2024.11.18 17:15–17:30
OceanPredict Symposium (OP’24)

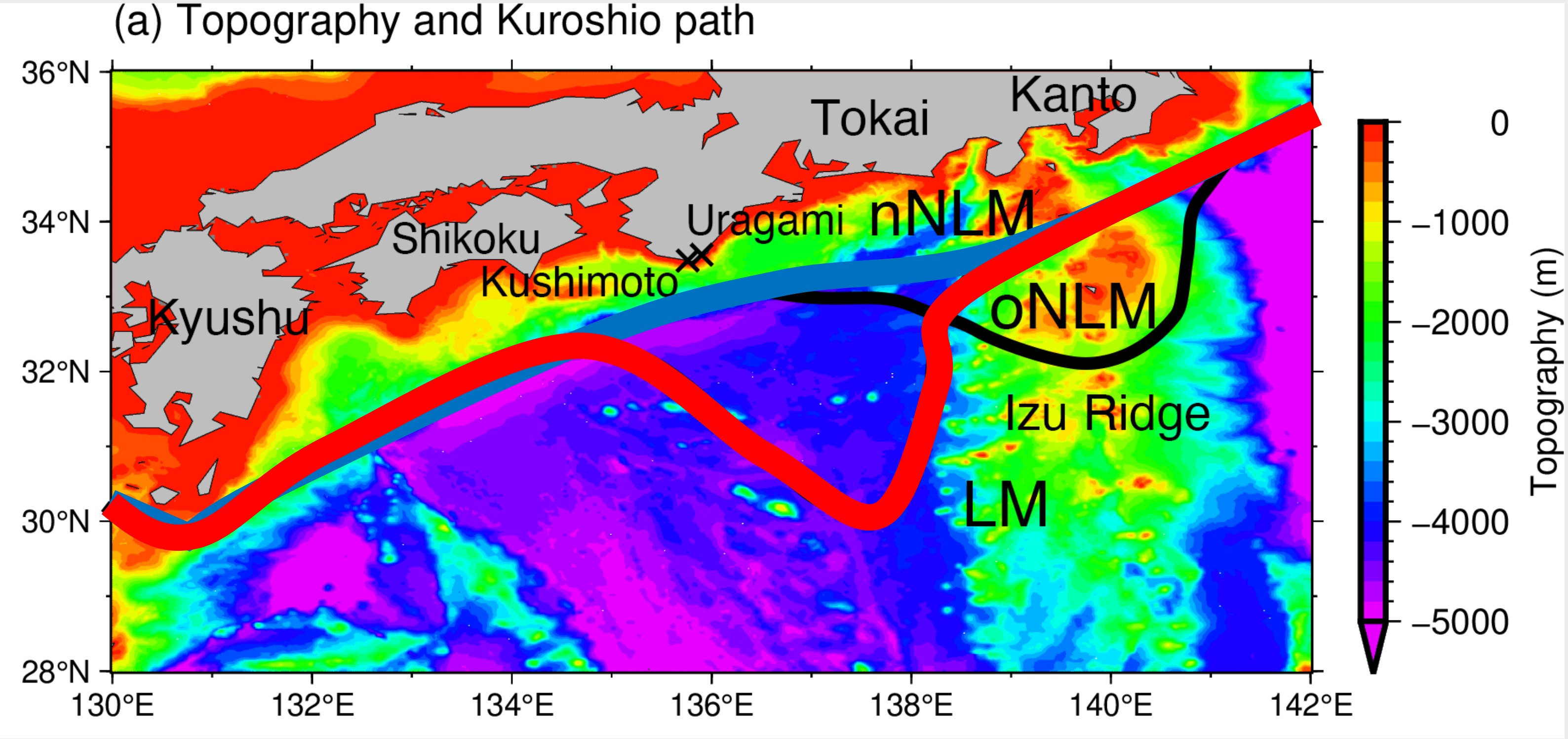
Deterministic and ensemble forecasts of Kuroshio south of Japan (Ohishi et al. in prep.)

Shun Ohishi[1], T. Miyoshi[1], and M. Kachi[2]

1: RIKEN/R-CCS, Japan, 2: JAXA/EORC, Japan

Introduction

1. Introduction – Kuroshio path south of Japan –

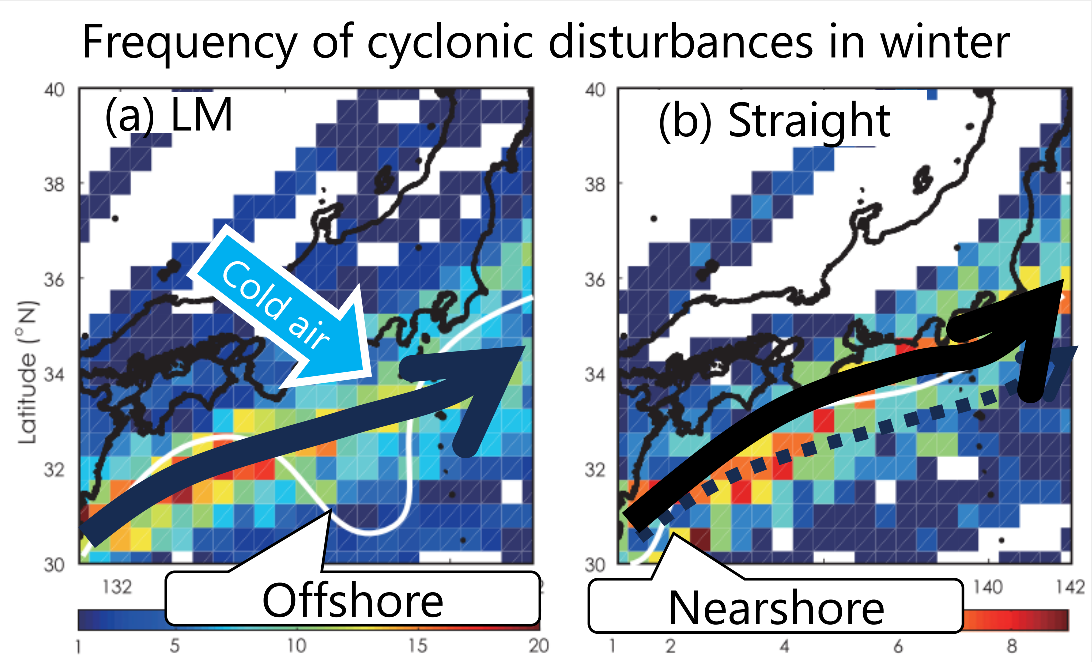


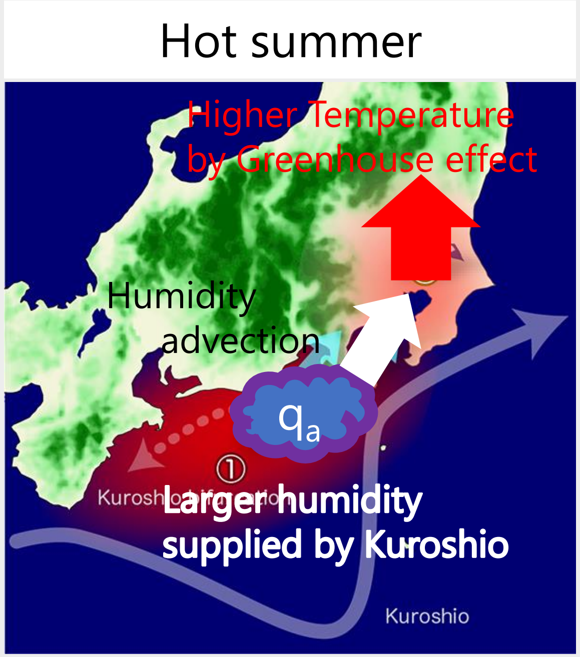
- Three typical paths in Kuroshio (Kawabe 1995)
  - Straight
  - oNLM (offshore NonLarge Meander)
  - Large Meander (LM)

1. Introduction – Impacts of the Kuroshio –

- **Ocean**
  - Marine transport & Fishery (Nakata et al. 2000)
- **Atmosphere**
  - Heavy snow & Hot summer in Kanto district

(Nakamura et al. 2012; Sugimoto et al. 2020)

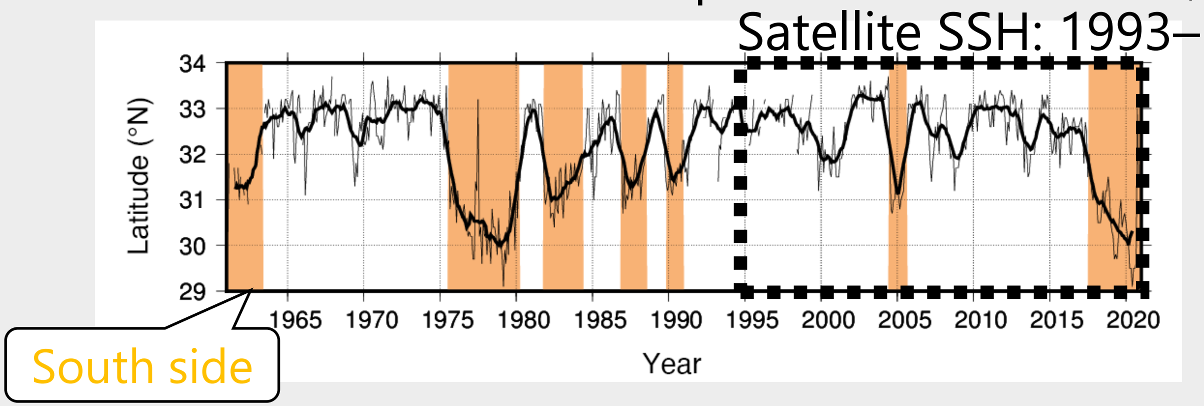




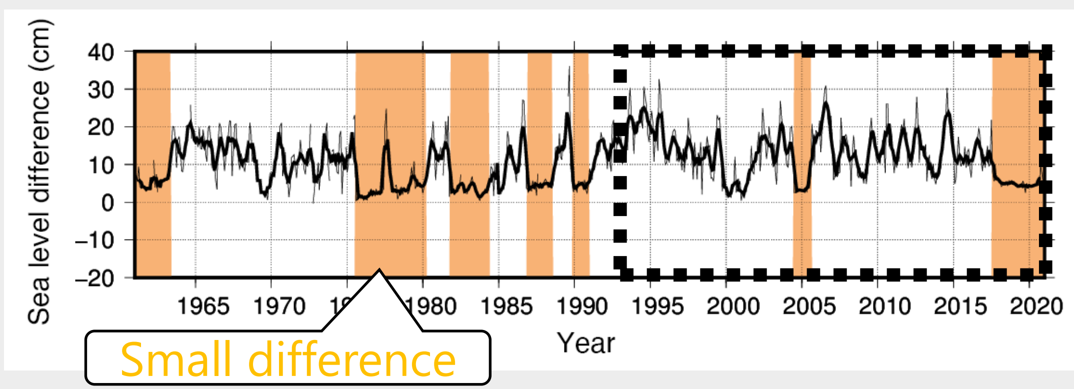
1. Introduction – LM indicators –

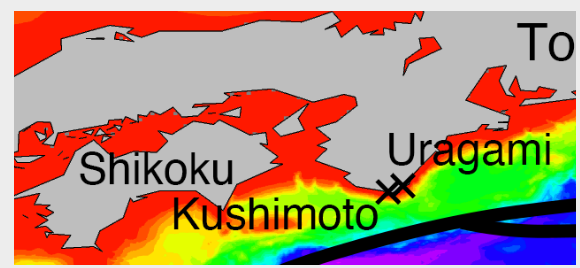
■ Japan Meteorological Agency (JMA)

- Kuroshio's southernmost position (estimated from temperature at sea surface and 100 m depth)



- Sea level differences between Kushimoto and Uragami (Kawabe 1980)





- Combination of the two indicators to detect LM

- **Only two events** since the start of satellite SSH observations

1. Introduction – Kuroshio prediction –

■ Predictability of the Kuroshio south of Japan

- Komori et al. (2003): 60 days
- Kamachi et al. (2006): 20 days (Meander → Straight)
  80 days (Straight → Meander)
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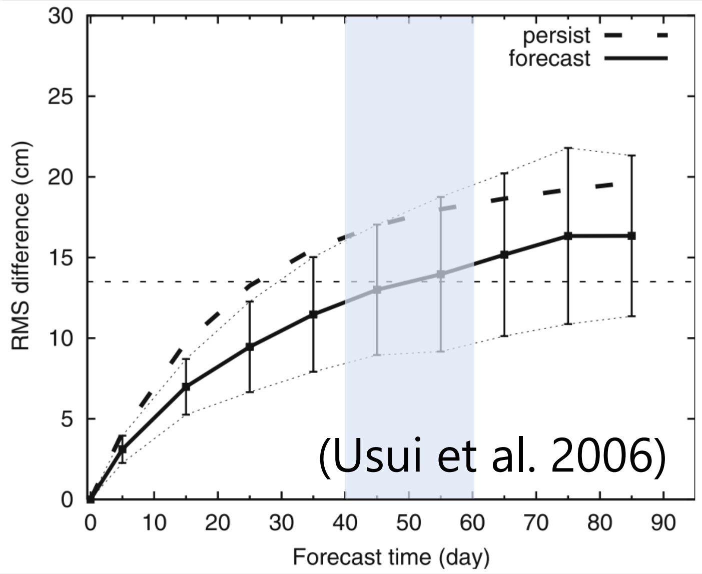
Forecast SSH RMSD



←Analysis standard deviation (SD)

Almost deterministic forecasts

1. Introduction – Existing ocean reanalysis datasets –

DA interval: 5 days
in-situ T & S only assimilated
Currently not available

■ Global reanalysis datasets

3D-VAR	4D-VAR	KF	EnKF
5 datasets	2	2	**PEODAS**

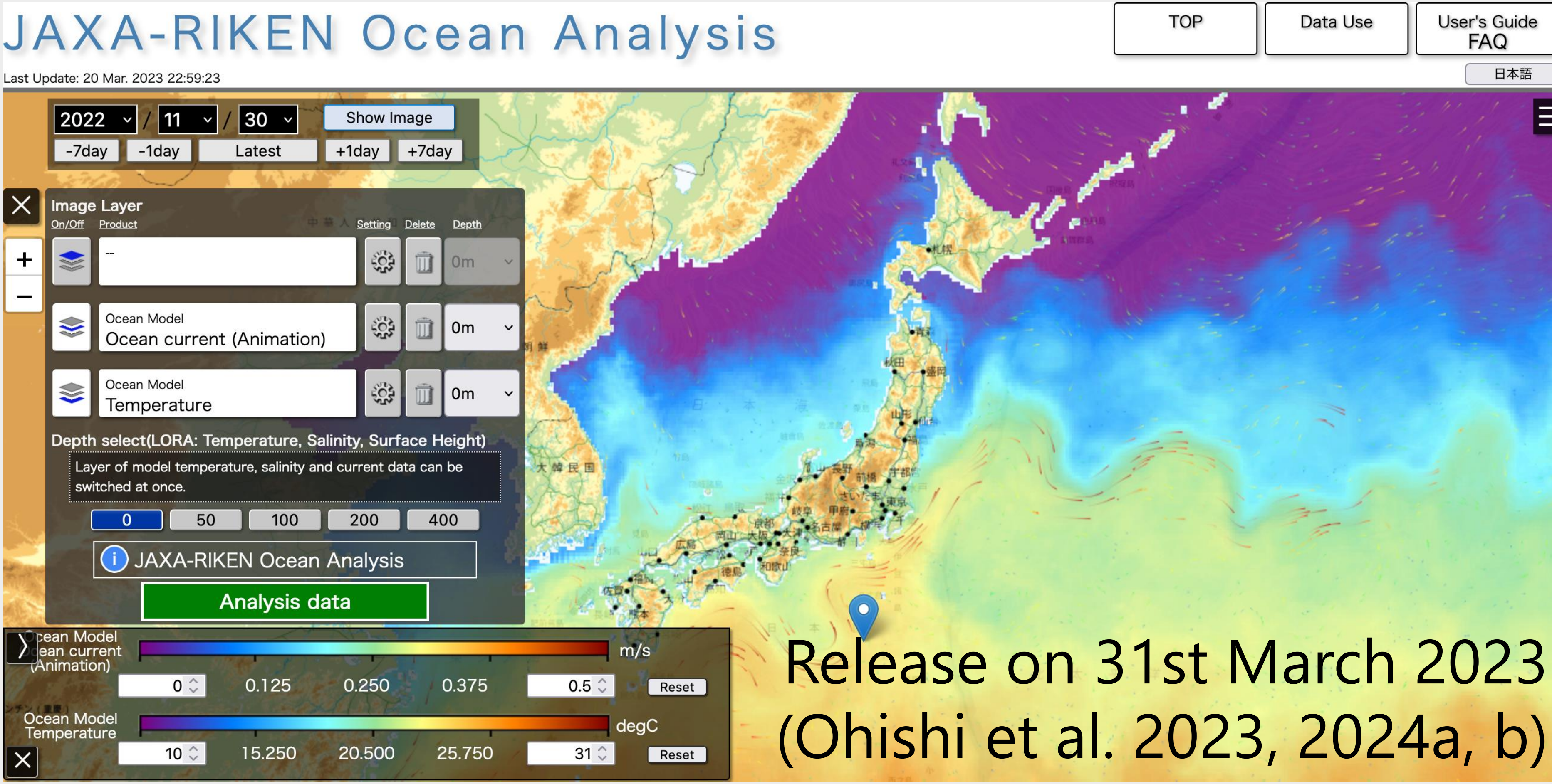
■ High-resolution regional reanalysis datasets (d
in

<u>Short</u> DA interval: 1 day
<u>All typical obs.</u> assimilated

3D-VAR	4D-VAR	KF	EnKF
JCOPE2M (JAMSTEC) FRA-ROMS (FRA)	FORA-WNP30 (MRI & JAMSTEC)	DREAMS (Kyushu Univ.)	**LORA**

(c.f. Balmaseda et al. 2015; Martin et al. 2015)
***3 (4)D-VAR:** 3 (4) Dimensional VARiational data assimilation
***KF:** Kalman Filter ***EnKF:** Ensemble Kalman Filter

We have developed a high-resolution EnKF-based ocean data assimilation system and created an ensemble analysis dataset called **LORA** (<u>L</u>ETKF-based <u>O</u>cean <u>R</u>esearch <u>A</u>nalysis; Ohishi et al. 2022a, b, 2023).



Release on 31st March 2023
(Ohishi et al. 2023, 2024a, b)

■ How to find the website

1. Google “JAXA RIKEN Ocean”

2. Scan the QR code

1. Introduction

- Aim
  - Validate the LORA dataset for the Kuroshio south of Japan
  - Investigate the predictability of deterministic and ensemble forecasts

Data & Method

2. Dataset – LORA –

■ Ocean model

Model: sbPOM version 1.0 (Jordi and Wang 2011; Ohishi et al. 2022a, b)

Domain: Western North Pacific [108°E–180°, 12°–50°N]

Resolution: dx = 0.1°×50 σ-layers

Atmospheric forcing: JRA55-do (Tsujino et al. 2018)

River discharge: TE-Global (https://www.eorc.jaxa.jp/water/)

Spin-up period: 2011.01-2015.06

■ Data assimilation

Data assimilation: LETKF (Hunt et al. 2007)

Ensemble size: 128, Assimilation interval: 1 day

Assimilated obs.: Satellite SST, SSS, and SSH, and in-situ T and S

Schemes: RTPP (Zhang et al. 2004), IAU (Bloom et al. 1996), AOEI (Minamide et al. 2018)

Assimilation period: 2015.07–Present

3. Method

■ Forecast experiment

- Deterministic forecast: Restart from ensemble mean
- Ensemble forecast: Restart from 128 ensemble

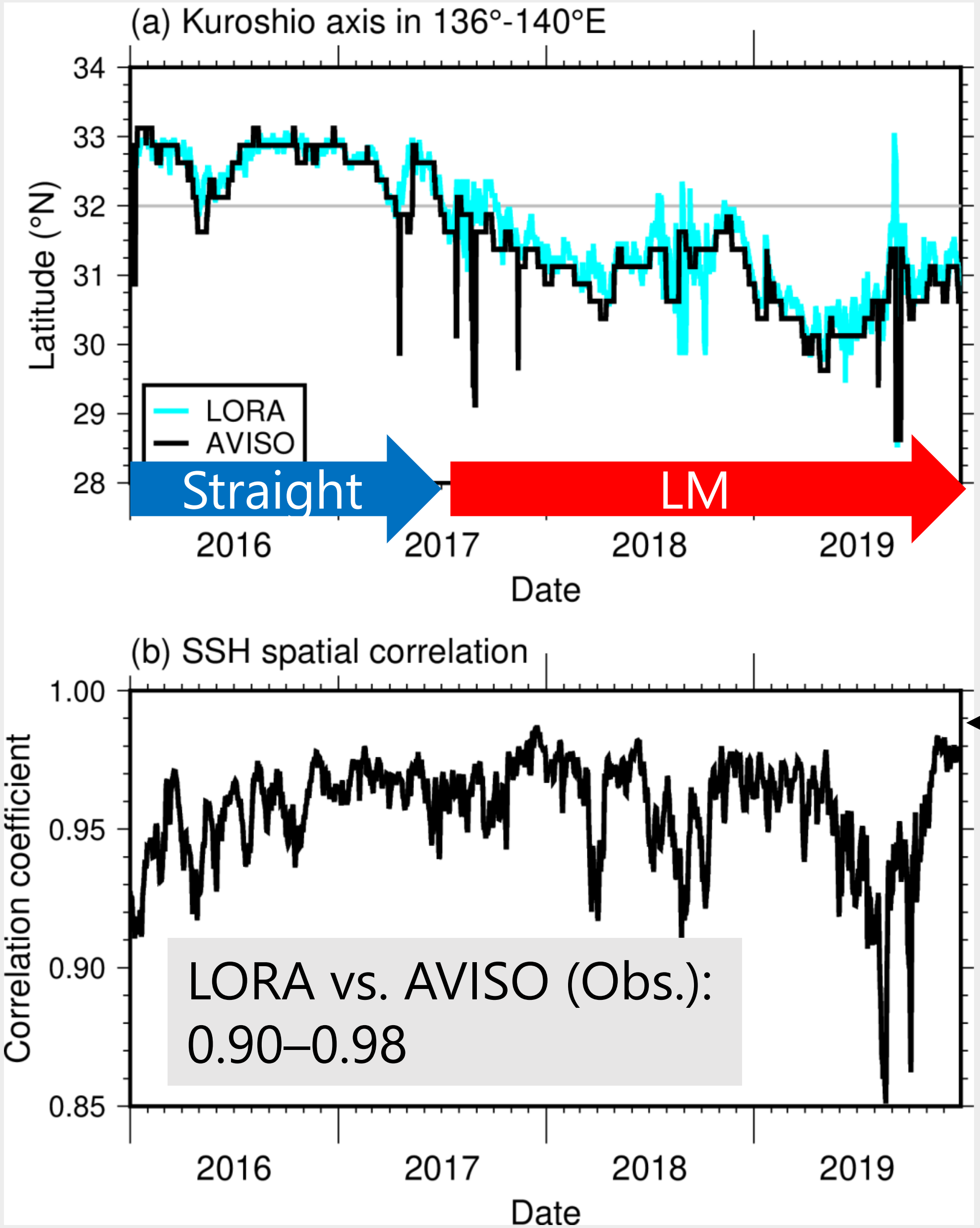
- Period: 6-month forecast for each month in 2016.01–2018.12
  → Total: 36 cases (2322-year integration)
- Atm. forcing: JRA55-do (Tsujino et al. 2018)
  → Assumption of perfect external forcing as in Usui et al. (2006)

■ Validation

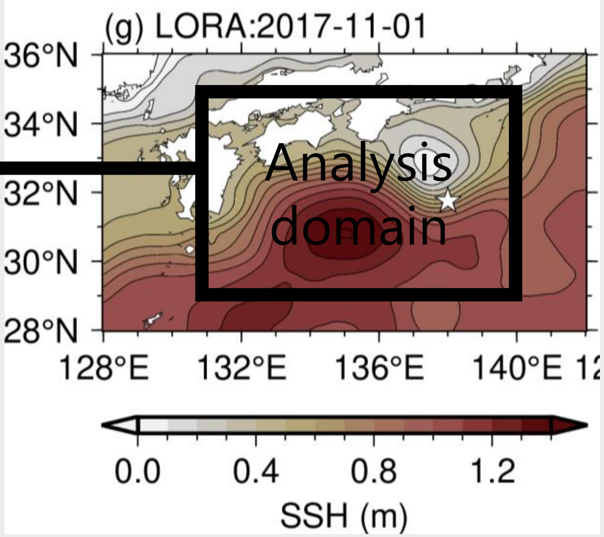
Forecast RMSDs relative to the LORA (i.e., analyses)

Result (Validation)

4. Result – Validation –



The Kuroshio variations including the formation of LM in summer 2017 are well captured by the LORA.



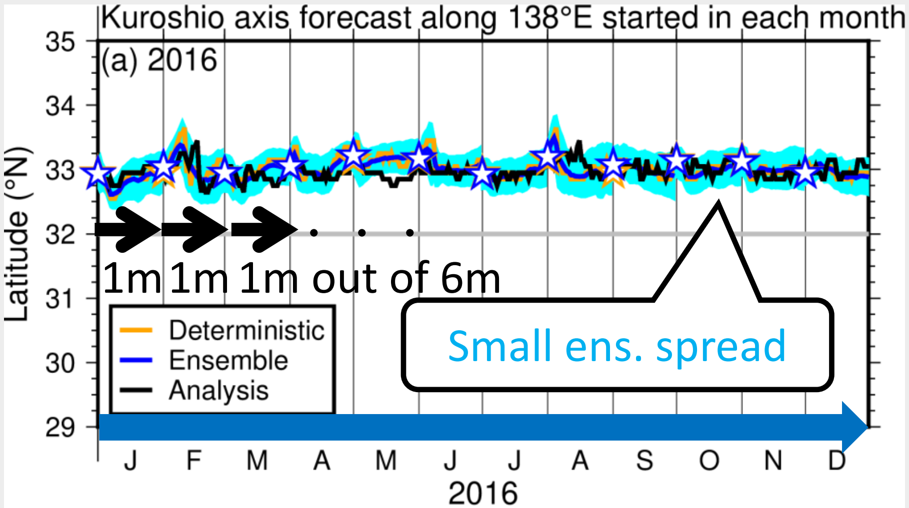
*(a): Max. geostrophic current within 28°–35°N

*(b): Analysis domain: 131°–140°E, 30°–35°N

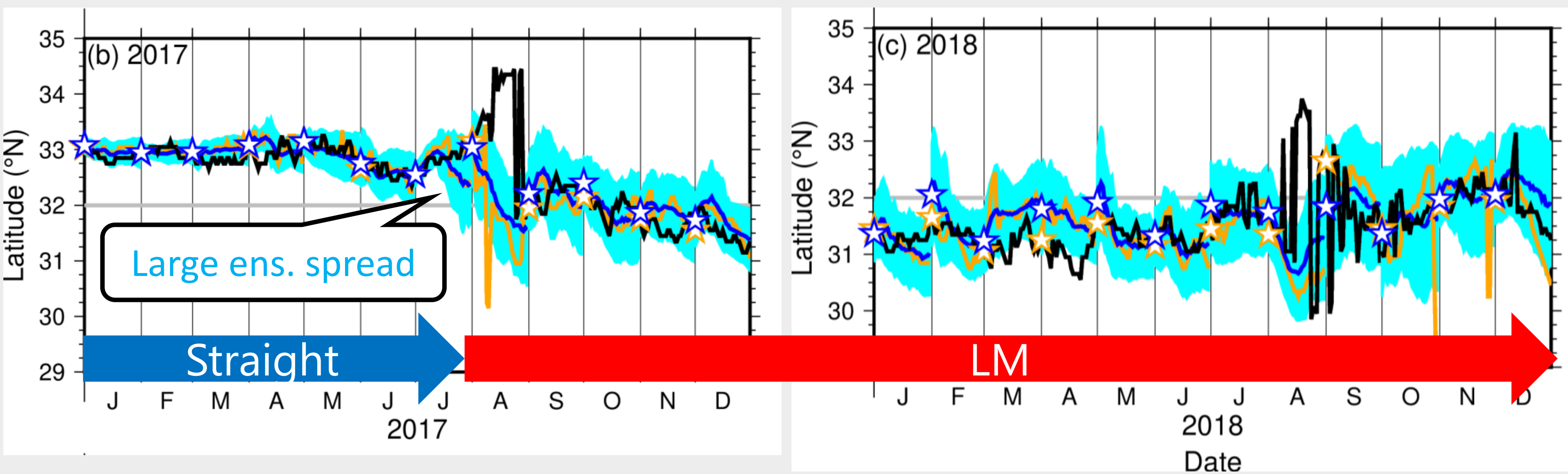
Result (Forecast)

4. Result – Forecast: Kuroshio axis –

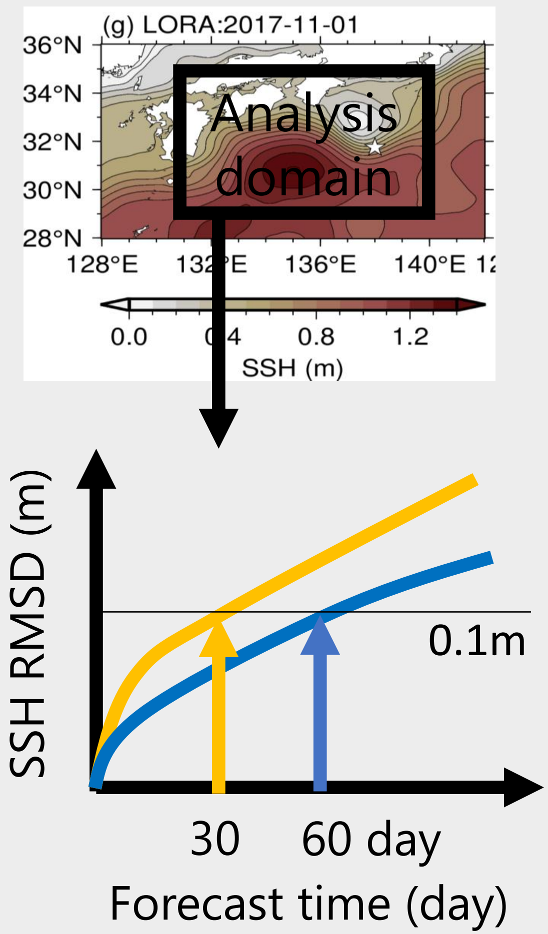
■ 1-month Kuroshio axis forecast initialized on 1st day of each month

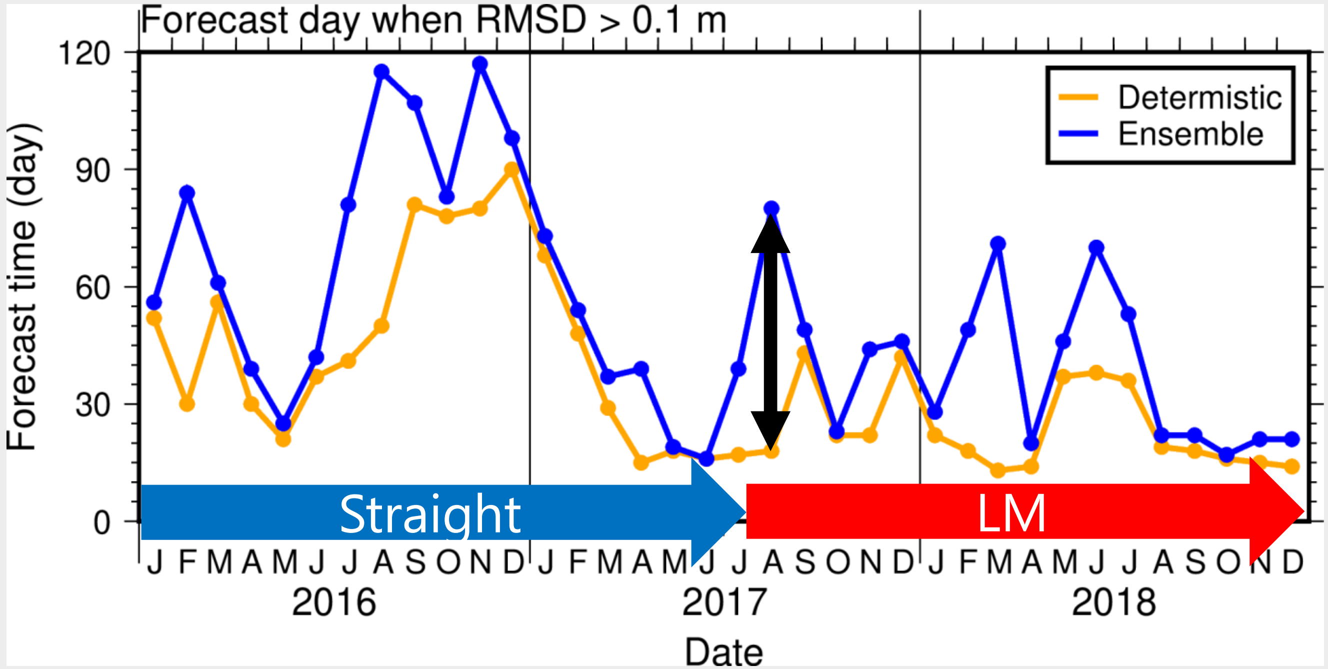


Deterministic and ensemble forecasts well capture the Kuroshio axis.



4. Result – Predictability –





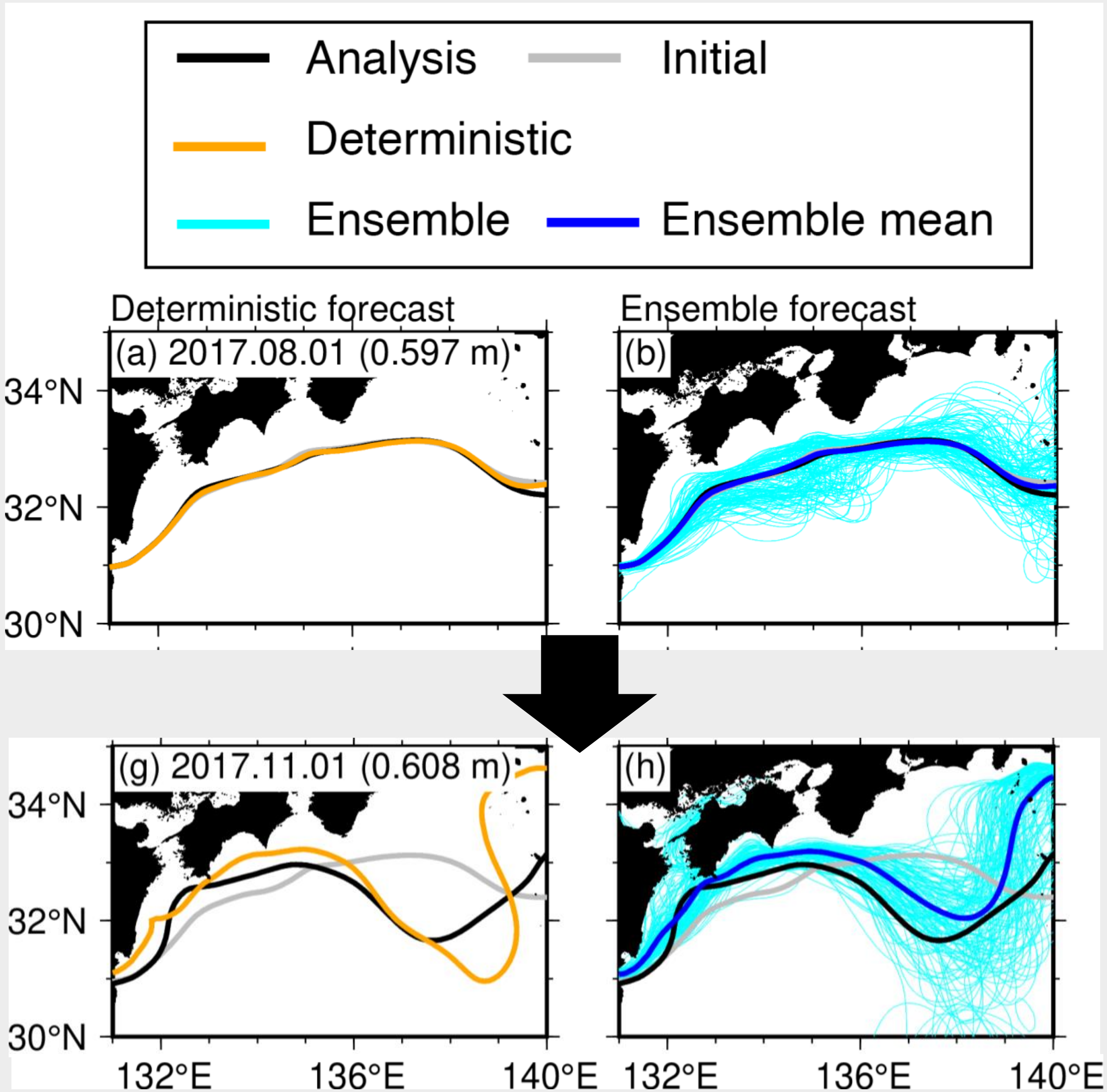
- The Ensemble forecast outperforms the deterministic forecast.

- During the large meander period, the predictability is shorter.

4. Result – Initial: 2017.08 (Straight to Meander) –

2017.08
(Initial)

2017.11
(3 month)



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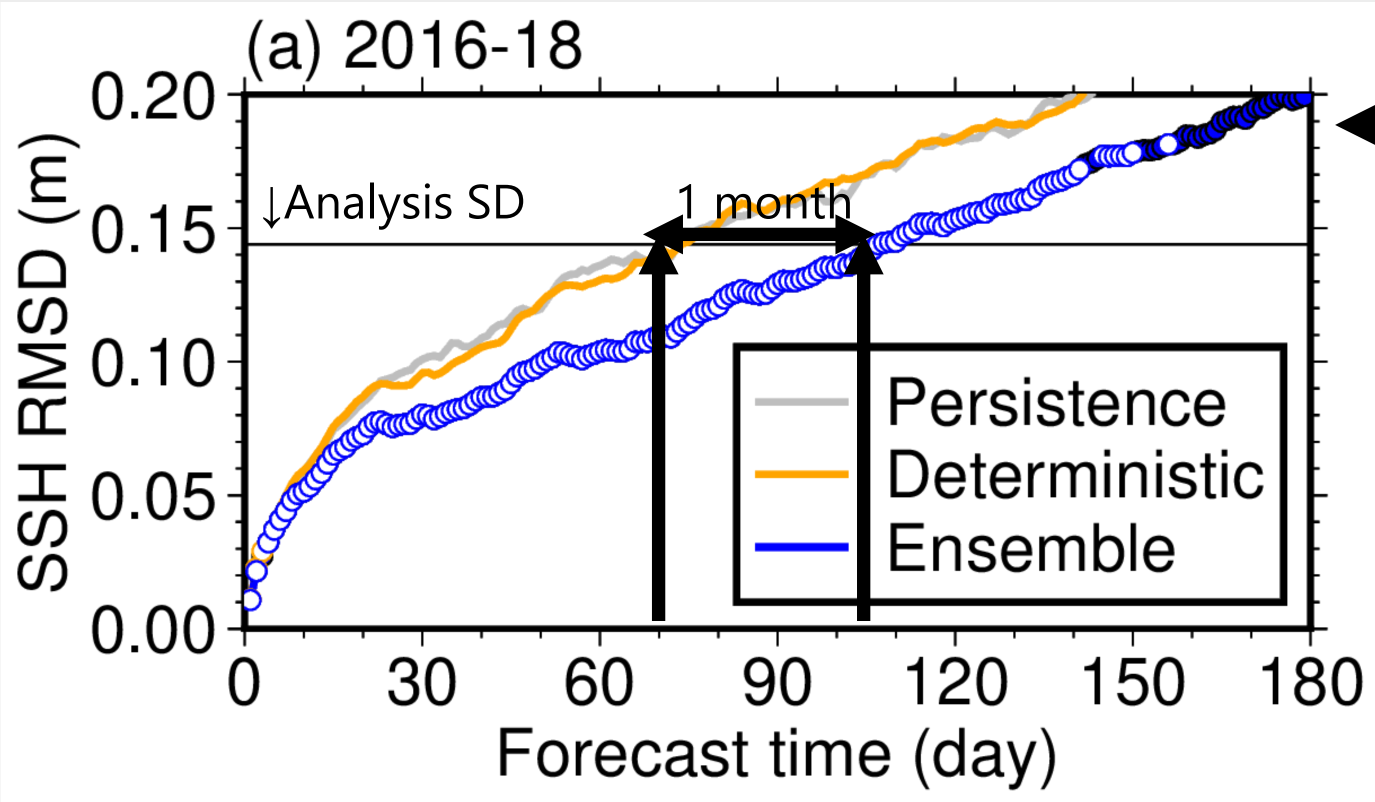

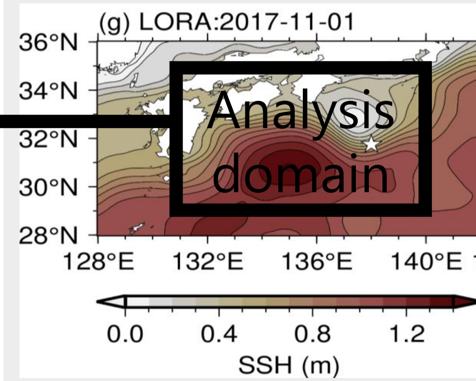

*Persistence: RMSD of the initial analysis condition
*Ensemble: RMSD of the forecast ensemble mean
*○: Significant difference relative to the persistence
*●: Significant difference relative to the deterministic forecast

Deterministic 70-80 days < **Ensemble 100-110 days**

Summary

5. Summary

- Validation for the Kuroshio south of Japan

  The LORA well represents the formation of the Kuroshio large meandering in the summer of 2017.

  → Sufficient accuracy for the Kuroshio forecast.

- Deterministic and ensemble forecasts

  - The ensemble forecast outperforms the deterministic forecast.

    → Deterministic: 70–80 days < Ensemble: 100–110 days

  - Positive SST and SSH forecast biases exist.

    → It is necessary to develop the ocean DA system.

- Plan

  Investigate important factors to generate the Kuroshio large meandering using ensemble sensitivity experiments

Appendix

Ensemble forecast of Kuroshio south of Japan

Shun Ohishi[1], Takemasa Miyoshi[1], and Misako Kachi[2]
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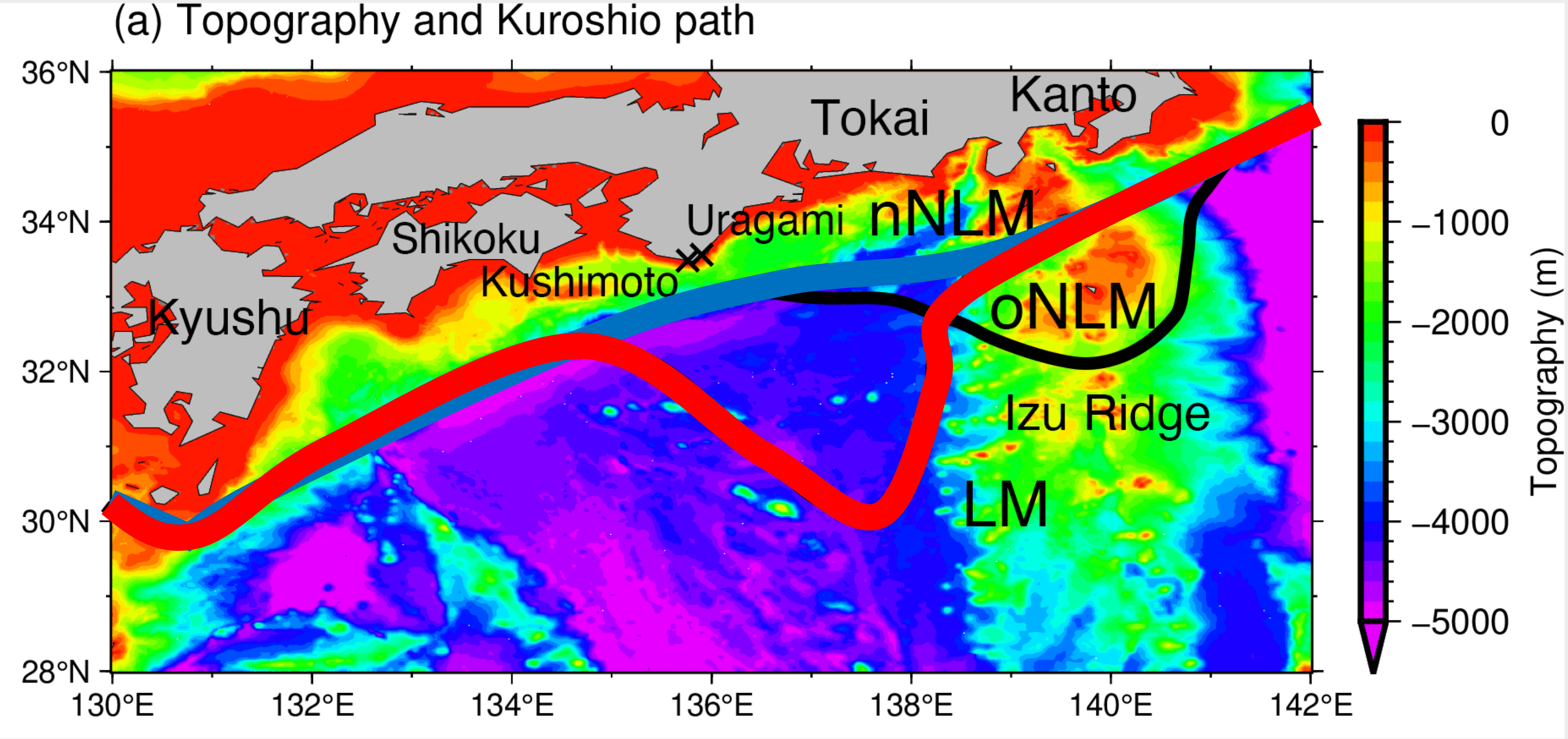

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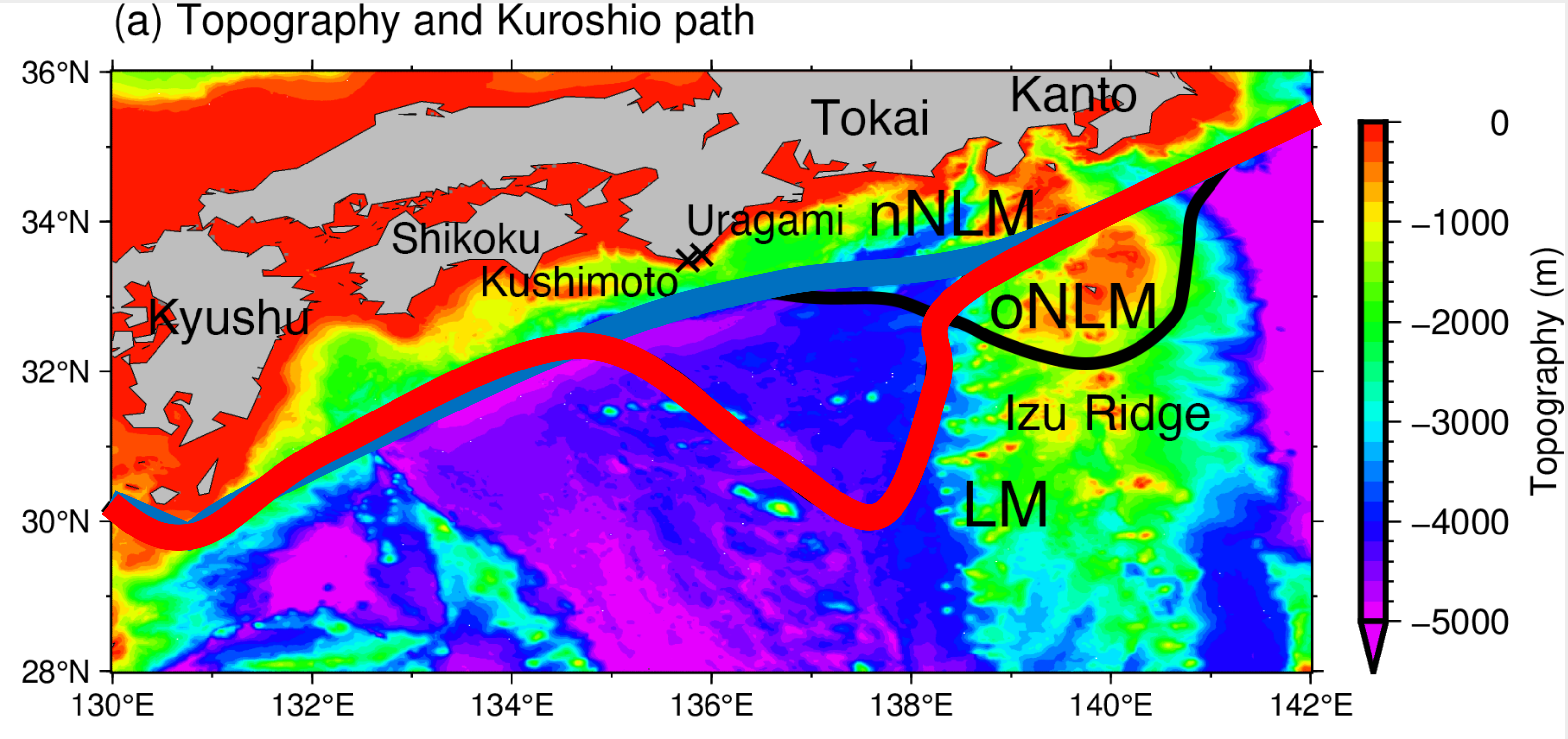

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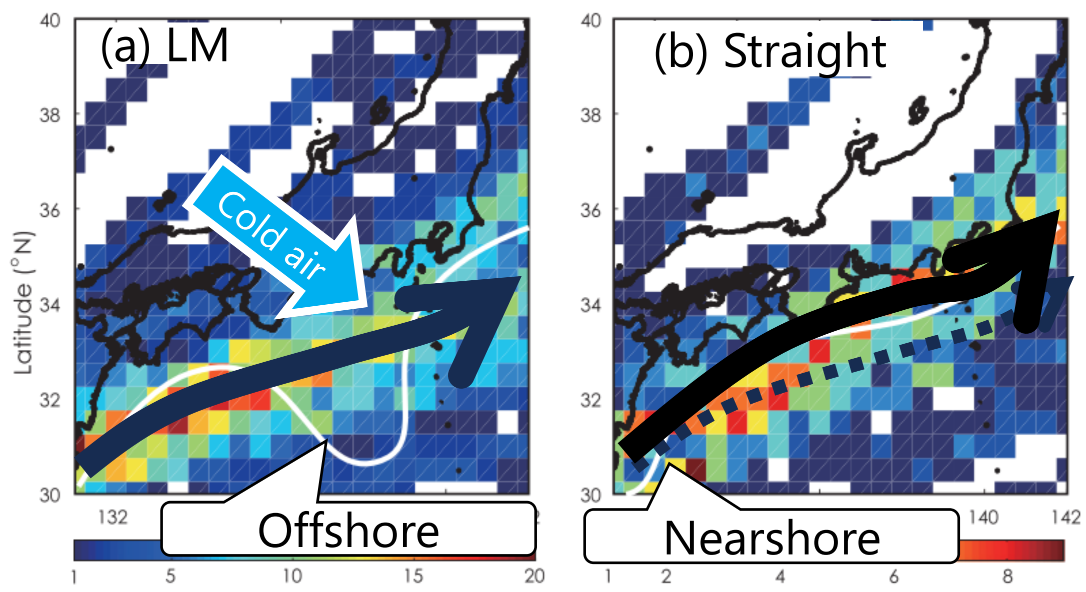
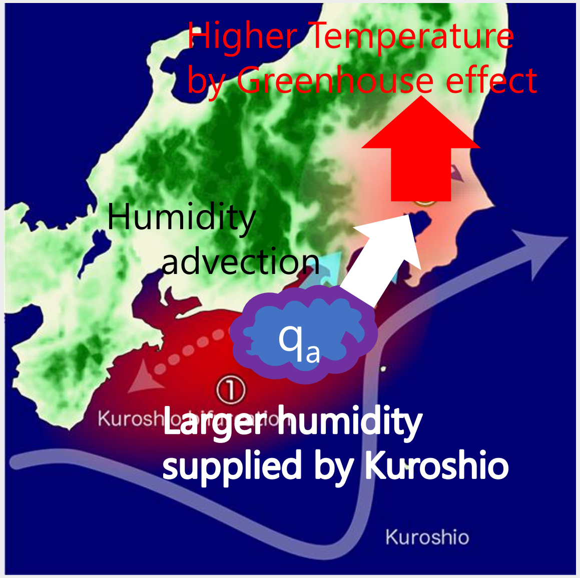
Frequency of cyclonic disturbances in winter



Hot summer



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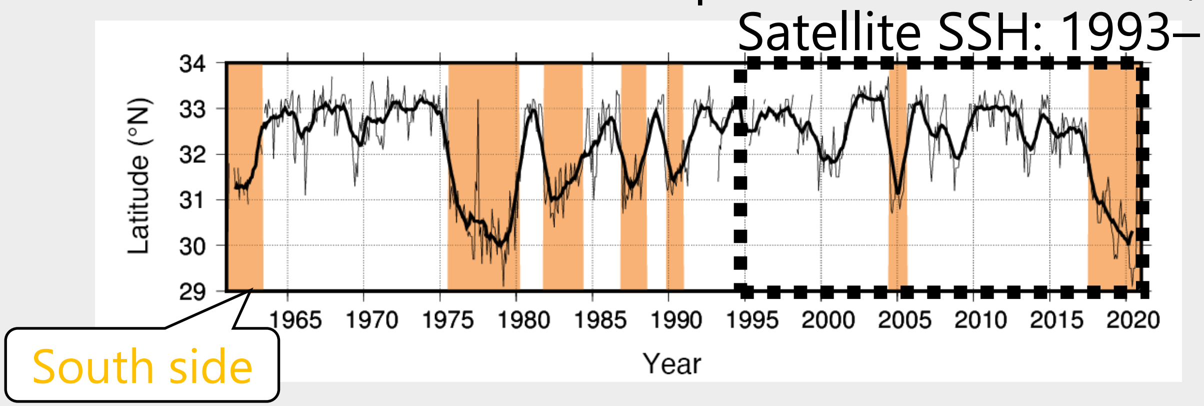

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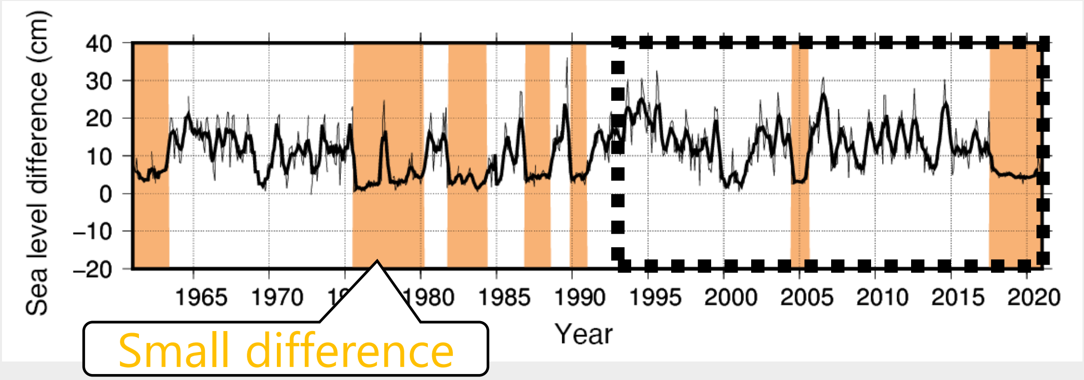

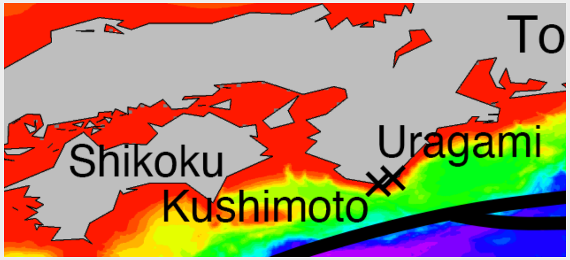

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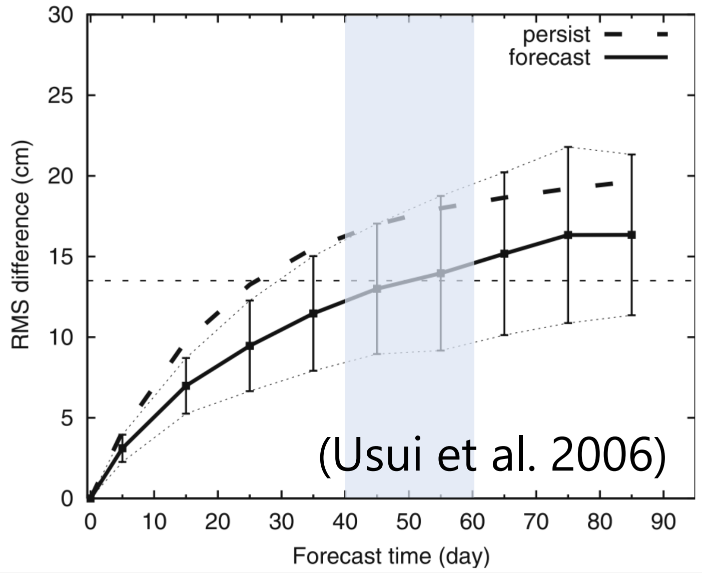

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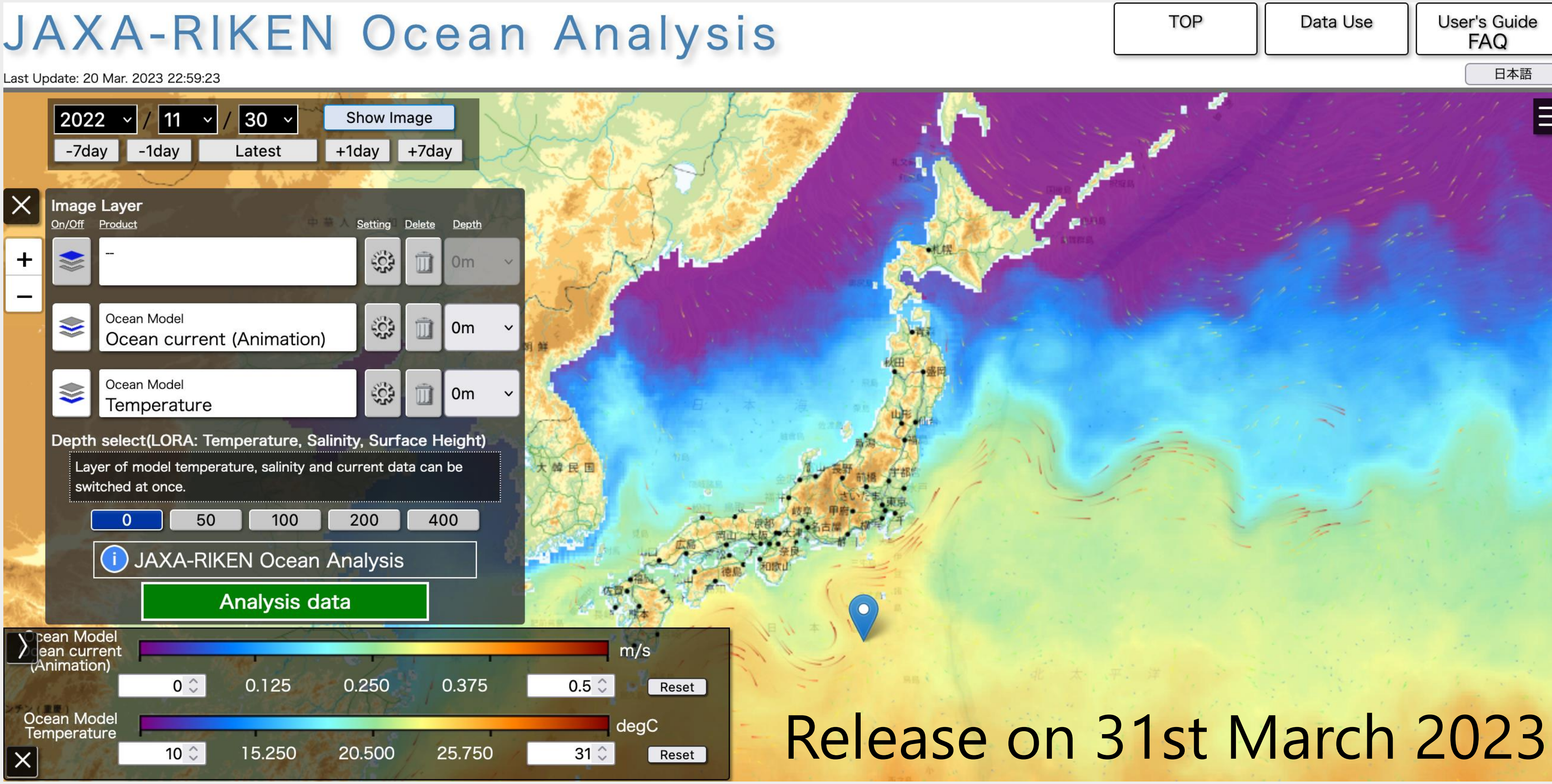

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Assimilation period: 2015.07–Present

2. Dataset – AVISO –

- AVISO

  Variable: SSH, SSHA, surface geostrophic velocity

  * SSH (x,y,t) = MDOT (x,y) + SSHA(x,y,t)

  Resolution: dx = 0.25°

  Period: 1993.01–2021.12

3. Method

■ Forecast experiment

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  → Total: 36 cases (2322-year integration)
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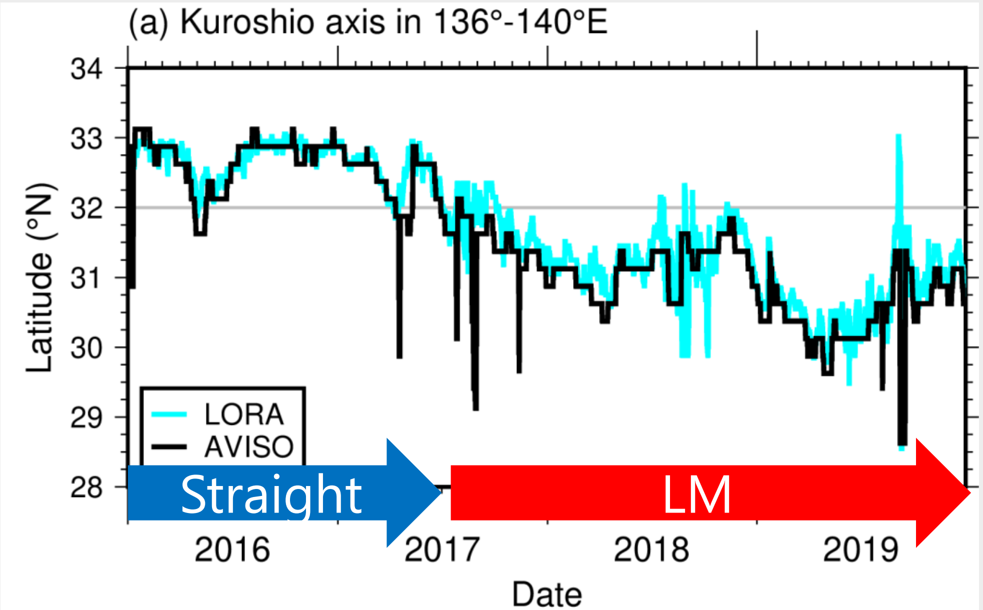
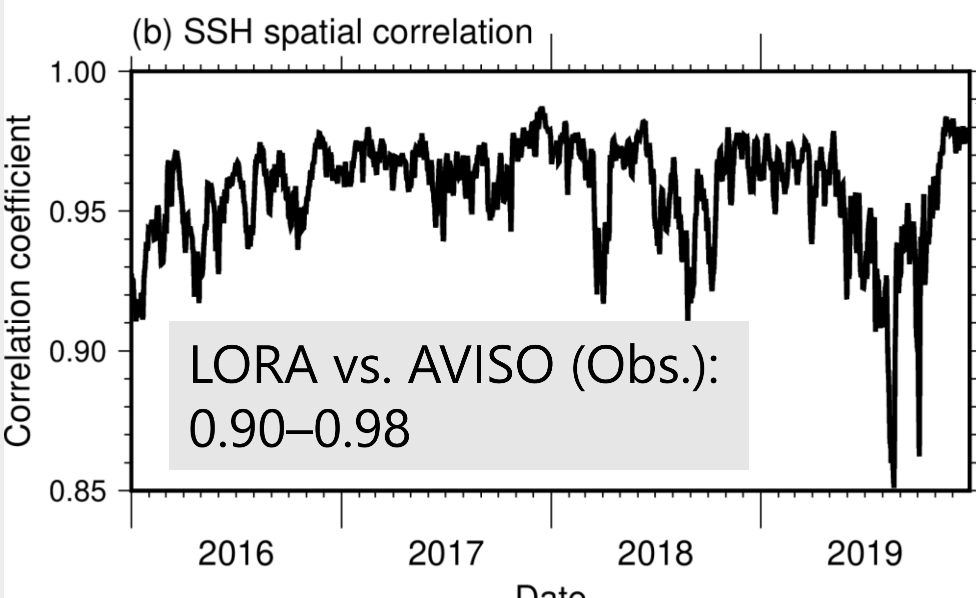
Result

4. Result – Validation –





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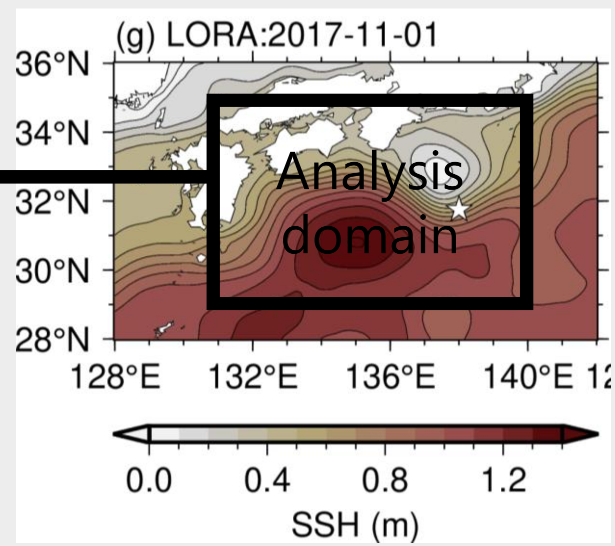
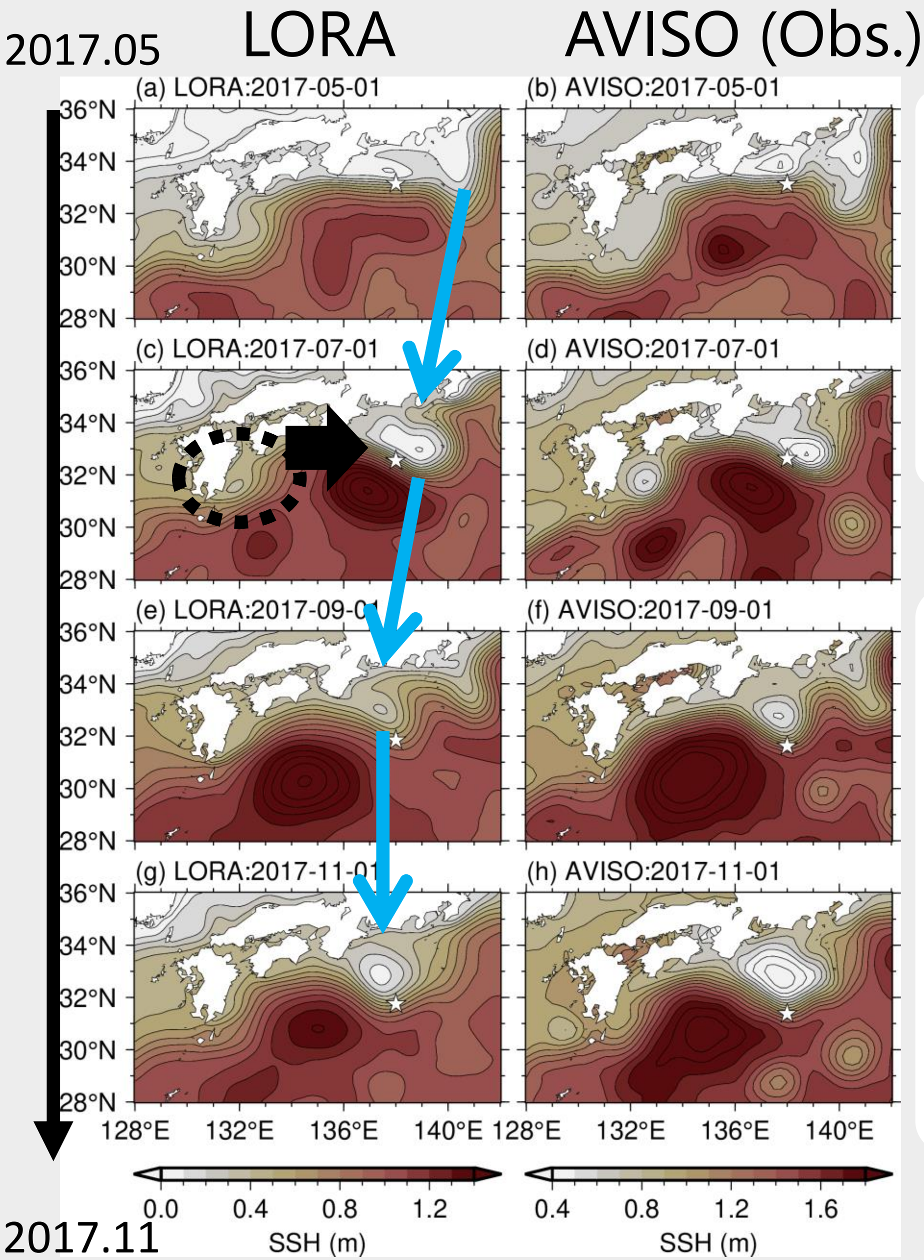


*(a): Max. geostrophic current within 28°–35°N

*(b): Analysis domain: 131°–140°E, 30°–35°N

4. Result – Validation: Spatial pattern in 2017 –



■ SSH spatial pattern

Consistent between the LORA and AVISO

→ Sufficient accuracy in LORA

to predict the LM

■ Mechanism by previous studies

(e.g., Usui et al. 2008)

Eastward propagation of meandering

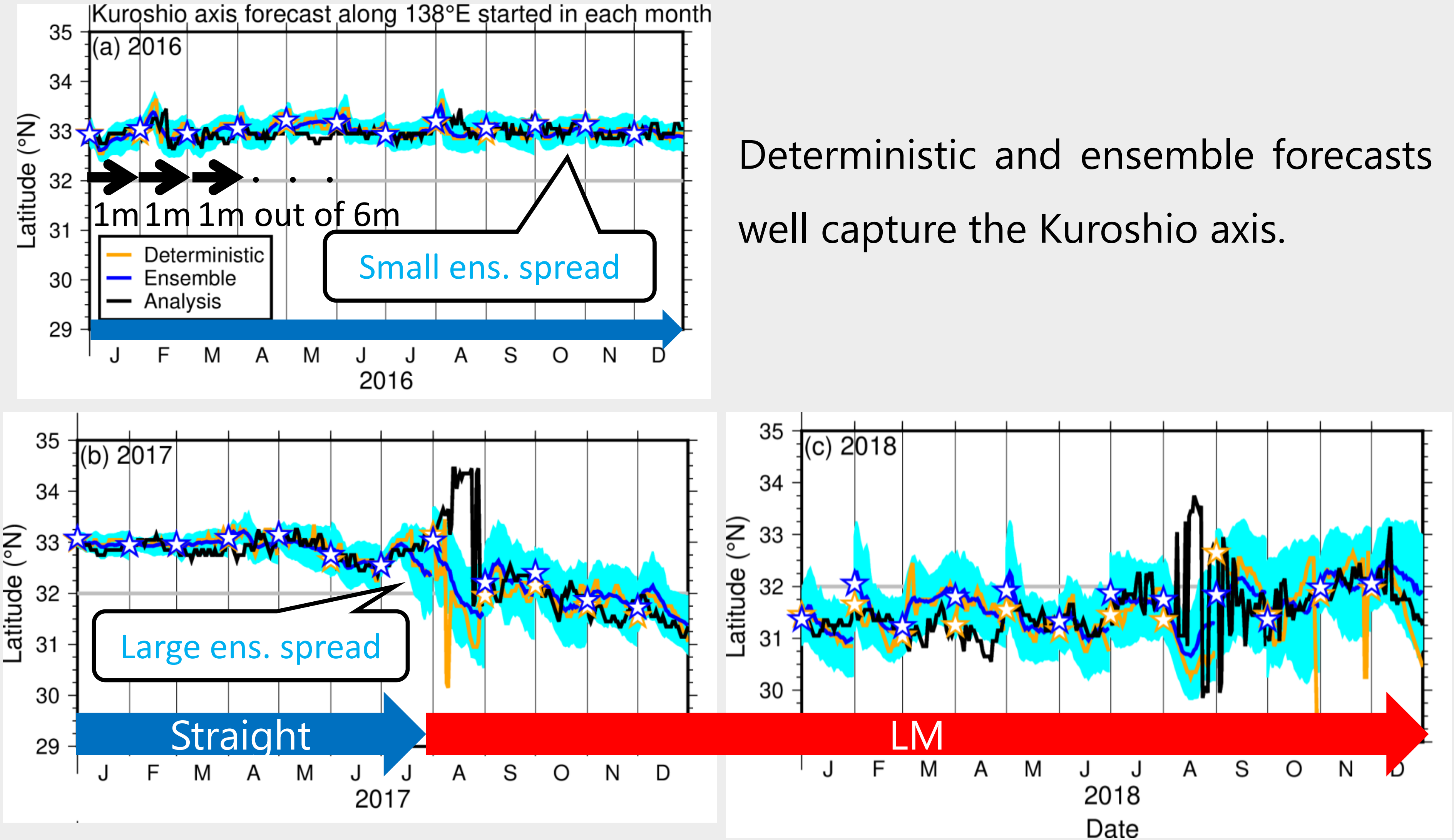
off the southeastern coast of Kyushu

+ Westward propagation of meandering?

→ Future work: Ensemble sensitivity analysis

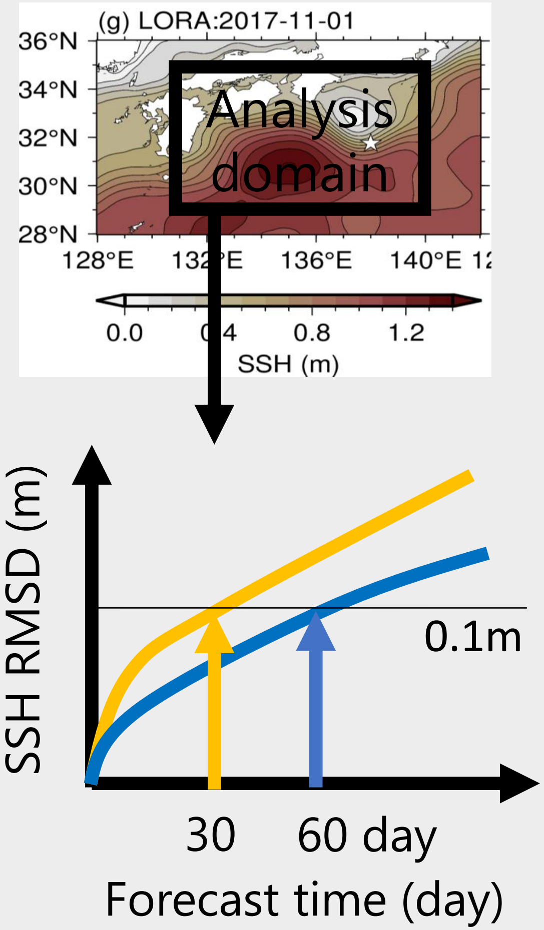
4. Result – Forecast: Kuroshio axis –

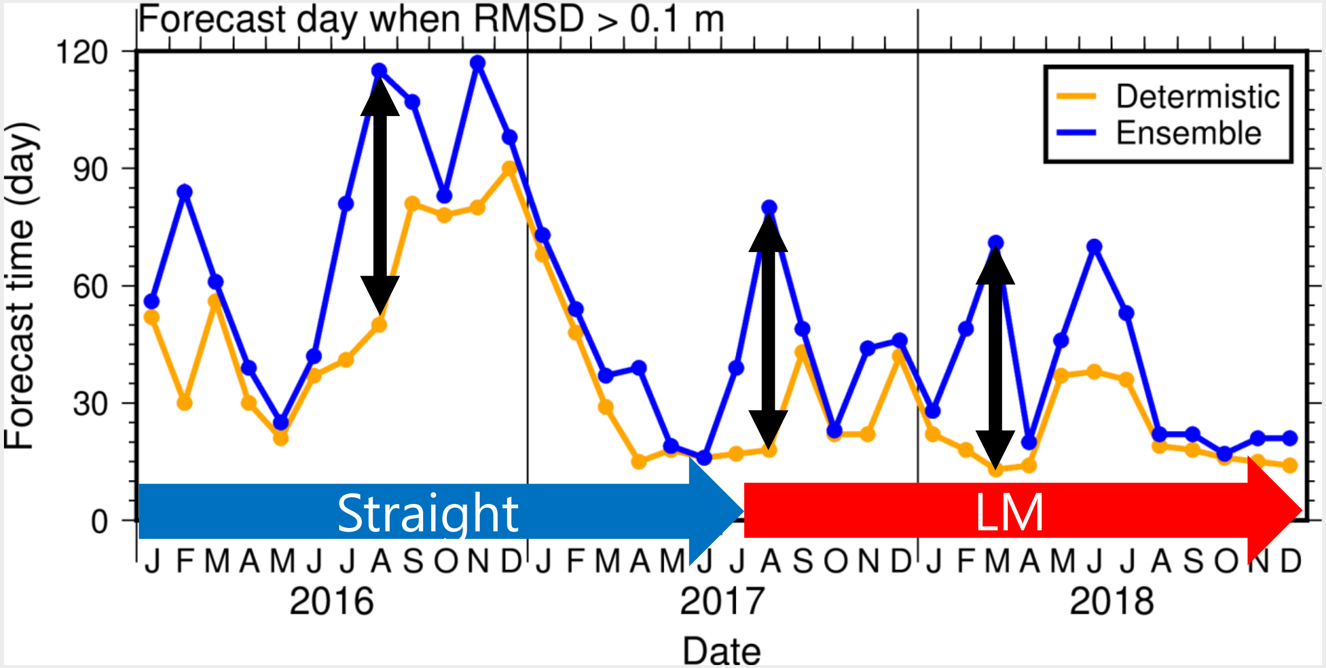
- 1-month Kuroshio axis forecast initialized on 1st day of each month



Deterministic and ensemble forecasts well capture the Kuroshio axis.

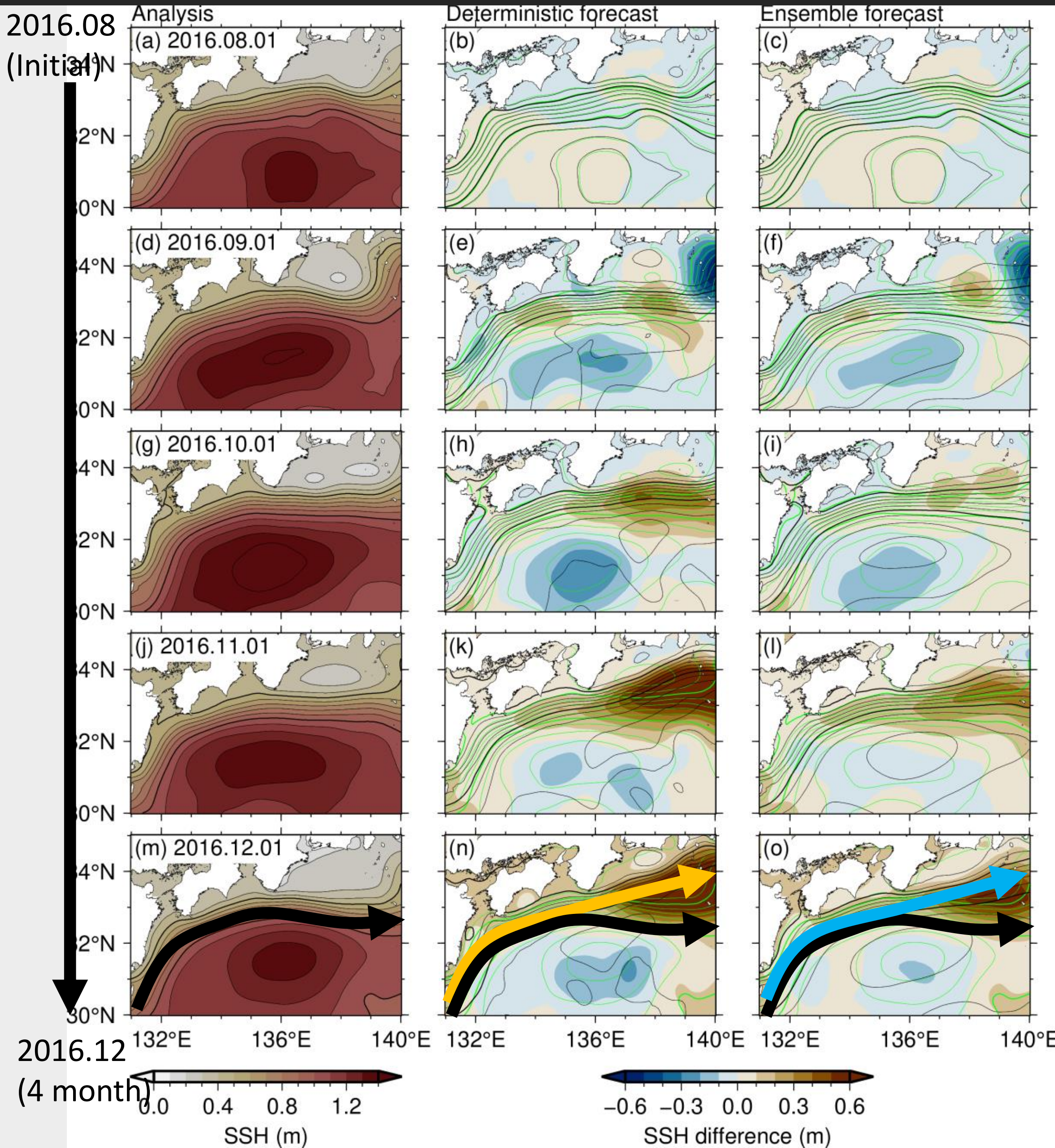
4. Result – Predictability –





- The Ensemble forecast outperforms the deterministic forecast.
- During the large meander period, the predictability is shorter.

4. Result – Initial: 2016.08 (Straight) –



Larger northward shift

in deterministic forecast

in 136–140°E

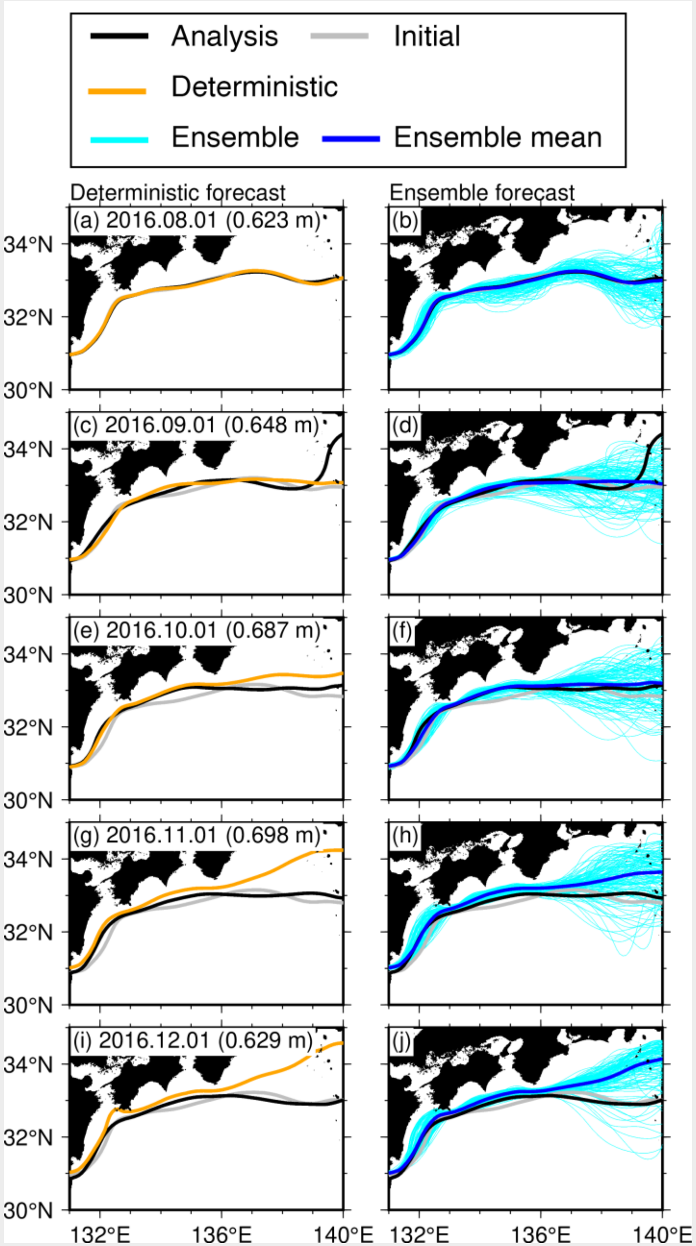
Black contour:
(left) analysis
(middle and right) forecast

Green contour:
(middle and right) analysis

4. Result – Initial: 2016.08 (Straight) –

2016.08
(Initial)

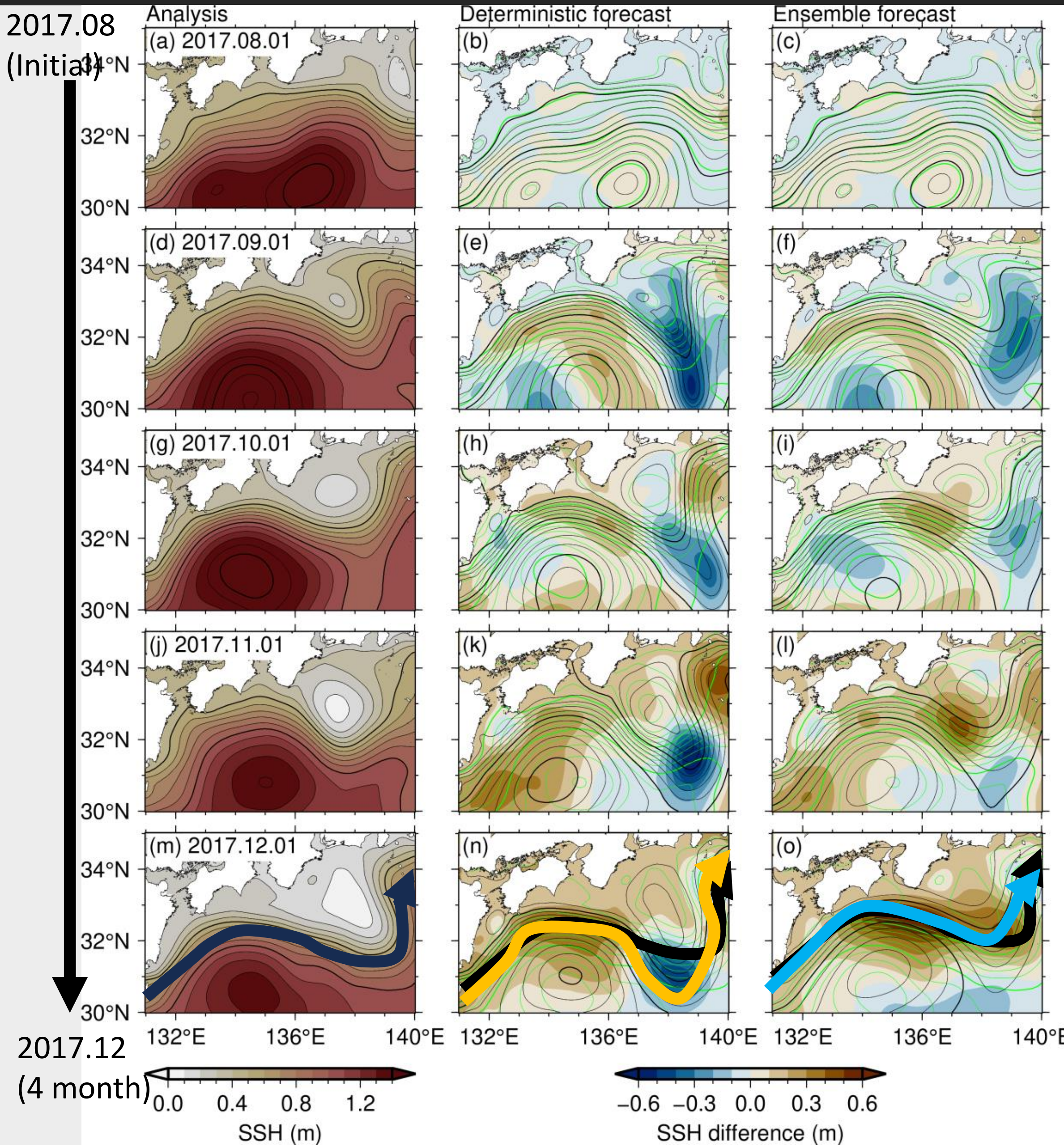
2016.12
(4 month)



- ■ Definition of SSH contour
  - Extract SSH analyses where the surface current is maximum for each longitude grid within 131°–140°E
  - Define median SSH contour as Kuroshio axis
    → Value inside parenthesis

Larger northward shift
in deterministic forecast
in 136–140°E

4. Result – Initial: 2017.08 (Straight to Meander) –



Larger southward meandering

in deterministic forecast

Black contour:
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(middle and right) forecast

Green contour:
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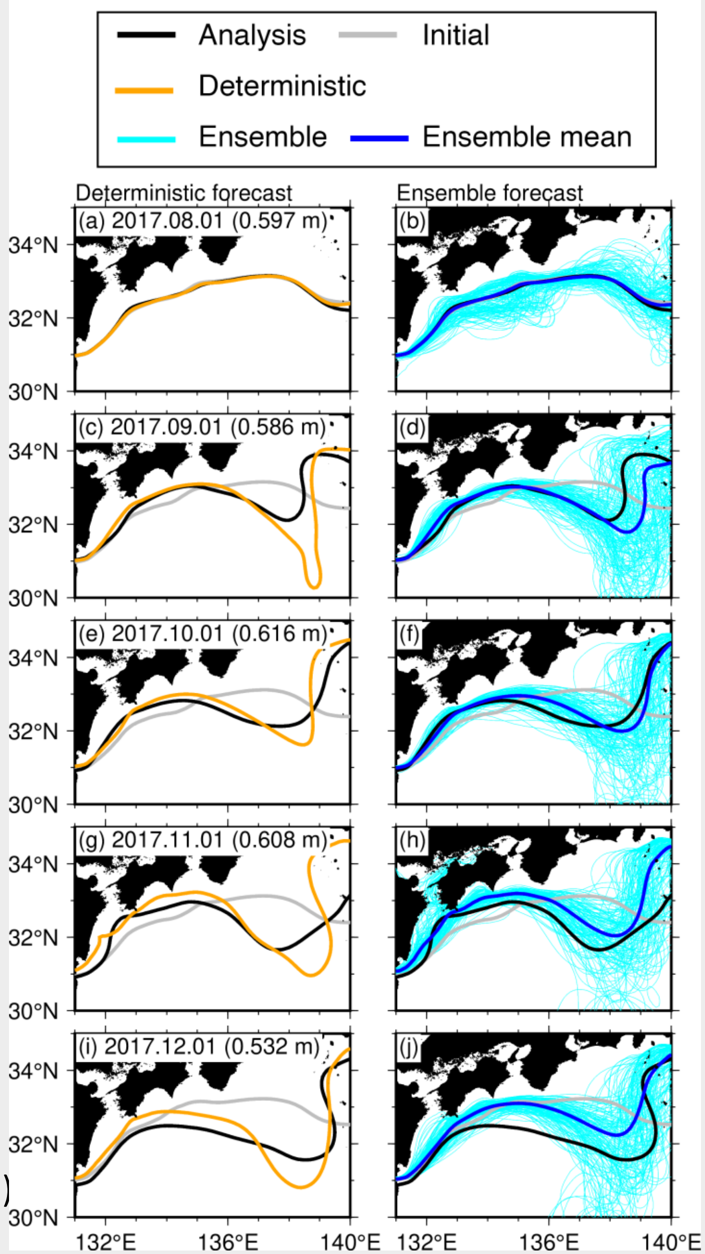
4. Result – Initial: 2017.08 (Straight to Meander) –

2017.08
(Initial)



2017.12
(4 month)

Larger southward meandering

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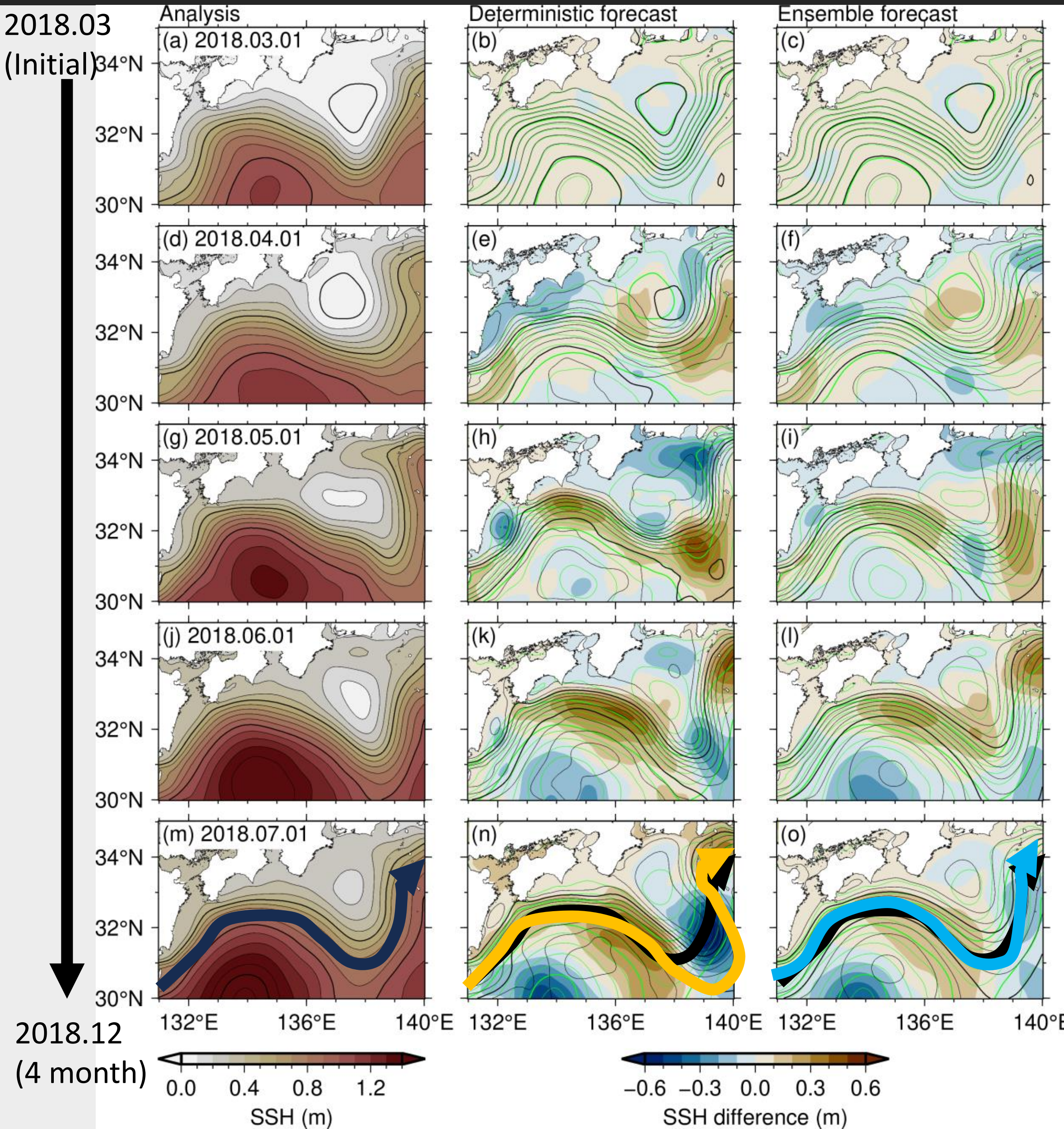
4. Result – Initial: 2018.03 (Meander) –



Meander extends

to the southeast

in deterministic forecast

Black contour: (left) analysis
(middle and right) forecast
Green contour: (middle and right) analysis

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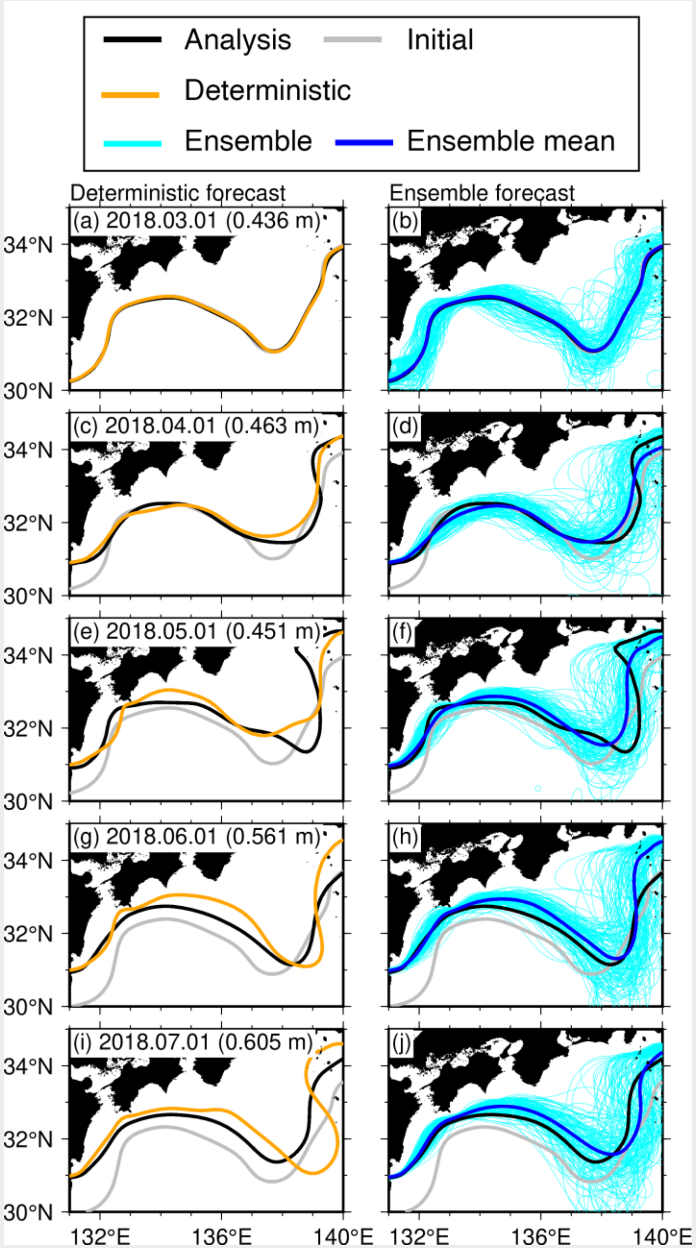
2017.08
(Initial)

2017.12
(4 month)



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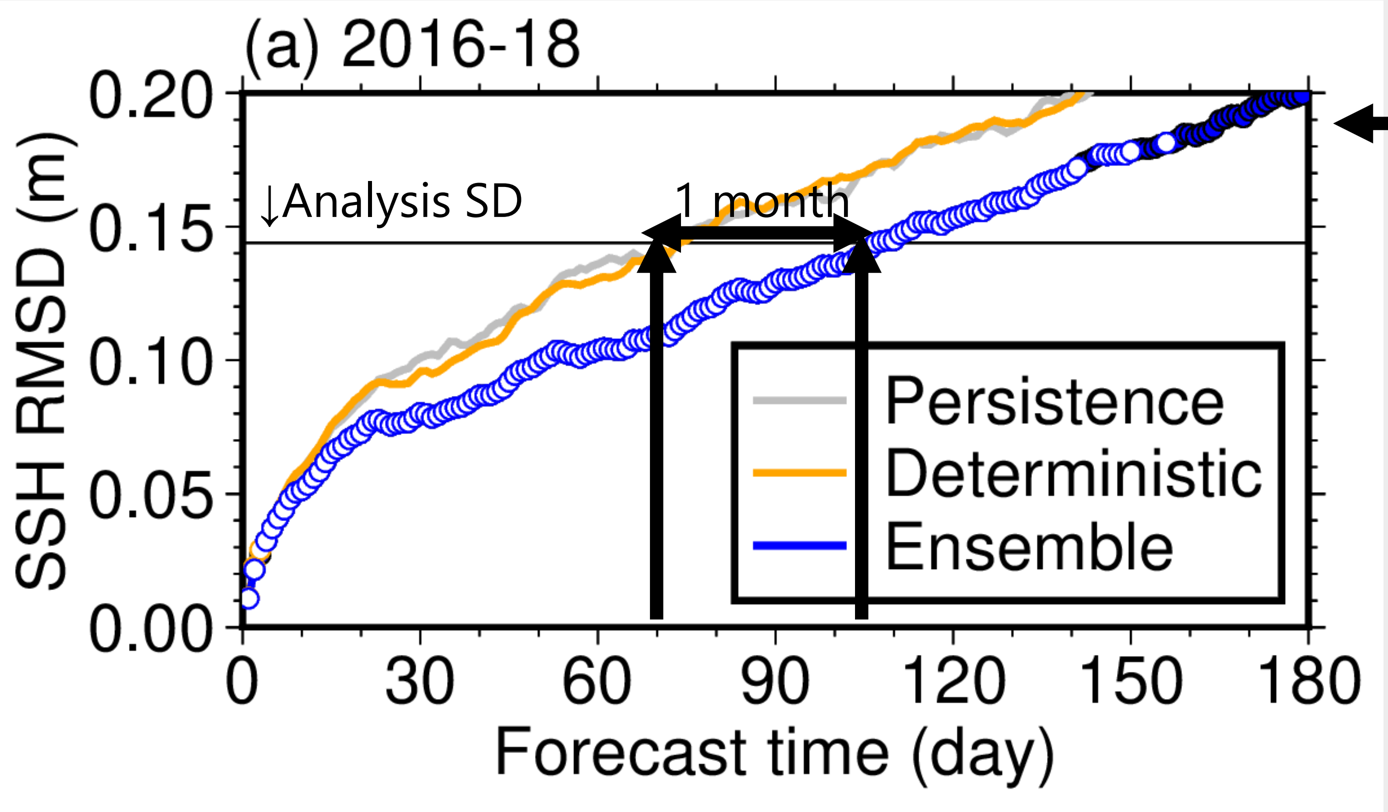
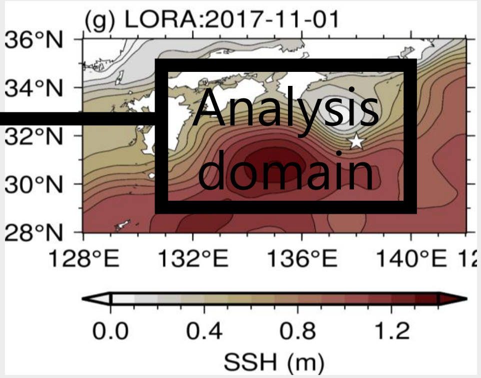
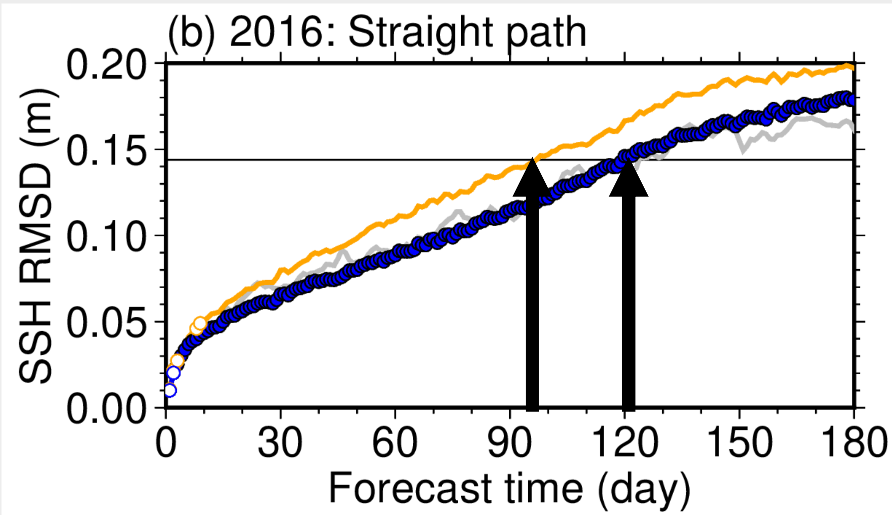




*Persistence: RMSD of the initial analysis condition
*Ensemble: RMSD of the forecast ensemble mean
*○: Significant difference relative to the persistence
*●: Significant difference relative to the deterministic forecast

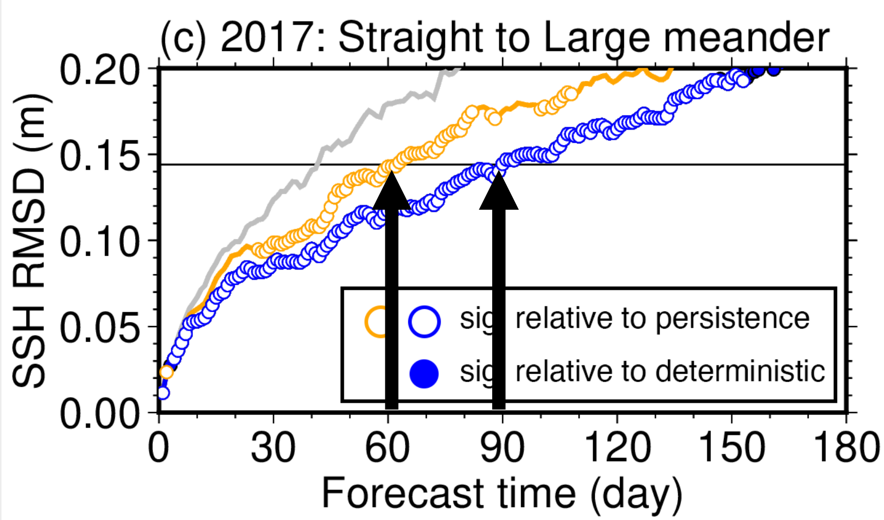
Deterministic 70-80 days < Ensemble 100-110 days

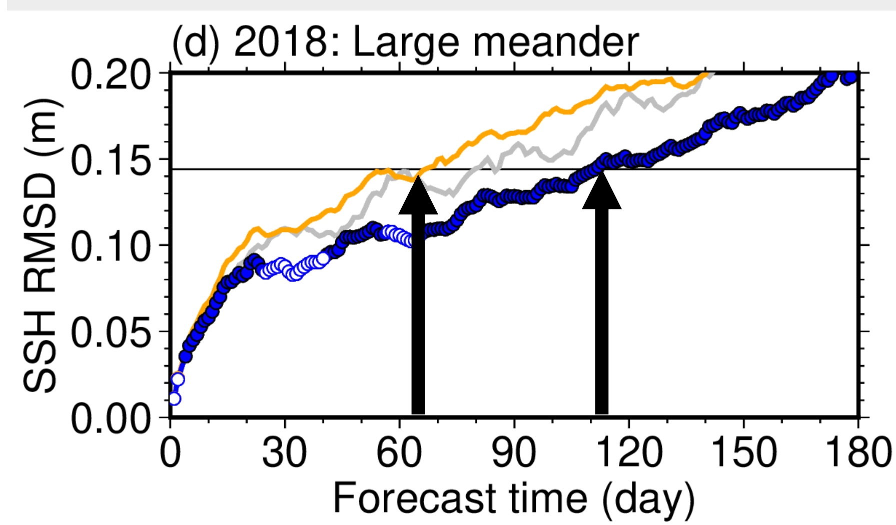
4. Result – Predictability –



- Predictability: 2017 < 2016, 2018
- Almost the same Kuroshio path

→ High persistence in 2016 and 2018





4. Result – Predictability –

How many members are required to outperform the deterministic forecast?

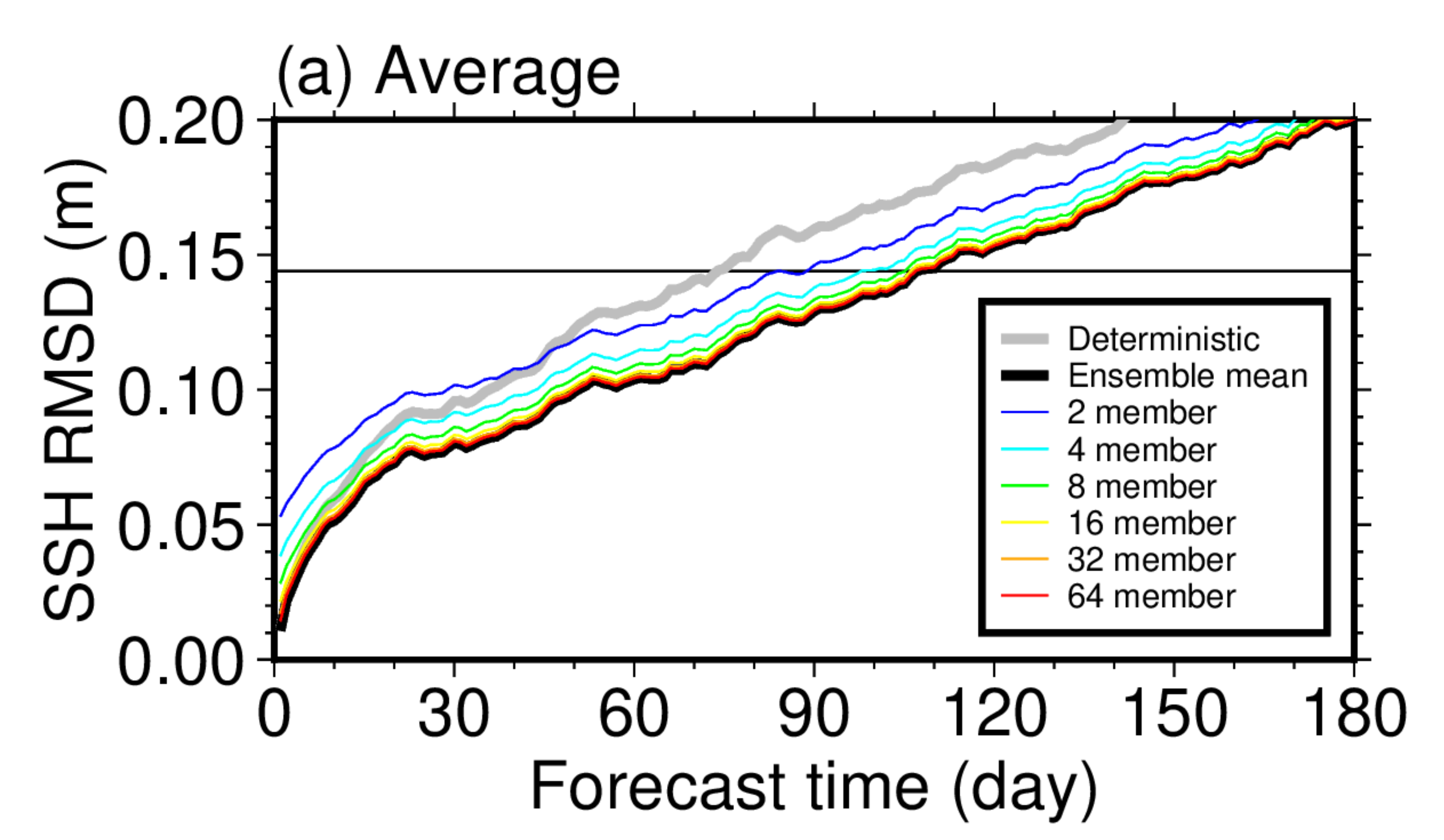
■ Method

For each ensemble size (2, 4, 8, …, 64):

1. Generate an ensemble mean SSH field averaged over randomly selected ensemble members (i.e., subsampling)
2. Calculate the forecast RMSDs
3. Repeat steps 1 and 2 1000 times
4. Calculate the average and standard deviation of the 1000 RMSDs

* This is not fully consistent with DA experiments with smaller ensemble sizes because the recentering method is not applied.

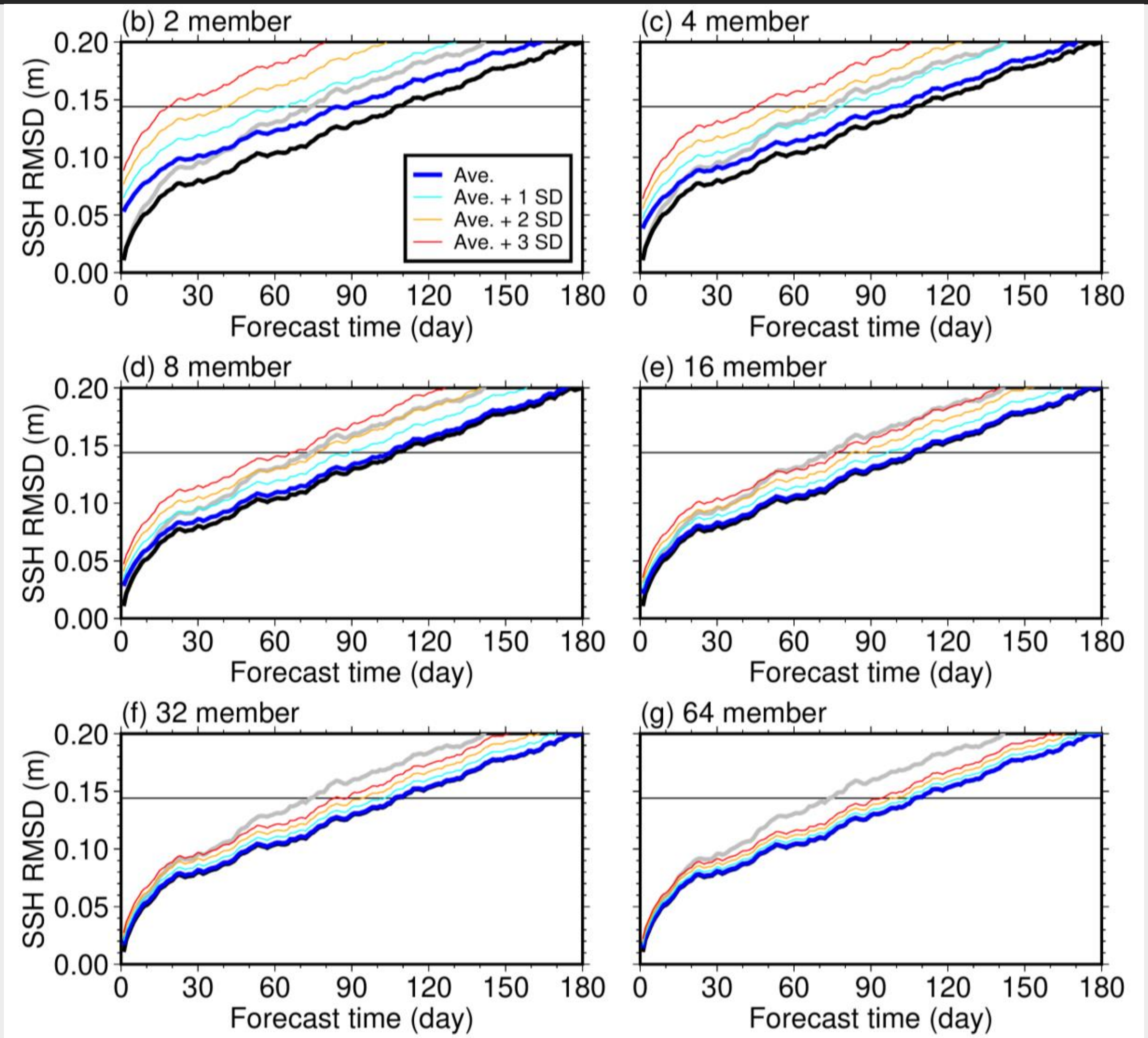
4. Result – Predictability –



Compared with the deterministic forecast,

- When ensemble size < 16,
  the forecast RMSD averages are larger for early forecast days.
- When ensemble size > 16,
  the forecast RMSD averages are smaller over throughout the forecast period.

4. Result – Predictability –



± 1 SD: 68 %

± 2 SD: 95 %

± 3 SD: 99 %

Deterministic

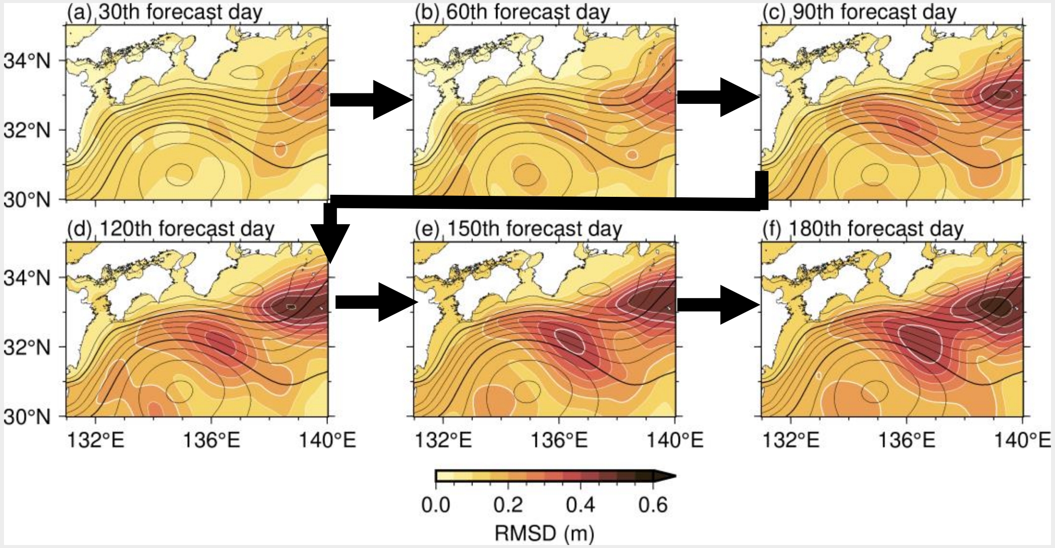
Ensemble mean

When ensemble size ≥ 32,

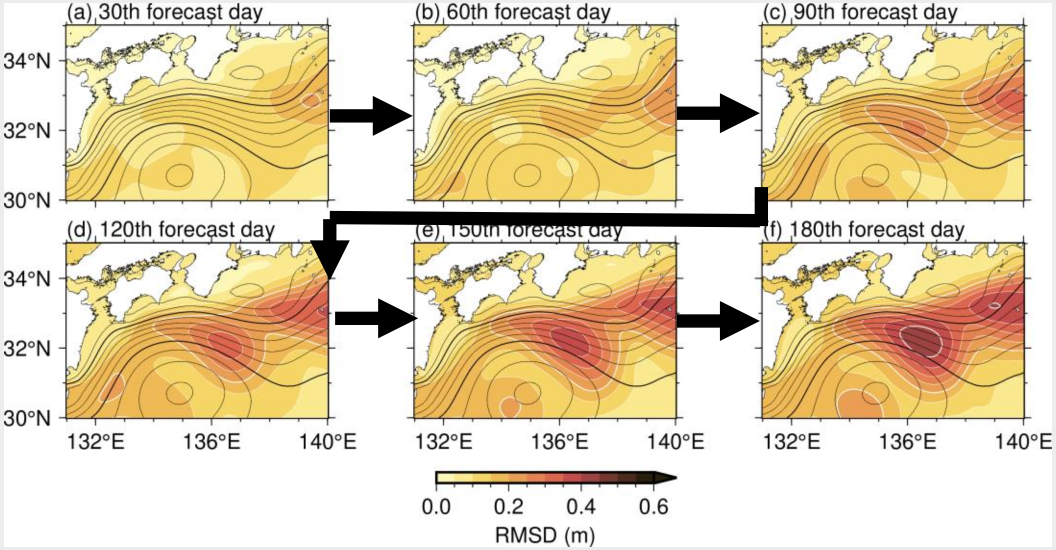
the forecast RMSD averages are almost certainly better than the deterministic forecast.

4. Result – SSH forecast RMSD –

Deterministic forecast



Ensemble forecast



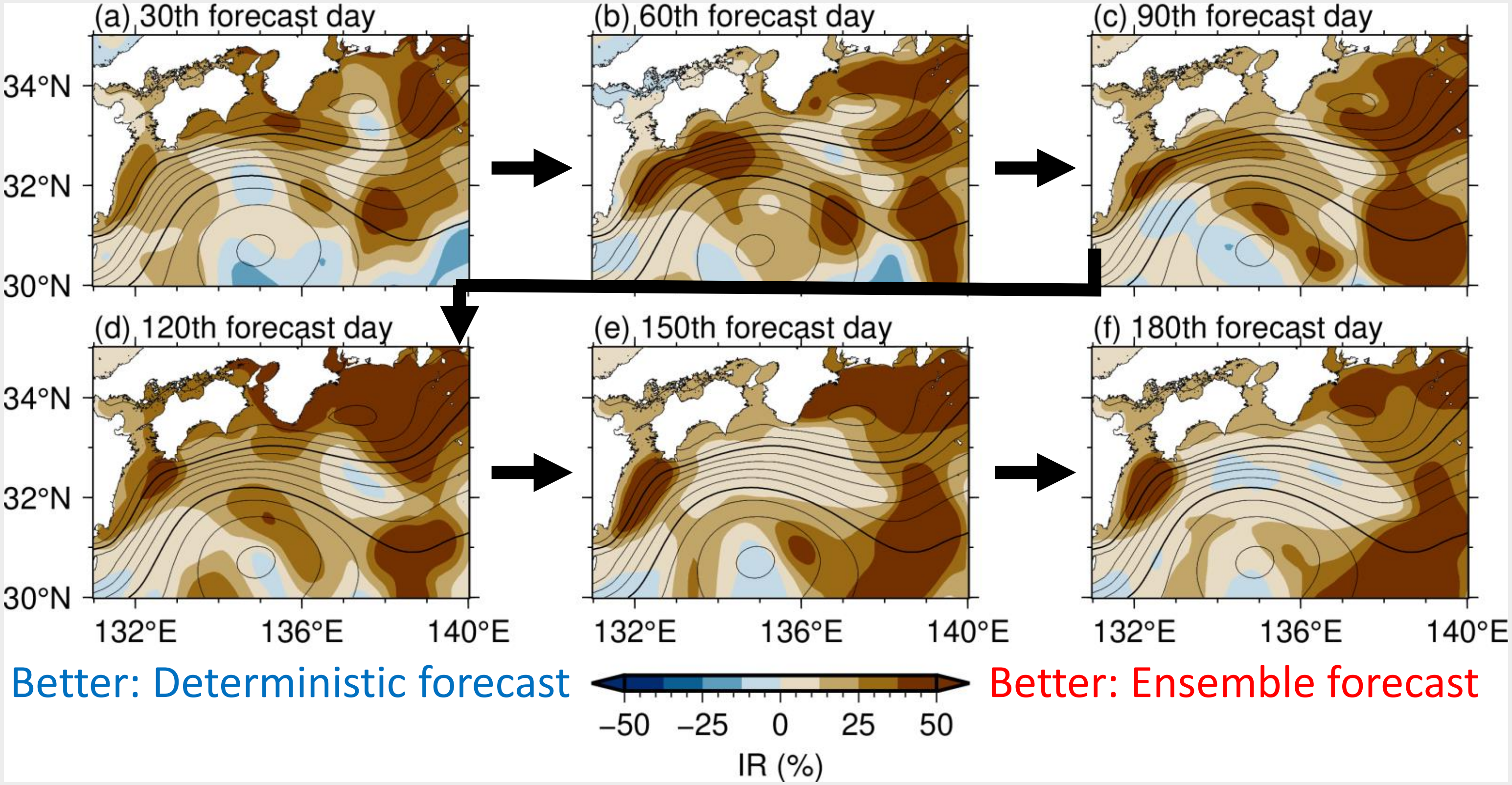
Spatial pattern is almost the same,

but the error growth rate is different.

Contour: Analysis SSH Climatology

4. Result – SSH forecast RMSD –

Improvement ratio [=$(RMSD_{ens}-RMSD_{det})/RMSD_{det}$]



Contour: Analysis SSH Climatology

Ensemble forecast is more accurate than deterministic forecast.

Discussion

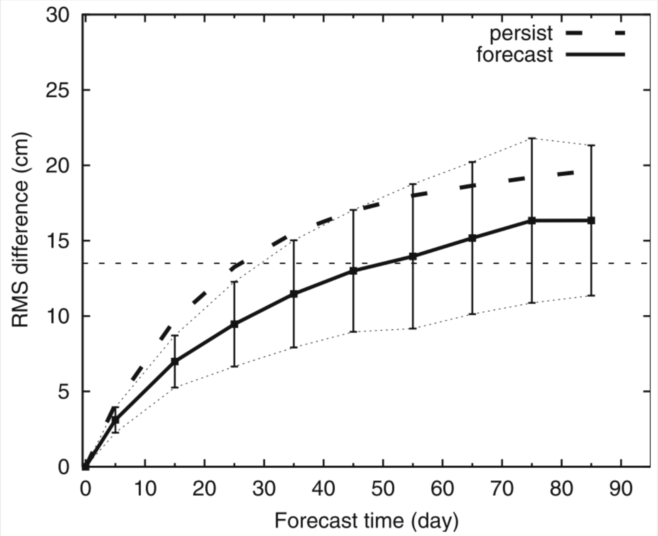
5. Discussion – Predictability –

■ List of predictability of the Kuroshio south of Japan

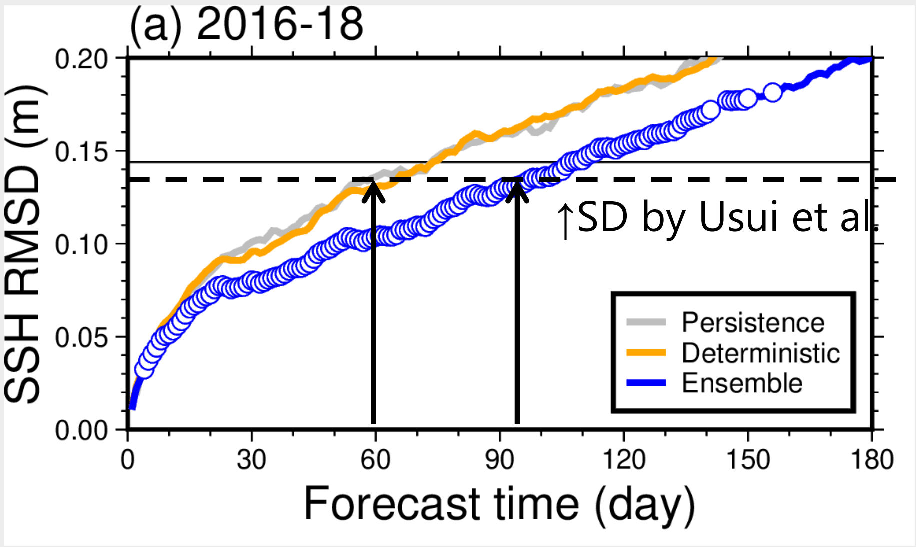
- Komori et al. (2003): 60 days
- Kamachi et al. (2006): 20–80 days (Short: Meander → Straight path)
- Usui et al. (2006): 40–60 days **<u>for 1993–2004</u>**
- This study: 70–80 days in the deterministic forecast
  100–110 days in ensemble forecast **<u>for 2016–18</u>**

→ Since these experiment periods are different, we cannot directly compare them.

Usui et al. (2006)

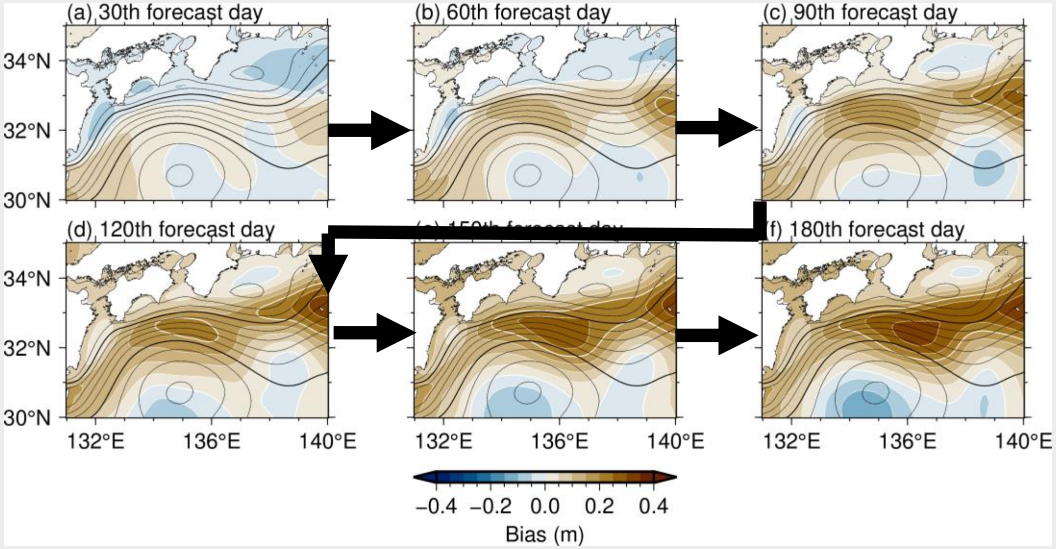


This study

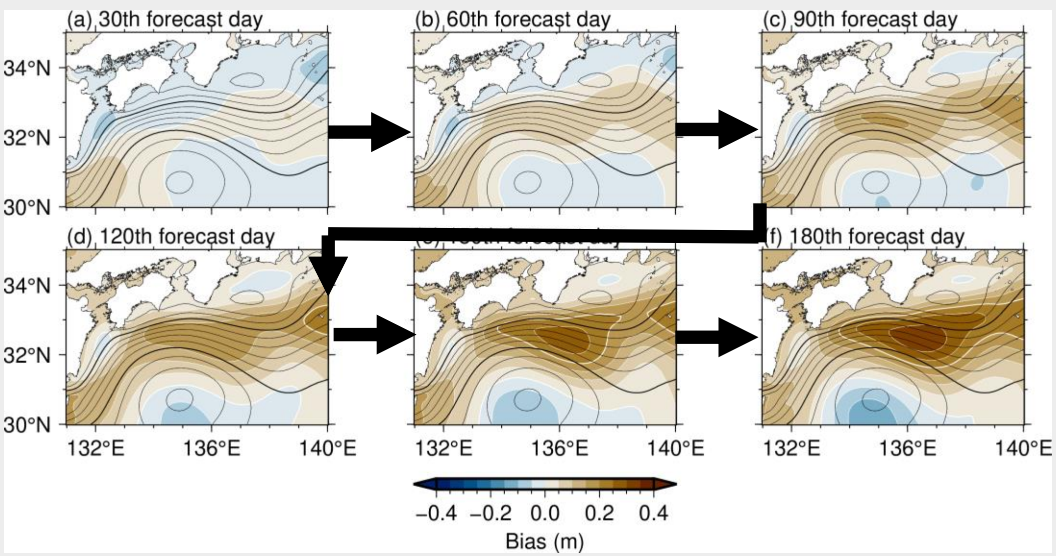


4. Result – SSH forecast bias –

Deterministic forecast



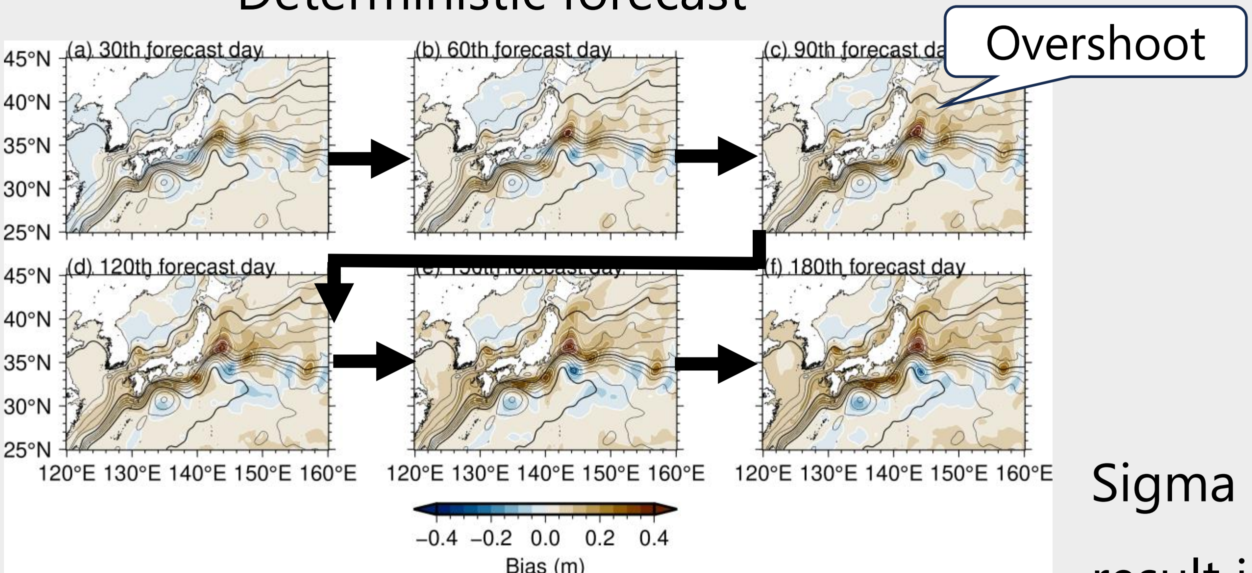
Ensemble forecast



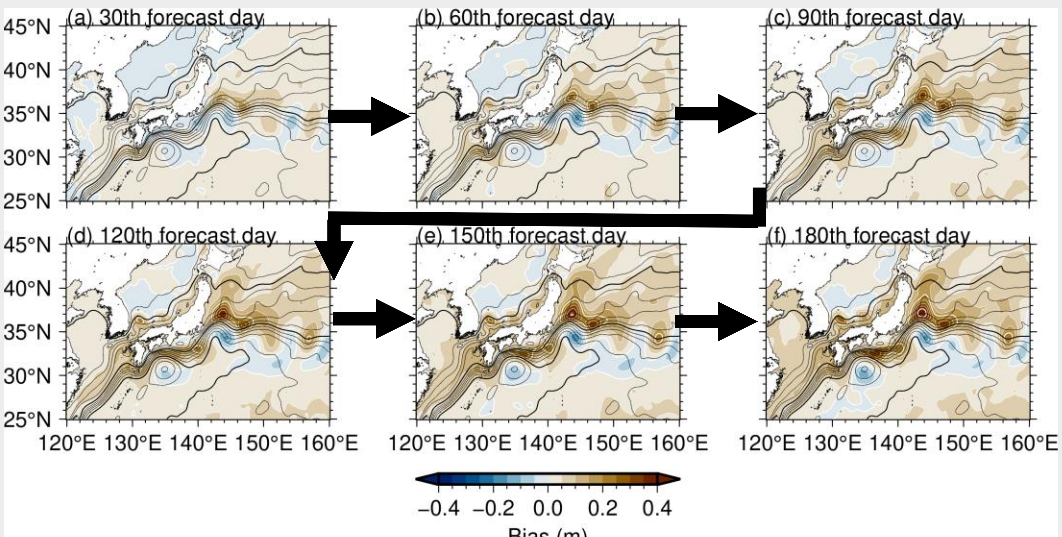
Forecast bias appears to contribute to degrade the forecast accuracy.

4. Result – SSH forecast bias –

Deterministic forecast



Ensemble forecast



Sigma coordinate model would result in Kuroshio overshoot.

→ MRI.COM with sigma-z coordinate would be better.

4. Result – Talagrand diagram –

■ Example: 4 ensemble members with $\boldsymbol{x}^f = (4\ 2\ 1\ 8)^{\mathrm{T}}$ and x^tor $\overline{x^a} = 2.5$

1. Sort $\boldsymbol{x}^f \rightarrow \boldsymbol{x}^f_{sort} = (1\ 2\ 4\ 8)^{\mathrm{T}}$

2. Set categories as follows:

$\overline{x^a} = 2.5$

↓

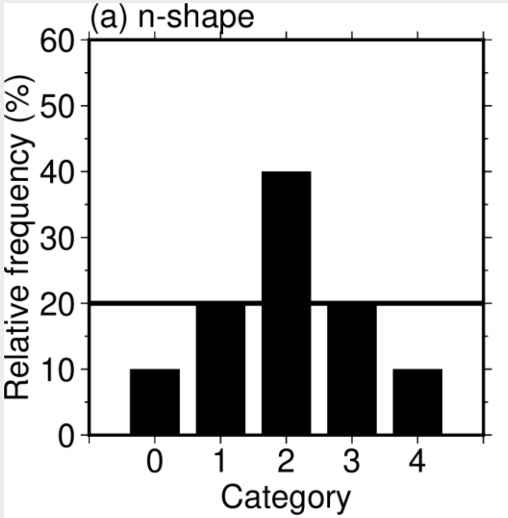
x^f		1		2		4		8	
Category	0		1		2		3		4

3. Count a category of $\overline{x^a}$

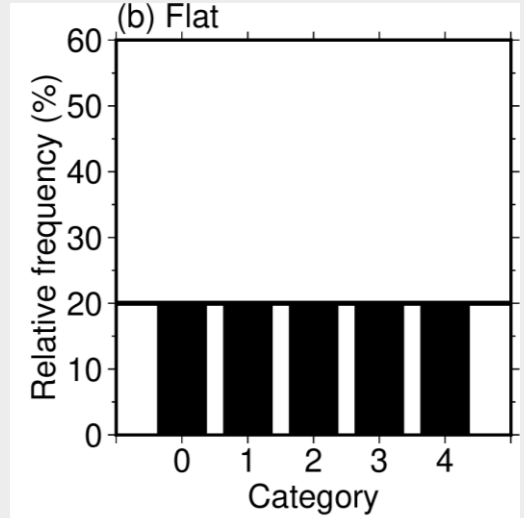
4. Repeat the process 1–3 at each grid for an analysis region at a forecast time

5. Make histogram

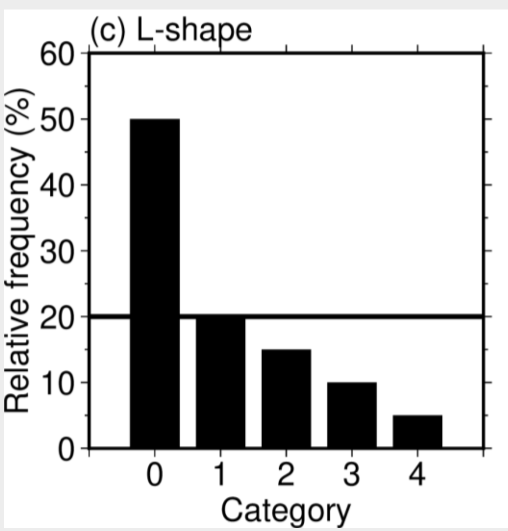
4. Result – Talagrand diagram –



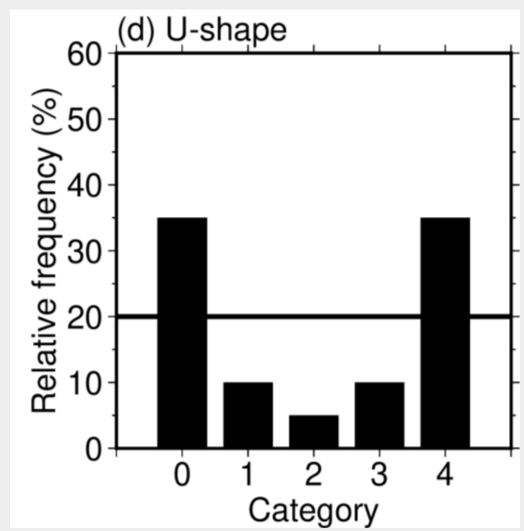
- Initial forecast
- Large σ^f



- Good sampling



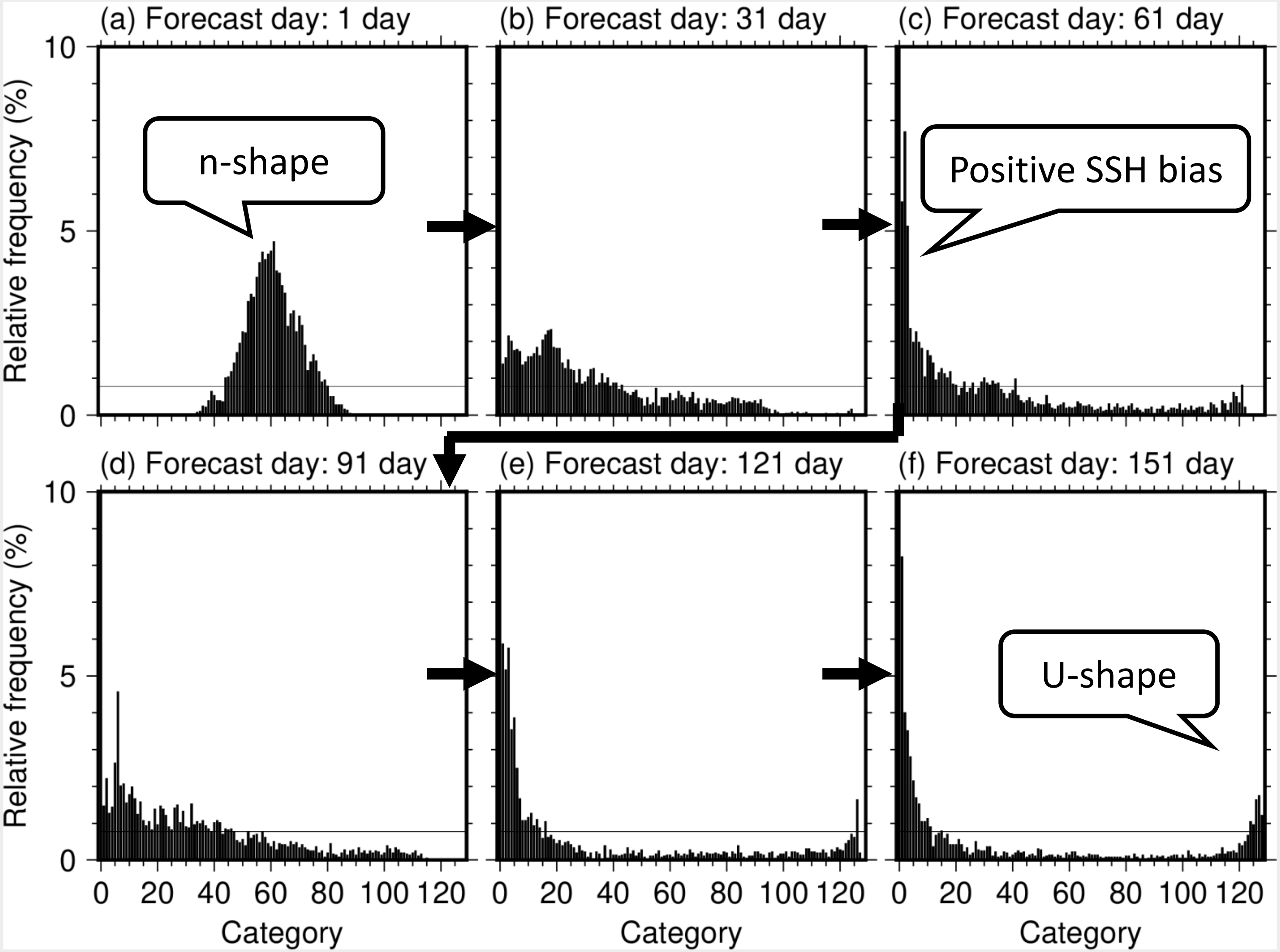
- Positive bias in forecasts



- Long forecast
- Small σ^f

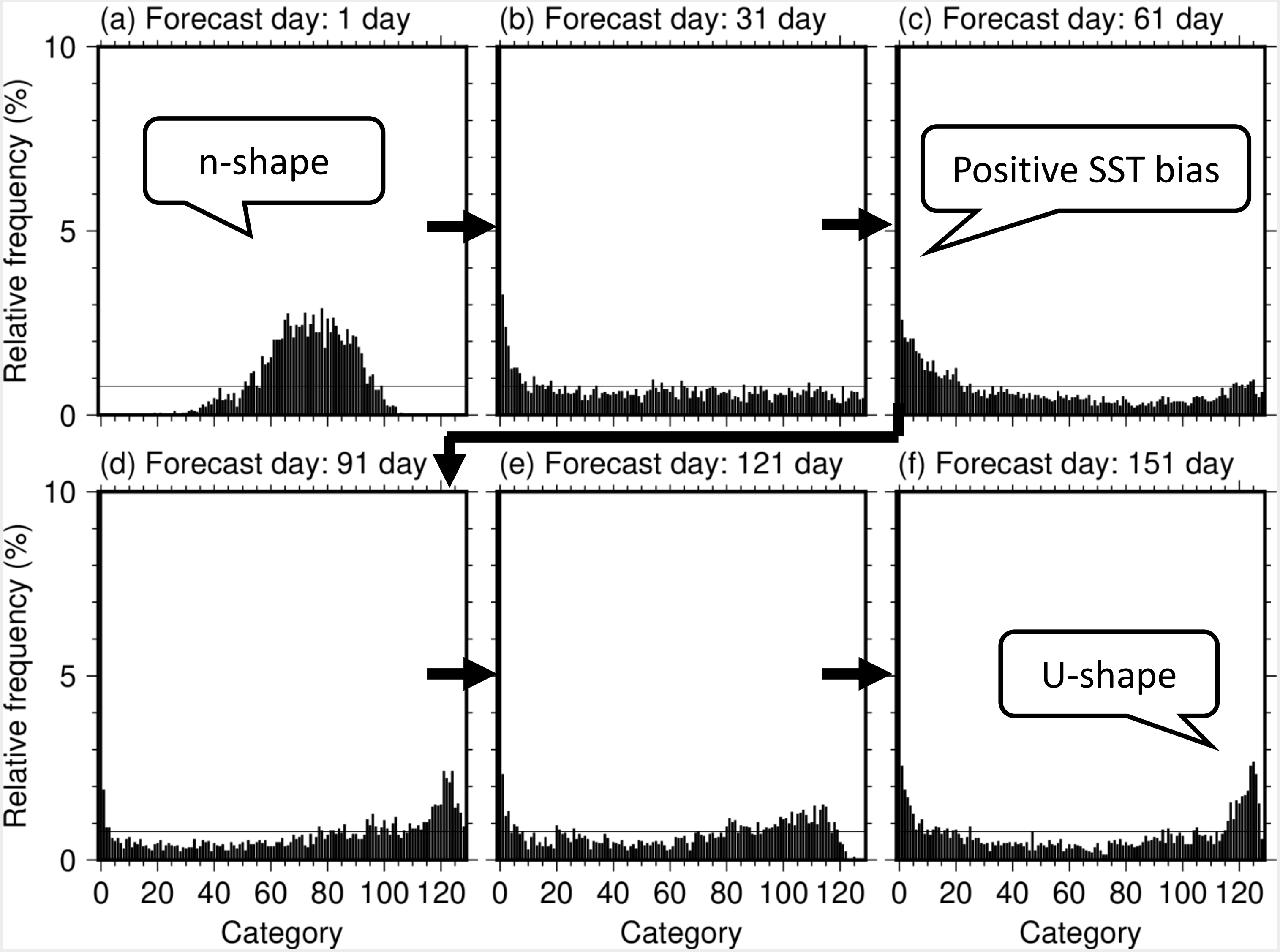
4. Result – Talagrand diagram –

■ SSH over south of Japan



4. Result – Talagrand diagram –

■ SST over south of Japan



Summary

6. Summary

■ Validation for the Kuroshio south of Japan

The LORA well represents the formation of the Kuroshio large meandering in the summer of 2017.

→ Sufficient accuracy for the Kuroshio forecast.

■ Deterministic and ensemble forecasts

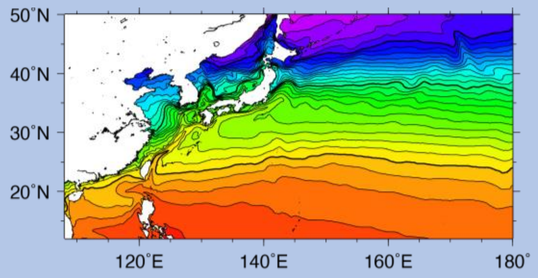
- The ensemble forecast outperforms the deterministic forecast.
  - → Deterministic: 70–80 days < Ensemble: 100–110 days
- Positive SST and SSH forecast biases exist.
  - → It is necessary to develop the ocean DA system.

■ Plan

Investigate important factors to generate the Kuroshio large meandering using ensemble sensitivity experiments

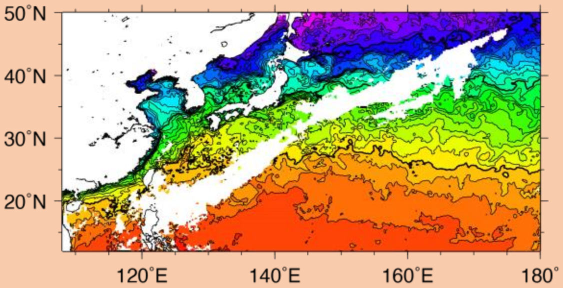
Appendix

Simulation



3D homogeneous grid, but less accurate

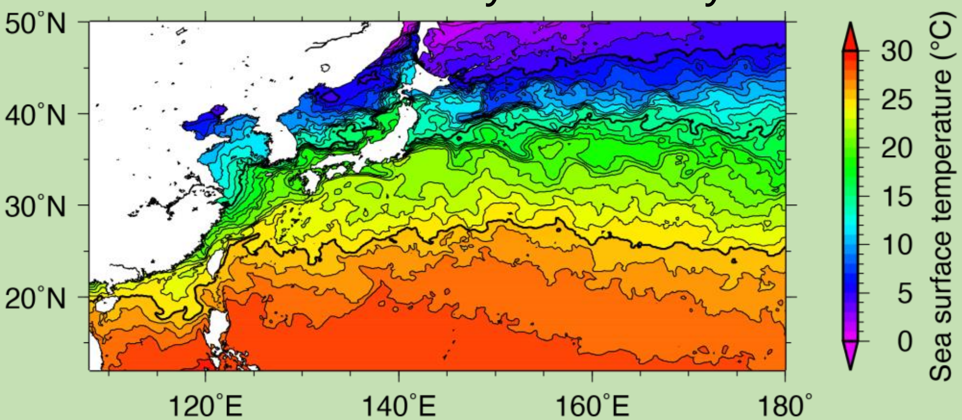
Satellite observation



Fine spatiotemporal variation, but missing values

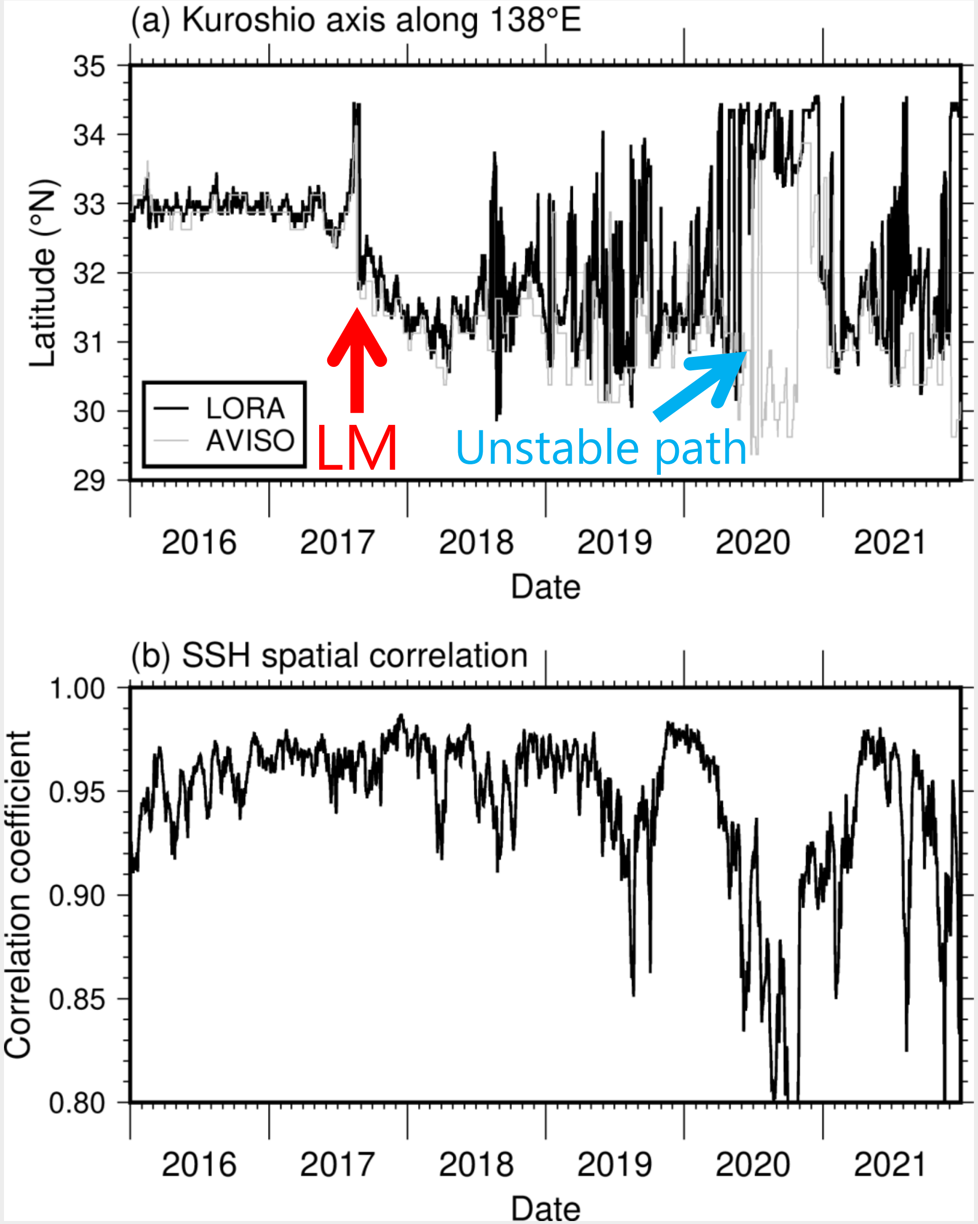
Data Assimilation

Optimal combination of ocean simulation and obs. with statistical methods and dynamical systems theory

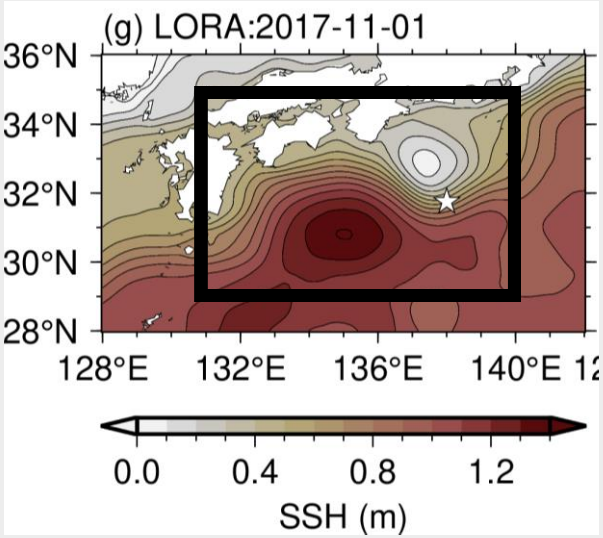


More accurate datasets without missing values

4. Result – Validation –



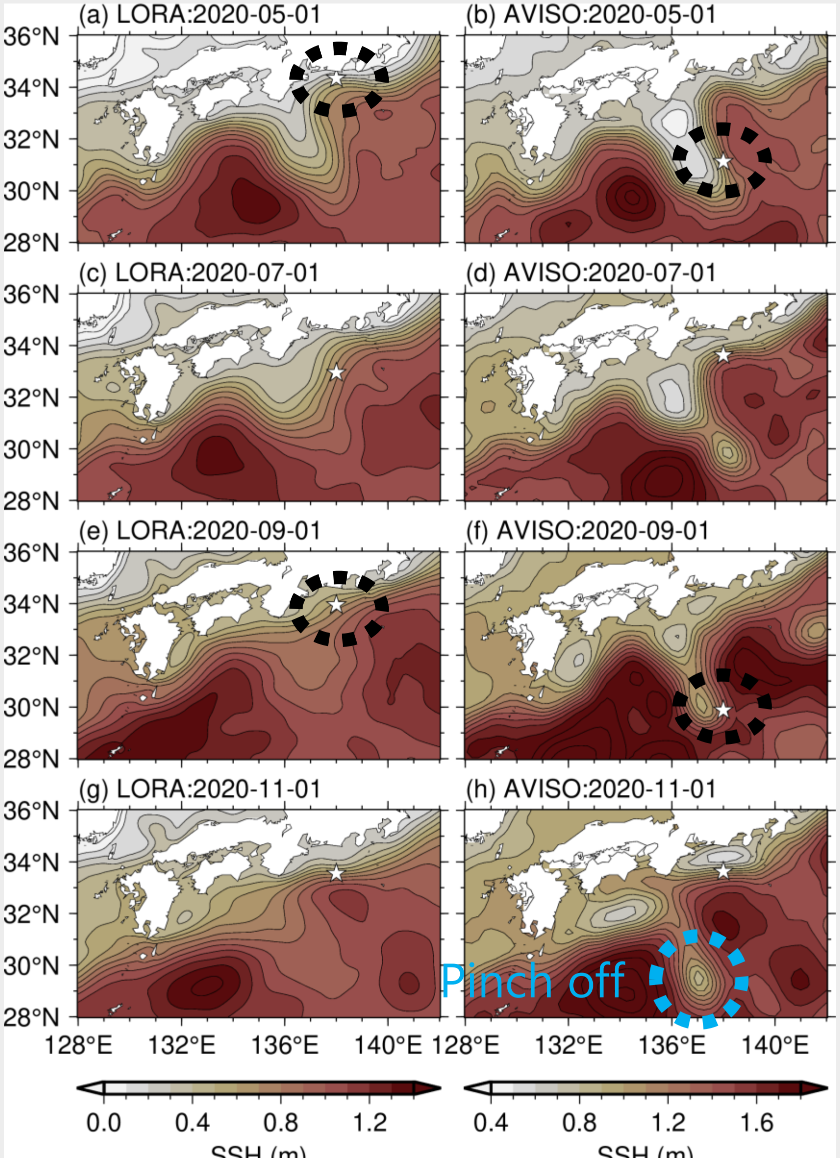
- The formation of Kuroshio LM in summer 2017 is well captured by the LORA
- In 2020 with unstable Kuroshio, the accuracy is low.



*(a): Max. geostrophic current within 28°–35°N
*(b): Analysis domain: 131°–140°E, 30°–35°N

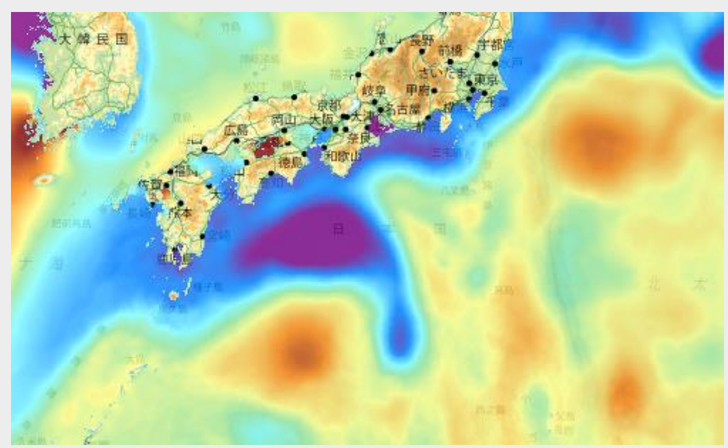
4. Result – Validation: Spatial pattern in 2020 –

LORA | AVISO

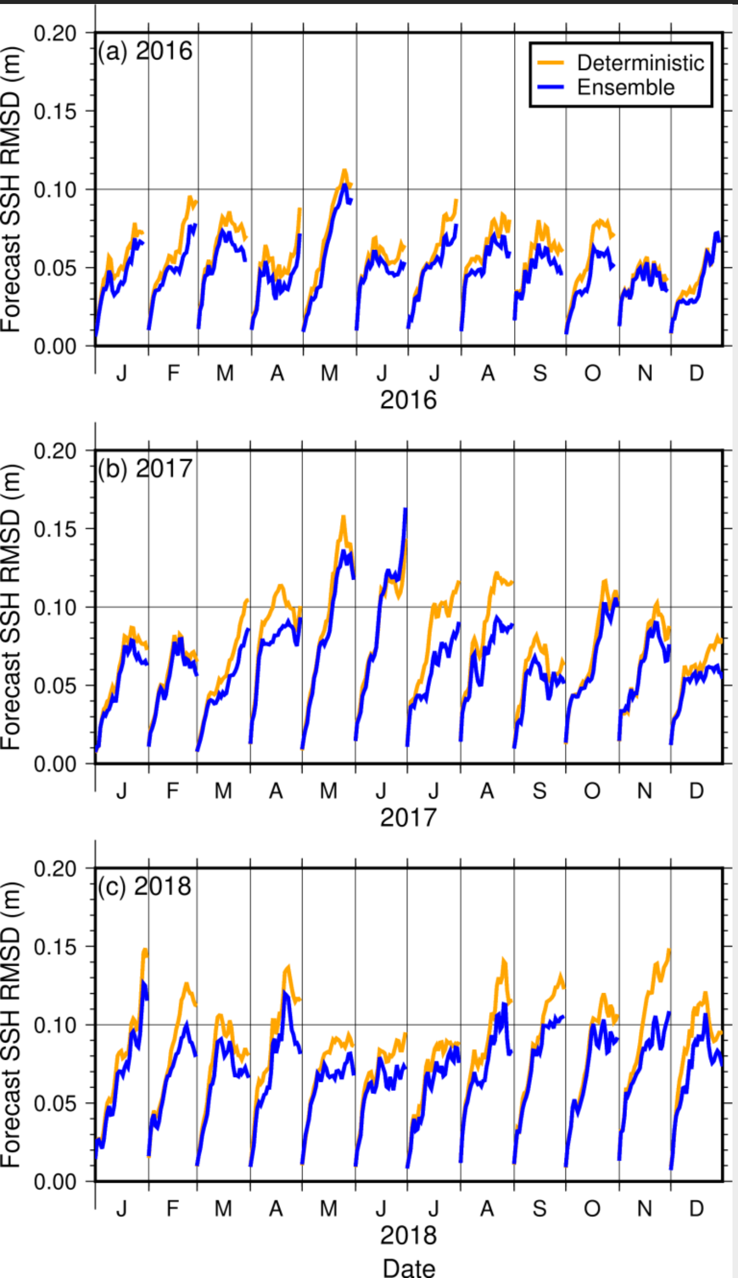


- Low accuracy
  - Different large meandering shape
  - Low reproducibility of pinching off a cyclonic eddy in LORA

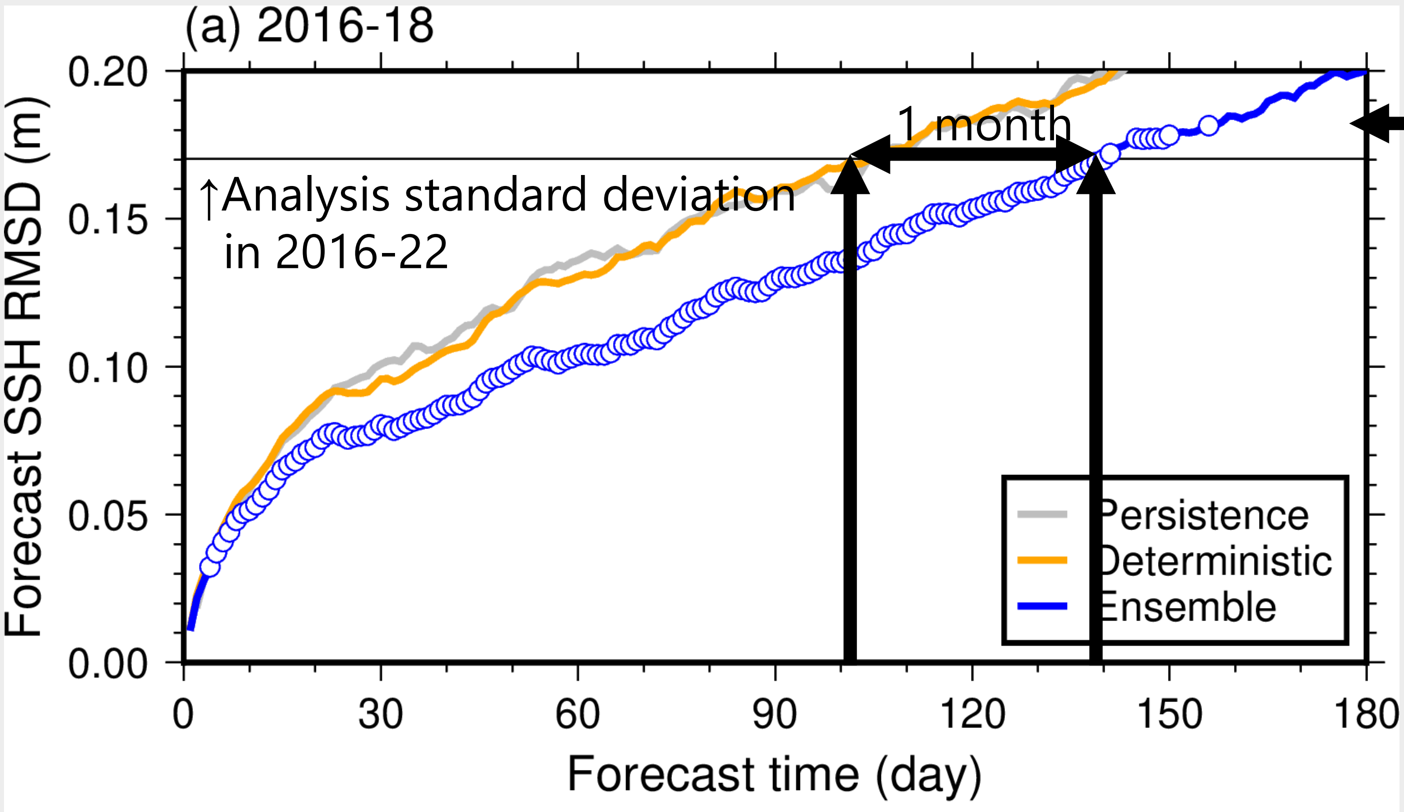
JCOPE T-DA (dx = 1/36°) @ 2020.11.01

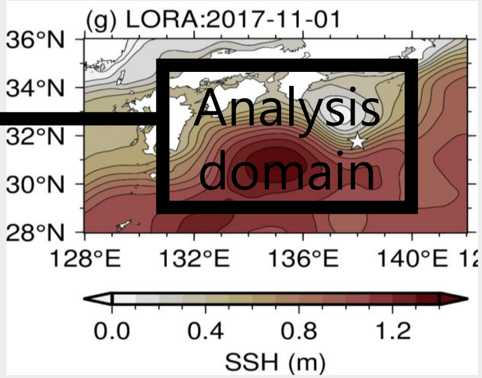


4. Result – Forecast SSH RMSD –



4. Result – Predictability –



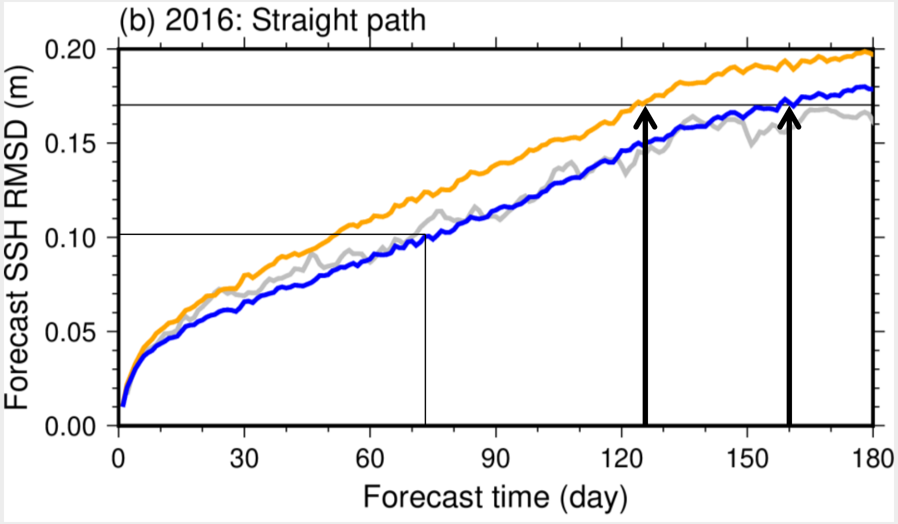


*Persistence: RMSD of the initial analysis condition
*Ensemble: RMSD of the forecast ensemble mean
*○: Significant difference relative to the persistence

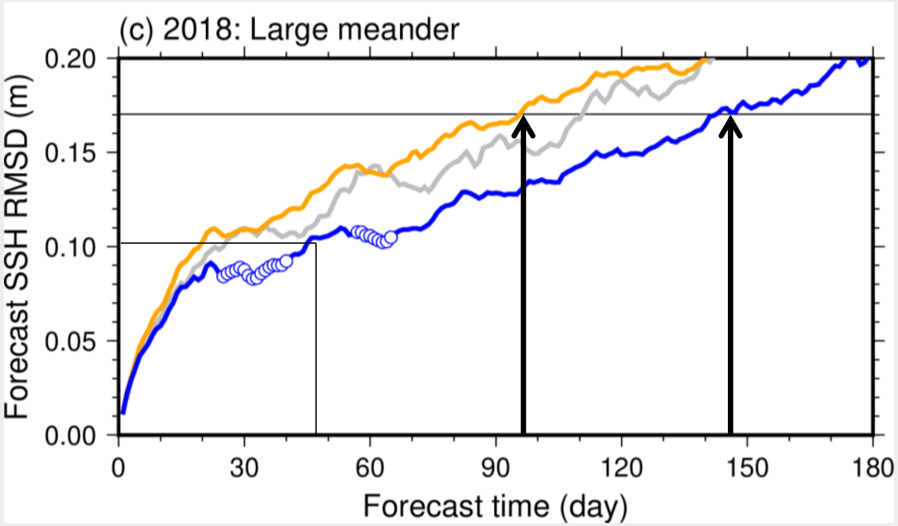
Deterministic: 100-110 days < Ensemble: 130-140 days

4. Result – Predictability –

2016 (Straight path)



2018 (Large meander)



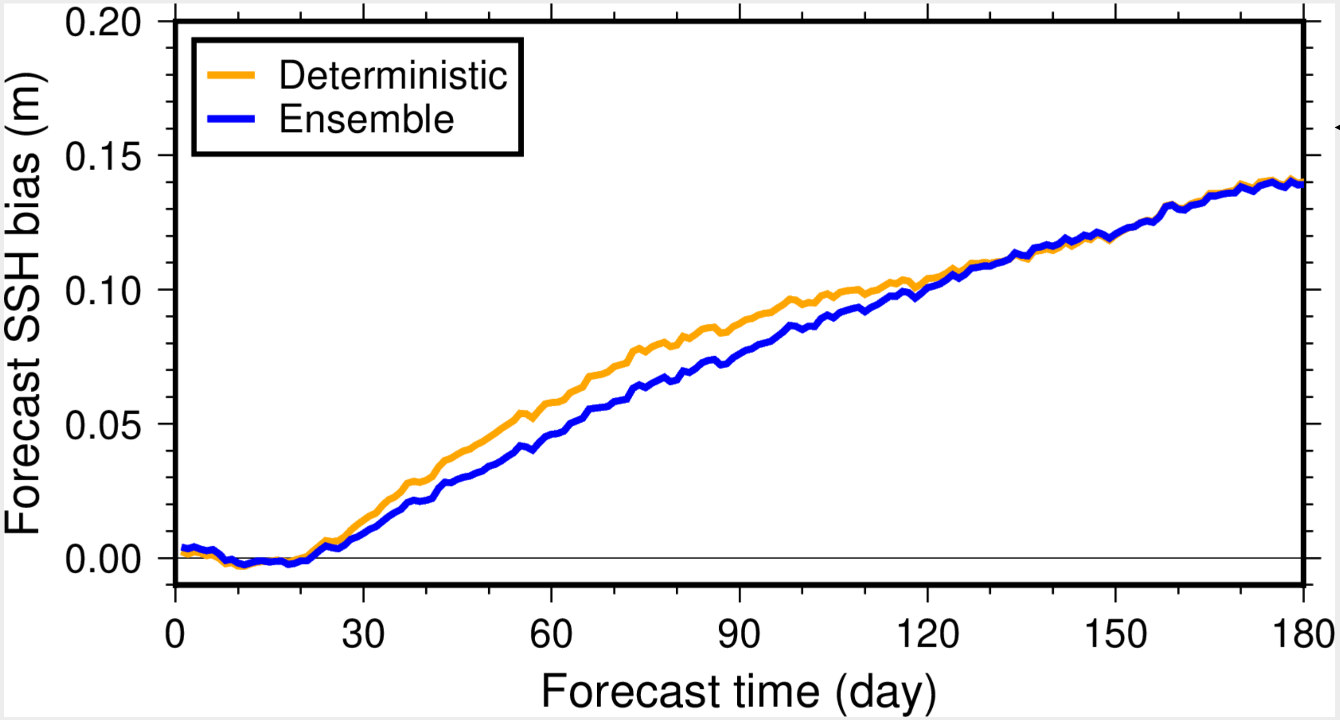
- Deterministic: 120 days
- Ensemble: 150 days

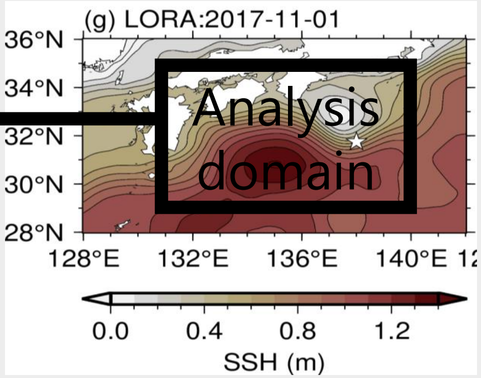
- Deterministic: 90 days
- Ensemble: 150 days

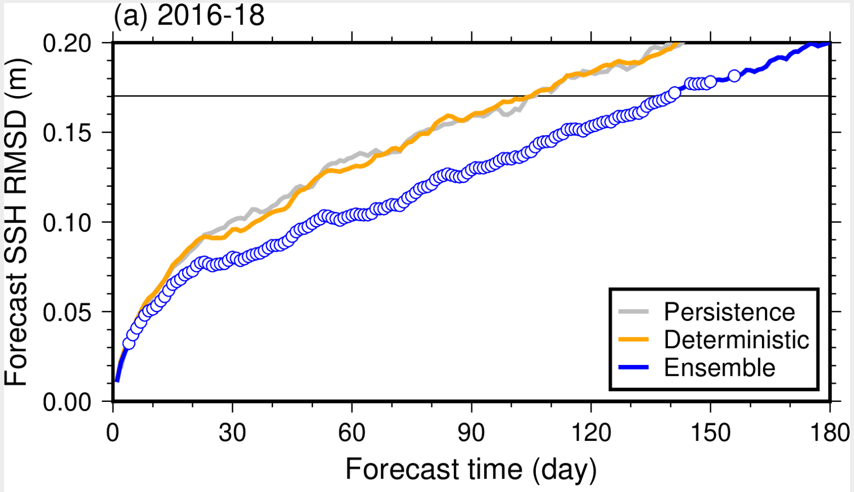
- Rapid RMSD increase during the large meander period

- Predictability of the deterministic forecast more depends on the Kuroshio path state.

4. Result – Forecast SSH bias –

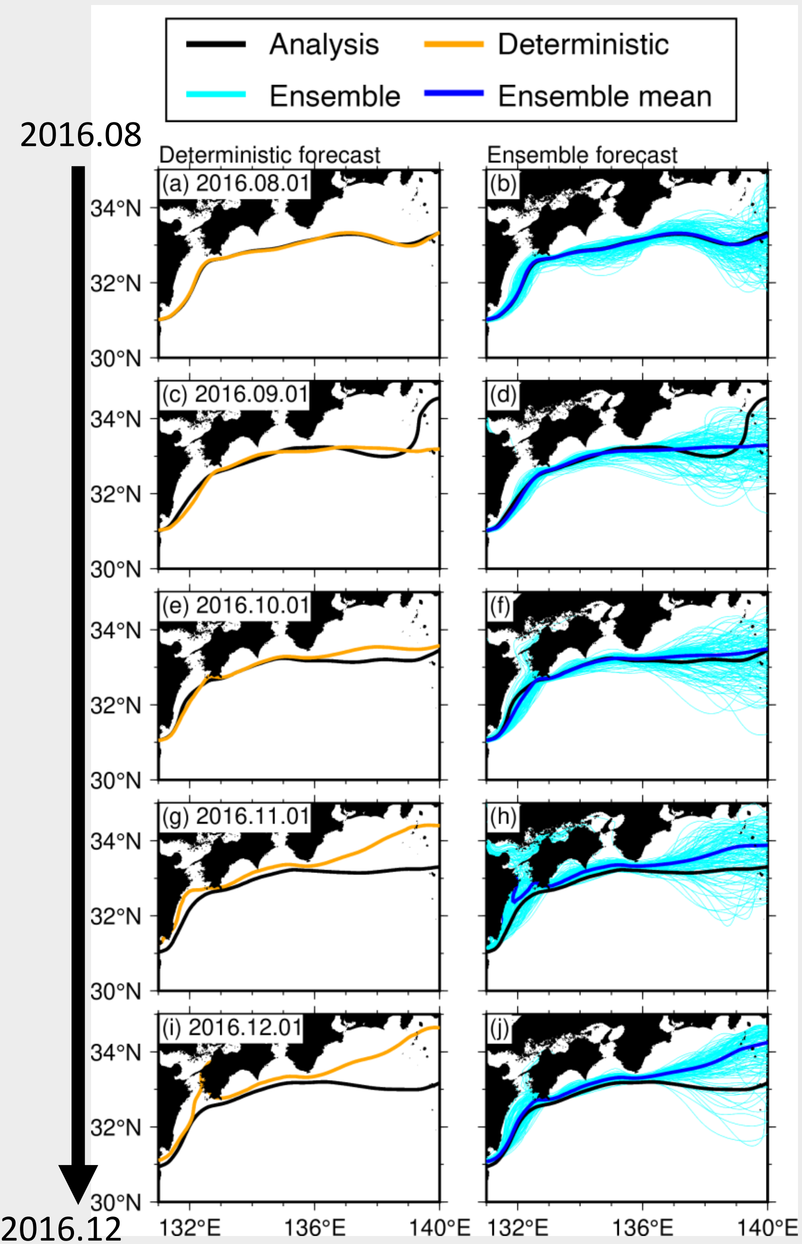






Forecast SSH biases substantially degrade the forecast accuracy.

4. Result – Initial: 2016.08 (Straight) –



■ Definition of SSH contour

- Extract analysis SSH where the surface current is maximum for each longitude grid within 131–140°E
- Take average over 2016-2018
- SSH contour: 0.56 m

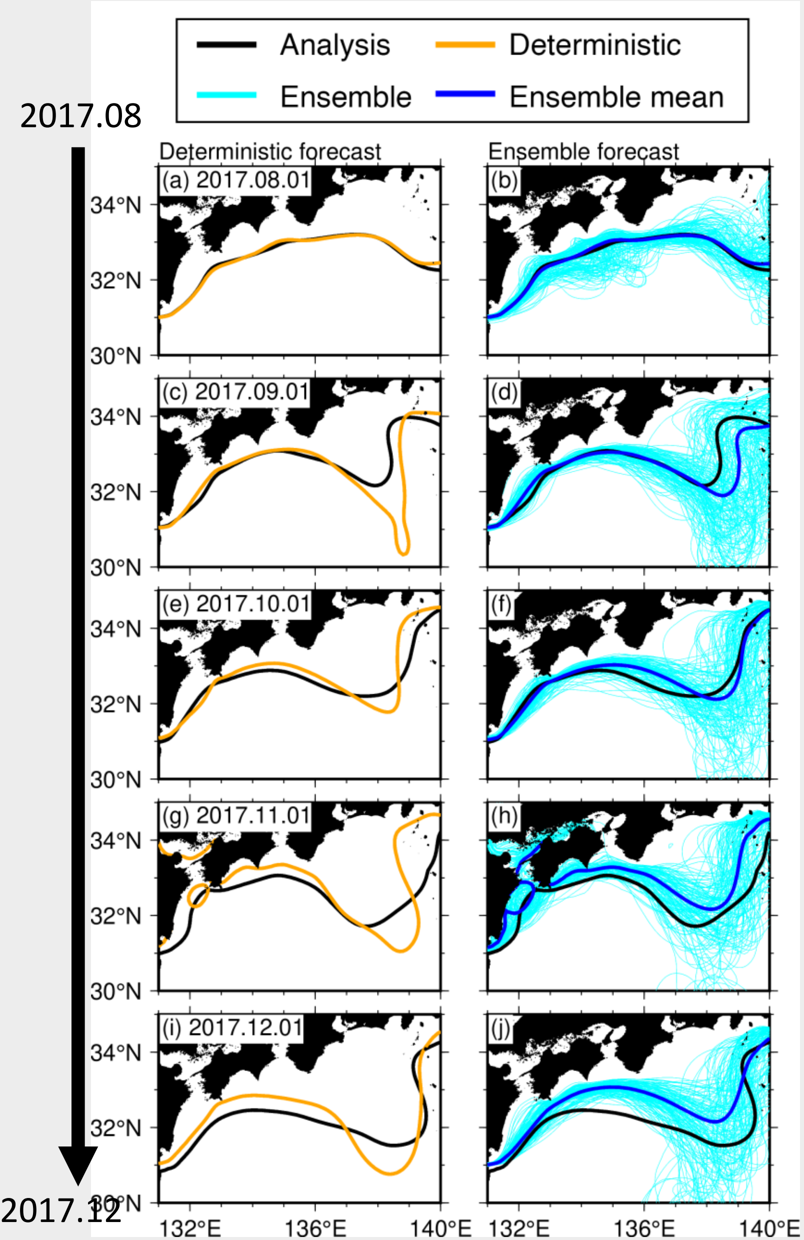
Larger northward shift

in deterministic forecast

in 136–140°E

*SSH contour: 0.56 m ~ Max. speed in 131–140°E

4. Result – Initial: 2017.08 (Straight to Meander) –

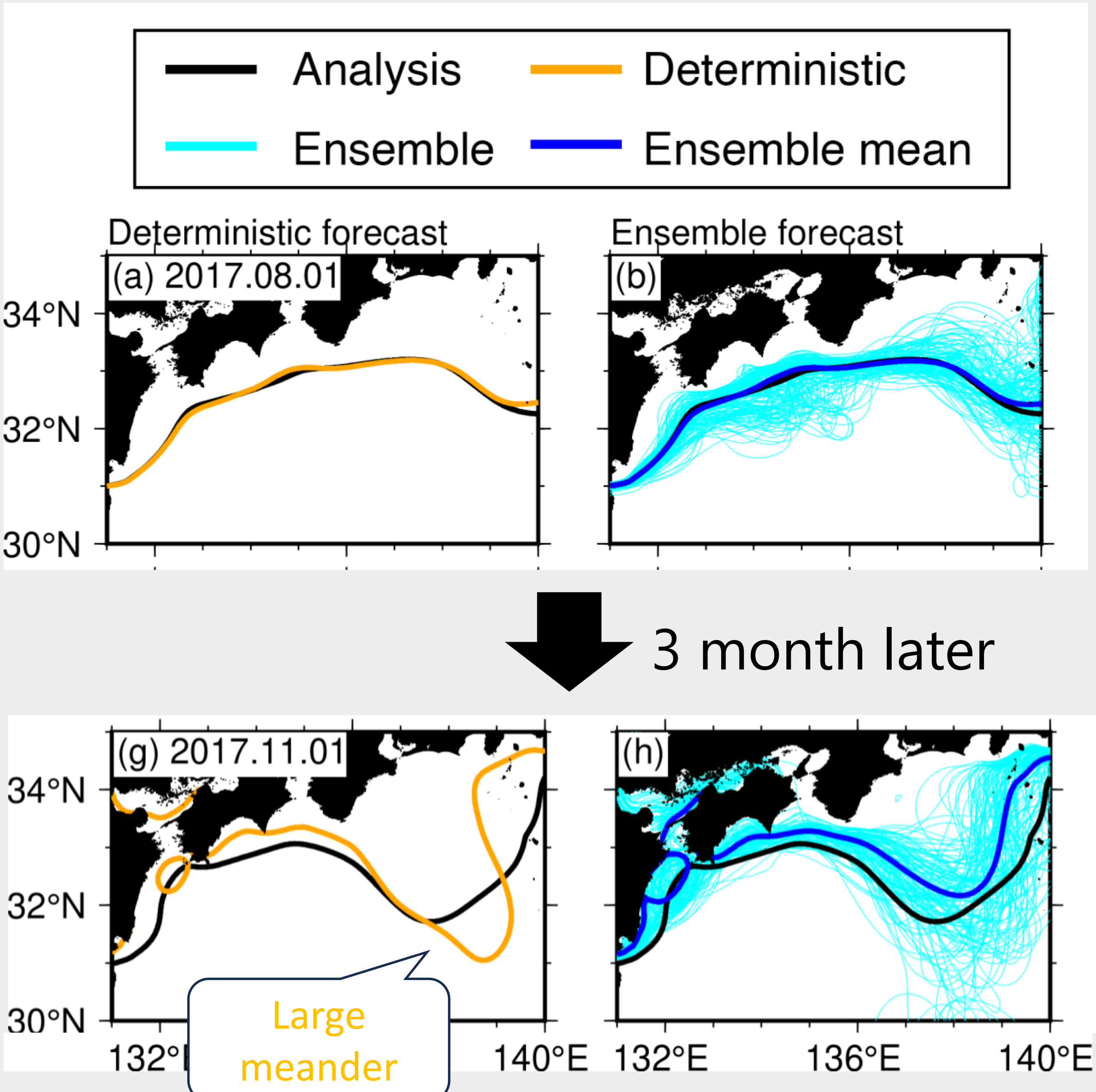


Larger southward meandering

in deterministic forecast

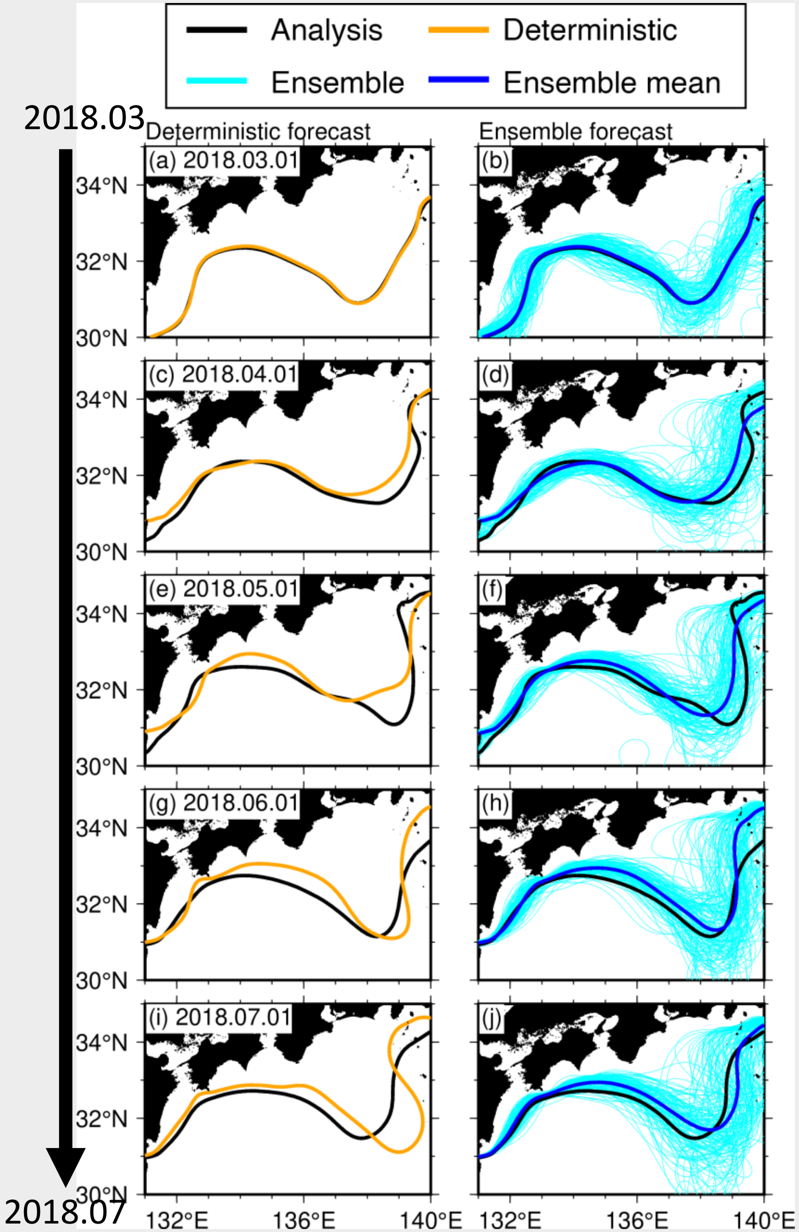
*SSH contour: 0.56 m ~ Max. speed in 131–140°E

4. Result – Initial: 2017.08 (Straight to Meander) –



*SSH contour: 0.56 m
~ Max. speed in 131–140°E

4. Result – Initial: 2018.03 (Meander) –



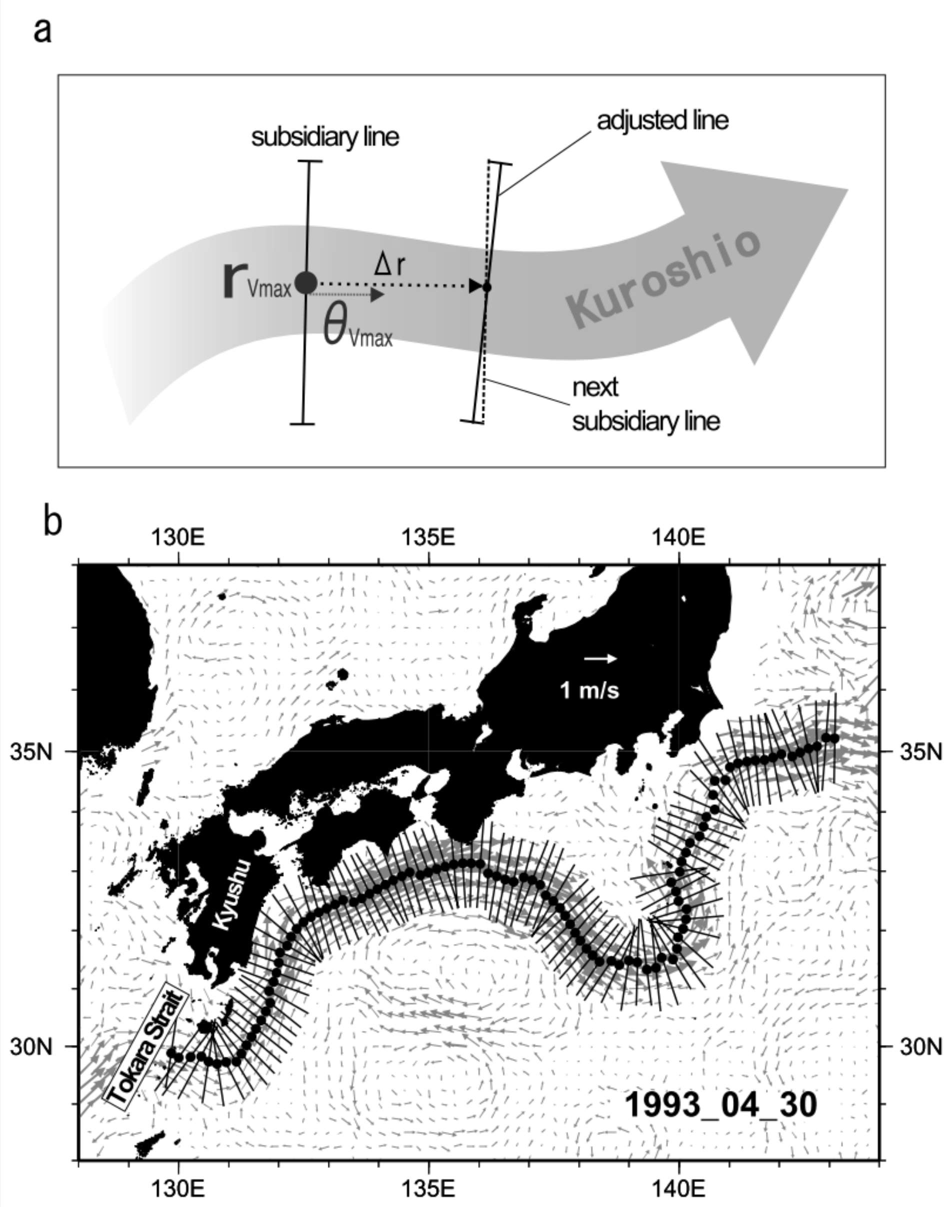
Meander extends

to the southeast

in deterministic forecast

*SSH contour: 0.56 m ~ Max. speed in 131–140°E

4. Result – Ambe et al. (2003) –



1. Make a subsidiary line (140 km width) crossing the Kuroshio almost perpendicularly at the start longitude
2. Extract a point where the surface current is maximum
3. Make a new subsidiary line downstream …

→ Next