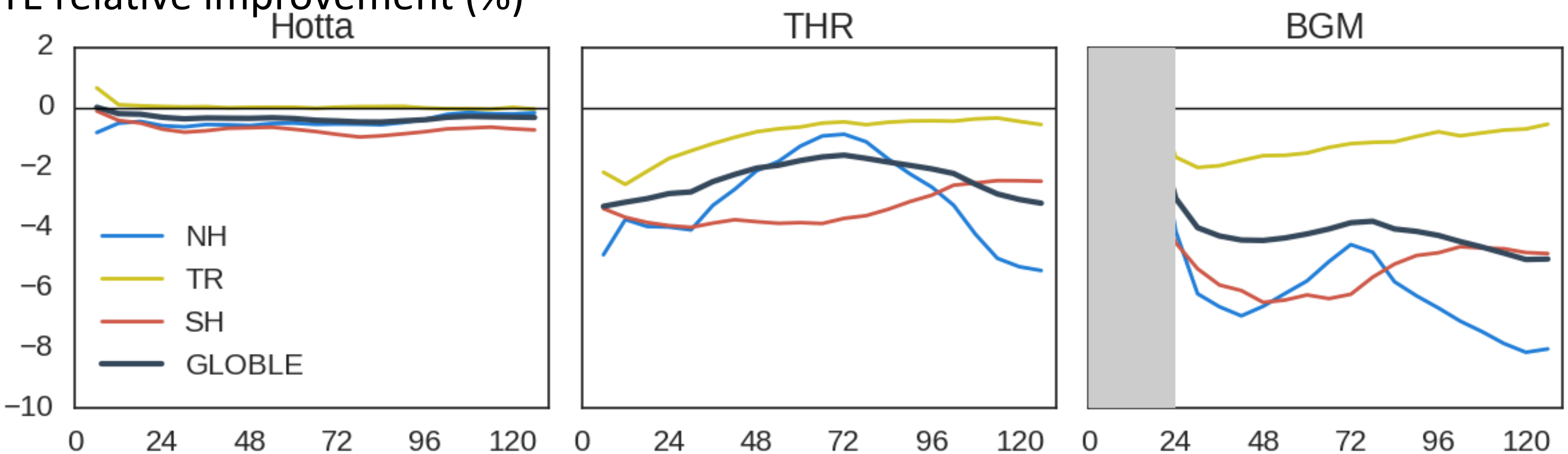
Threshold: 37951 rejected
7% of non-radiance obs.



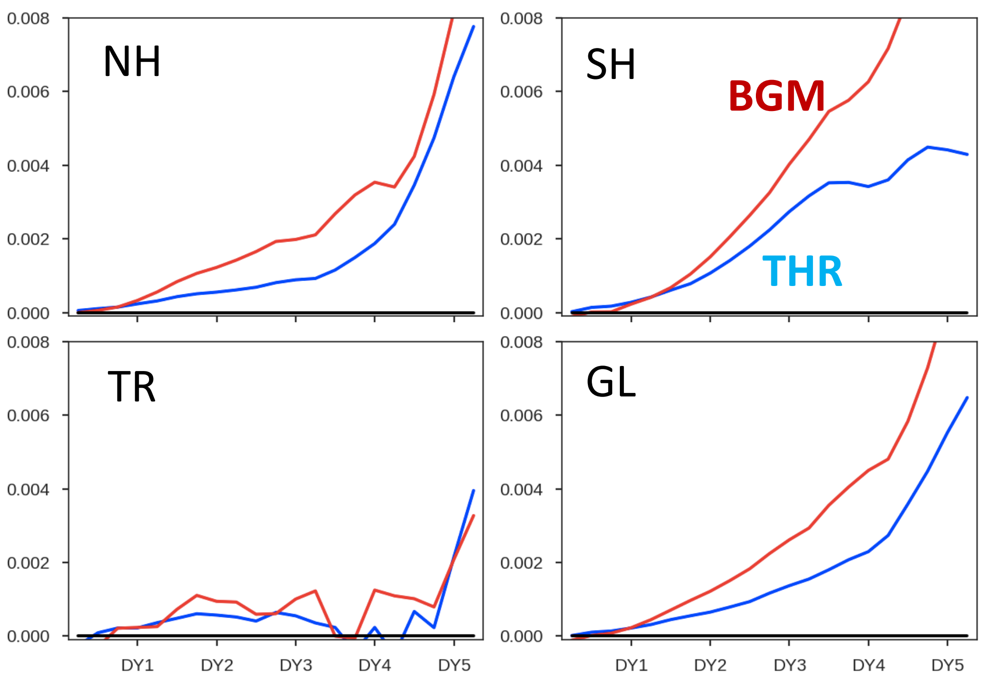
BGM: 287289 rejected
53% of non-radiance obs.

Offline Experiment: 18 cases

MTE relative improvement (%)



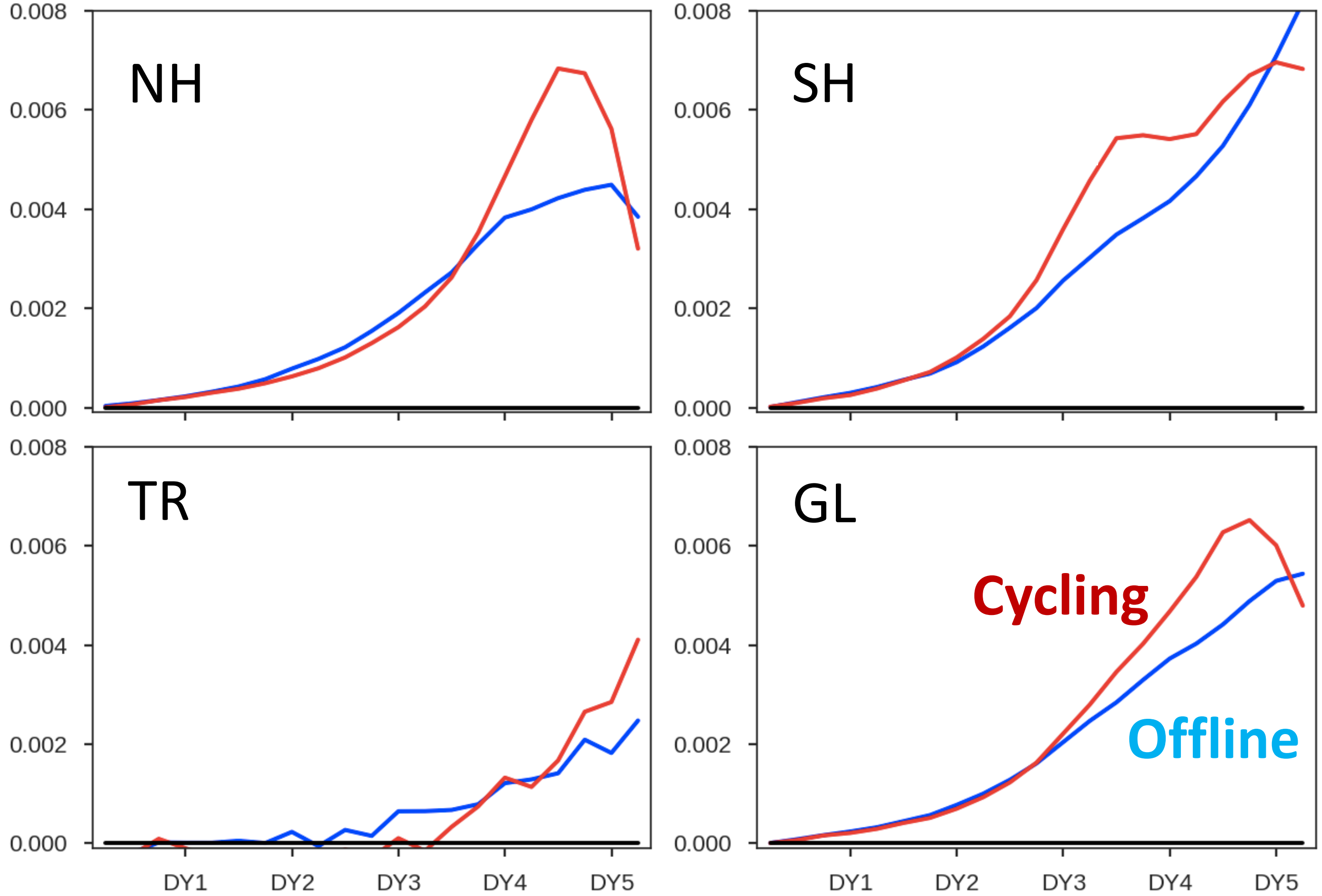
Z500 ACC Improvement: THR(blue) v.s. BGM(red):



- PQC corrects analysis and the subsequent forecast.
- All three methods improve model forecasts on average.
- The **BGM** and **THR** method have forecast improvements much larger than **Hotta** method.

Cycling PQC Experiment: 40 cycles

Z500 ACC Improvement: Offline-THR(blue) v.s. Cycling-THR(red)



Improvement by **cycling PQC** maximizes around 3-5 day forecasts by accumulated beneficial effect of past PQCs.

Is it necessary to redo the Analysis?

Estimated PQC correction using **same Kalman gain K:**

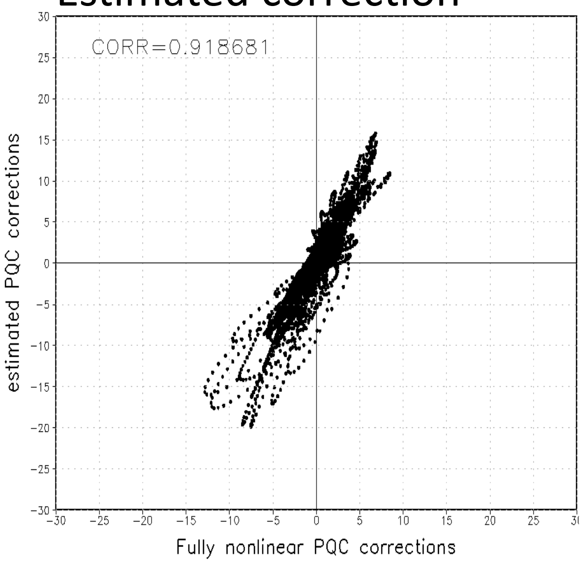
- K is actually depending on H, which is determined by observations
- Non-inflated analysis perturbations should be used
- Slight overestimation: Only 75% of **B** is from the ensemble

$$\bar{\mathbf{x}}_0^{a,\mathrm{deny}} - \bar{\mathbf{x}}_0^{a} \approx -\mathbf{K}\delta\bar{\mathbf{y}}_0^{ob,\mathrm{deny}}$$

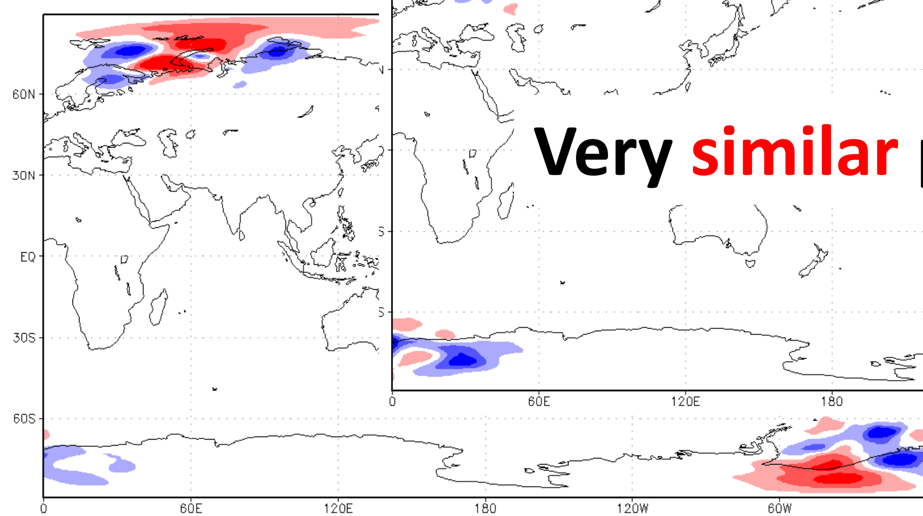
$$\mathbf{K} \approx \frac{1}{K-1}\mathbf{X}_0^a\mathbf{X}_0^{aT}\mathbf{H}^T\mathbf{R}^{-1} \approx \frac{1}{K-1}\mathbf{X}_0^a\mathbf{Y}_0^{aT}\mathbf{R}^{-1}$$

(Hotta, 2017)

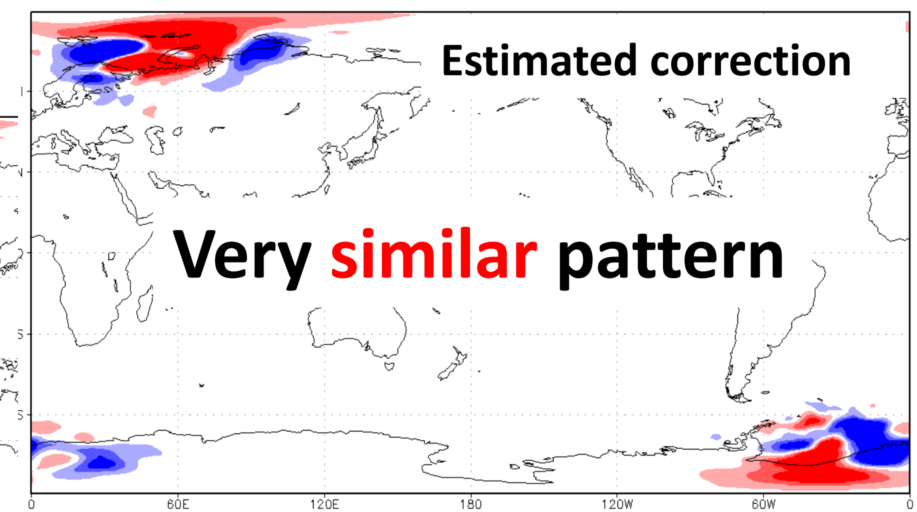
True correction v.s.
Estimated correction



True correction



Estimated correction



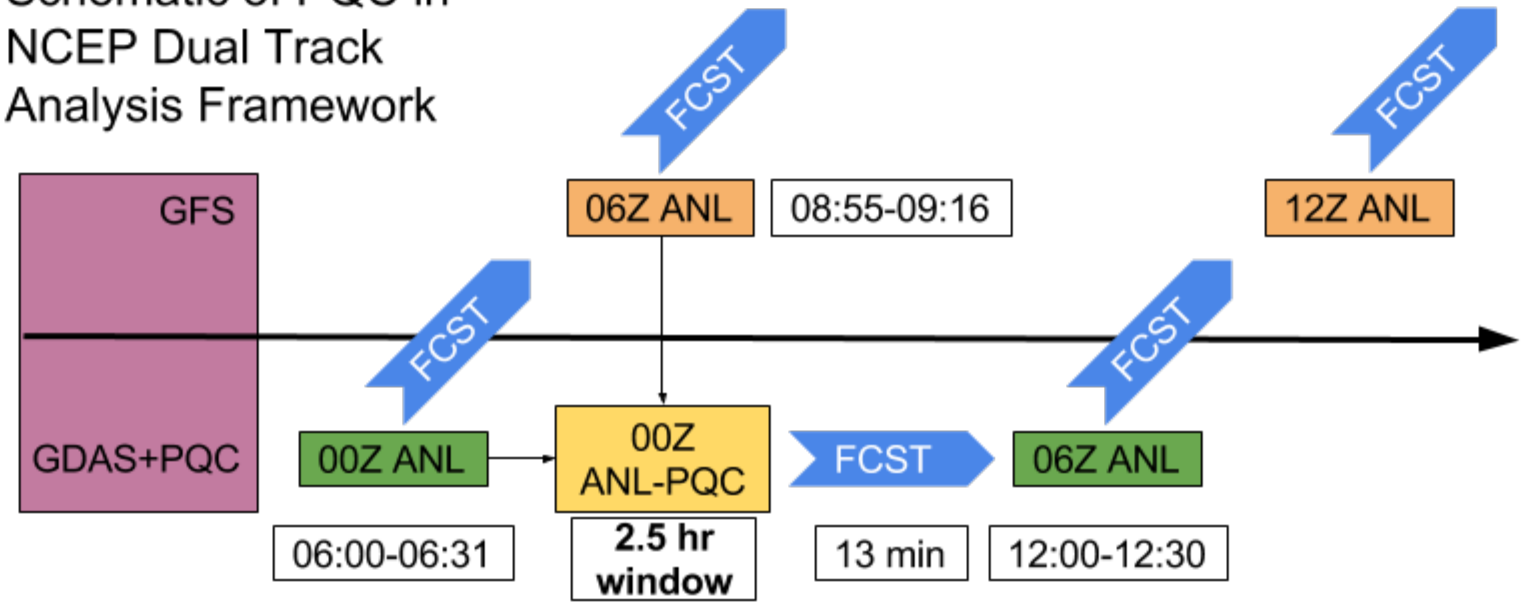
PQC corrections: Z500

PQC in NCEP Dual Track Analysis

Using **GFS-analysis** saves 3 hours of waiting

- PQC provides better **GDAS-analysis** product.
- The real-time **GFS-forecast** benefits from the PQC done **12** hours ago and the beneficial impact **accumulates** over each cycle.

Schematic of PQC in NCEP Dual Track Analysis Framework



Adapted from Hotta (2017)

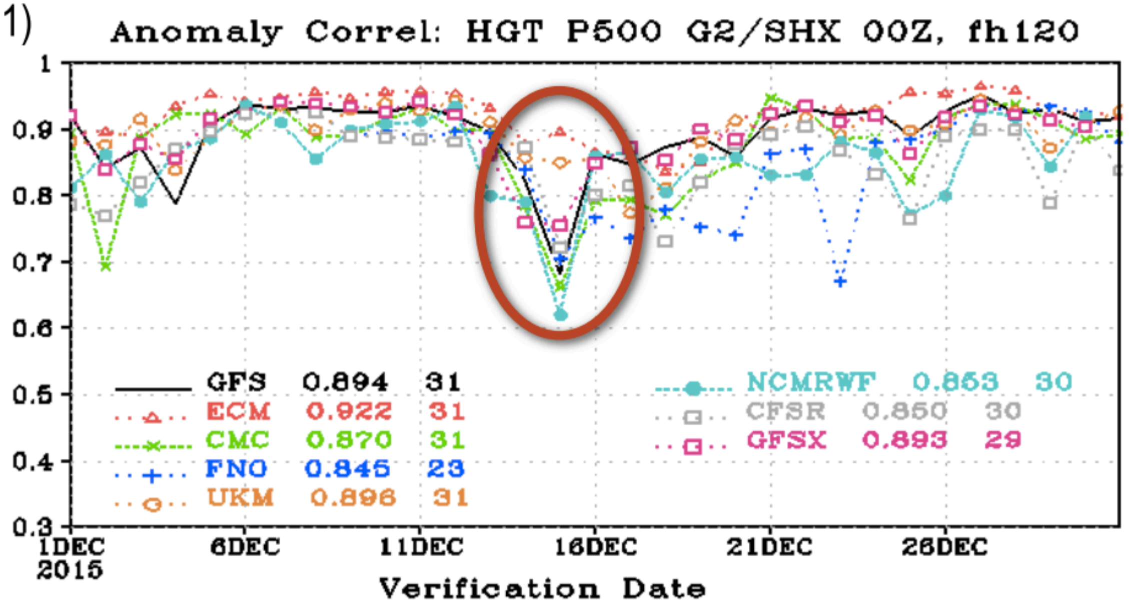
Collaboration: Testing at NCEP

We are collaborating with
NCEP GFS Forecast Skill Dropout Team:

Drs. Jordan Alpert and Krishna Kumar

- Culprit: Detrimental observations
- Contaminated radiances found causing some dropout cases

1)



Example skill dropout case:
GFS drops below 0.7
EC, UK remains above 0.85

EFSO/PQC can help identify these detrimental observations

Brief Summary

- EFSO is an efficient tool for:
  - Identifying detrimental observations
  - Online monitoring the impact on model forecast of assimilating each observation.
- PQC-THR (for operations) improves analysis and the subsequent forecast for up to 5 days.
- PQC-BGM allows doing assimilation within beneficial growing mode in **reanalysis**.
- Almost no-cost PQC approximation to the analysis after deleting detrimental observations.

Some more results obtained from idealized system: Lorenz 96

Experimental Setup

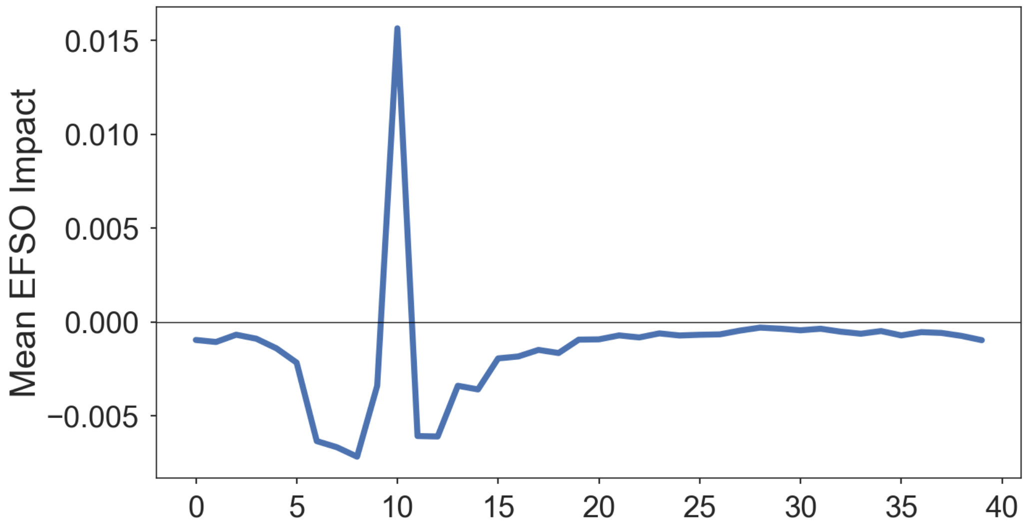
Model	40-variable Lorenz 96 $$\frac{dx_i}{dt} = -x_{i-2}x_{i-1} + x_{i-1}x_{i+1} - x_i + F$$ F = 8, dt = 0.05, 4^{th} order Runge-Kutta
Period	5000 cycles (plus 500 cycles of spin up)
Data Assimilation	ETKF-40 members
Observations	40 variables from truth (OSSE), N(0, 0.1)

EFSO can find Flawed Obs.

Large random error

at the 10th grid point:

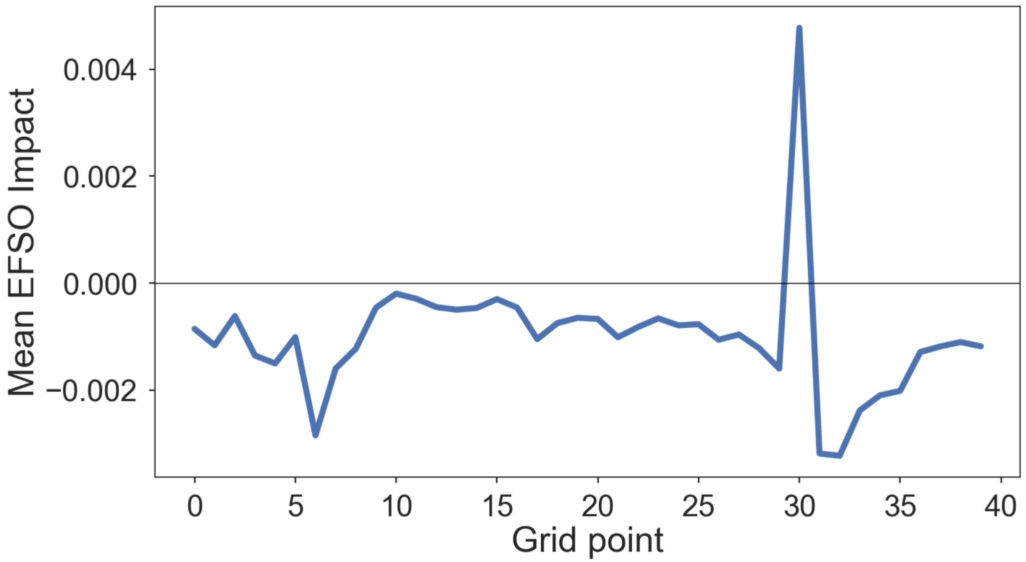
- 8 times larger than specified in R
- Neighboring grid points become more helpful



Biased observation

at the 30th grid point:

- Bias = 0.3 (Range of L96 is 28)
- Neighboring grid points become more helpful



Truly flawed obs. can be detected by EFSO

Adapted from Kalnay (2012)

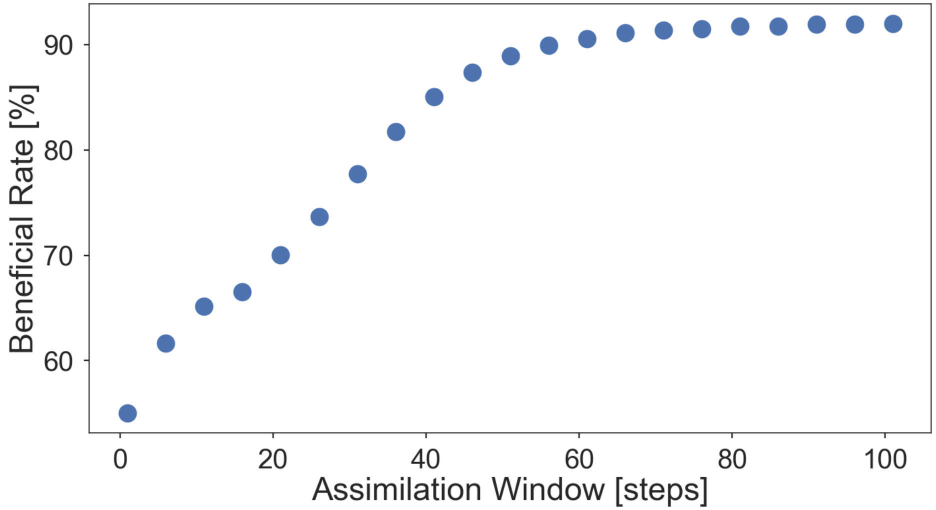
Low % of Beneficial Obs in (E)FSO

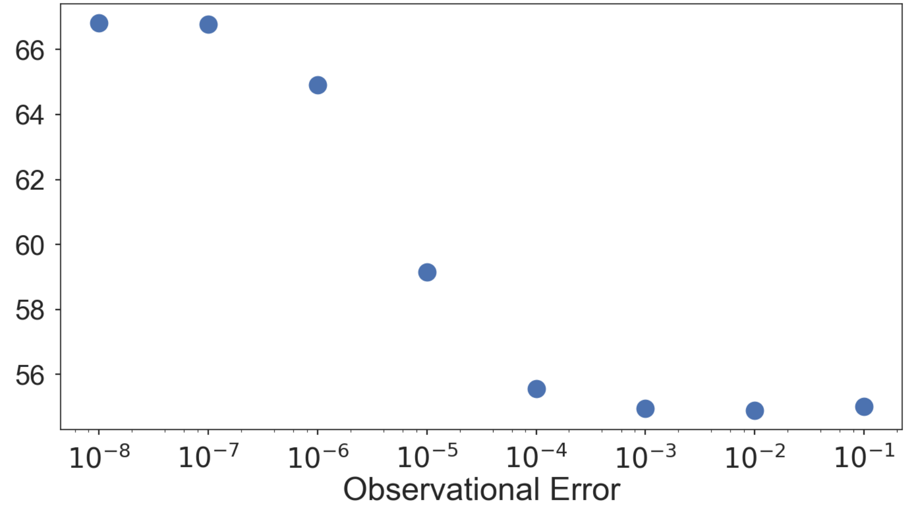
In literatures:

- Inaccurate verifying analysis (Daescu 2009)
- Statistical nature of DA (Gelaro 2010, Ehrendorfer 2007)
- Inaccurate B and modes with different growth rates (Lorenc and Marriot 2014)

Our findings:

- Background quality is as important as to Observational quality



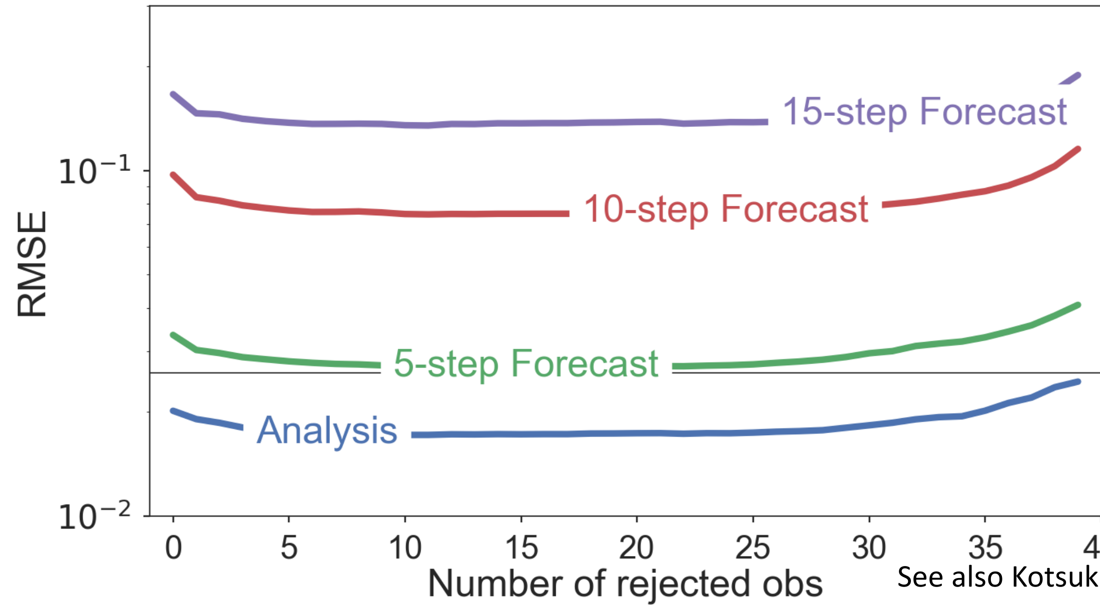


Most of the observations become very useful when background is not good. i.e. Our forecasts are doing a very good job

Proactive QC in L96

Single cycle PQC:

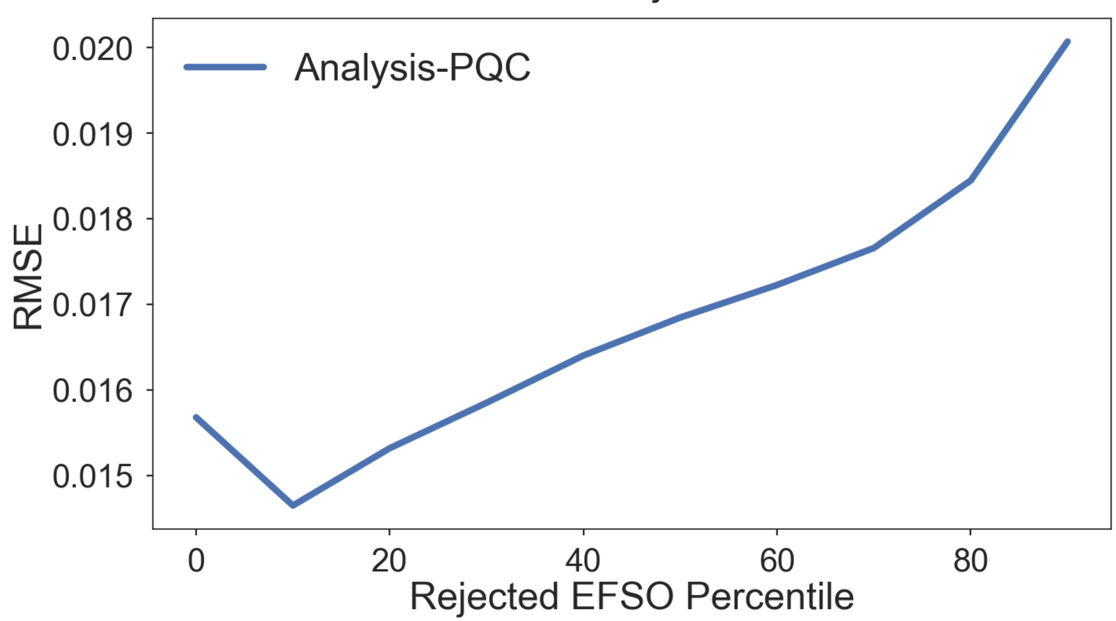
- Reject some **Detrimental** observations improves analysis.
- Flat bottom U-shape
- PQC impact remains in forecast beyond 15 steps.



See also Kotsuki (2017)

Cycling PQC:

- Reject 10% **Detrimental** observations improves analysis.
- No Flat bottom U-shape: Initial small error may grow
- PQC impact remains in forecast beyond 15 steps.



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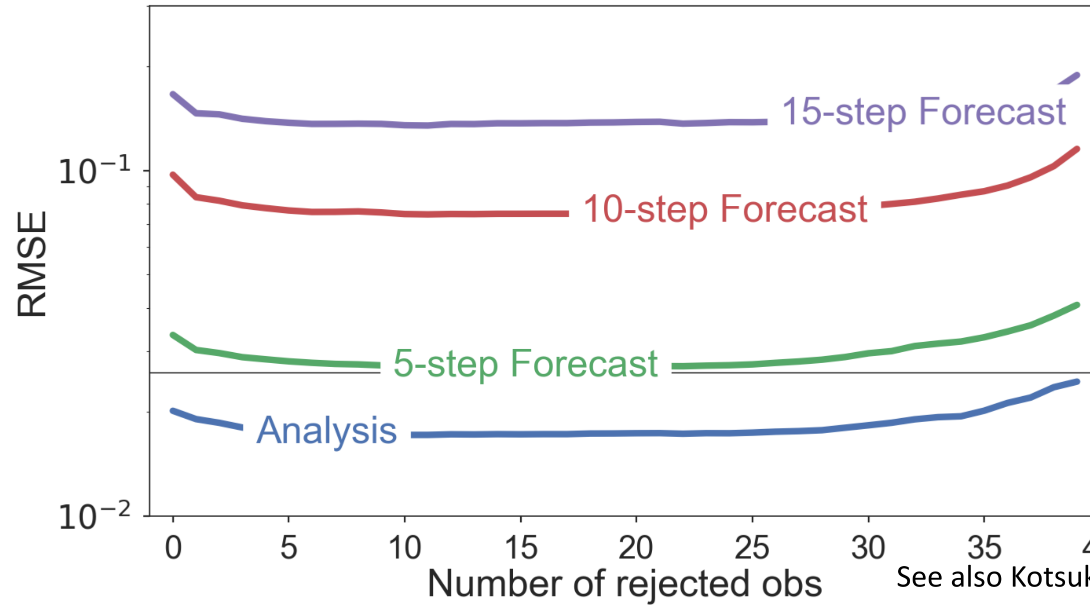

See also Kotsuki (2017)

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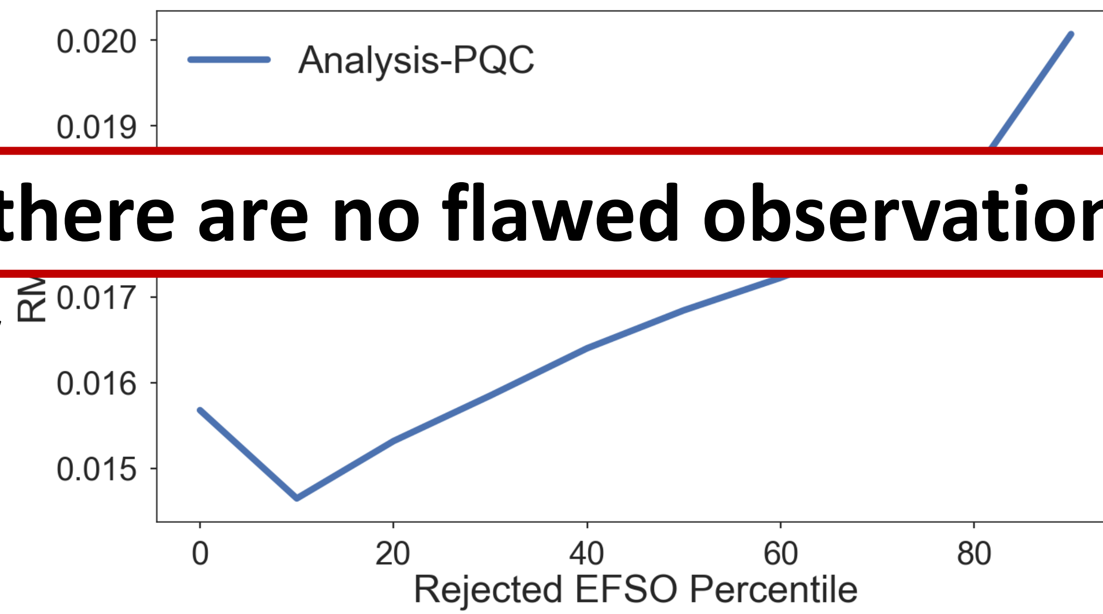


PQC works even if there are no flawed observations

Brief Summary (Lorenz 96)

- An explanation of low beneficial rate if offered: Forecast is comparably accurate as Observation
- EFSO detects flawed observations.
- EFSO identifies the detrimental observations even if it is not flawed.
- **PQC works even if no flawed observation exists**

Future Directions

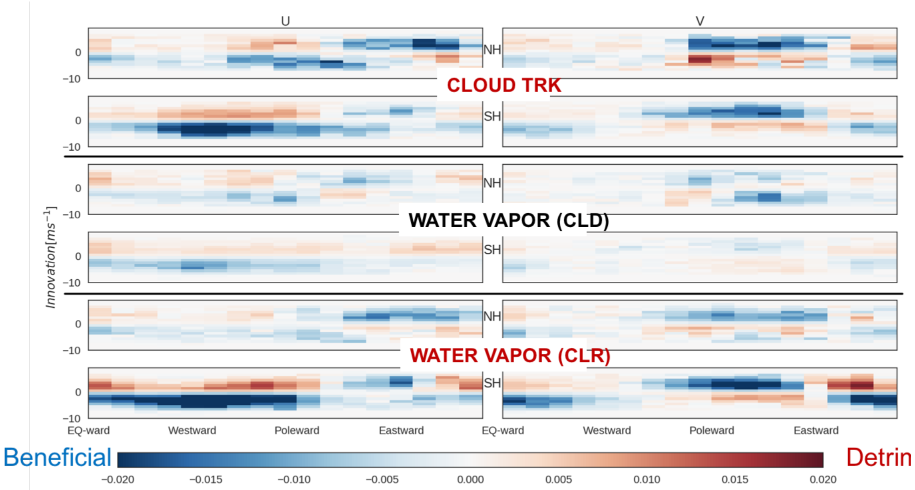
- Continue investigating the cause of detrimental MODIS polar winds.
- Use EFSO to help QC in radiance observations e.g. channel selection
- Expand PQC to reject radiance observations
- Explore the connections between PQC and Assimilation in Unstable Subspace (AUS)

Thank you very much for your attention

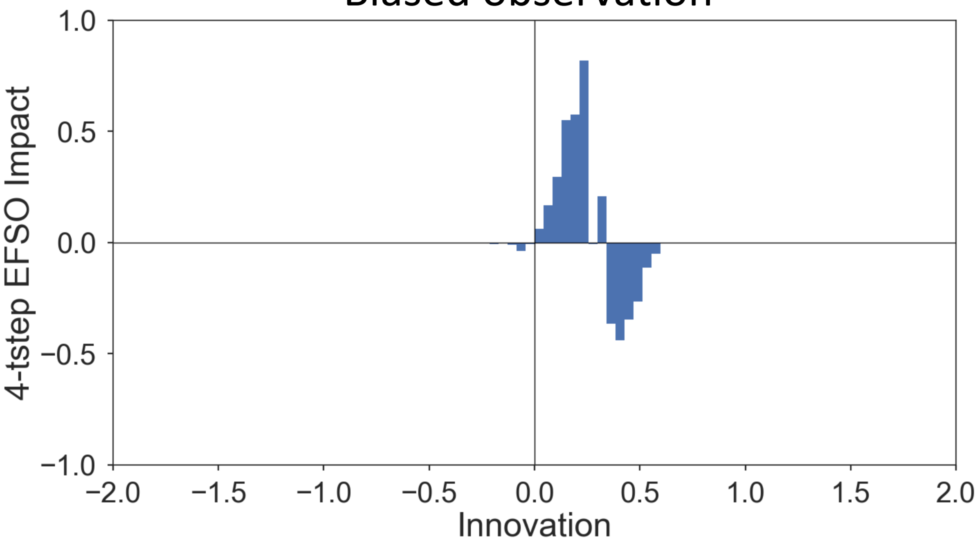
Backup Slides

Innovation Bias

MODIS Polar Winds

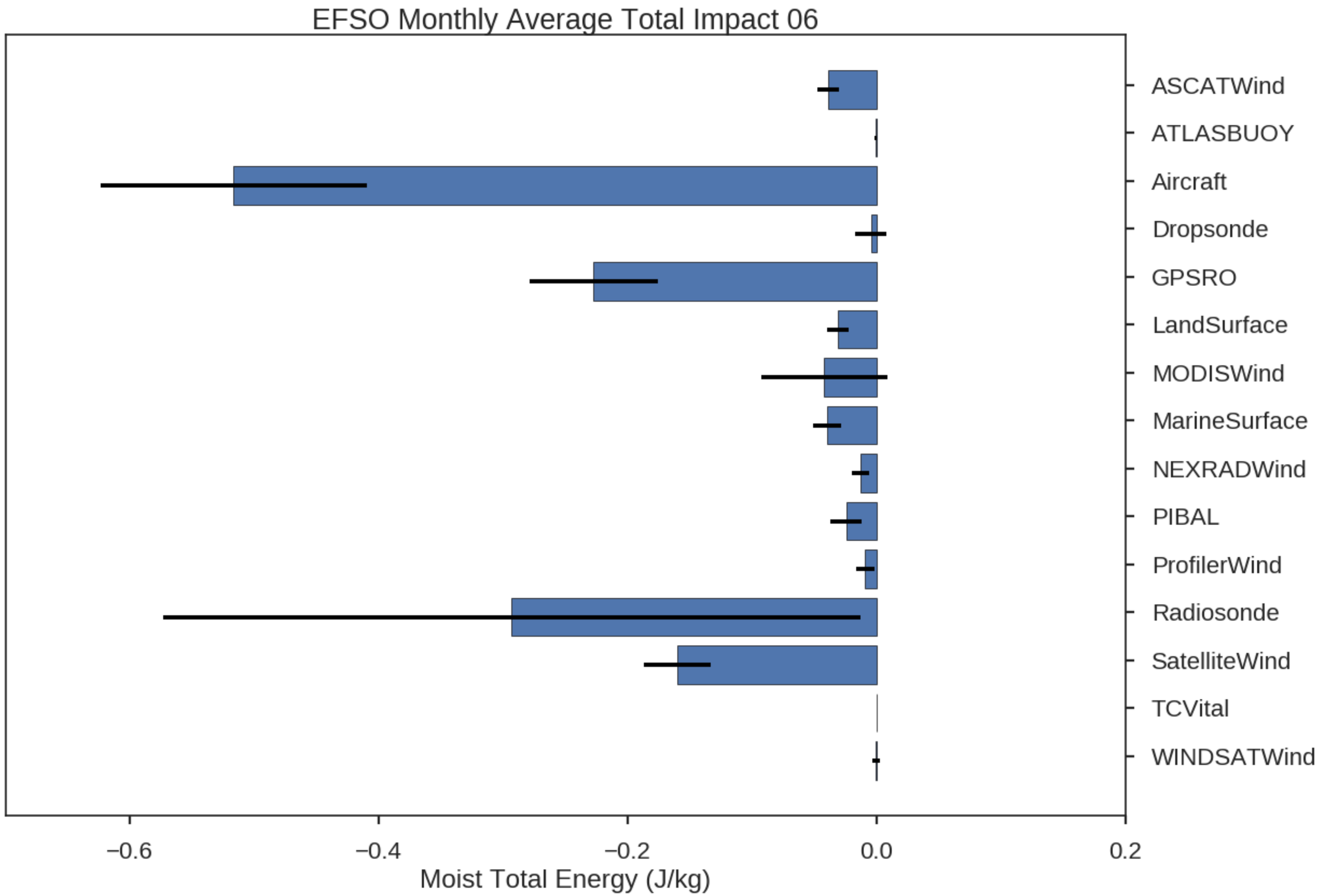


Biased observation

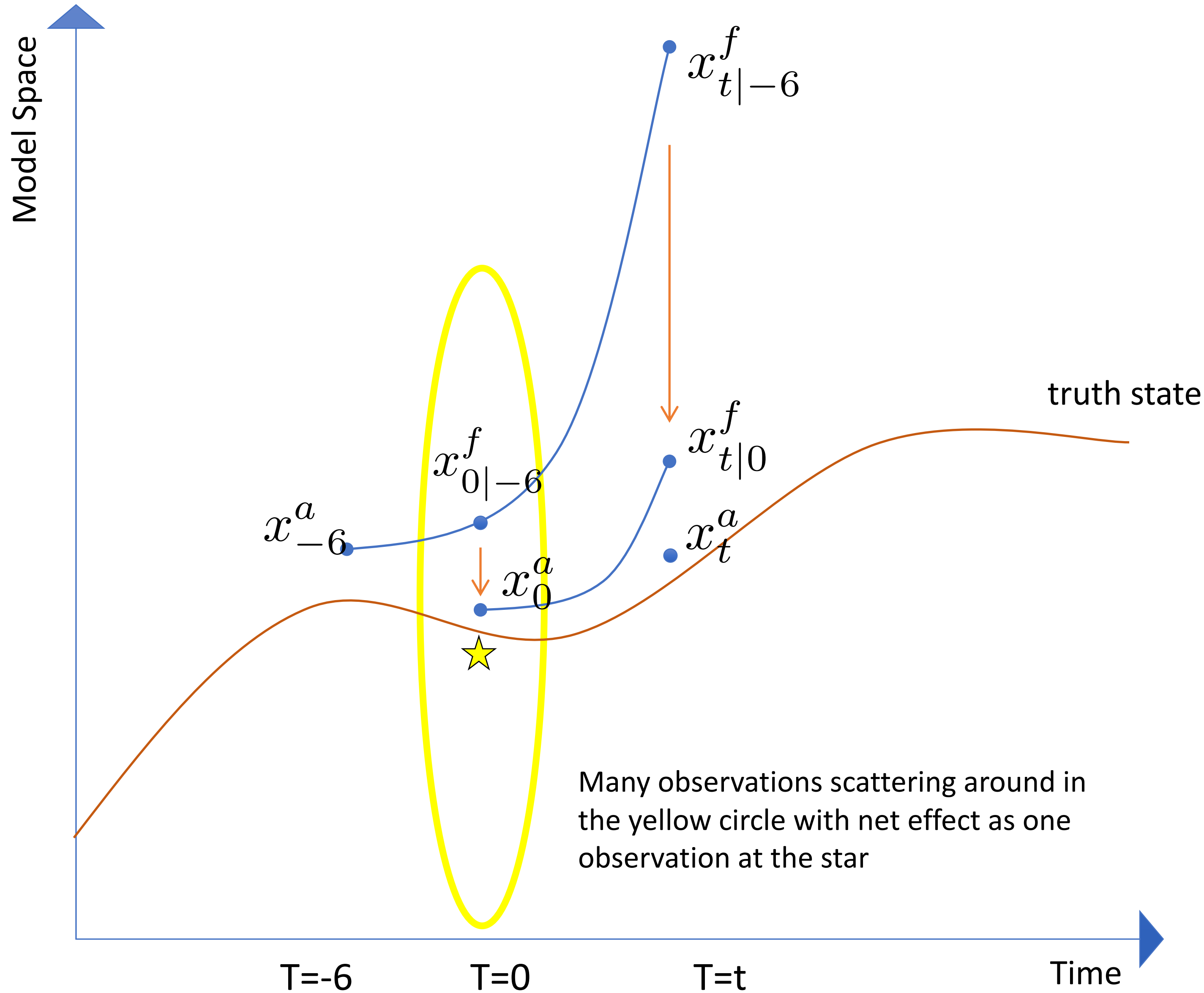


- Similar innovation bias is found in Lorenz 96 model caused by observational bias
- This innovation bias is not centered at zero.
- This may or may not be the case of MODIS wind

Total impact of each observing system



What is EFSO measuring?



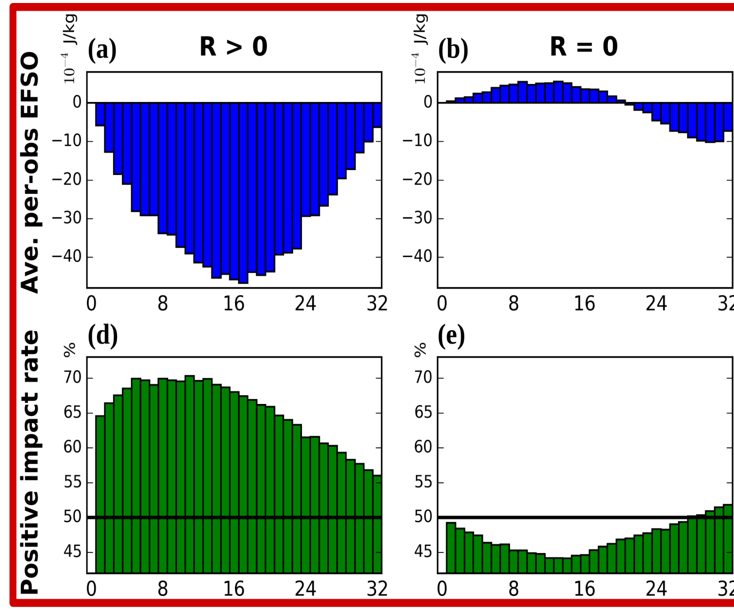
Fixed QC from EFSO (e.g. Lien 2017)

Assimilating TMPA Precipitation

1mR/24mR

Observational precipitation

$R_{threshold}$ (0.06 mm/6h) — above	-	V	V
below	-	-	V
		1mR	24mR



Precipitation members in the model background

Average 0-120 h forecast errors