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Mesoscale Hybrid EnKF-4D-Var DA System based on JMA Nonhydrostatic Model

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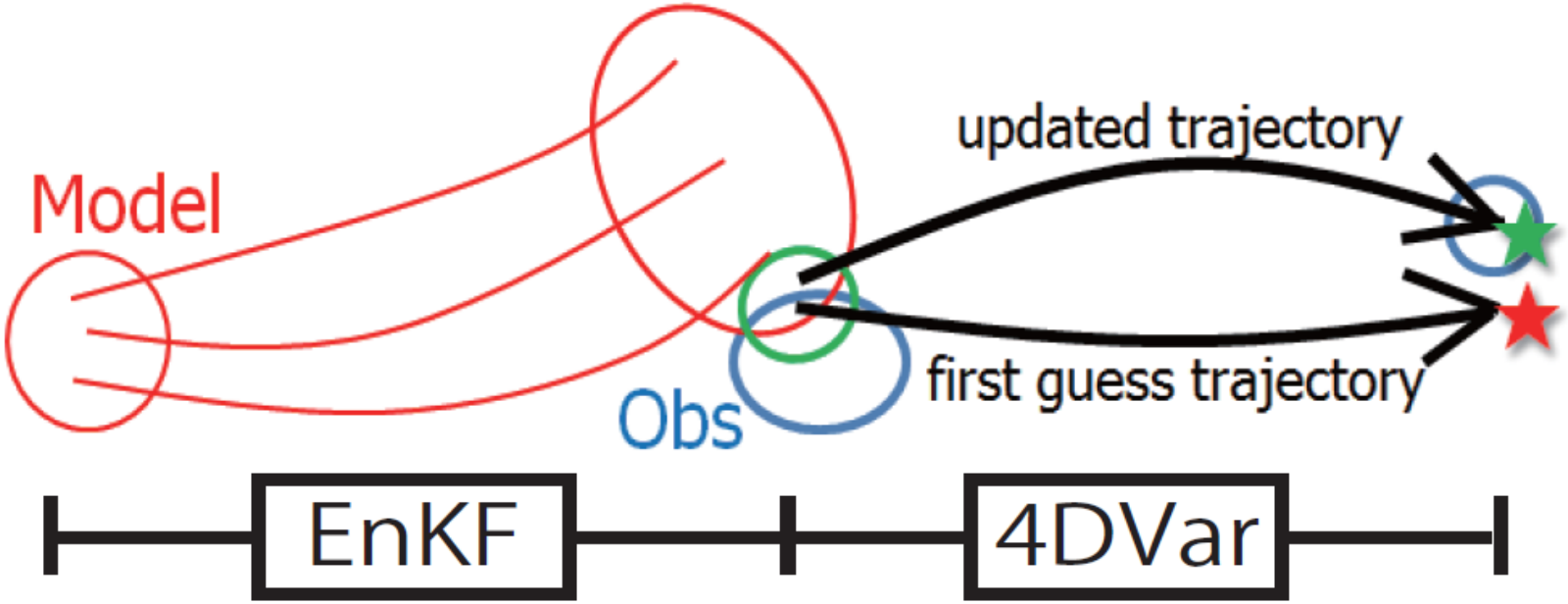
What is a hybrid EnKF-4D-Var system?

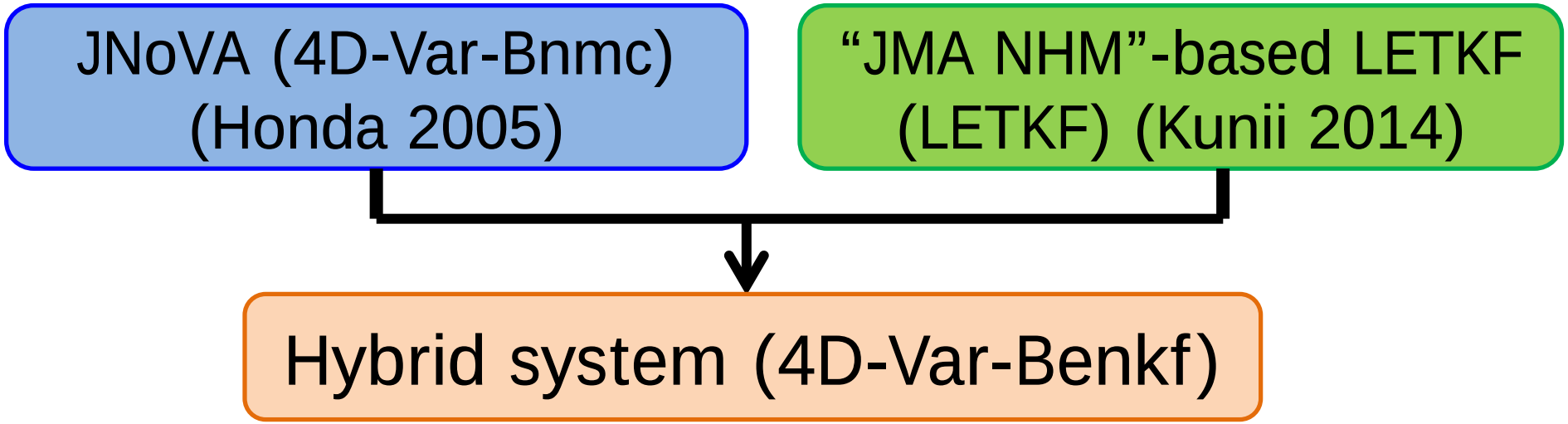
(Lorenc, 2003; Wang et al. 2007; Buehner et al. 2010a,b)

- The solution of 4D-Var depends on a model, obs, and **B**.
- A 4D-Var system requires a prescribed **B**
  - Traditional (NMC-method): Climatological error statistics
  - Hybrid: EnKF-based error statistics
- Errors around severe weather events should substantially deviate from climatology.



Motivation

- The number of studies on a mesoscale hybrid EnKF-4D-Var system is still limited (e.g., Poterjoy and Zhang 2014).
- Making sure the benefits with JMA operational mesoscale 4D-Var system (JNoVA) by applying a *t*-test.
  --> To do so, we conduct a large number of forecasts.
- Checking dependency on the choice of implementation:
  (1) Spatial localization, (2) Spectral localization
  (3) Neighboring ensemble apparoach.

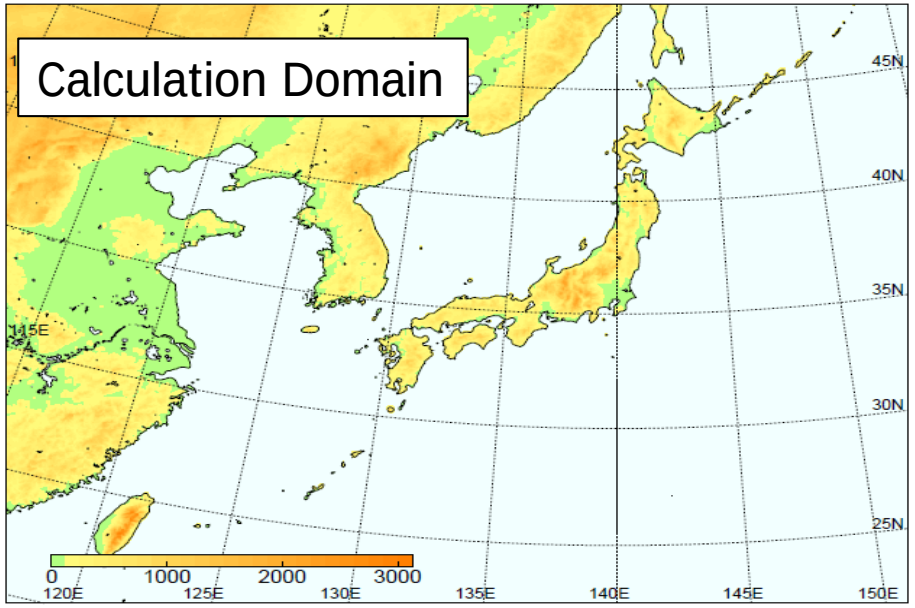


Specification of a hybrid system

- Numerical model --> JMA nonhydrostatic model (JMA-NHM)
- System --> adjoint-based 4D-Var + LETKF
- Interaction between 4D-Var and LETKF
  --> one-way (LETKF-based **B** --> 4D-Var)
- Mixture of $\mathbf{B}_{nmc}$ and $\mathbf{B}_{enkf}$ --> $\mathbf{B}_{hybrid} = 0.2\mathbf{B}_{nmc} + 0.8\mathbf{B}_{enkf}$
- Several types of implementation were tested.
  - 4D-Var-BenkfL: Spatial Localization (Wang et al. 2007)
    No error correlation between separated grid points
  - 4D-Var-BenkfS: Spectral Localization (Buehner & Charron 2007)
    No error correlation between separated wave numbers
  - 4D-Var-BenkfN: Neighboring ensemble (Aonashi et al. 2013)
    B_{enkfS} with a coarsely defined analysis grid points
  - (For reference) 4D-Var-Benkf0: using “raw” perturbations
  - Control vector length (Substantial high cost in $\mathbf{B}_{enkfL}$)
    $\mathbf{B}_{enkfL}$ $O(4 \times 10^8)$ >> $\mathbf{B}_{enkfS}$ 3000 > $\mathbf{B}_{enkfN}$ 450 > $\mathbf{B}_{enkf0}$ 50

JNoVA (4D-Var; Operational)

- "JMA-nonhydrostatic model" based 4DVAR (Honda 2005)
- Forecast model coordinate dx=5 km, 50 layers
- Adjoint model coordinate dx=15 km, 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 12 h forecast and 6 h forecast (Jan 2005-Dec 2005).



NHM-LETKF (LETKF)

- "JMA-nonhydrostatic model" based LETKF (Kunii 2014)
- Analysis system dx = 15 km, 50 layers
- KF scheme
- Ens. Mean: Geographically fixed
- 3 h DA update cycles
- Horizontal & vertical Localization
- Adaptive inflation (Miyoshi 2011)
- 50 members

$\mathbf{B}_{enkfN}$ $\mathbf{B}_{enkfS}$ $\mathbf{B}_{enkfL}$

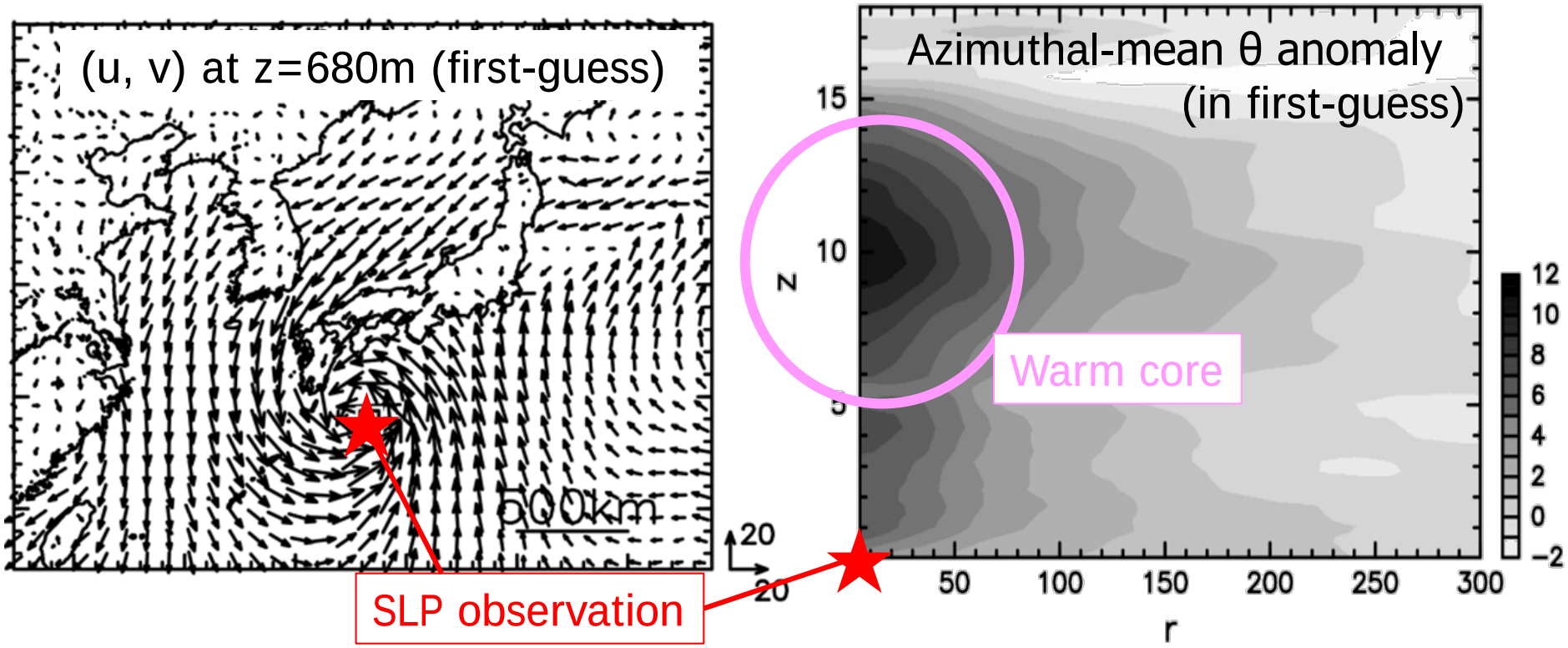
Spatial Localization

Spectral Localization

Neighboring ensemble approach

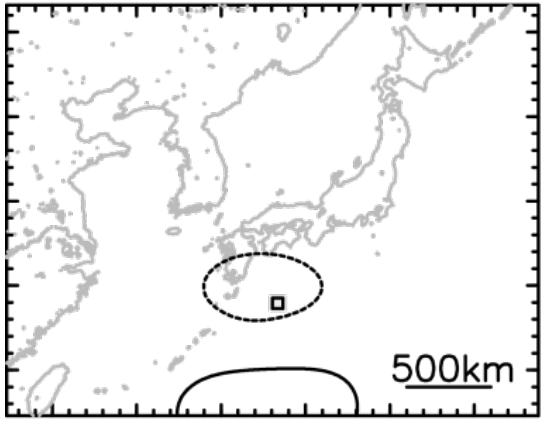
Single observation test: Reference field

- Observation
  - ➢Type: SLP at the center of TC Roke (2011)
  - ➢Magnitude: δSLP=+5 hPa (weakening TC intensity)
  - ➢Time: End of the assimilation window (t = 3 h)

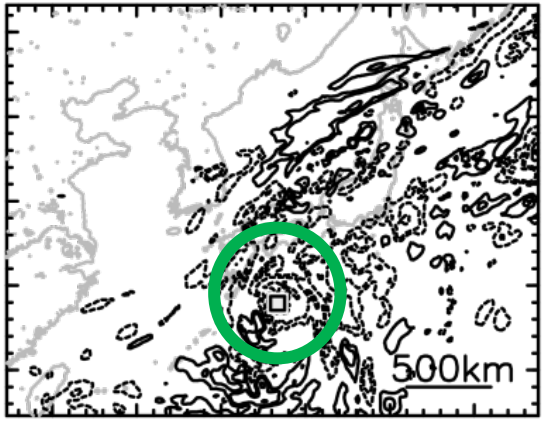


θ increment at z=10km and t=0h

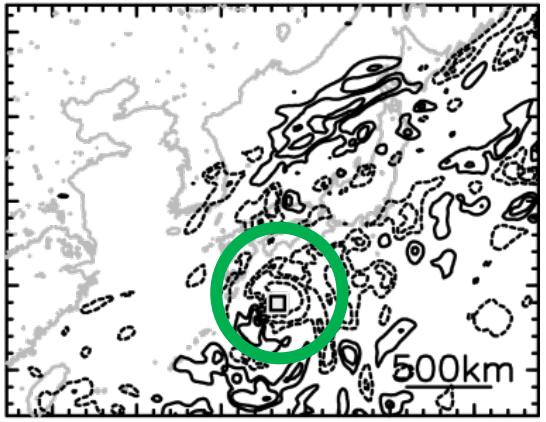
δθ(4D-Var-Bnmc)



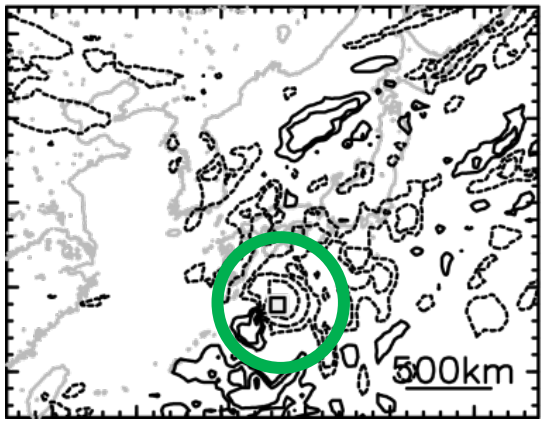
δθ(4D-Var-Benkf0)



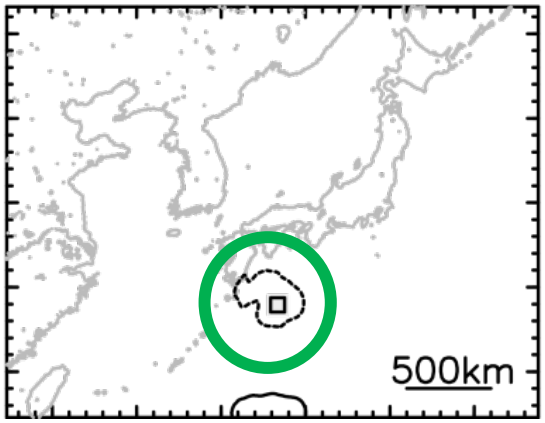
δθ(4D-Var-BenkfS)



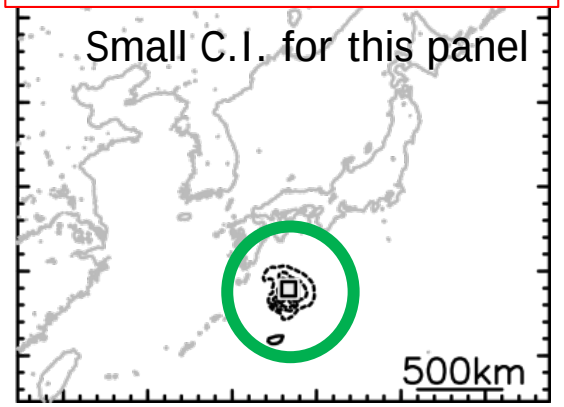
δθ(4D-Var-BenkfN)



δθ(4D-Var-BenkfL)



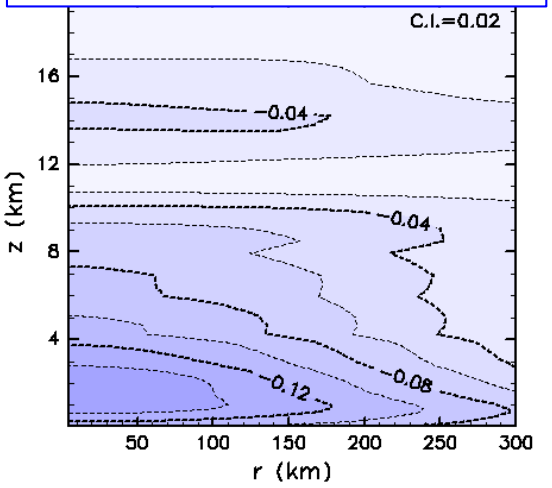
Ensemble-based part of δθ(4D-Var-BenkfL)



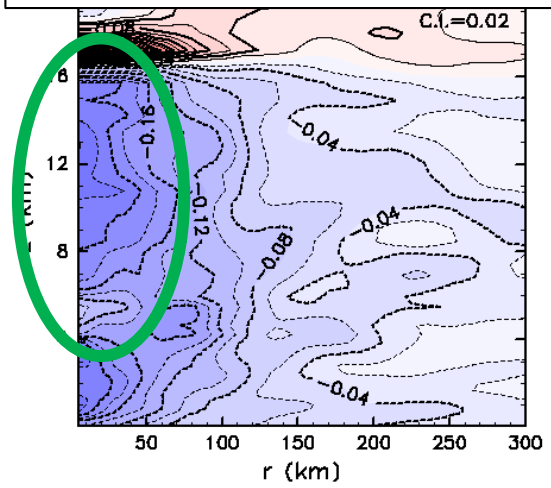
○ Crescent-shaped pattern near the TC center

Azimuthal-mean θ increment at t=0h

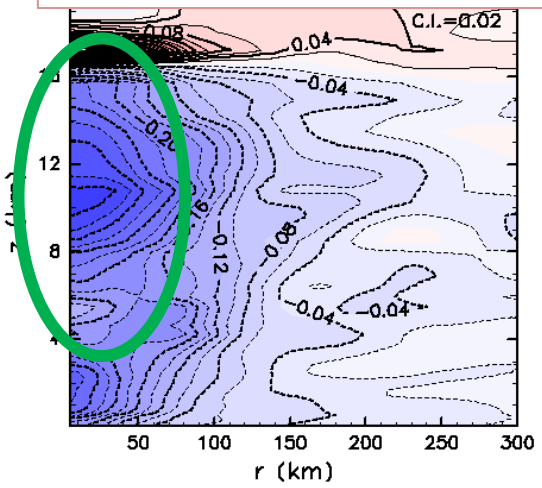
δθ(4D-Var-Bnmc)



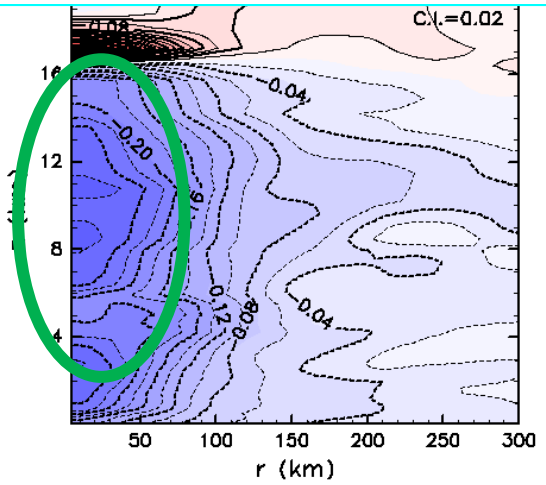
δθ(4D-Var-Benkf0)



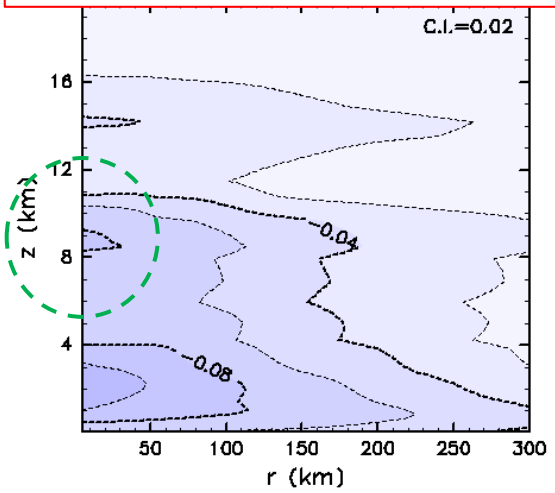
δθ(4D-Var-BenkfS)



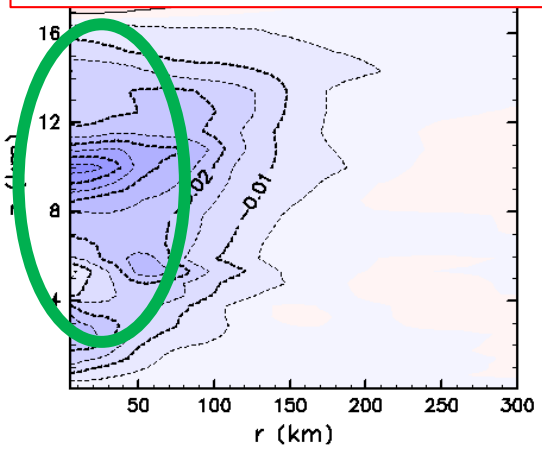
δθ(4D-Var-BenkfN)



δθ(4D-Var-BenkfL)

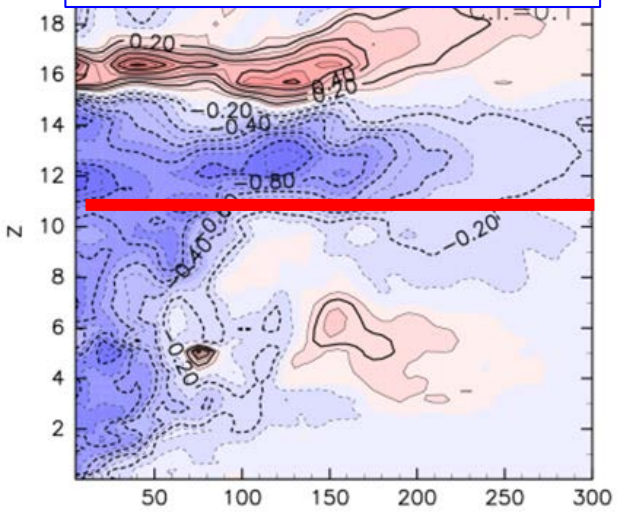


Ensemble-based part of δθ(4D-Var-BenkfL)

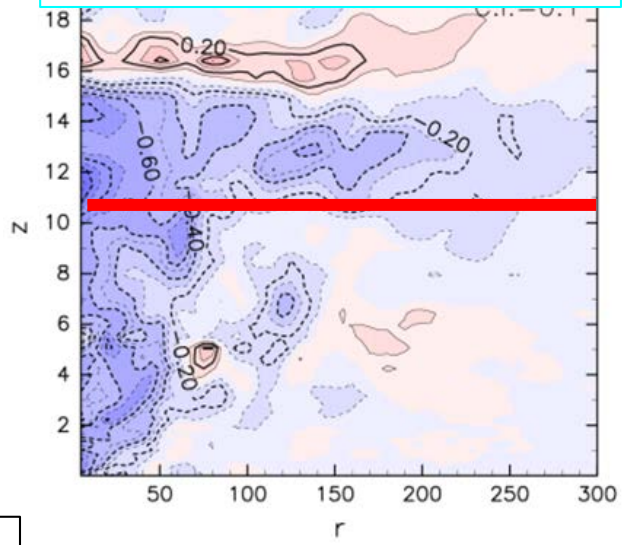


Azimuthal-mean θ increment at t=3h

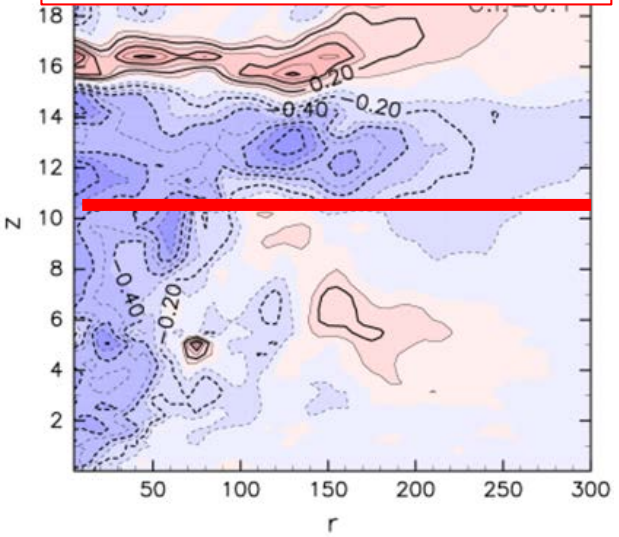
δθ(4D-Var-Bnmc)



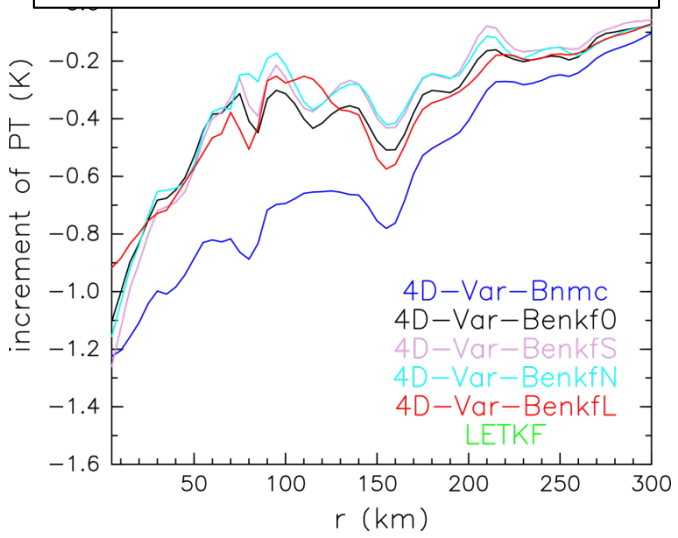
δθ(4D-Var-BenkfN)



δθ(4D-Var-BenkfL)



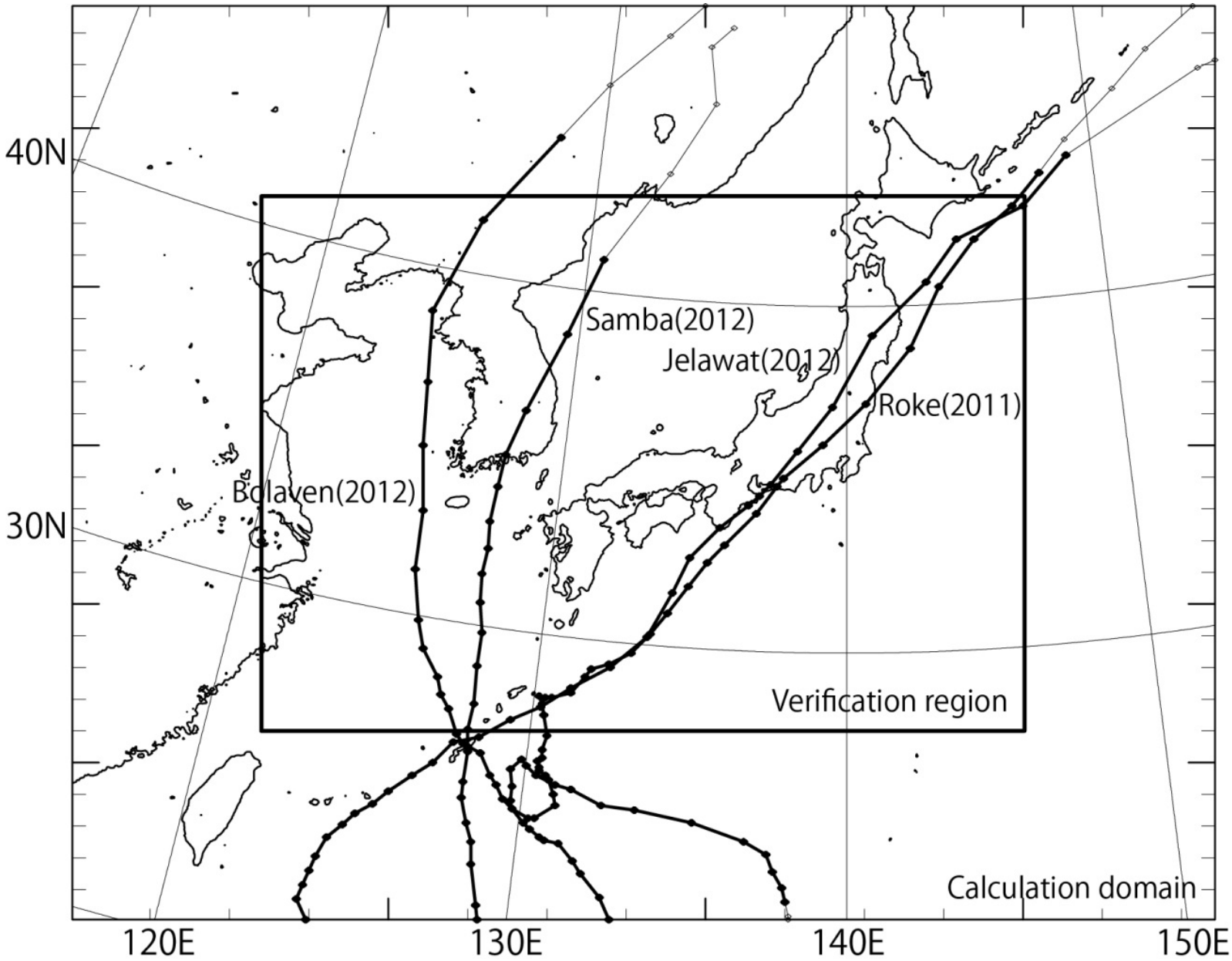
values at z_h=11.5km



Comparison b/w 4D-Var-Bnmc & hybrid

- Similarity:
  - ➢ Weakening a warm core
  - ➢ θ increase in stratosphere
- Difference
  - ➢ 4D-Var-Bnmc increment has a horizontally large structure.

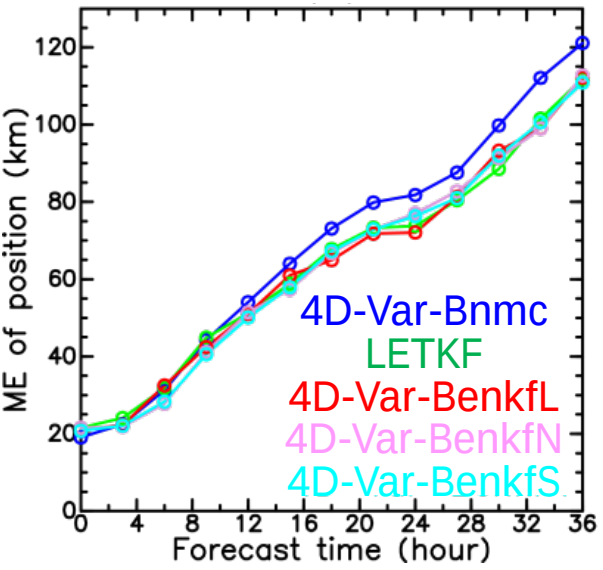
Real DA and forecasts: 4 intense TCs



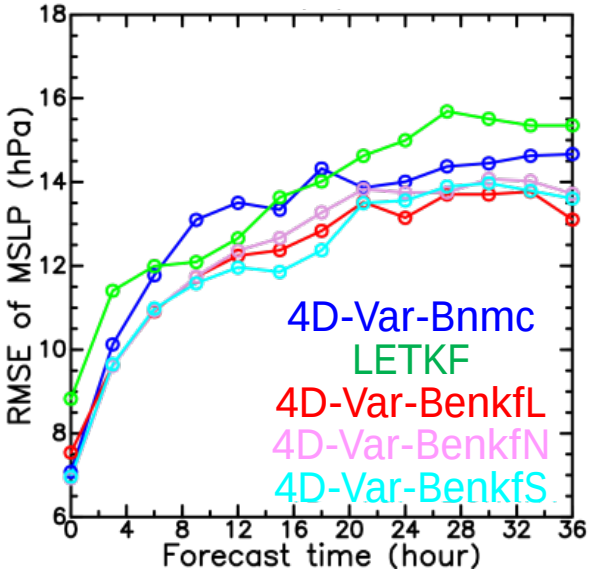
Forecast skill (based on 62 forecasts)

- Track forecast skill:
  Hybrid systems, LETKF > 4D-Var-Bnmc
- Intensity forecast skill:
  Hybrid systems > 4D-Var-Bnmc, LETKF
- Skill in hybrids was insensitive to the implementation.
- In general, these results are statistically significant.
  (a paired sample *t*-test considering the temporal persistency)

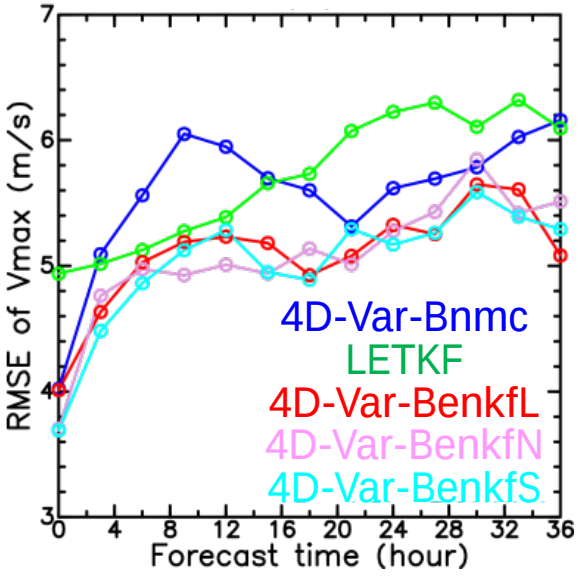
Track error



MSLP error



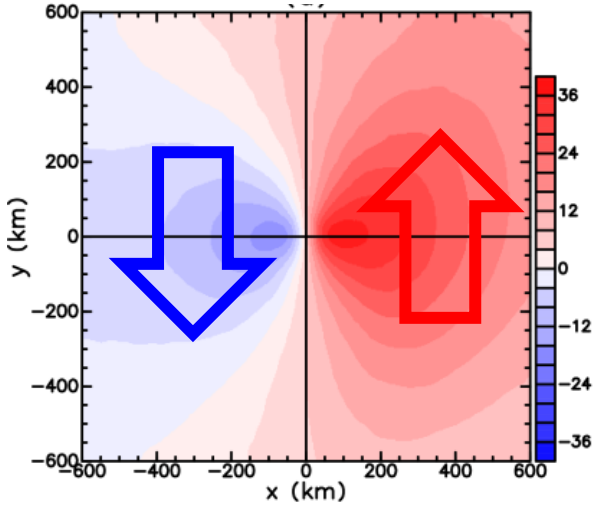
Vmax error



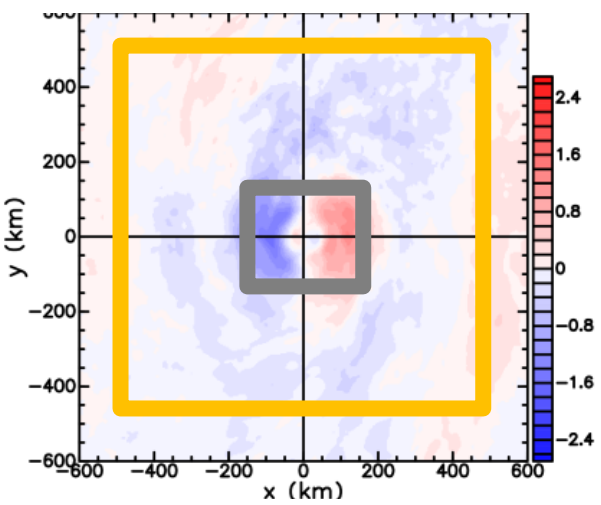
Composite of analysis meridional wind

- Wind averaged over the surrounding region is similar in hybrids and LETKF, while inner-core structure is substantially different.

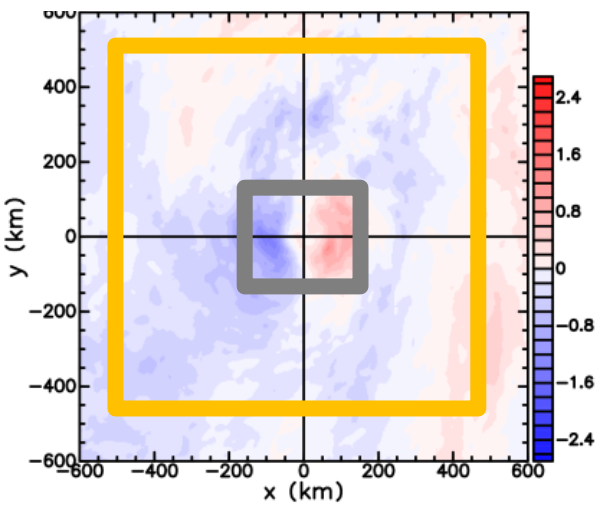
4D-Var-Bnmc



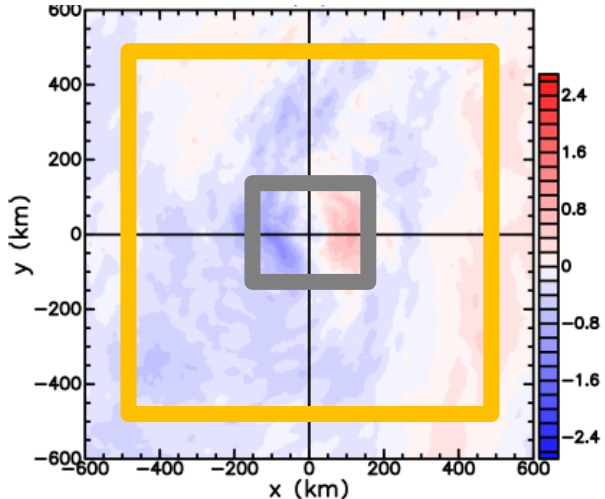
4D-Var-BenkfL — 4D-Var-Bnmc



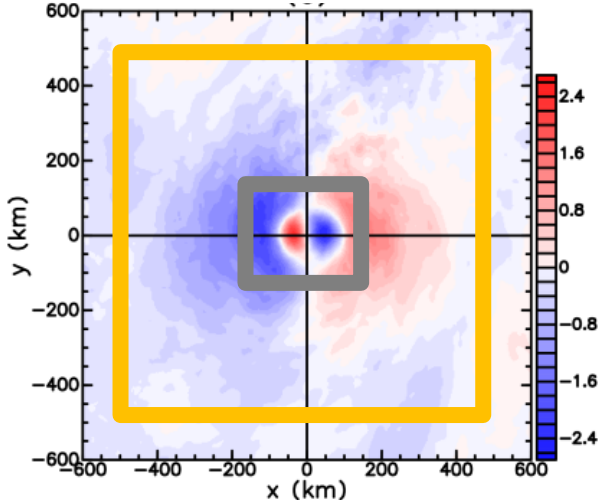
4D-Var-BenkfS — 4D-Var-Bnmc



4D-Var-BenkfN — 4D-Var-Bnmc



LETKF — 4D-Var-Bnmc



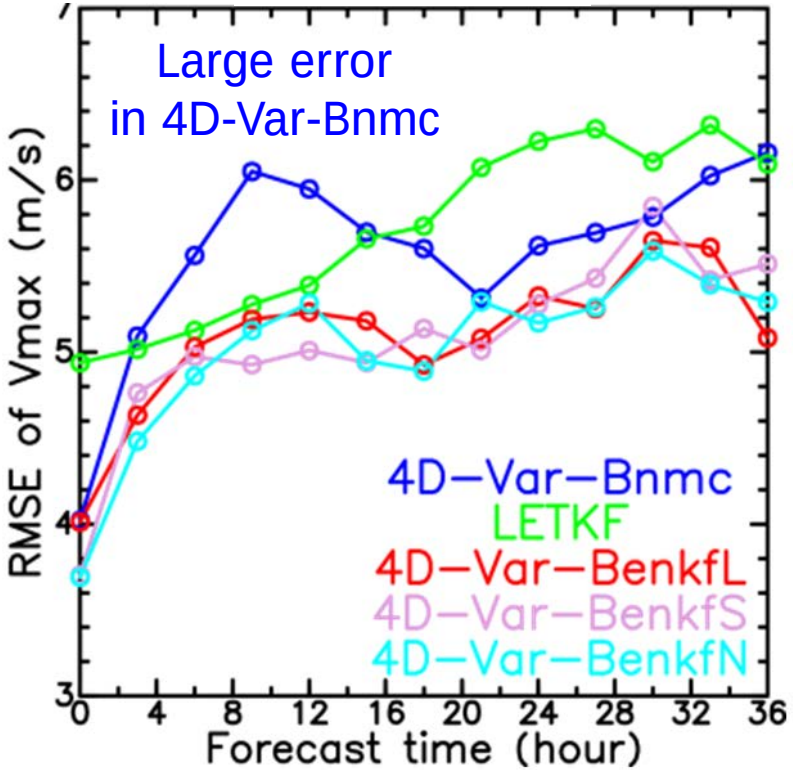
1000 km x 1000 km

300 km x 300 km

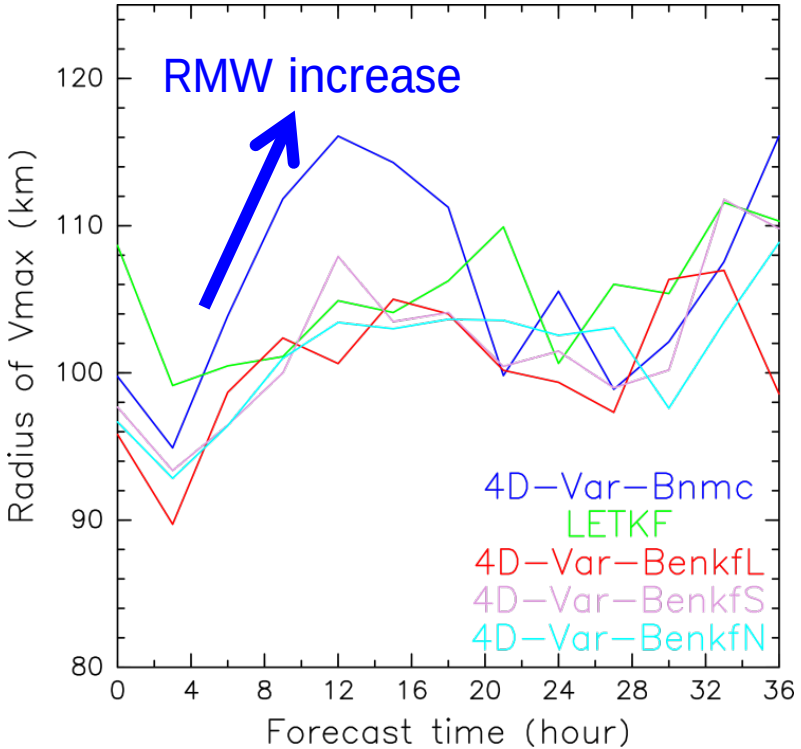
Composite of radius of maximum wind (RMW)

- Worst forecast skill in 4D-Var-Bnmc around FT = 9 h can be explained by the rapid increase of RMW.
  - ➢ Quasi-conservation of angular momentum --> Vmax bias
  - ➢ 4D-Var-Bnmc may distribute more energy to a large scale.
- In LETKF, initial RMW is large due to taking ens. mean.

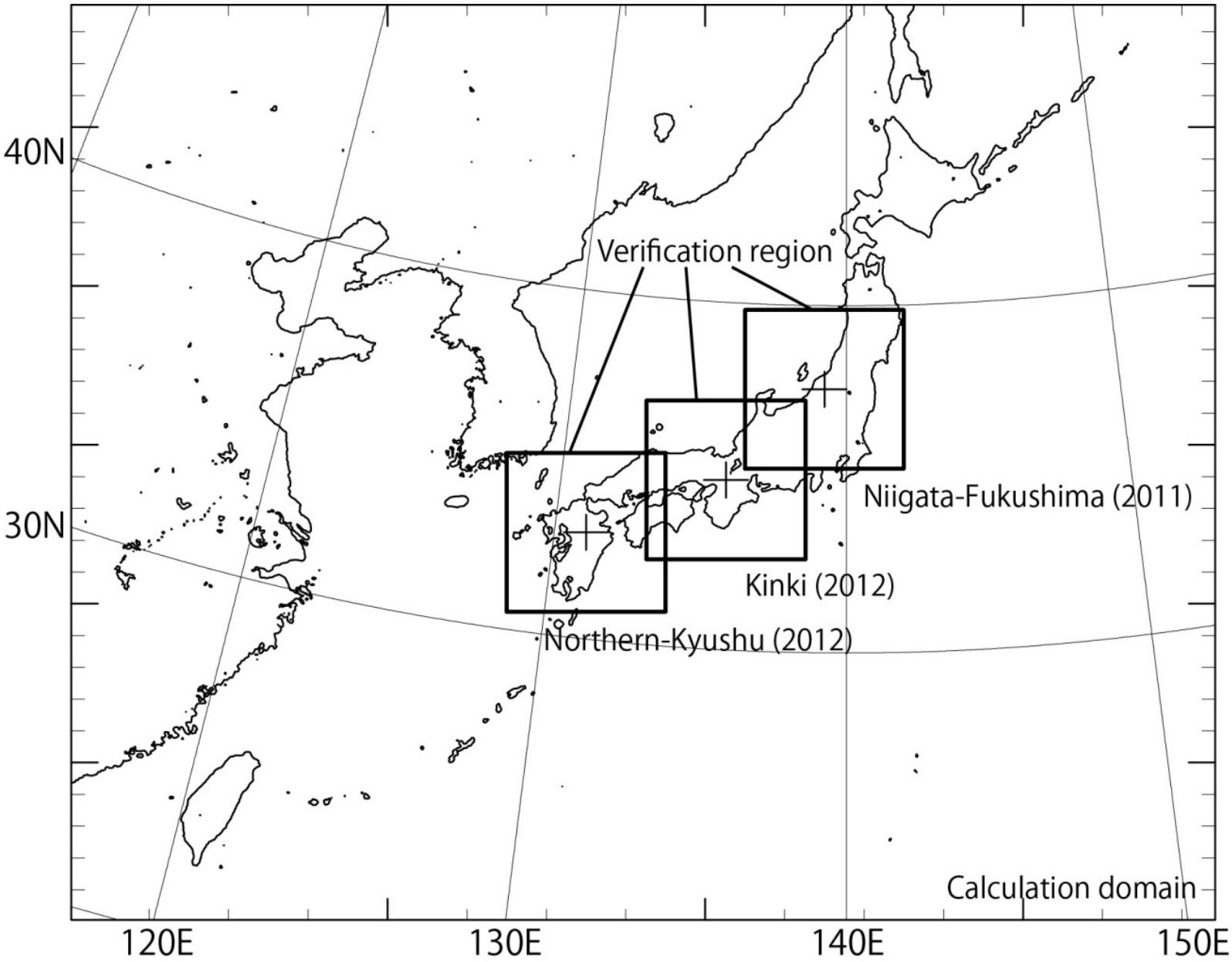
Vmax error



Radius of maximum wind

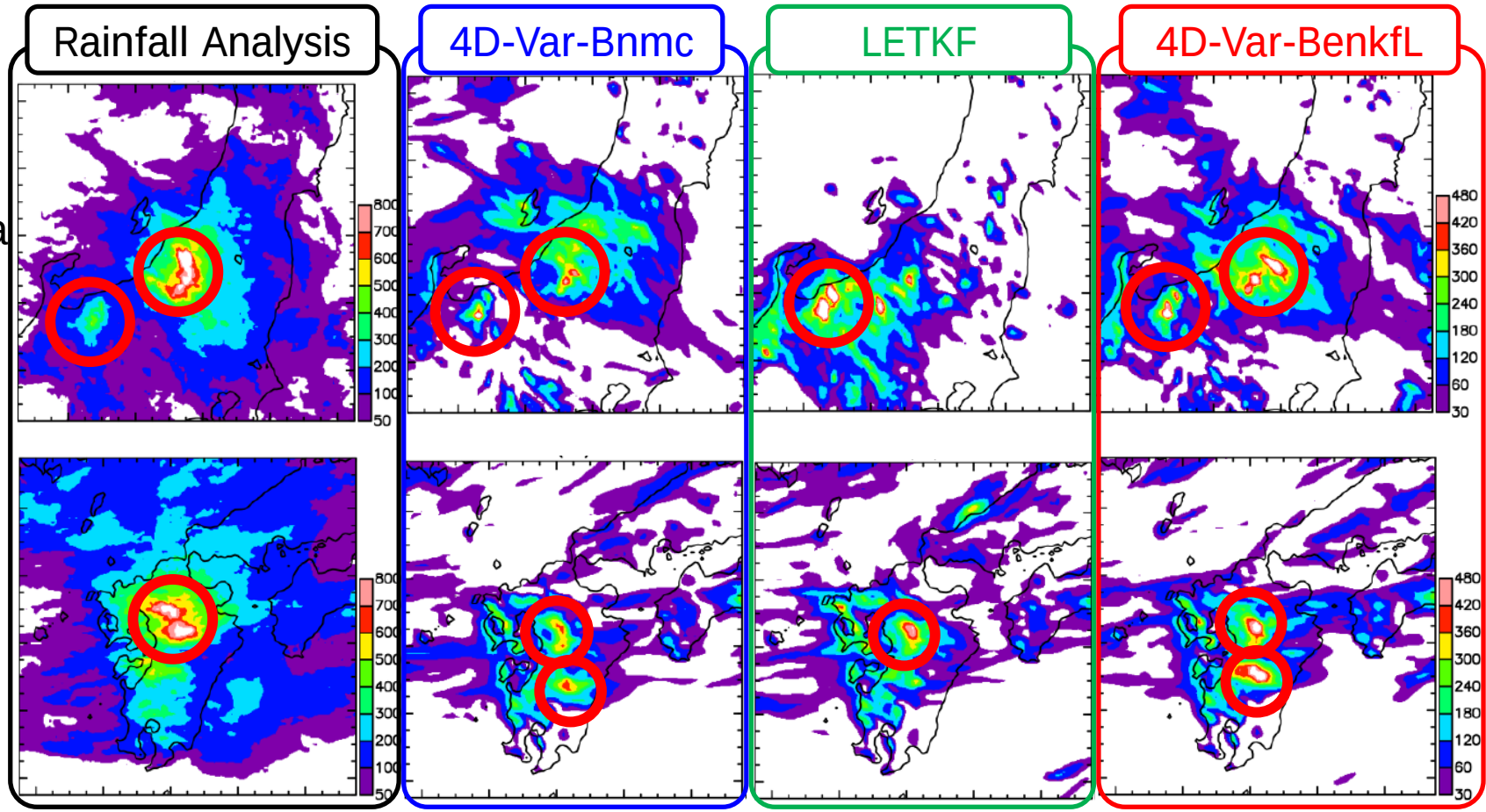


Real DA and forecasts: 3 heavy rainfall cases



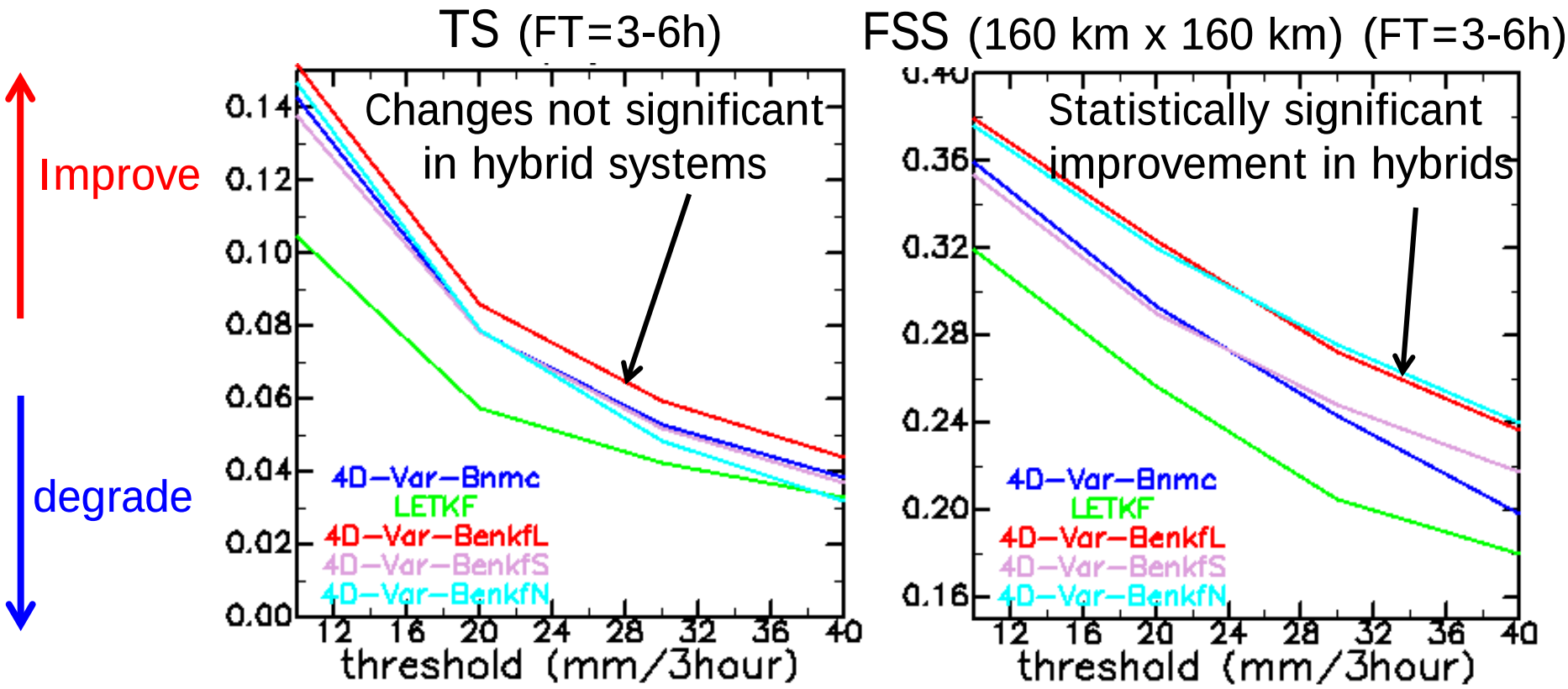
Total accumulated rainfall amount

- All DA systems yield the extraordinary amount of rainfall exceeding 100 mm day^{-1}.
- Better DA scheme depends on the choice of cases (Niigata-Fukushima: Hybrid systems, Northern-Kyushu: LETKF)



Overall statistics

- Cases: 104 forecasts for 3 severe rainfall events in Japan
- Threat score: No significant difference among DA methods
- Fraction skill score: Statistically significant improvements in hybrid systems compared to the others for FT=0-6 h & 30-36h
- More experiments are needed to confirm this finding.

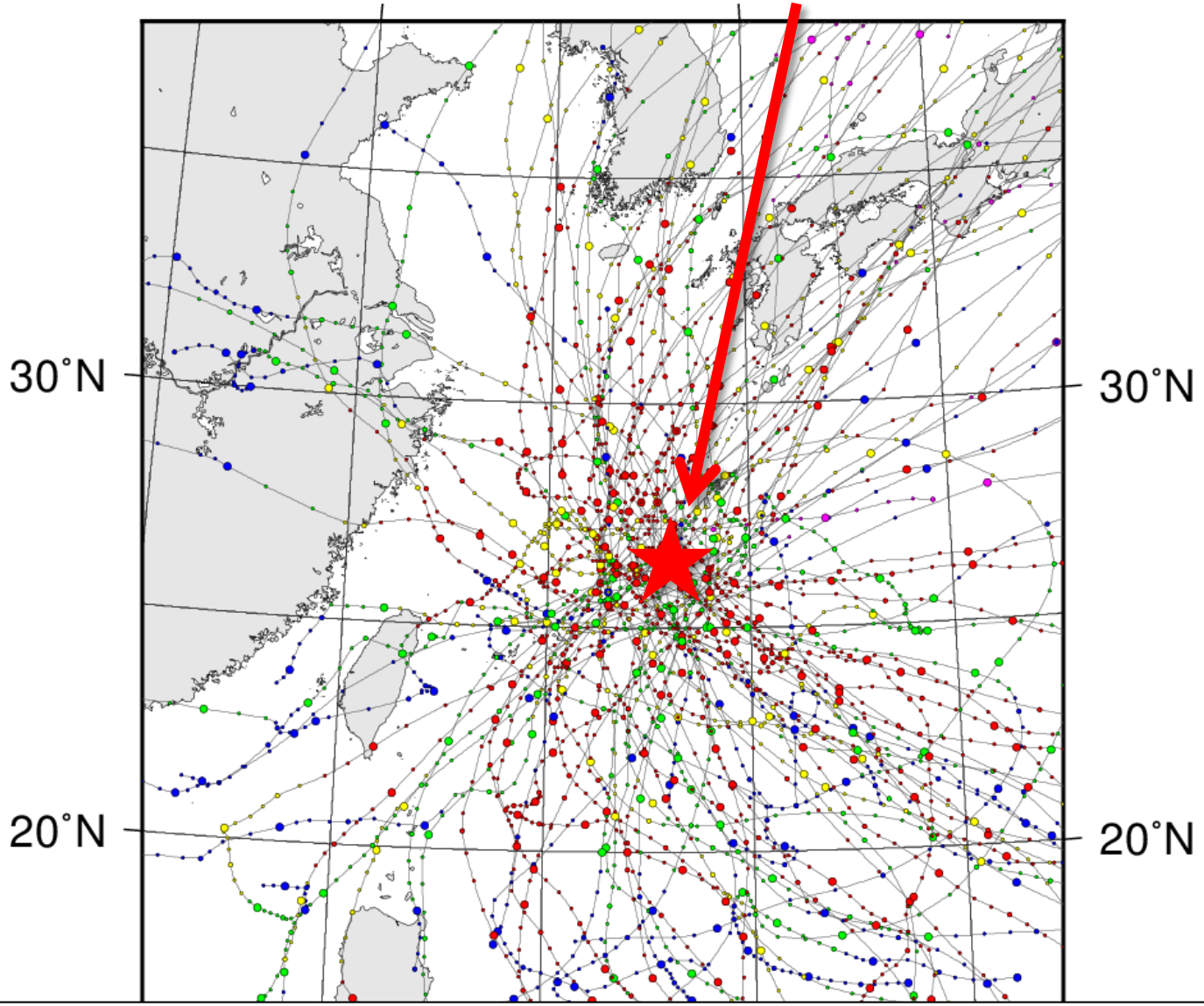


Summary (Ito et al., MWR, in print)

Hybrid systems yield better initial condition for predicting severe weather events than 4D-Var-Bnmc.

- Single observation test:
  - t=0h: 4D-Var-Bnmc increment is not reasonable.
  - t=3h: Increment structure becomes closer to each other, but 4D-Var-Bnmc prefers large scale.
- 62 TC forecasts:
  - Track: Hybrid systems, LETKF > 4D-Var-Bnmc
  - Intensity: Hybrid systems > 4D-Var-Bnmc, LETKF
- 104 Local heavy rainfall forecasts:
  - FSS: Hybrid systems > 4D-Var-Bnmc, LETKF (For FT = 0-6 h, 30-36 h)
  - Threat score: No significant differences.
- Note: 4D-Var & EnKF use different resolution here.

Thanks for your attention.
Come visit me in Okinawa if you have a chance.

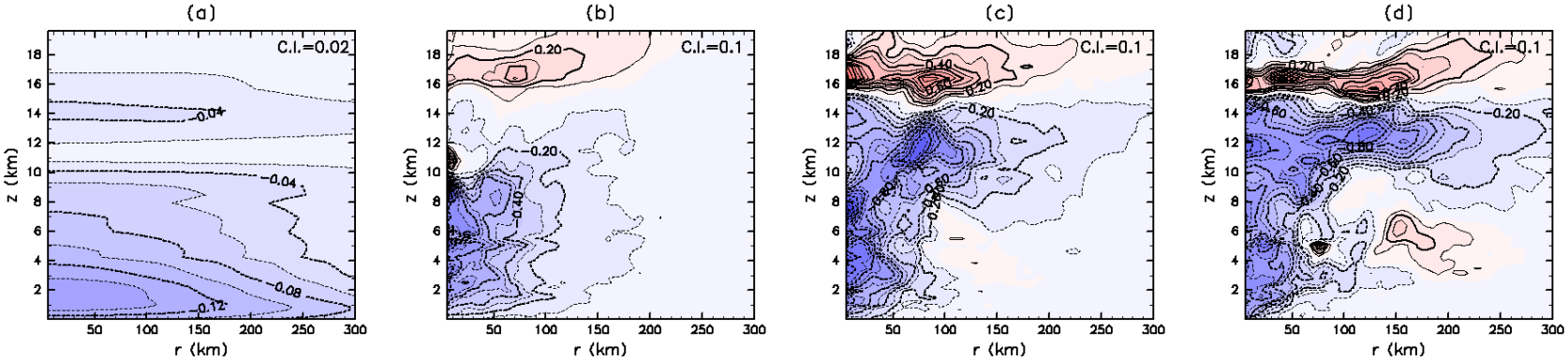


Tropical cyclones approached to Okinawa (1981-2014). Digital Typhoon.

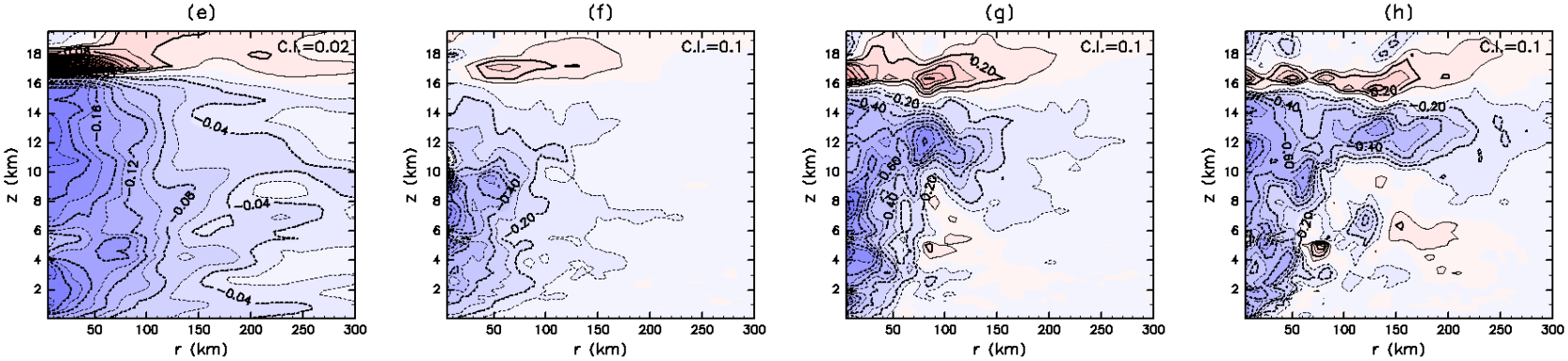
Supplemental slides

t = 0 h | t = 1 h | t = 2 h | t = 3 h

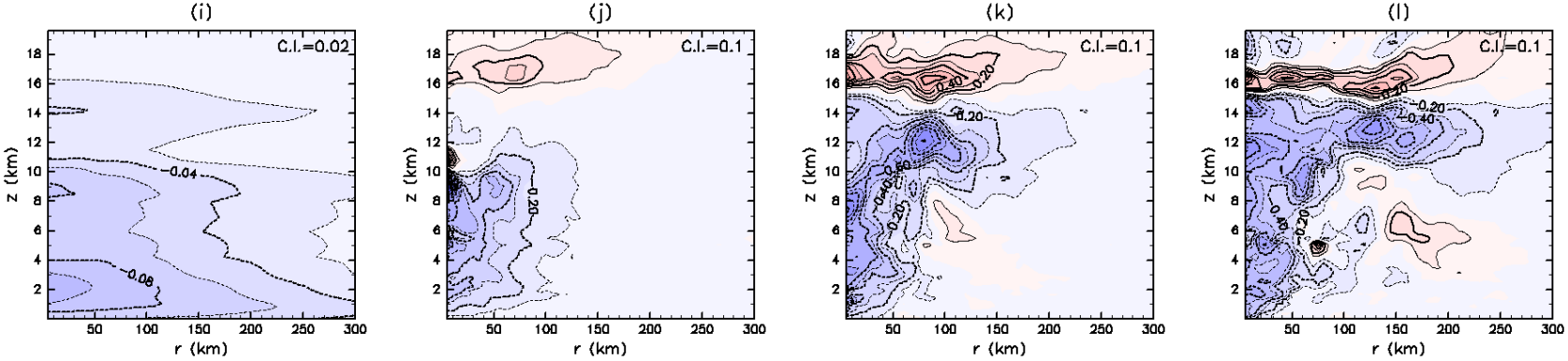
4D-Var-Bnmc



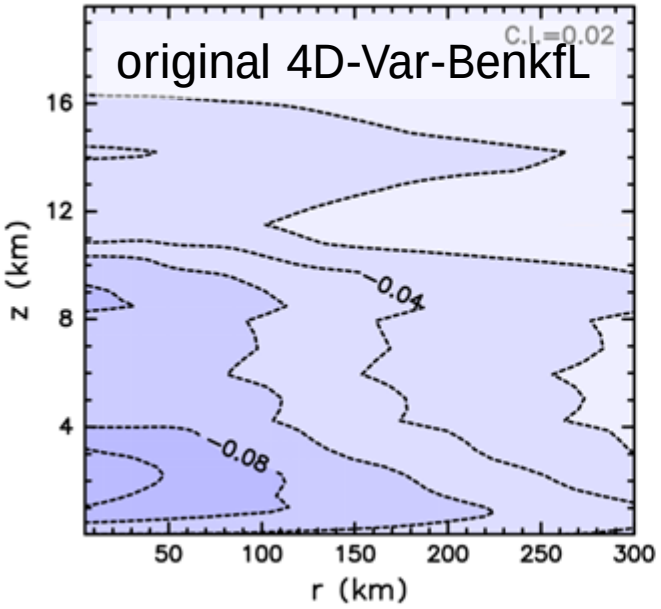
4D-Var-Benkf0

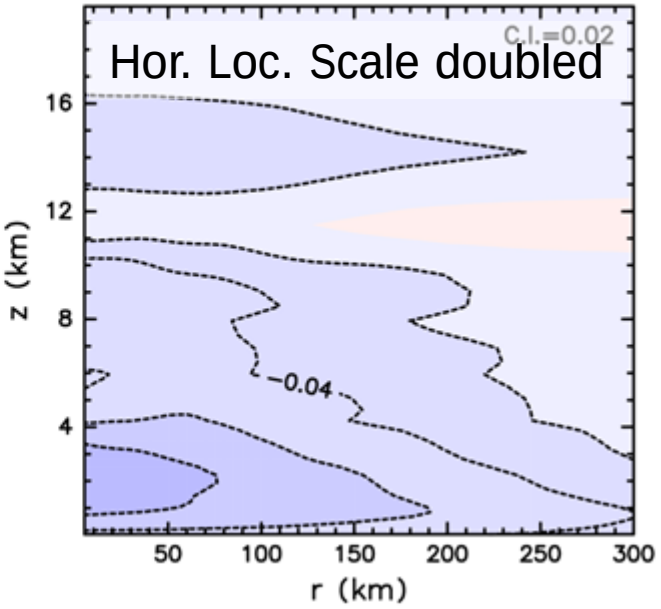


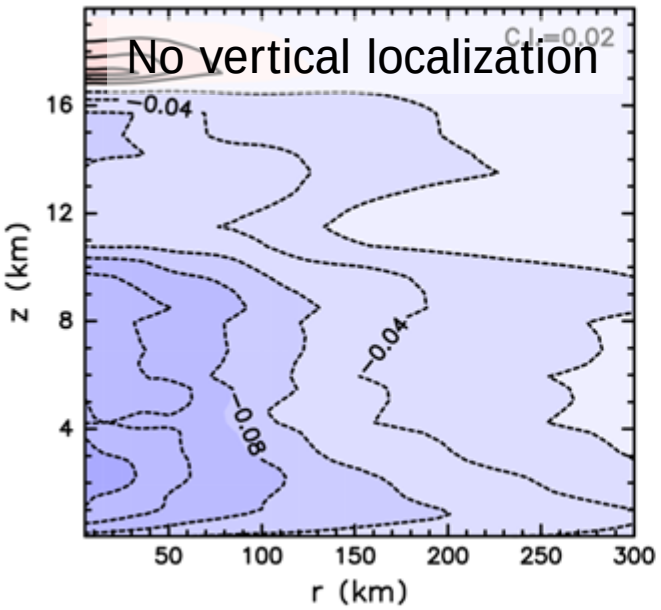
4D-Var-BenkfL

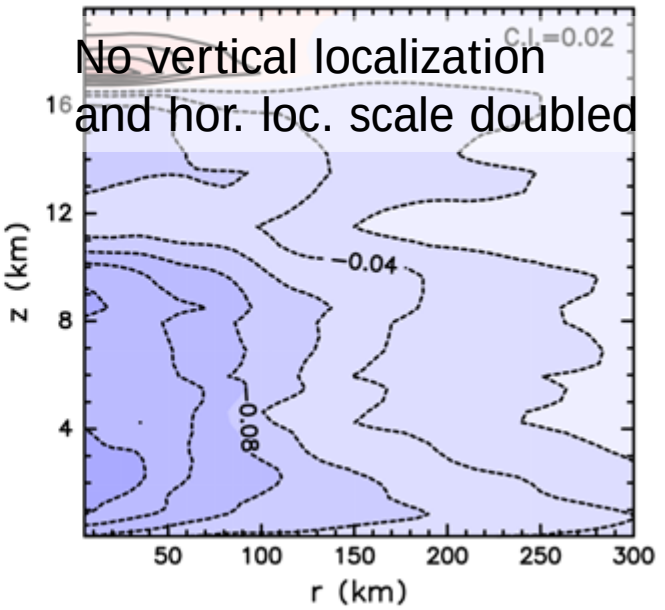


Vertical localization suppress the magnitude of vertically coherent structure of 4D-Var-enkfL









Statistical significant *t*-test results for TCs: Improvements relative to 4D-Var-Bnmc

A paired sample *t*-test considering the temporal persistency