Impact of Geostationary Satellite Borne Precipitation Radar on NWP: An OSSE with an EnKF for a Typhoon Case

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JAXA Explore to Realize

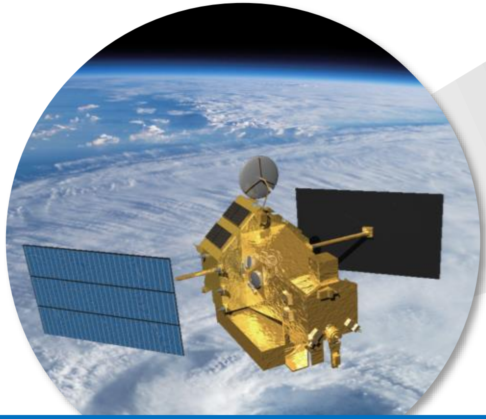
NICT 国立研究開発法人 情報通信研究機構

25 April 2019 @ DA seminar, R-CCS

What's next for satellite-borne radar?

GPR (**G**eostationary satellite borne **P**recipitation **R**adar)
is one of the potential mission as a successor of GPM/DPR

TRMM/PR
1997-2015



GPM/DPR
2014-

Next Generation Rainfall Measurement Satellite

?

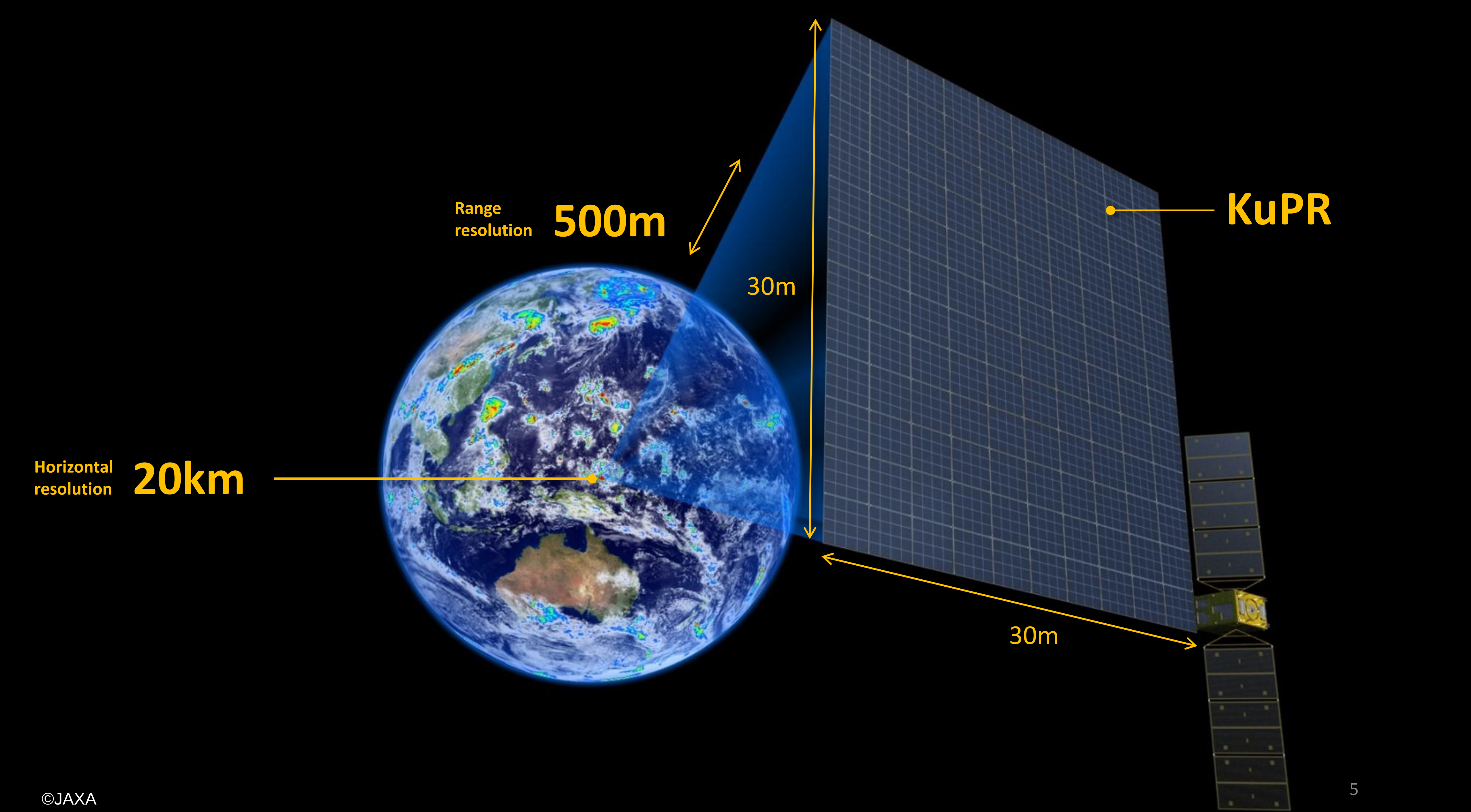
GOAL: To investigate the impact of GPR on typhoon forecast

Today's contents

1. What kind of observation can GPR get?
2. Impact of GPR on NWP

Simulating precipitation radar observations from GPR

Okazaki, Honda, Kotsuki, Yamaji, Kubota, Oki, Iguchi, and Miyoshi, Atomos. Meas. Tech. Discuss., 2018.


Range resolution
500m
30m
KuPR
Horizontal resolution
20km
30m

What kind of observation can GPR get?

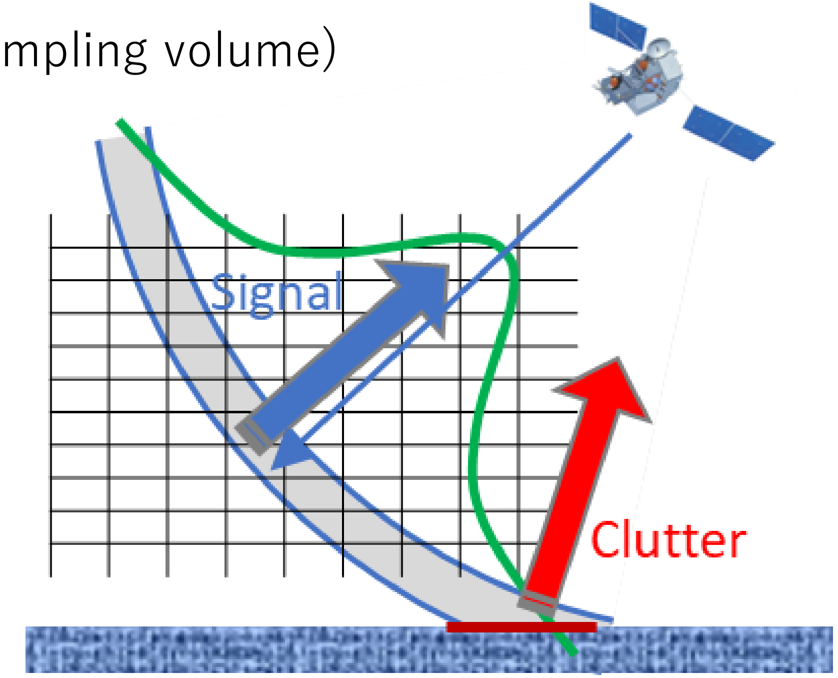
Advantage

- Quasi-continuous precipitation observation
  (c.f. TRMM overpasses 500km-500km box 1-2 times/day)

Disadvantage

- Relatively coarse horizontal resolution (i.e. large sampling volume)
  (c.f. 5km in GPM/DPR)
- Tilted sampling volume at the off-nadir

→ severe ground clutter



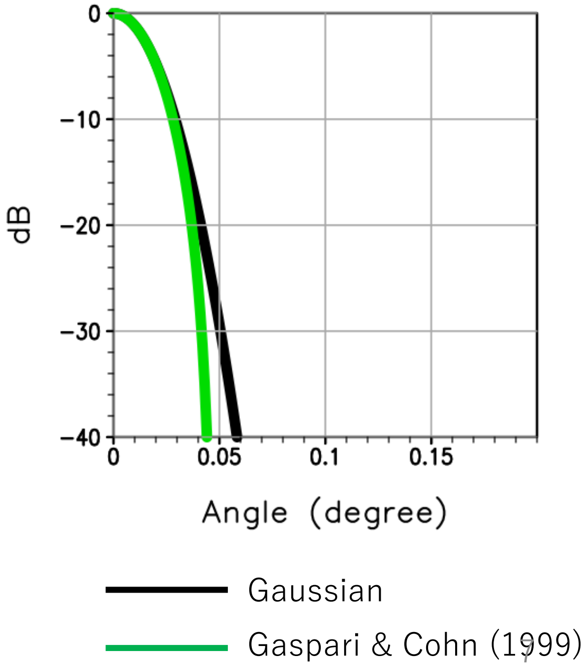
Simulation of GPR observation

Radar-received power from precipitation (P_r):

$$\mathrm{P_r} = \frac{P_t \lambda^2}{(4\pi)^3} \int_{r_0 - c\tau/4}^{r_0 + c\tau/4} \int_{\theta_0 - \pi}^{\theta_0 + \pi} \int_{\phi_0 - \pi/2}^{\phi_0 + \pi/2} f^4(\theta, \phi) \bar{\sigma}_b(r, \theta, \phi)\, r^{-2}\, cos\theta\, d\phi\, d\theta\, dr$$

θ, ϕ:	Scan angle
r:	Range
$f^4(\theta, \phi)$:	Beam pattern (2-way). Gaussian pattern approximated by 5th order polynomial is used
$\bar{\sigma}_b(r, \theta, \phi)$:	total backscattering calculated with Joint-Simulator (Hashino et al., 2013; Masunaga & Kummerow, 2005). Single particle backscattering is calculated by assuming the Mie-approximation.

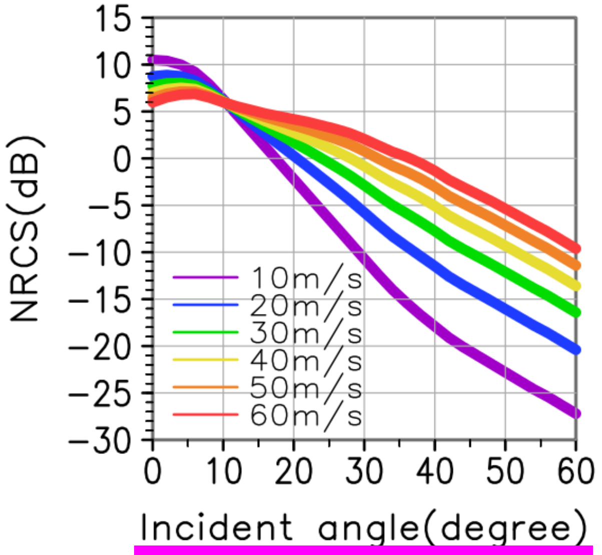
Beam pattern



Simulation of GPR observation

Radar-received power from the surface (P_s)

$$\mathrm{P_s} = \frac{P_t \lambda^2}{(4\pi)^3} \iint_A \frac{f^4(\theta,\phi)\sigma_0}{r^4} dA$$

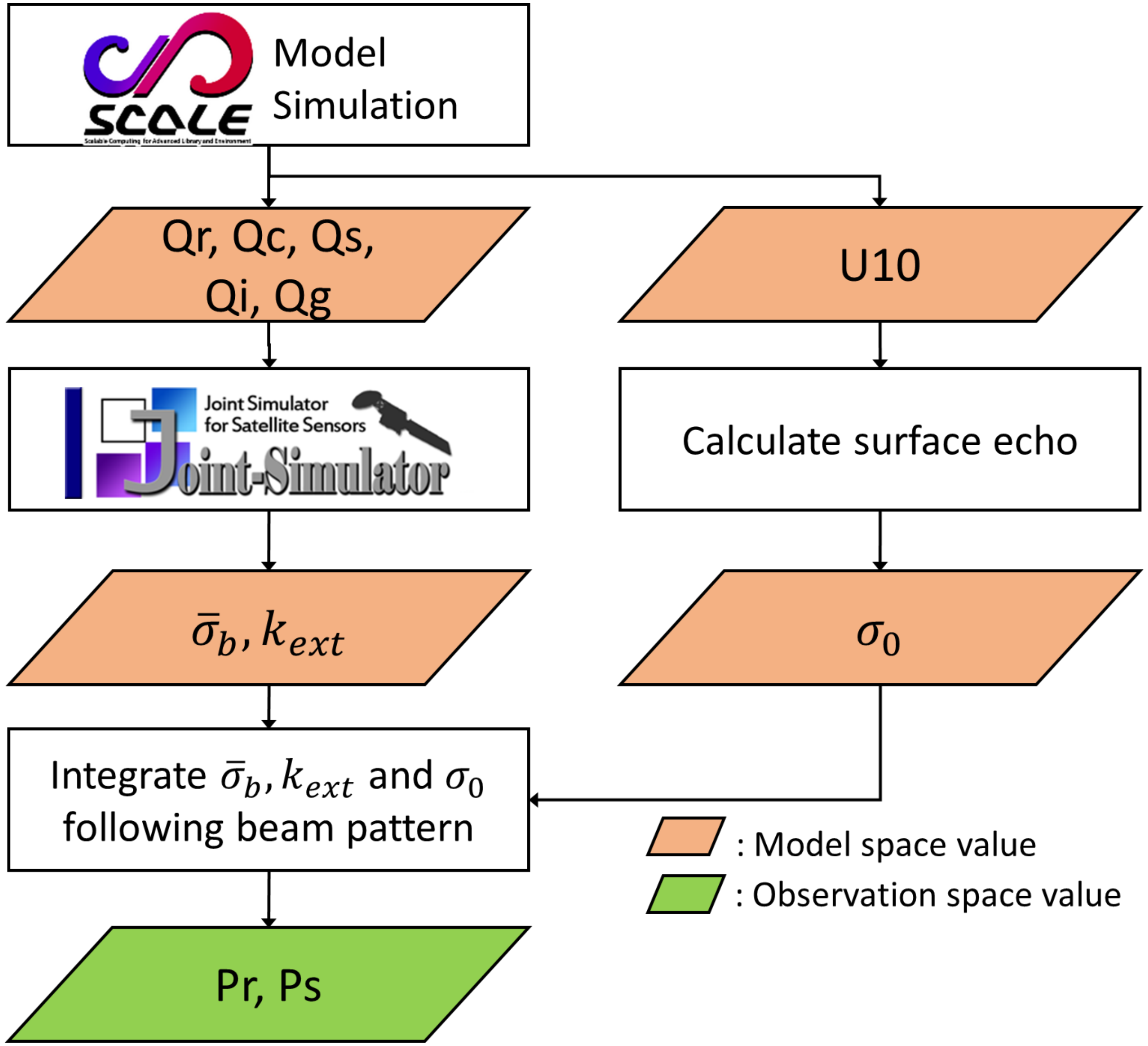


Normalized radar cross section (NRCS) for sea surface
(Wentz et al., 1984)

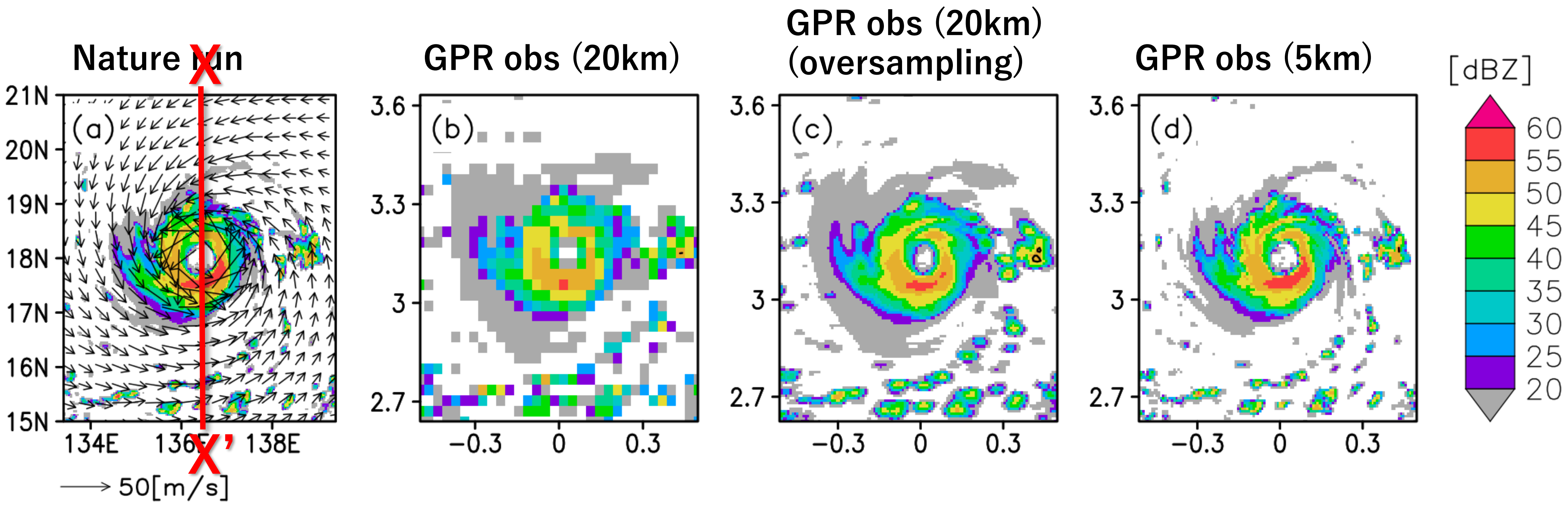
$$\sigma_0 = b_0(U_{10})^{b_1}$$

$P_s \sim$ surface wind speed and incident angle

Simulation of GPR observation

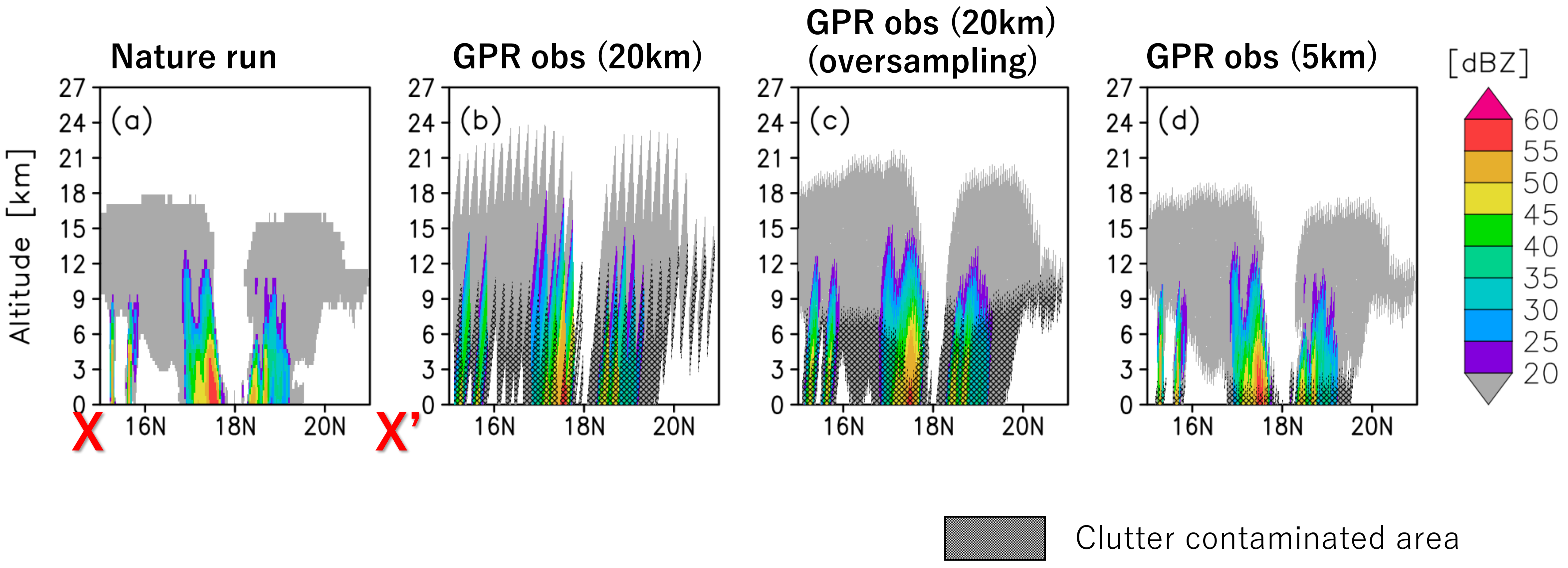


Simulation of GPR observation: A real case



Okazaki et al.: Simulating precipitation radar observations from a geostationary satellite, *Atmos. Meas. Tech.*, 2019.

Simulation of GPR observation: A real case



Okazaki et al.: Simulating precipitation radar observations from a geostationary satellite, *Atmos. Meas. Tech.*, 2019.

Simulation of GPR observation (revised)

Radar-received power from precipitation (P_r):

$$\mathrm{P_r} = \frac{P_t \lambda^2}{(4\pi)^3} \int_{r_0 - c\tau/4}^{r_0 + c\tau/4} \int_{\theta_0 - \pi}^{\theta_0 + \pi} \int_{\phi_0 - \pi/2}^{\phi_0 + \pi/2} f^4(\theta, \phi) \bar{\sigma}_b(r, \theta, \phi) A_P(r, \theta, \phi)\, r^{-2} \cos\theta \, d\phi \, d\theta \, dr$$

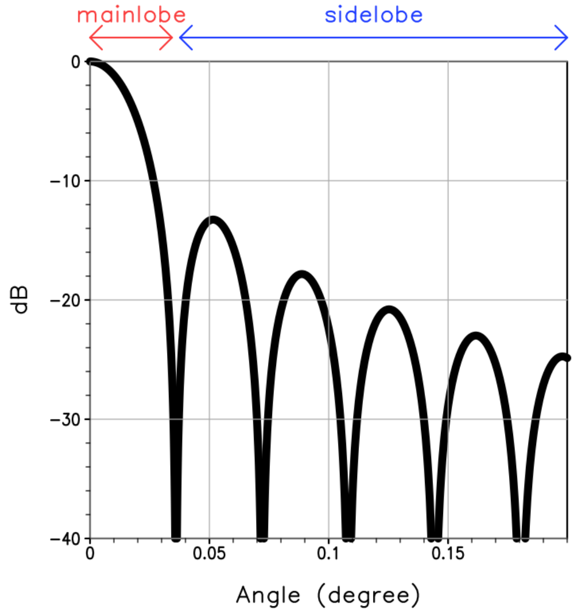
θ, ϕ: Scan angle

r: Range

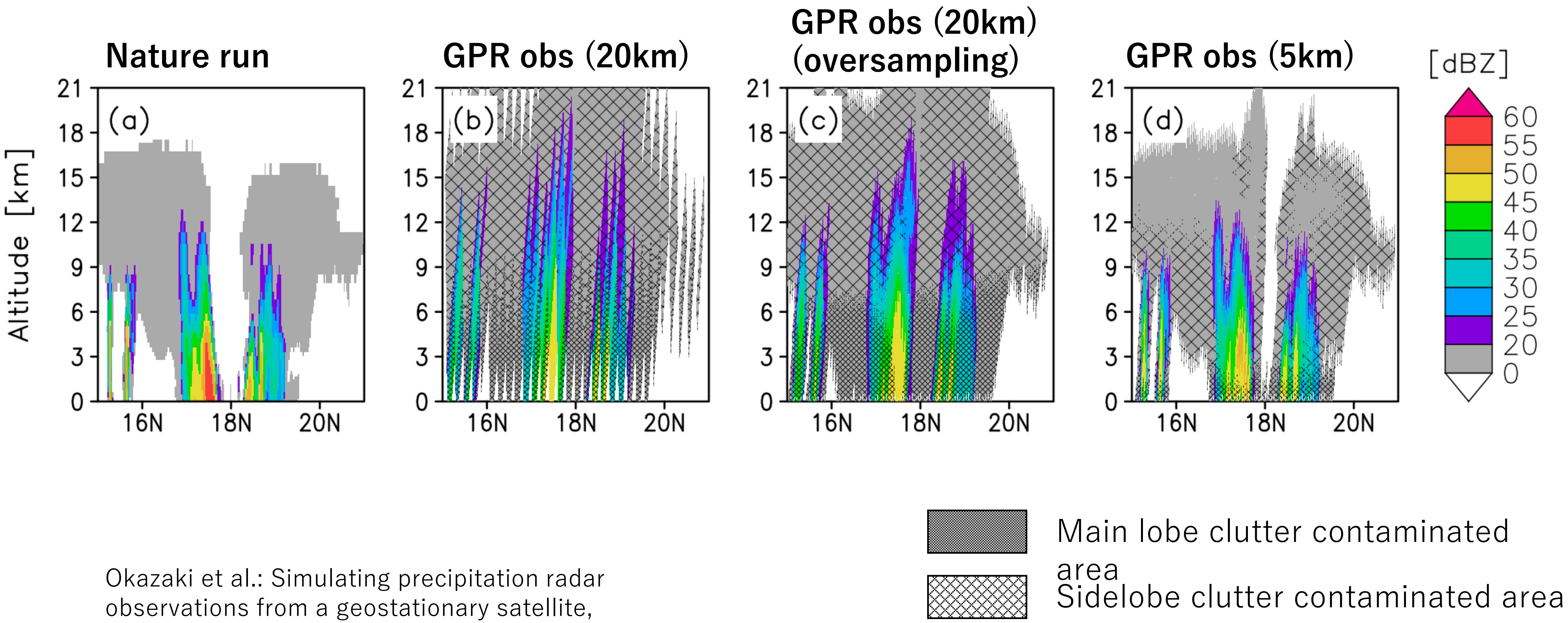
$f^4(\theta, \phi)$: Beam pattern (2-way). Uniform-distribution is assumed

$\bar{\sigma}_b(r, \theta, \phi)$: total backscattering calculated with Joint-Simulator (JS; Masunaga & Kummerow, 2005). Single particle backscattering is calculated by assuming the Mie-approximation.

$A_P(r, \theta, \phi)$: Attenuation coefficient.
$A_P(r, \theta, \phi) = \exp\left[-2 \int_0^r \bar{k}_{ext}(r', \theta, \phi) dr'\right]$, where $\bar{k}_{ext}$ is extinction coefficient calculated by JS

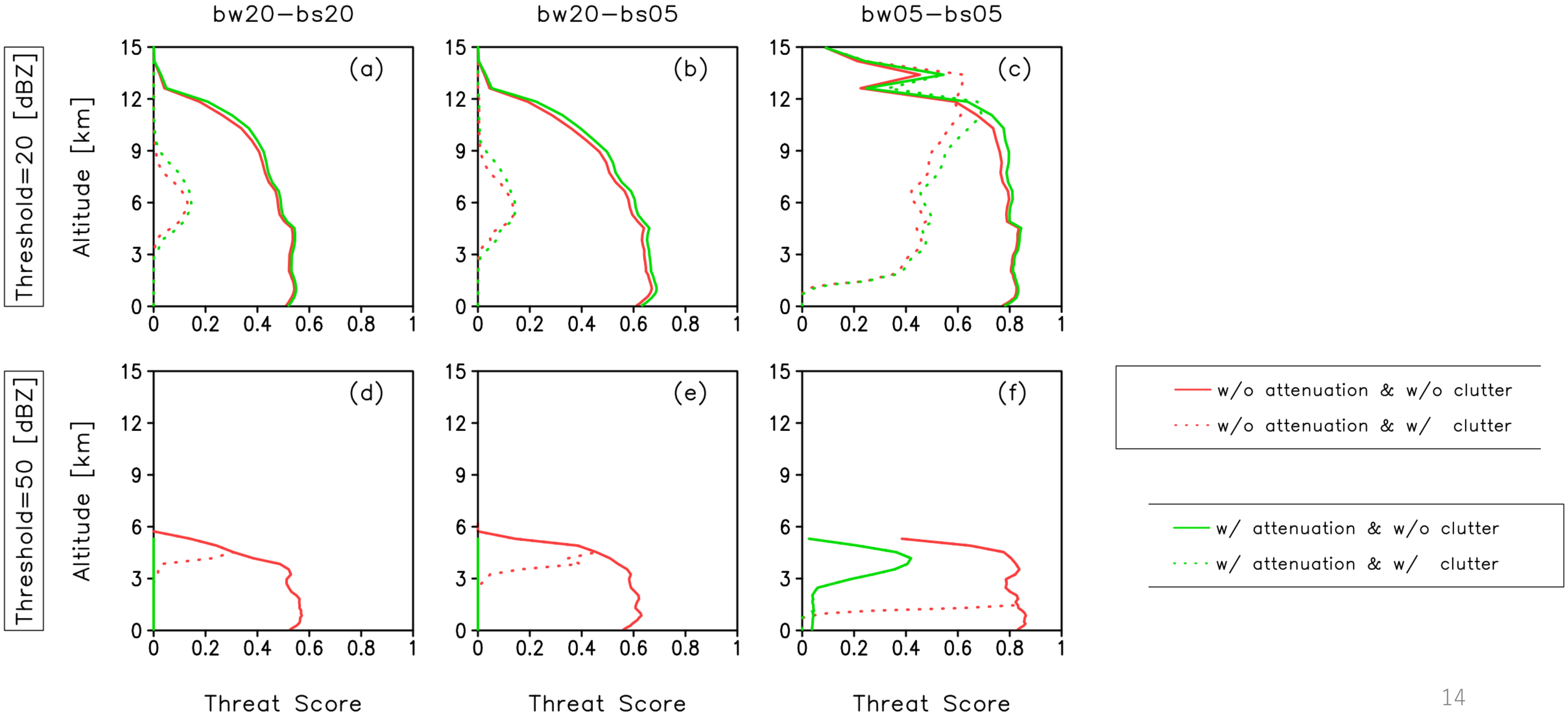


Simulation of GPR observation: A real case w/ sidelobe clutter & attenuation



Okazaki et al.: Simulating precipitation radar observations from a geostationary satellite, *Atmos. Meas. Tech.*, 2019.

Simulation of GPR observation: A real case w/ sidelobe clutter & attenuation

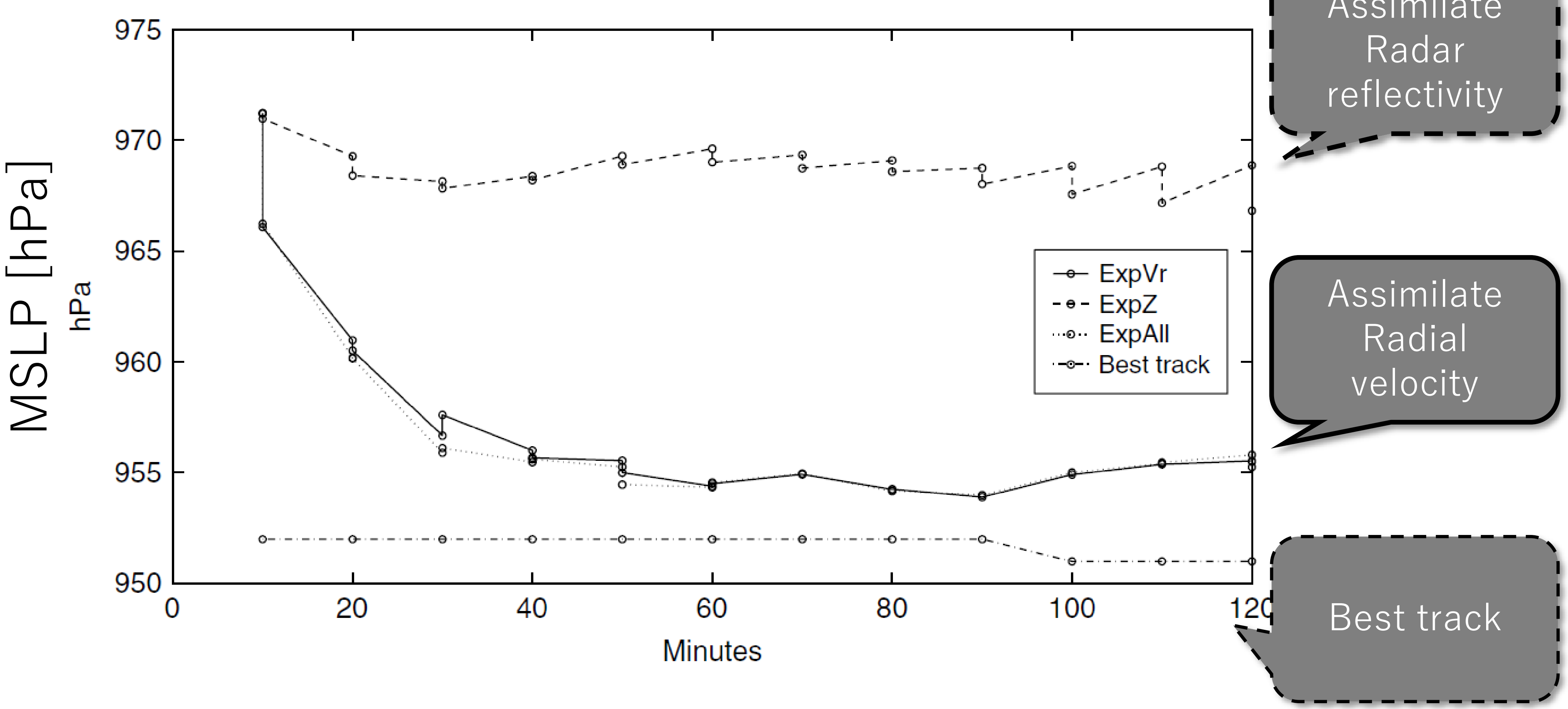


Assimilation of Radar reflectivity for Tropical Cyclone with an EnKF

Preparatory experiments for GPR assimilation

Difficulty in reflectivity assimilation

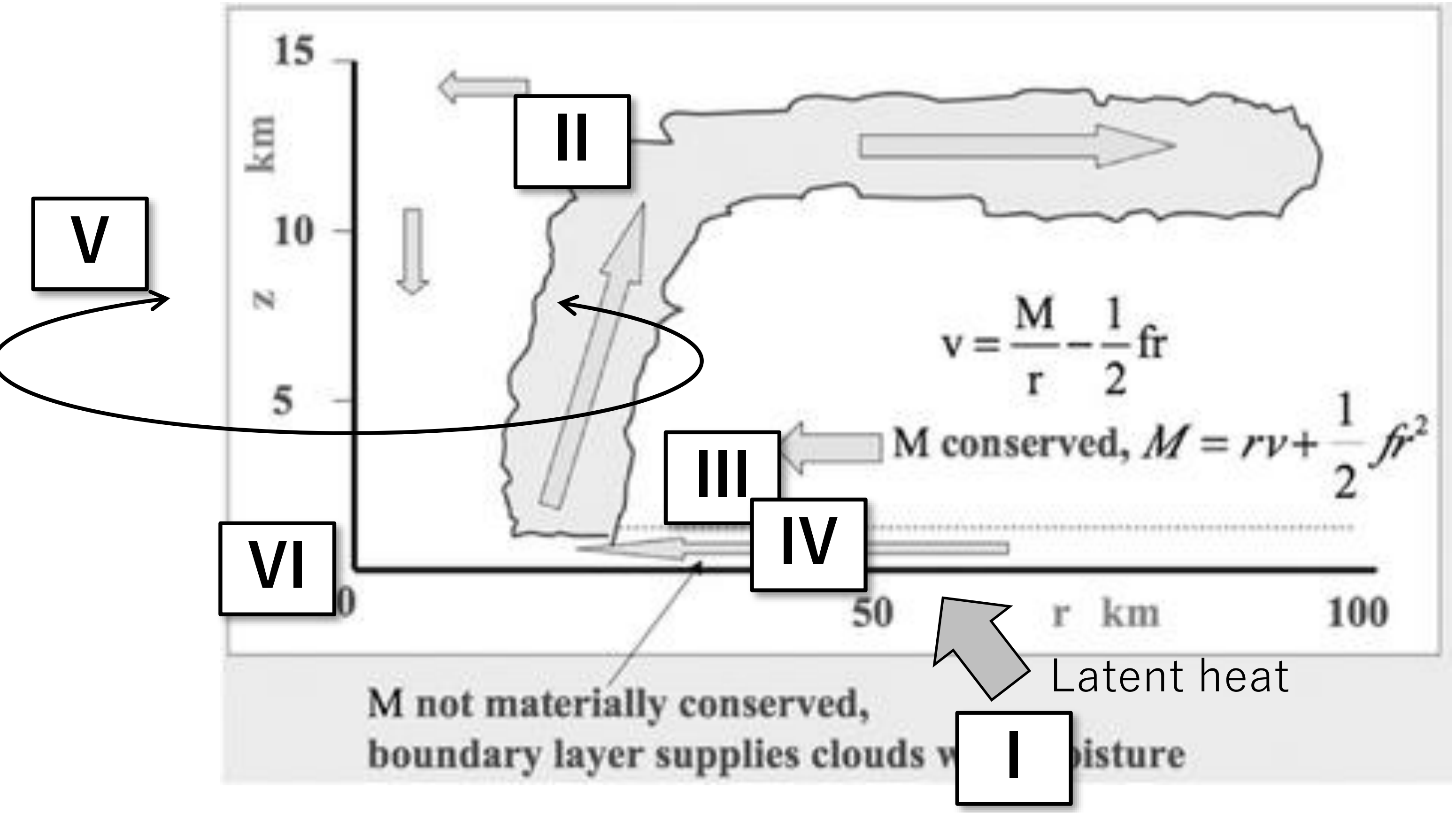
- Assimilation of radar reflectivity fails to produce deepening of tropical cyclone (Dong & Xue, 2013)



Update p, qv, & hydrometeors

Is it possible to simulate TC only with Z...?

Conventional view of TC intensification



Schematic of height-radius cross-section of TC
Montgomery & Smith (2010)

I. Inflowing air acquires heat
II. Convection in the inner-core region
III. Convergence in the lower boundary layer is accelerated
IV. advects angular momentum
V. intensify primal circulation
VI. TC deepening through gradient adjustment

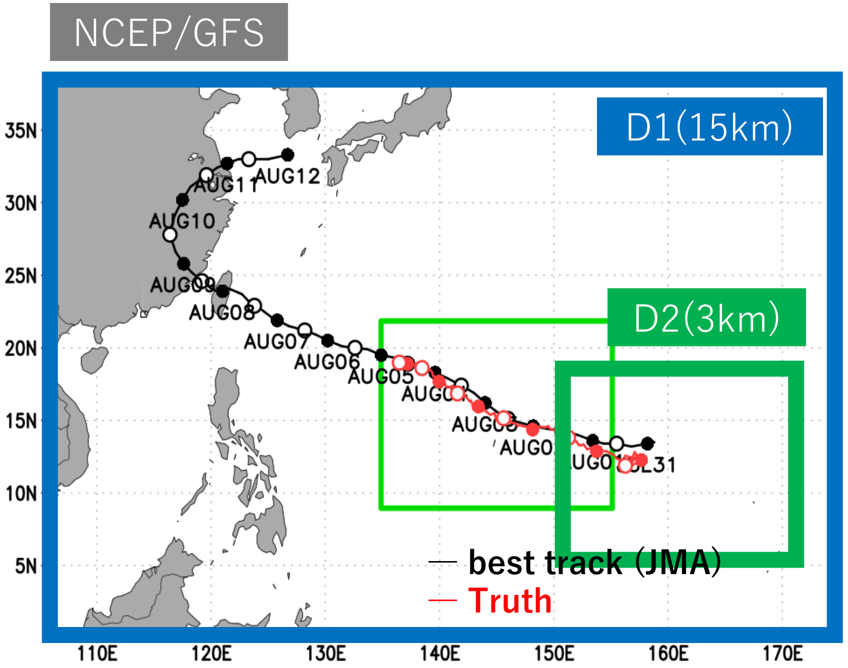
TC must be intensified by assimilating reflectivity

Experimental Design

- **Experiment type**
  - Perfect model OSSE
- **Case**
  - Typhoon Soudelor (2015)
- **Observation**
  - Radar reflectivity at all the model grid point
  - Frequency: 1 [h]
  - Error: 5 [dBZ]
- **DA system**
  - SCALE-LETKF (Lien et al., 2017)
  - Joint-Simulator (Hashino et al., 2013) to calculate radar reflectivity
  - 50 members
  - Localization: H: 10km, V: 0.3lnp
  - Inflation: RTPP with $\alpha = 0.8$ (Zhang et al., 2004)
  - Thinning: 1/25 horizontally & 1/5 vertically
  - Clear reflectivity shift (G.-Y. Lien, personal communication)

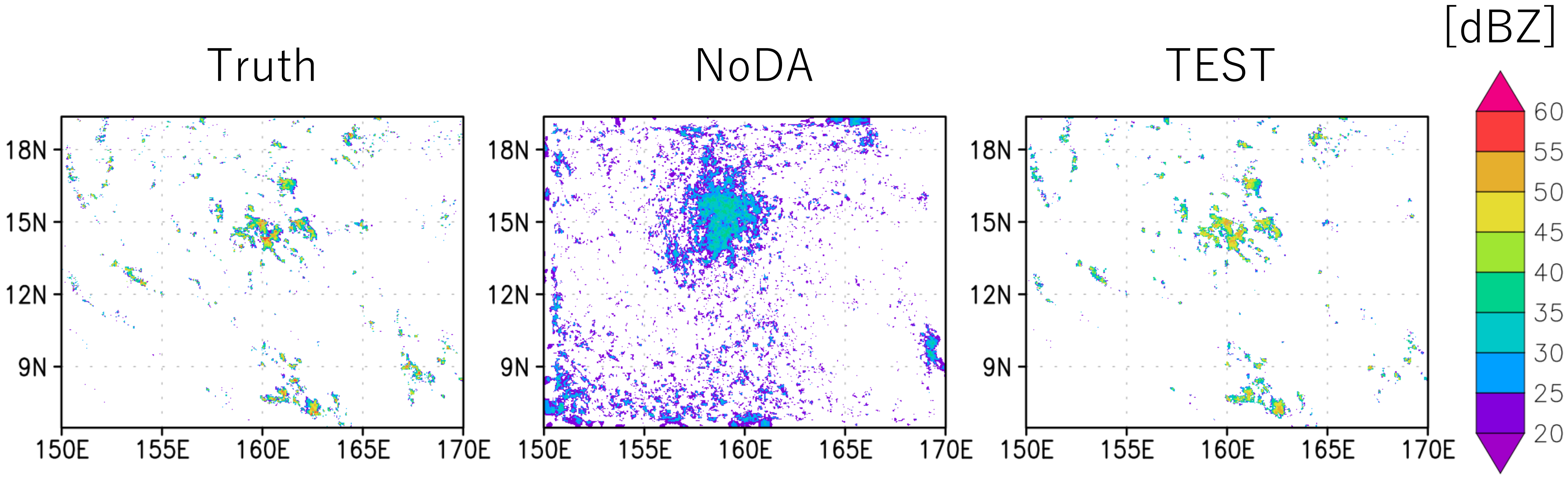
$$y = \begin{cases} y \ (y \geq 20dBZ) \\ 15 \ (y < 20dBZ) \end{cases}$$

(similar to Aksoy et al., 2009, but leave a 5-dBZ gap)



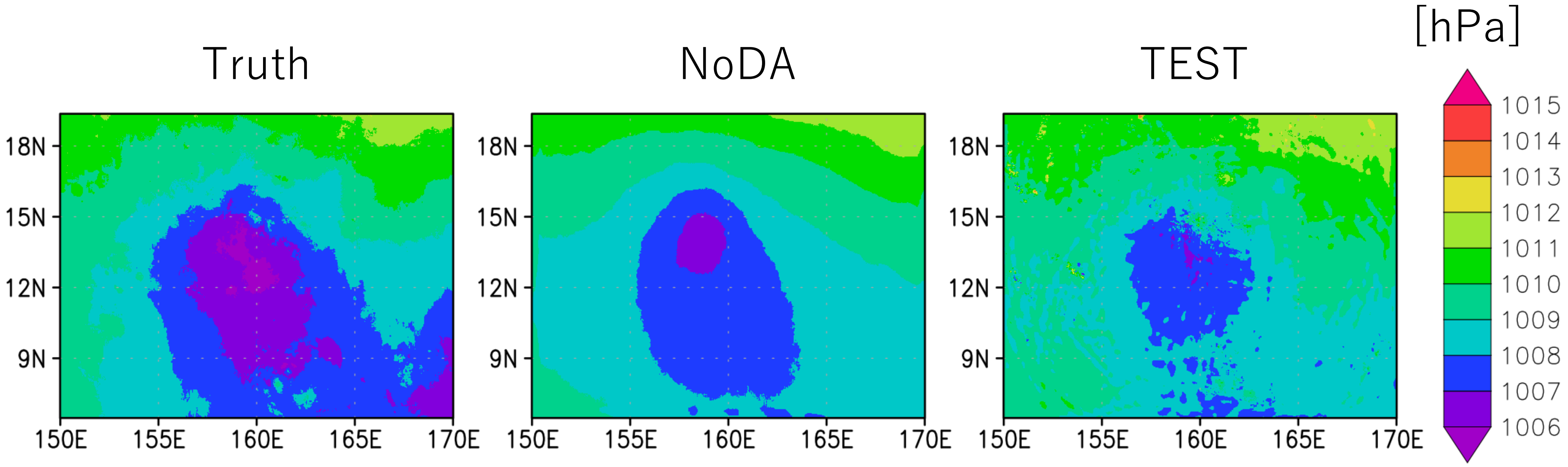
Z @ 1000[m]: temporal evolution

2015/7/29 0700 – 2015/7/30 0900



SLP: temporal revolution

2015/7/29 0700 – 2015/7/30 0900

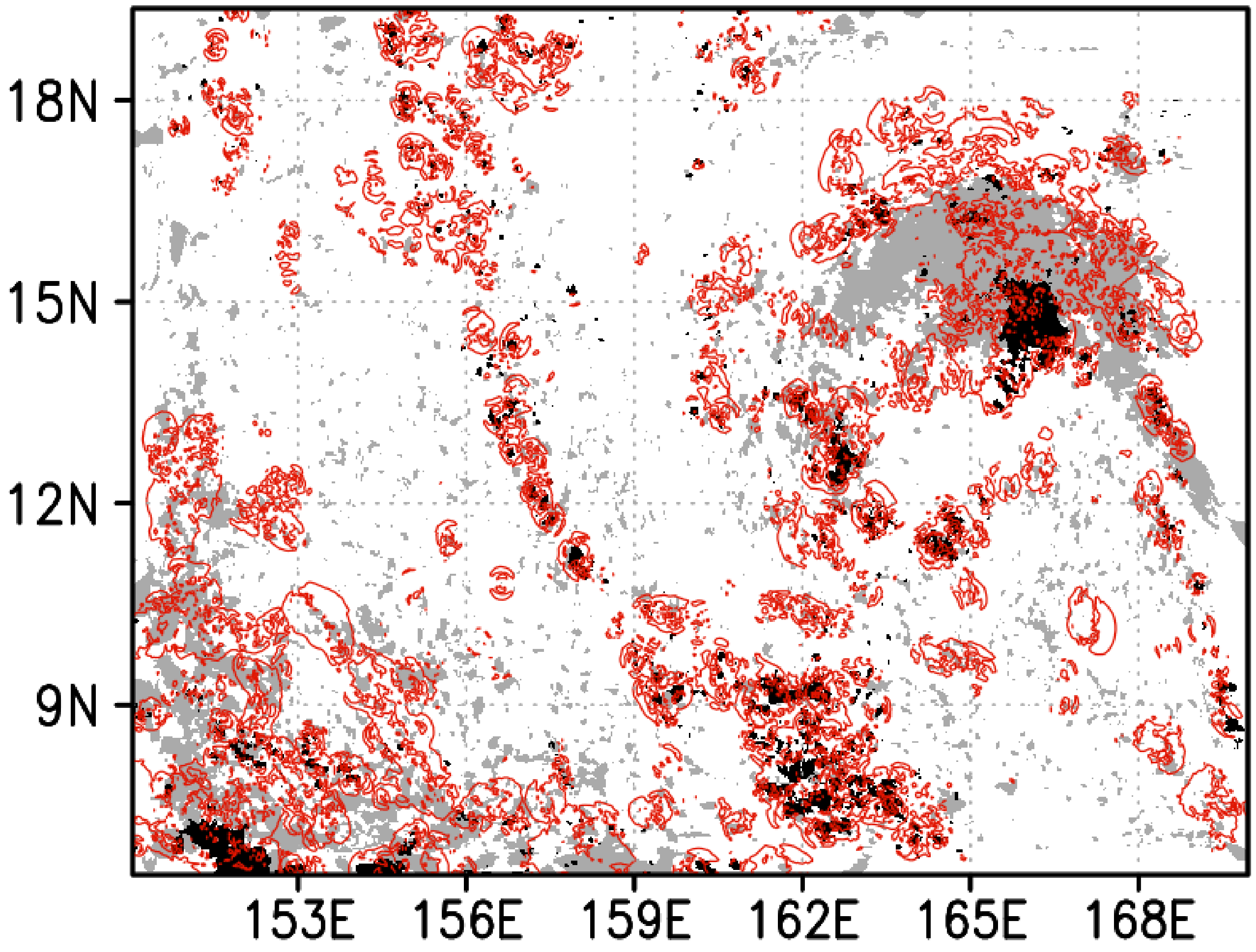


SLP fields are contaminated by noise!

Where does the noise come from?

■: $\mathrm{dBZ}_{\mathrm{anal}}$ (>20)
■: $\mathrm{dBZ}_{\mathrm{gues}}$ (>20)
□: $|\partial P_s/\partial t|$ (=1 Pa s^{-1})

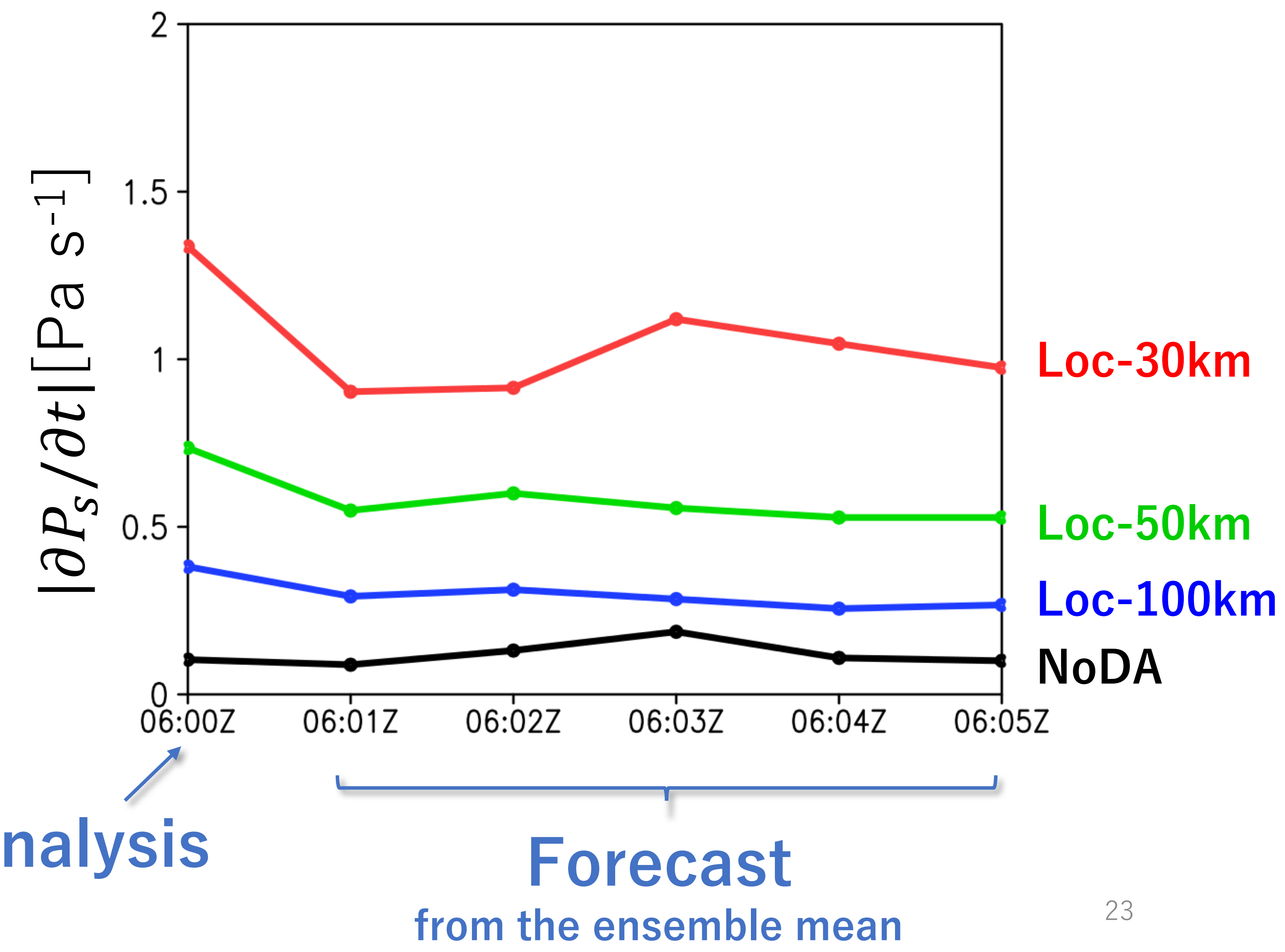
$|\partial P_s/\partial t|$: metric of imbalances
(Lange and Craig, 2014; Bick et al., 2016)



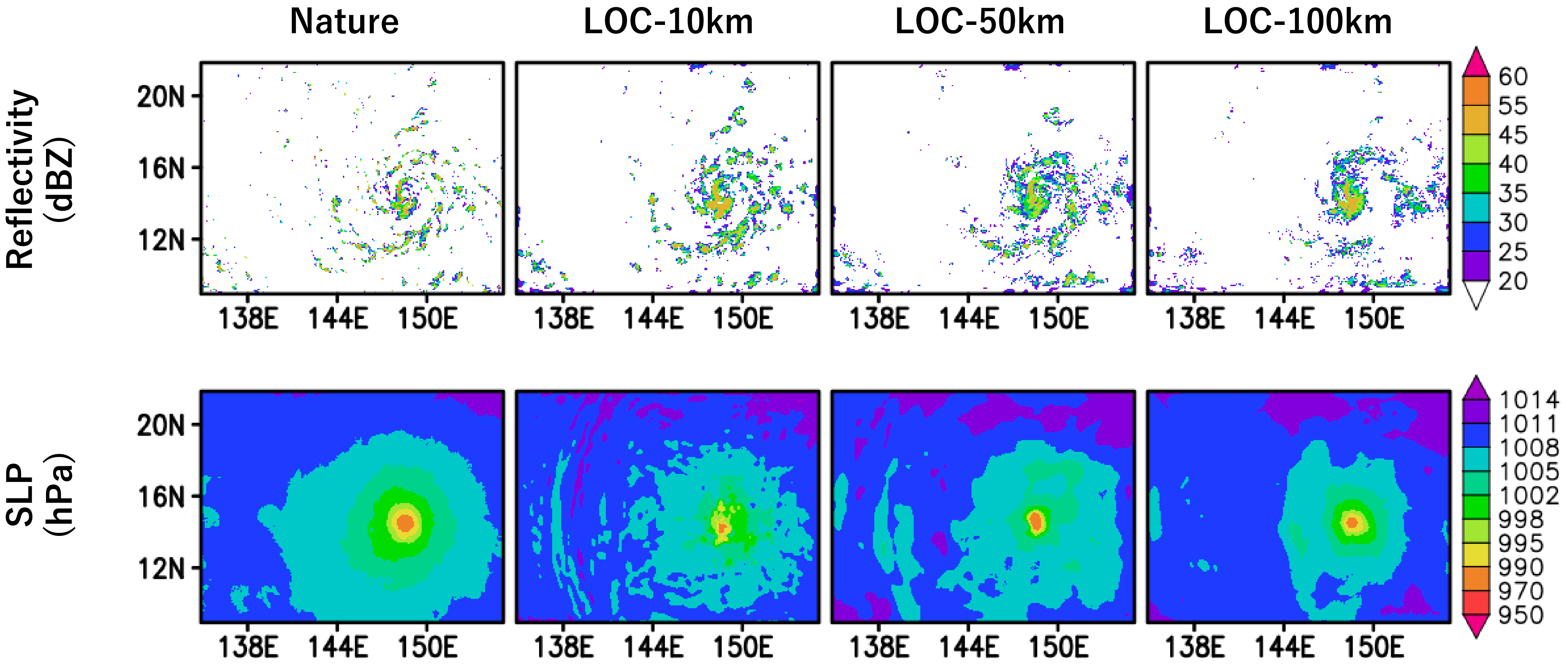
Localization and Imbalance

- Localization induces imbalance (Lorenc, 2003; Greybush et al., 2011)

Exp.	Obs.	Localization
NoDA	-	-
Loc-30km	Z	$\sigma_H = 30km$
Loc-50km	Z	$\sigma_H = 50km$
Loc-100km	Z	$\sigma_H = 100km$



Sensitivity to the localization scale



Localization in previous radar-DA

Reference	Ensemble size	Analysis grid (km)	Localization cutoff (*r*, km)
Snyder and Zhang (2003)	50	2	H : 4; V : 4
Dowell et al. (2004)	50	2	H : 6; V : 6
Tong and Xue (2005)	100	2	H : 8; V : 8
Caya et al. (2005)	100	2	H : 7.3; V : 7.3
Aksoy et al. (2009)	50	2	H : 5; V : 4
Dowell and Wicker (2009)	50	1	H : 6; V : 6
Dowell et al. (2011)	50	1	H : 6; V : 6
Dong et al. (2011)	50	2	H : 6; V : 6
Dawson et al. (2012)	30	1	H : 12; V : 6

Sobash and Stensrud (2013)

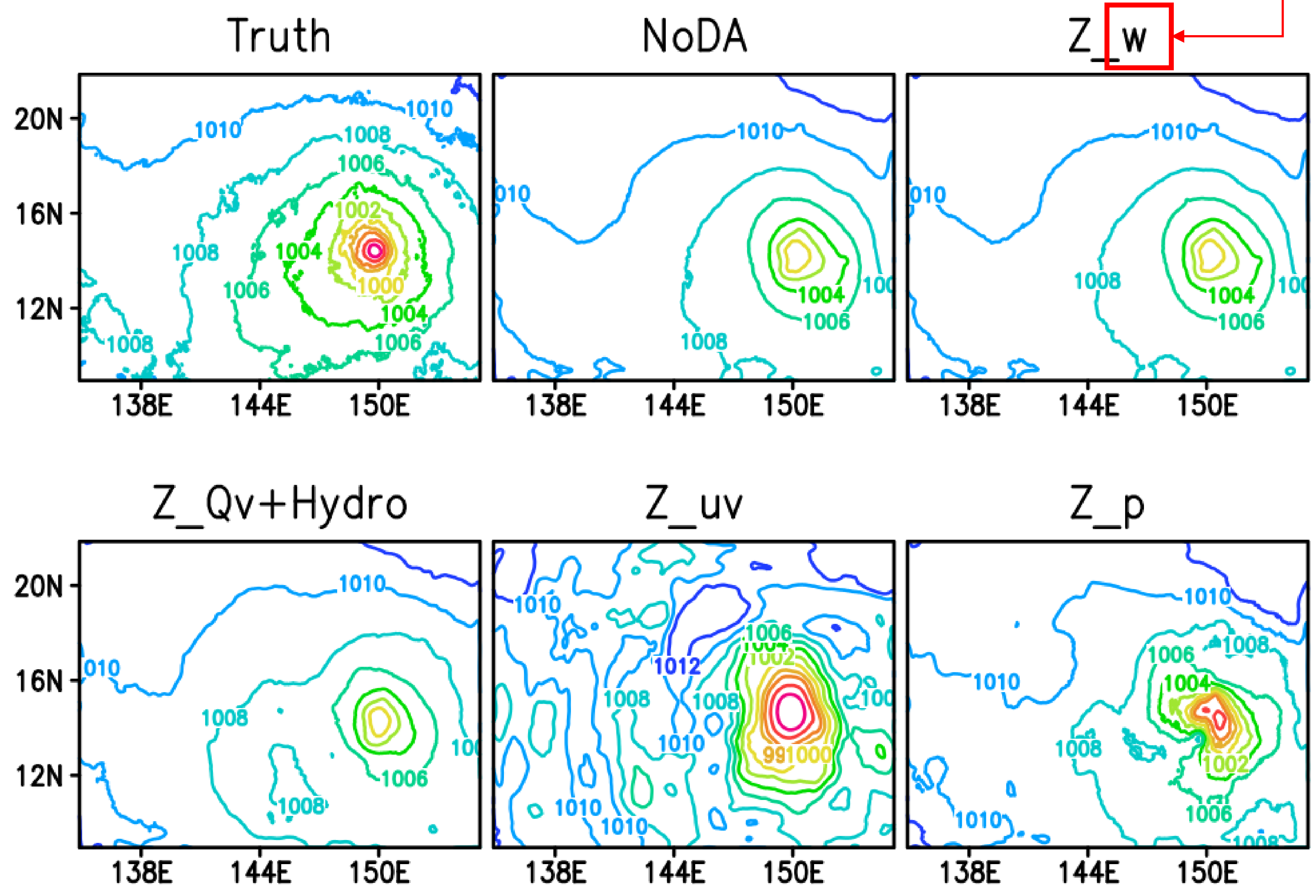
TC case

	Zhang et al. (2009)	30	4.5	H: 135, 405 (SCE)
	Aksoy et al. (2012)	30	3	H: 240
Reflectivity→	Dong and Xue (2013)	32	4	H : 12; V : 4
Brightness → Temperature	Zhang et al. (2016)	60	3	H: 30 (200) for hydro (others)
	Honda et al. (2018)	50	3	H: 219

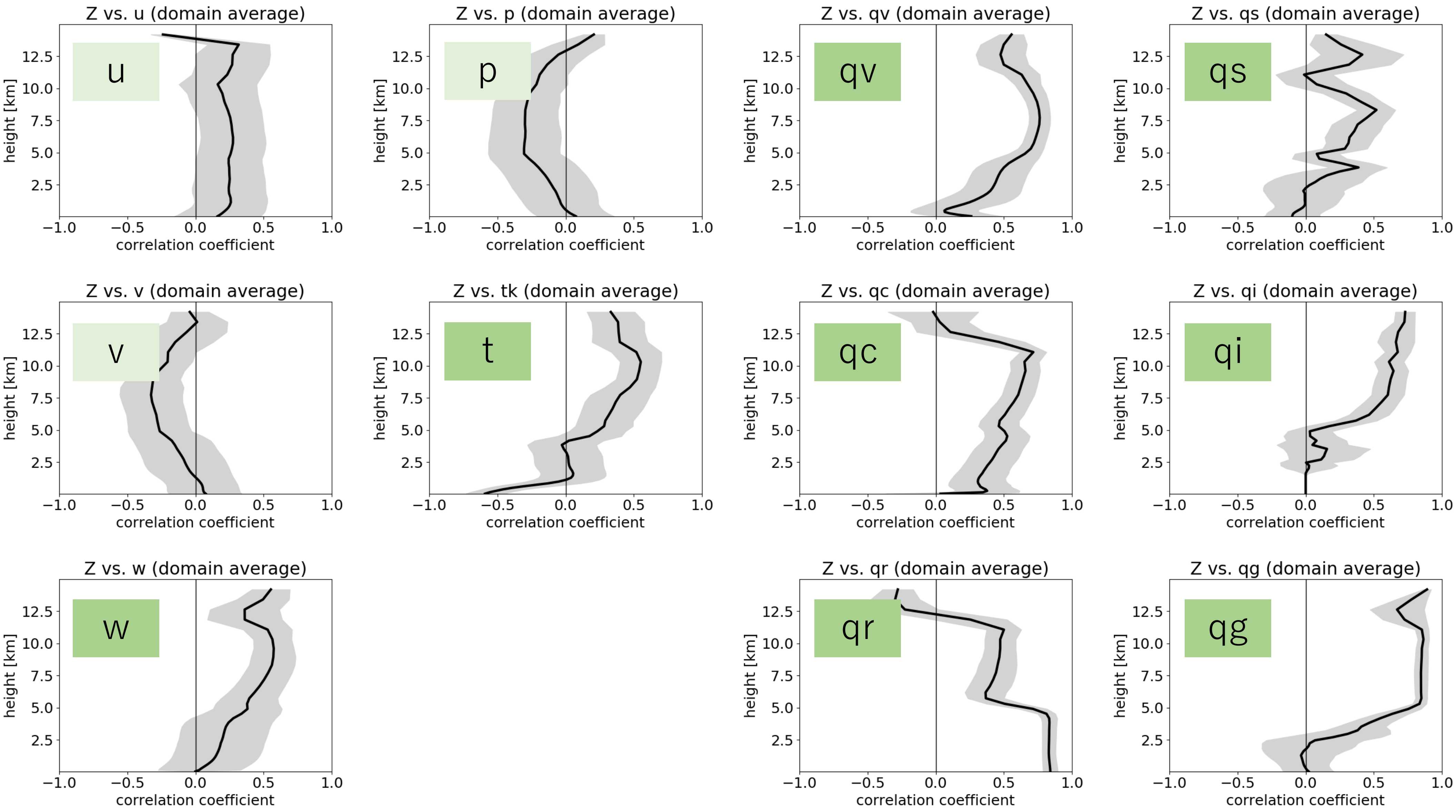
Another source of noise in SLP

UPDATE ONLY

- Sea Level Pressure (hPa)
- Variable localization (Kang et al., 2011)



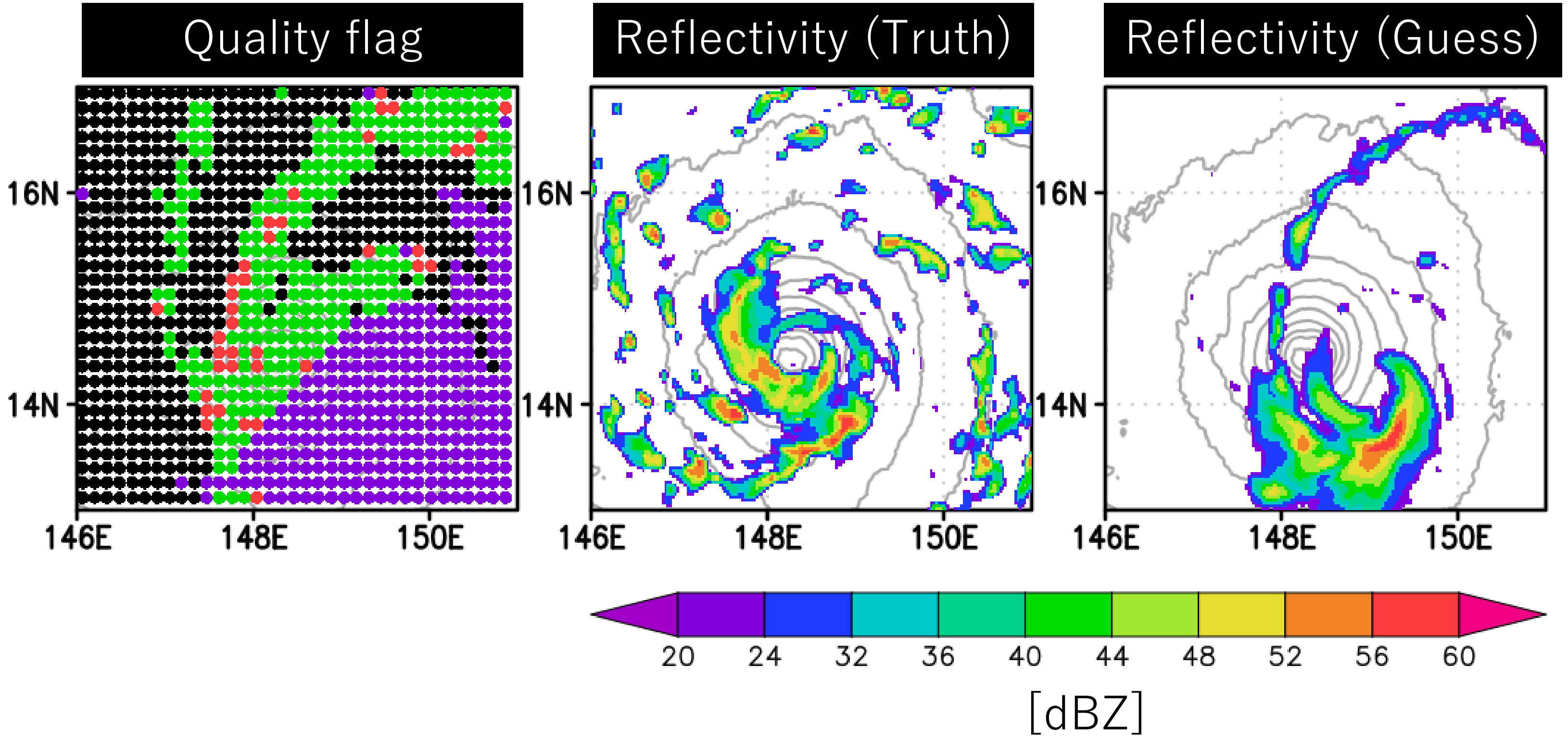
Correlation b/w reflectivity and model prognostic variables



Another issue: #Observation

More than 60% of the observations were rejected!

- qc_good
- qc_ref_mem
- qc_gross_error
- qc_out_vlo



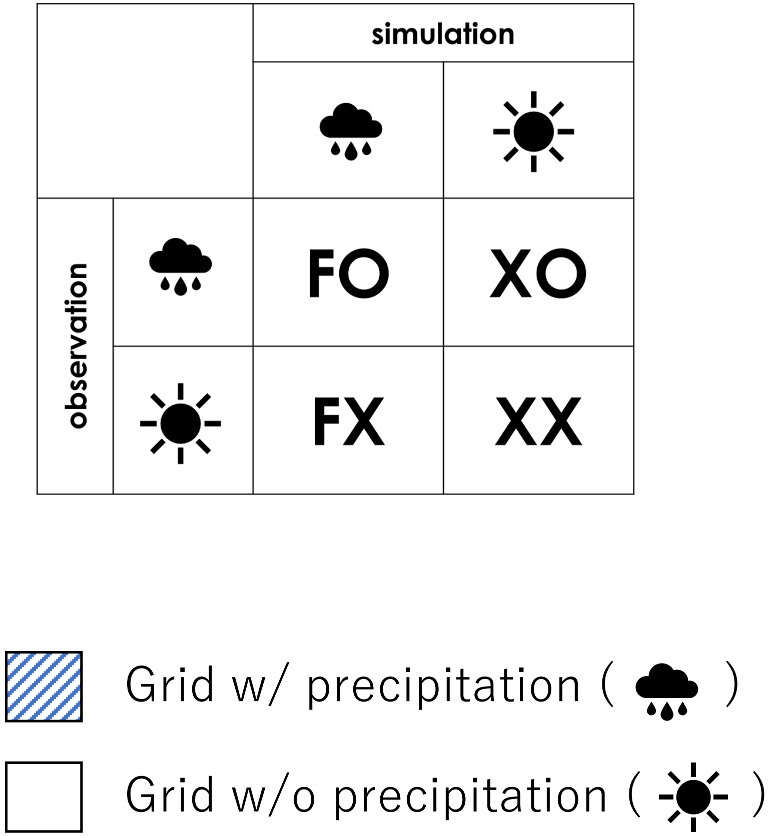
Difficulty in reflectivity assimilation with EnKF

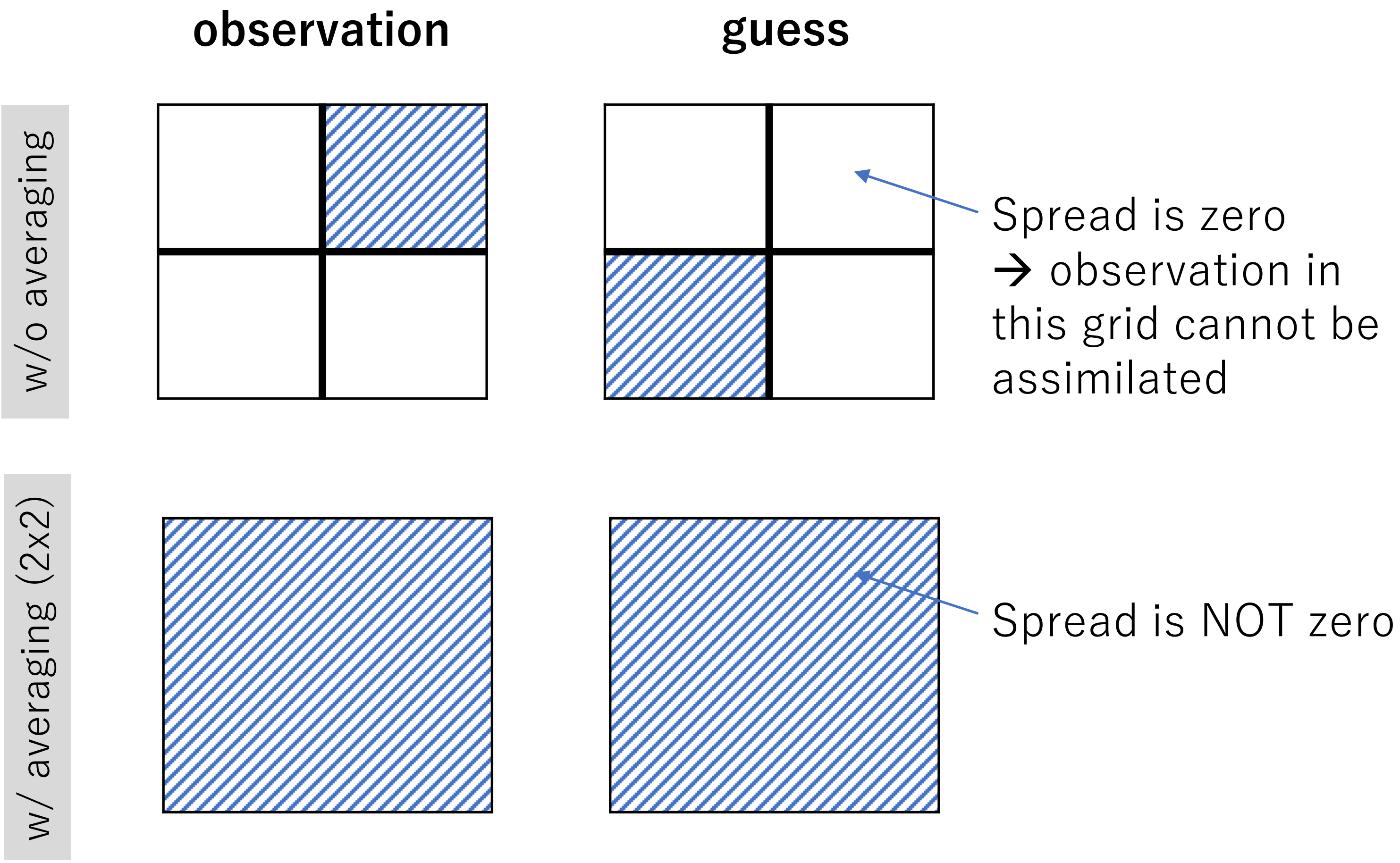
		simulation	
			
observation		**FO**	**XO**
		**FX**	**XX**

- Increment is zero in case of **XO**, in which all the ensemble members do not have precipitation

$$x^a = x^f + \frac{\cancelto{0}{cov\left(x^f, \mathcal{H}\left(x^f\right)\right)}}{B+R}\left(y^o - \mathcal{H}(x^f)\right)$$

A technique to avoid XO: Averaging





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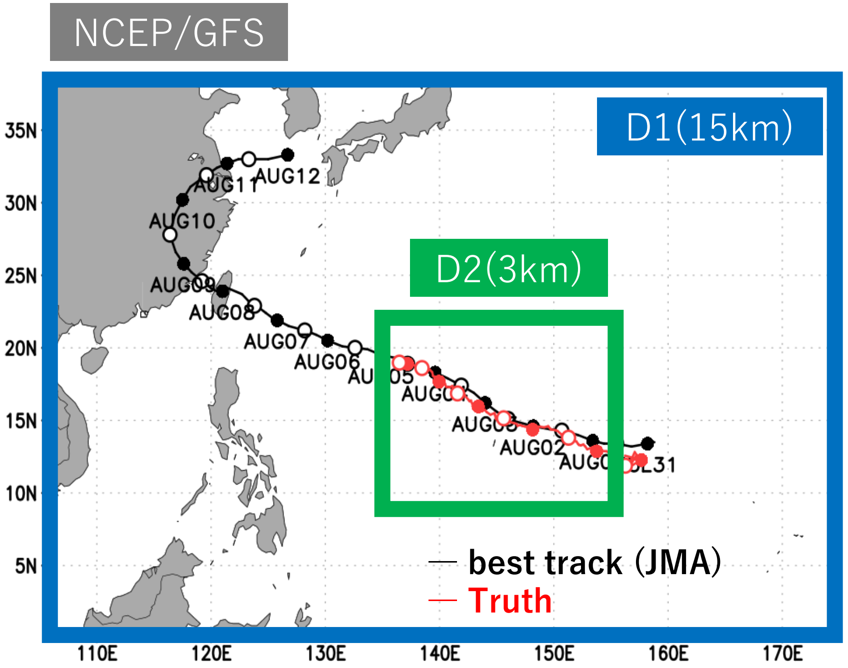
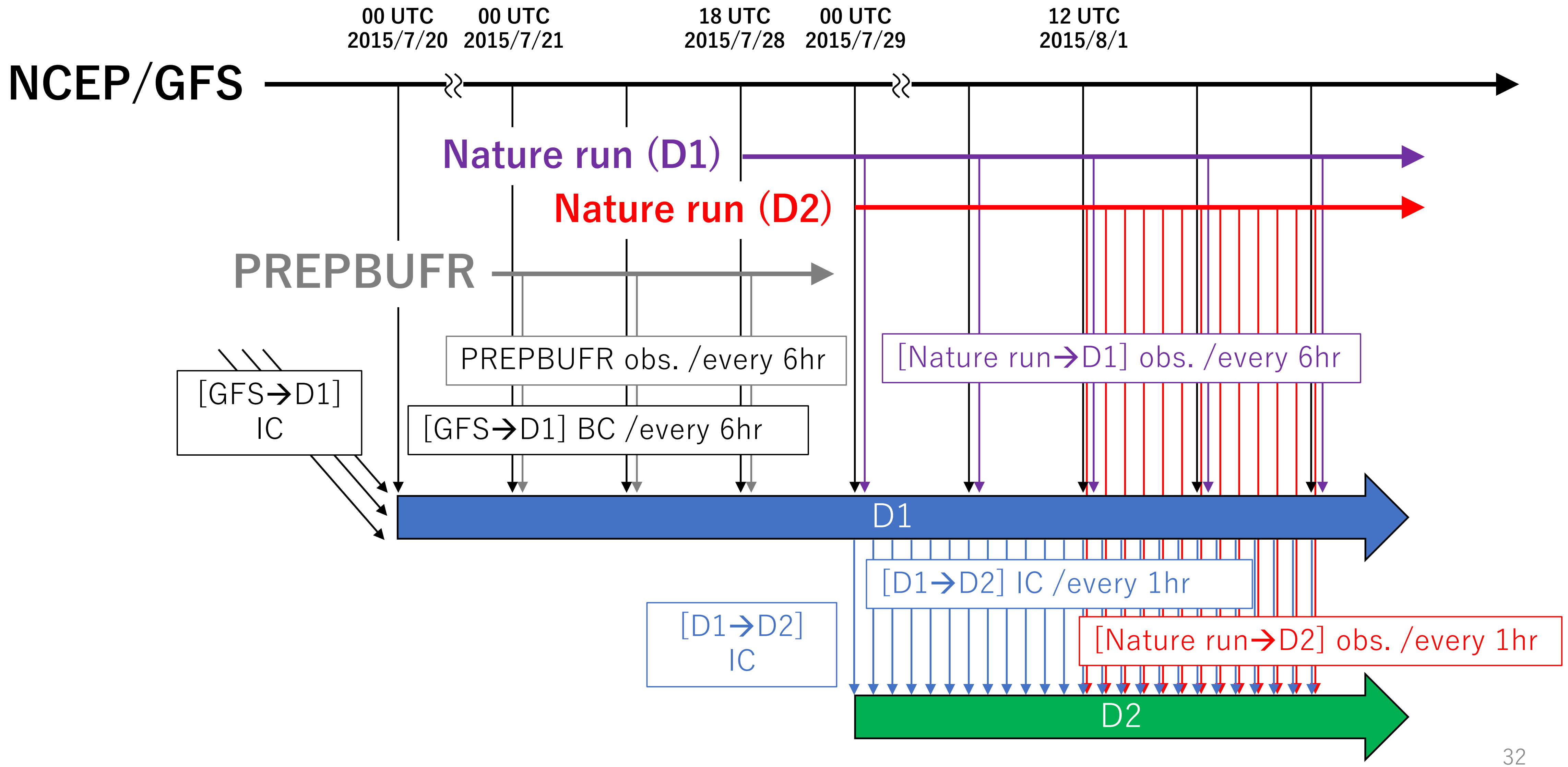
- **DA system**
  - SCALE-LETKF (Lien et al., 2017)
  - Joint-Simulator (Hashino et al., 2013) to calculate radar reflectivity
  - 50 members
  - Localization: **H: 100km**, V: 0.2km
  - Inflation: RTPP with $\alpha = 0.8$ (Zhang et al., 2004)
  - Clear reflectivity shift (GY Lien, personal communication)

$$y = \begin{cases} y \ (y \geq 20dBZ) \\ 15 \ (y < 20dBZ) \end{cases}$$

(similar to Aksoy et al., 2009, but leave a 5-dBZ gap)

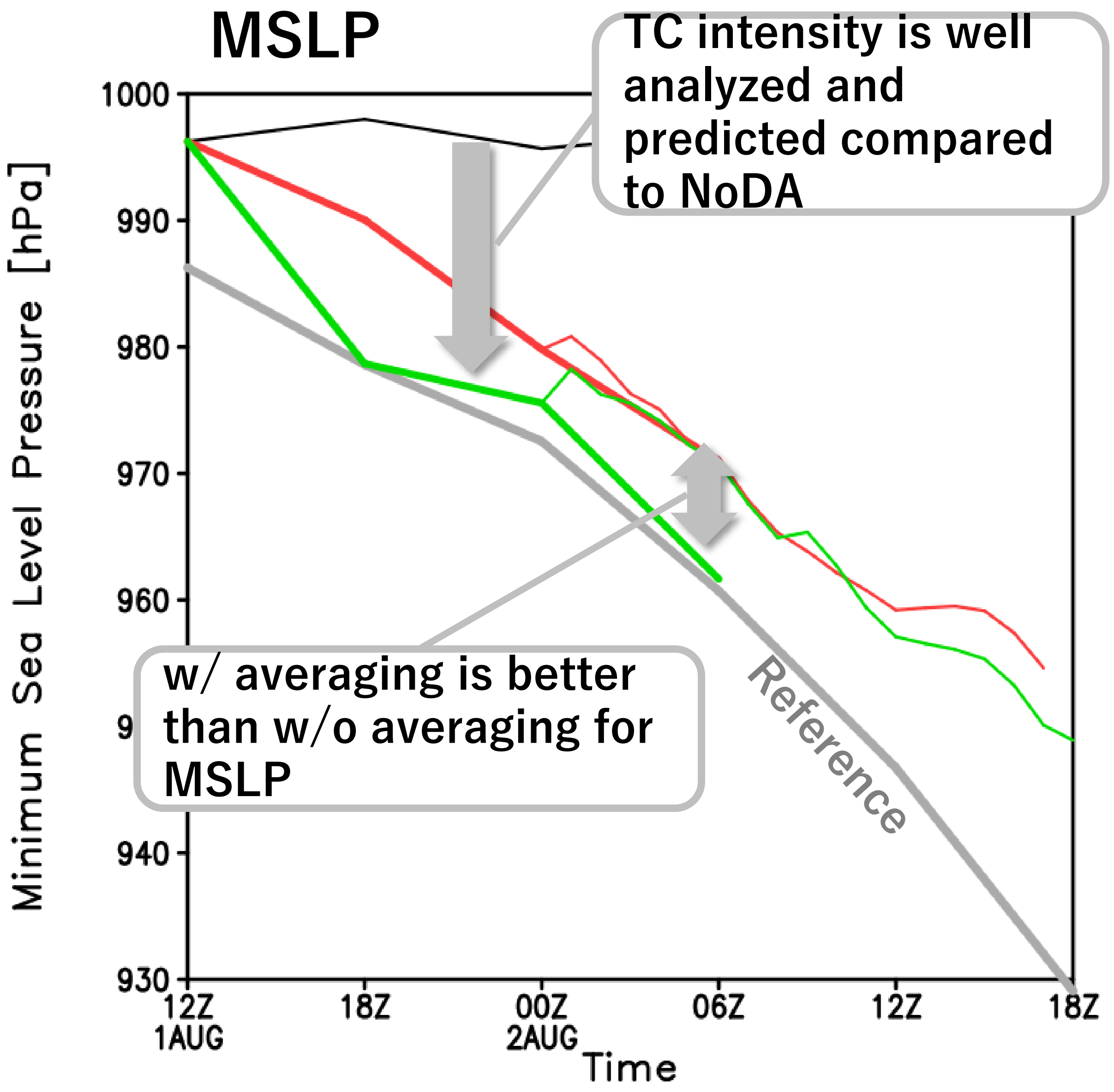


Experimental Design (cont.)

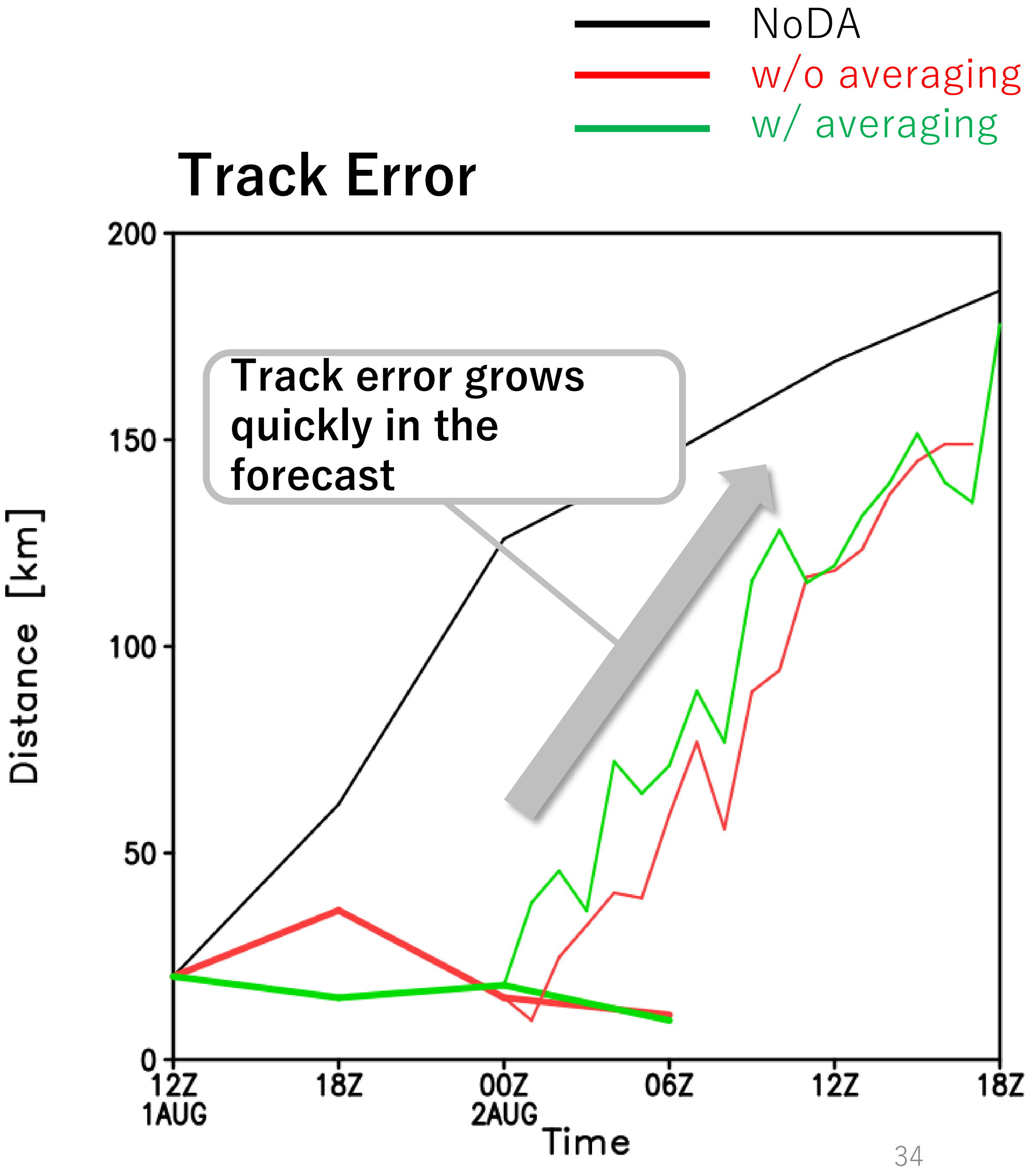


Experimental Design (cont.)

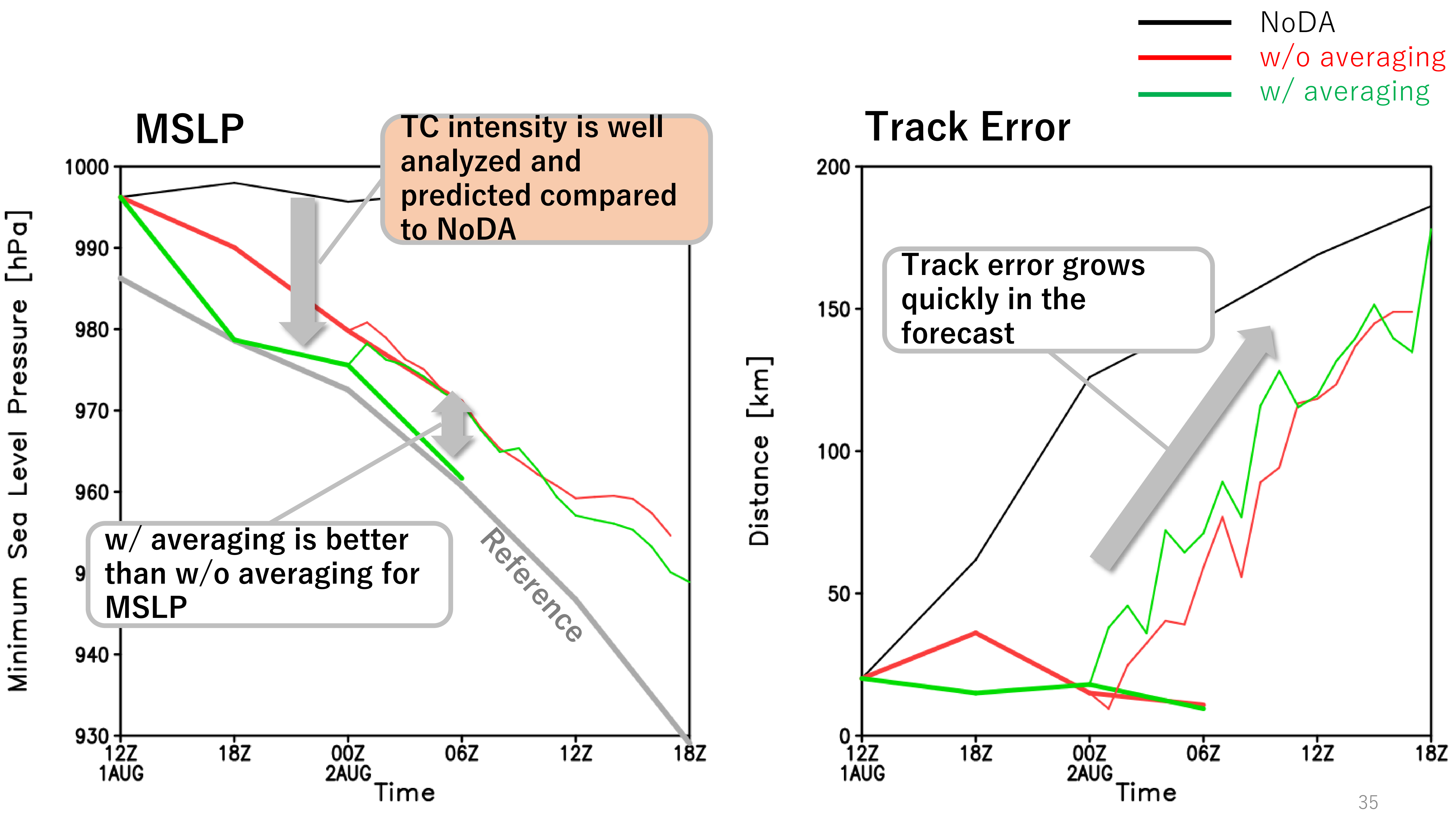
- **Experiments**
  - **NoDA**
    - Free run
  - **w/o averaging**
    - Assimilate radar reflectivity
    - Thinning: 1/25 horizontally & 1/5 vertically
  - **w/ averaging**
    - Assimilate averaged radar reflectivity
      $y^o, Hx^b = 10\ln\left(\sum Z^{o,b}\right)$
    - Averaging scale: 5x5 horizontally
    - Thinning: 1/5 vertically
    - the number of obs is the same as w/o averaging



NoDA
w/o averaging
w/ averaging
MSLP
TC intensity is well analyzed and predicted compared to NoDA
w/ averaging is better than w/o averaging for MSLP
Reference
Minimum Sea Level Pressure [hPa]
1000
990
980
970
960
940
930
12Z 1AUG
18Z
00Z 2AUG
06Z
12Z
18Z
Time



Track Error
Track error grows quickly in the forecast
Distance [km]
200
150
100
50
0
12Z 1AUG
18Z
00Z 2AUG
06Z
12Z
18Z
Time



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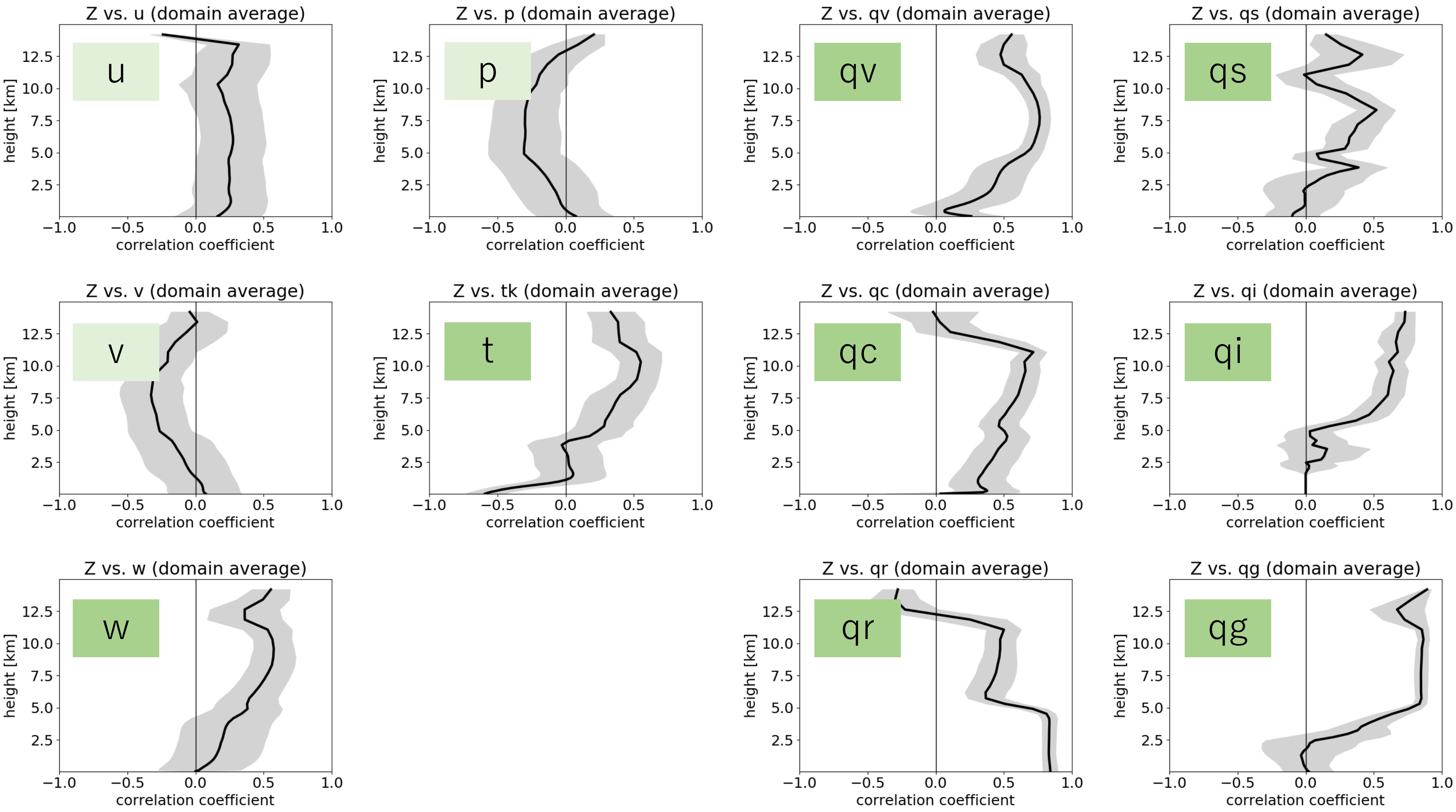
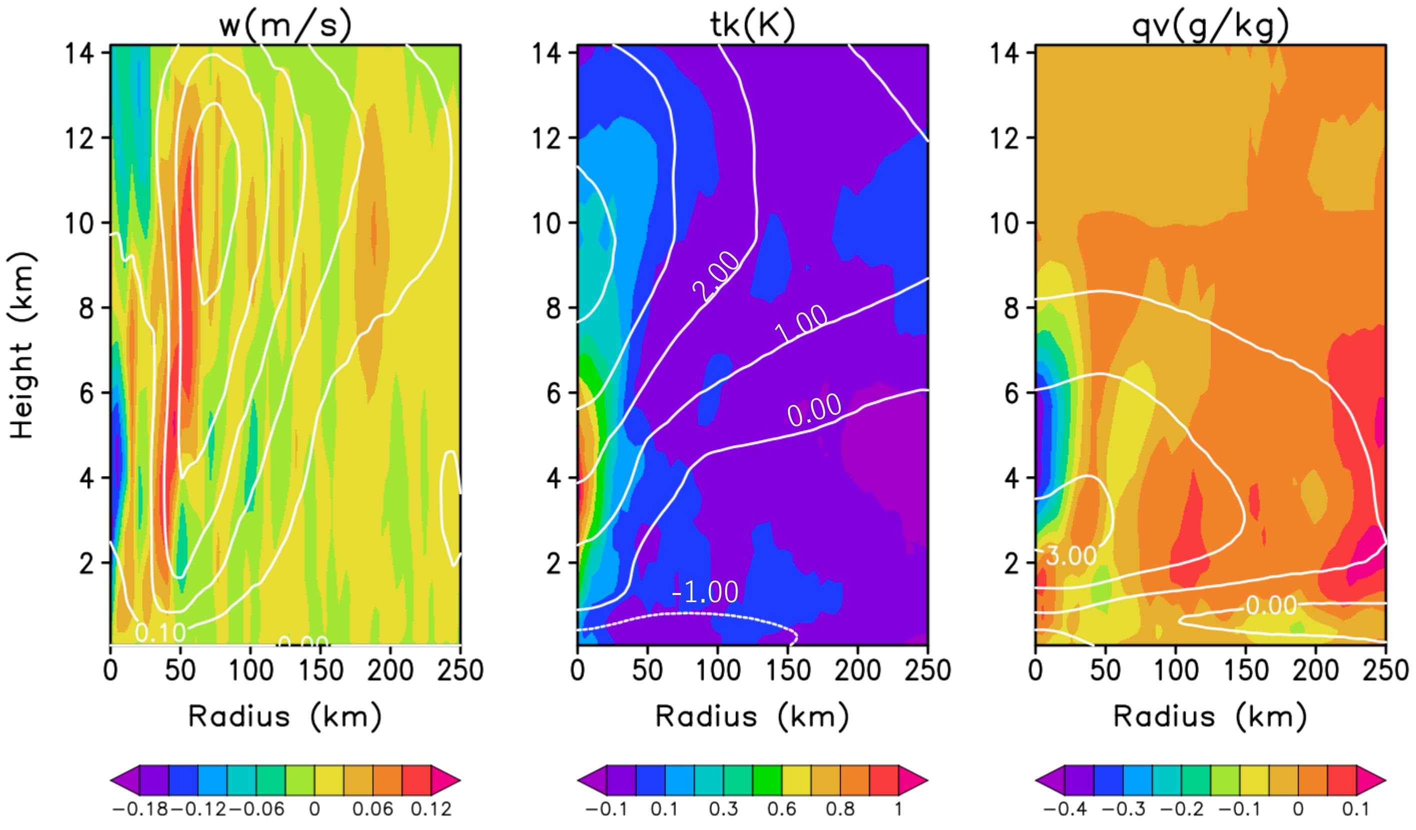
Correlation b/w reflectivity and model prognostic variables



Increment in height-radius cross section



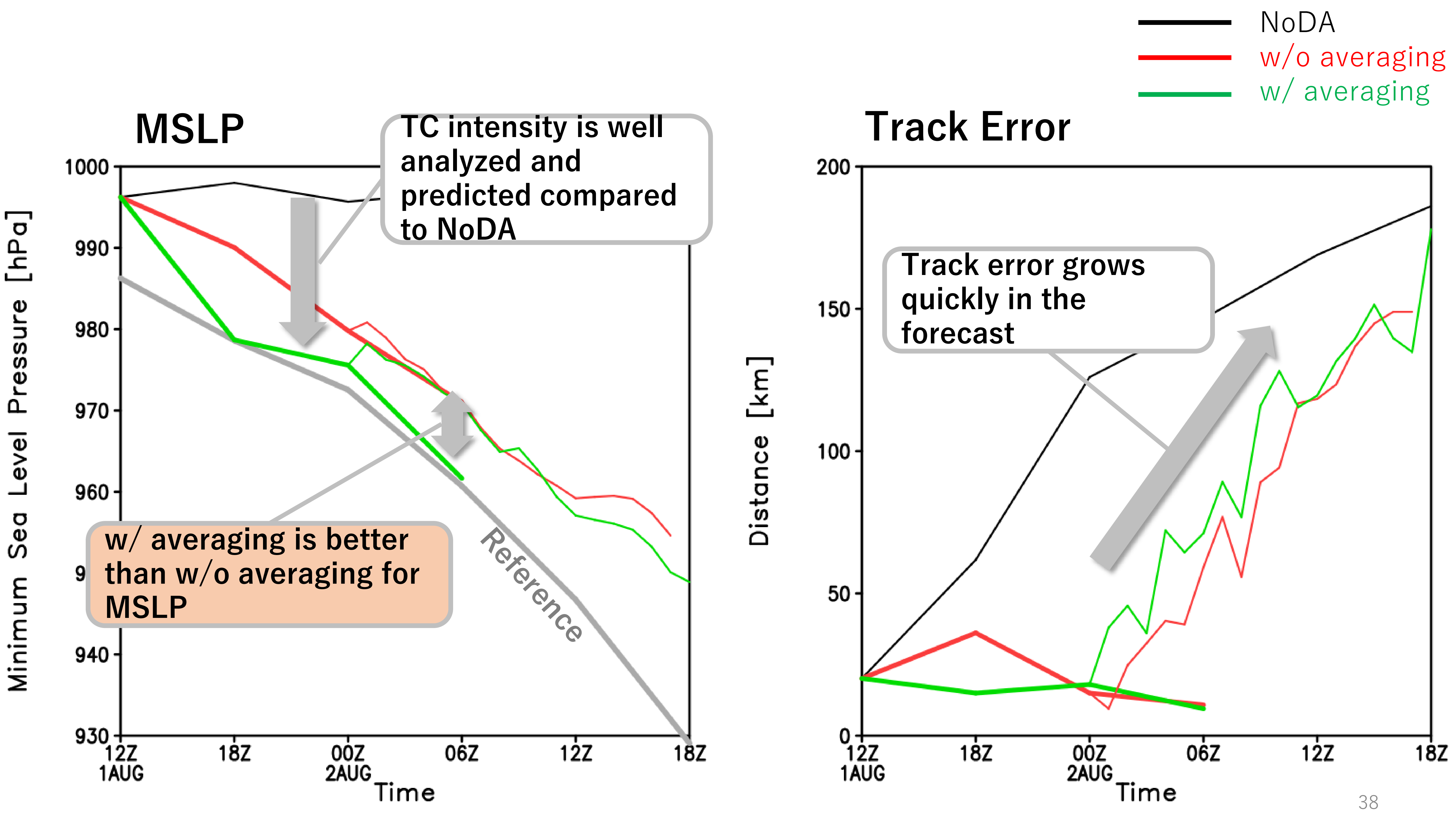
Composites of azimuthally averaged radius–height cross sections
at 10 different times (every hour from 1800 UTC 1 Aug to 0000 UTC 2 Aug).

Intensified secondary circulation

→ Angular momentum advection inward (strengthen tangential wind)

→ Deepening of TC following gradient balance

$$\frac{1}{\rho}\frac{\partial p}{\partial r} = \frac{v^2}{r} + fv$$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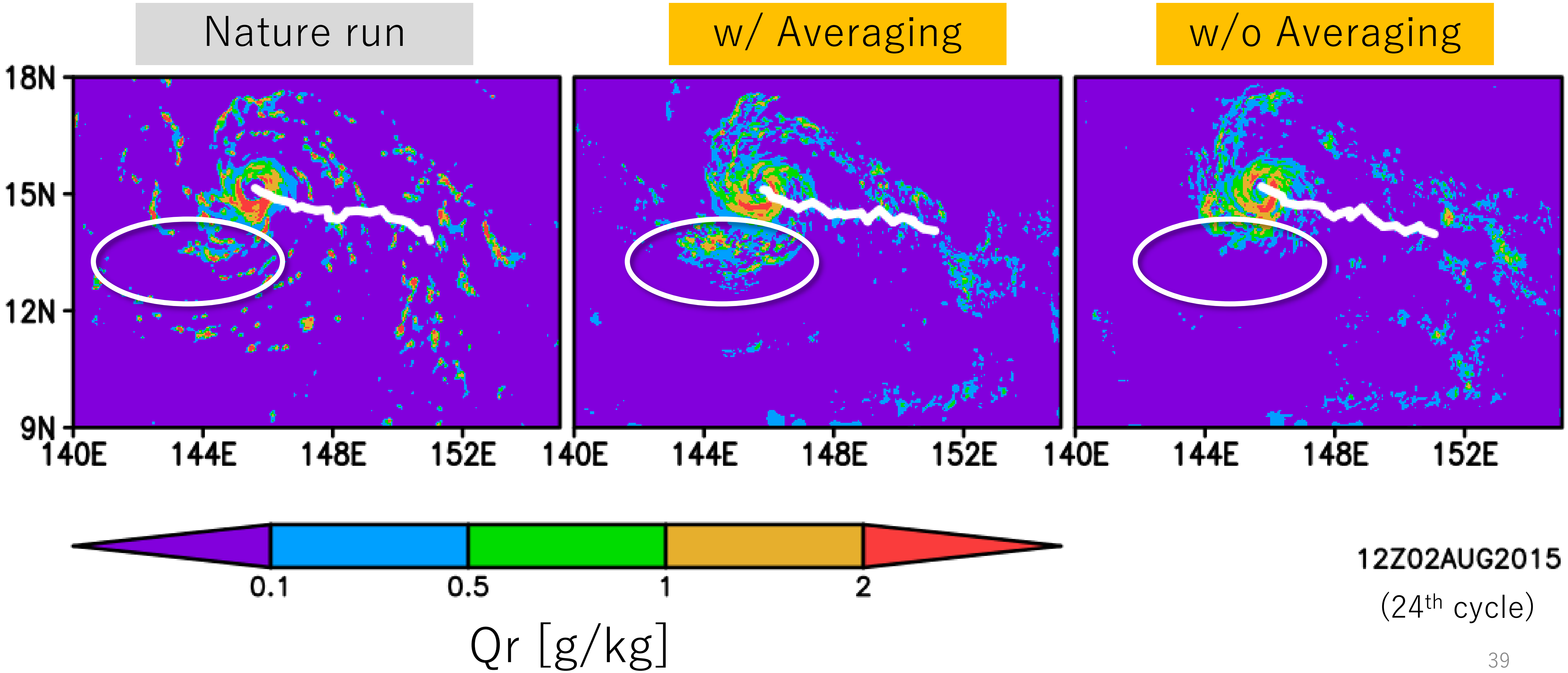
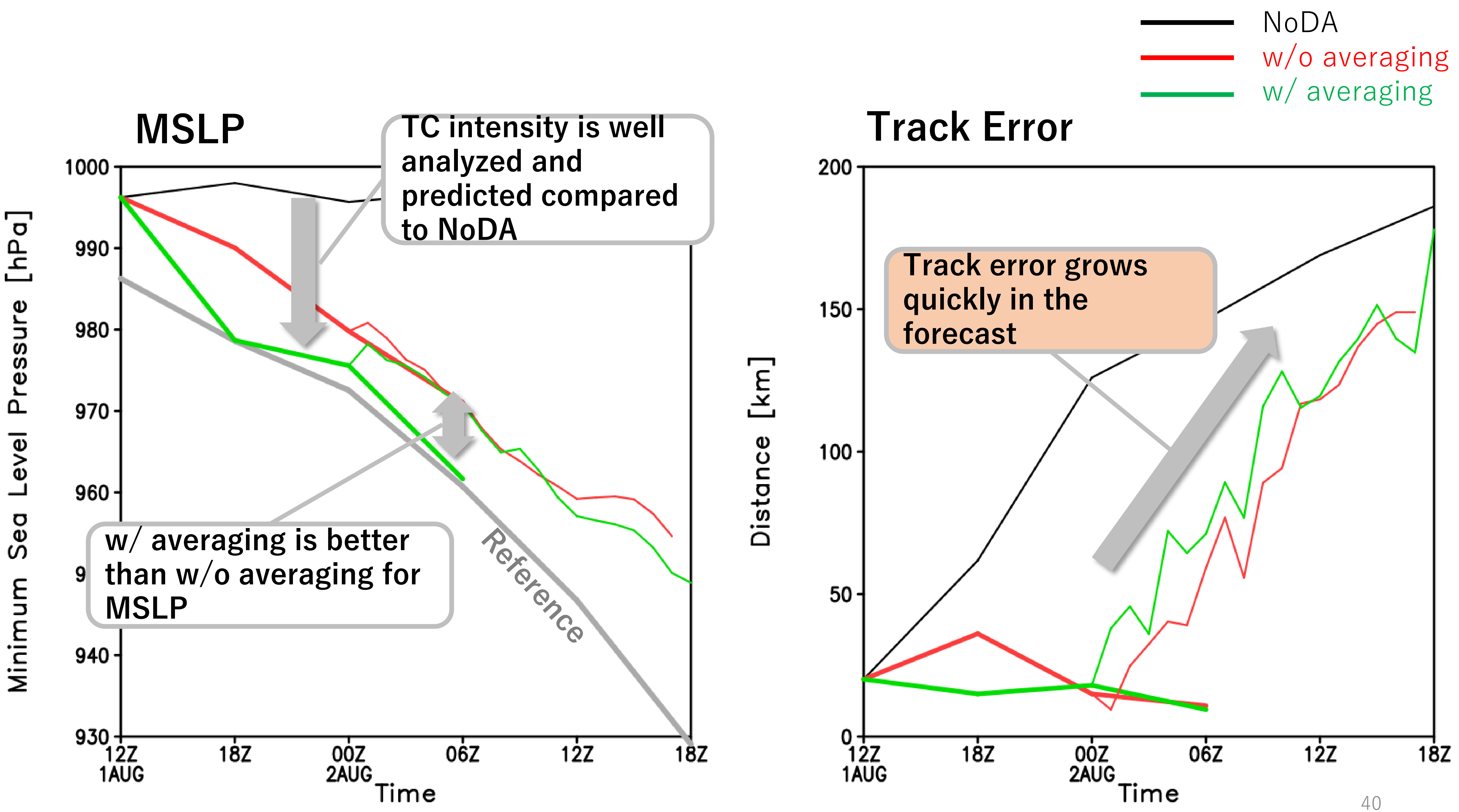
12Z
18Z
Time

Averaging improves precipitation

#Obs (after QC)
59704→75807
@1st cycle



12Z02AUG2015
(24th cycle)



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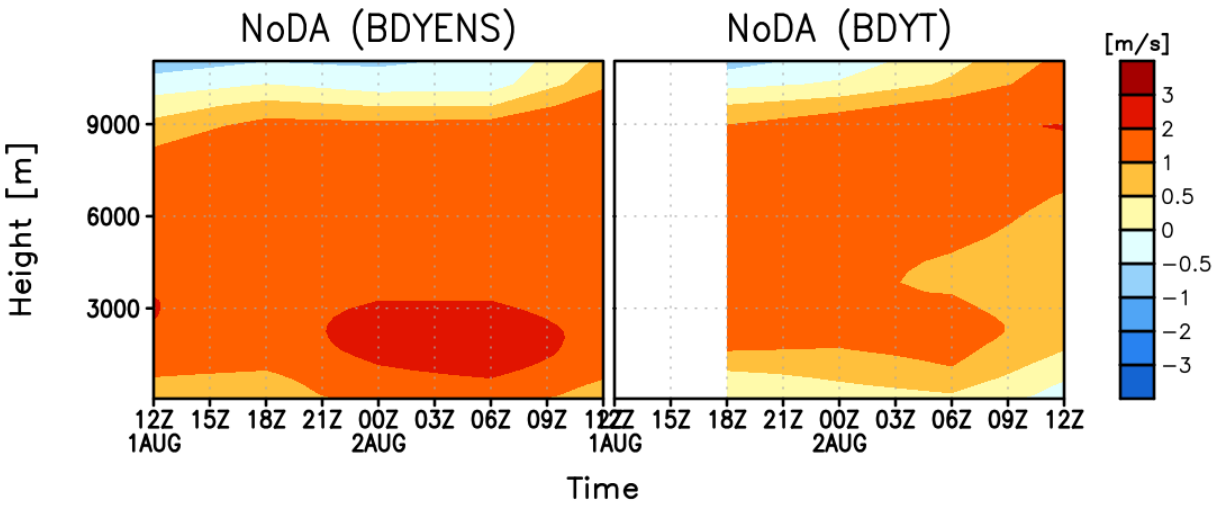
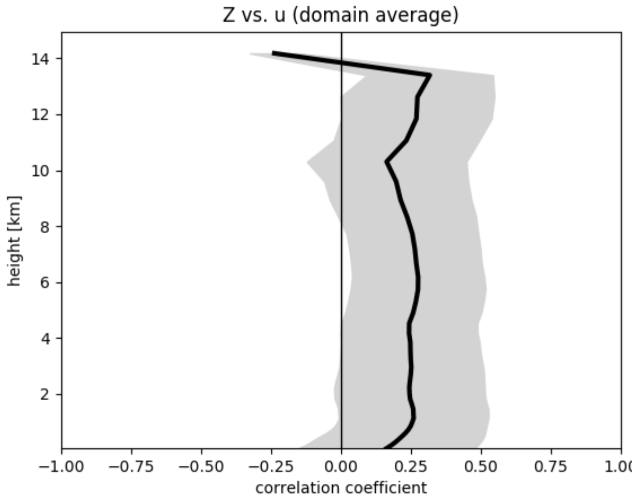
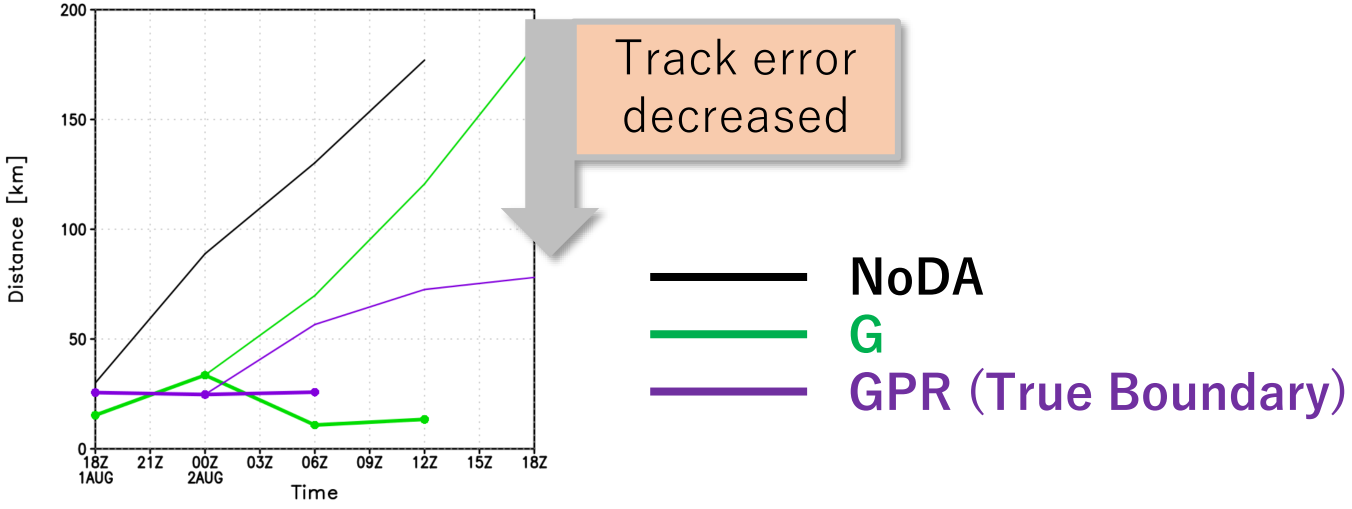
12Z
18Z
Time

Why does the forecast track error grow quickly?

TC track is largely controlled by steering flow and β -effect



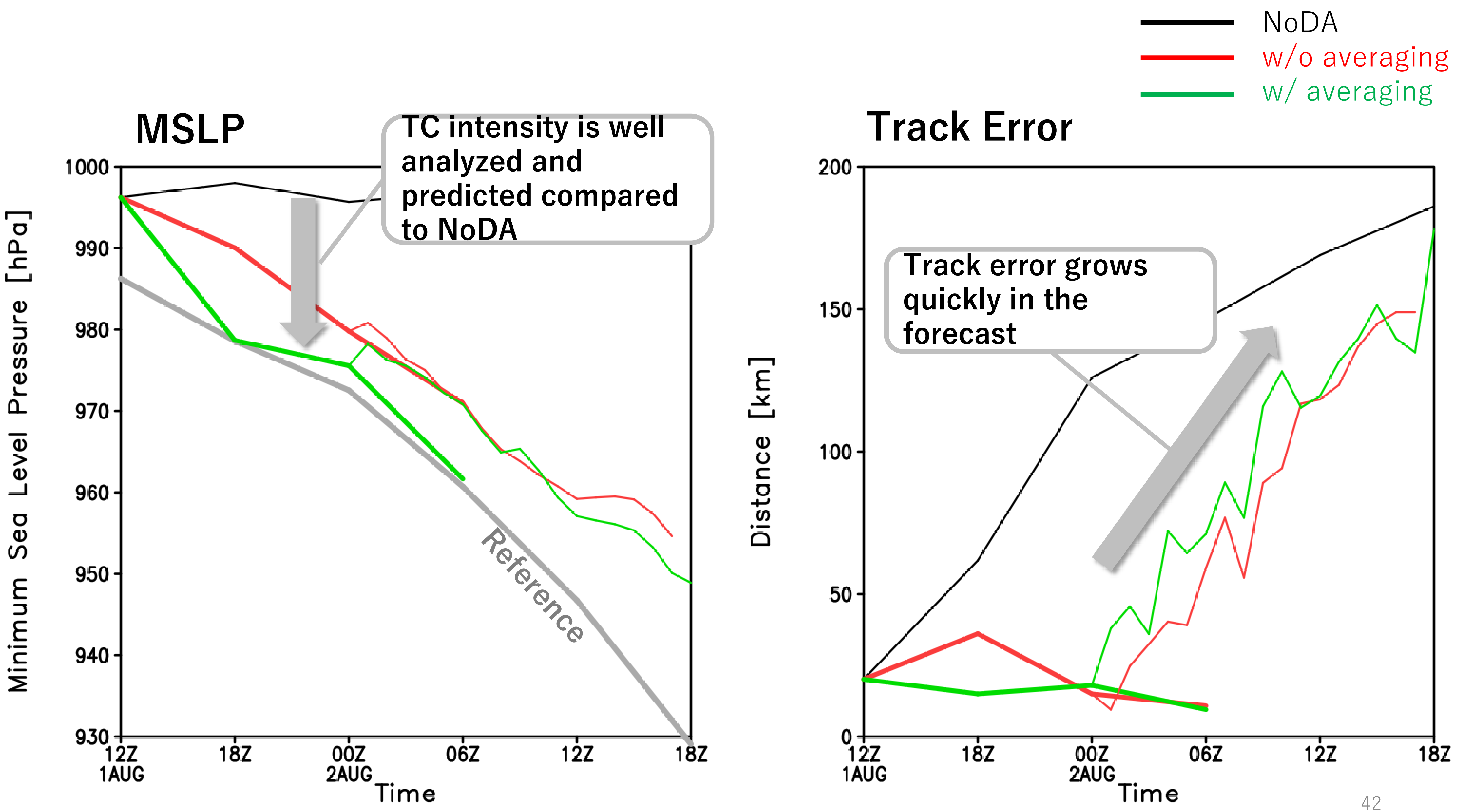




Westerly bias due to BC

- ✓ Substituting BC results in better track forecast

➔ **Large track error is not because of reflectivity assimilation!**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18Z
00Z 2AUG
06Z
12Z
18Z
Time
Track Error
Track error grows quickly in the forecast
Distance [km]
200
150
100
50
0
12Z 1AUG
18Z
00Z 2AUG
06Z
12Z
18Z
Time

GPR Assimilation with an EnKF

An Observing System Simulation Experiment for a Typhoon Case

Experimental Design

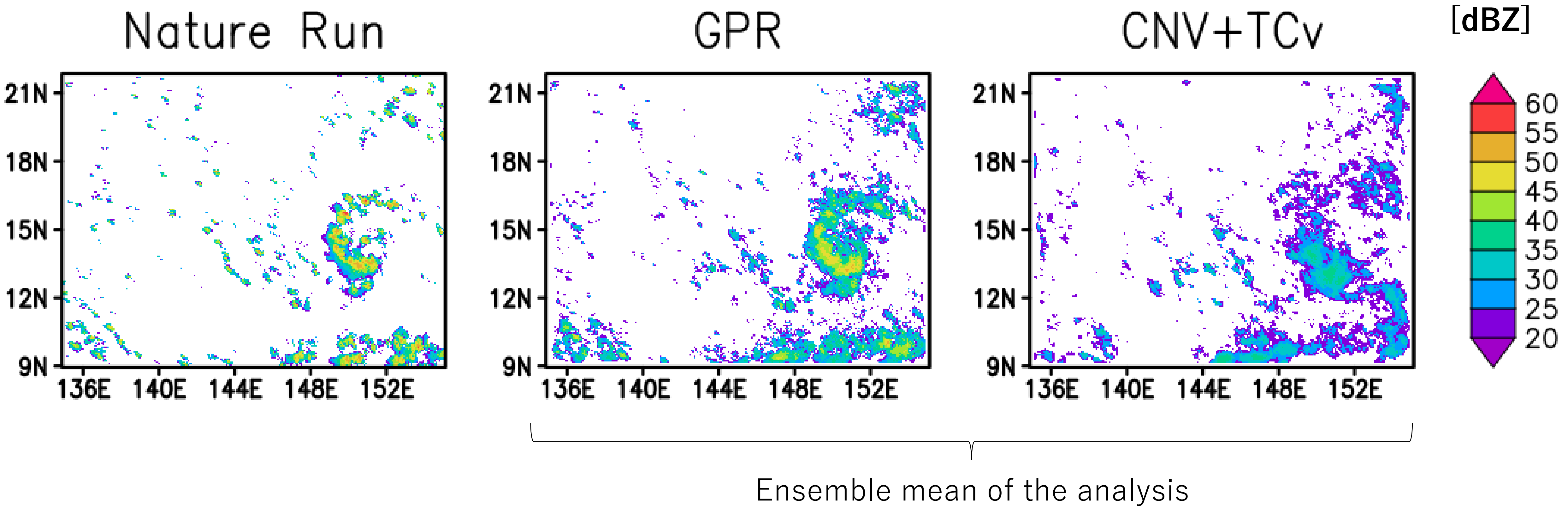
- **Observation**
  - **GPR** (20km resolution / 20km sampling span; hourly)
  - TC-vital (TC-center position & MSLP; hourly)
  - Conventional data (PREPBUFR; hourly)
- **DA system**
  - SCALE-LETKF (Lien et al., 2017)
  - Joint-Simulator (Hashino et al., 2013) with GPR simulator (Okazaki et al., 2019)
  - 50 members
  - Localization: H: 100km, V: 0.2km
  - Inflation: RTPP with $\alpha = 0.8$ (Zhang et al., 2004)
  - Thinning: 1/25 horizontally & 1/5 vertically
  - Clear reflectivity shift (G.-Y. Lien, personal communication)

$$y = \begin{cases} y \ (y \geq 20dBZ) \\ 15 \ (y < 20dBZ) \end{cases}$$

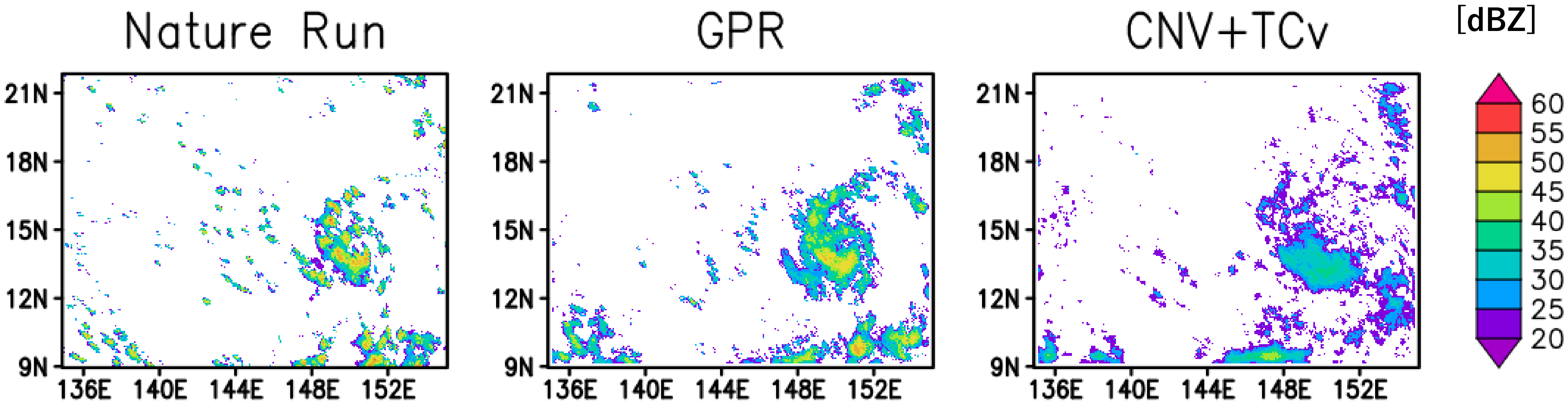
(similar to Aksoy et al., 2009, but leave a 5-dBZ gap)

EXP	Observation
CNV+TCV	Conventional obs. TC-vital
GPR	Conventional obs. TC-vital GPR measured Z
GPR w/ clutter	Conventional obs. TC-vital GPR measured Z (above 5km)

GPR at 1st DA cycle (13Z1AUG)

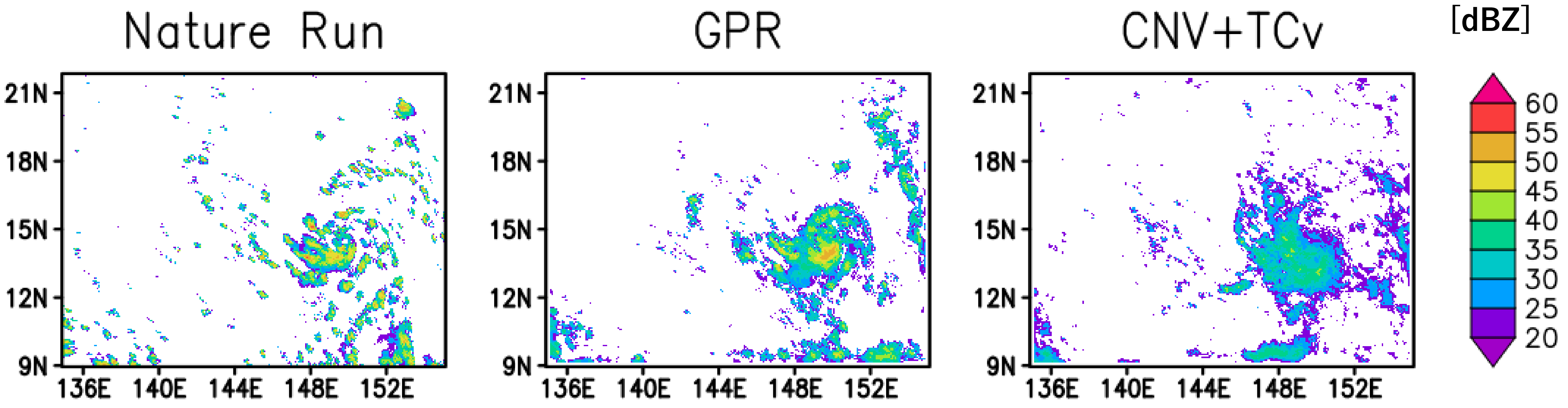


GPR at 3rd DA cycle (15Z1AUG)



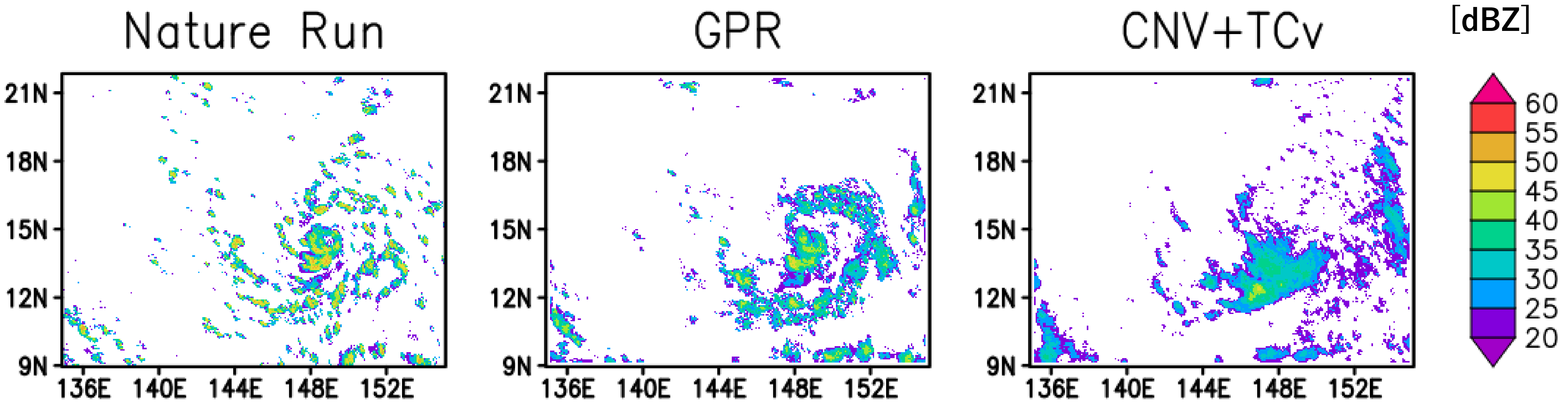
Ensemble mean of the analysis

GPR at 6th DA cycle (18Z1AUG)



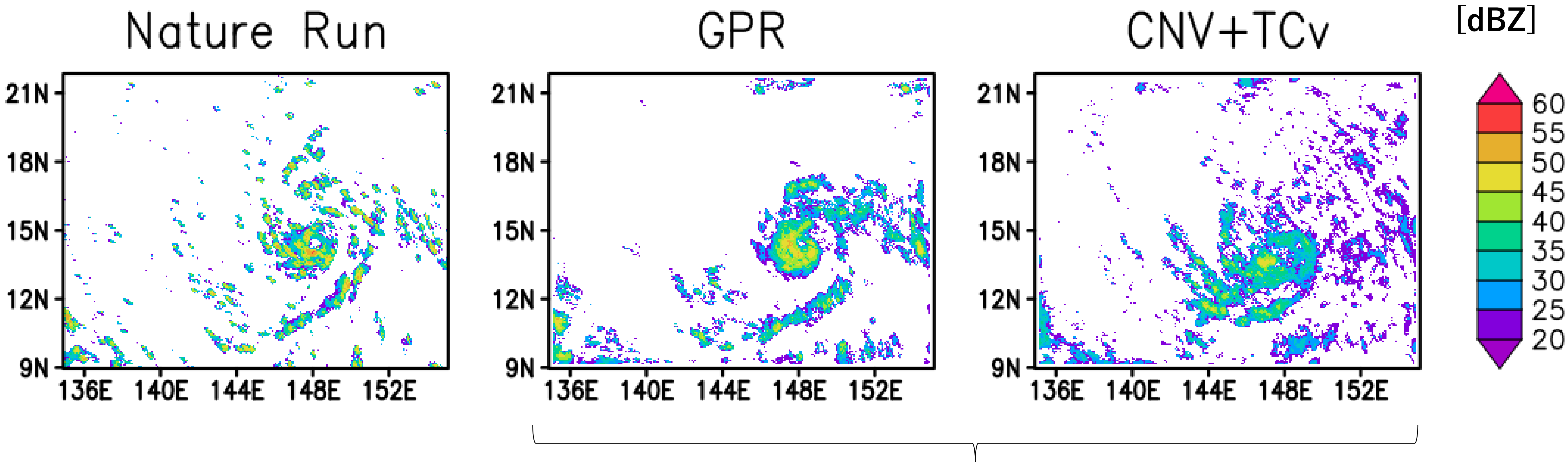
Ensemble mean of the analysis

GPR at 9th DA cycle (21Z1AUG)

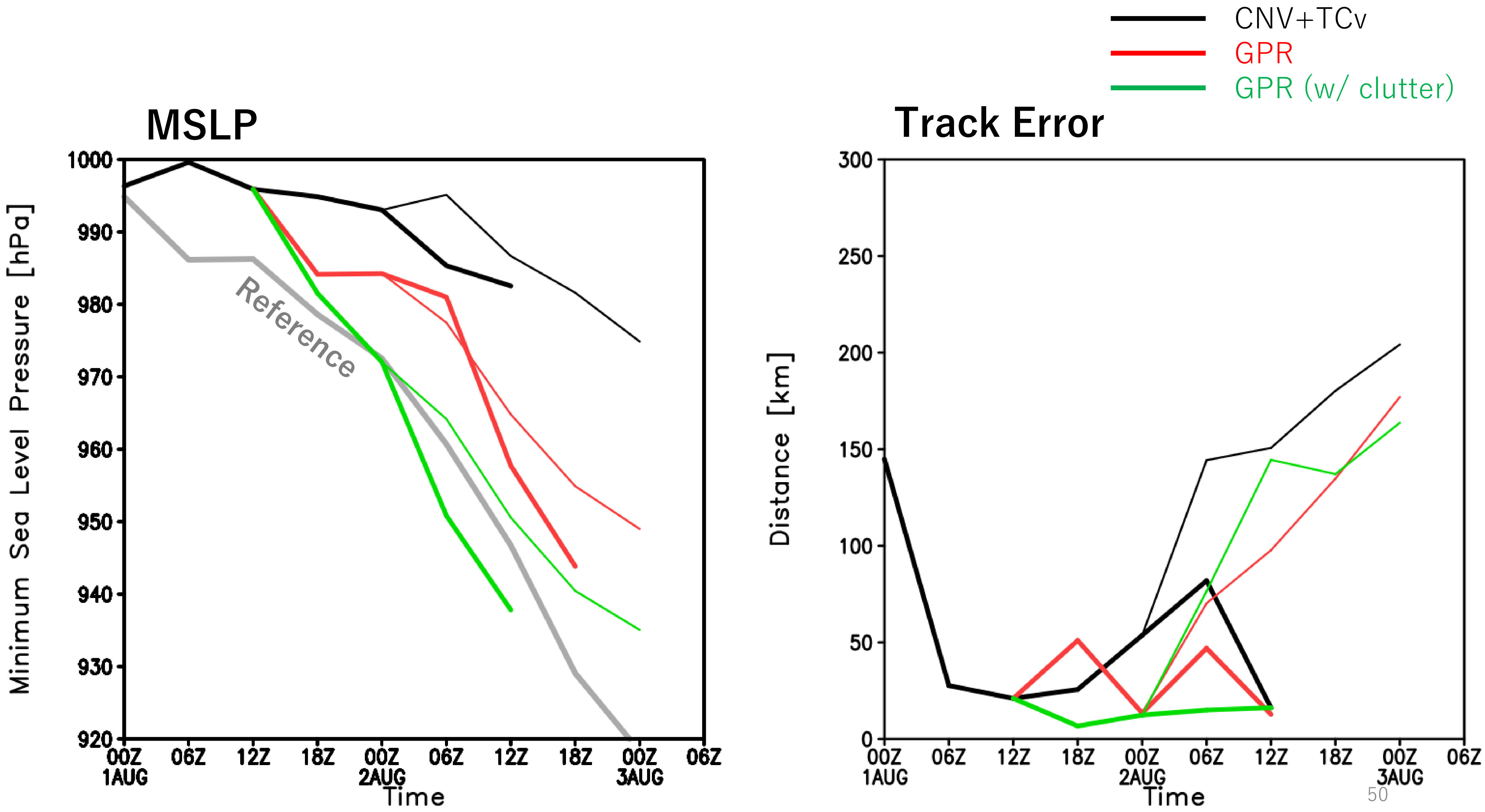


Ensemble mean of the analysis

GPR at 12th DA cycle (0Z1AUG)



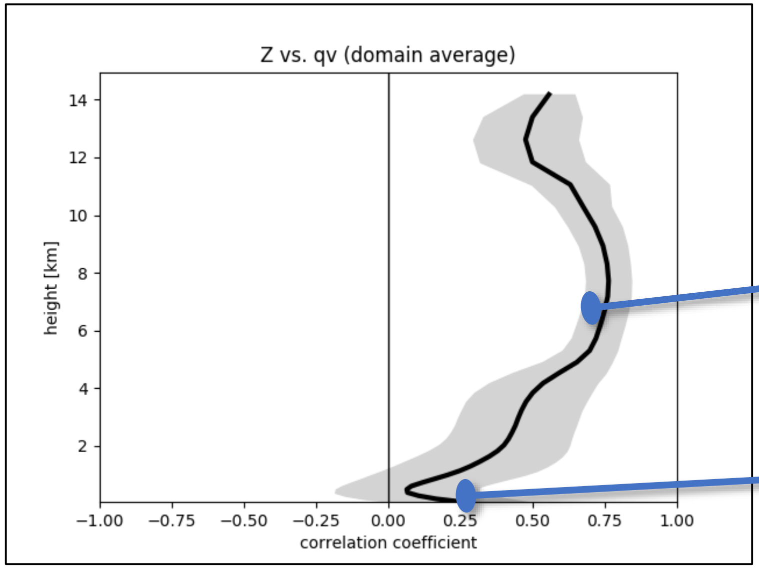
Ensemble mean of the analysis


CNV+TCv
GPR
GPR (w/ clutter)
MSLP
Minimum Sea Level Pressure [hPa]
1000
990
980
970
960
950
940
930
920
Reference
00Z 1AUG
06Z
12Z
18Z
00Z 2AUG
06Z
12Z
18Z
00Z 3AUG
06Z
Time
Track Error
Distance [km]
300
250
200
150
100
50
0
00Z 1AUG
06Z
12Z
18Z
00Z 2AUG
06Z
12Z
18Z
00Z 3AUG
06Z
Time

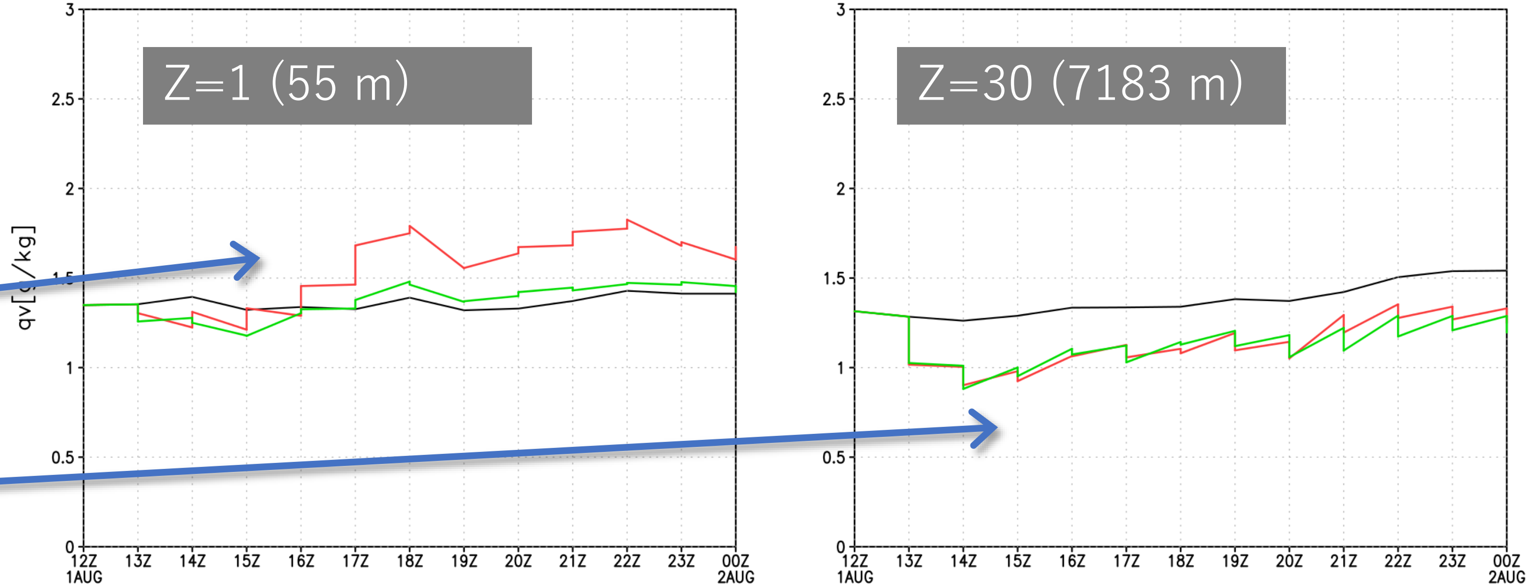
Why GPR (w/ clutter) is better?

NoDA
GPR (w/o clutter)
GPR (w/ clutter)

Correlation between Z and Qv



RMSE for Qv (Rainy-area average)



- **Reflectivity observations are detrimental for lower atmosphere**

Summary and Future work

- We evaluated the potential of GPR for a typhoon case
- We demonstrated that GPR has a potential to improve forecasts for typhoon intensity
- GPR assimilation may benefit from its relatively large sampling volume
- The impact of surface clutter should be small on TC case
    - Reflectivity has high correlations at high altitude
    - TC is a tall system
- Additional impact of GPR when assimilated together with Himawari-8

Thank you!

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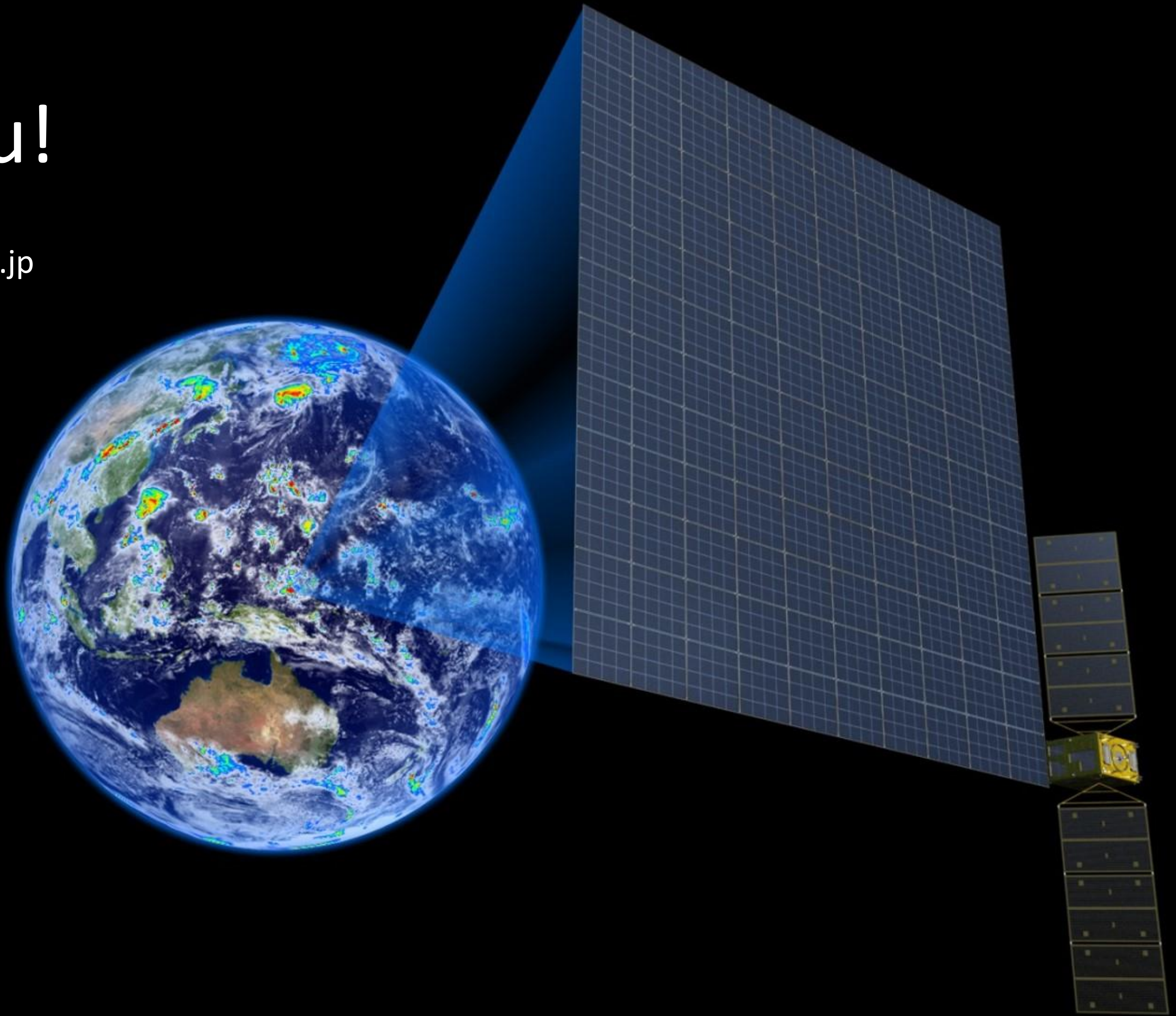
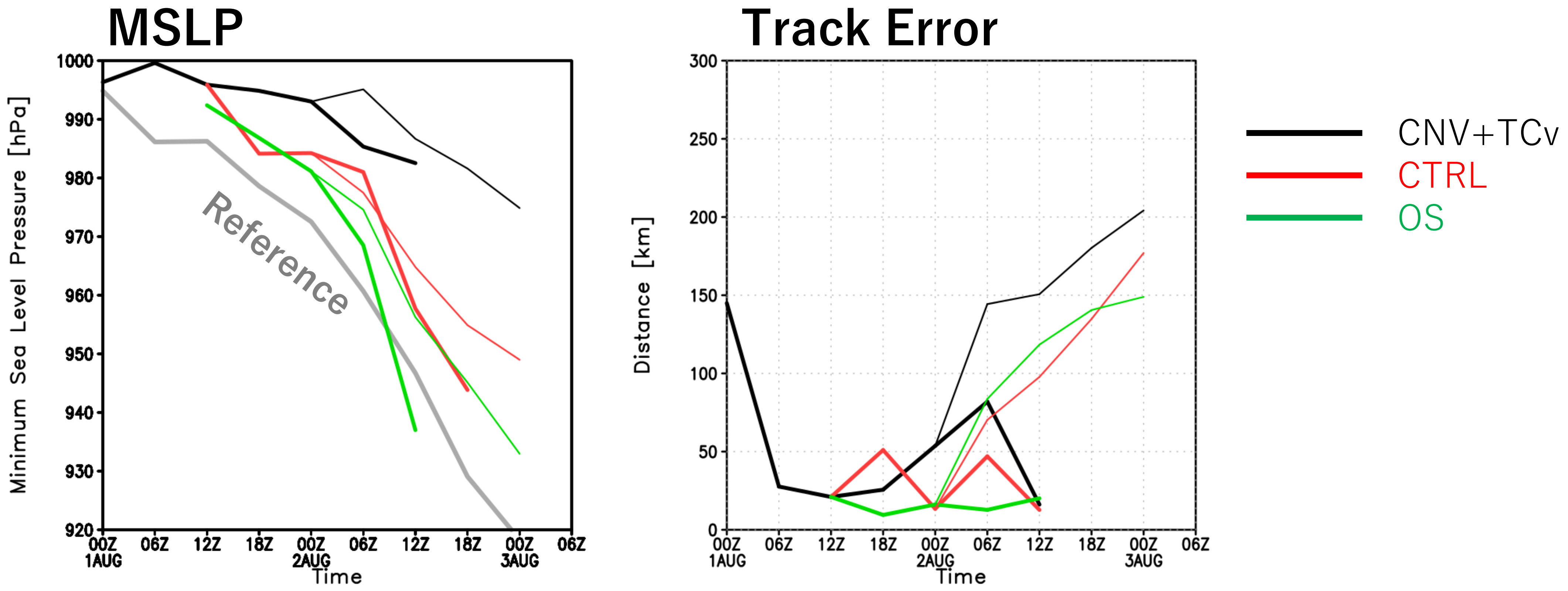


What is the best operation for GPR?

- GPR can measure the area around TCs densely (i.e. over-sampling)



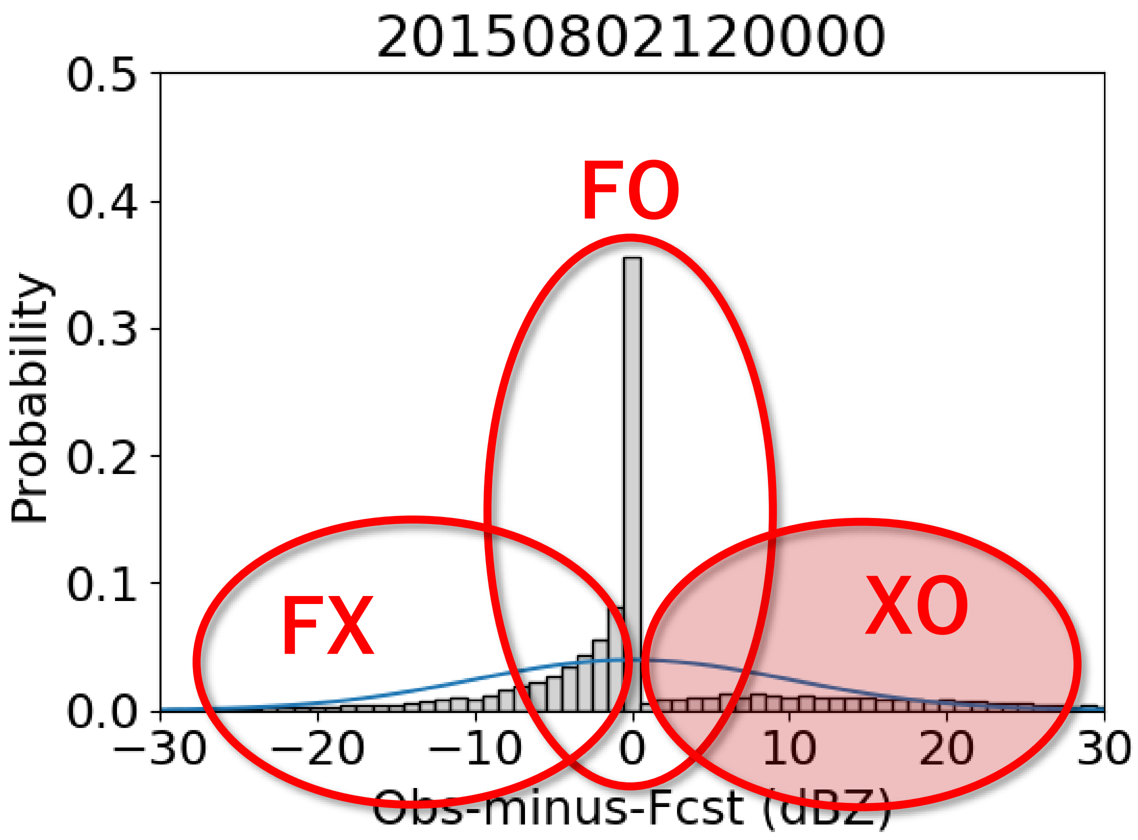
Remaining issues…

- Highly non-Gaussian error distribution
  - Additive noise (Dowell & Wicker, 2009)
  - Pseudo-RH (e.g. Caumont et al., 2010)

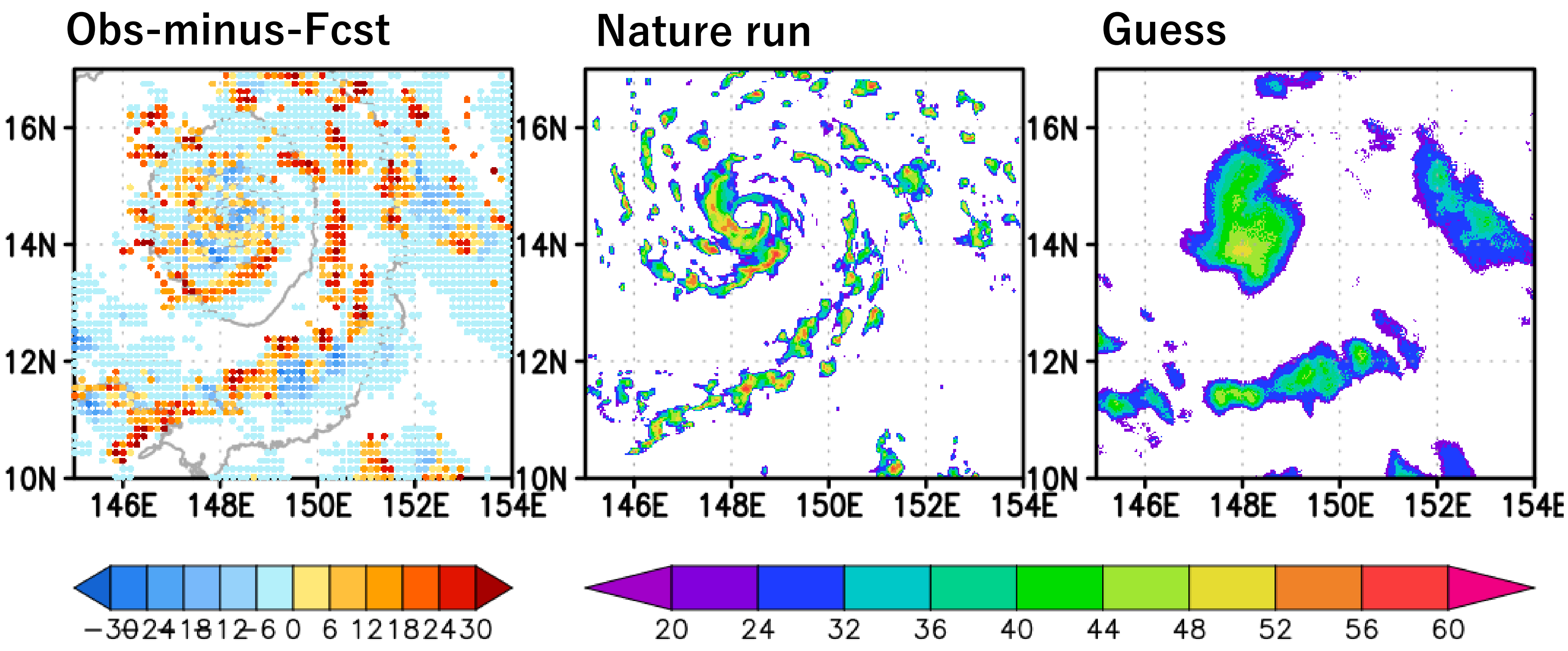
  did not solve the problem

- Non-Gaussianity combined with nonlinearity in $\mathcal{H}$ makes it difficult to assimilate radar reflectivity effectively with EnKF
  - Gaussian Transform (Lien et al., 2013; 2016; Kotsuki et al., 2017)
  - Local PF (Poterjoy, 2016)
  - Hybrid-DA (e.g. E4DVar, EnVar)

  may be a good option?



(QCed samples are used)


Obs-minus-Fcst
Nature run
Guess
16N
14N
12N
10N
146E 148E 150E 152E 154E
−30 −24 −18 −12 −6 0 6 12 18 24 30
20 24 32 36 40 44 48 52 56 60