EFSOの現状と
惑星気象研究への発展の可能性

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第19回惑星圏研究会, Feb. 28, 2018 @ 東北大学・青葉ホール

Who am I?

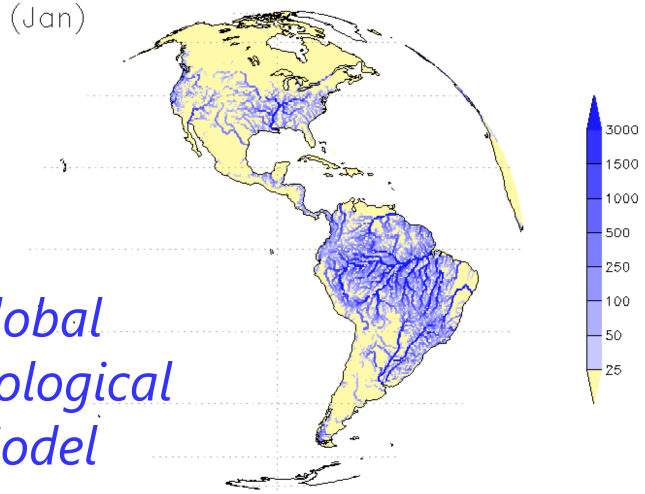
~2013.12
- **Ph.D. student, Kyoto-Univ.**
- **Research Fellow, JSPS**

2014.01 ~ 2017.09
- **Postdoc, RIKEN-AICS**

2017.04 ~
- **Part-time lecturer, Kyoto Univ.**

2017.10 ~
- **Research Scientist, RIKEN-AICS**
- **TAKUETSU Researcher, MEXT**

Hydrology & Water Resources (civil engineering)



Global Hydrological Model

Field survey @ Thailand Temple

Who am I?

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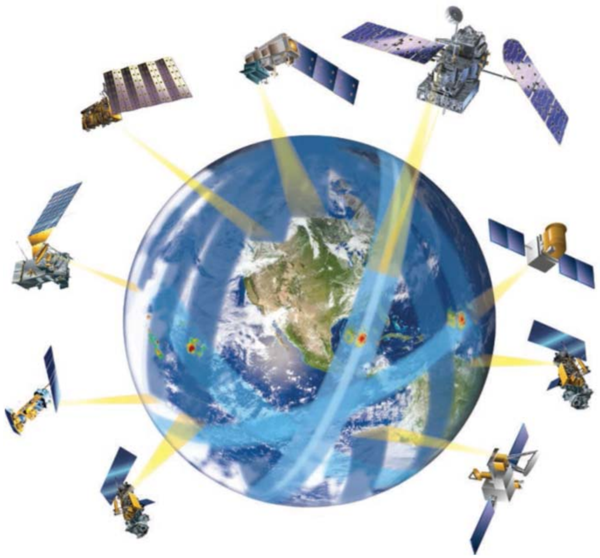
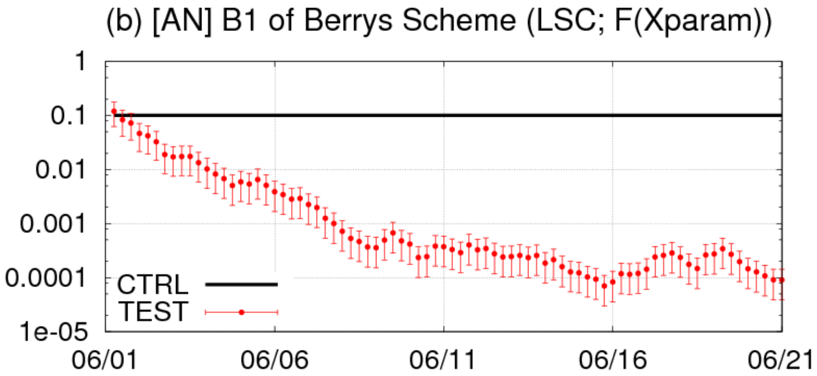
DA & Global Atmosphere



Satellite-sensed Precip. DA

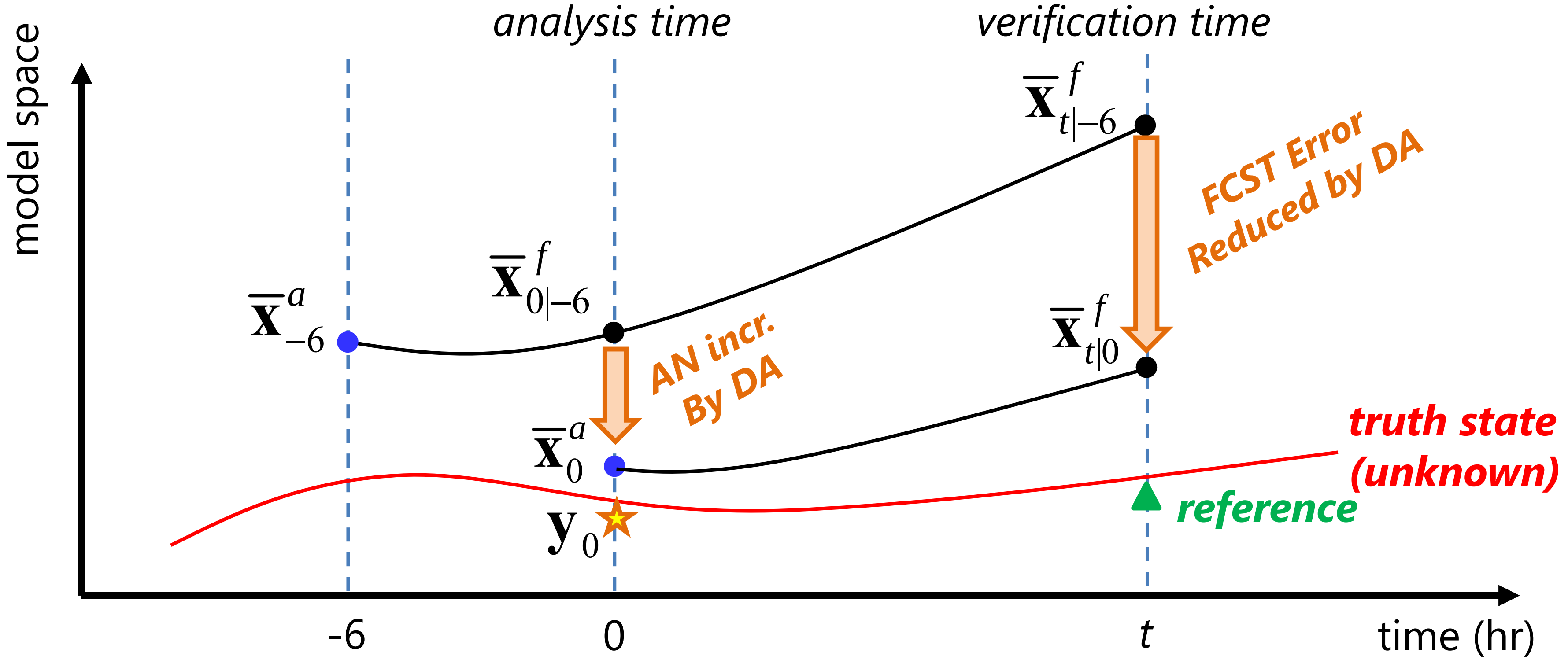


Parameter Estimation of NWP model

Ensemble FSO

（観測のインパクト評価）

FSO: Forecast Sensitivity to Observation



- L2 norm for Toy models (e.g. L63, L96)

$$e_{L2}^2 = \frac{1}{2}\mathbf{e}^{\mathrm{T}}C\mathbf{e} = \frac{1}{2N}\sum_{i=1}^{N} e_i^2 \qquad \mathbf{e}_t = \overline{\mathbf{x}}_t^f - \mathbf{x}_t^{ANL}$$

Derivation

$$\Delta e^2 = \frac{1}{2}\left(\mathbf{e}_{t|0}^{\mathrm{T}} C \mathbf{e}_{t|0} - \mathbf{e}_{t|-6}^{\mathrm{T}} C \mathbf{e}_{t|-6}\right) = \frac{1}{2}\left(\mathbf{e}_{t|0} - \mathbf{e}_{t|-6}\right)^{\mathrm{T}} C \left(\mathbf{e}_{t|0} + \mathbf{e}_{t|-6}\right)$$

$$\approx \frac{1}{2}\frac{1}{m-1}\delta\mathbf{y}_0^{\mathrm{T}}\mathbf{R}^{-1}\mathbf{Y}_0^{a}\mathbf{X}_{t|0}^{f\mathrm{T}} C\left(\mathbf{e}_{t|0} + \mathbf{e}_{t|-6}\right)$$

$$\mathbf{e}_{t|0} - \mathbf{e}_{t|-6} = \overline{\mathbf{x}}_{t|0} - \overline{\mathbf{x}}_{t|-6}$$

① liner error growth approximation

$$\approx \underline{M\left(\overline{\mathbf{x}}_0^{a} - \overline{\mathbf{x}}_{0|-6}^{b}\right)}$$

★

$$= M\mathbf{K}\delta\mathbf{y}_0 = M\mathbf{A}\mathbf{H}^{\mathrm{T}}\mathbf{R}^{-1}\delta\mathbf{y}_0$$

② ensemble error covariance approximation

$$\boxed{\mathbf{A} = \frac{1}{m-1}\mathbf{X}_0^{a}\left(\mathbf{X}_0^{a}\right)^{\mathrm{T}}}$$

$$\approx \frac{1}{m-1} M\mathbf{X}_0^{a}\left(\mathbf{H}\mathbf{X}_0^{a}\right)^{\mathrm{T}}\mathbf{R}^{-1}\delta\mathbf{y}_0$$

$$= \frac{1}{m-1}\mathbf{X}_{t|0}^{f}\mathbf{Y}_0^{a\mathrm{T}}\mathbf{R}^{-1}\delta\mathbf{y}_0$$

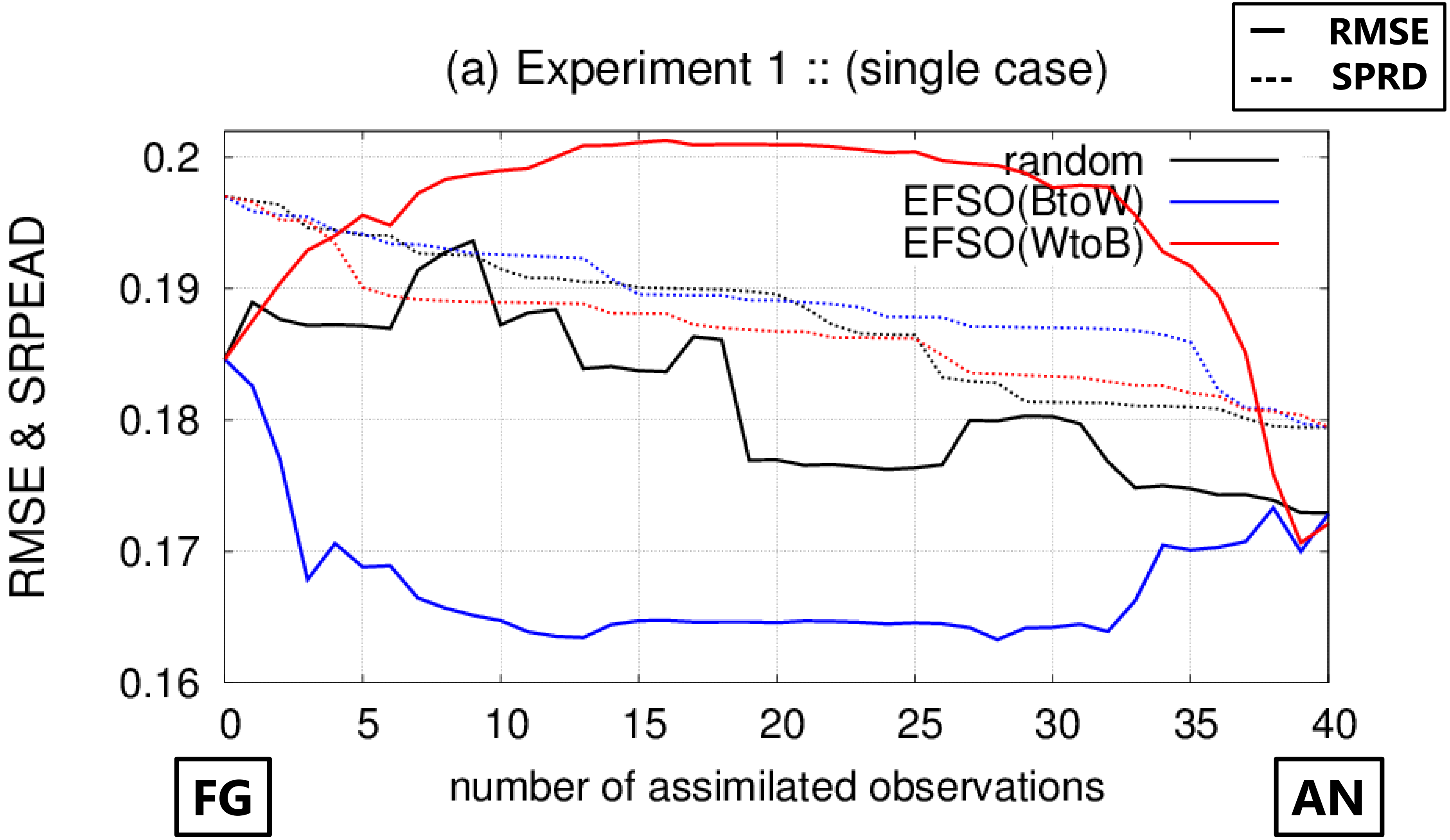
An example with Lorenz-96

- Serial EnSRF (Whitaker and Hamill 2001)
  - Ensemble size : 8
  - # of observations : 40
  - Adaptive multiplicative inflation (Miyoshi 2011)

- Assimilation order
  1. Random
  2. From worse to better impacts based on EFSO
  3. From better to worse impacts based on EFSO

Kotsuki et al. (2017, MWR)

RMSE during serial assimilation (one case)

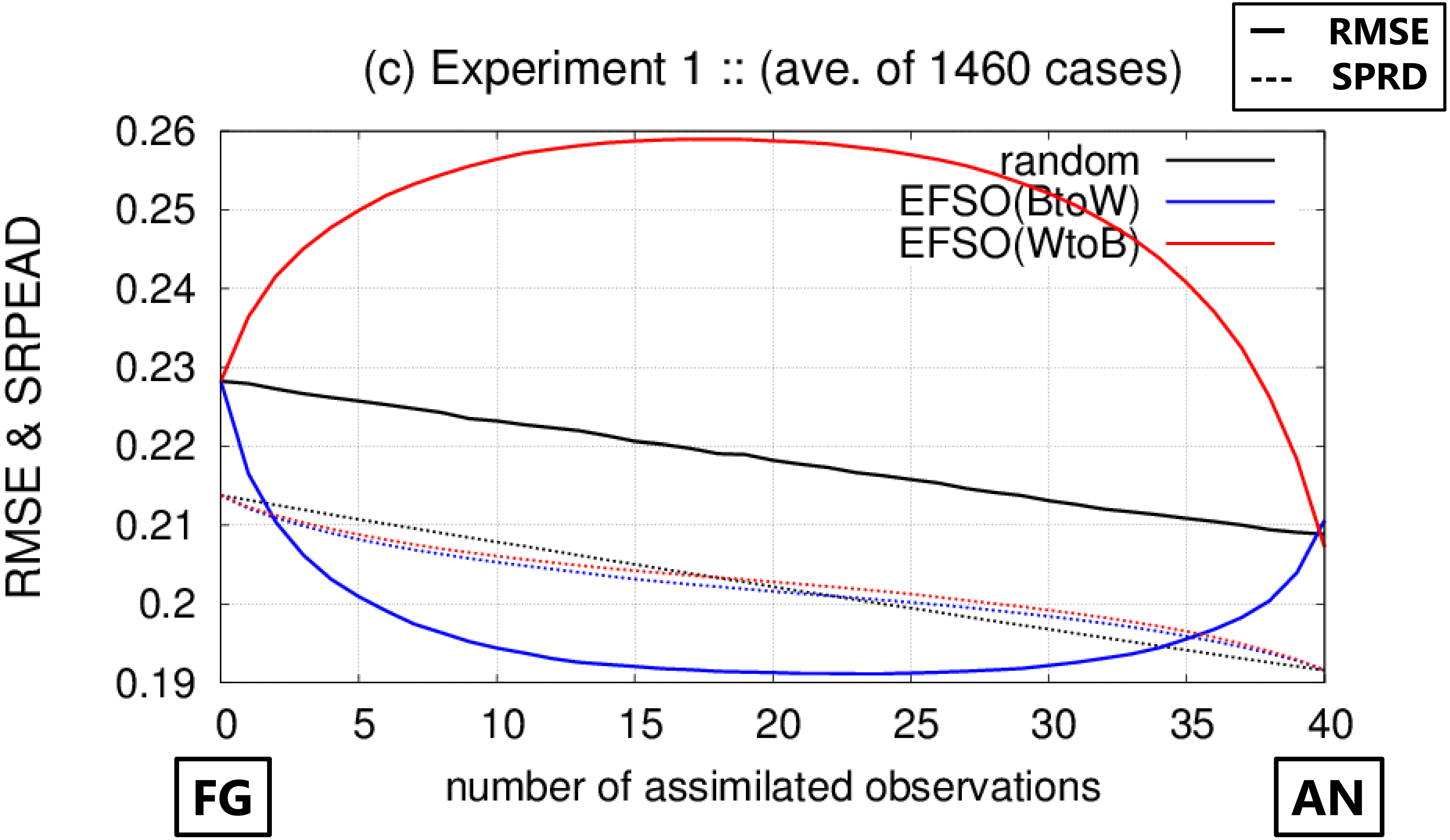


– : random order

– : EFSO better → worse obs.

– : EFSO worse → better obs.

RMSE during serial assimilation (ave of 1460 cases)



—: random order

—: EFSO better → worse obs.

—: EFSO worse → better obs.

EFSO with NICAM-LETKF

Error Norms

- L2 norm for Toy models (e.g. L63, L96)

$$e_{L2}^2 = \frac{1}{2}\mathbf{e}^{\mathbf{T}} C \mathbf{e} = \frac{1}{2N}\sum_{i=1}^{N} e_i^2$$

- Moist Total Energy norm for Atmospheric models

$$e_{MTE}^2 = \frac{1}{2}\mathbf{e}^{\mathbf{T}} C \mathbf{e} = \frac{1}{2}\left(KE + PE + ME\right)$$

KE: kinetic energy
PE: potential energy
ME: moist energy

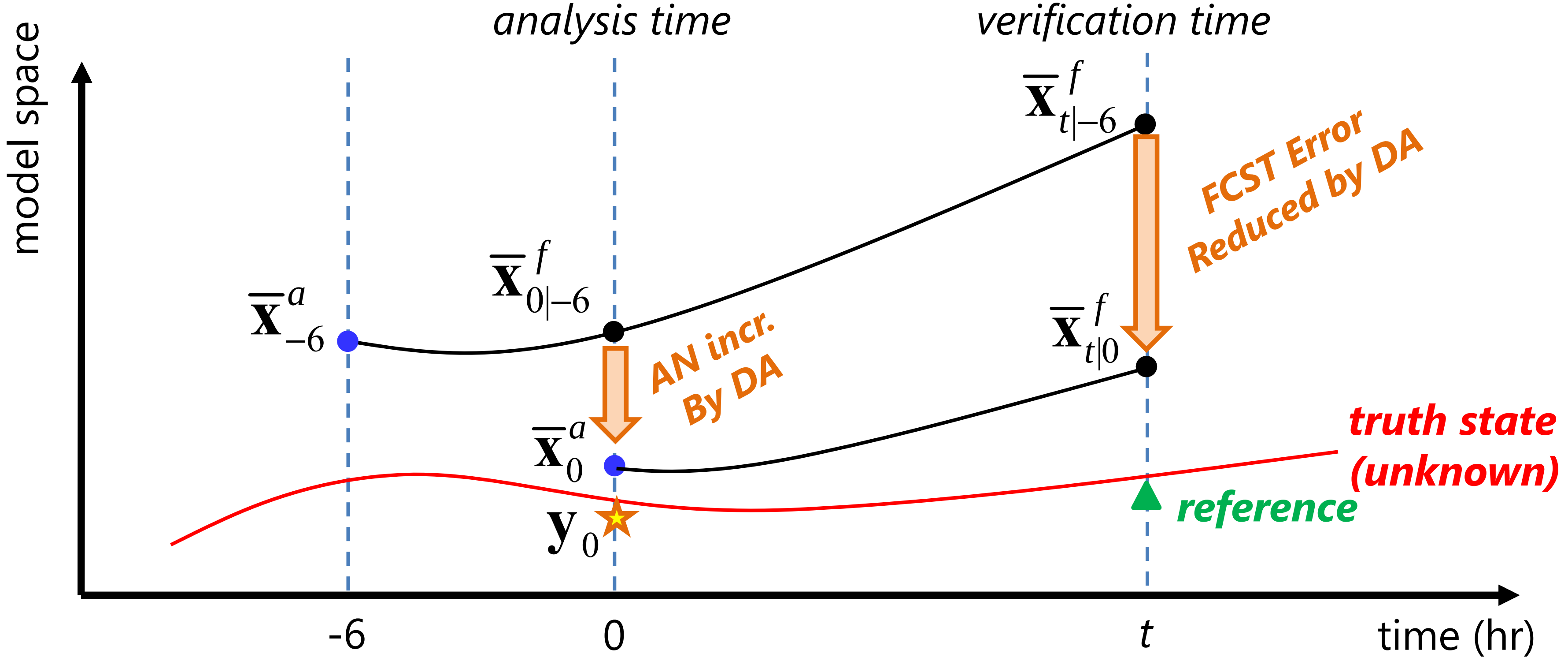
$$KE = \frac{1}{S}\int_S \int_0^1 \left(u'^2 + v'^2\right) d\sigma_v dS$$

$$PE = \frac{1}{S}\int_S \left[\int_0^1 \frac{C_p}{T_t} T'^2 \, d\sigma_v + \frac{R_d T_r}{p_r^2} T p_s{}'^2\right] dS$$

$$ME = \frac{1}{S}\int_S \int_0^1 \frac{L^2}{C_p T_r} q'^2 \, d\sigma_v dS$$

cf. Ota et al. (2013, Tellus)

FSO: Forecast Sensitivity to Observation



Moist Total Energy for Error Norm

$$\Delta e^2_{MTE} = \left(\mathbf{e}^{\mathrm{T}}_{t|0} C \mathbf{e}_{t|0} - \mathbf{e}^{\mathrm{T}}_{t|-6} C \mathbf{e}_{t|-6}\right) / 2 \qquad \mathbf{e}_t = \overline{\mathbf{x}}^f_t - \mathbf{x}^{ERA,ANL}_t$$

Normalized Obs. Departure for Error Norm

$$\Delta e^2_{NOD} = \left(\mathbf{d}^{\mathrm{T}}_{t|0} \mathbf{R}^{-1}_t \mathbf{d}_{t|0} - \mathbf{d}^{\mathrm{T}}_{t|-6} \mathbf{R}^{-1}_t \mathbf{d}_{t|-6}\right) / Np \qquad \mathbf{d}_t = \mathbf{y}^o_t - H\overline{\mathbf{x}}^f_t$$

Ensemble-based FSO

Moist Total Energy for Error Norm (Kalnay et al. 2012)

$$\Delta e^2_{MTE} = \left(\mathbf{e}^{\mathrm{T}}_{t|0} C \mathbf{e}_{t|0} - \mathbf{e}^{\mathrm{T}}_{t|-6} C \mathbf{e}_{t|-6}\right)/2 \qquad \mathbf{e}_t = \overline{\mathbf{x}}^f_t - \mathbf{x}^{ERA,ANL}_t$$

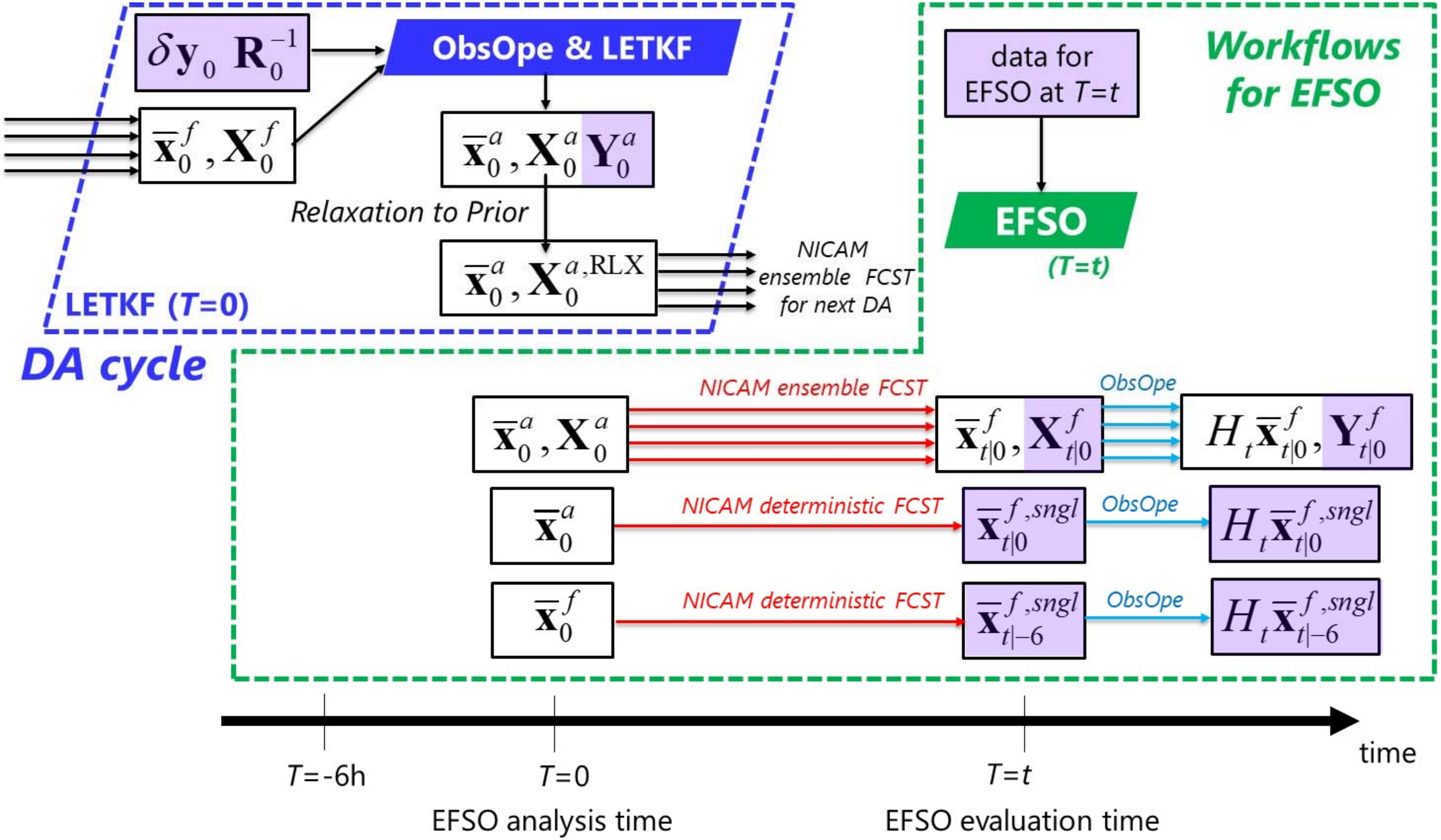
$$\approx \frac{1}{2}\frac{1}{m-1} \underbrace{\delta\mathbf{y}^{\mathrm{T}}_0}_{\text{obs-minus-FG}} \mathbf{R}^{-1}_0 \underbrace{\mathbf{Y}^a_0}_{\text{AN ptb in obs space}} \underbrace{\mathbf{X}^{f\mathrm{T}}_{t|0}}_{\text{FCST ptb}} C\left(\mathbf{e}_{t|0} + \mathbf{e}_{t|-6}\right)$$

Normalized Obs. Departure for Error Norm (Sommer and Weissmann 2016)

$$\Delta e^2_{NOD} = \left(\mathbf{d}^{\mathrm{T}}_{t|0} \mathbf{R}^{-1}_t \mathbf{d}_{t|0} - \mathbf{d}^{\mathrm{T}}_{t|-6} \mathbf{R}^{-1}_t \mathbf{d}_{t|-6}\right)/Np \qquad \mathbf{d}_t = \mathbf{y}^o_t - H\overline{\mathbf{x}}^f_t$$

$$\approx -\frac{1}{Np}\frac{1}{m-1} \underbrace{\delta\mathbf{y}^{\mathrm{T}}_0}_{\text{obs-minus-FG}} \mathbf{R}^{-1}_0 \underbrace{\mathbf{Y}^a_0}_{\text{AN ptb in obs space}} \underbrace{\mathbf{Y}^{f\mathrm{T}}_{t|0}}_{\text{FCST ptb}} \mathbf{R}^{-1}_t \left(\mathbf{d}_{t|0} + \mathbf{d}_{t|-6}\right)$$

EFSO with NICAM-LETKF



$\delta\mathbf{y}_0\ \mathbf{R}_0^{-1}$

ObsOpe & LETKF

$\overline{\mathbf{x}}_0^f, \mathbf{X}_0^f$

$\overline{\mathbf{x}}_0^a, \mathbf{X}_0^a\, \mathbf{Y}_0^a$

Relaxation to Prior

$\overline{\mathbf{x}}_0^a, \mathbf{X}_0^{a,\mathrm{RLX}}$

NICAM ensemble FCST for next DA

LETKF (*T*=0)

DA cycle

data for EFSO at *T*=*t*

EFSO

(T=t)

Workflows for EFSO

$\overline{\mathbf{x}}_0^a, \mathbf{X}_0^a$ *NICAM ensemble FCST* $\overline{\mathbf{x}}_{t|0}^f, \mathbf{X}_{t|0}^f$ *ObsOpe* $H_t\overline{\mathbf{x}}_{t|0}^f, \mathbf{Y}_{t|0}^f$

$\overline{\mathbf{x}}_0^a$ *NICAM deterministic FCST* $\overline{\mathbf{x}}_{t|0}^{f,sngl}$ *ObsOpe* $H_t\overline{\mathbf{x}}_{t|0}^{f,sngl}$

$\overline{\mathbf{x}}_0^f$ *NICAM deterministic FCST* $\overline{\mathbf{x}}_{t|-6}^{f,sngl}$ *ObsOpe* $H_t\overline{\mathbf{x}}_{t|-6}^{f,sngl}$

time

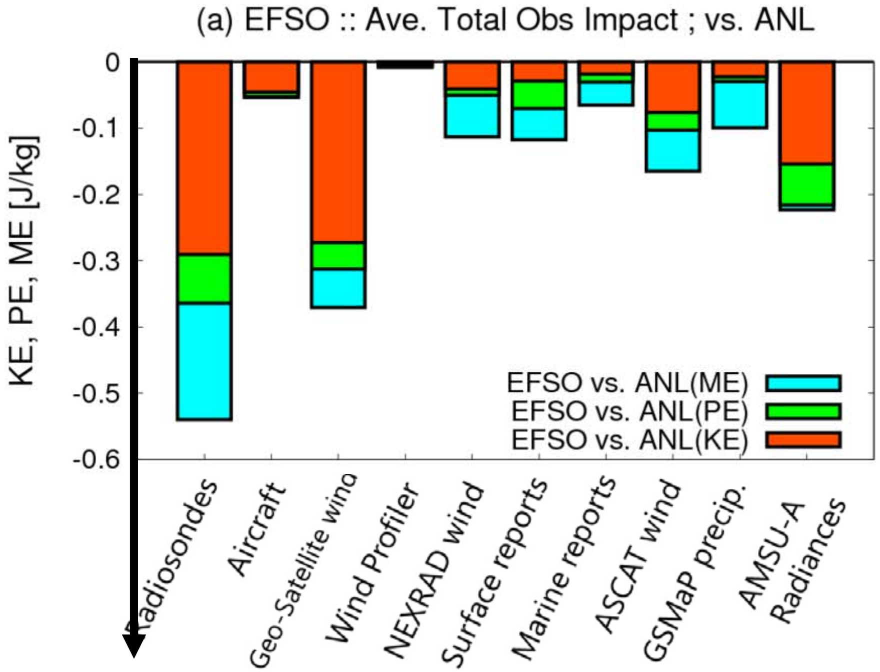
T=-6h

T=0
EFSO analysis time

T=*t*
EFSO evaluation time

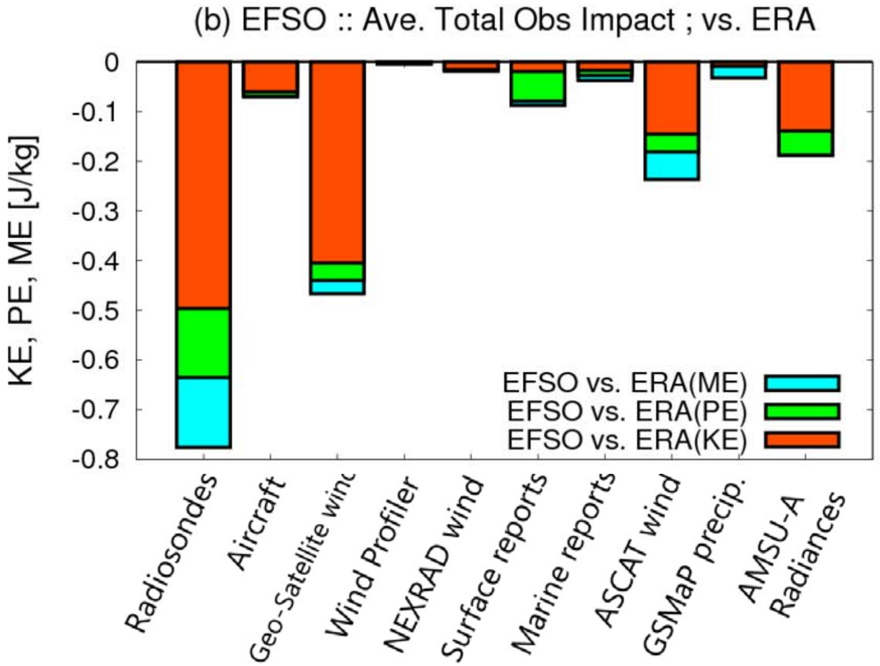
EFSO: FCST **MTE** Error Reduction (2014/07)

vs. NICAM-LETKF



Positive Impact (improving 6-hr FCST)

vs. ERA Interim



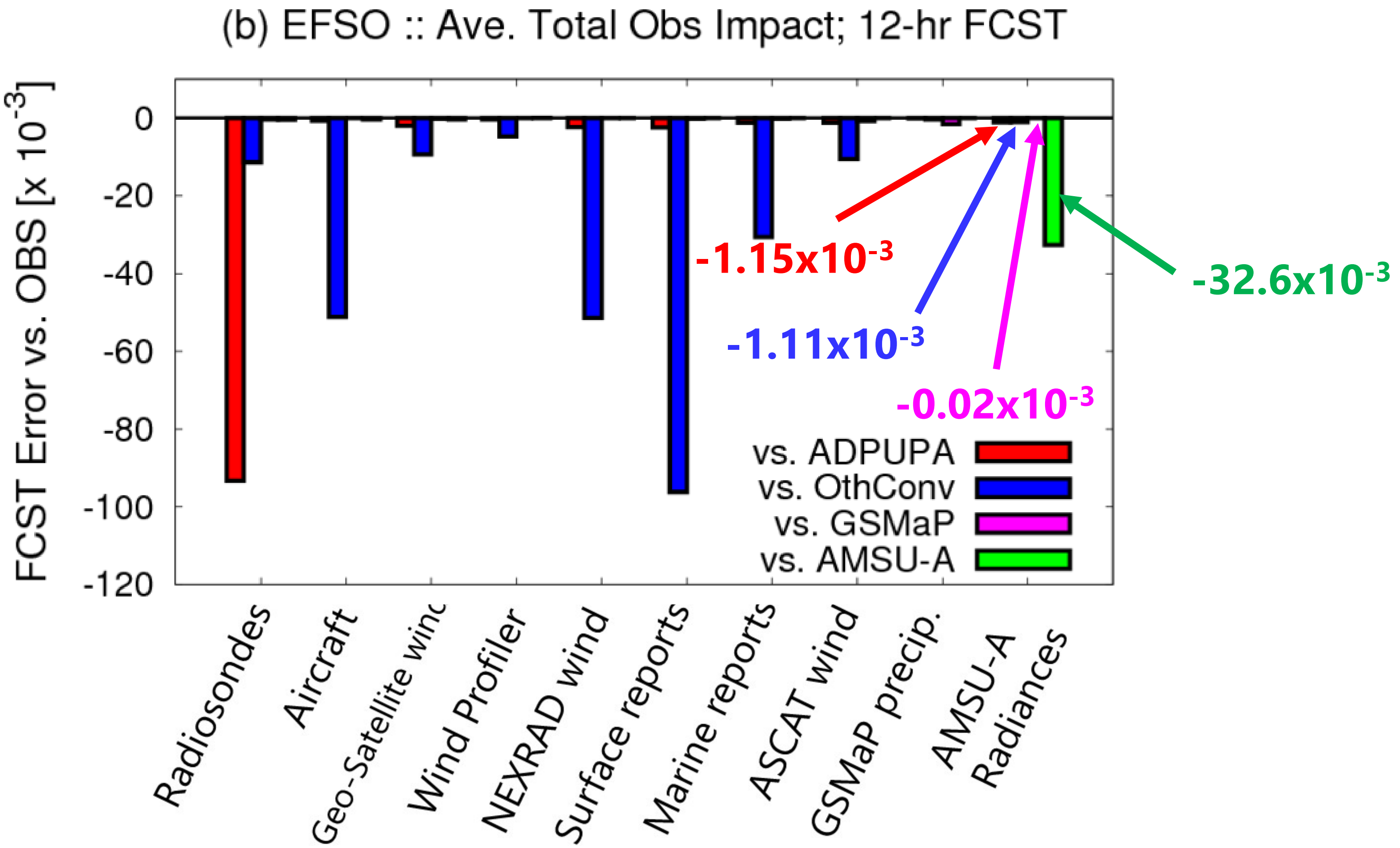
🟦 **ME : Moist Energy**

🟩 **PE : Potential Energy**

🟥 **KE : Kinetic Energy**

Monthly average in July 2014; FT 06hr

EFSO: FCST **NOD** Error Reduction (2014/07)


(b) EFSO :: Ave. Total Obs Impact; 12-hr FCST

$-1.15\text{x}10^{-3}$

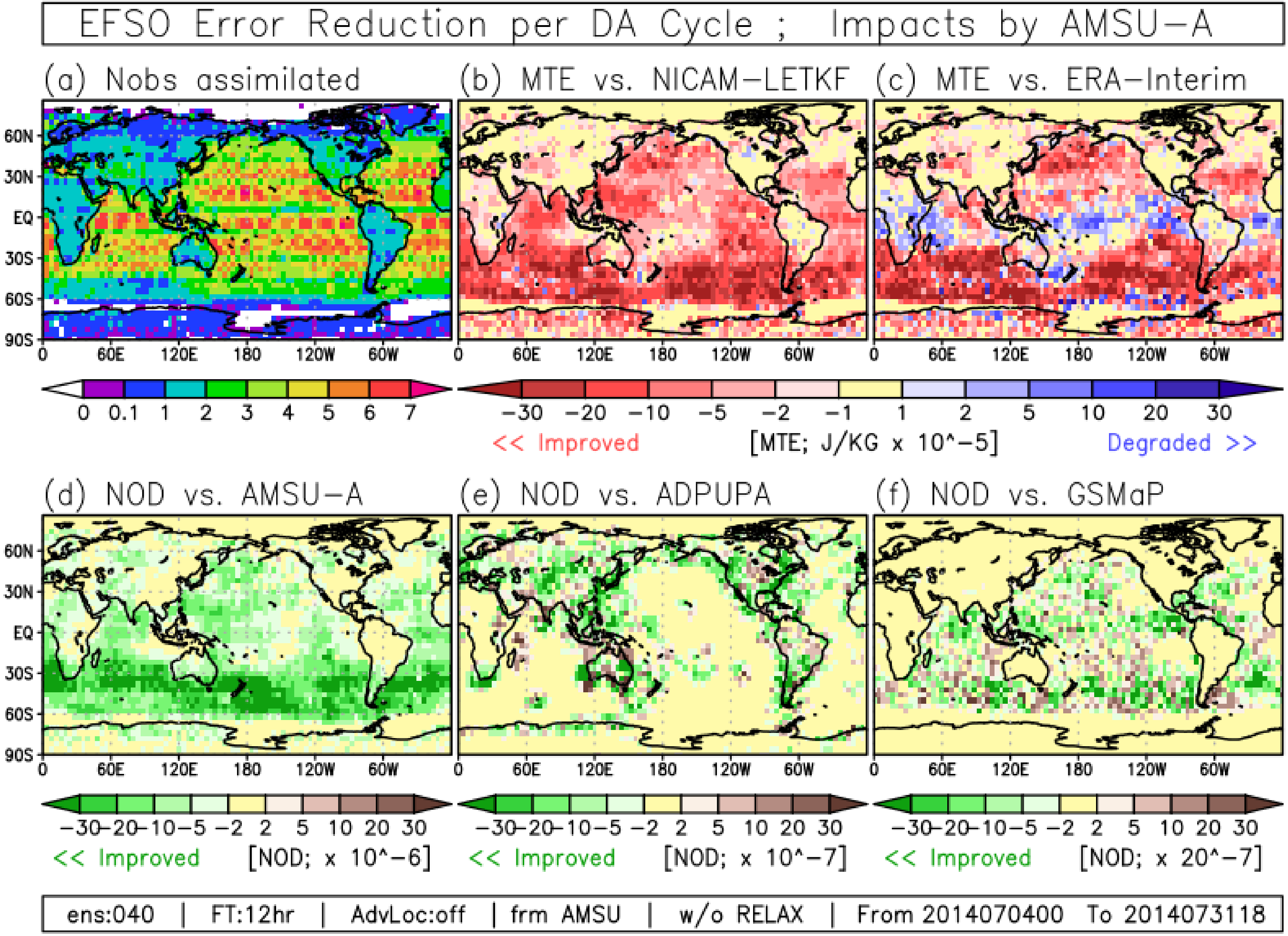
$-1.11\text{x}10^{-3}$

$-0.02\text{x}10^{-3}$

$-32.6\text{x}10^{-3}$

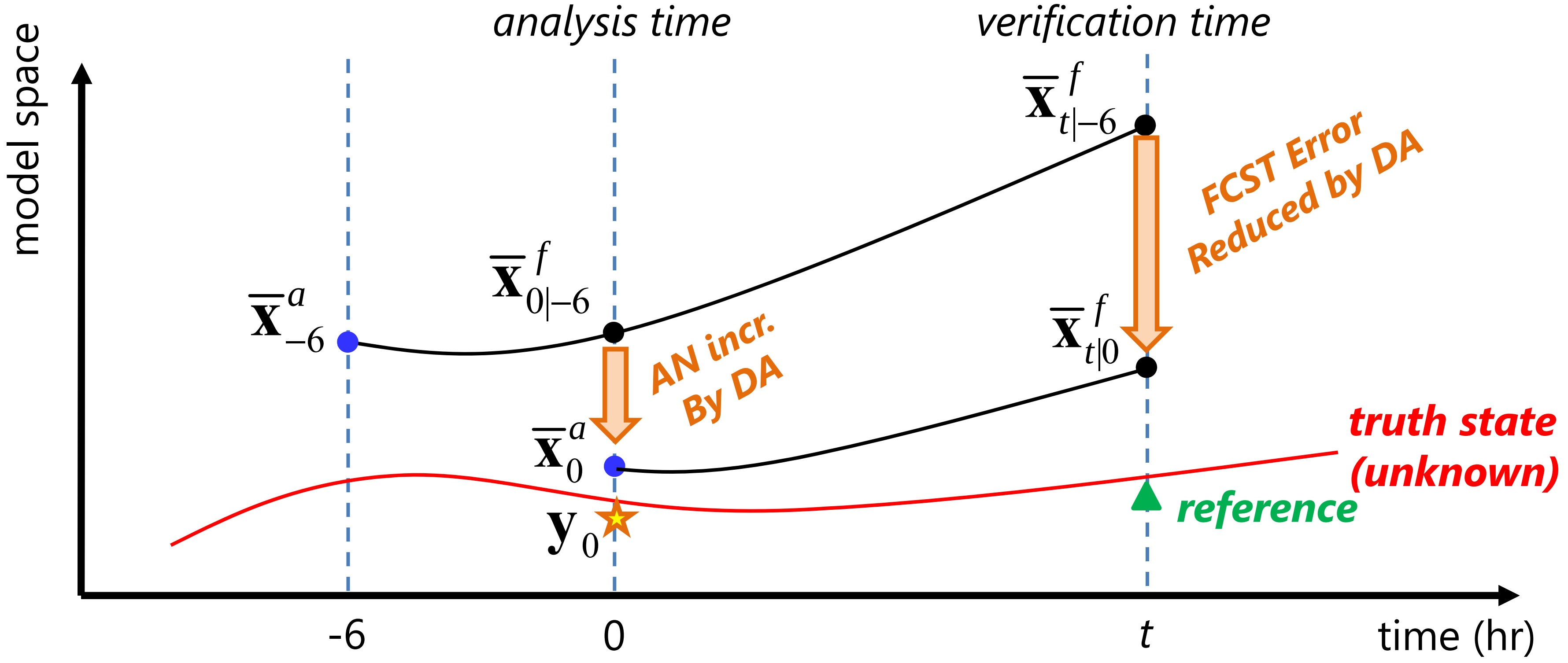
Each type of observations mainly contributes to the improvement of the observed variable!

Spatial Pattern of AMSU-A impacts



Beneficial Observation Rate

FSO: Forecast Sensitivity to Observation



Moist Total Energy for Error Norm

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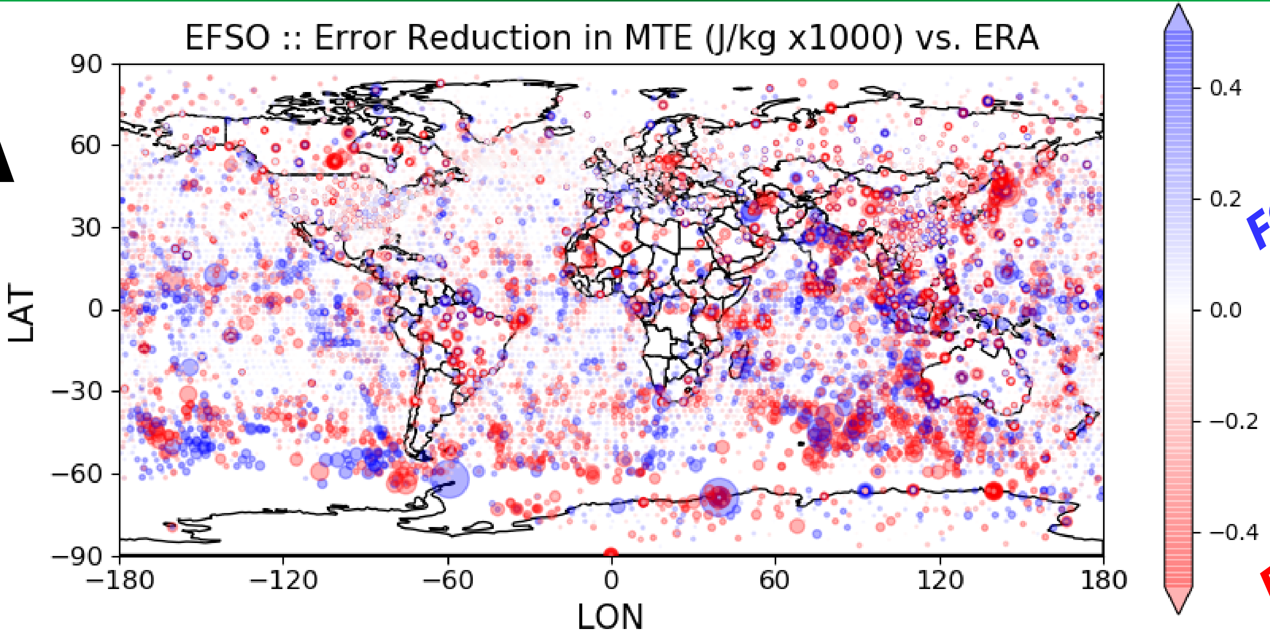
Normalized Obs. Departure for Error Norm

$$\Delta e^2_{NOD} = \left(\mathbf{d}^{\mathrm{T}}_{t|0} \mathbf{R}^{-1}_t \mathbf{d}_{t|0} - \mathbf{d}^{\mathrm{T}}_{t|-6} \mathbf{R}^{-1}_t \mathbf{d}_{t|-6}\right) / Np \quad \mathbf{d}_t = \mathbf{y}^o_t - H\bar{\mathbf{x}}^f_t$$

FCST Error Reduction per Obs (2014/07/11/00)

vs. ERA



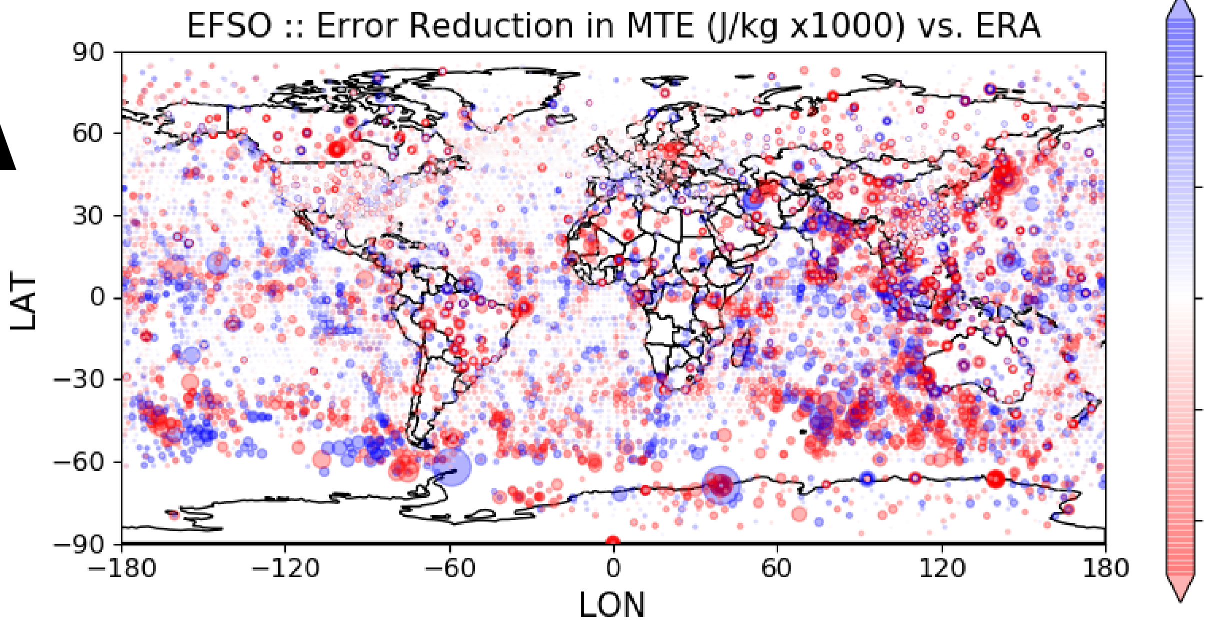
FCST degraded

FT 06hr

FCST improved

FCST Error Reduction per Obs (2014/07/11/00)

vs. ERA

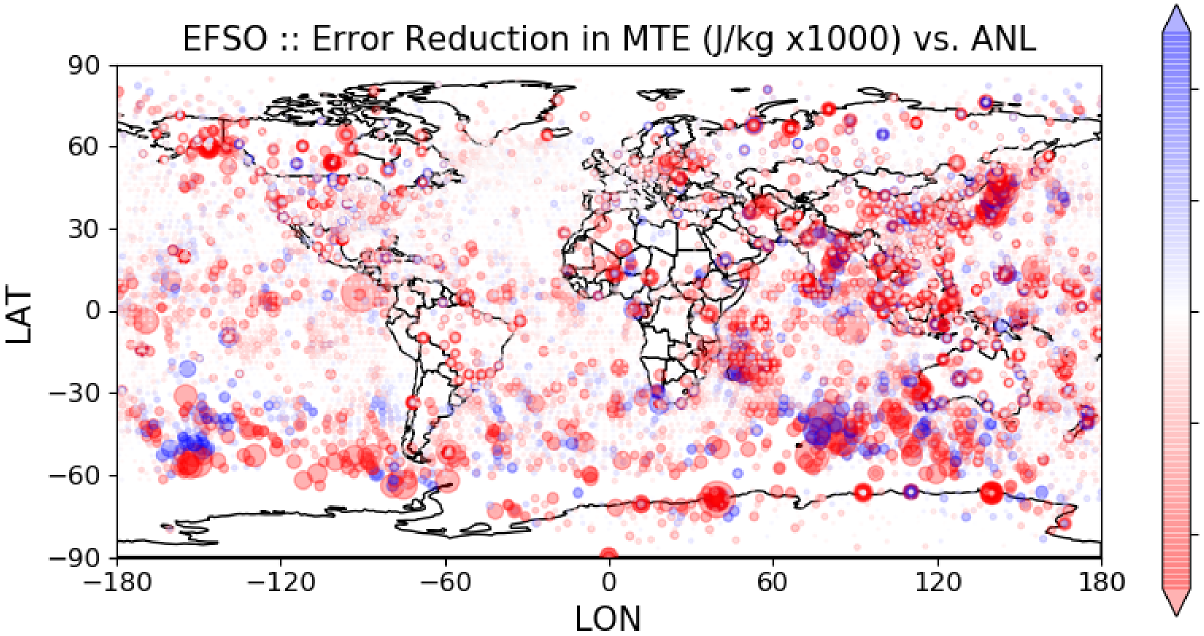


FCST degraded

FT 06hr

FCST improved

vs. NICAM -LETKF



FCST degraded

FT 06hr

FCST improved

Fraction of beneficial observations (ave. 2014/07)

Reference	Own Analysis	ERA Interim	AMSU-A
FT 06hr	**58.8 %**	55.3 %	53.1 %
FT 12hr	**56.1 %**	54.2 %	53.1 %

FSO may overestimate observational impact if we use the own analysis for verification reference.

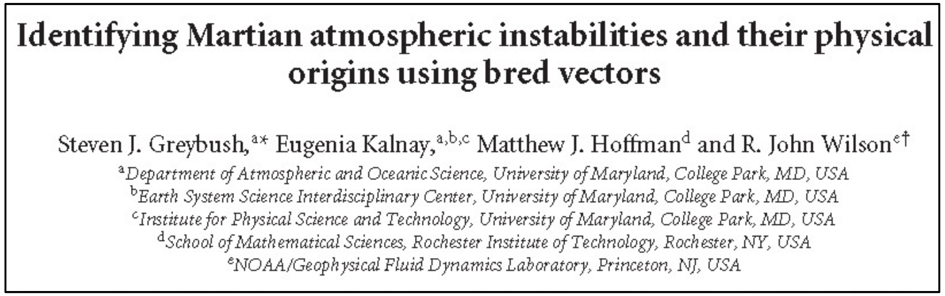
Summary

- 観測インパクト推定 (EFSO)
  - 対解析・対観測によるインパクト推定が可能
  - データ同化は、観測へのフィッティングを大幅に改善するが、他変数の改善は限定的
  - 対自身の解析EFSOはインパクトを過大に評価
  - 良いインパクトの観測は、概ね50+%

Kotsuki et al. (2017, MWR)
Kotsuki et al. (2018, in prep.)

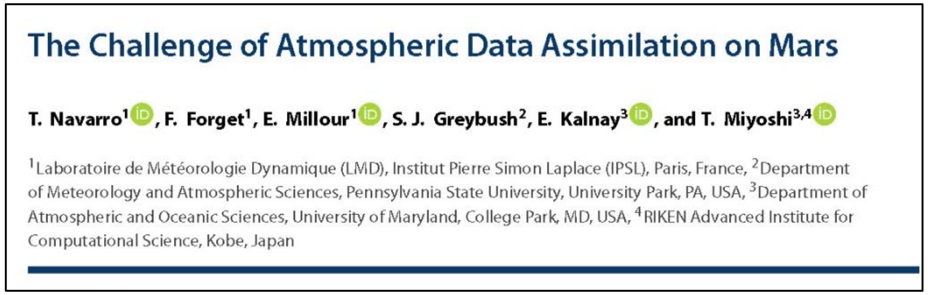
惑星気象研究への発展可能性

Martian Atmosphere



Identifying Martian atmospheric instabilities and their physical origins using bred vectors

Steven J. Greybush,[a*] Eugenia Kalnay,[a,b,c] Matthew J. Hoffman[d] and R. John Wilson[e†]
[a]*Department of Atmospheric and Oceanic Science, University of Maryland, College Park, MD, USA*
[b]*Earth System Science Interdisciplinary Center, University of Maryland, College Park, MD, USA*
[c]*Institute for Physical Science and Technology, University of Maryland, College Park, MD, USA*
[d]*School of Mathematical Sciences, Rochester Institute of Technology, Rochester, NY, USA*
[e]*NOAA/Geophysical Fluid Dynamics Laboratory, Princeton, NJ, USA*



The Challenge of Atmospheric Data Assimilation on Mars

T. Navarro[1], F. Forget[1], E. Millour[1], S. J. Greybush[2], E. Kalnay[3], and T. Miyoshi[3,4]

[1]Laboratoire de Météorologie Dynamique (LMD), Institut Pierre Simon Laplace (IPSL), Paris, France, [2]Department of Meteorology and Atmospheric Sciences, Pennsylvania State University, University Park, PA, USA, [3]Department of Atmospheric and Oceanic Sciences, University of Maryland, College Park, MD, USA, [4]RIKEN Advanced Institute for Computational Science, Kobe, Japan

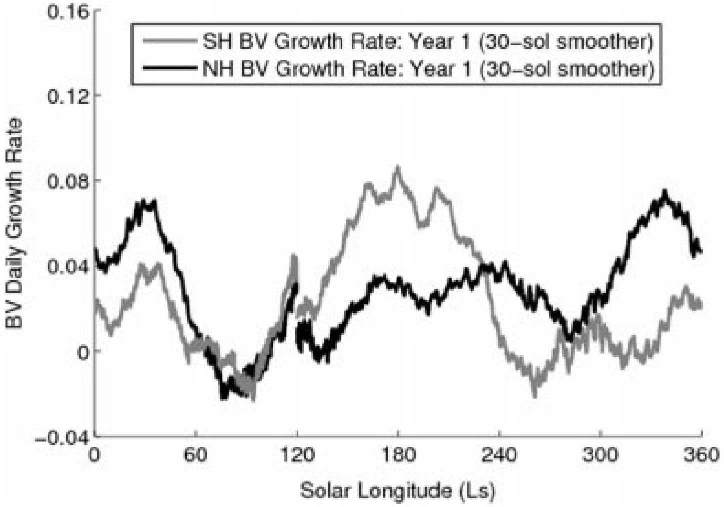


Figure 2. Bred vector amplitude (top, temperature-squared norm, K^2) and daily growth rate (bottom) time evolution. SH amplitudes are in grey/blue, NH in black/red. Raw BV amplitudes every 6 hours are depicted as scattered dots, whereas 30-sol smoothed values from year 1 are in dark shading. This figure is available in colour online at wileyonlinelibrary.com/journal/qj

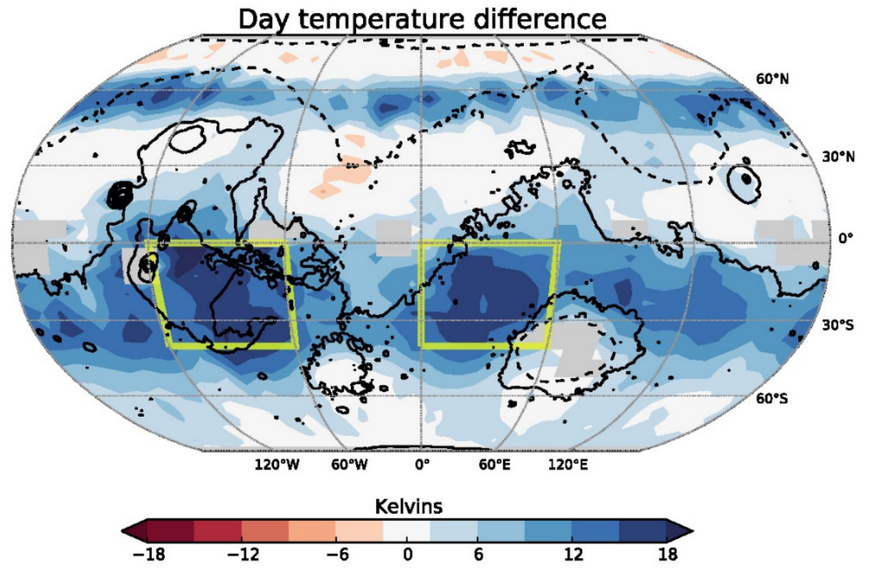
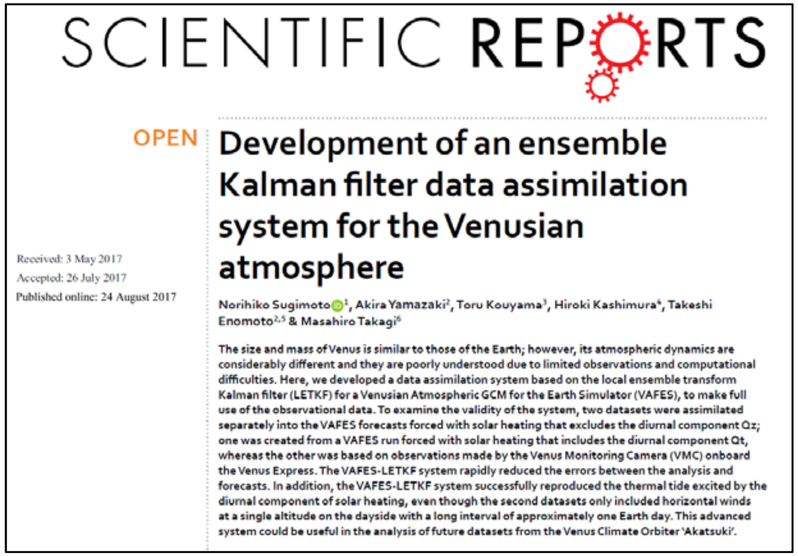


Figure 12. Map of difference in (top) nighttime and (bottom) daytime temperature between MCS and the background of the TuT-TuD experiment, for vertical level $\sigma = 0.4$, from Ls = 290° to Ls = 310°. Red (blue) indicates that the model is warmer (colder) than the observations. The yellow boxes indicate the Syria Planum and Terra Sabaea regions detailed in Figure 13. Black contours indicate the topography.

- 力学系の理解や衛星データ同化が進行中

Venusian Atmosphere

金星でも、あかつきのデータ同化が進みつつある（Sugimoto et al. 2017）



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Development of an ensemble Kalman filter data assimilation system for the Venusian atmosphere

Norihiko Sugimoto[1], Akira Yamazaki[2], Toru Kouyama[3], Hiroki Kashimura[4], Takeshi Enomoto[2,5] & Masahiro Takagi[6]

The size and mass of Venus is similar to those of the Earth; however, its atmospheric dynamics are considerably different and they are poorly understood due to limited observations and computational difficulties. Here, we developed a data assimilation system based on the local ensemble transform Kalman filter (LETKF) for a Venusian Atmospheric GCM for the Earth Simulator (VAFES), to make full use of the observational data. To examine the validity of the system, two datasets were assimilated separately into the VAFES forecasts forced with solar heating that excludes the diurnal component Qz; one was created from a VAFES run forced with solar heating that includes the diurnal component Qt, whereas the other was based on observations made by the Venus Monitoring Camera (VMC) onboard the Venus Express. The VAFES-LETKF system rapidly reduced the errors between the analysis and forecasts. In addition, the VAFES-LETKF system successfully reproduced the thermal tide excited by the diurnal component of solar heating, even though the second datasets only included horizontal winds at a single altitude on the dayside with a long interval of approximately one Earth day. This advanced system could be useful in the analysis of future datasets from the Venus Climate Orbiter 'Akatsuki'.

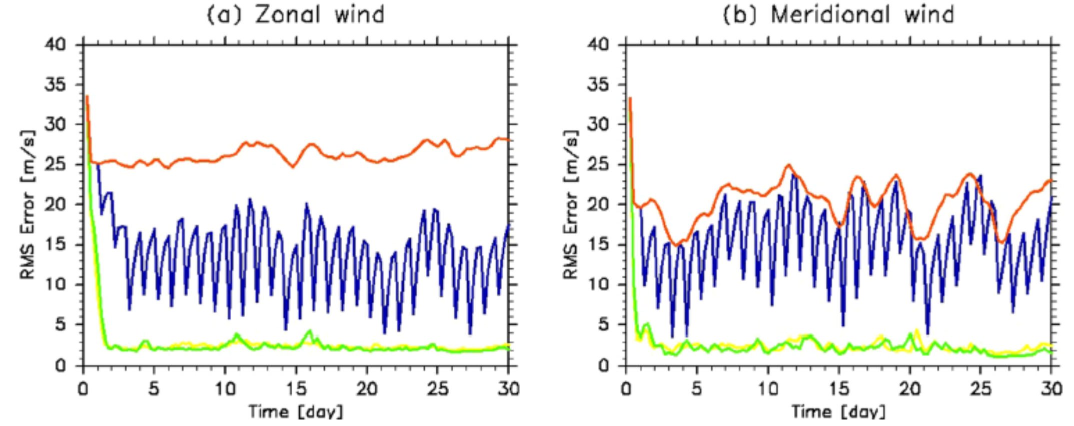

Figure 1. Time evolutions of the root-mean-square (RMS) errors from idealised observations at 70 km in (**a**) zonal and (**b**) meridional winds (m s^{-1}) for Cases H1 (1-h observations; yellow), H6 (6-h observations; green), H24 (24-h observations; blue) and Frf (background; red).

- 惑星気象データ同化研究の展望
  - 力学系を理解する(bred vector, Lyapunov exponent)
  - 双子実験やFSOで、センサ・観測網を事前に調査
  - 画像データから、状態やモデルパラメータを推定