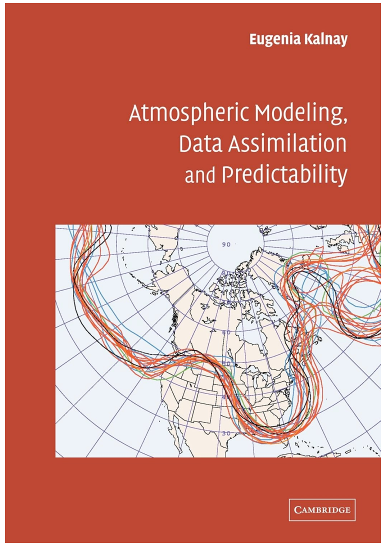
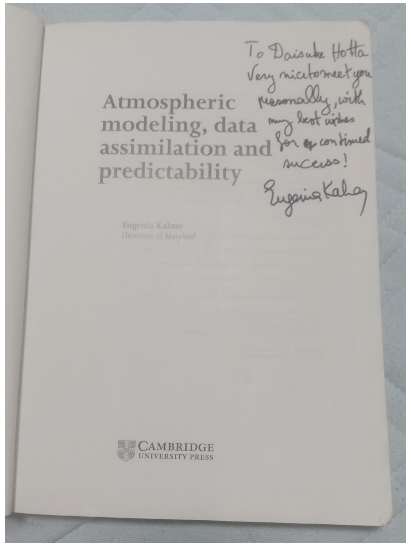
Ensemble Forecast Sensitivity to Observations (EFSO) and its applications





Autograph by Eugenia in 2009 who was visiting Tsukuba, Japan as a keynote invitee at
10th China-Japan-Korea Joint Conference on Meteorology

Daisuke Hotta (MS 2011-2013, PhD 2011-2014)

MRI/JMA

Eugenia Kalnay memorial session, 10th ISDA

Oct 21 2024

Kobe, Japan

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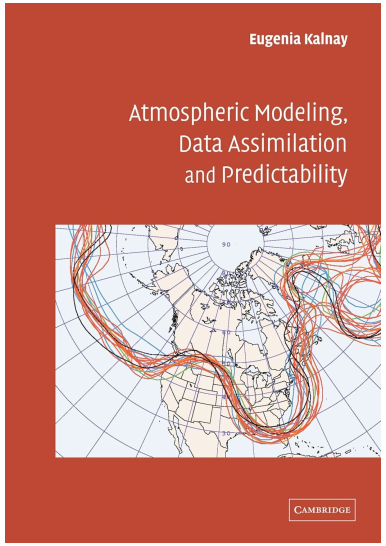

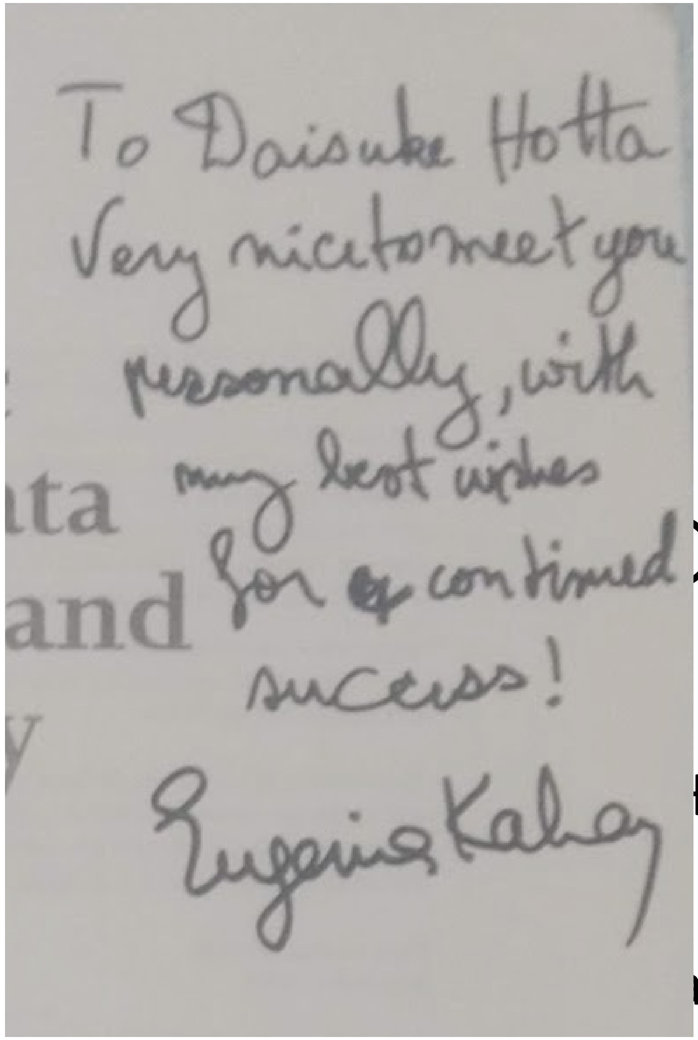

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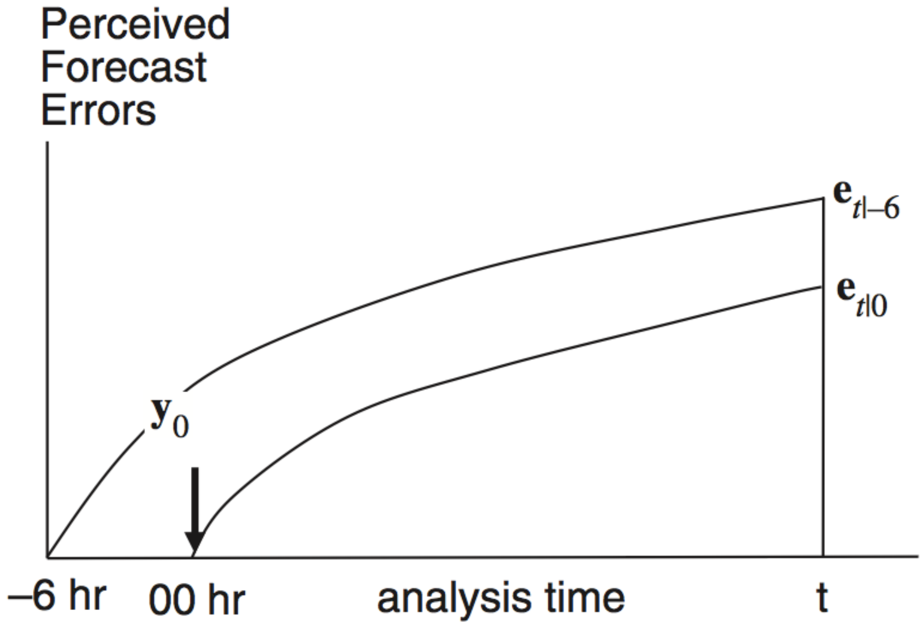
"Everything you can do with Var (adjoint), you can do with ensemble as well".

"Everything you can do with Var (adjoint),
you can do with ensemble as well ***(and better)".***

FSO: Forecast Sensitivity to Observations

adjoint-based derivation by Langland and Baker (2004)



From Kalnay et al (2012)
adapted from Langland and Baker (2004)

- $J(\mathbf{e}) = \mathbf{e}^T\mathbf{C}\mathbf{e}$, $\mathbf{e}$: vector of forecast error
- $\Delta J = \mathbf{e}_{t|0}^T\mathbf{C}\mathbf{e}_{t|0} - \mathbf{e}_{t|-6}^T\mathbf{C}\mathbf{e}_{t|-6}$

$$\approx \mathbf{d}^{\mathrm{O-B}^T}\left(\frac{\partial \mathbf{x}_0^a}{\partial \mathbf{y}^{\mathrm{o}}}\right)\left(\frac{\partial \mathbf{x}_{t|0}^f}{\partial \mathbf{x}_0^a}\right)\left(\frac{\partial J}{\partial \mathbf{x}_{t|0}^f}\right)\Bigg|_{(\mathbf{x}_{t|0}^f+\mathbf{x}_{t|-6}^f)/2}$$

$$= \mathbf{d}^{\mathrm{O-B}^T} \quad \underset{\text{assimilation sensitivity}}{\mathbf{K}^T} \quad \underset{\text{forecast sensitivity}}{\mathbf{M}^T} \quad \mathbf{C}\left(\mathbf{e}_{t|0} + \mathbf{e}_{t|-6}\right)$$

Ensemble-based derivation of FSO by Liu and Kalnay (2008), corrected by Hong Li et al. (2010)

$$\Delta e^2 \approx \delta\mathbf{y}_0^T \mathbf{K}^T \mathbf{M}^T C\left(\mathbf{e}_{t|0} + \mathbf{e}_{t|-6}\right)$$
$$\approx \delta\mathbf{y}_0^T \tilde{\mathbf{K}}^T \mathbf{X}_{t|-6}^{fT} C\left(\mathbf{e}_{t|0} + \mathbf{e}_{t|-6}\right)$$

with $\tilde{\mathbf{K}} = \left[(K-1)\mathbf{I} + (\mathbf{HX}^b)^T \mathbf{R}^{-1}\mathbf{HX}^b\right]^{-1}(\mathbf{HX}^b)^T\mathbf{R}^{-1}$

being the gain matrix expressed in the ensemble subspace computed in (L)ETKF

- Tested with Lorenz ’96 model by Liu and Kalnay (2008) and Li et al. (2010)
- Then implemented on a real system (WRF-LETKF) by Kunii, Miyoshi and Kalnay (2012)

Ensemble-based derivation of FSO by Liu and Kalnay (2008), corrected by Hong Li et al. (2010)

$$\Delta e^2 \approx \delta \mathbf{y}_0^T \mathbf{K}^T \mathbf{M}^T C \left(\mathbf{e}_{t|0} + \mathbf{e}_{t|-6} \right)$$
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with $\tilde{\mathbf{K}} = \left[(K-1)\mathbf{I} + (\mathbf{H}\mathbf{X}^b)^T \mathbf{R}^{-1} \mathbf{H}\mathbf{X}^b \right]^{-1} (\mathbf{H}\mathbf{X}^b)^T \mathbf{R}^{-1}$

- Limitations:
  - Only applicable to LETKF
  - Difficult to account for localization because, in LETKF, $\tilde{\mathbf{K}}$ is different for each grid point

New ensemble derivation of FSO by Kalnay et al. (2012)

- I became a student of Eugenia in August 2011
- Winter of 2011, Eugenia excitedly told us “I derived a new expression for FSO!”
  - Eugenia was on an airplane, doing maths on some random slips of paper trying to figure out a new formula for FSO
  - When she derived the new expression (see below), she modestly shouted *“Wow!”,* the passenger sitting next her asked her what happened and then congratulated her.

$$\Delta e^2 \approx \delta \mathbf{y}_0^T \mathbf{K}^T \mathbf{M}^T C\left(\mathbf{e}_{t|0} + \mathbf{e}_{t|-6}\right)$$

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

- **Simpler** than the previous derivation
- **Easy to introduce localization** because $Y^a X^{fT}$ is the covariance between analysis in obs-space and forecast in state-space

New ensemble derivation of FSO by Kalnay et al. (2012)

- Eugenia looked for someone to implement the new formulation
- Yoichiro Ota was visiting NCEP/EMC on secondment from JMA, and he implemented the new EFSO on Lorenz 96
  - → Published as Kalnay et al. (2012)
- Eugenia, Yoichiro and Takemasa organized regular meetings, Yoichiro reported his results to Eugenia and Takemasa, who then provided new ideas for further exploration
- I often joined the discussion (as an observer), this was one of the most exciting periods of my life.
- It was around this time that Eugenia coined the acronym EFSO.

Ota et al. (2013) and the idea of “Proactive QC”

- Yoichiro continued research on EFSO, implemented it on quasi-operational GFS-EnSRF. Published as Ota et al. (2013)
- He showed that EFSO can identify observations that degraded forecast skills
- and that removing such observations does improve forecasts *(Wow!)*

→ Idea of "Proactive QC (PQC)” emerged in Eugenia’s mind

Ota et al. (2013) and the idea of "Proactive QC"

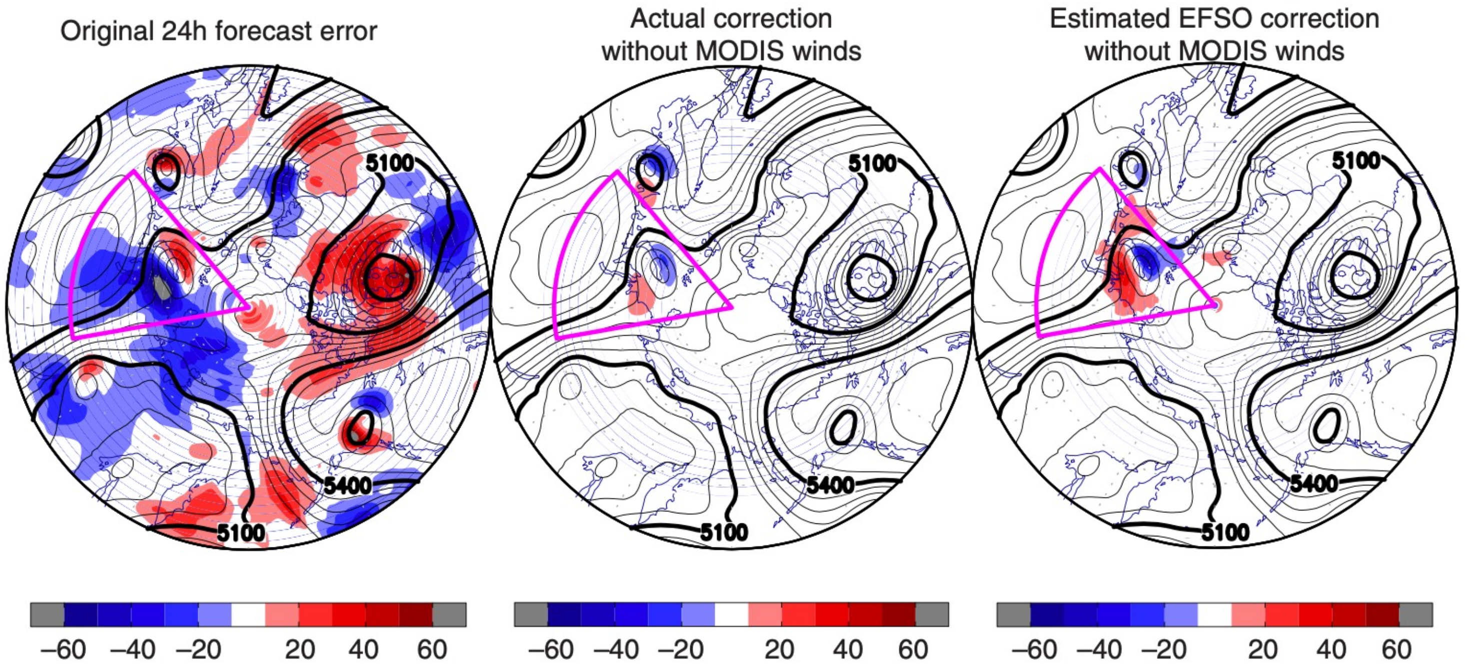

Fig. 9. Twenty-four hour forecast error of 500 hPa geopotential height (unit: m, 18 UTC 6 February 2012 initial) from original analysi (left) and forecast change due to the removal of the MODIS polar wind observations in the data-denial experiment (middle: actual chang and right: projection on the ensemble perturbations). Black contours show the analysis. Magenta cones show the target area of the observation impact estimate.

From Ota et al. (2013)

- EFSO identified satellite winds as having negative impact on fcst.
- Denying the identified obs did improve the fcst.
- Proactive QC:
  - detect "bad" obs
  - then withdraw them and do the analysis again

→ main project of my PhD

My PhD thesis (2014)

- Three-part thesis
- Part 1: Systematic investigation of “Proactive QC”
  - adapted Yoichiro’s code to run on the hybrid GFS-GSI-LEKTF
  - One-month evaluation of EFSO, detect detrimental observations
  - then conducted data-denial experiments to show removing detrimental obs does indeed improve forecasts
- Part 2: Adapting EFSO to compute forecast sensitivity to observation error covariance (EFSR)
- Part 3: Developing semi-implicit version of Lorenz *N*-cycle time integration scheme (numerical analysis; not covered in this talk)

EFSR: application of EFSO to optimize observation error covariance matrix R

- While I was doing Proactive QC for my thesis, in August 2013, Prof. Dacian Daescu visited UMD and presented his Daescu and Langland (2013) paper at Weather-Chaos seminar.
- He showed how an *adjoint-based* formulation of forecast sensitivity to **R** matrix can guide us to improve **R**
- Listening to his talk, I realized we can formulate an ***ensemble*** version based on **EFSO** by Kalnay et al. (2012) :

$$\frac{\partial e^f_{t|0}}{\partial R_{i,j}} = -(\mathbf{R}^{-1}\delta\mathbf{y}^{oa})_j (2\mathbf{K}^{\mathrm{T}}\mathbf{M}^{\mathrm{T}}_{t|0}\mathbf{C}\mathbf{e}_{t|0})_i \approx -(\mathbf{R}^{-1}\delta\mathbf{y}^{oa})_j \frac{2}{K-1}(\mathbf{R}^{-1}\mathbf{Y}^a\mathbf{X}^{f\mathrm{T}}_{t|0}\mathbf{C}\mathbf{e}_{t|0})_i,$$

- Excited, I chatted with my colleagues/friends I wanted to try this out
- They persuaded me not to do this until I finish my PhD ("Finish you thesis first!")
- **But Eugenia respected my passion and encouraged me to do both!**

Many follow-on studies on EFSO(just to pick up a few...)

(by Eugenia's students)

- Guo-Yuan Lien, EFSO statistics to help us to derive optimal QC criteria for assimilation of new types of observations
- Tse-Chun Chen, further exploration and refinement of PQC
- Chu-Chun Chang, EFSO for atmosphere-ocean coupled DA

Eugenia's idea continues to inspire many other scientists

- Sommer and Weissman (2014,2016): EFSO for reginal DA.
- Buehner et al. (2018): derivation of FSO for EnVar.
- EFSO as a guide to optimize the order of assimilating observations in serial data assimilations (Kotsuki et al. 2019)
- Dr. Sugimoto, EFSO on Venus DA
- Honda and Yamazaki (2024) proposes real-time PQC by using AI surrogate model as verifying truth
- ... many more!

In this ISDA (Wednesday poster session)

- **Casaretto et al**, EFSO for convection-permitting DA (**P3-01**)
- **Yamazaki et al**, EFSO implementation on AFES-LETKF, climatology of EFSO (**P3-05**)
- **Griewank et al**, Error sources of EFSO estimation (**P3-16**)
- **Hattori et al**, Buoy-obs impact assessment with EFSO (**P3-19**)

What I learned from Eugenia (and I want everyone here to know)

- Sharing *"Wow!"* moments (curiosity and excitement) with students
- Healthy skepticisms
  - to yourself *("Have you convinced yourself?")*
  - and to the established theory
- Never satisfied with what you have already solved
- Respecting student's motivations
- Care and compassion
- Welcoming smile

Eugenia Kalnay (left) and Daisuke Hotta (right) on the day of Daisuke's thesis defense (July 2014).