Verification of EFSO at different geographical locations: Dynamics of propagation of observation impacts

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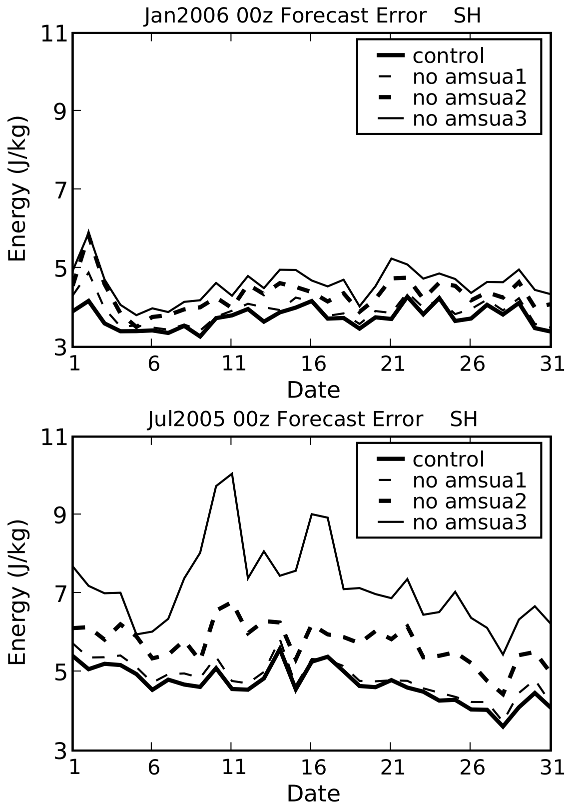
Motivation

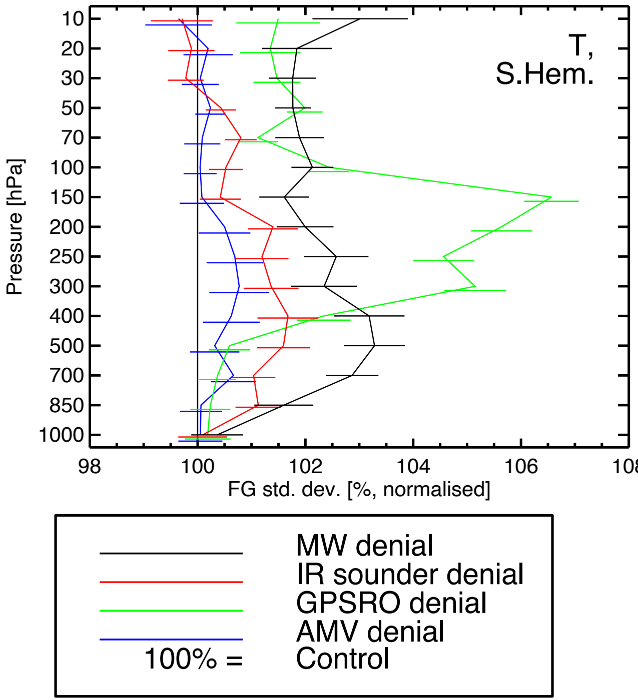
- Is it possible to use (E)FSO alternative to an OSE?
  - (E)FSO: (Ensemble-based) Forecast Sensitivity to Observations
  - OSE: Observing-System Experiment
- Use the FSO monitoring (map) to search high-impact observational spots proactively (before observing)?

OSEs done at 'operational' centers

- Add/exclude specific observations to/from global observing systems.



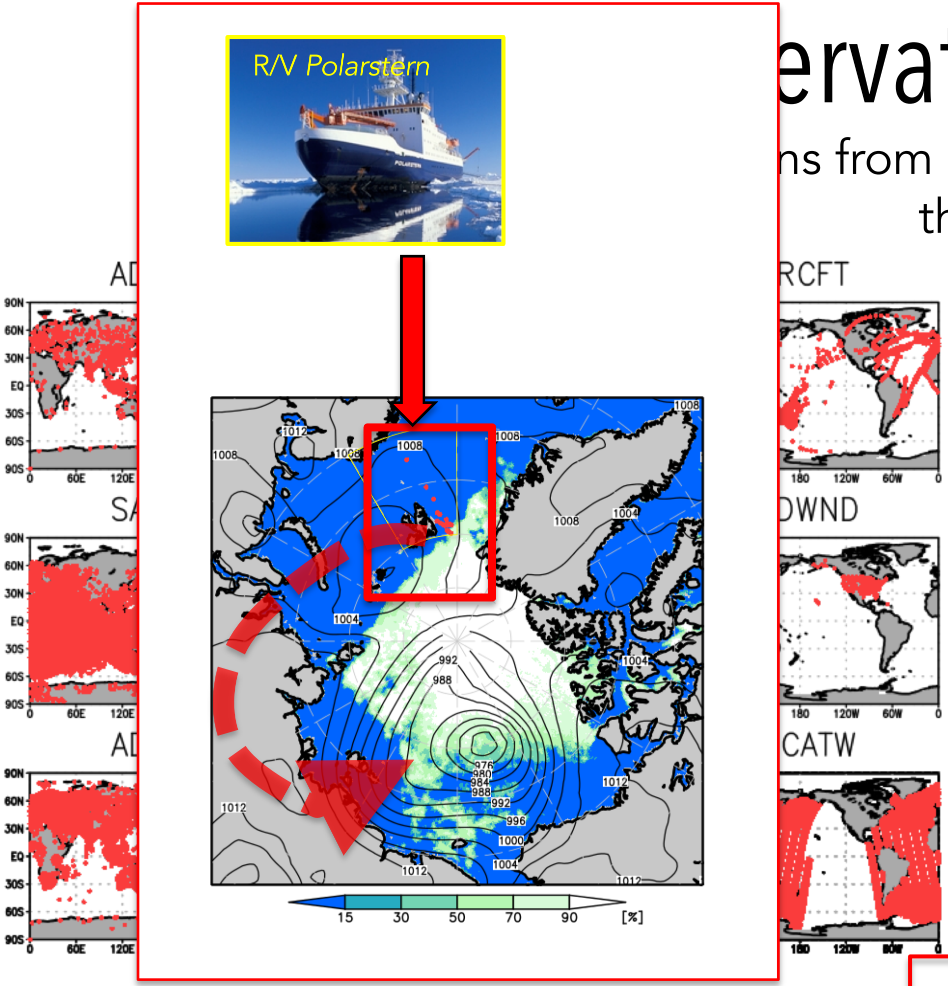
Gelaro and Zhu (2009 Tellus)



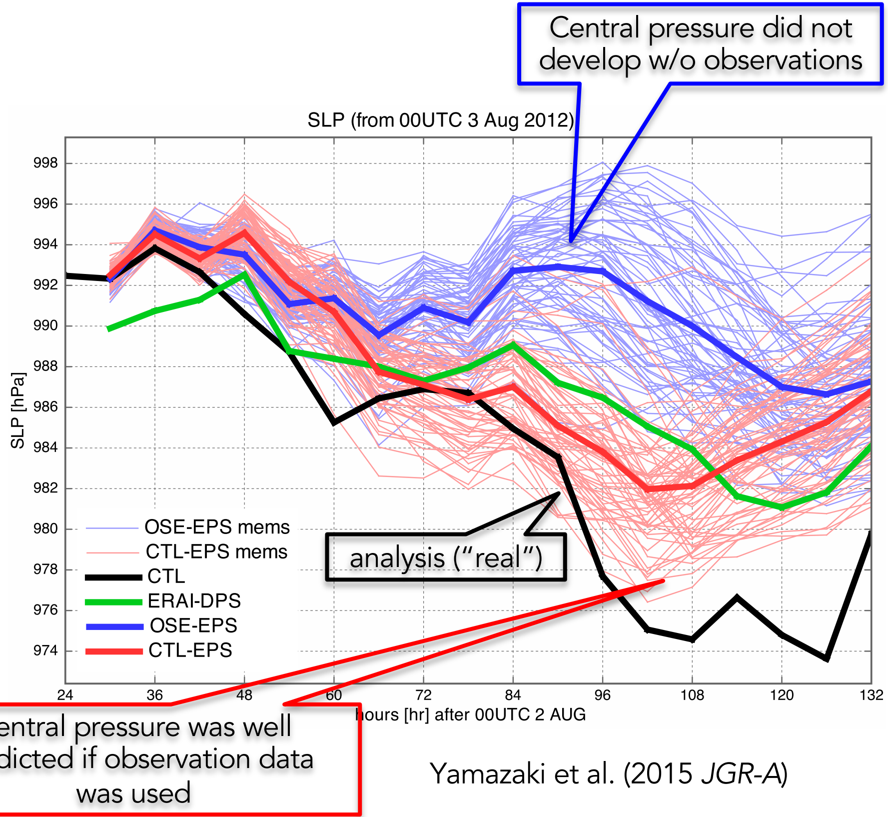
Bormann+(2019 ECMWF Tech Rep)

ervational campaigns

ns from R/V *Polarstern* improved the forecast skill of the "great" Arctic cyclone on 6 August 2012.



Global observing system in ALERA2

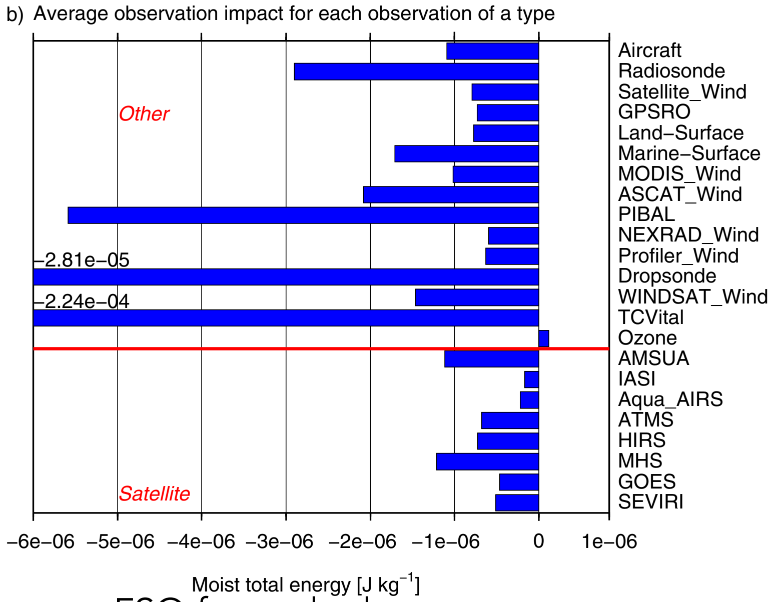


Yamazaki et al. (2015 *JGR-A*)

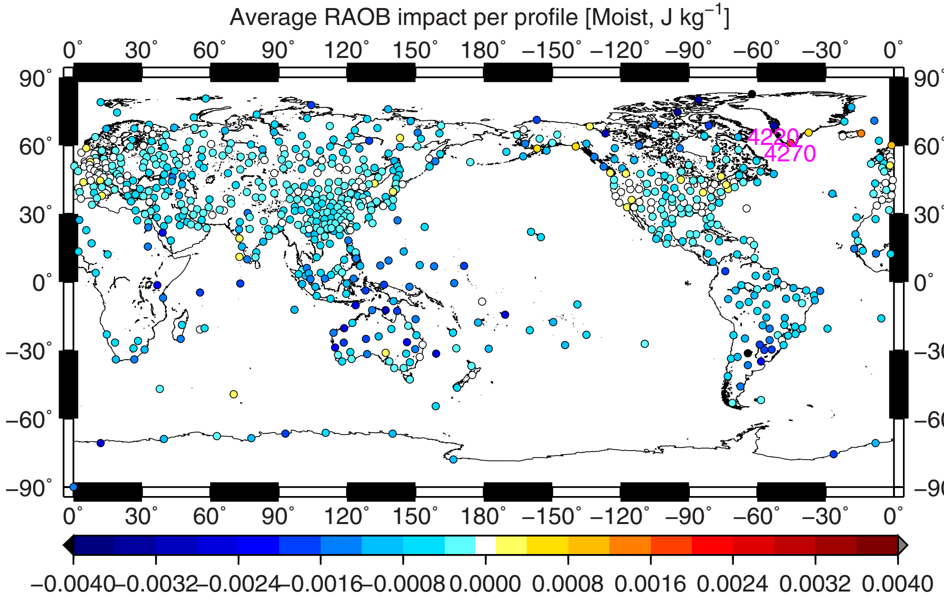
What is (E)FSO?

Forecast Sensitivity to observations (FSO)
Langland and Baker (2004 *Tellus*)

- Enable to diagnose individual observation impact (without OSEs!!)
- Kalnay et al. (2012 *Tellus*) proposed the ensemble-based FSO (EFSO) for EnKF data assimilation systems originally developed for adjoint-based systems.



FSO for each obs. type

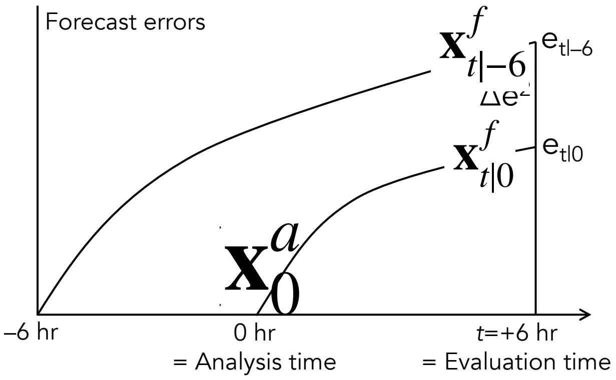


FSO map for radiosonde obs.

Ota et al. (2013 *Tellus*)

EnKF-based FSO (EFSO)

without the adjoint model



$$\mathbf{e}_{t|0} = \mathbf{x}^f_{t|0} - \mathbf{x}^{true}_t$$

$$\mathbf{e}_{t|-6} = \mathbf{x}^f_{t|-6} - \mathbf{x}^{true}_t$$

$$\Delta e^2 = (e^2_{t|0} - e^2_{t|-6})$$

$$\Delta e^2 \approx [\mathbf{M}_{t|0}(\mathbf{x}^a_0 - \mathbf{x}^f_{0|-6})]^{\mathrm{T}}\mathbf{C}(\mathbf{e}_{t|0} - \mathbf{e}_{t|-6})$$

$$= (\mathbf{M}_{t|0}\mathbf{K}\delta\mathbf{y}^{ob}_0)^{\mathrm{T}}\mathbf{C}(\mathbf{e}_{t|0} - \mathbf{e}_{t|-6})$$

in EnKF:

$$\mathbf{K} = \mathbf{P}^a\mathbf{H}^{\mathrm{T}}\mathbf{R}^{-1} = \frac{1}{K-1}\mathbf{x}^a\mathbf{x}^{a\mathrm{T}}\mathbf{H}^{\mathrm{T}}\mathbf{R}^{-1}$$

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

correlation in ensemble space

$$\Delta e^2 \approx \frac{1}{K-1}(\mathbf{M}_{t|0}\mathbf{X}^a_0\mathbf{Y}^{a\mathrm{T}}_0\delta\mathbf{y}^{ob}_0)^{\mathrm{T}}\mathbf{C}(\mathbf{e}_{t|0} - \mathbf{e}_{t|-6})$$

$$\approx \frac{1}{K-1}(\mathbf{X}^f_{t|0}\mathbf{Y}^{a\mathrm{T}}_0\delta\mathbf{y}^{ob}_0)^{\mathrm{T}}\mathbf{C}(\mathbf{e}_{t|0} - \mathbf{e}_{t|-6})$$

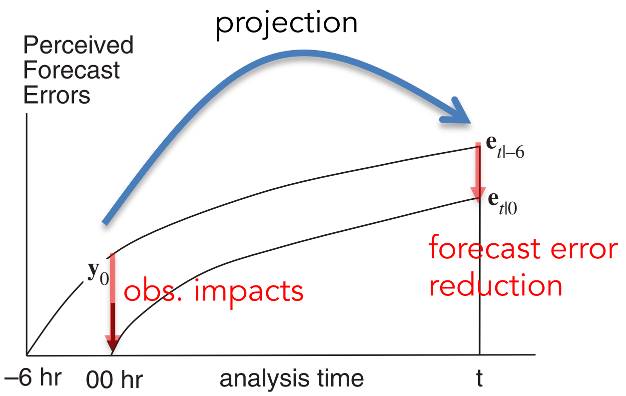
$$= \delta\bar{\mathbf{y}}^{ob}_0\frac{1}{K-1}\mathbf{R}^{-1}\mathbf{Y}^a_0\mathbf{X}^{f\mathrm{T}}_{t|0}\mathbf{C}(\mathbf{e}_{t|0} - \mathbf{e}_{t|-6})$$

correlation between analysis ensemble in obs. space and forecast forecast ens in model space

Kalnay et al. (2012 *Tellus*); Hotta et al. (2017 *MWR*)

Backgrounds of OSE and FSO studies

- OSE
  😃: evaluate of actual and quantitative observation impacts.
  😩: too computationally expensive (not very practical).
- FSO
  😃: estimate all the impacts cheaply and separately (proactively).
  😩: estimate impacts for only short-range (6–24-hr) forecast (close to the assimilation window length).

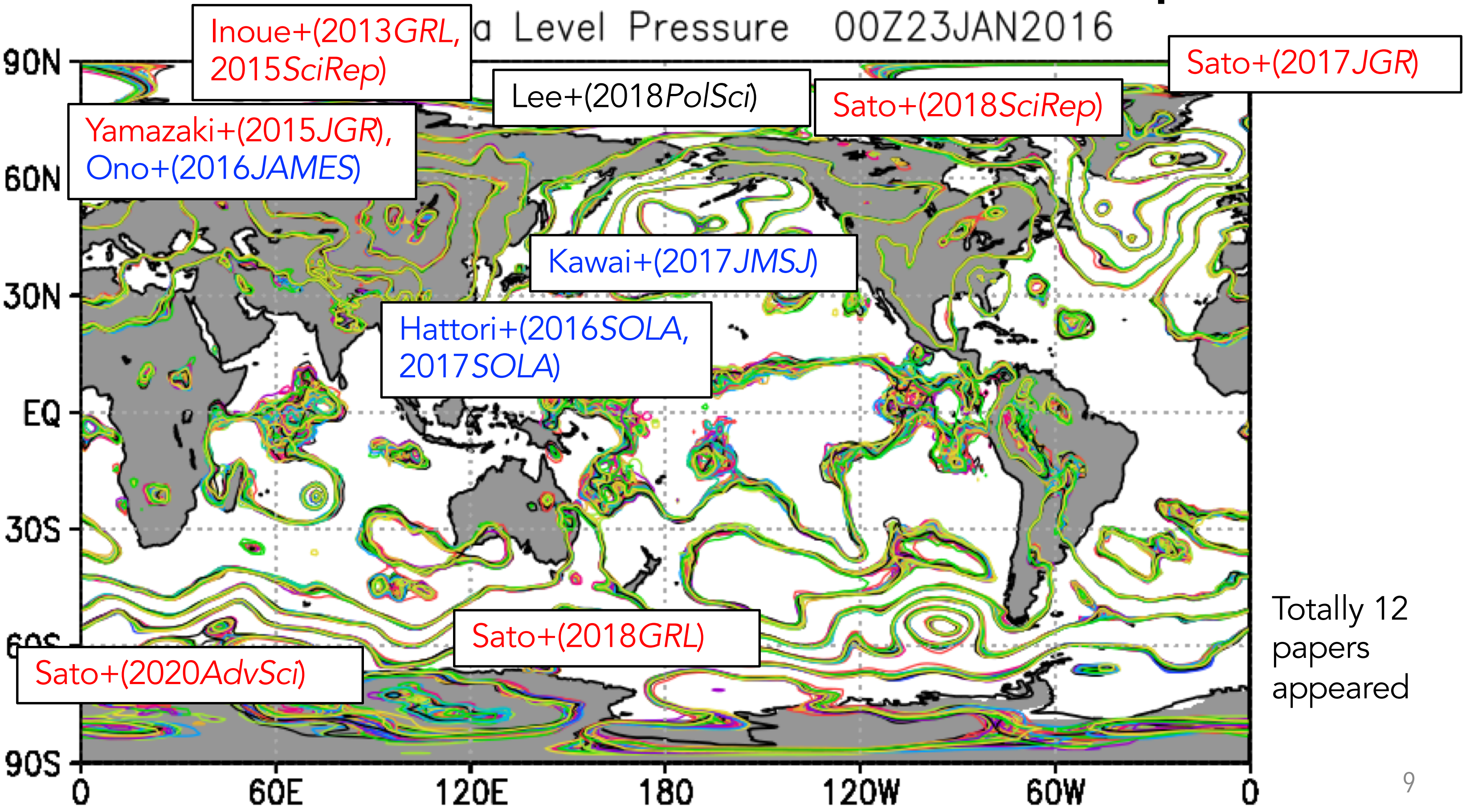


Use of FSO for observational campaigns

- Operationally, FSO and OSEs are used to decide which observation types should be selected and/or regulating massive observations for the global observing system.

➢ Rather would like to focus on impacts of adding or reducing small subsets of obs. in the system by an obs. campaign, to investigate their remote influences (for more than short-range forecasts).

Our OSE studies for obs. campaigns



Totally 12 papers appeared

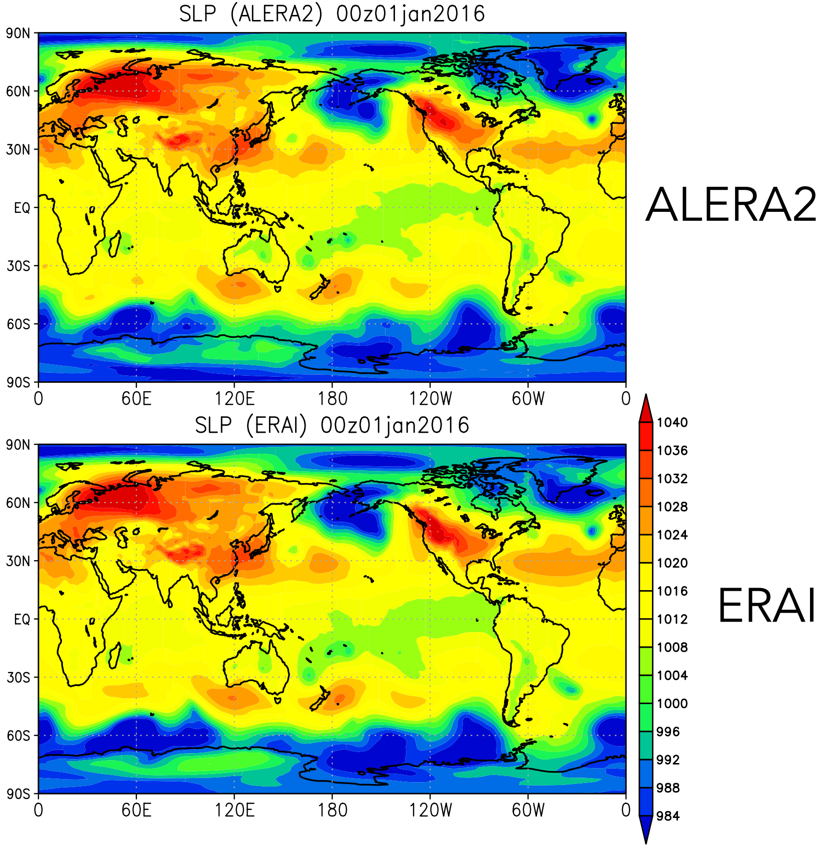
Aim of this study

- How well the FSO diagnosis can estimate true (actual) impacts of observations done at various geographical locations.
- How the impacts of observations can dynamically propagate for weekly short- to medium-range forecast (6-hour~7 days)?

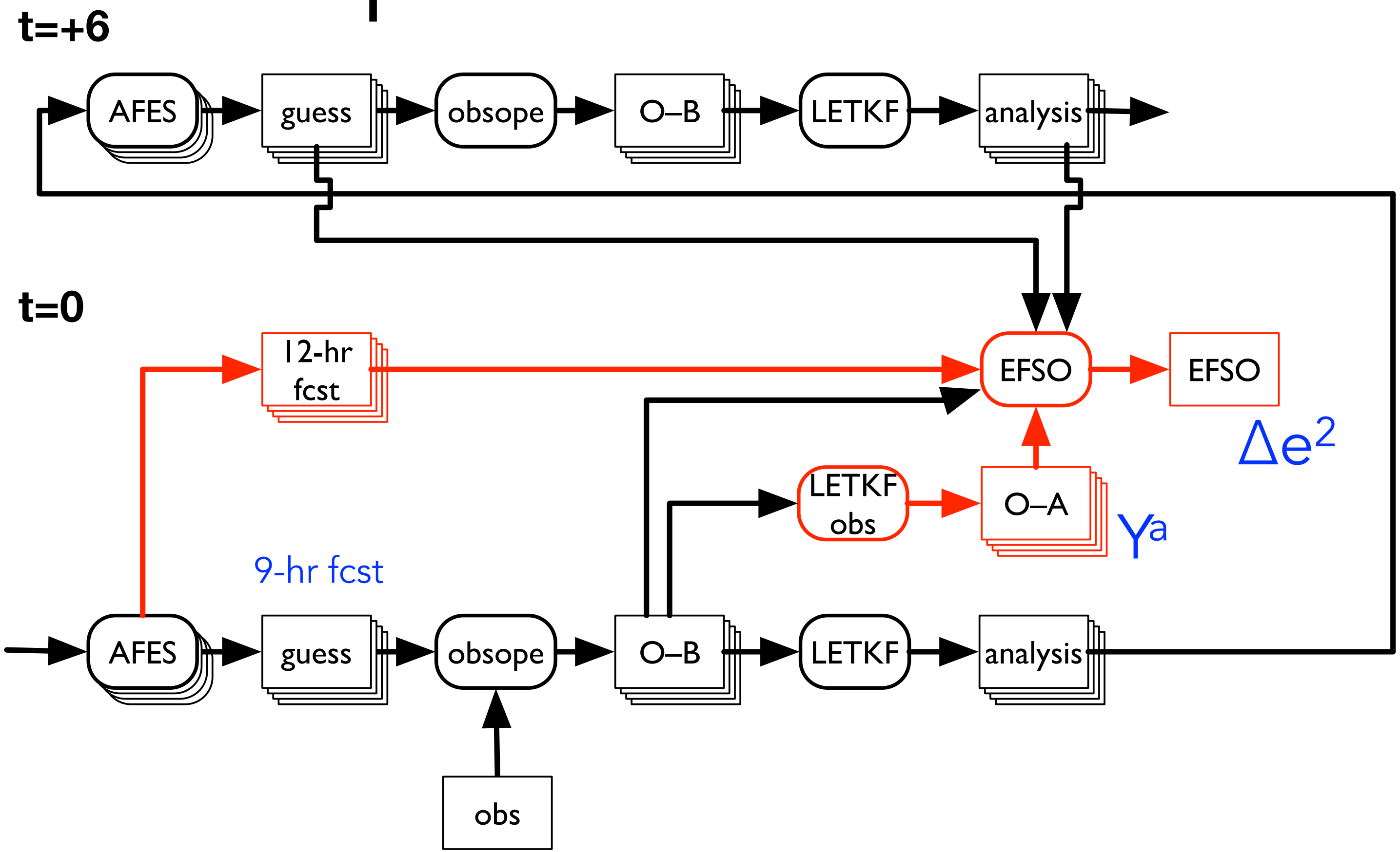
AFES(AGCM)-LETKF Data Assimlation System: ALEDAS
AFES-LETKF experimental Ensemble ReAnalysis ver. 2: ALERA2

	ALERA (version 2)
Model	AFES T119L48 (~1°×1°, up to ~3 hPa)
Analysis scheme	LETKF
Ensemble size	63
localization	400 km (horizontal) / 0.4 ln*p* (vertical)
Inflation	10% (fixed)
Observation	NCEP PREPBUFR (conventional + satellite wind)
Boundary condition	OISST/ICE daily ¼°
DA window	6 hour
References	Miyoshi & Yamane (2007 *MWR*); Miyoshi et al. (2007a;b *SOLA*); Enomoto et al. (2013); Yamazaki et al. (2017 *SOLA*)

snapshots of SLP



EFSO implemented into ALEDAS



Evaluation metric (error norm)

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

- Moist total energy (MTE) [J kg^{-1}]:

$$\Delta e^2_{\mathrm{MTE}} = -\frac{1}{2}\frac{1}{p_s}\int_{p_s}^{0}(u'^2 + v'^2) + \frac{c_p}{T_r}T'^2 + \frac{L^2}{c_p T_r}q'^2\,\mathrm{d}p + \frac{R_d T_r}{p_r}p_s'^2$$

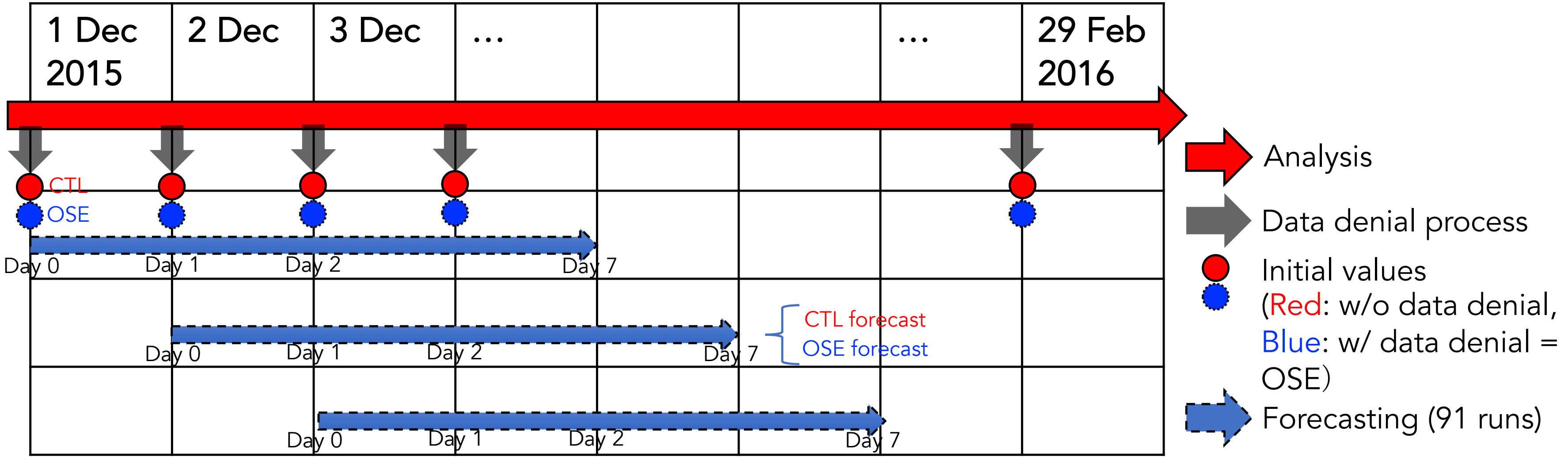
- EFSO values: MTE averaged over the whole global domain.

✓ Actual (true) observation impact: MTE of the difference

$\overline{\mathbf{x}}^f_{\mathrm{CTL}} - \overline{\mathbf{x}}^f_{\mathrm{OSE}}$ (ensemble mean)

Experimental designs

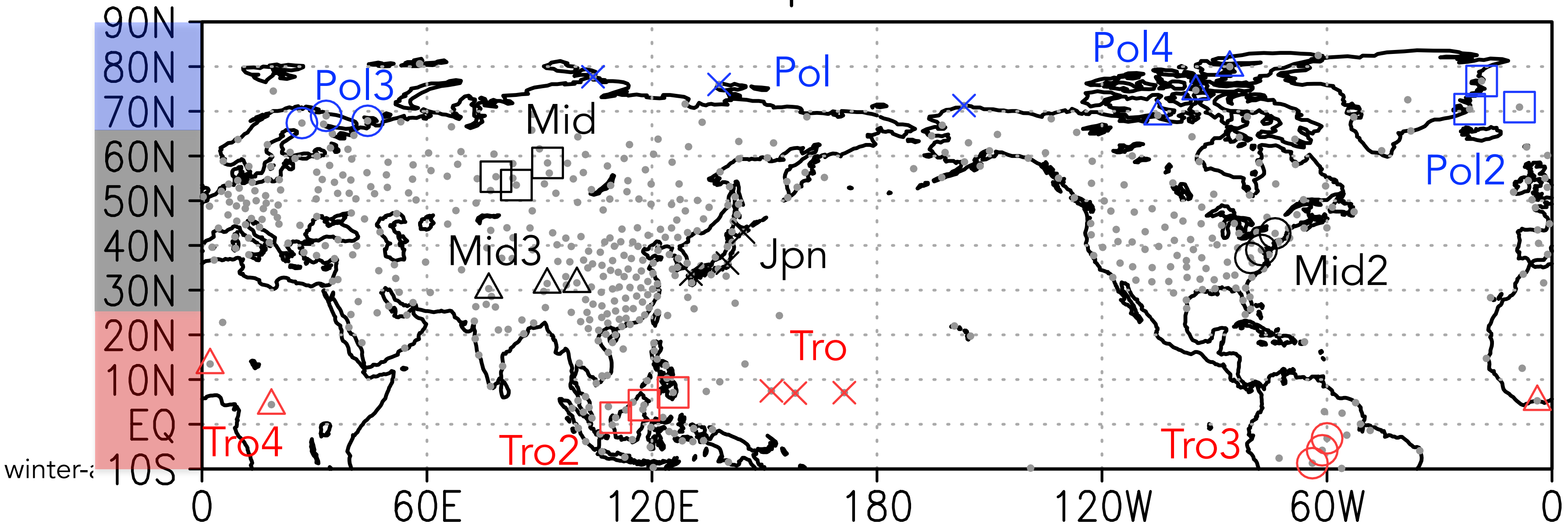
- The experiments were conducted for the period from 1 December 2015 to 29 February 2016.
- 7-day ensemble forecasting were conducted from every 0000 UTC during the period initialized by ALERA2, called the CTL experiment.
- 91 times (at every 0000 UTC during the winter) of 7-day forecast experiments for each CTL and OSE.



EFSO values and OSEs (data denial experiments)

- A subset of radiosonde observations that had been launched at a spot comprising 3 adjacent routine observation sites was excluded.
- 4 spots of 12 were selected from the midlatitudes, the Arctic, and the tropics .

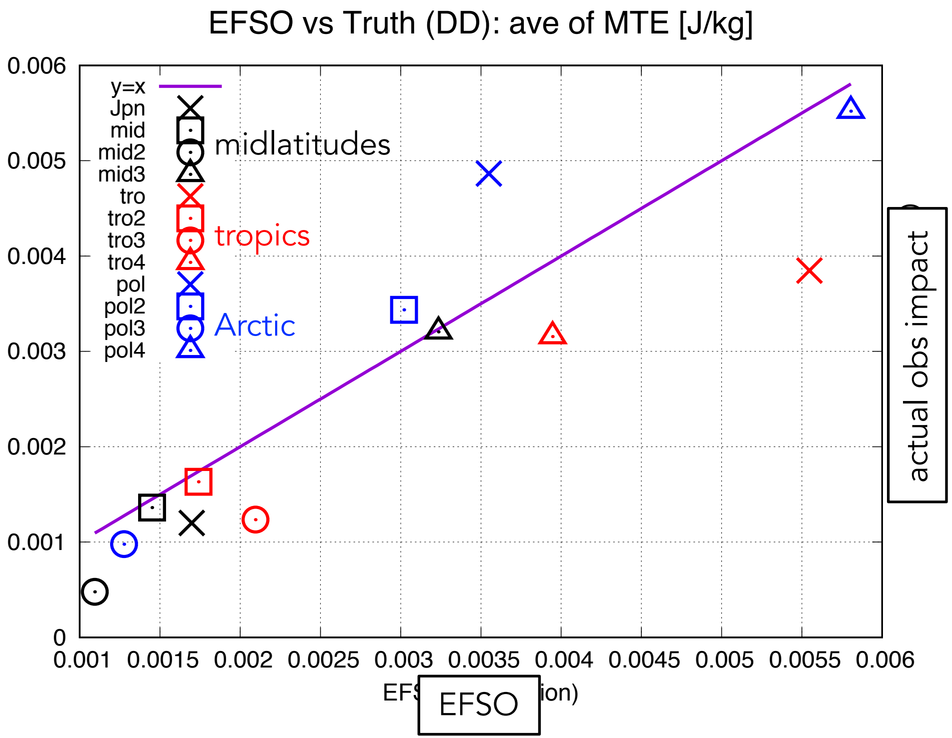
Observation points for the OSEs



×: Jpn, Pol, Tro □: Mid, Pol2, Tro2 o: Mid2, Pol3, Tro3 △: Mid3, Pol4, Tro4

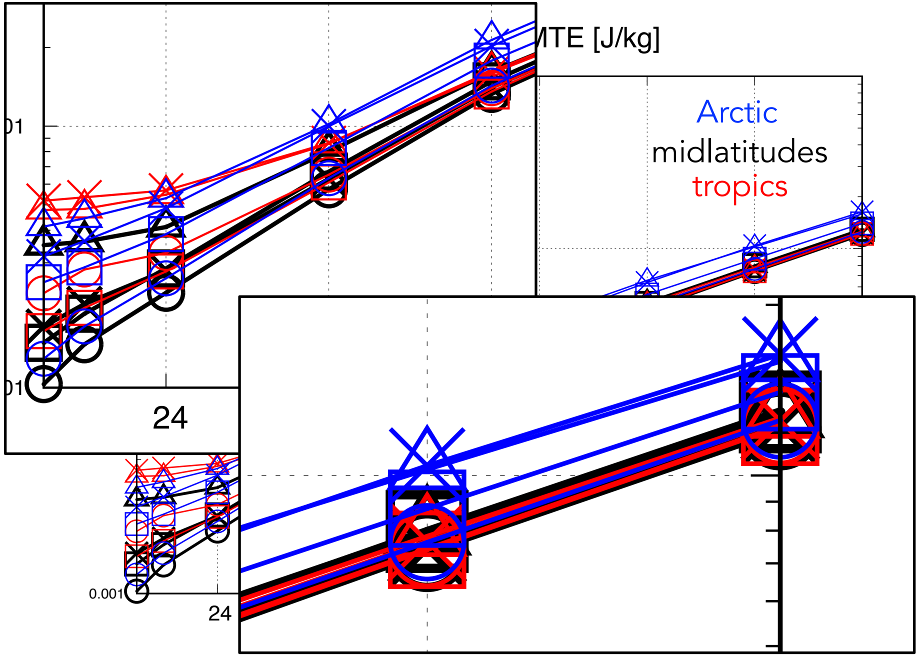
6-hr EFSO vs actual obs. impacts

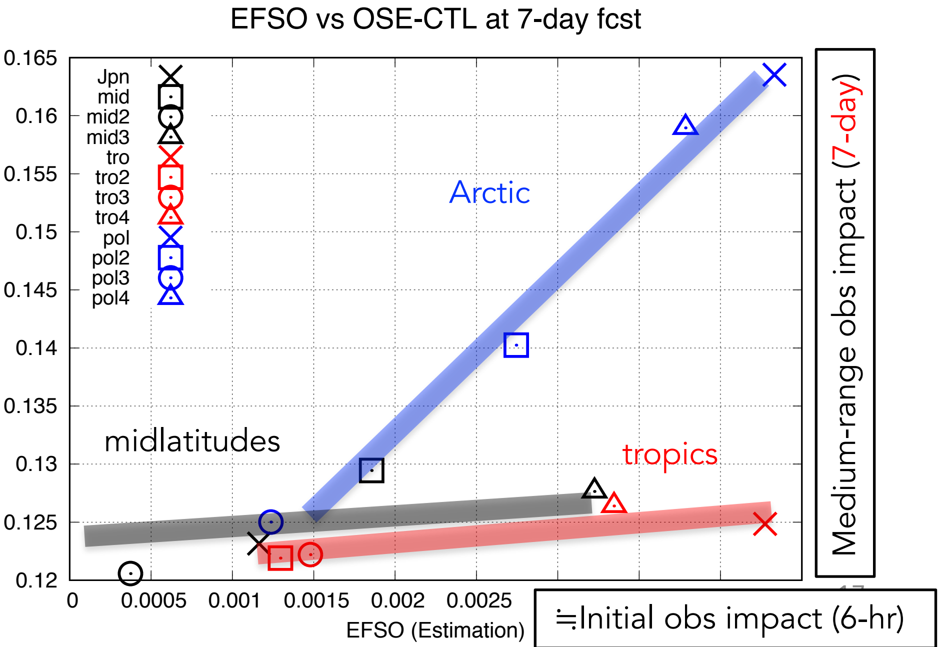
- The EFSO values are quantitatively accurate estimates of the actual observation impacts evaluated by OSEs.
- The magnitudes of the actual observation impacts are not sensitive to the latitudinal bands where observations have been conducted.



Is the 6-hour EFSO diagnosis useful for weekly forecasts?

- Relative differences (rankings) of the initial (actual) observation impacts at 6-hour forecasts retain during the short-range forecast (1–2 days), regardless of the latitudinal bands.
- Those for the Arctic observations retain even in the medium range forecast (7 days).

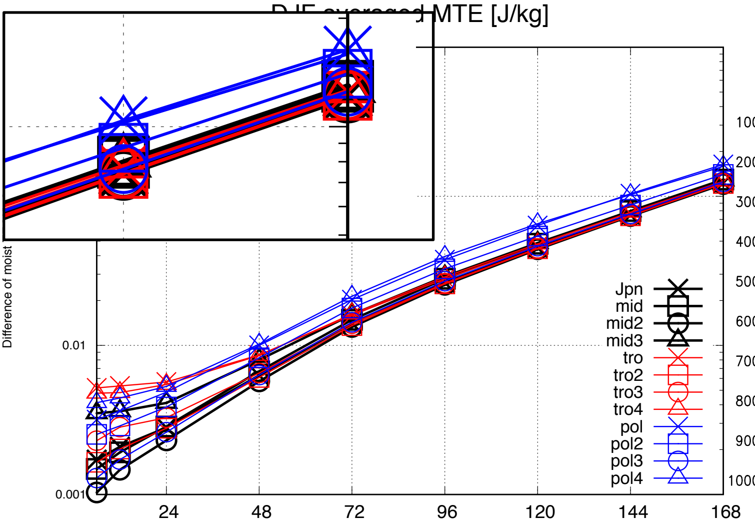




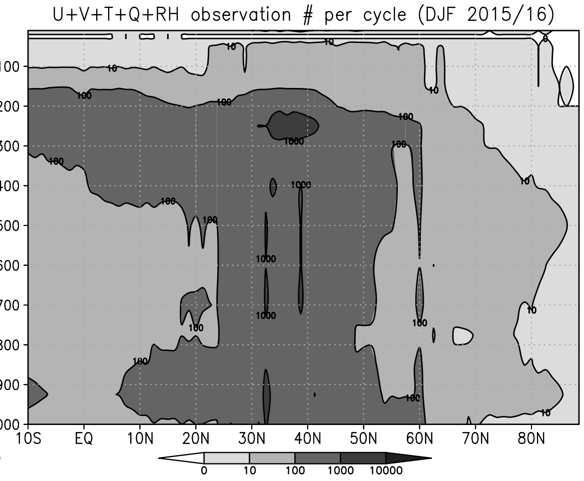
Why the Arctic observations have the largest observation impacts in the medium range?

1. Small number of Arctic observations.
2. The Arctic is located upstream of the dynamical propagation.

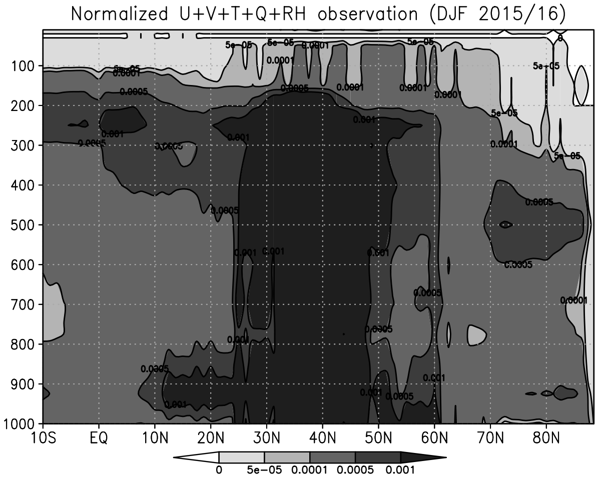
Observation number & density in ALERA2



obs number



norm obs density

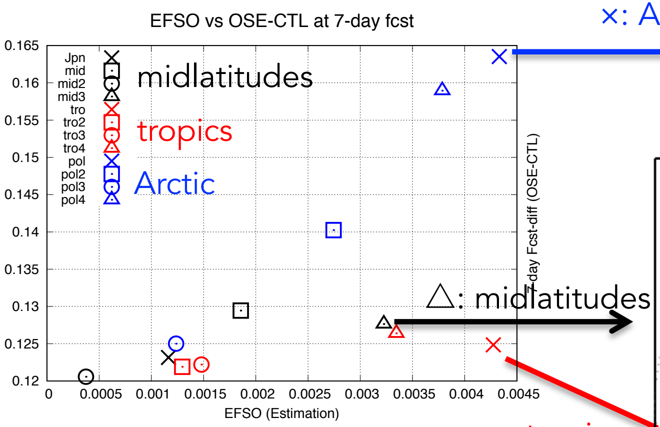


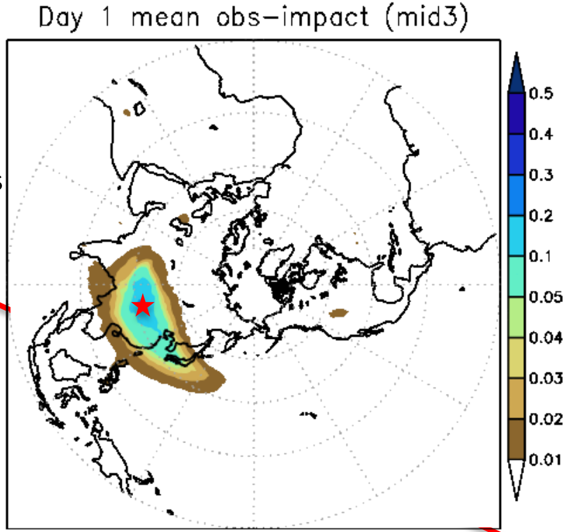
- Arctic obs. impacts overwhelm those for the midlatitudes.

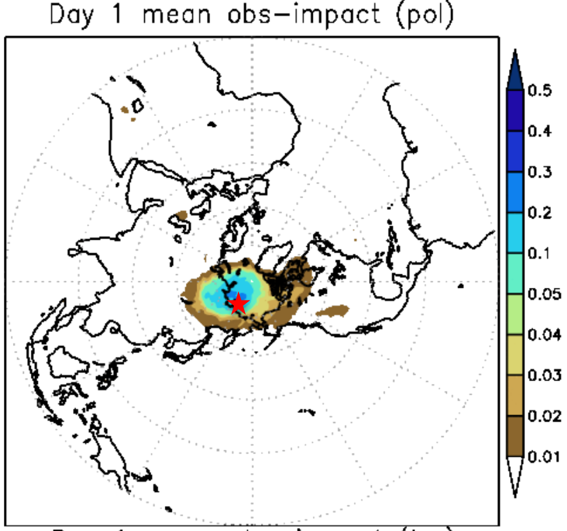
✓ The observation density, normalized by area (km^2) in the Arctic and the tropics are almost the same in the troposphere.

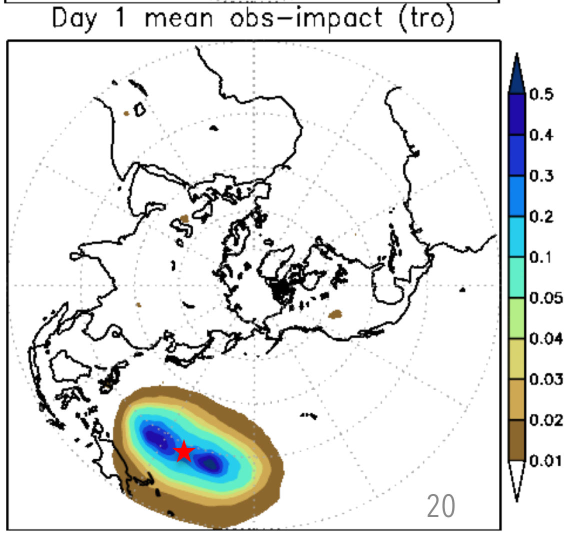
Propagation of obs. impacts

Animations (Day 1–7)





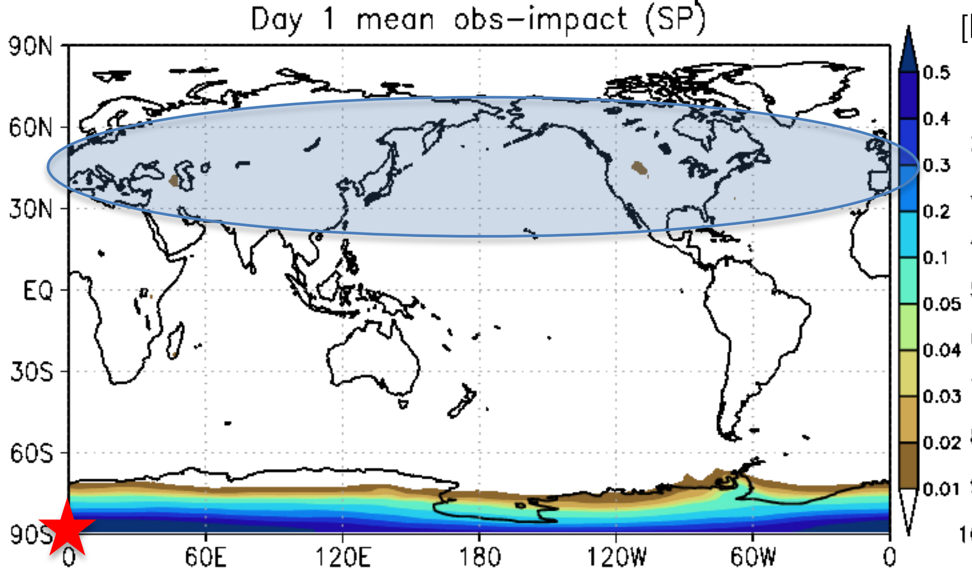


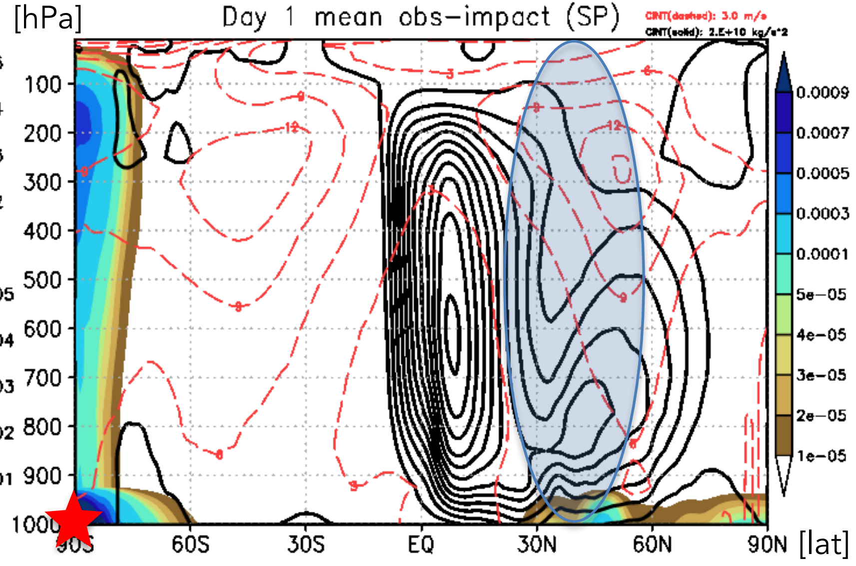


- Observation impacts are dynamically propagated (phase/group velocity and advection) in the initial stage (short-range forecast)
- Obs. impacts in the midlatitudes are spontaneously amplified during the medium range forecast?

Spontaneous error growth in midlatitudes

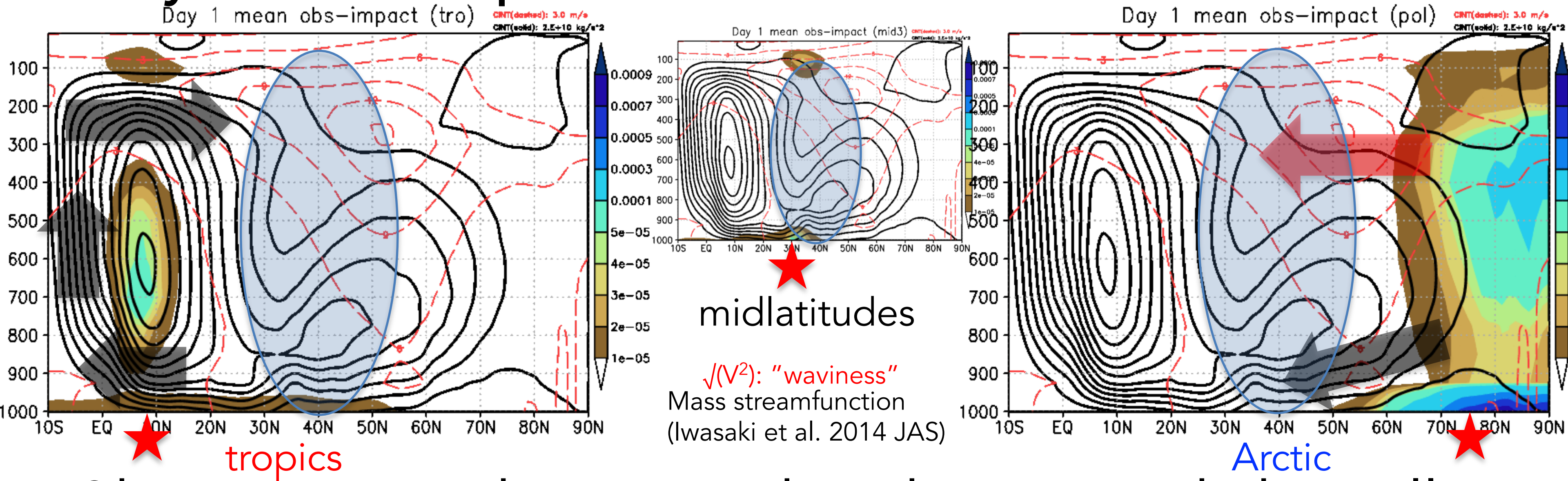
The obs. impact of radiosondes at the South Pole.





- Trivial errors are rapidly amplified during the medium-range (3- to 7-day) forecast where the storm tracks are active.
- Such amplification must highlight a chaotic nature of the general atmospheric circulation, which stems from the contamination of observation impacts arising from the rapid growth of trivial numerical processes .
- “Chaos seeding” (Hodyss and Majumdar 2007 *QJ*; Ancell et al. 2018 *BAMS*)

Dynamical upstream/downstream of midlat.



- Obs. impacts tend to retain when they are seeded initially at dynamically upstream regions of the midlatitudes where the trivial errors rapidly and spontaneously grow up.

Summary

- The EFSO values reasonably estimated the observation impacts on short-range (6-hour to 2-day) forecasts, irrespective of the latitudinal bands where observations had been conducted.
- The initial Arctic observation impacts, which could be estimated by EFSO, remained in medium-range (7-day) forecasts.
- It is important to seed initial obs. impacts at the upstream of dynamical propagation toward the regions where small perturbations grow rapidly and spontaneously (midlatitudes).

Implication (1)

- Essence of the ensemble-based FSO is to calculate covariance between analysis ensemble in obs. space and short-range forecast ensemble.
  - without adjoint (tangent-linear) model.
  - could substitute covariance between analysis ensemble in model space and short-range forecast ensemble.

$$\Delta e^2 \approx \frac{1}{K-1}\left(\mathbf{M}_{t|0}\mathbf{X}_0^a\mathbf{Y}_0^{a\mathrm{T}}\delta\mathbf{y}_0^{\mathrm{ob}}\right)^{\mathrm{T}}\mathbf{C}(\mathbf{e}_{t|0}-\mathbf{e}_{t|-6})$$

Tangent-linear model

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

Ensemble forecast

$$= \delta\bar{\mathbf{y}}_0^{\mathrm{ob}}\frac{1}{K-1}\mathbf{R}^{-1}\mathbf{Y}_0^{a}\mathbf{X}_{t|0}^{f\mathrm{T}}\mathbf{C}(\mathbf{e}_{t|0}-\mathbf{e}_{t|-6})$$

covariance

Implication (2)

- Arctic observations have the largest impact for weekly (weather) forecasts.
  - This stems from the atmospheric dynamics of atmospheric general circulations (flow-dependent).
- Results will be changed if we focus on, coupled systems in the subseasonal-to-seasonal timescales (c.f., Doi et al. 2019).
  - However, such dynamical consideration must be helpful for the other timescales.

Why the Arctic observations have the largest observation impacts?

1. Smaller numbers of observations than midlat obs numbers.
2. Impacts of the Arctic obs. can faster propagate toward the midlats than those of the tropical obs.
3. Metrics of the moist total energy.
   – emphasize the midlatitude storm-track activities.
4. A typical AGCM is used
   – T119L48M63, hydrostatic dynamical core
   ➢ Dynamical propagation (realistic process) may be more emphasized than the numerical contamination (unrealistic)