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Advanced data assimilation techniques for predicting tropical cyclone intensities

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- Introduction: Tropical cyclone (TC) intensity
- Optimization of air-sea exchange coefficients in a strong wind condition
- Hybrid EnKF-4DVar data assimilation

Introduction

Working at Ryukyu Islands: "Beloved" by TCs

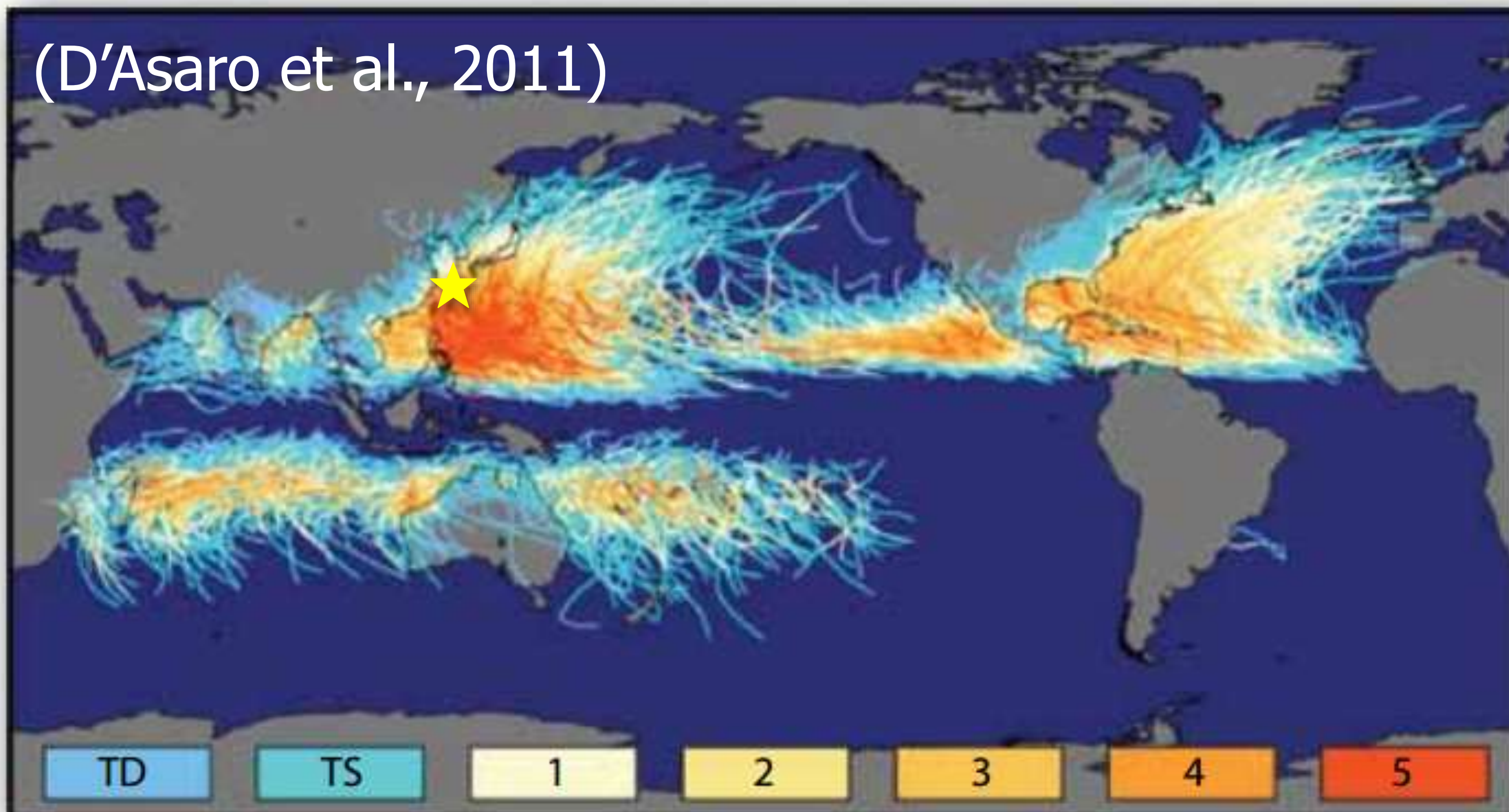
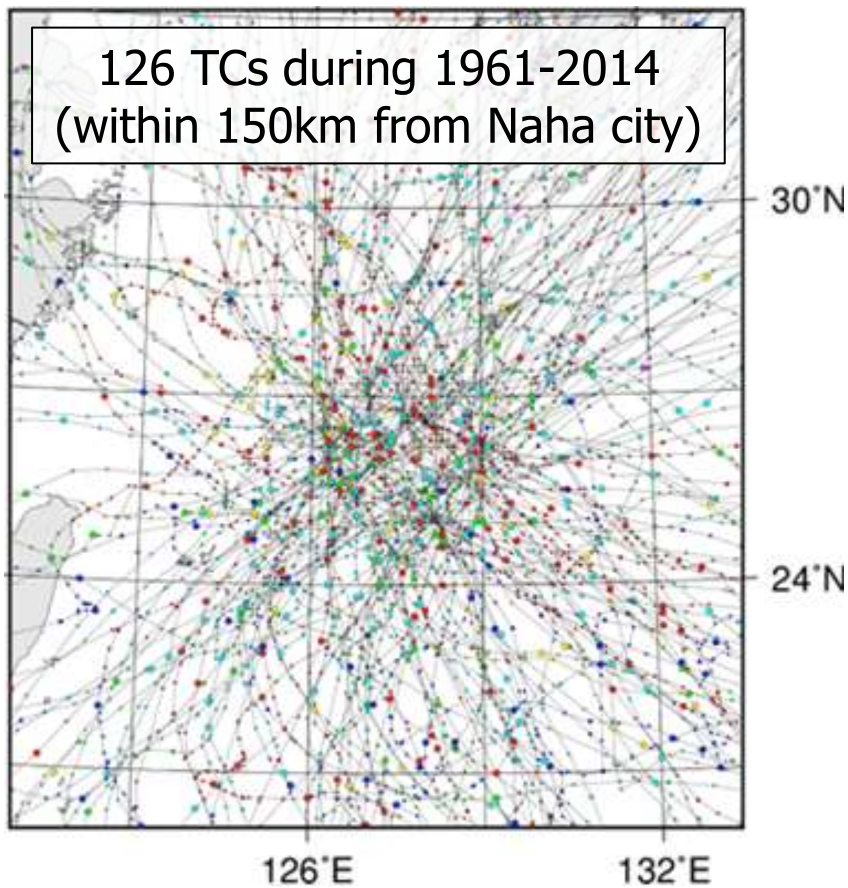


Figure 1. Worldwide tropical cyclone tracks through 2006 from the National Hurricane Center and the Joint Typhoon Warning Center, spanning nearly 150 years. Each track is colored by storm intensity using the Saffir-Simpson storm categories (Tropical Depression, Tropical Storm, and Tropical Cyclone categories 1 [wind 33–42 m s^{-1}] to 5 [wind > 70 m s^{-1}]). The tracks show that the regions of most frequent and intense storms are in the western North Pacific. *Image courtesy of NASA Earth Observatory*

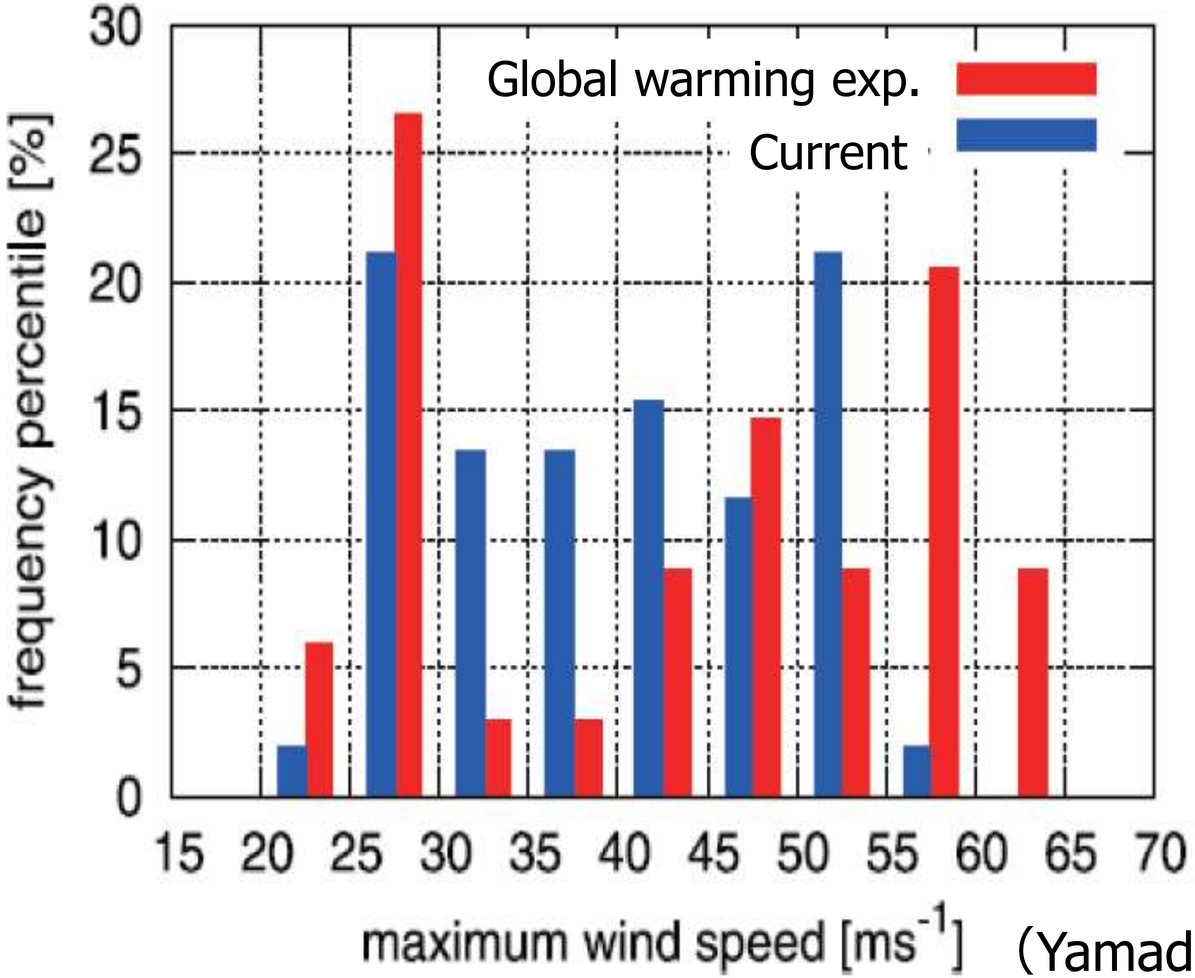
Very intense TCs approached to Okinawa



(Digital Typhoon)

Global warming --> More intense TCs?

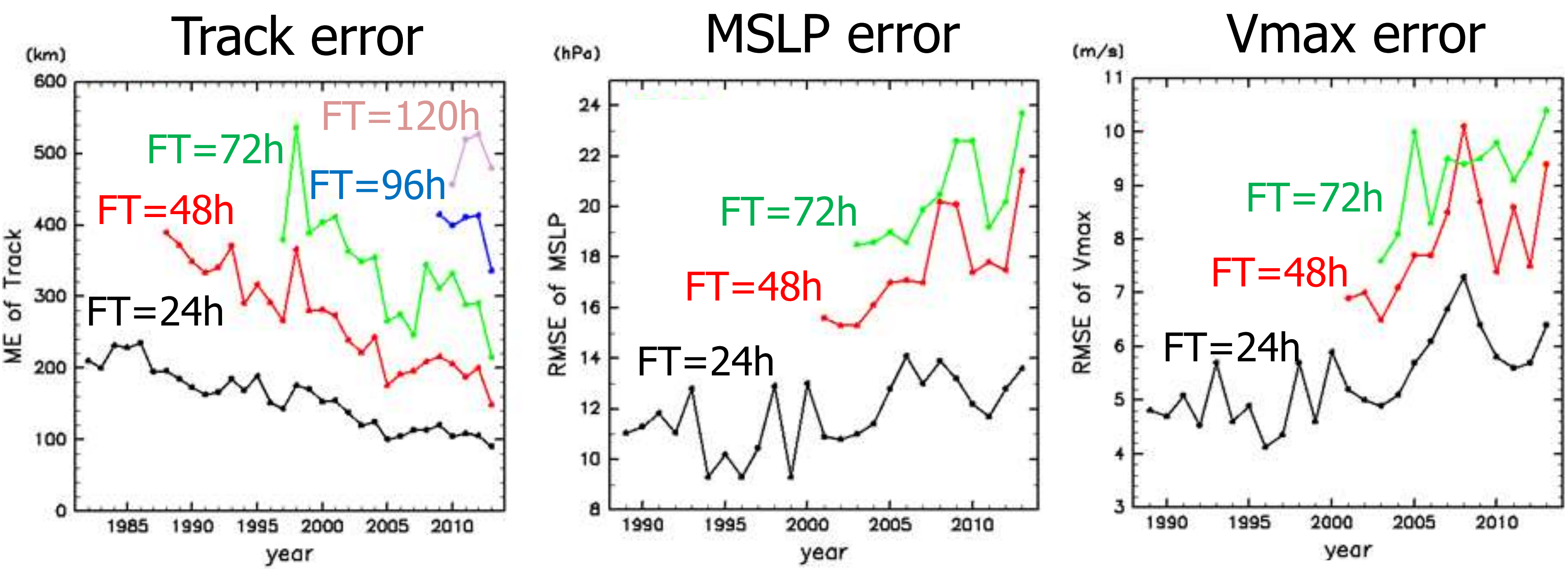
- Numerical models predict the smaller # of TC genesis and the increased # of intense TCs.



(Yamada et al., 2010)

TC forecast errors

- TC track forecast errors have been improved over the last three decades.
- In contrast, prediction of minimum sea level pressure (MSLP) and maximum wind speed (Vmax) has not been improved.

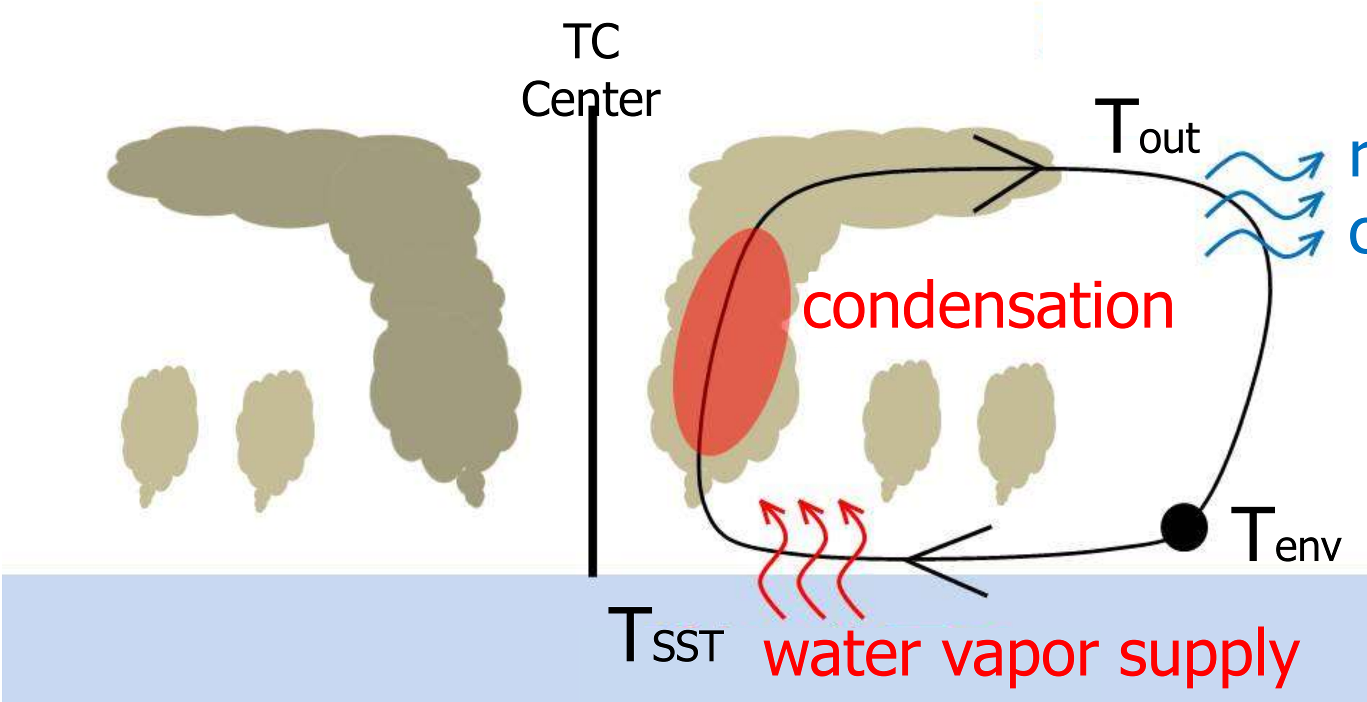


(Ito et al. 2015, in prep.)

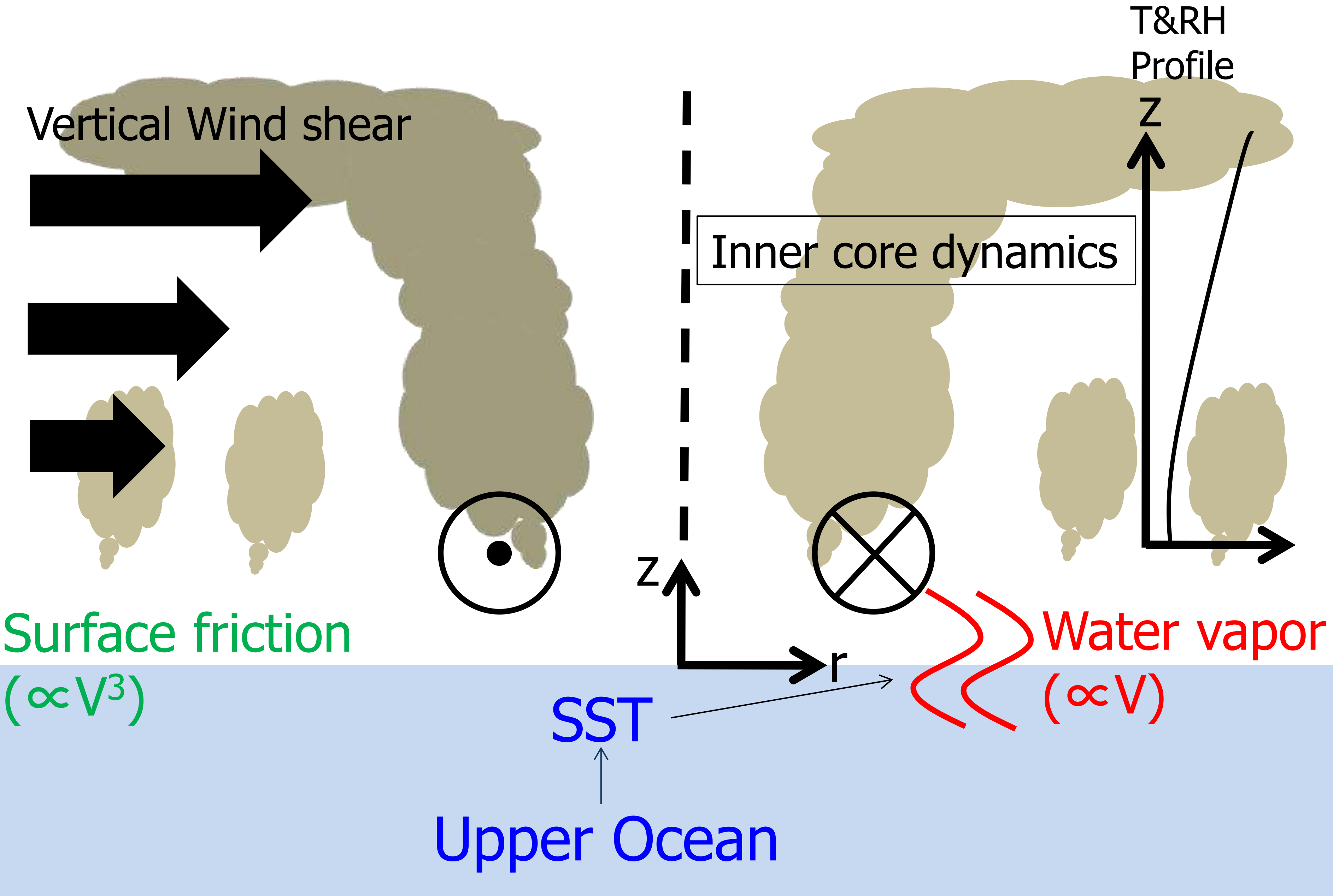
TC: Similar to Carnot cycle engine

- TC is a near-gradient balanced vortex.
- TC intakes energy from condensation in the eyewall, while the conversion efficiency from heat to momentum (wind) is $\eta = 1 - T_{out}/T_{SST}$ (WISHE theory; Emanuel, 1986).
- Analytical solution for V_{max}: An axisymmetric, gradient-wind and hydrostatic balanced vortex in a neutral and steady state.

$$V^2 = (1 - T_{out}/T_{SST})(C_k/C_D)(C_pT_{SST} + Lq_{SST} - C_pT_{env} - Lq_{env})$$



Important Factors on TC intensity



What should we do for better predicting TC intensities?

- Better model
  - High-Res. model to resolve a TC inner core
  - Atmosphere(-wave)-ocean coupled model
- Better observation
  - Obs needed both in atmosphere and ocean, in particular, observations near a TC center
  - "Best track" contains large uncertainty (～20 m/s)
- Better DA scheme
  - better initial condition
  - improving parameter values used in the model
- Better guidance

My strategy: Physics-based approach

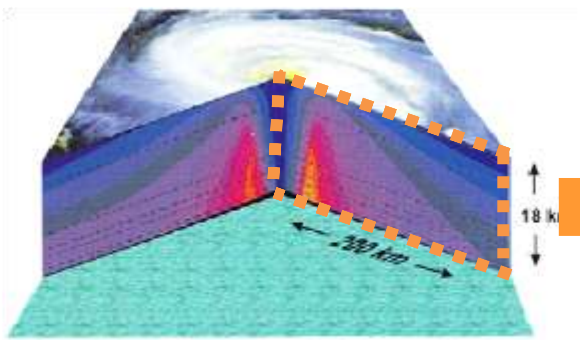
- DA is originally constructed on the framework of "information" and is independent from "physics."
- However, physical point of view gives the good insight for the design of a DA system:
  - ➢Selection of the important physical variables to consider the covariances.
  - ➢We can interpret the solution of DA as it subtracts the faster growing (unstable) mode of **B** evolved by the model physics **M** in time.

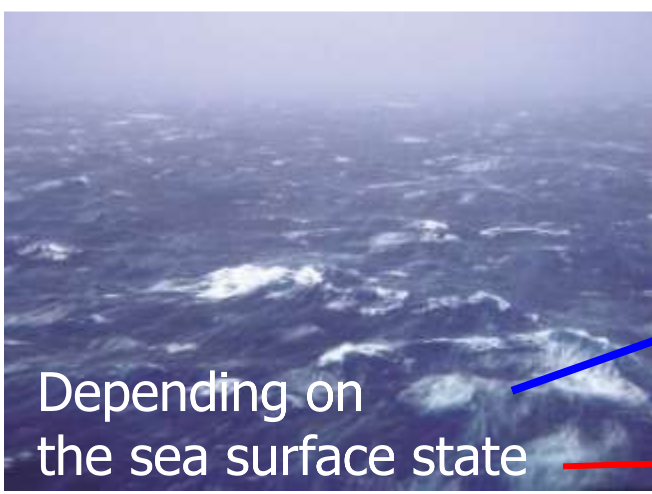
Optimization of air-sea exchange coefficients in a strong wind condition (Ito et al. 2010, 2013)

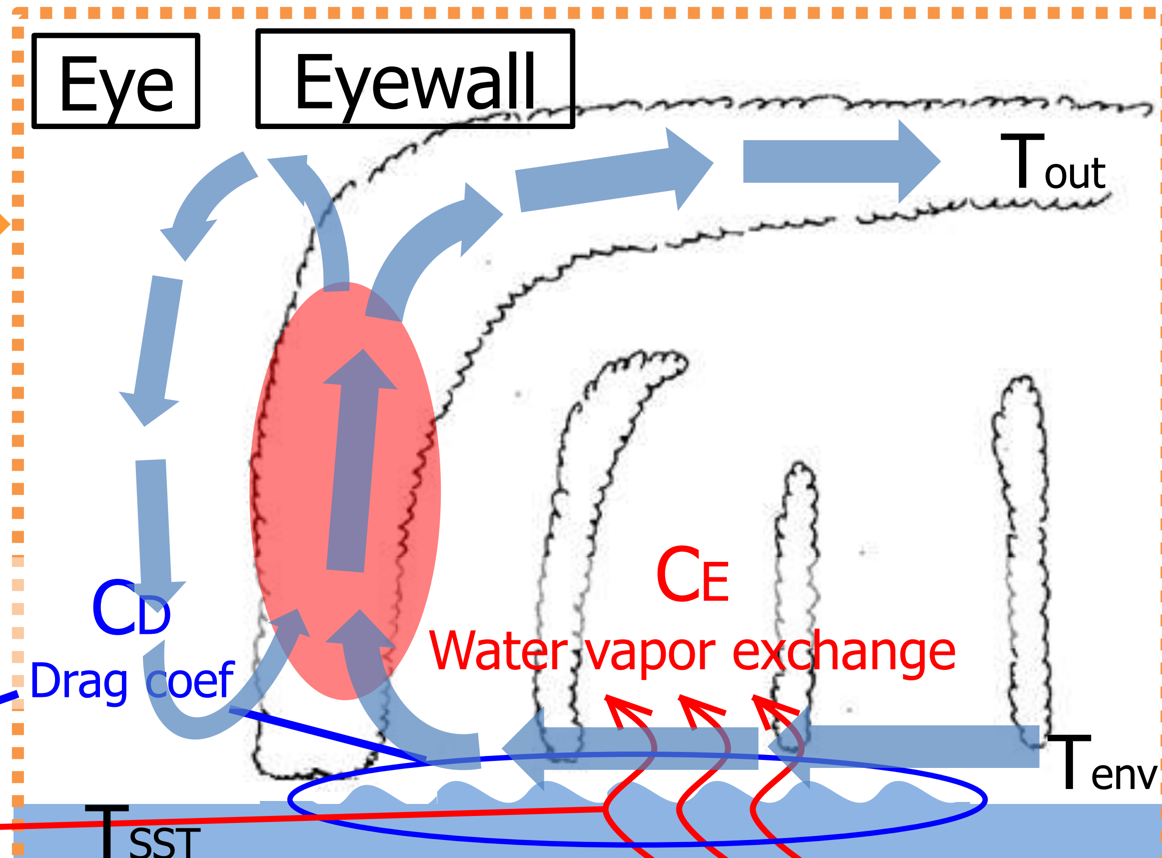
Analytical solution of Vmax (Emanuel, 1986 and follow-ups)

$$V^2 = \left(1 - \frac{T_{out}}{T_{SST}}\right)\frac{\boxed{C_k}}{\boxed{C_D}}\left(C_p T_{SST} + Lq_{SST} - C_p T_{env} - Lq_{env}\right)$$

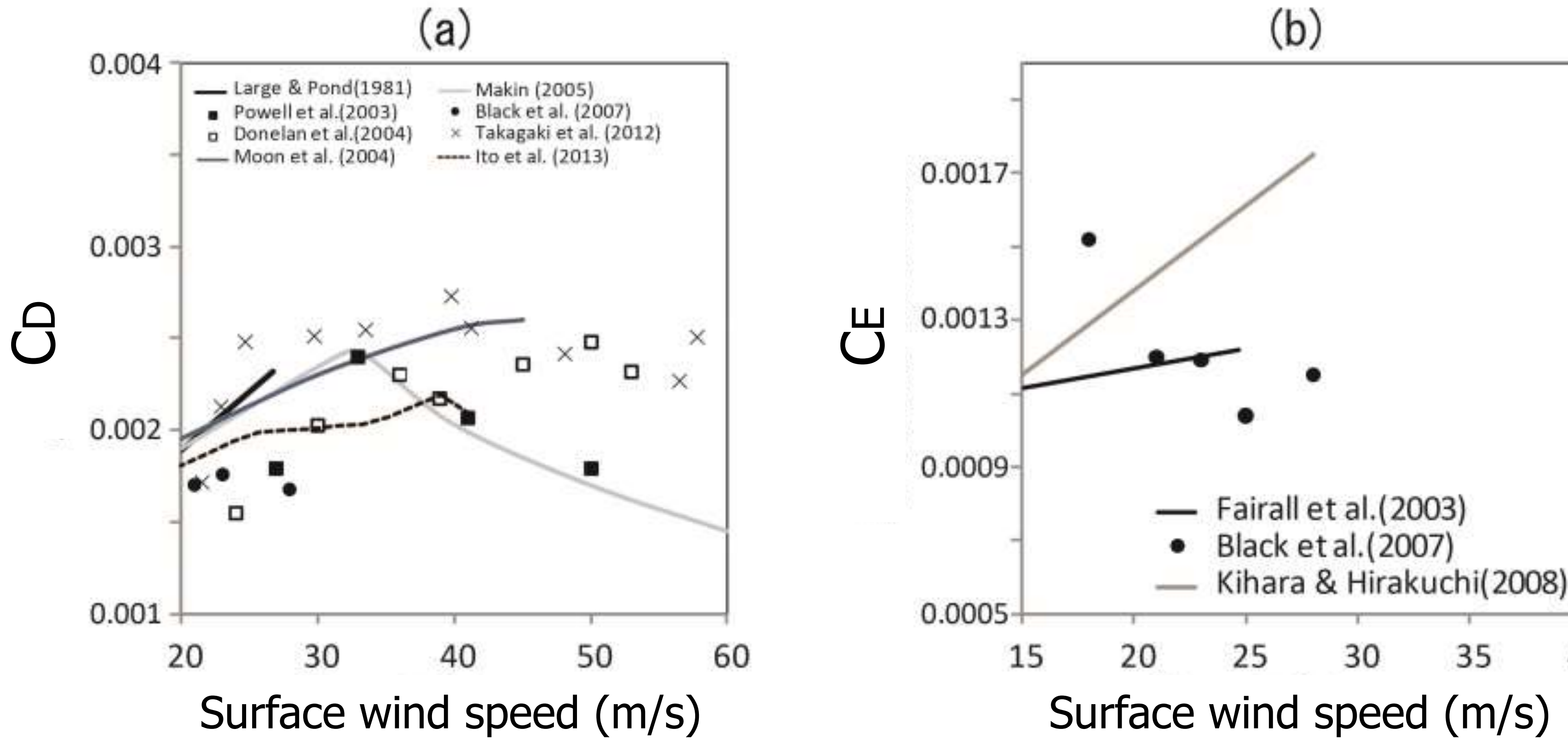
- C_E: Water vapor exchange coef. ($\sim C_K$), C_D: Drag coef.







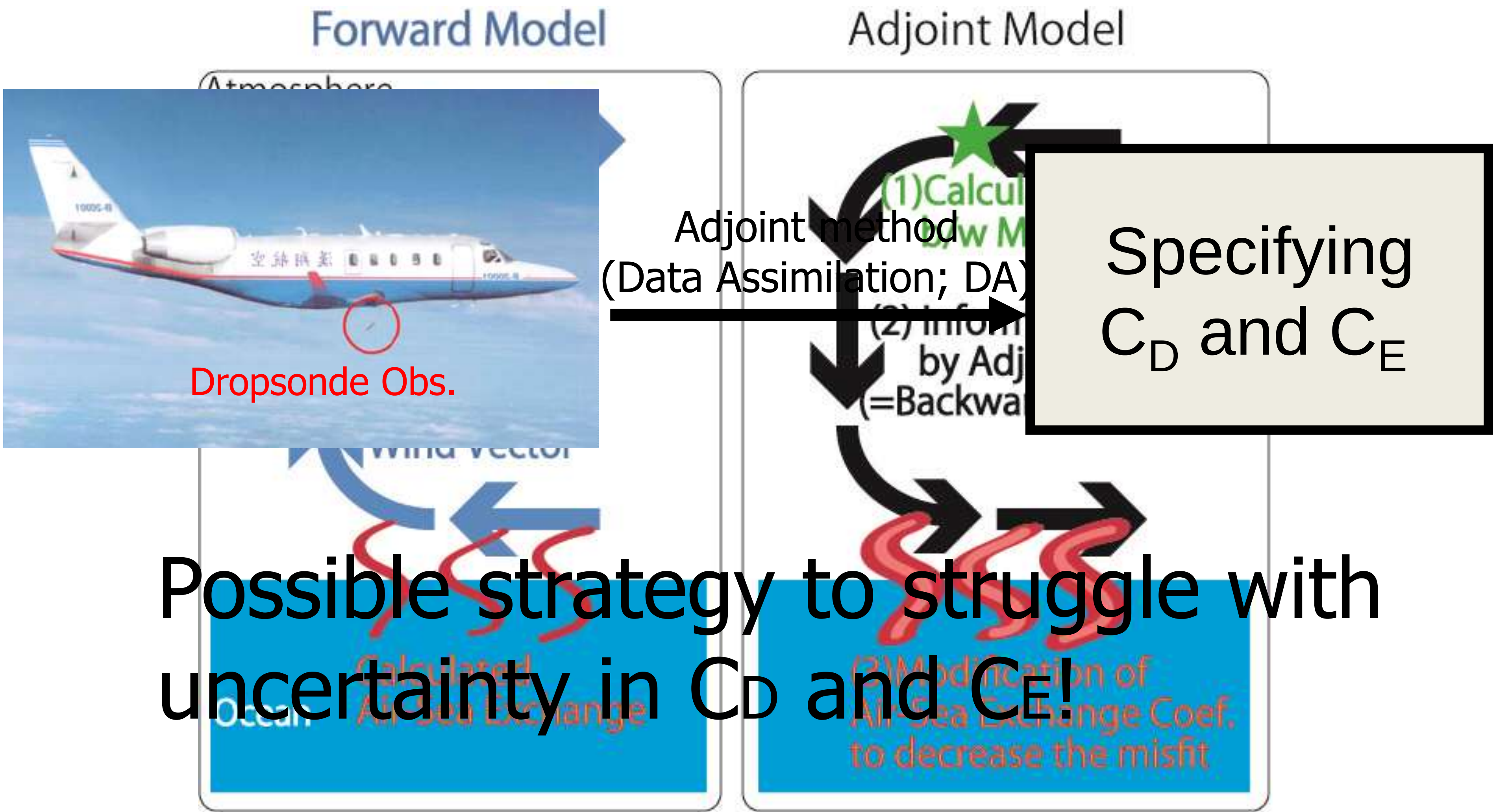
Uncertainties in CD and CE
(Recently reported values)



- CD and CE is highly uncertain (～50%) in the strong wind condition.

Specifying C_D and C_E by an adjoint equation

- Parameter values (C_D and C_E in this talk) are determined so as to minimize the misfit between the model trajectory and obs.



Possible strategy to struggle with uncertainty in C_D and C_E!

Idealized DA system: Identical Twin Experiment

■ Components of Identical Twin Experiment

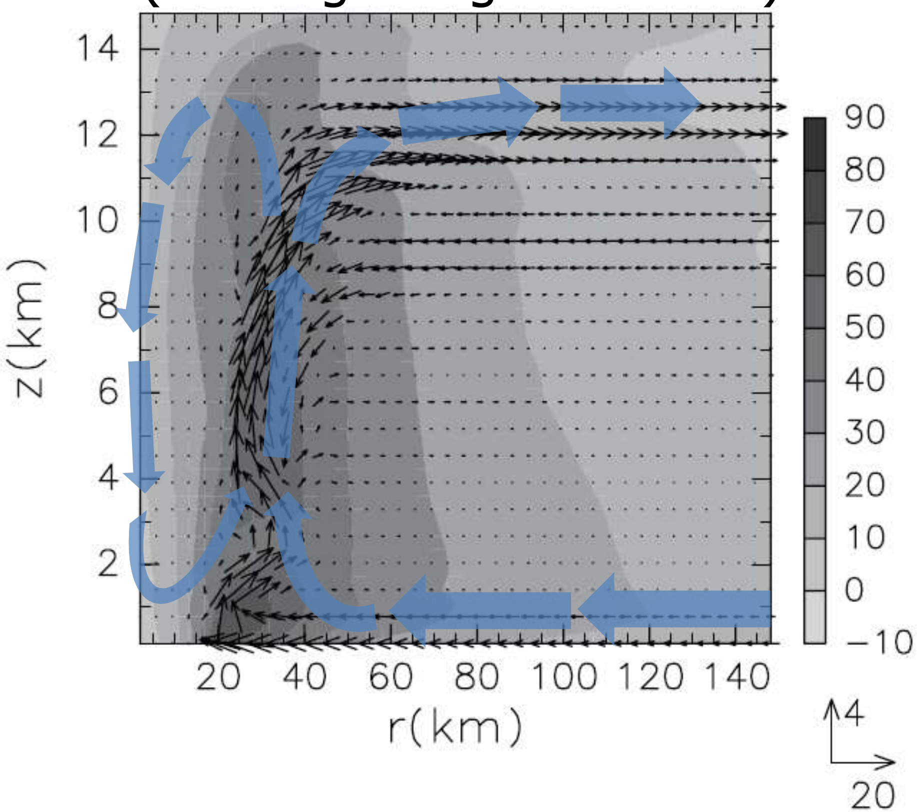
True	run with “true” CD, CE and initial state
Obs.	True field + Gaussian noise (We assume the datasets are sampled as in multiple aircraft missions.)
NoAsm	run with “wrong” CD, CE and initial state
Asm_NoCoef	Initial state alone is adjusted by DA
Asm_Coef	CD, CE, initial state are adjusted by DA

➢DA is successful if (Asm_Coef) ～ (True) because it indicates that optimization of CD, CE and initial state yields the better results.

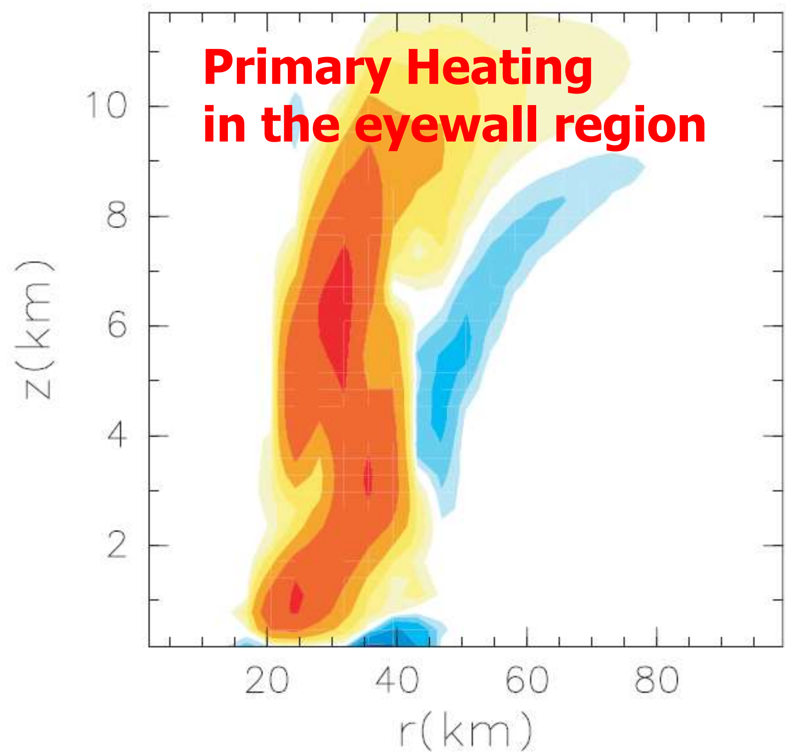
Physical Model: Axisymmetric TC model (Rotunno and Emanuel, 1987)

- This model is relatively simple and yet in a good agreement with the real TC (Degree of freedom ~ 2×10^5)

Wind field
(Shading: Tangential Wind)



Adiabatic Heating Profile



Result 1: Adjusted C_D and C_E

Run with "wrong" CD and CE

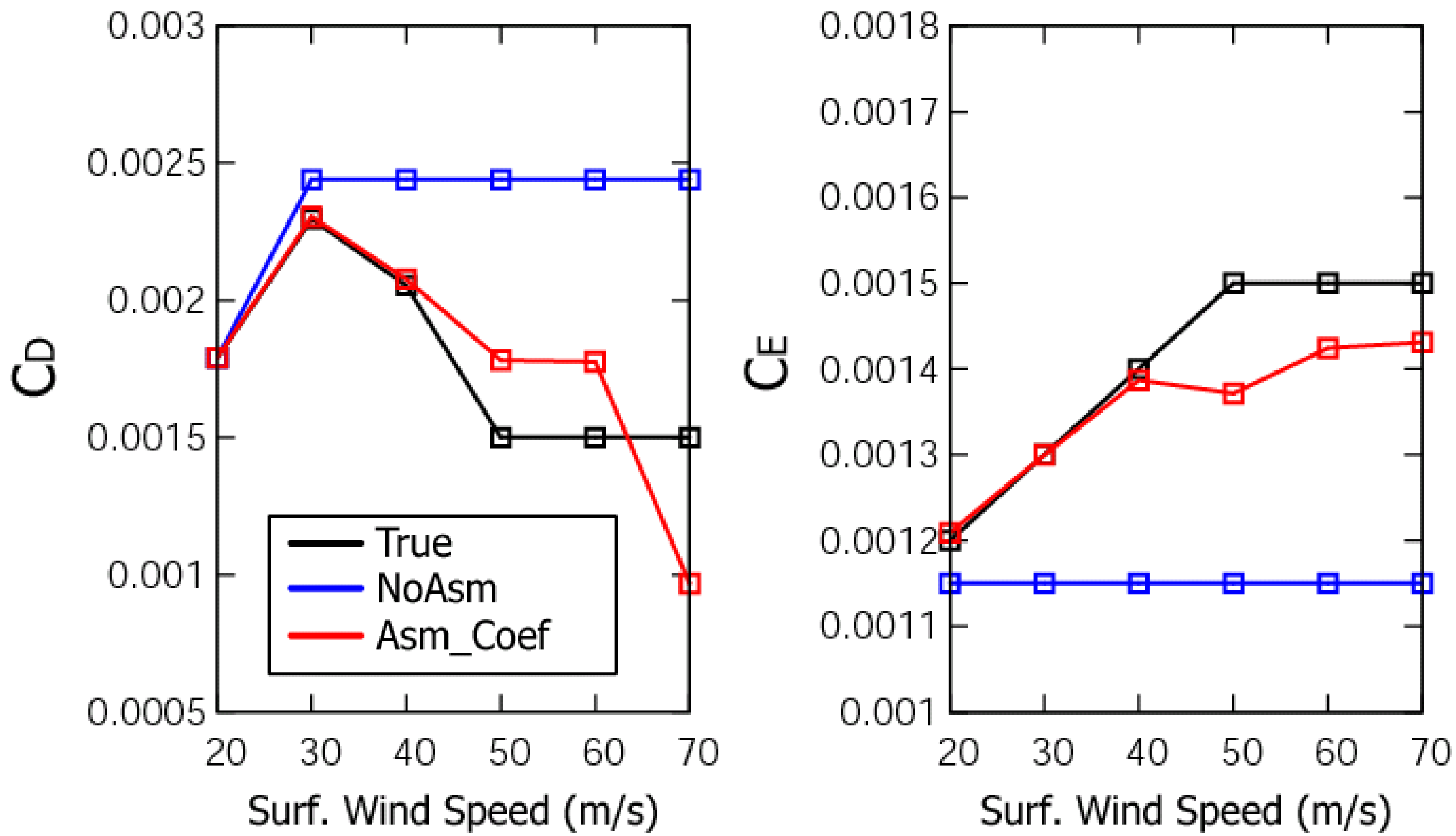
Dropsonde obs.

Adjoint-based DA method

updated CD and CE

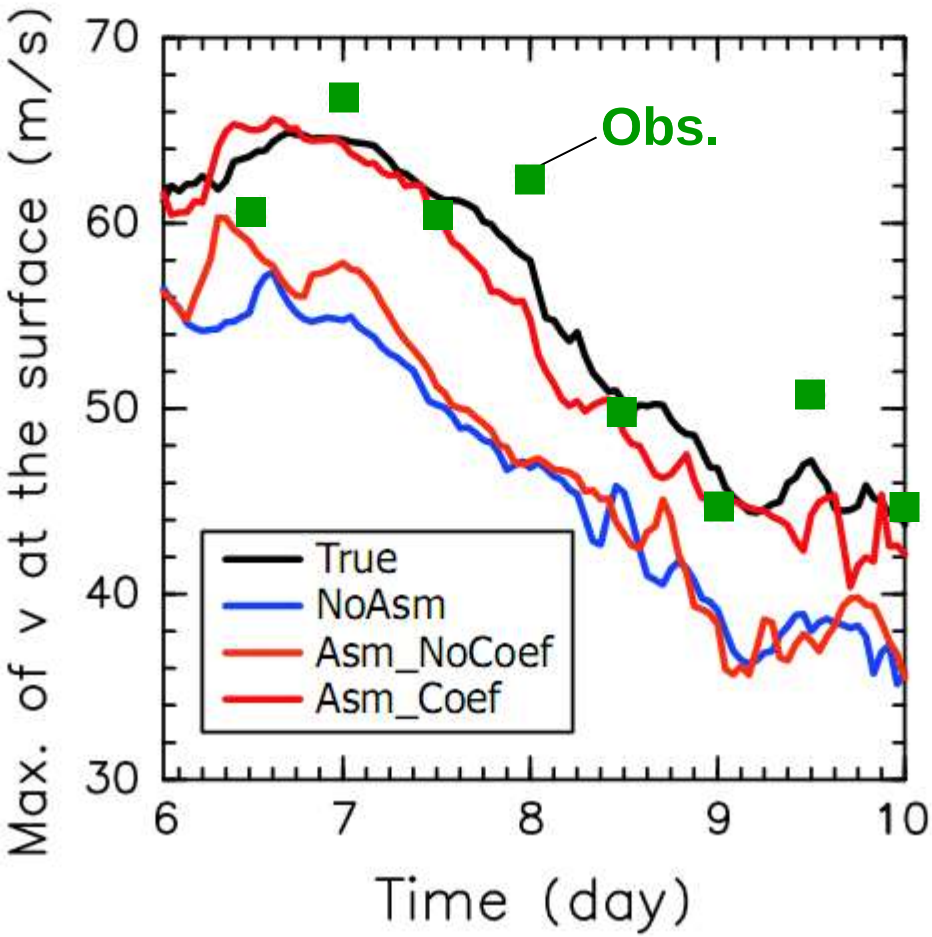
≒

"true" CD and CE



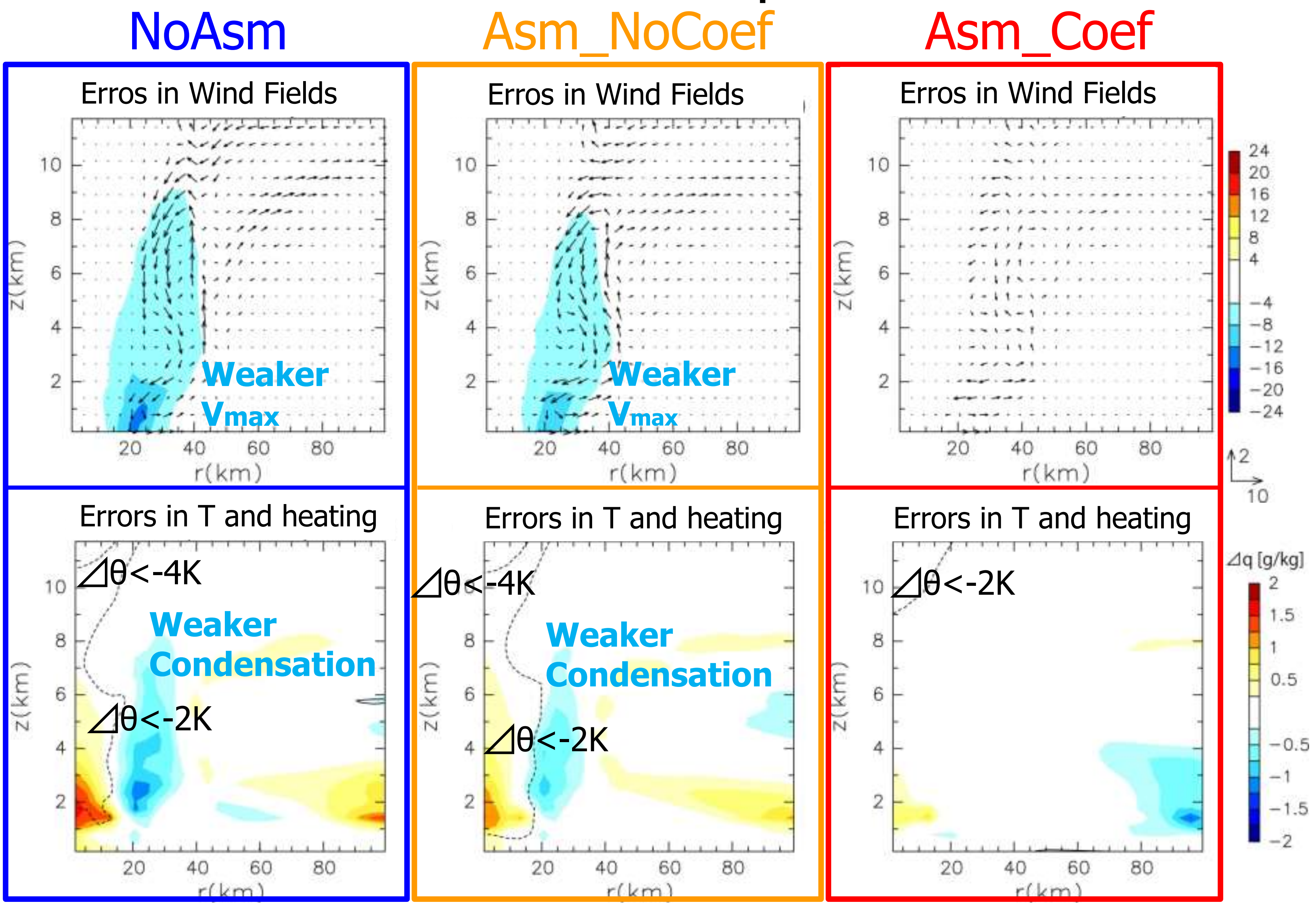
Result 2: Improved inner-core dynamics

Maximum Tangential Wind Speed V_θ at the surface



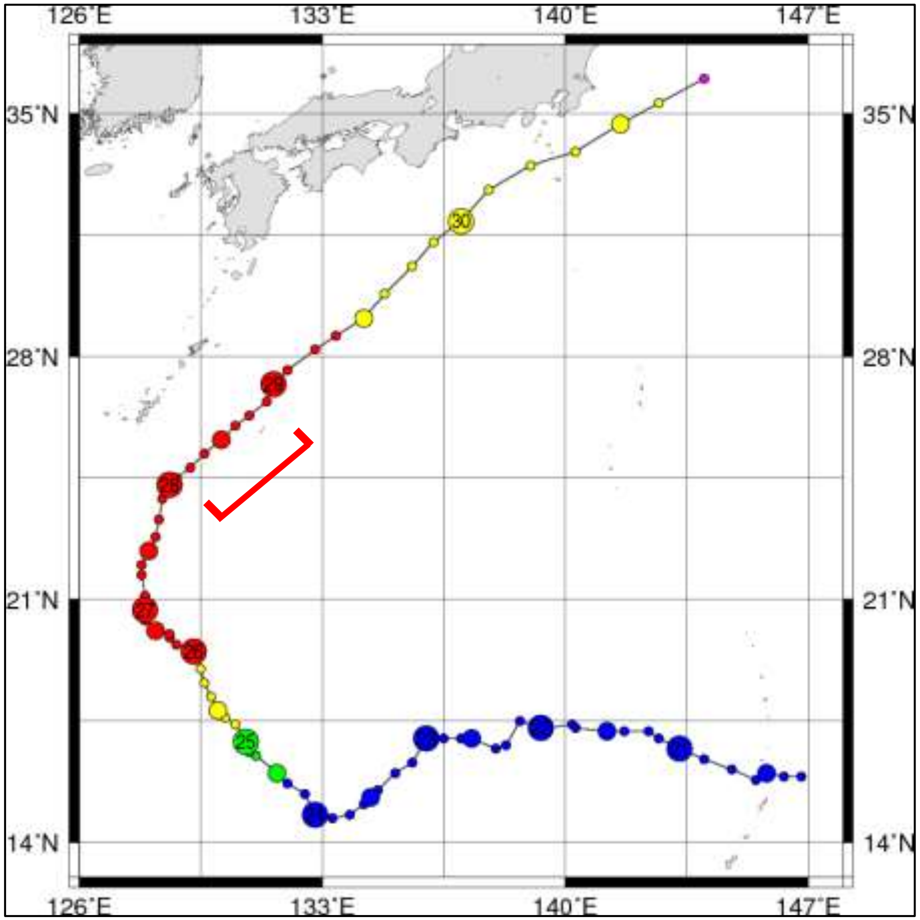
- RMSE from "True" case
  "NoAsm": 8.9 m/s
  "Asm_NoCoef" 7.9 m/s
  "Asm_Coef" 2.1 m/s
- TC intensity largely controlled by C_D and C_E.

Errors in wind and temperature fields

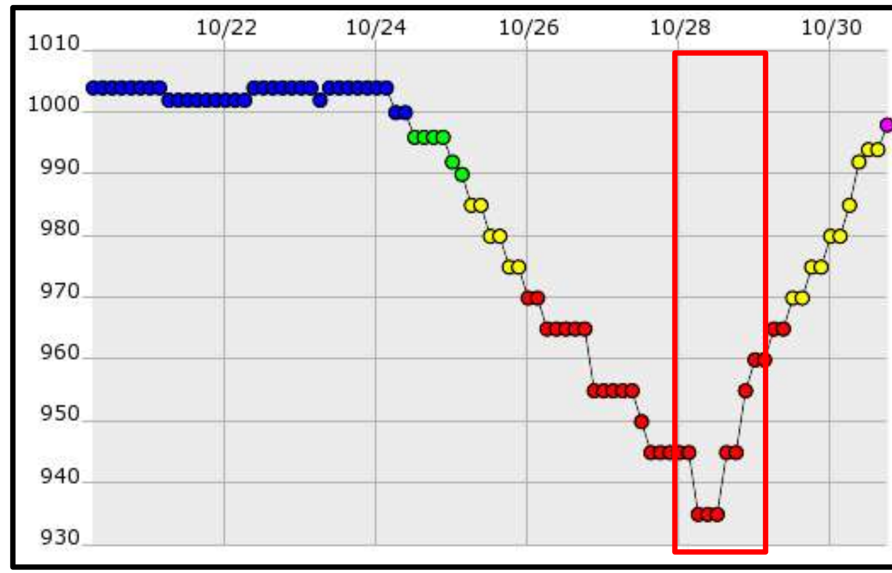


More real DA in collaboration with JMA
Case of TC Chaba (2010)

Typhoon Chaba's track



Minimum sea level pressure (hPa)



(Digital Typhoon Archives)

(Ito, Kawabata, Kato, Honda, Ishikawa, Awaji, 2013, JMSJ)

Framework of DA experiments

- JMA Nonhydrostatic Variational DA system (JNoVA) used for daily forecasts (Degree of freedom $\sim 10^8$).

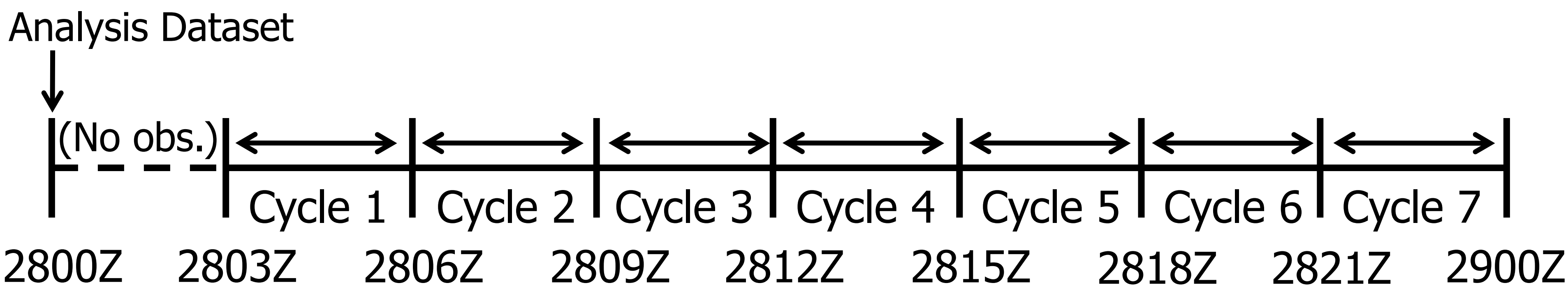
  "NoCoef": Optimization of initial state alone

  "Coef": Optimization of C_D, C_E and initial state

- Observational Dataset :

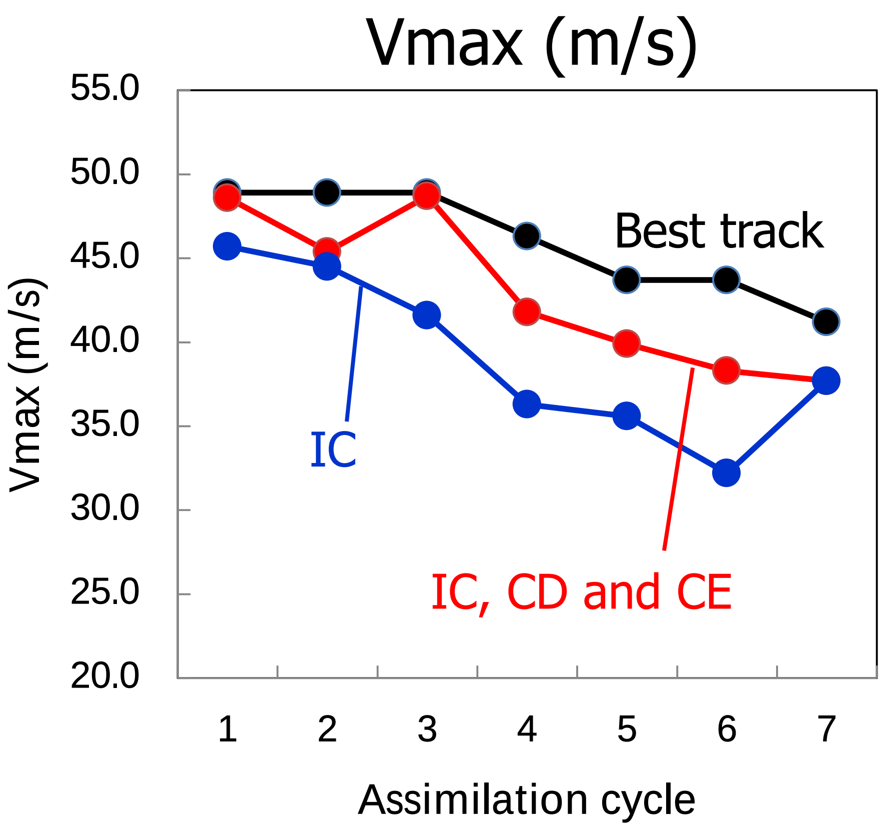
  Same as operational forecast archived at Japan Meteorological Agency

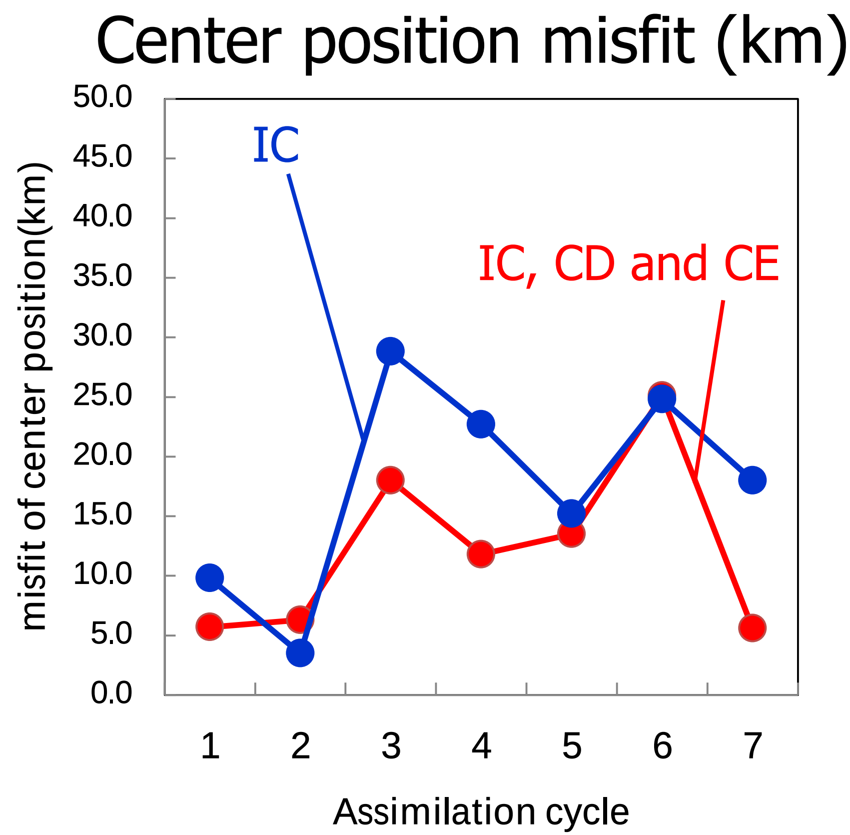
- Period of DA experiments : 21 hours => 7 Cycles (from 03UTC October 28 to 00UTC October 29)



Application to TC Chaba (2010) with JNoVA Intensity and center position

- Intensity and center location in the analysis become closer to the RSMC best track.

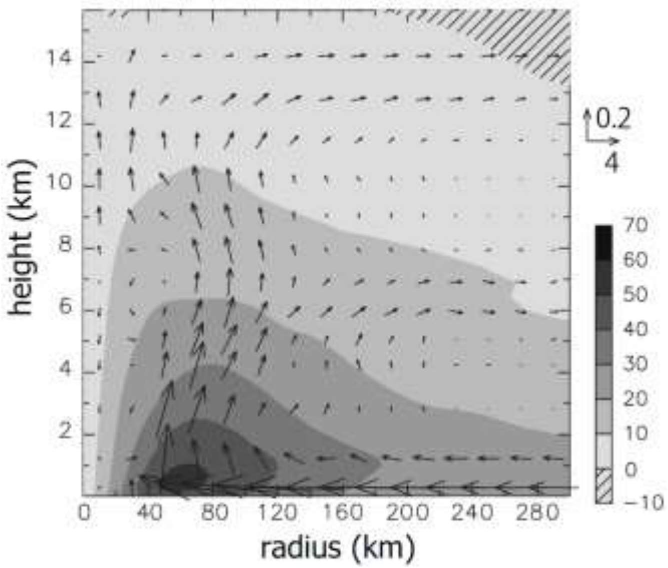




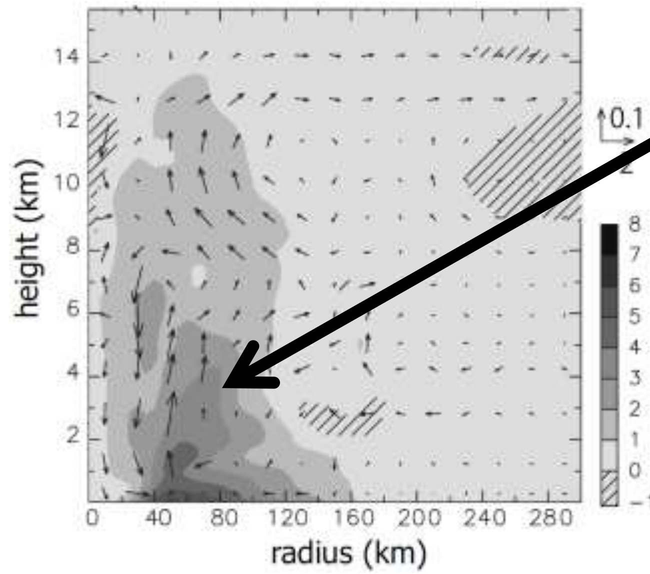
(Ito et al. 2013)

Structual Changes in typhoon Chaba

Wind field [Coef]

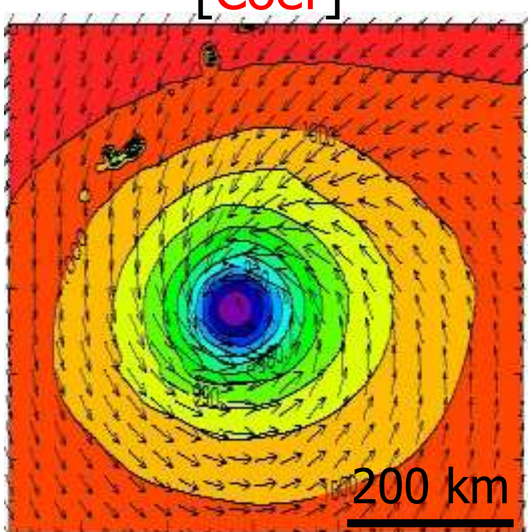


Wind field [Coef - NoCoef]

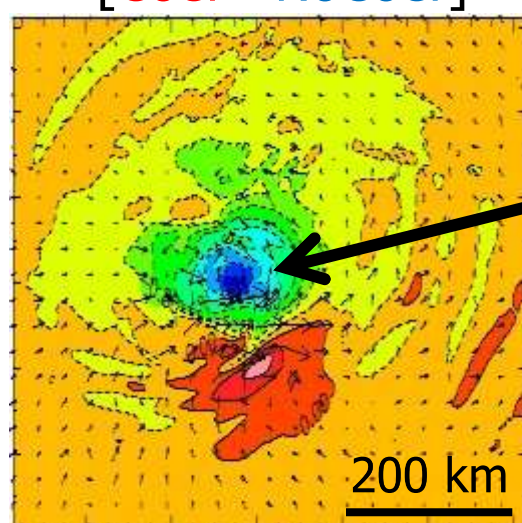


Vmax changes as in idealized experiment

Psrf, (Usrf, Vsrf)
[Coef]



⊿Psrf, (⊿Usrf, ⊿Vsrf)
[Coef - NoCoef]



Decrease in the pressure field & Northward displacement of Chaba in the Coef experiment

(Ito et al. 2013)

Summary (Ito et al. 2010, 2013)

- Tropical cyclone (TC) intensity largely relies on C_D & C_E, though they are quite uncertain.
- We have proposed an optimization of them through a variational data assimilation (VDA) method which fully utilizes available observations away from sea surfaces.
- Idealized and realistic VDA experiments exhibits a significant improvement in the analysis of TC intensity, inner-core structure and track.

Hybrid EnKF-4DVar data assimilation
(Ito et al., in revision)

Solution of 4D-Var and KF

- Solution of 4D-Var obtained from minimizing cost function J.

J_B = Difference b/w the first guess and the analysis initial state

$$J = \boxed{\frac{1}{2}(\mathbf{x}_0 - \mathbf{x}_\mathrm{b})^\mathrm{T}\mathbf{B}^{-1}(\mathbf{x}_0 - \mathbf{x}_\mathrm{b})} + \boxed{\frac{1}{2}\sum_t(\mathbf{y}_t - \mathbf{H}\mathbf{x}_t)^\mathrm{T}\mathbf{R}^{-1}(\mathbf{y}_t - \mathbf{H}\mathbf{x}_t)}$$

J_O = Difference b/w observation and model variables

- For linear dynamics with a Gaussian PDF, the solution of 4D-Var is ideally the same as that obtained from Kalman filter.

increment

$$\mathbf{x}_{a,t} = \mathbf{x}_{b,t} + \boxed{\mathbf{MBM}^T\mathbf{H}^T\left(\mathbf{R} + \mathbf{HMBM}^T\mathbf{H}^T\right)^{-1}(\mathbf{y} - \mathbf{H}\mathbf{x}_{b,t})}$$

Interpretation of the increment (Johnson et al. 2005)

- Let $\mathbf{x}' \equiv \left(\mathbf{MB}^{1/2}\right)^{-1}\mathbf{x}$ and $\mathbf{y}' \equiv \mathbf{R}^{-\frac{1}{2}}\mathbf{y}$
- Then, the solution becomes

$$\begin{aligned}
\mathbf{x}'_a &= \mathbf{x}'_b + \boxed{\left(\mathbf{I}_p + \mathbf{V}\mathbf{D}^T\mathbf{D}\mathbf{V}^T\right)^{-1}\mathbf{V}\mathbf{D}^T\mathbf{U}^T\mathbf{R}^{-1/2}\mathbf{d}} \\
&= \mathbf{x}'_b + \boxed{\sum_{l=1}^{m}\frac{\lambda_l^2}{1+\lambda_l^2}\frac{\mathbf{u}_l^T\mathbf{R}^{-1/2}\mathbf{d}}{\lambda_l}\mathbf{v}_l}
\end{aligned}$$

"increment"

where $\mathbf{L} \equiv \mathbf{R}^{-1/2}\mathbf{HMB}^{1/2} \overset{\text{SVD}}{=} \mathbf{UDV}^T = \sum_{l=1}^{m}\mathbf{u}_l\lambda_l\mathbf{v}_l^T$, d=$(\mathbf{y} - \mathbf{H}\mathbf{x}_b)$

- Interpretation:
  Increment is added to the direction of singular vector of **L** if singular value > 1.
  --> If **R**=**H**=**I**, the faster growing modes of **MB**$^{1/2}$ are likely to be captured.

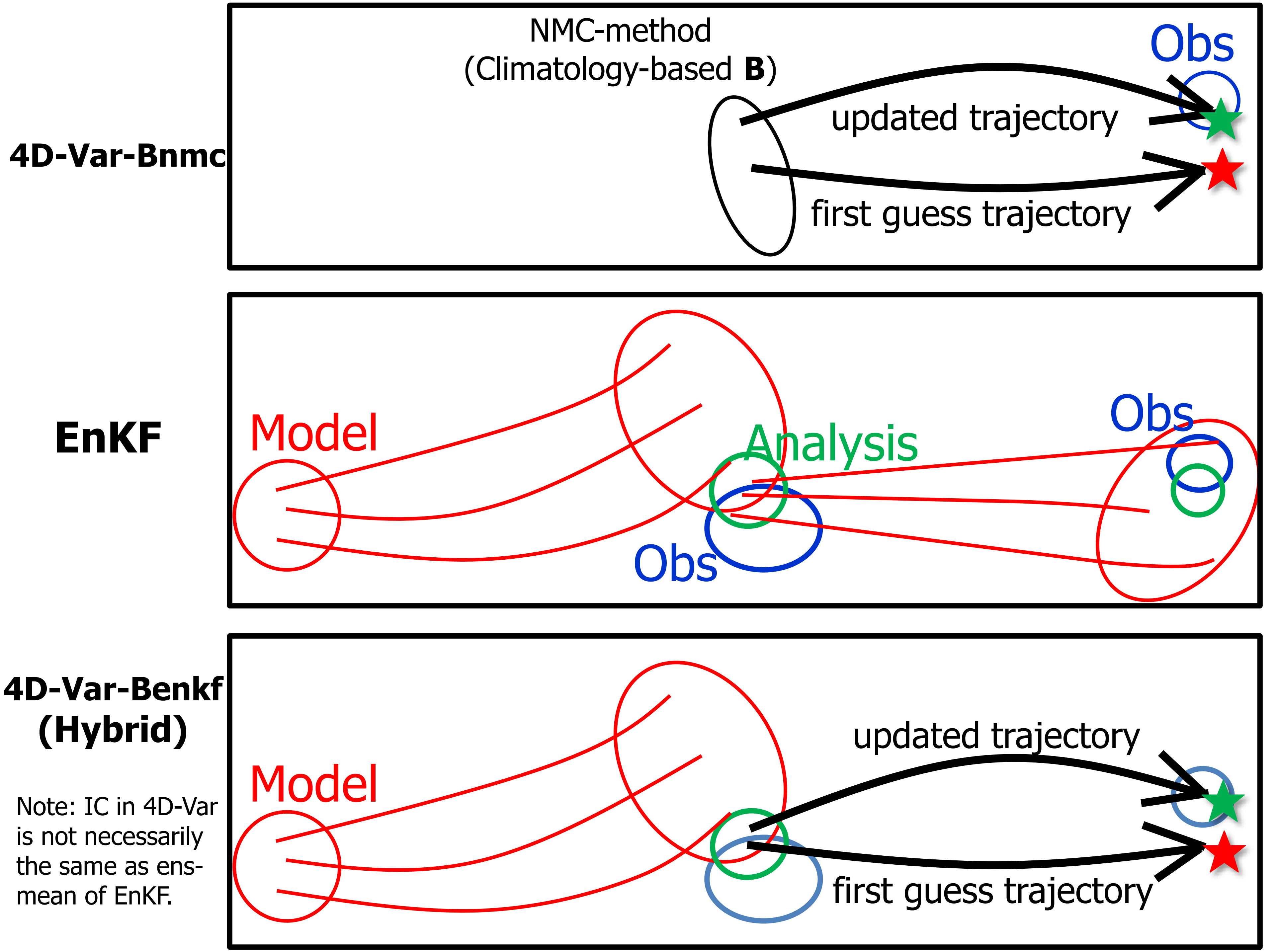
4D-Var, EnKF, and Hybrid

- In an idealized case (linear dynamics and Gaussian PDF), difference b/w 4D-Var and EnKF only comes from the specification of **M** and **B**.

$$\mathbf{x}_{a,t} = \mathbf{x}_{b,t} + \mathbf{M}\mathbf{B}\mathbf{M}^T\mathbf{H}^T\left(\mathbf{R} + \mathbf{H}\mathbf{M}\mathbf{B}\mathbf{M}^T\mathbf{H}^T\right)^{-1}(\mathbf{y} - \mathbf{H}\mathbf{x}_{b,t})$$

Method	Background error **B**	Model dynamics **M**
4D-Var-Bnmc	NMC (climatology)	**(Implicitly) Exact**
EnKF	**Ensemble-based** (**MBM**^{T} is approximated by **XX**^{T})	
4D-Var-Benkf (Hybrid)	**Ensemble-based**	**(Implicitly) Exact**

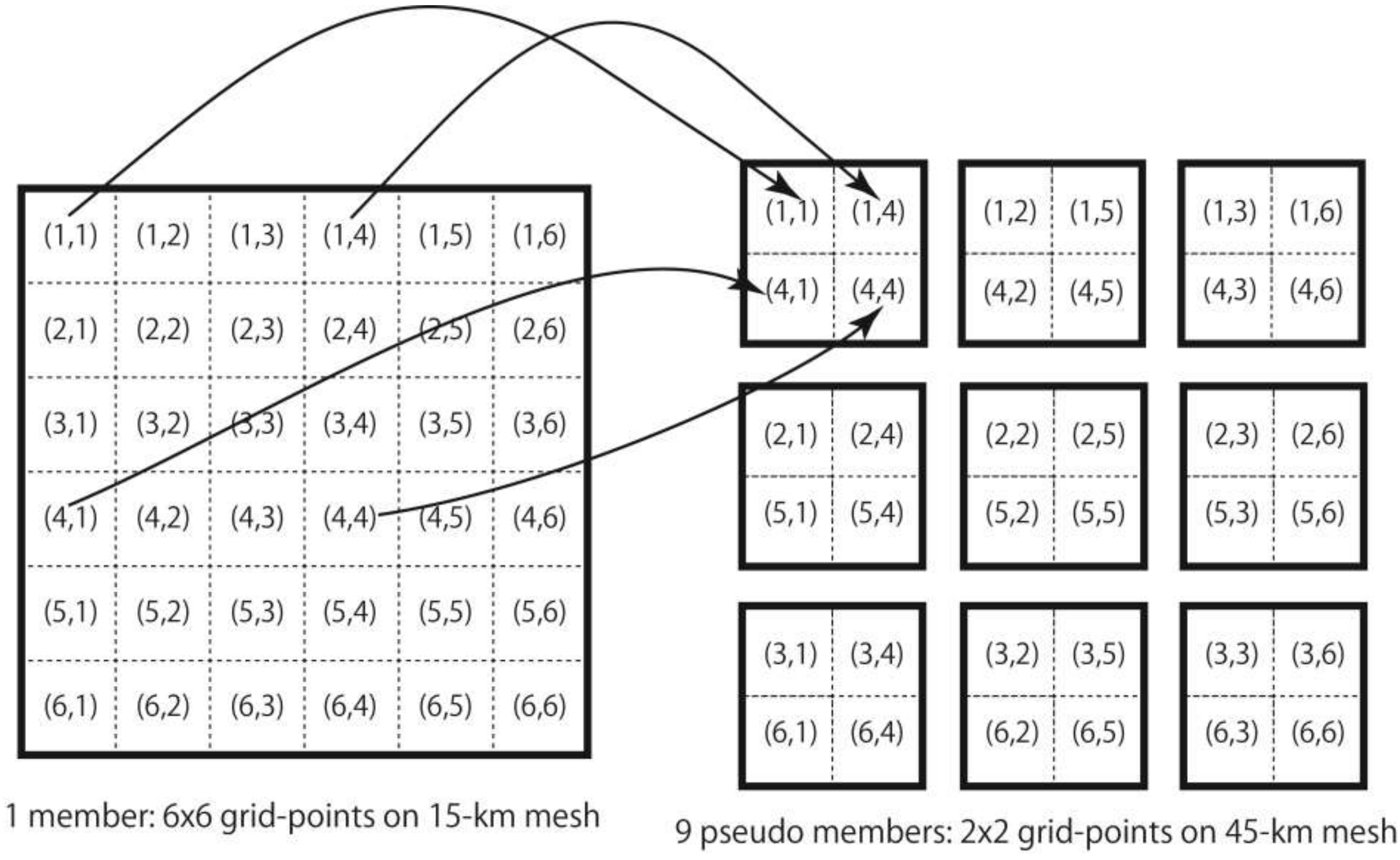
- We expect hybrid is the best in this framework. But it is not so straightforward in the real DA system (Non-linearity, non-Gaussian and special treatments).


4D-Var-Bnmc
NMC-method
(Climatology-based **B**)
Obs
updated trajectory
first guess trajectory
EnKF
Model
Analysis
Obs
Obs
4D-Var-Benkf
(Hybrid)
Model
updated trajectory
first guess trajectory
Note: IC in 4D-Var is not necessarily the same as ens-mean of EnKF.

Motivation: A meso hybrid system

- Benefits of hybrid DA system can be pronounced for predicting severe weather events because NMC-based **B** just represents climatological error covariances.
- Nevertheless, so far, only a few studies have focused on mesoscale weather prediction using a hybrid EnKF-4DVAR system (Poterjoy & Zhang, 2014).
- We evaluate the potential of a hybrid system in terms of predicting severe weather events by comparing:
  - 4D-Var-Bnmc: adjoint-based 4DVAR using NMC-based **B**
  - LETKF: Local Ensemble Transform Kalman filter
  - 4D-Var-BenkfL: 4D-Var using LETKF-based **B** (localization)
  - 4D-Var-BenkfN: 4D-Var using LETKF-based **B** (neighboring)

Neighboring ensemble approach (Aonashi 2012)



Practical implementation in Hybrid (4D-Var-Benkf)

- In 4D-Var, $\mathbf{B}^{-1}$ is not explicitly calculated.
- Instead, we define $\mathbf{v}$ by $\delta\,\mathbf{x}=\mathbf{B}^{1/2}\mathbf{v}$ and $\mathbf{B}=\beta\mathbf{B}_{NMC}+(1-\beta)\mathbf{B}_{ens}$.
- If we assume increment is,

$$J=\frac{1}{2}\delta\mathbf{v}_{NMC}^{T}\delta\mathbf{v}_{NMC}+\frac{1}{2}\delta\mathbf{v}_{ens}^{T}\delta\mathbf{v}_{ens}+\frac{1}{2}\sum_{t}(\mathbf{d}_t-\mathbf{HM}\delta\mathbf{x}_0)^T\mathbf{R}_t^{-1}(\mathbf{d}_t-\mathbf{HM}\delta\mathbf{x}_0)+J_p,$$

$$\frac{\partial J}{\partial\delta\mathbf{v}_{ens}}=\delta\mathbf{v}_{ens}+\sqrt{\beta}\mathbf{B}_{ens}^{1/2}\frac{1}{2}\sum_{t}\mathbf{M}_t^T\mathbf{H}_t^T\mathbf{R}_t^{-1}(\mathbf{d}_t-\mathbf{H}_t\mathbf{M}_t\delta\mathbf{x}_0)+\frac{\partial J_p}{\partial\delta\mathbf{v}_{ens}},$$

	No localization	Localization(α-vector method)
$\mathbf{B}_{ens}$	$\mathbf{XX}^T$ [n x n]	$\mathbf{XX}^T \circ \mathbf{S}$ [n x n]
$\mathbf{B}_{ens}^{1/2}$	$\mathbf{X}$ [n x m]	$(\mathrm{diag}(\mathbf{x}_1)\mathbf{S}^{1/2},\ldots,\mathrm{diag}(\mathbf{x}_m)\mathbf{S}^{1/2})$ [n x mn]
$dJ/d\mathbf{v}$	$\mathbf{B}_{ens}^{1/2}dJ/d\delta\mathbf{x}$ [m]	$\mathbf{B}_{ens}^{1/2}dJ/d\delta\mathbf{x}$ [mn]
$\delta\mathbf{x}_{ens}$	$\mathbf{B}^{1/2}\mathbf{v}$ [n]	$\mathbf{B}_{ens}^{1/2}\mathbf{v}_{ens}$ [n]

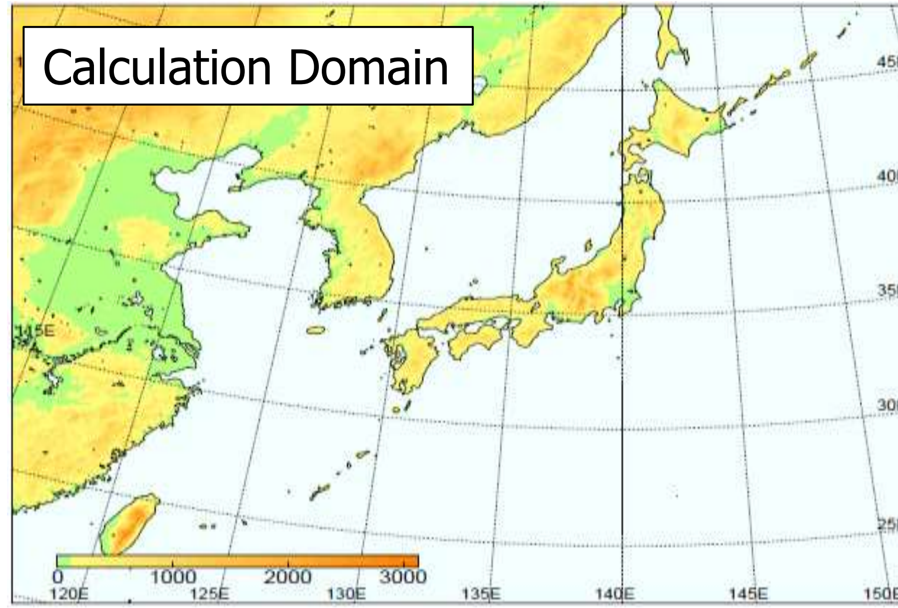
[ ]: size of matrix or vector, $\circ$: Schur product

$\mathbf{X}$: a matrix whose columns are deviations from ens.-mean, $\mathbf{x}_k$.

n: DOF of model, m: # of ens. members, $\mathbf{S}$: Localization operator

JNoVA (4DVAR)

- "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).



$\mathbf{B}_{enkfN}$

$\mathbf{B}_{enkfL}$

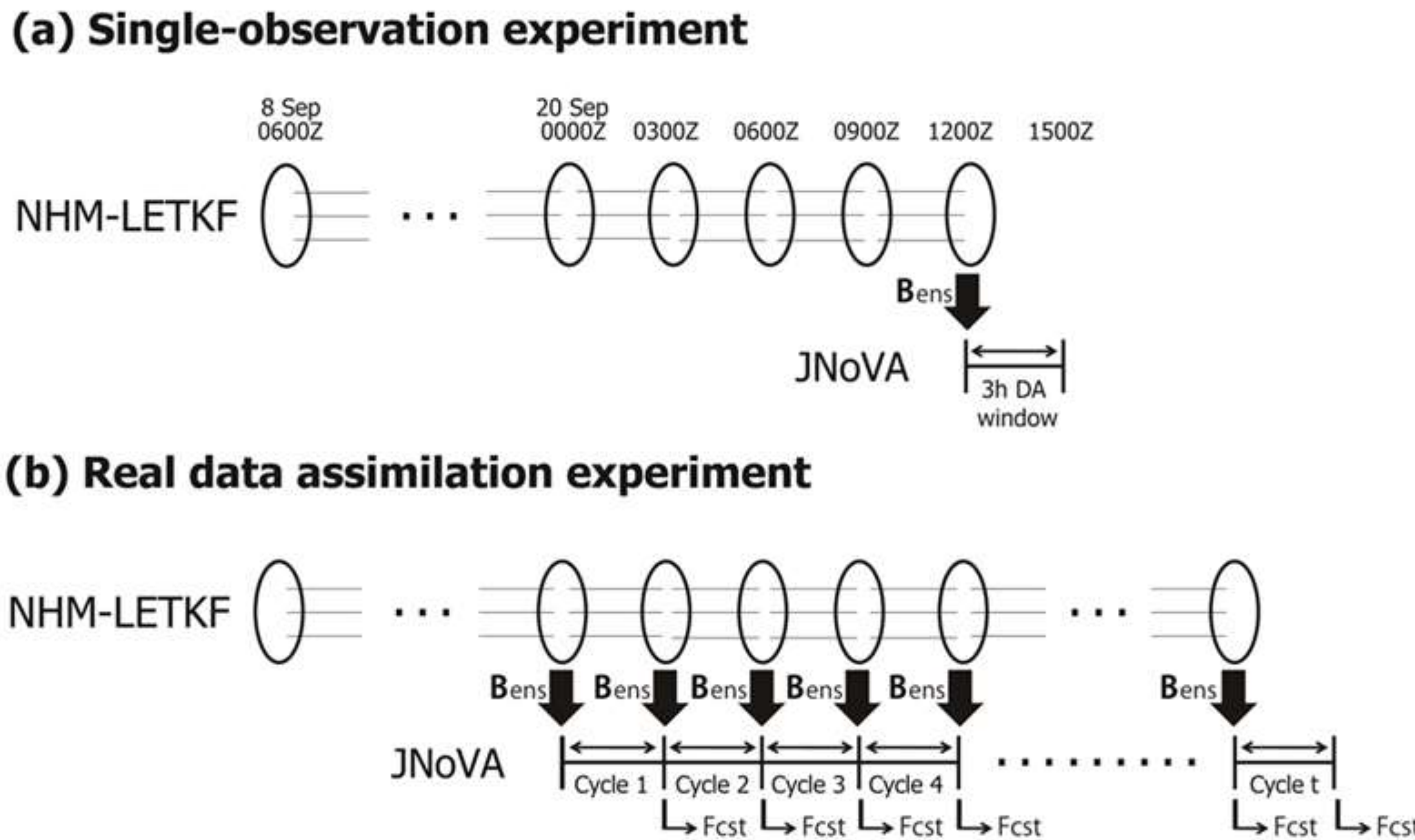
Localization for hybrid

3 x 3 Neighboring, N = 459 member

NHM-LETKF (LETKF)

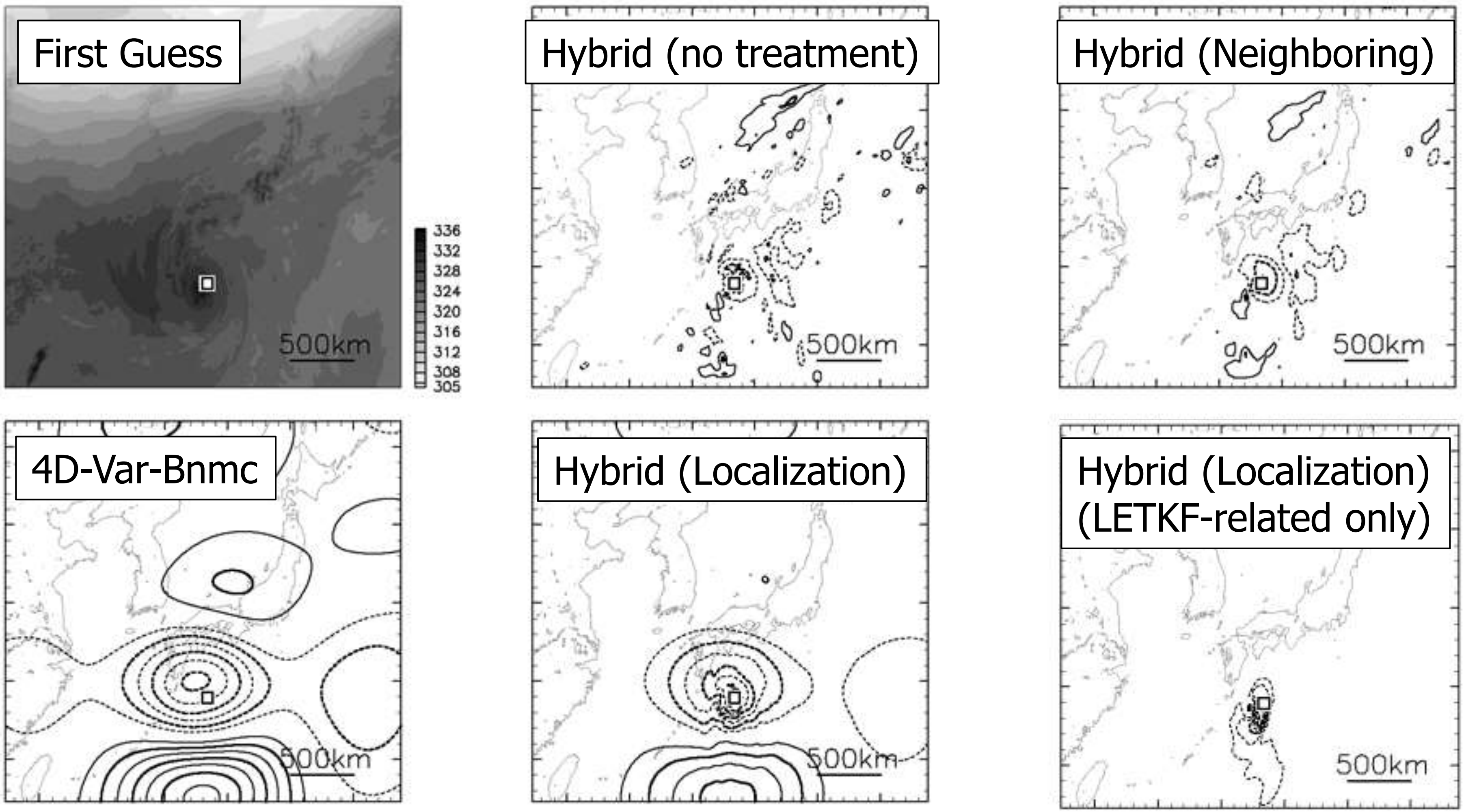
- "JMA-nonhydrostatic model" based LETKF (Kunii 2014)
- Kain-Fritsch scheme
- Analysis system dx = 15km, 50 layers
- 3-h DA update cycles
- Localization scale = 200km
- Adaptive inflation (Miyoshi 2011)
- 51 members

Time scheduling

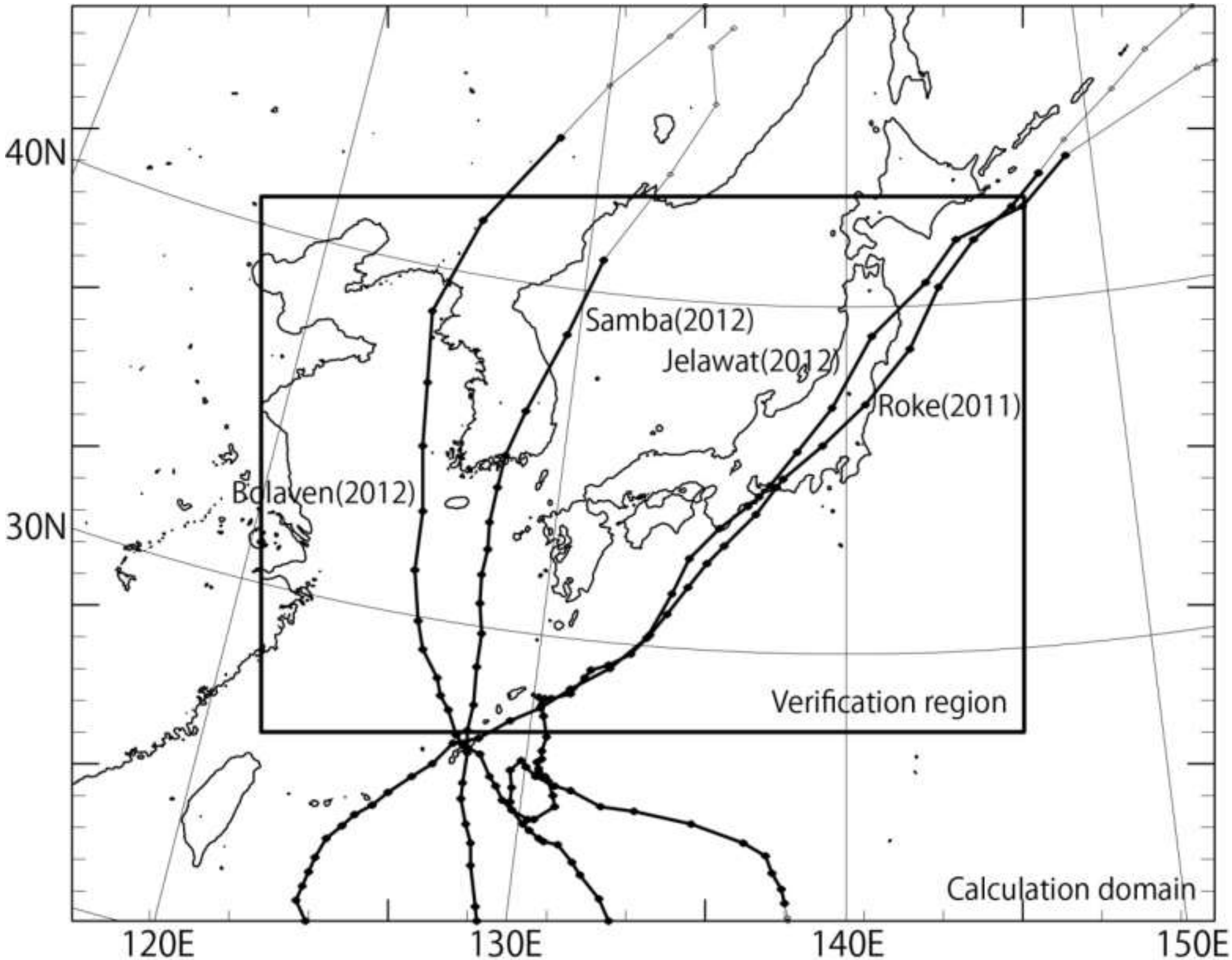


Completely same dynamics is used in fcst, while the dynamics is slightly different in DA process. Ens-mean is used for IC following the LETKF.

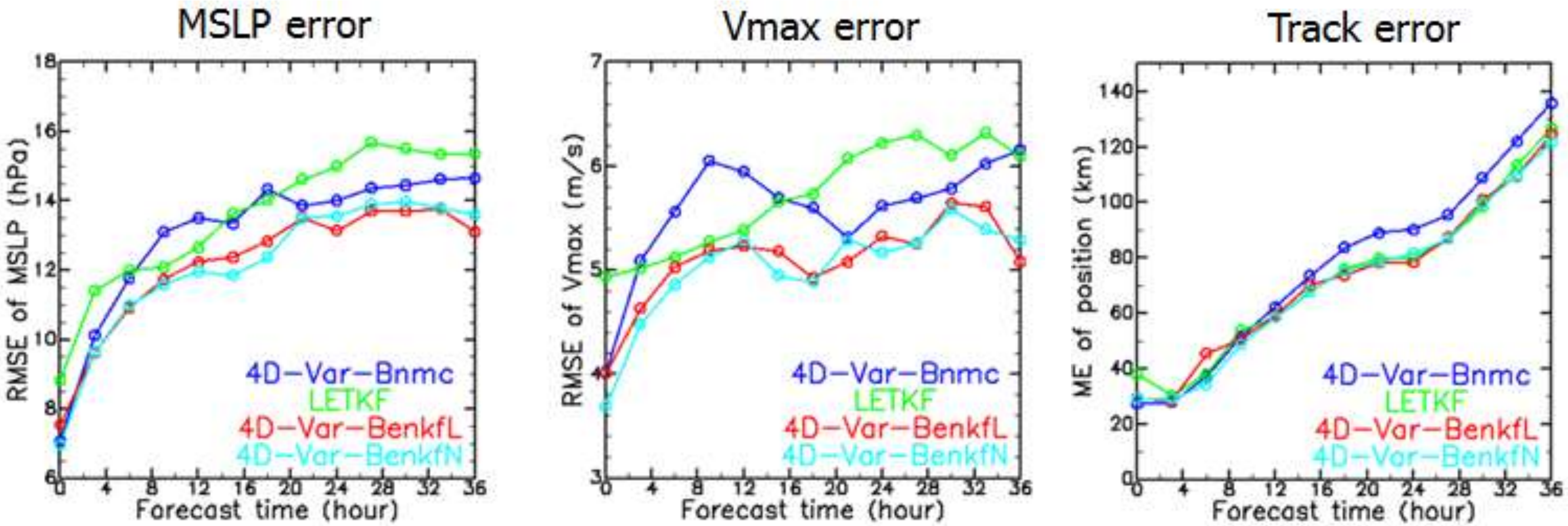
Increment of θ at t=-3 h as a response to the innovation of central pressure

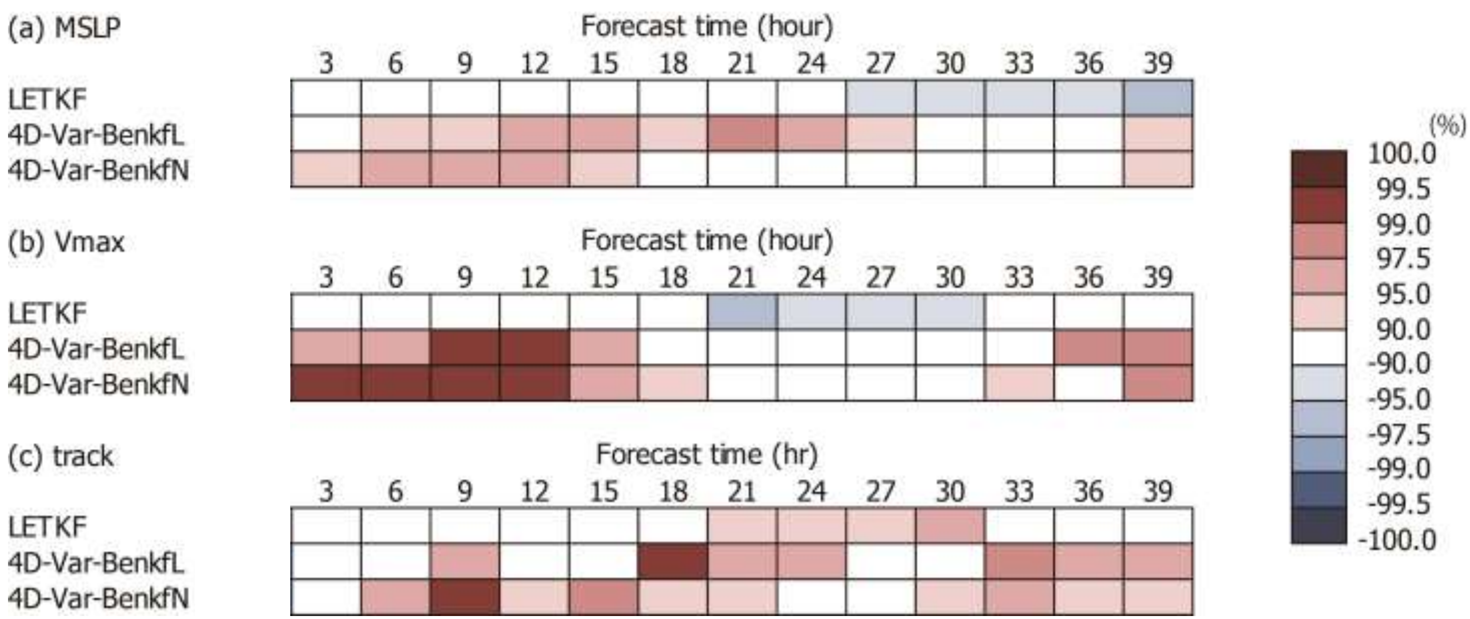


Selected cases: Four intense TCs



Forecast error and statistical significance

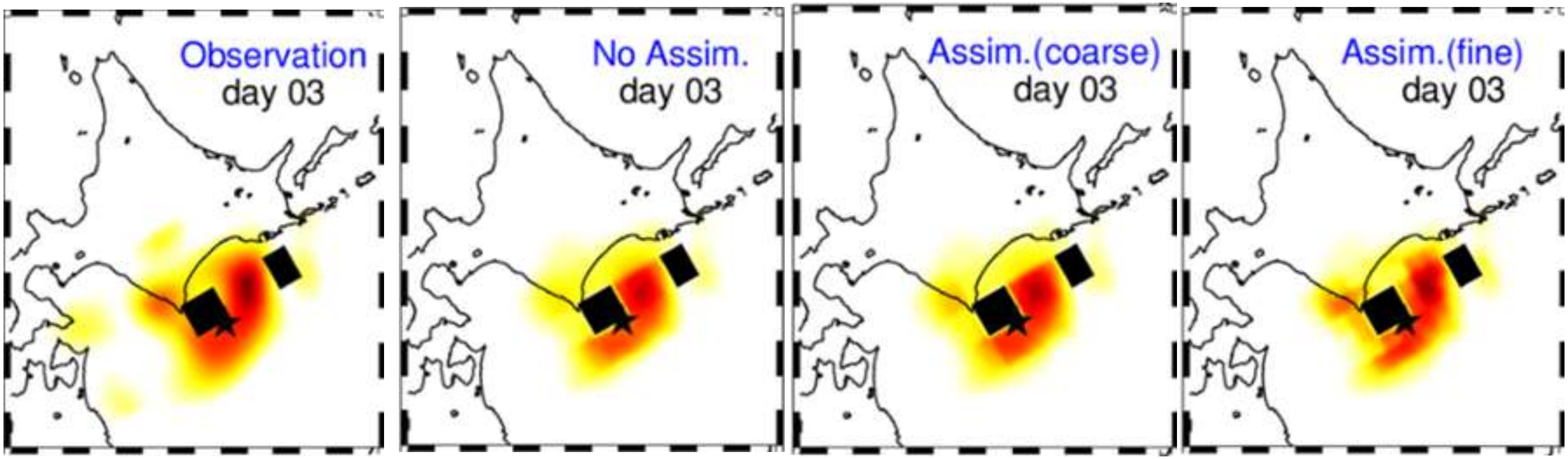


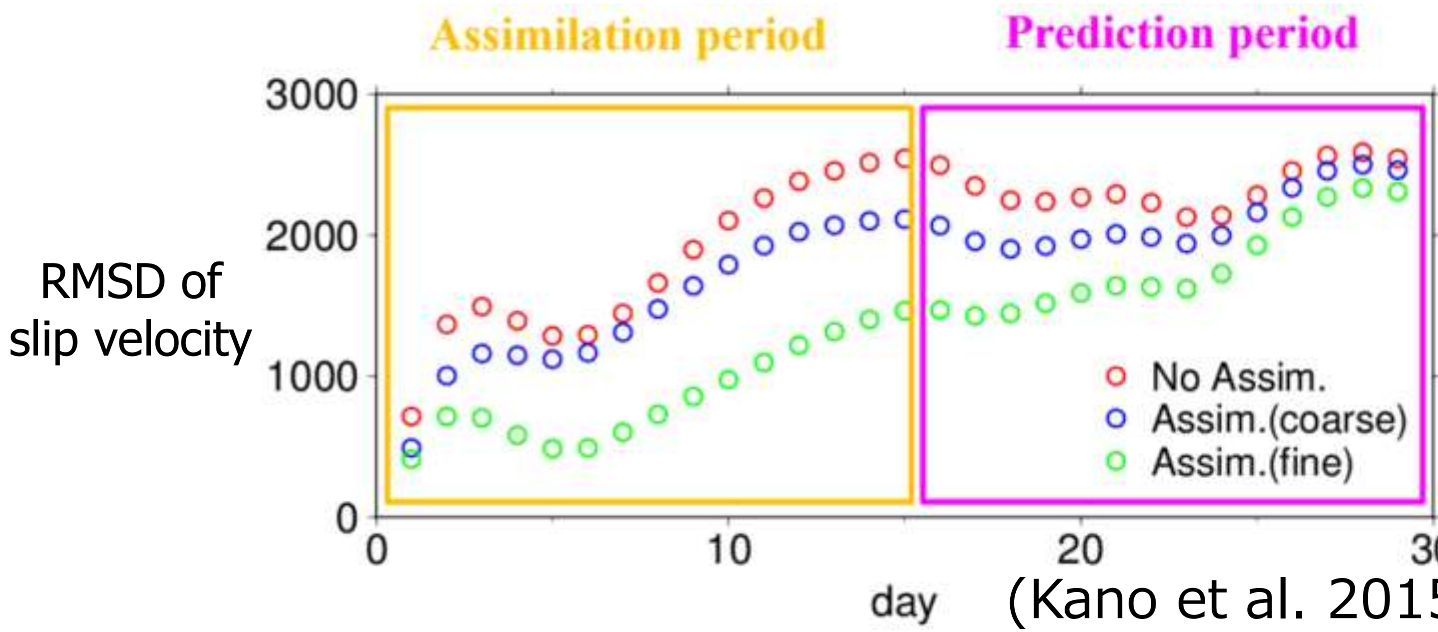


Summary

- 4D-Var-Benkf should be better DA method in an idealized situation (Linearity, Gaussian).
- We tested hybrid DA schemes with localization and neighboring ensemble.
- Single observation DA experiment shows that 4D-Var-Bnmc cannot capture the TC-related feature at the beginning of window.
- We conduct real DA experiments based on 62 forecasts for intense 4 TCs. TC intensity forecast is better in the hybrid systems, while track is better in the hybrid and LETKF.

Advertisement: Real DA (4D-Var) for the afterslip triggered by Tokachi-Oki earthquake (2003)





(Kano et al. 2015; ERI, U. Tokyo)