The 6th Research Meeting of
Ultra-high Precision Meso-Scale Weather Prediction
Kyoto
2016/3/7

気象庁非静力学モデルを用いた ハイブリッドデータ同化システム

Hybrid data assimilation systems based on the JMA nonhydrostatic model

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<Acknowledgment> This work was supported by the Ministry of Education, Culture, Sports, Science and Technology (MEXT) through the Strategic Programs for Innovative Research (SPIRE). This research was conducted using the K computer at the RIKEN Advanced Institute for Computational Science (proposal number: hp120282, hp130012, hp140220, and hp150214).

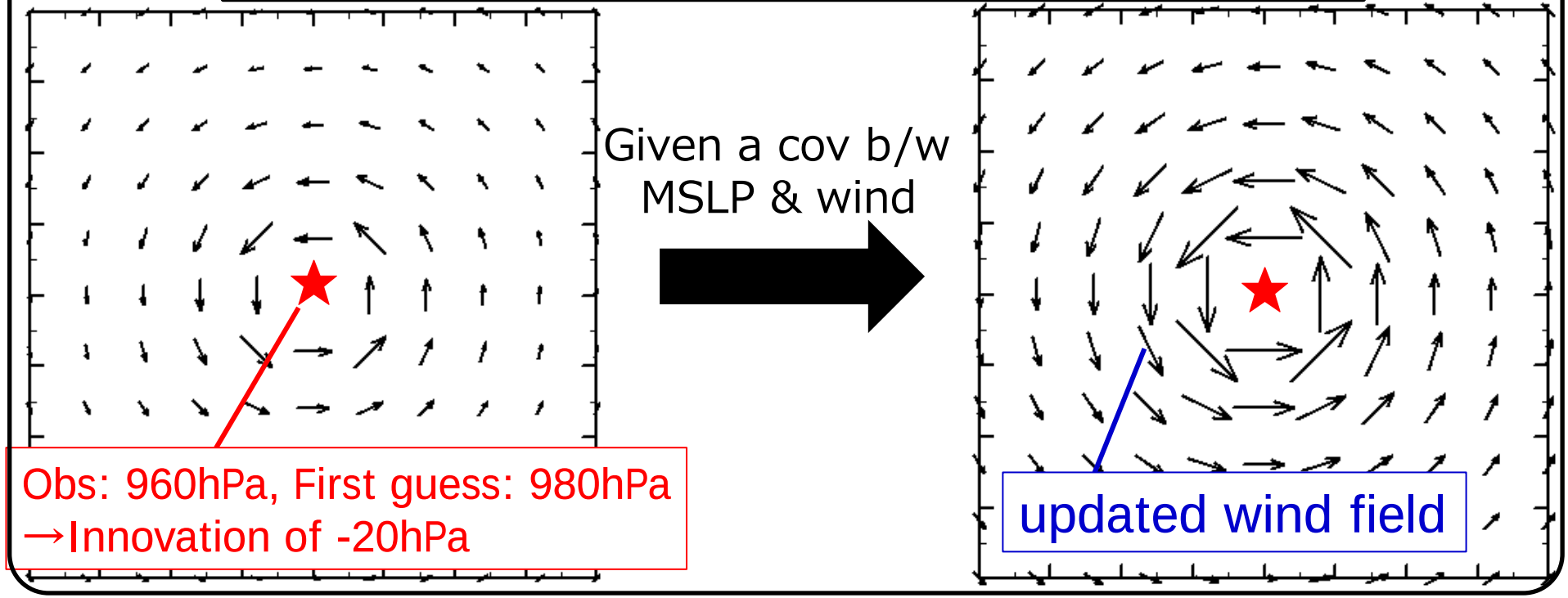
What is a data assimilation?

Innovation
(obs – first guess)

Estimated
Covariance

→ Increment
(updated guess – first guess)

Example: Single observation of MSLP in TC



How to calculate covariances?
(Linearity and Gaussian PDF assumed)

- Physical valuables in a model: $O(10^8\text{-}10^{10})$
  --> Cov of physical valuables: $O(10^{16}\text{-}10^{20})$
- Calculating covariances of physical variables
  - ➢ Initial value of covariance **B**
  - ➢ Time evolution of covariance $\mathbf{MBM}^T$

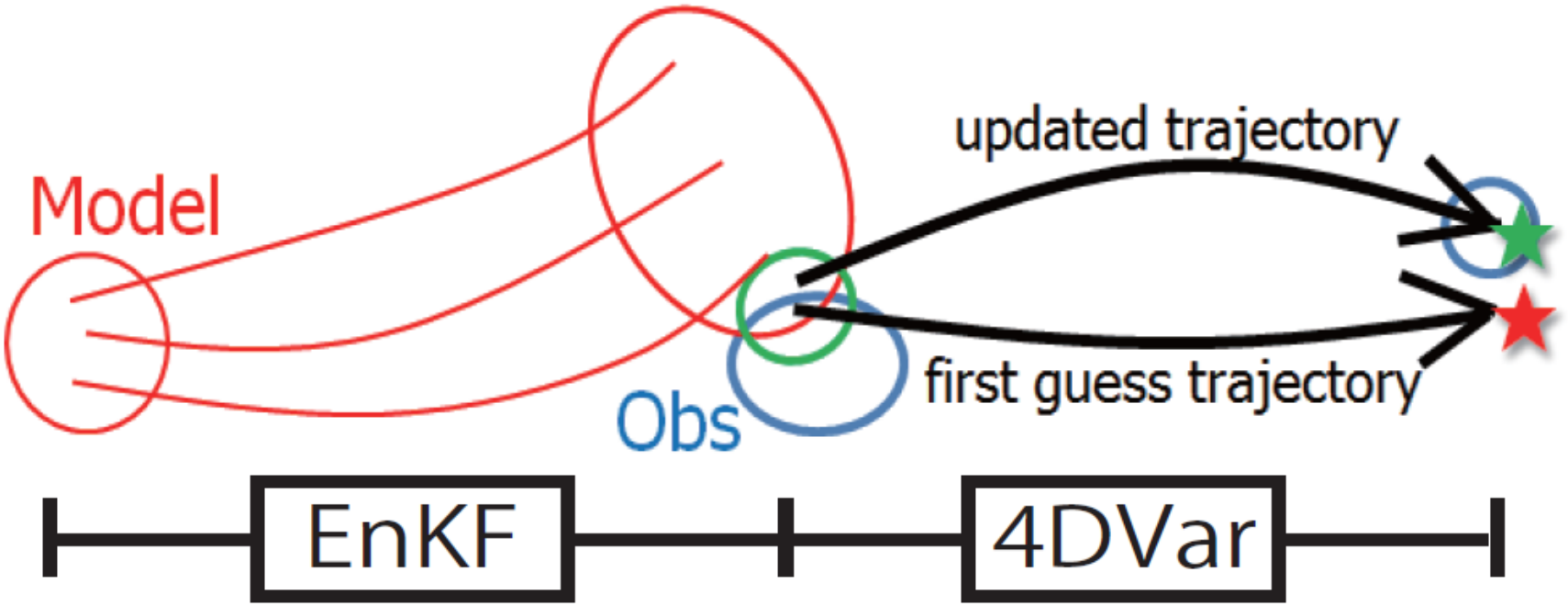
Method	Initial value of cov.	Time evolution of cov.
4D-Var-Bnmc	NMC (climatology)	(Implicitly) Exact
EnKF	Ens.-based approx.	Ens.-based approx.
4D-Var-Benkf (Hybrid)	Ens.-based approx.	(Implicitly) Exact

- Hybrid presumably exhibits the best quality.

Hybrid DA system

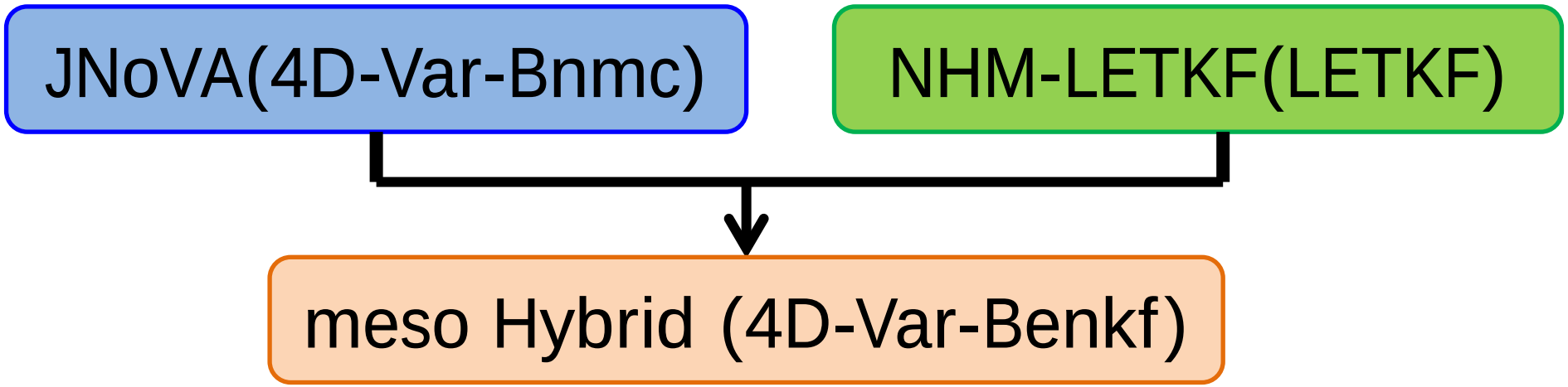
(Lorenc, 2003; Wang et al. 2007; Buehner et al. 2010a,b)

- 4D-Var system requires a prescribed **B**
- EnKF-based perturbations are used to construct **B** in a hybrid system.



The aim of this work

- Question: Does really an EnKF-based **B** enhance the skill of JMA operational 4D-Var system in terms of predicting the severe weather events?
- JNoVA: Operational 4D-Var system for regional forecasts using the JMA nonhydrostatic model (NHM) (Honda 2005; Honda and Sawada, 2009)
- NHM-LETKF: LETKF system using the JMA-NHM developed by Kunii (2014).



Formulation of hybrid DA systems

- Cost function

$$J = \frac{1}{2}\delta\mathbf{x}_{nmc}^{T}\mathbf{B}_{nmc}^{-1}\delta\mathbf{x}_{nmc} + \frac{1}{2}\delta\mathbf{x}_{enkf}^{T}\mathbf{B}_{enkf}^{-1}\delta\mathbf{x}_{enkf}$$

$$+\frac{1}{2}\sum_{t}(\mathbf{d}_t - H_t(M_t(\mathbf{x}_b)) + H_t(M_t(\delta\mathbf{x}_0 + \mathbf{x}_b)))^{T}\mathbf{R}_t^{-1}(\mathbf{d}_t - H_t(M_t(\mathbf{x}_b)) + H_t(M_t(\delta\mathbf{x}_0 + \mathbf{x}_b))) + J_p$$

- Interaction between 4D-Var and EnKF
  --> one-way (LETKF based **B** --> 4D-Var)
- Do we mix $\mathbf{B}_{nmc}$ and $\mathbf{B}_{enkf}$?
  --> $\mathbf{B}_{hybrid} = 0.2\mathbf{B}_{nmc} + 0.8\mathbf{B}_{enkf}$
- We implemented two types of $\mathbf{B}_{enkf}$

4D-Var-BenkfL

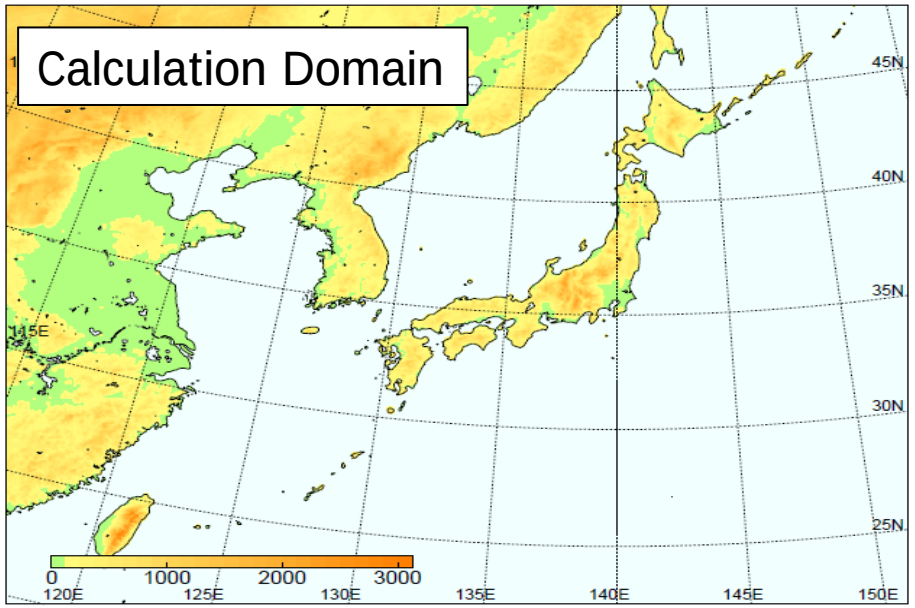
  - Spatial Localization (Wang et al. 2007)
    --> $\mathbf{B}_{enkfL} = \mathbf{X}\mathbf{X}^{T} \circ \mathbf{C}$ ($\circ$: Schur product, **C**: Correlation matrix for localization)
    --> Using a so-called “alpha control vector”

  - Neighboring ensemble approach (Aonashi et al. 2013)
    --> $\mathbf{B}_{enkf} = \mathbf{X}\mathbf{X}^{T}$
    --> Artificial increase of ensemble members by regarding a spatially-shifted result as a different realization of ensemble run.

4D-Var-BenkfN

JNoVA (4D-Var; Operational)

- "JMA-nonhydrostatic model" based 4DVAR (Honda 2005)
- Forecast model coordinate dx=5km, 50 layers
- Adjoint model coordinate dx=15km, 40 layers
- Large-scale condensation
- Assimilation window = 3-h
- L-BFGS (Liu and Nocadel, 1999)
- Background error cov. $\mathbf{B}_{nmc}$ Statistics based on differences b/w 12h forecast and 6 h forecast (Jan 2005-Dec 2005).



NHM-LETKF (LETKF)

- "JMA-nonhydrostatic model" based LETKF (Kunii 2014)
- Analysis system dx = 15km, 50 layers
- KF scheme
- 3-h DA update cycles
- Hor. Localization scale = 200km
- Adaptive inflation (Miyoshi 2011)
- 51 members

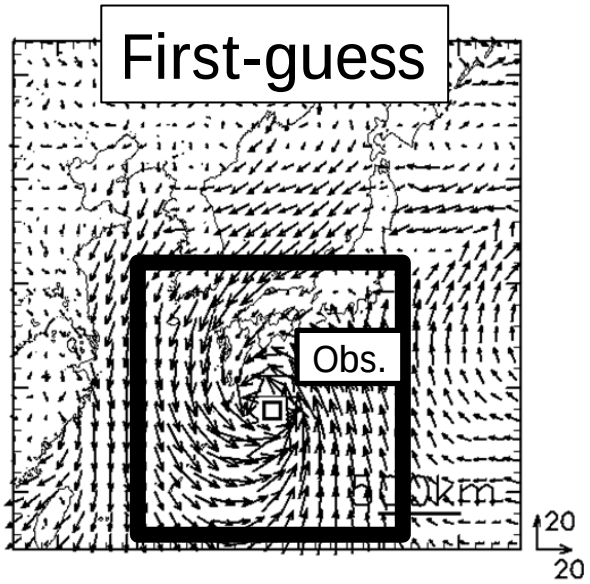
$\mathbf{B}_{enkfN}$

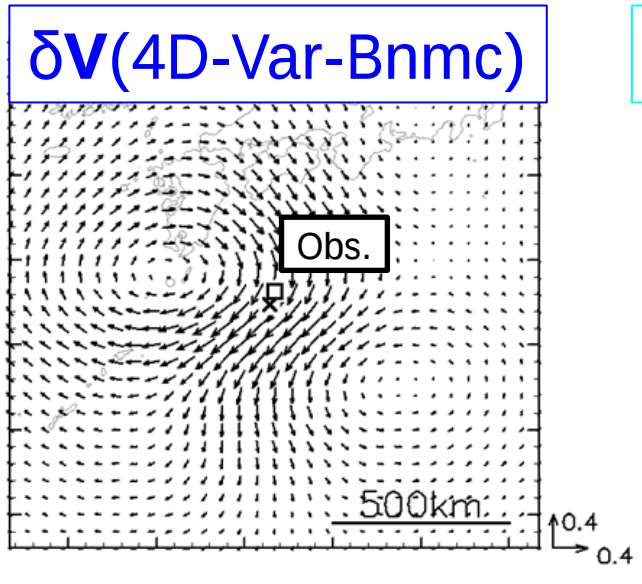
$\mathbf{B}_{enkfL}$

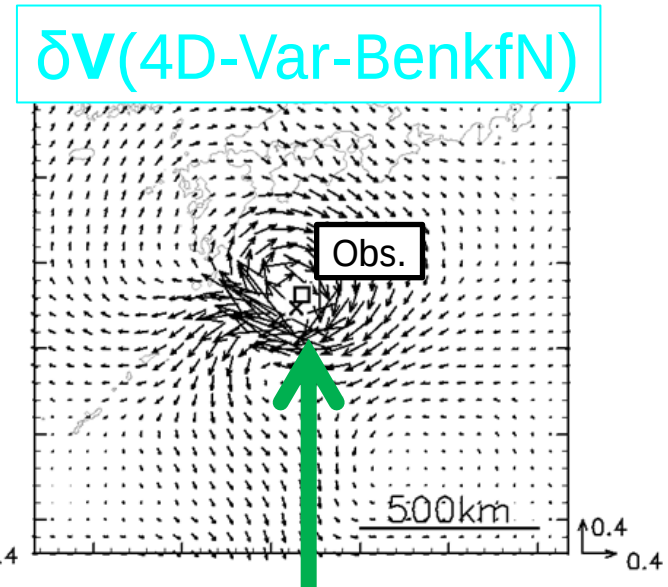
Localization as in LETKF

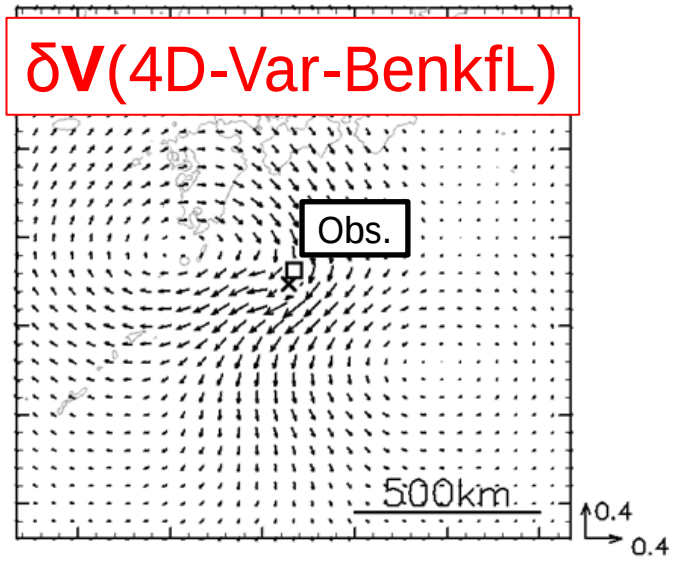
3 x 3 Neighboring, N = 459 member

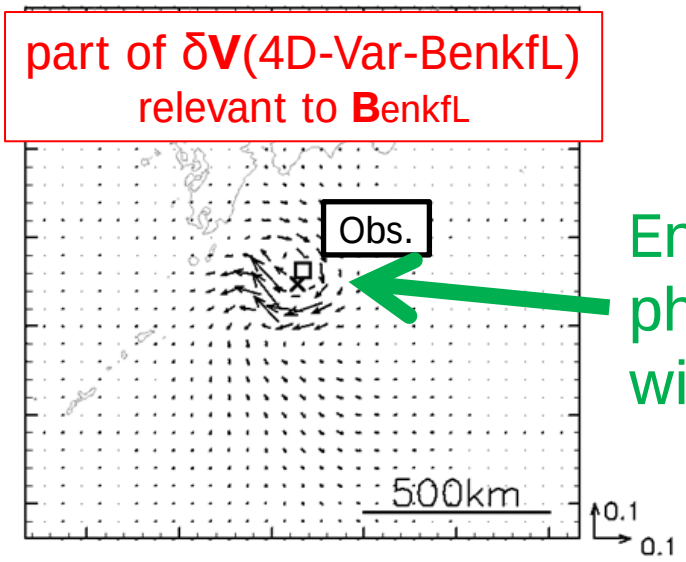
Single Obs. DA: Innovation of +MSLP obs at t=3 --> Increment of V=(u,v) at t=0







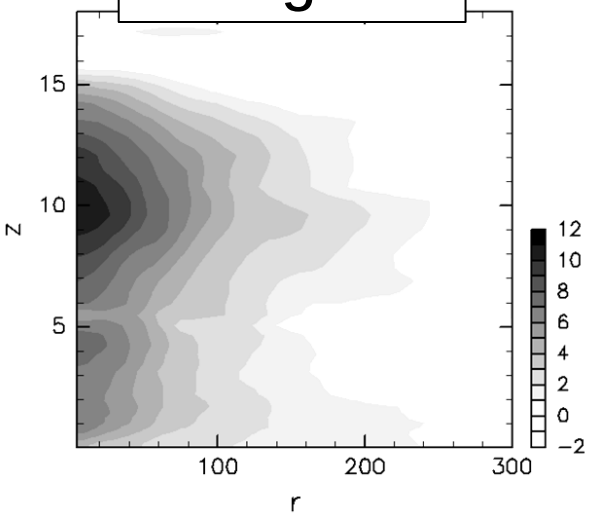




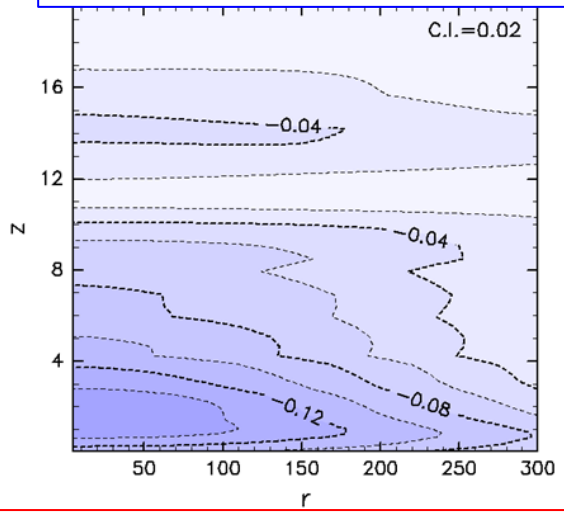
EnKF-based **B** yields physically reasonable wind increment

Single Obs. DA: Innovation of +MSLP obs at t=3 --> Increment of θ at t=0

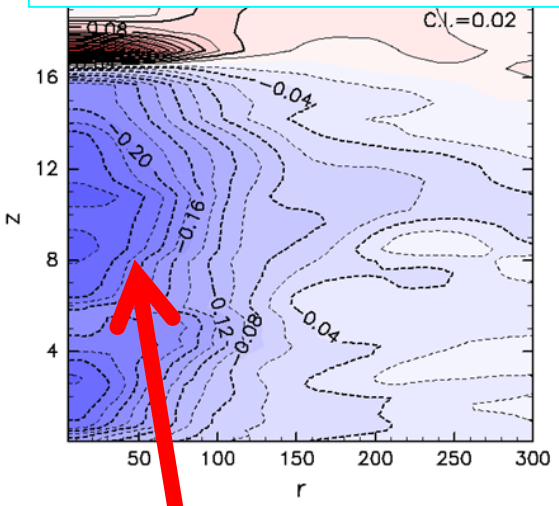
First-guess



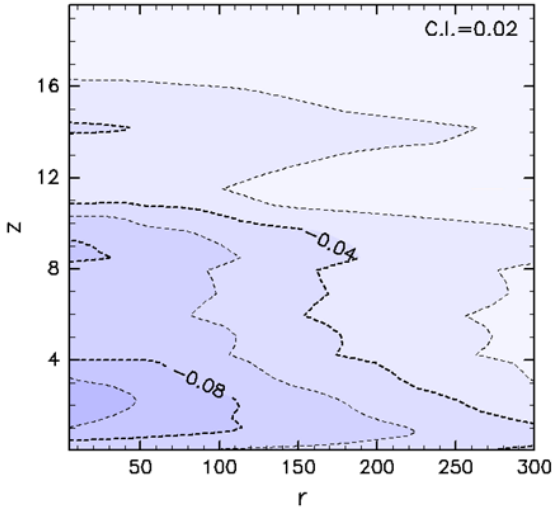
δθ(4D-Var-Bnmc)



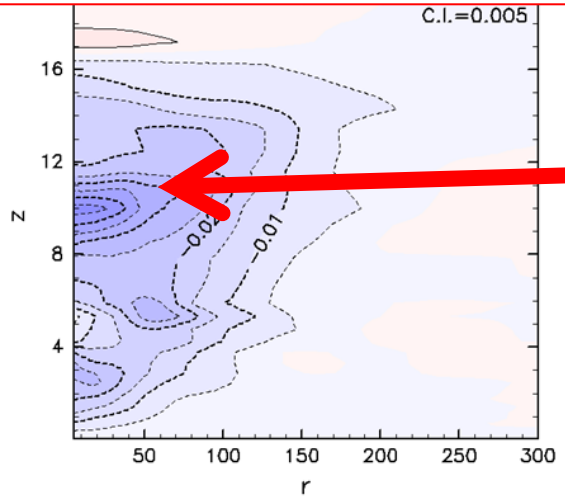
δθ(4D-Var-BenkfN)



δθ(4D-Var-BenkfL)



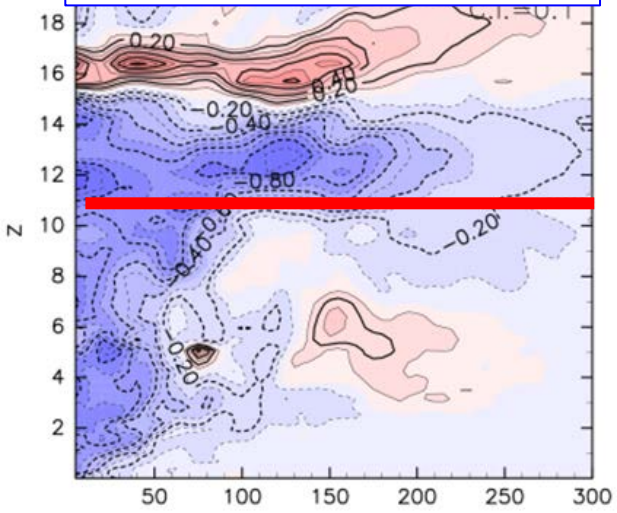
Part of δθ (4D-Var-BenkfL)
relevant to **B**enkfL



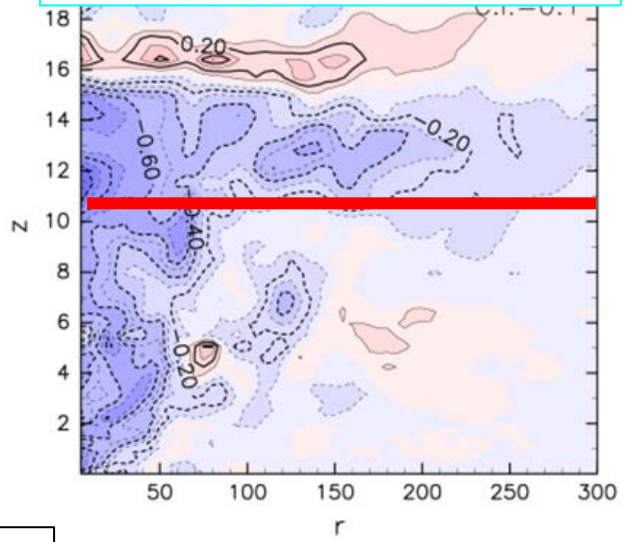
EnKF-based **B** weakens warm core of the TC.

Single Obs. DA: Innovation of +MSLP obs at t=3 --> Increment of θ at t=3

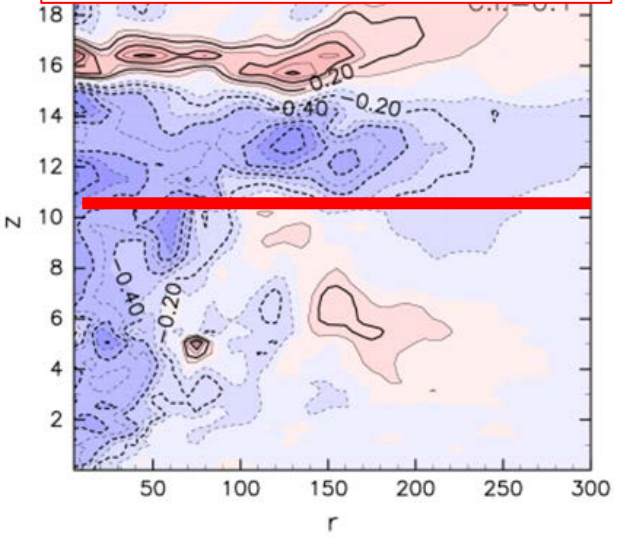
δθ(4D-Var-Bnmc)



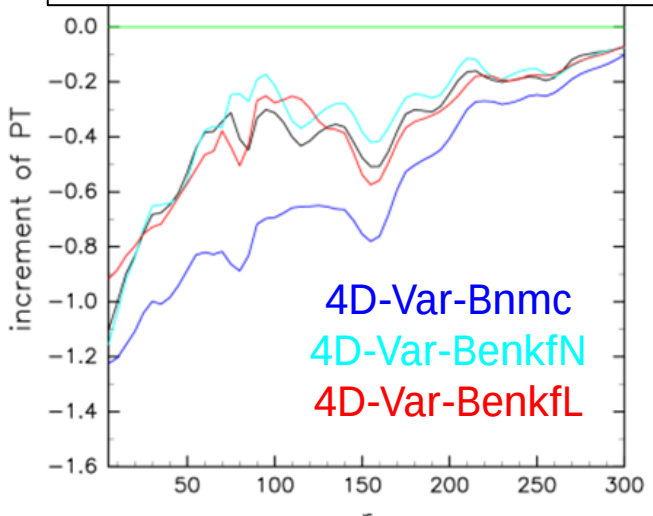
δθ(4D-Var-BenkfN)



δθ(4D-Var-BenkfL)

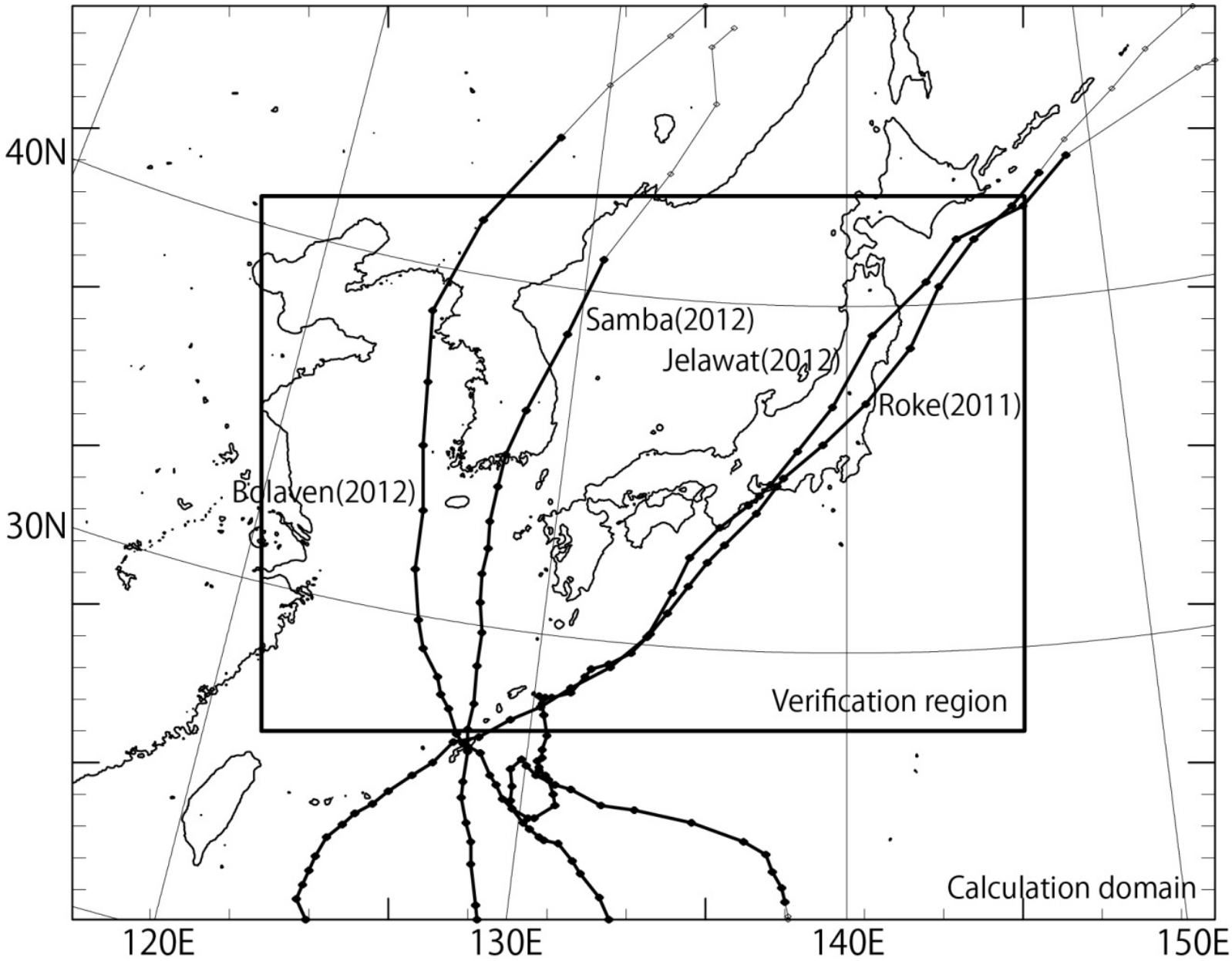


values at z_h=10.5km



- Increments become similar to each other.
  (4D-Var-Bnmc, 4D-Var-BenkfN, 4D-Var-BenkfL)
- Nevertheless, 4D-Var-Bnmc tends to capture horizontally large scale.

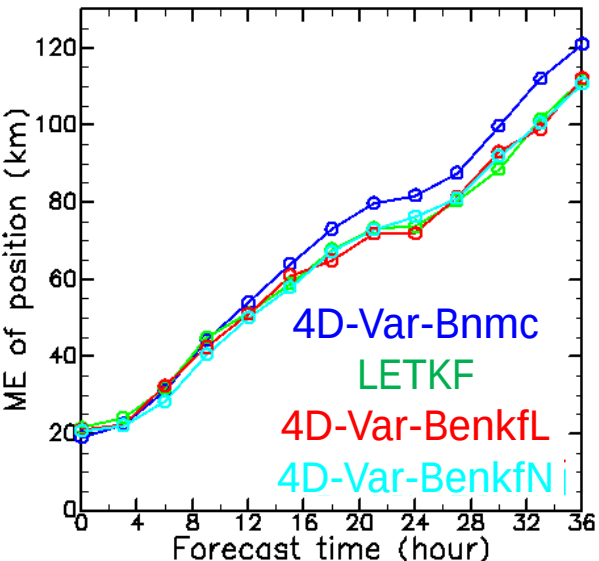
Real DA and forecasts: 4 intense TCs



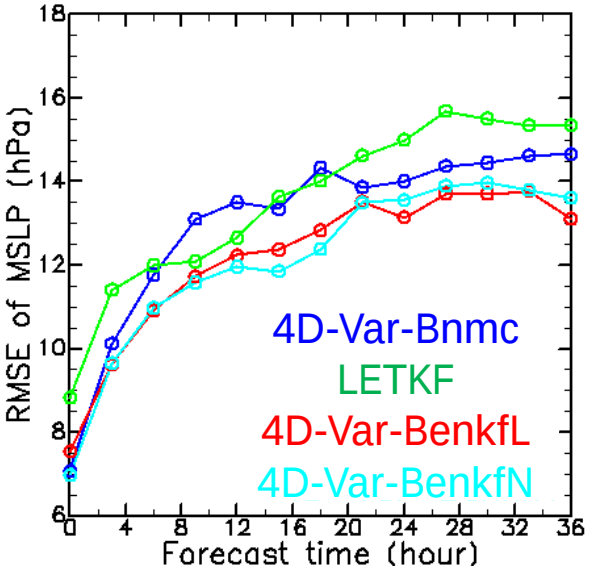
Forecast skill (based on 62 forecasts)

- Track forecast skill:
  LETKF, 4D-Var-BenkfL, 4D-Var-BenkfN > 4D-Var-Bnmc
- Intensity forecast skill:
  4D-Var-BenkfL, 4D-Var-BenkfN > 4D-Var-Bnmc
- In general, these results are statistically significant.
  (paired sample *t*-test considering the temporal persistency)

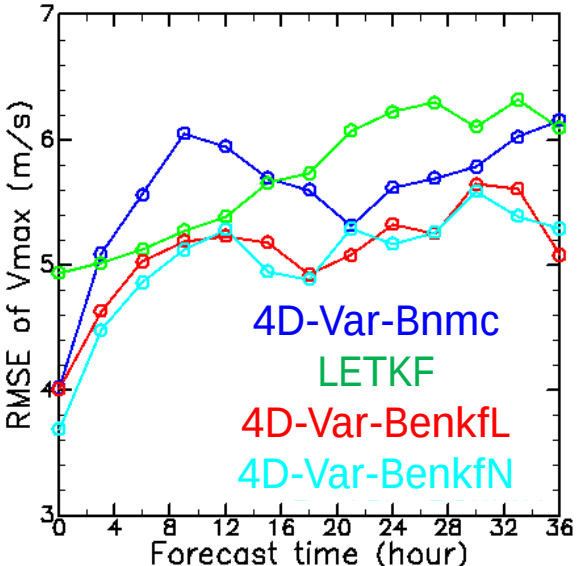
Track error



MSLP error



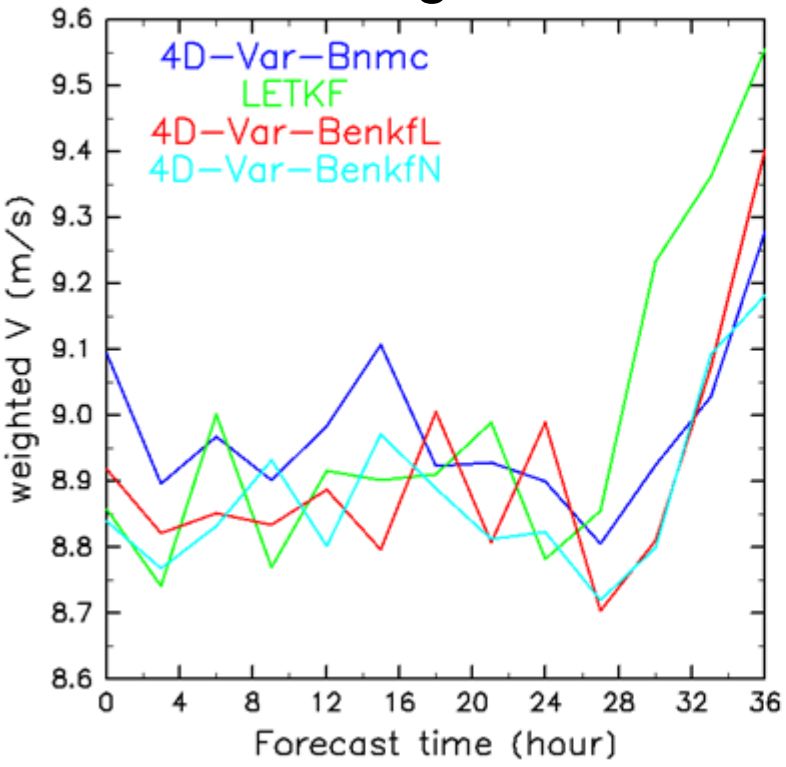
Vmax error



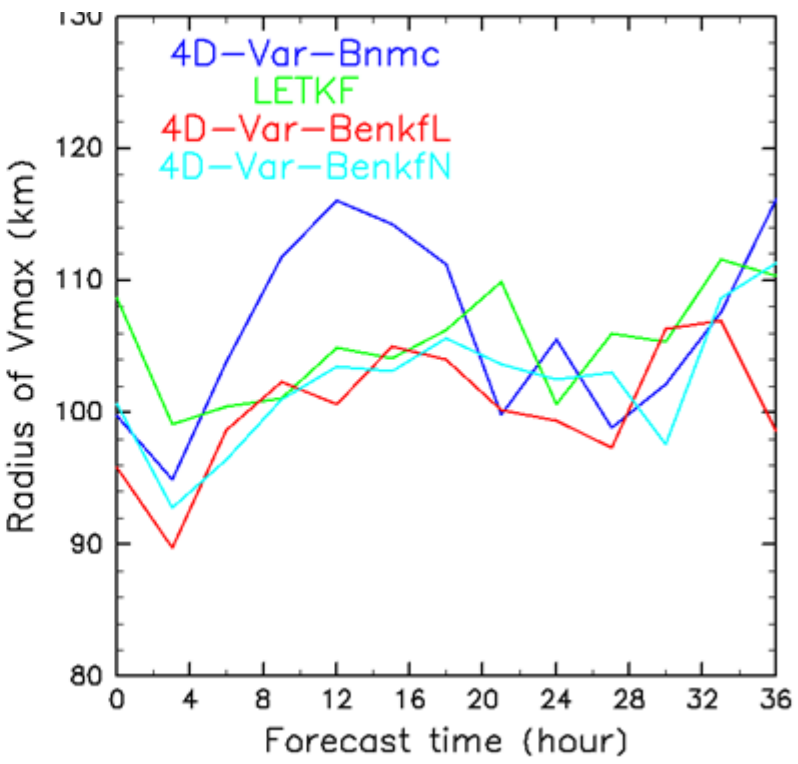
Composite analysis

- Steering flow is similar among LETKF, 4D-Var-BenkfL, 4D-Var-BenkfN, which is consistent with track error.
- Radius of maximum wind tends to increase in 4D-Var-Bnmc causing the negative bias of intensity.

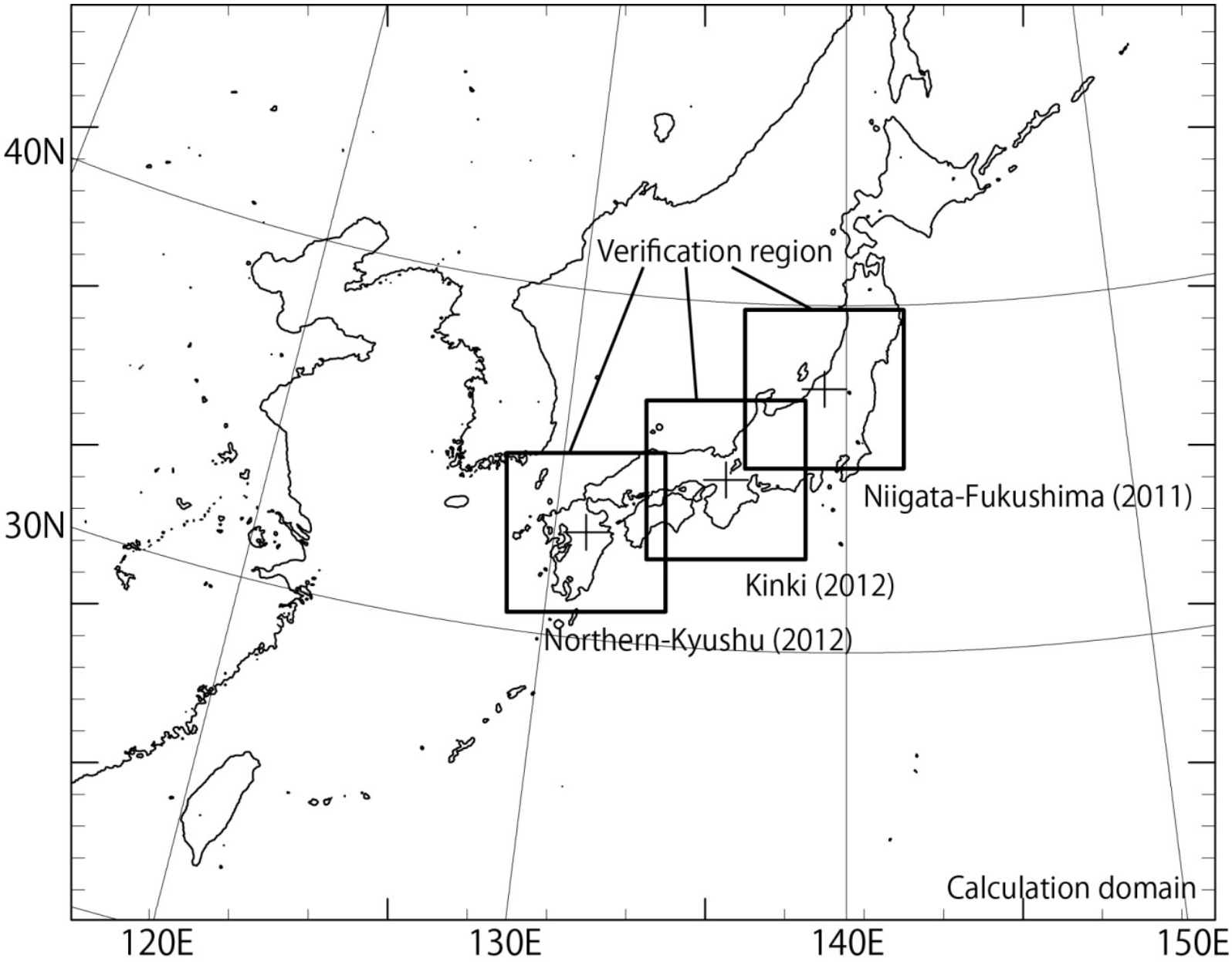
Steering flow



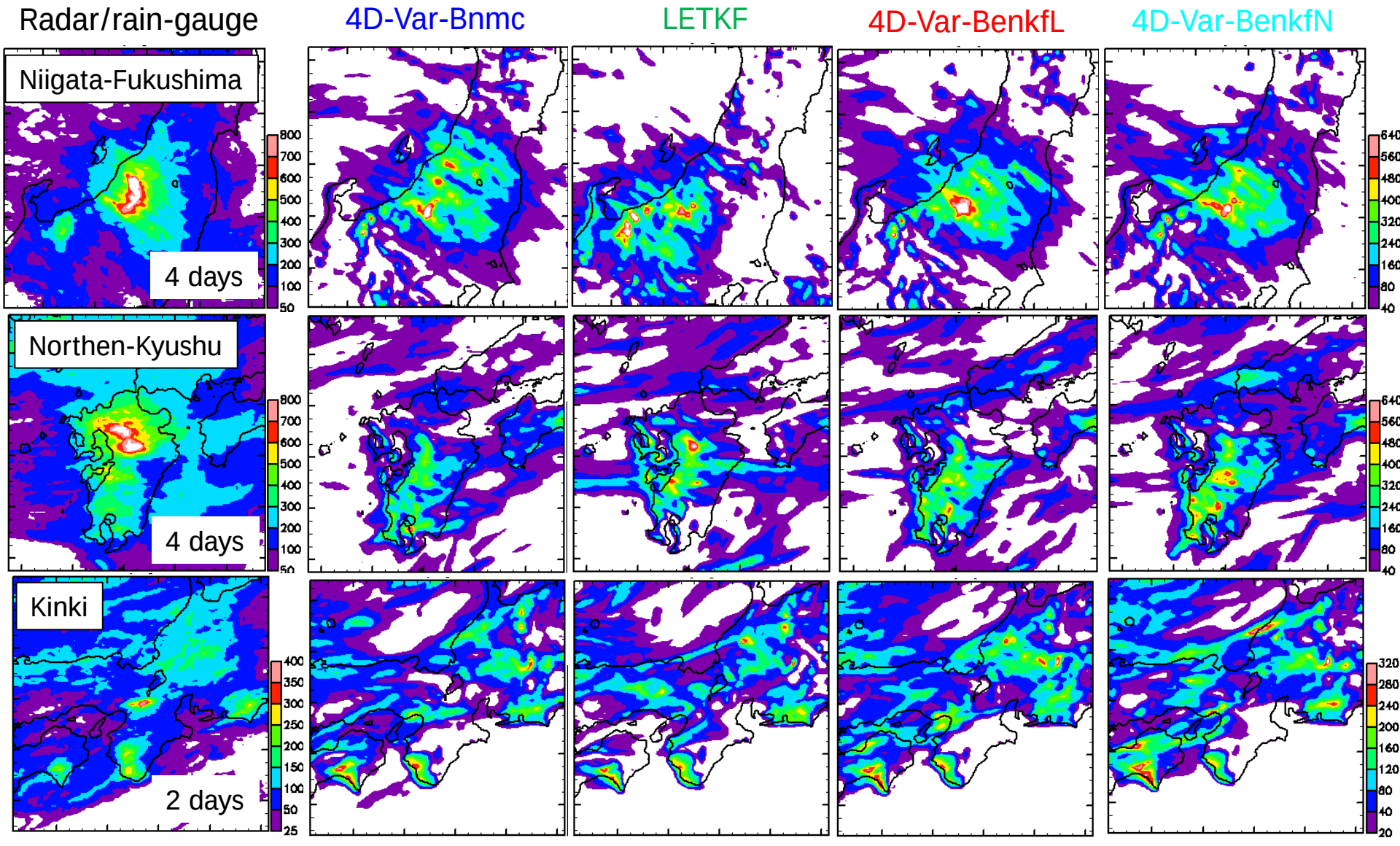
Radius of maximum wind



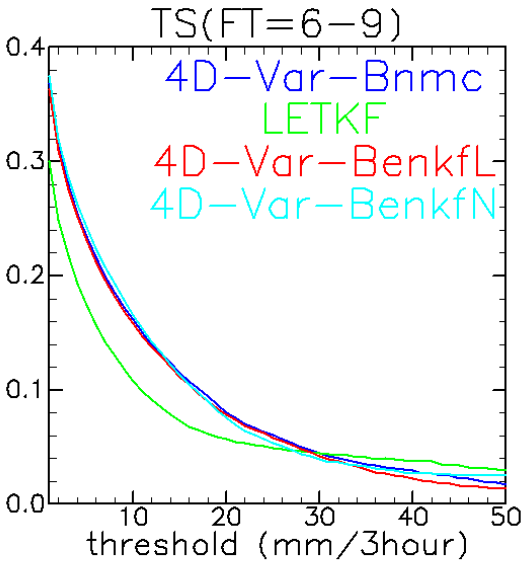
Real DA and forecasts: 3 heavy rainfall cases

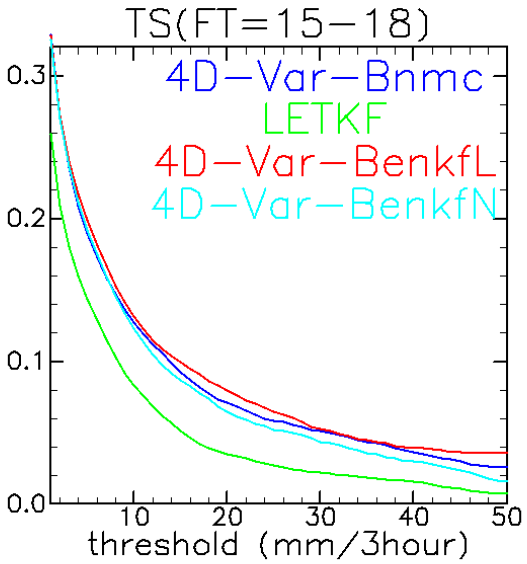


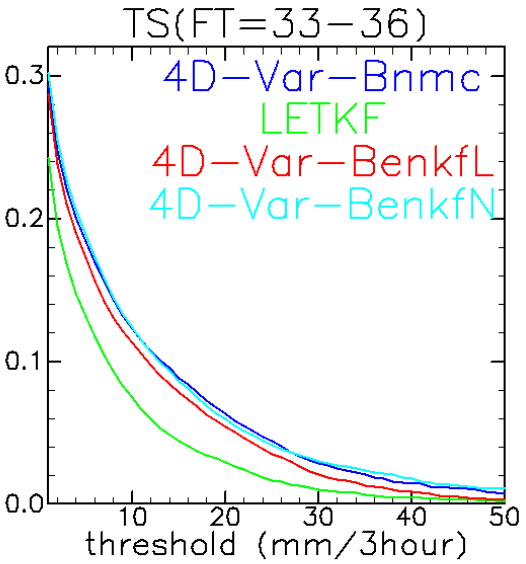
Total rainfall amount in radar/rain-gauge analysis and corresponding forecasts (FT=21-24)

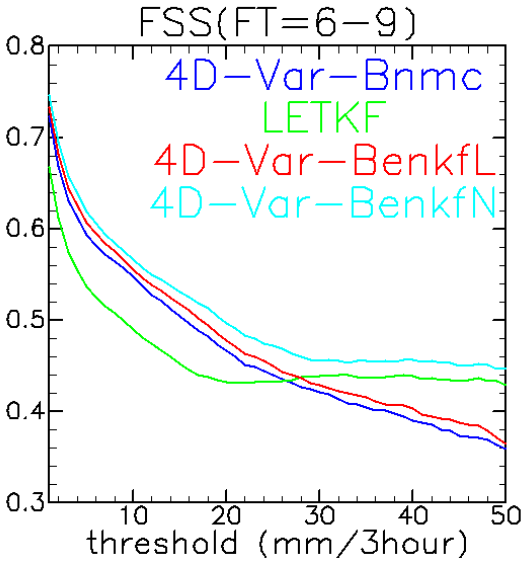


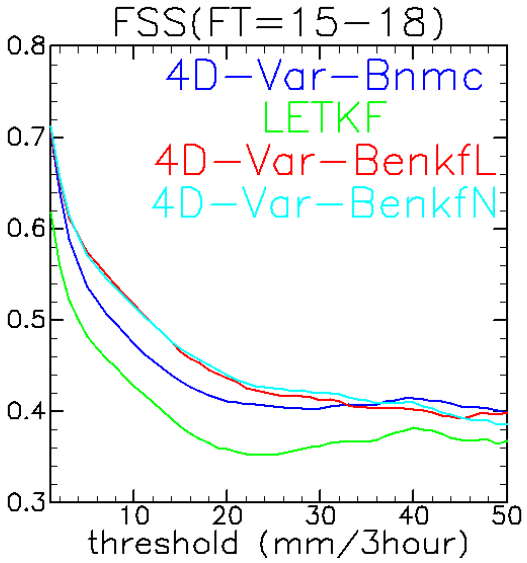
Statistics based on 104 forecasts: Threat score (TS) and fractions skill score (160x160 km^2; FSS)

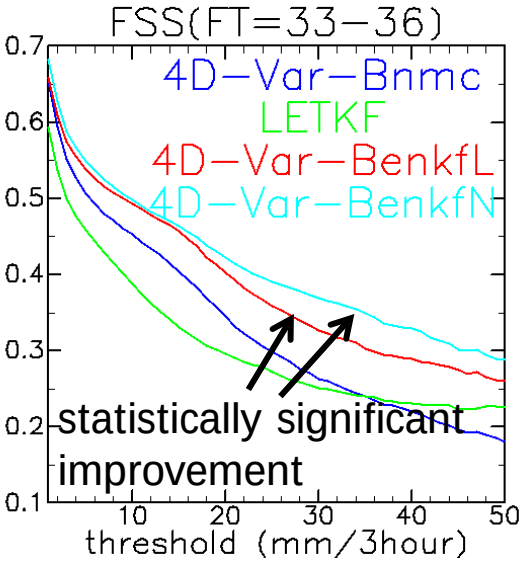












Summary (Ito et al., in revision)

Hybrid systems are better than 4D-Var-Bnmc in terms of predicting severe weather events.

- Two types of mesoscale hybrid EnKF-4D-Var DA system has been developed, in which the JMA-NHM is used as a physical model.
- One obs. DA: 4D-Var-Bnmc yields physically unreasonable increment at the beginning. The increment becomes closer to that in the other systems but still favor large-scale features at the end.
- TC forecasts
  - Track: LETKF, Hybrid systems > 4D-Var-Bnmc
  - Intensity: Hybrid systems > 4D-Var-Bnmc
- Local heavy rainfall is better predicted in the hybrid systems in terms of FSS (160 km x 160 km).