Development of 4DVAR Global Ocean Data Assimilation System for Coupled Predictions in JMA

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1. Introduction of the Coupled Prediction System and the global ocean 4DVAR system in JMA

☆ Specifications of Coupled Prediction System (CPS) in JMA

		CPS3 (February 2022)
Atmospheric model	Model version	GSM2003C
	Horiz. resolution	TL319 (~55 km)
	Vertical levels	100 levels
Ocean model	Model version	MRI.COM v4.6
	Horiz. resolution	1/4°
	Vertical levels	60 levels
Initial conditions	Atmosphere	Global Analysis (4DVAR)
	Ocean/Sea ice	MOVE/MRI.COM-G3 (0.5˚x1˚, 4DVAR)
Ensemble generation	Size and Frequency	5 members per day
	Perturbation	✓ Breeding and Singular vectors for the atmosphere ✓ Stochastic physics in the atmosphere ✓ Ocean perturbations from the minimization history of 4DVAR

◆ Last Upgrade: Feb. 2022

◆ Reference:
Hirahara et al. 2023
https://doi.org/10.2151/jmsj.2023-009

MRI.COM: Meteorological Research Institute Community Ocean Model.

☆ Global Ocean 4DVAR System, MOVE/MRI.COM-G3

◆ MOVE/MRI.COM-G3 is constituted of the 2 models, that is, the analysis model G3A and the downscaling model G3F.

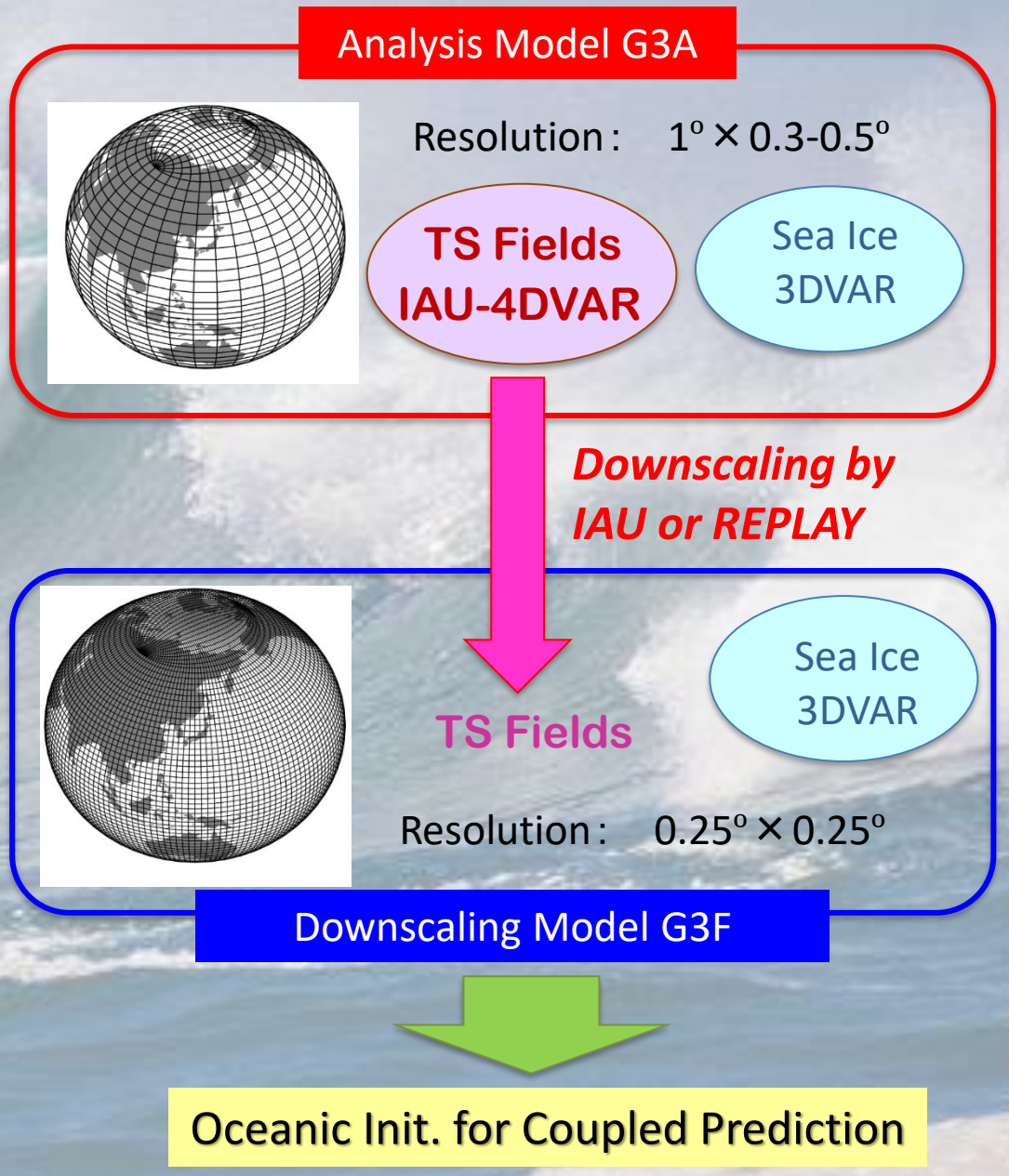
◆ The data assimilation method is mostly the same as the JMA's eddy-resolving ocean prediction system, MOVE/MRI.COM-Jpn.

➢ Analysis Model (G3A)

- Global tripolar grid coordinate, resolution: 1° × 0.3-0.5°
- In-situ TS profiles, satellite altimetry data, and SST objective analysis are assimilated through IAU-4DVAR.
- Sea Ice 3DVAR (Toyoda et al. 2016, partly modified)

➢ Downscaling Model (G3F)

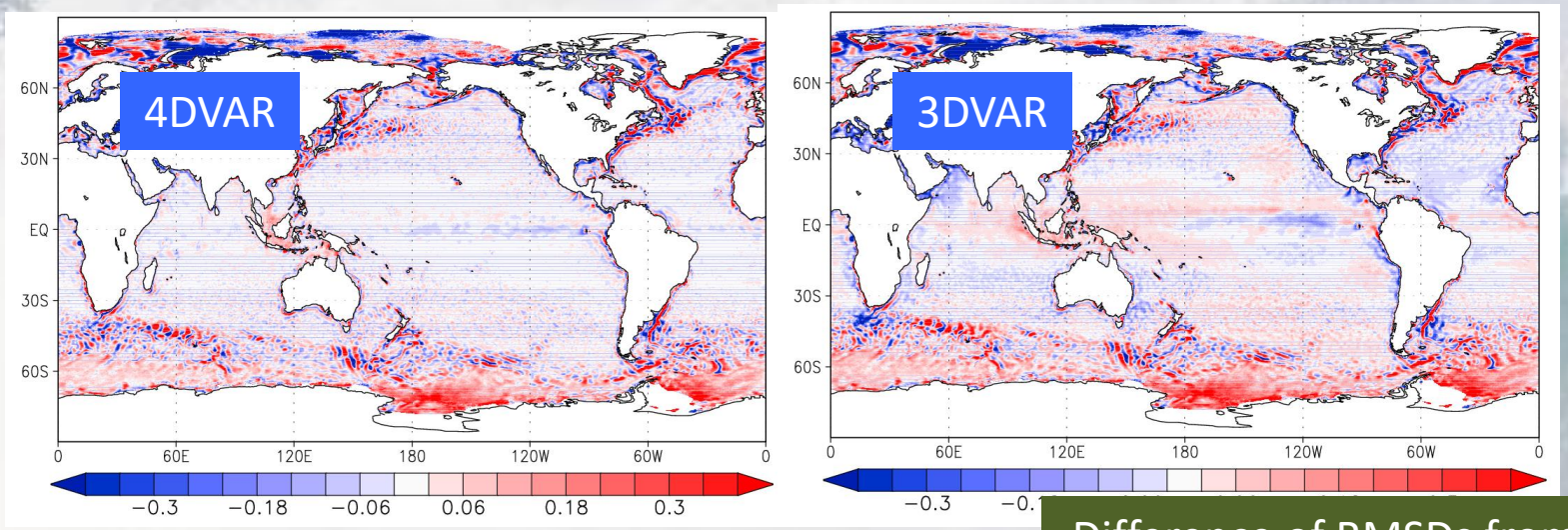
- Global tripolar grid coordinate, resolution: 0.25° × 0.25°
- Constrained to TS fields of G3A by IAU (downscaling)
- Sea Ice 3DVAR (the same as G3A)
- GPVs of G3F are used as the oceanic initial condition of the coupled predictions.



3. Advantage of 4DVAR in the global system

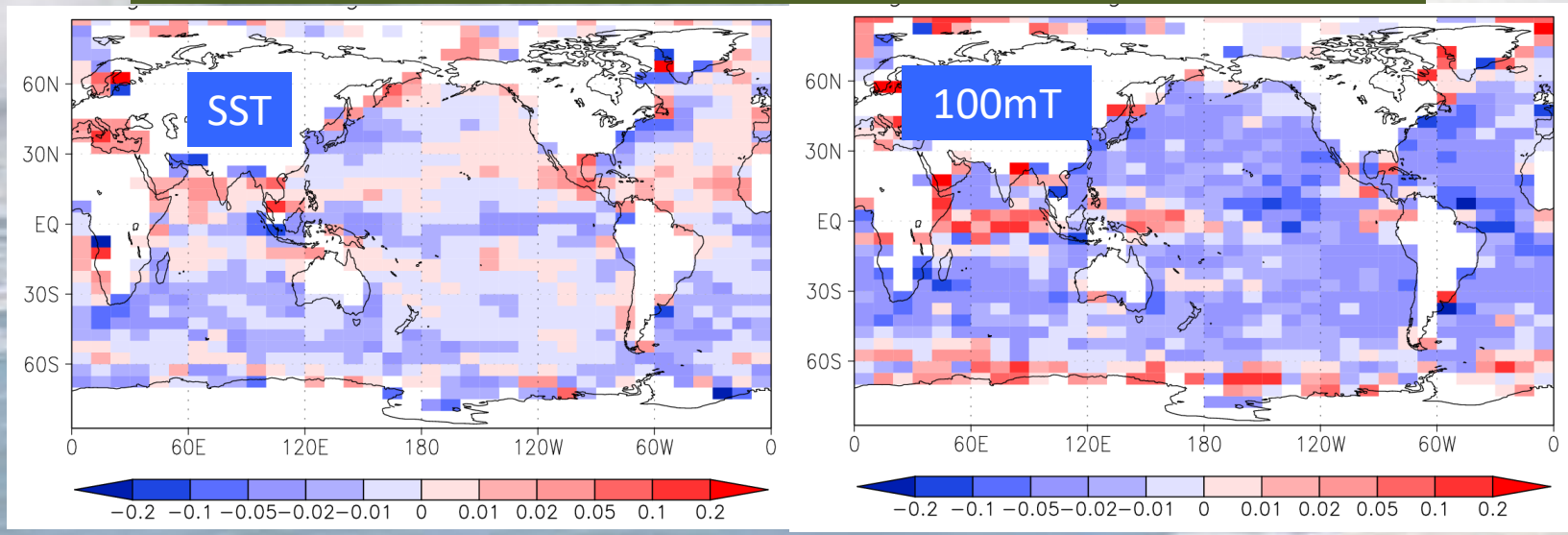
★ Capacity to reduce data-misfits effectively (Comparison with assimilated data)

Bias from the objective SST analysis



- 4DVAR effectively reduces the SST bias from the objective SST analysis witch is assimilated compared with 3DVAR.

Difference of RMSDs from assimilated Argo data (4DVAR－3DVAR)

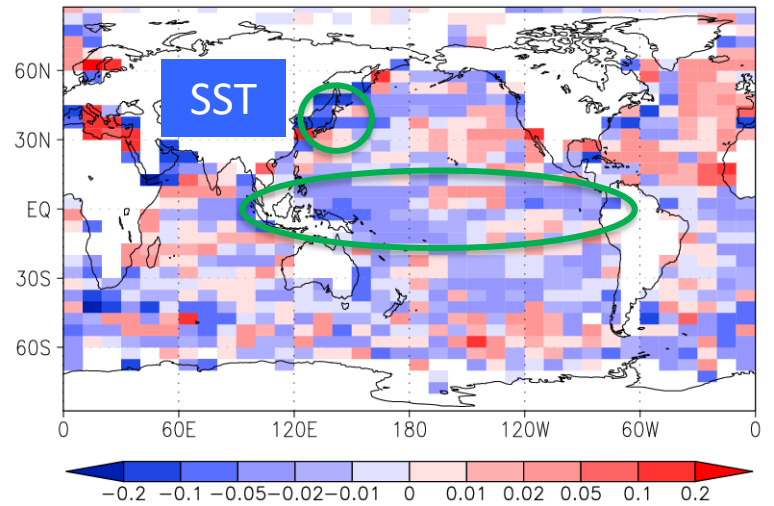


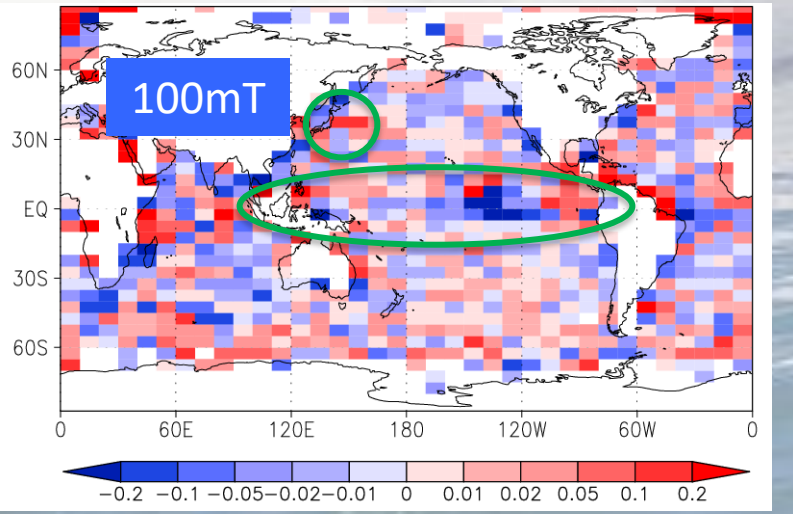
- RMSDs from assimilated Argo data are also generally reduced by 4DVAR.
- Thus, 4DVAR more effectively reduces the data-misfits.

Blue: 4DVAR is better

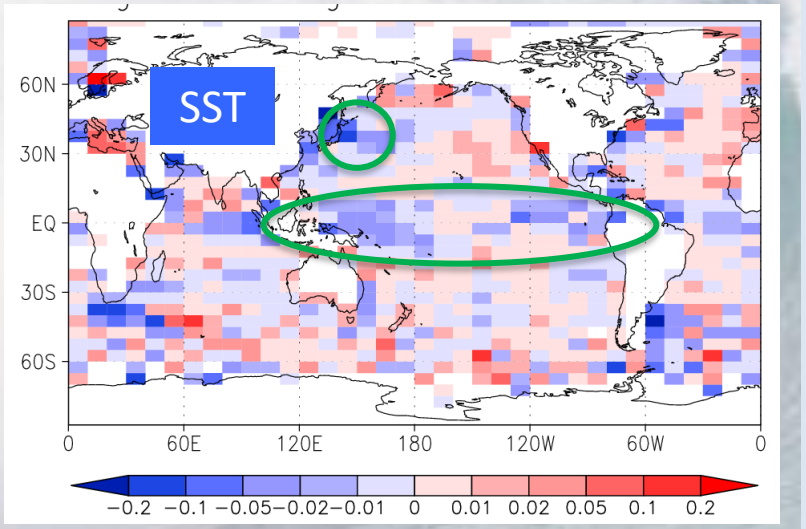
★ Capacity to reducing actual errors (Comparison with Argo not assimilated)

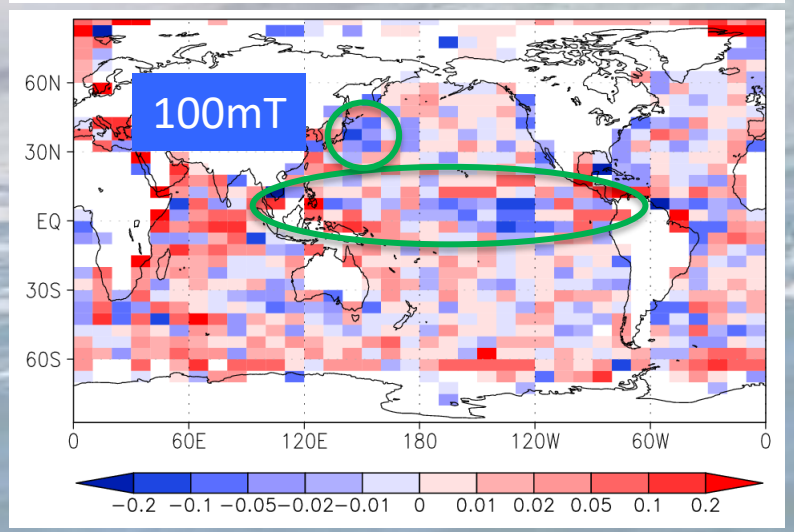
Difference of absolute biases from the independent Argo data (4DVAR－3DVAR)





Difference of RMSDs from the independent Argo data (4DVAR－3DVAR)



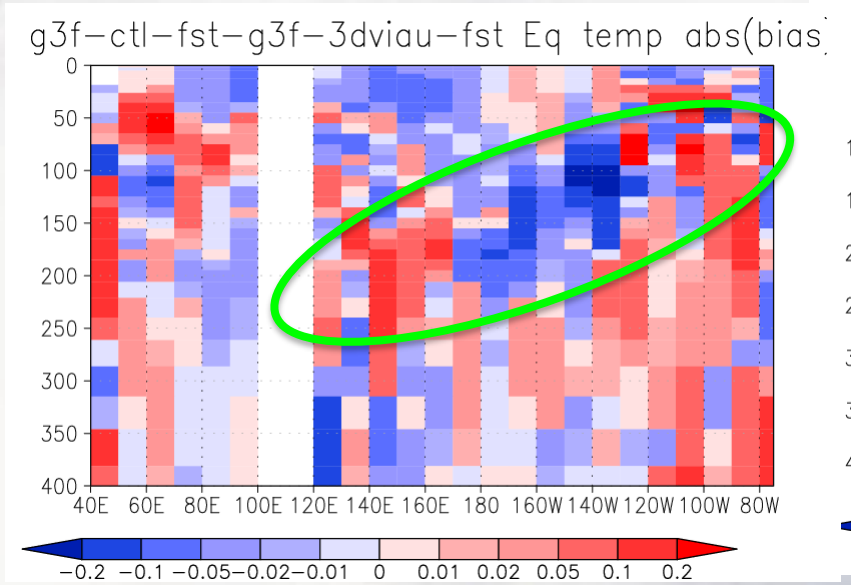


- 4DVAR reduces the SST bias more effectively than 3DVAR.
- The impact of 4DVAR on 100mT bias and RMSD of SST and 100mT seems to be neutral, probably because the model does not sufficiently represent the real physics due to the low resolution.
- But 4DVAR performs better than 3DVAR in the equatorial Pacific and the Kuroshio Extension area.
- Actually, 4DVAR reproduce variation of the equatorial Pacific thermocline much better than 3DVAR
- 4DVAR tends to reproduce large variations better than 3DVAR.

Blue: 4DVAR is better

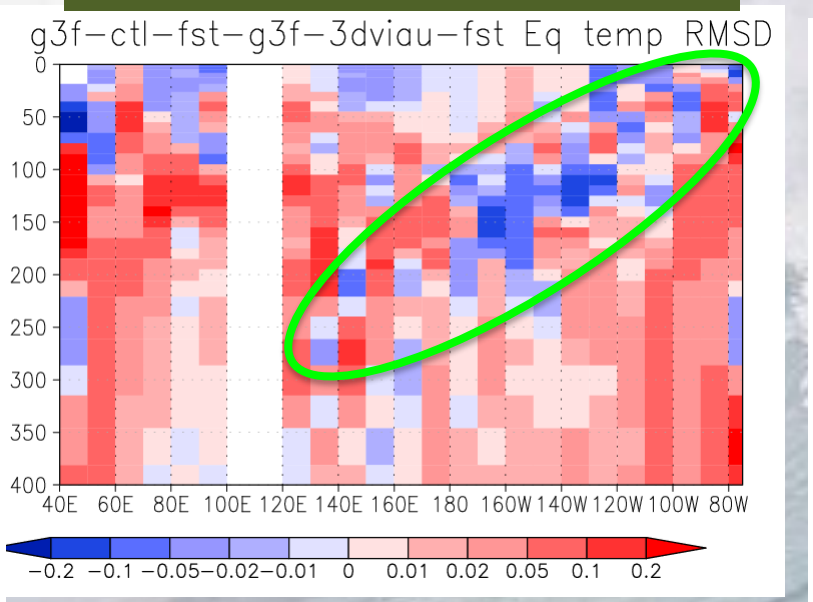
★ G3F-CTL vs G3F-3DVAR: Validation using the eq. Pacific Vertical Section

Difference of the absolute bias from independent Argo data



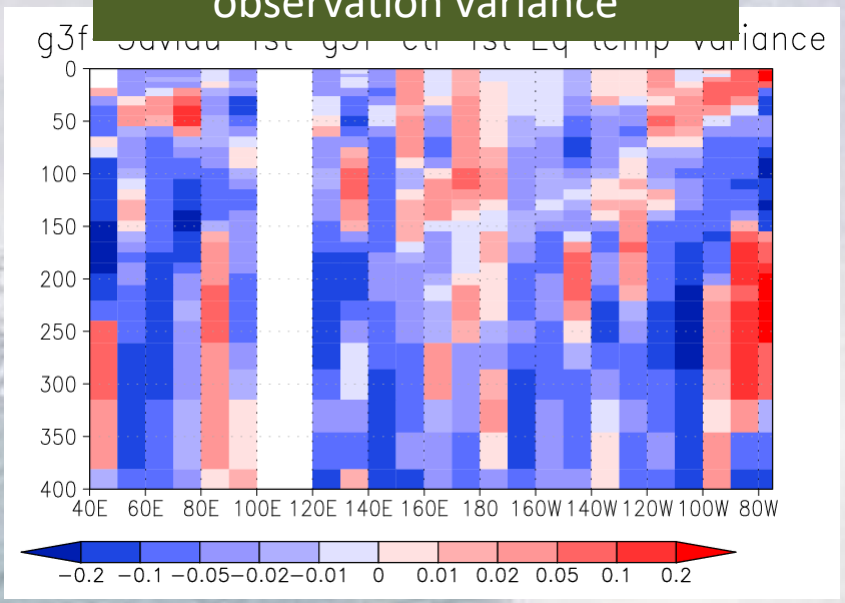
Blue : G3F-CTL is better.

Difference of the RMSE from independent Argo data



Blue : G3F-CTL is better.

Difference of the analysis variance normalized by the observation variance



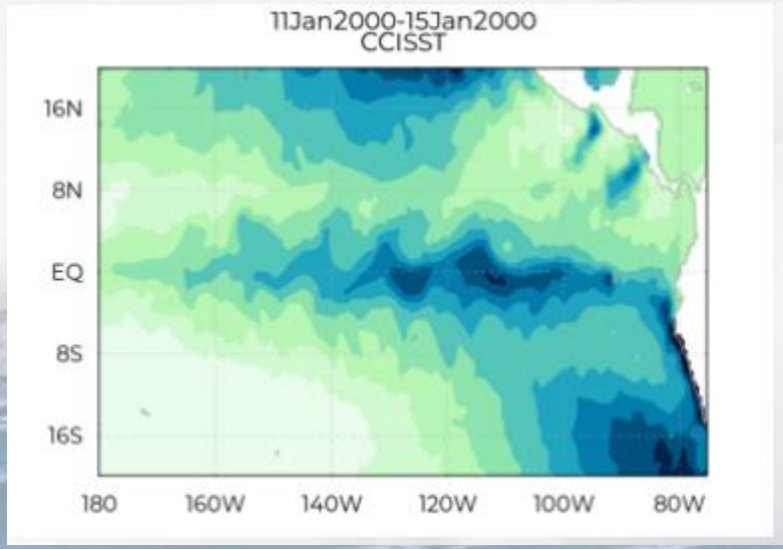
Blue : G3F-CTL is larger.

- The absolute bias of temperature is generally smaller in 4DVAR, in particular, around the thermocline.
- Although the 4DVAR result (G3A-CTL) has larger RMSDs in the large part of the section, RMSEs are smaller around the thermocline.
- 4DVAR generally has larger variances. This seems to be a major cause of larger RMSEs.

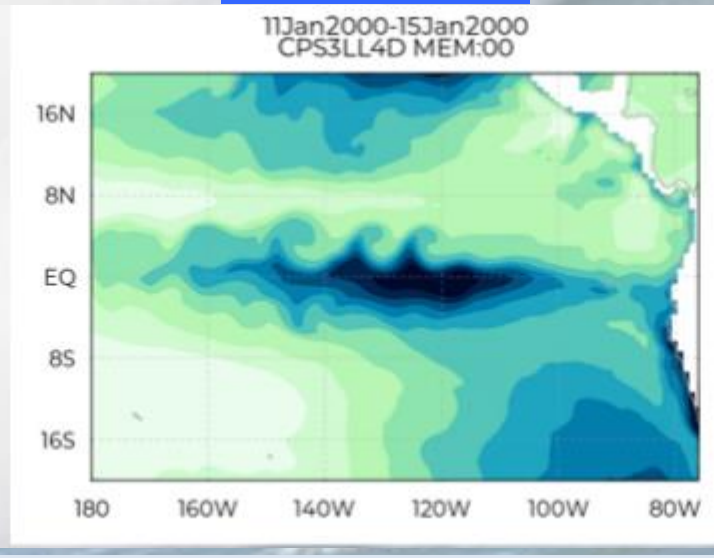
☆Sensitivity experiments of forecasts from 4DVAR and 3DVAR initialization

- ◆ Model：Atm⇒TL159 (about 110km), Ocn⇒the model used in G3A（1x0.3−0.5°）
  (The model resolutions are lower than the operational system.)
- ◆ 10 ensemble member forecasts
- ◆ Initialization by the 4DVAR system (4DVAR-FCST) and its 3DVAR version (3DVAR-FCST)

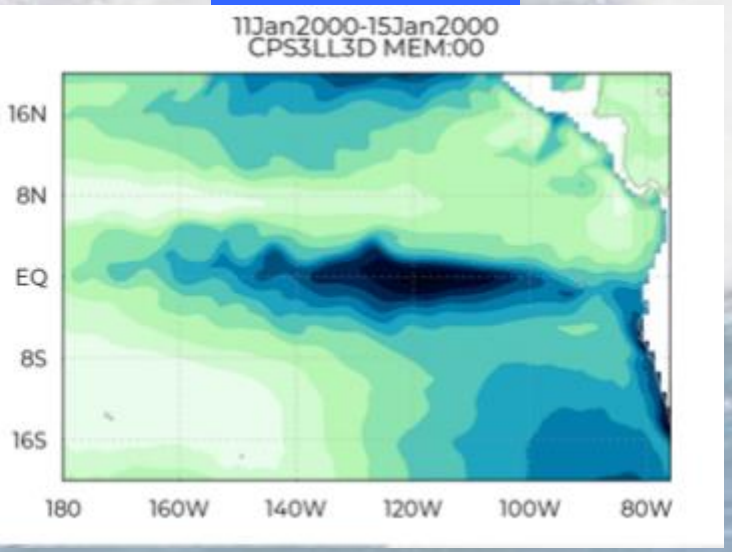
Observation (ESA SST CCI)



4DVAR-FCST



3DVAR-FCST



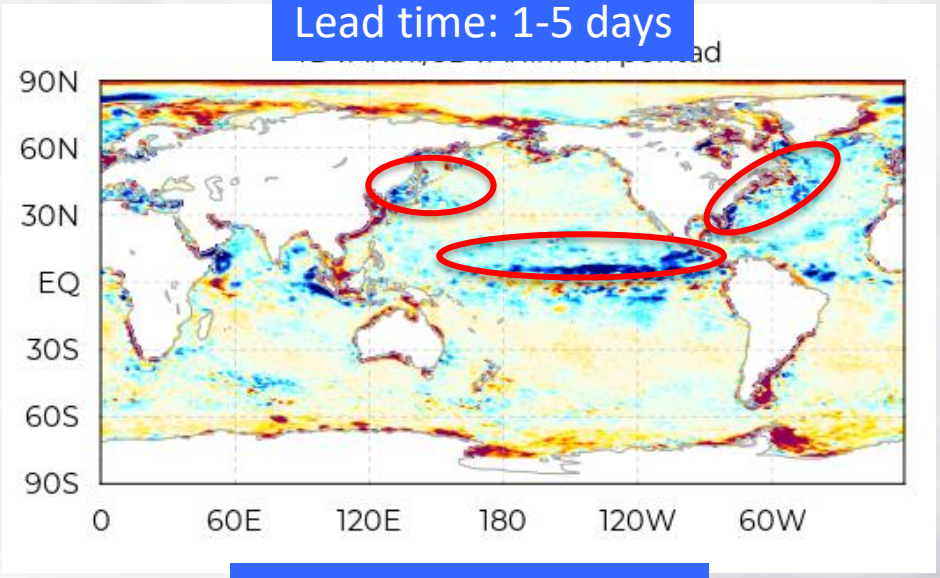
- ➢ Although some TIWs are not clear because they are smoothed in the 3DVAR-FCST, 4DVAR reproduces TIWs clearly.

☆ Impact of 4DVAR on the coupled Prediction (using a lower resolution model)

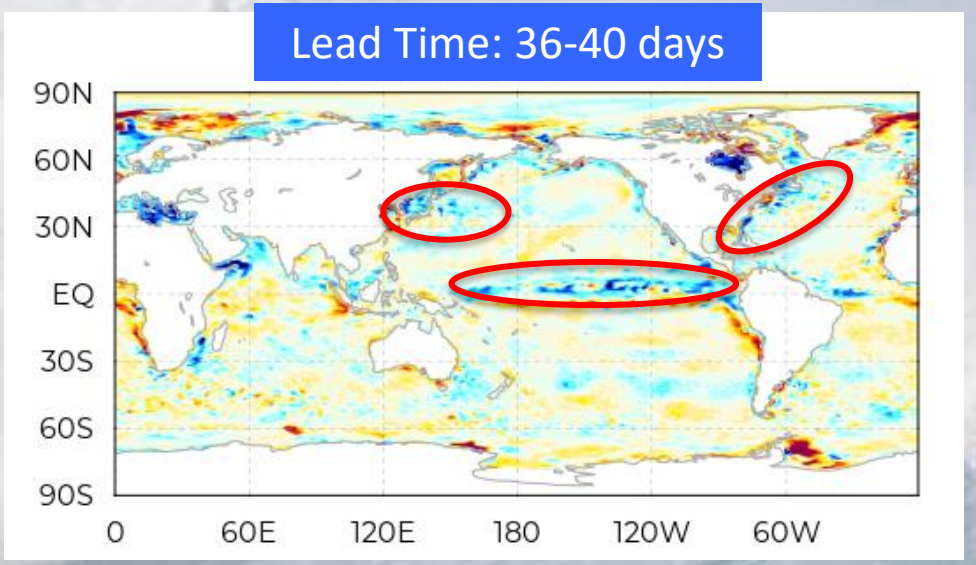
Ratio of SST prediction RMSE（4DVAR/3DVAR）

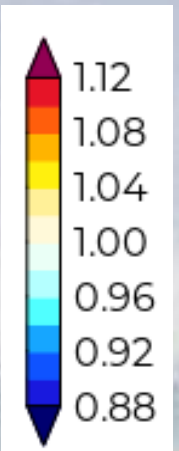
Resolution: Atom. ~110km, Ocean 0.3-0.5 x 1.0°

Lead time: 1-5 days

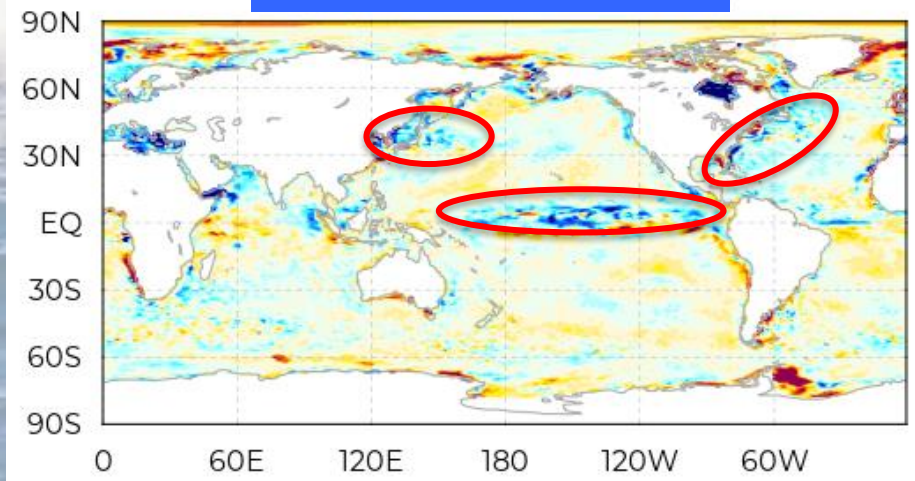


Lead Time: 36-40 days





Lead time: 21-25 days



Blue : 4DVAR is better

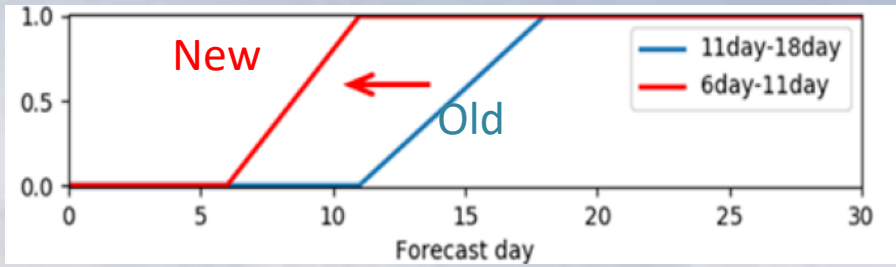
- 4DVAR predicts SST variations better in the regions where TIWs are active and the western boundary current regions.
- The impacts can be seen even in the forecasts more than a month ahead.
- Due to better physical balance in the 4DVAR?

3. Recent Developments and activities

★ Use of CPS3 predicted SST in the uncoupled predictions

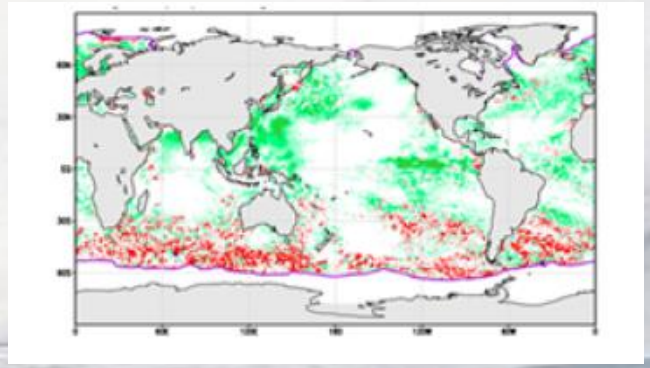
- Earlier transition of SST forcing from anomaly persistence to CPS3 in the uncoupled subseasonal predictions improves the forecasts.
- Now, we apply the global CPS3 SST as the forcing in the operation, but it used only in the tropics in the test.

Transition weight of CPS3 SST

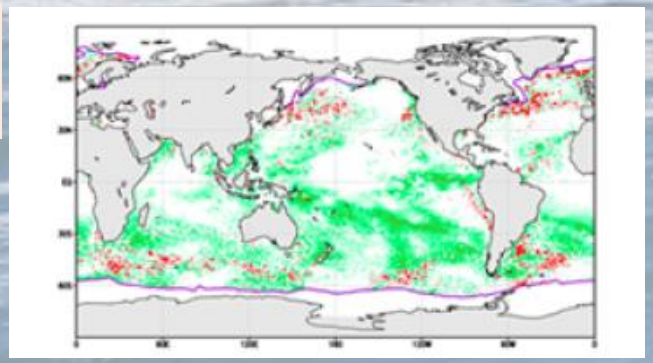


Difference in SST ACC score:
[CPS3] — [anomaly persistence]
(Green means CPS3 is better.)

2019 summer

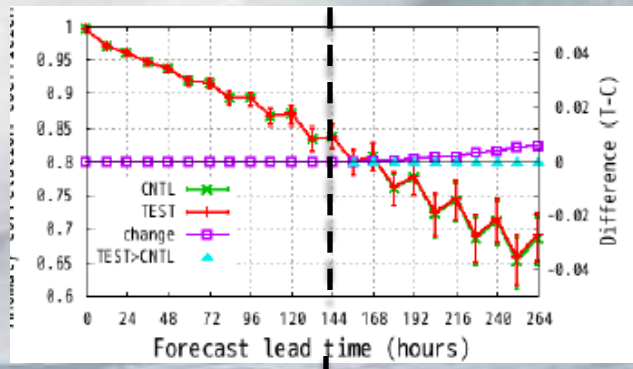


2019/20 winter

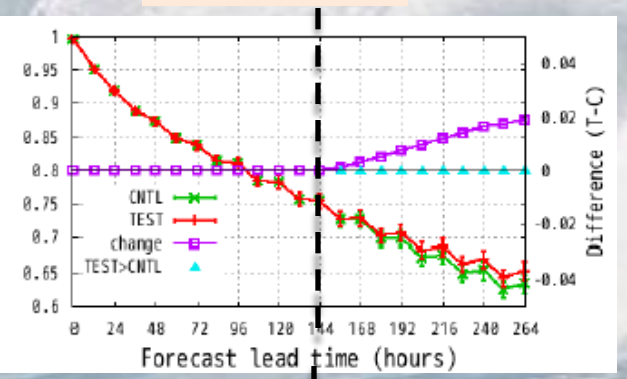


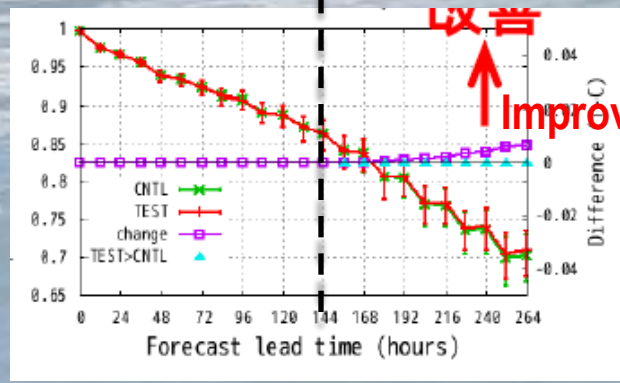
Comparison of the time-series of ACC score in the tropics

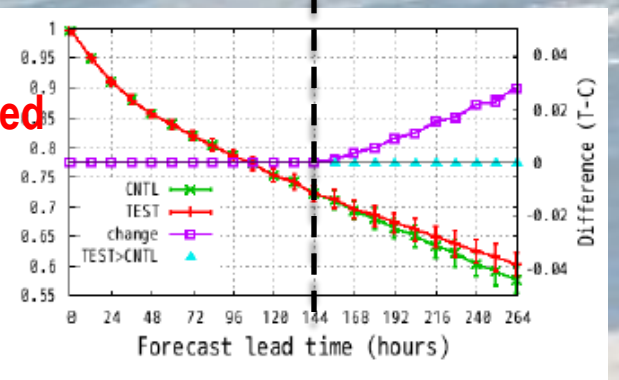
Sea Lev. Pres.



1000hPa T





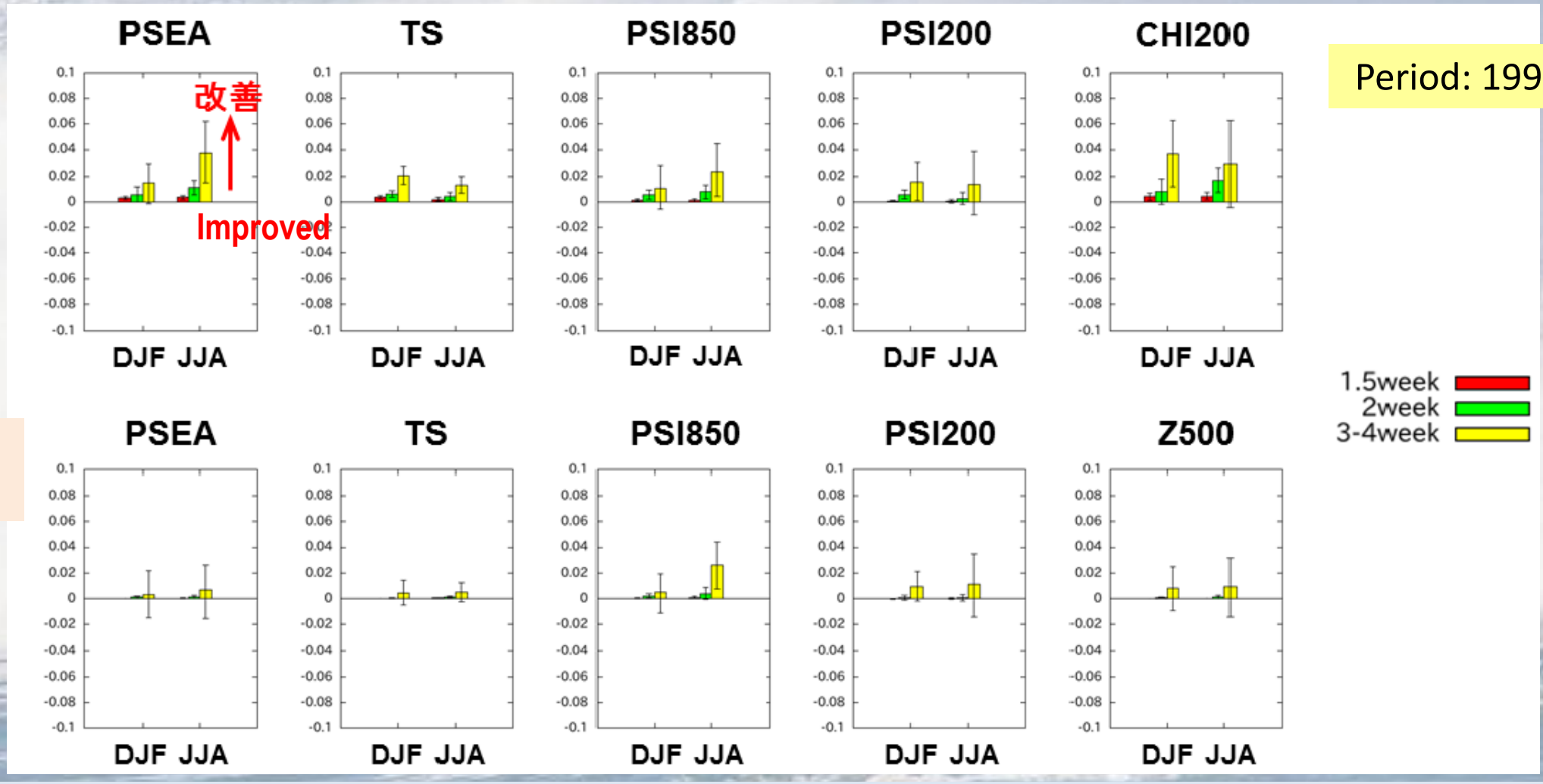


Old
New
Difference
Significance

★ Impact of earlier transition to CPS3 predicted SST for the longer lead-time

Tropics

North Hemisphere



Period: 1991-2020

- Earlier transition to the CPS3 SST improves the forecasts especially for longer lead times.
- The positive impact mainly appears in the tropics but is also found in the mid-latitude regions.

  → Indicating the importance of SST prediction in the subseasonal forecasts

Improvement of model-bias correction scheme

$\mathbf{x}_t^b = \mathbf{x}_t^p + \mathbf{b}_t$ (The model prediction to which the estimated bias is added is used as the background state.)

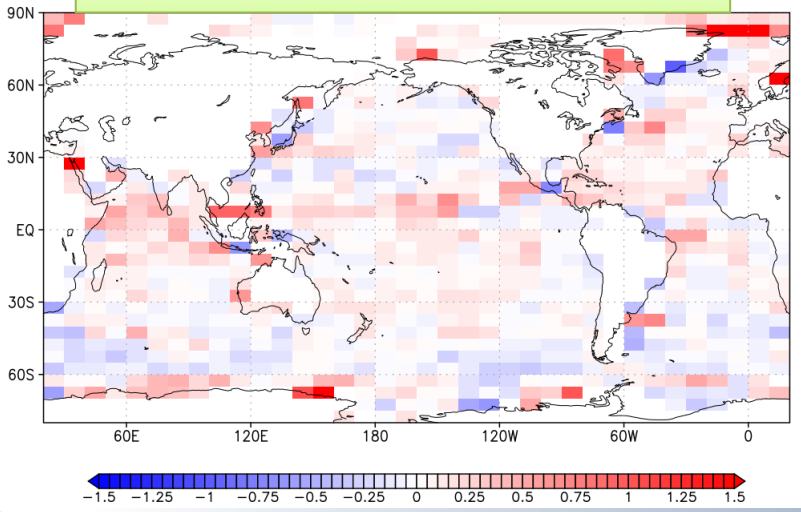
$$\mathbf{b}_t = (1-w)\mathbf{b}_{t-1} + w\Delta\mathbf{x}_{t-1}^a + \mathbf{b}_t^c - \mathbf{b}_{t-1}^c$$

The bias is estimated online from the analysis increments.

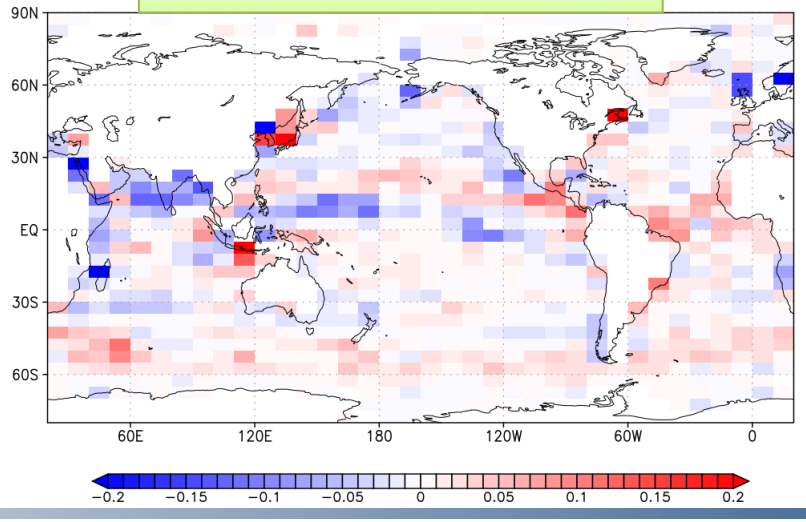
(New) Offline term of **climatological seasonal variation** of the bias estimated a priori from analysis increments in preliminary reanalysis.

Verification results of temperature fields at 100 m depth from 1991 to 2020

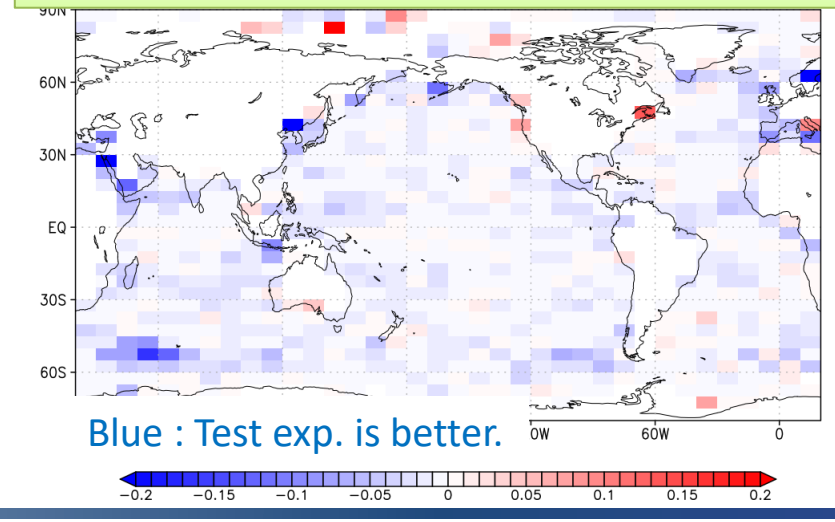
Biases (Anal. – Obs.) of control exp.



Bias differences : Test – Cntl



Normalized RMSE differences : (Test – Cntl)/Cntl



Blue : Test exp. is better.

★ Introduction of 1/4˚ resolution oceanic 4DVAR

◆ Current System

- ➢ 4DVAR with 0.3-0.5 x 1˚ resolution model
- ➢ Downscaled to (replay in) 1/4˚ resolution
- ➢ 4DVAR analysis window: 10 days
- ➢ Max iteration Num.: 30
- ➢ First Guess from preliminary 3DVAR

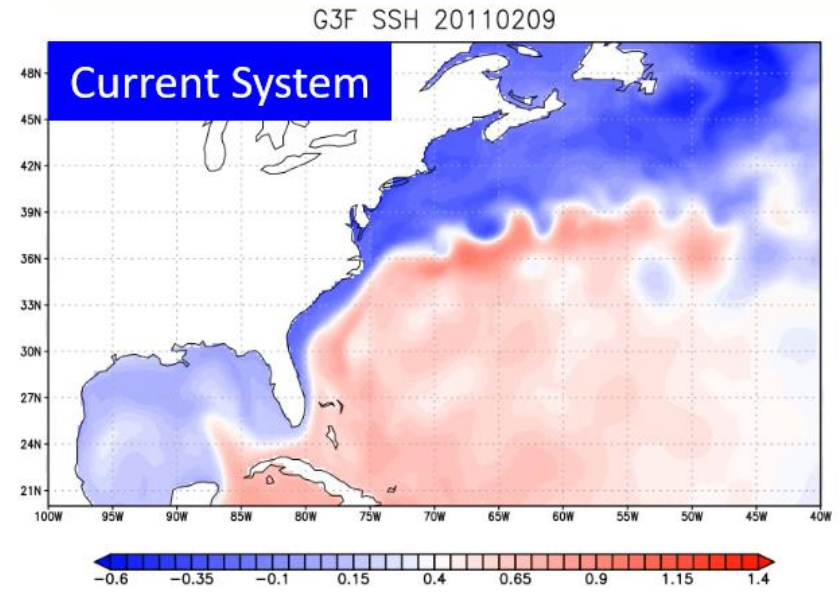
Improve eddy activities? →

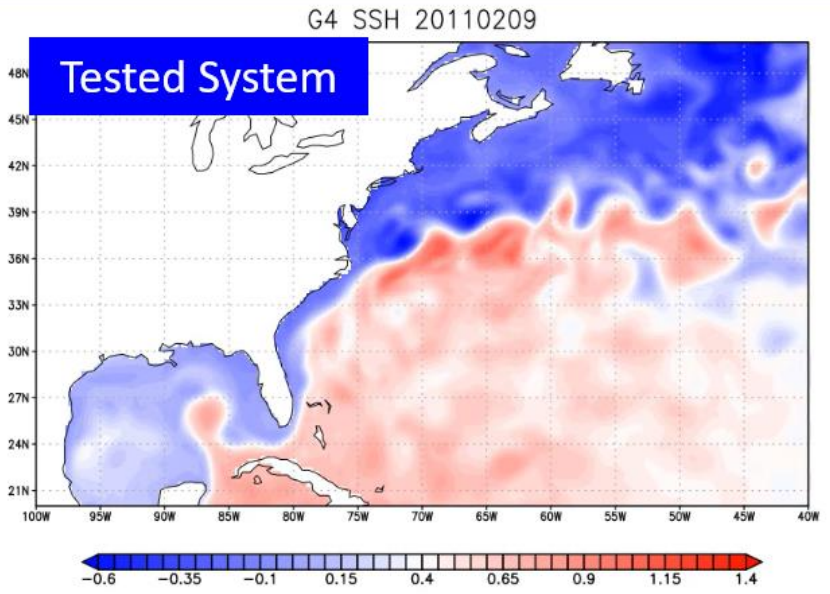
Degrade the balance? →

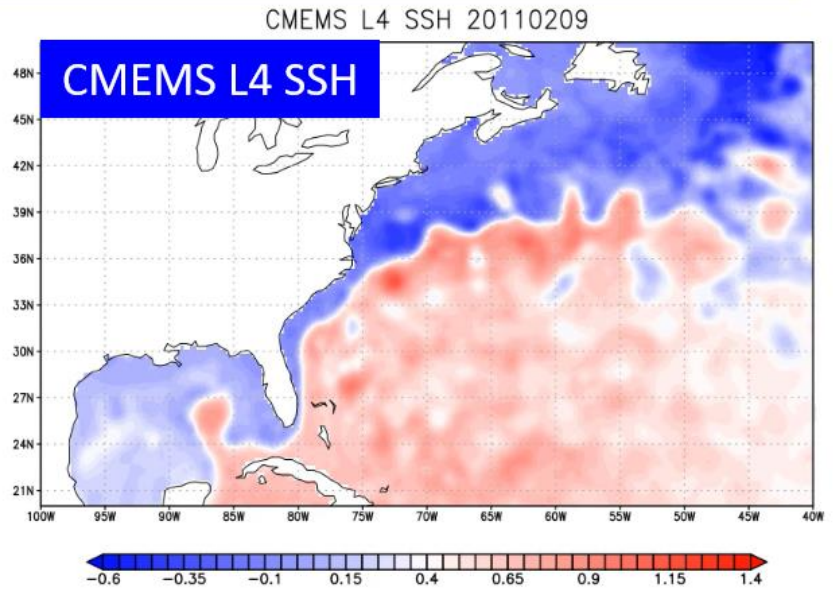
◆ Tested system

- ➢ 4DVAR with 1/4˚ resolution model
- ➢ No downscaling
- ➢ 4DVAR analysis window: 2 days
- ➢ Max iteration Num.: 10 (3 in the test)
- ➢ First Guess from preliminary 3DVAR

Additional computational cost due to the higher resolution is balanced with the time reduction by the shorter analysis window and the smaller iteration number.





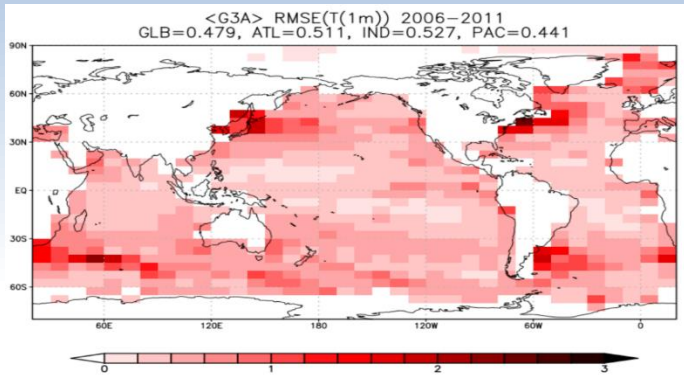


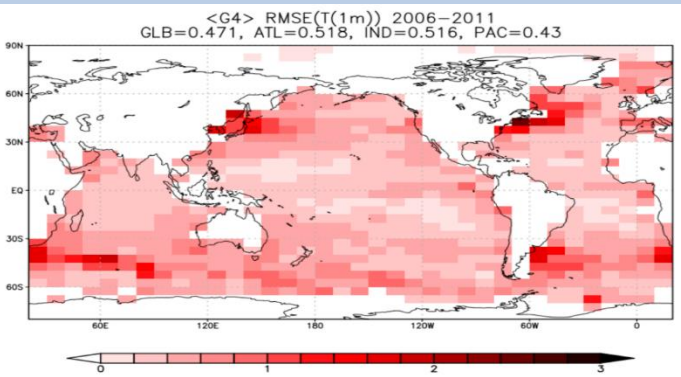
* Bias is subtracted for visualization purpose

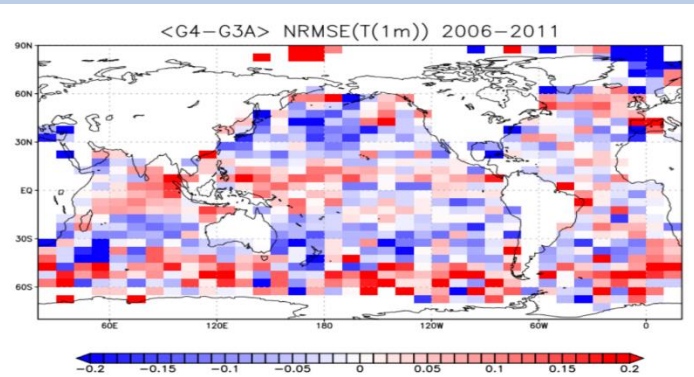
RMSE to independent Argo data

Current System | Tested System | Normalized change (blue: improved)

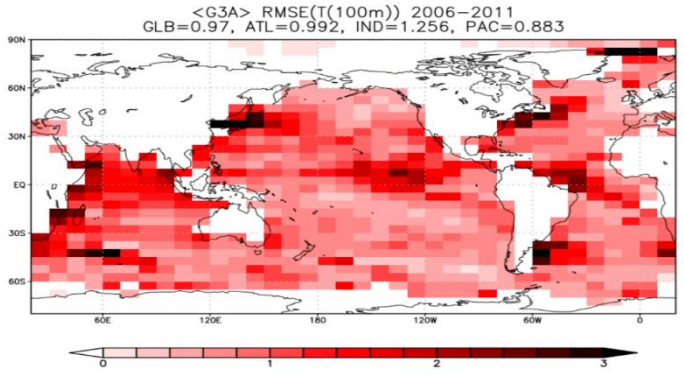
SST

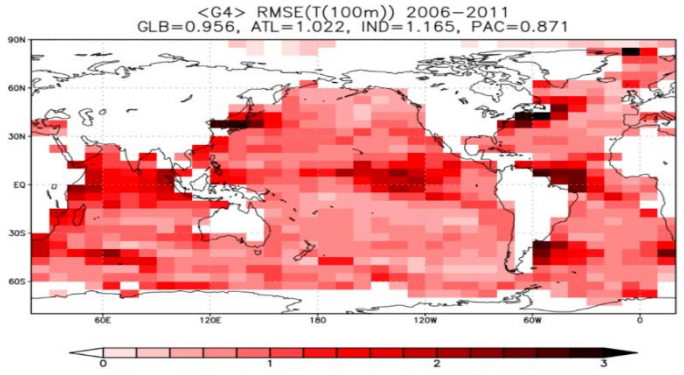


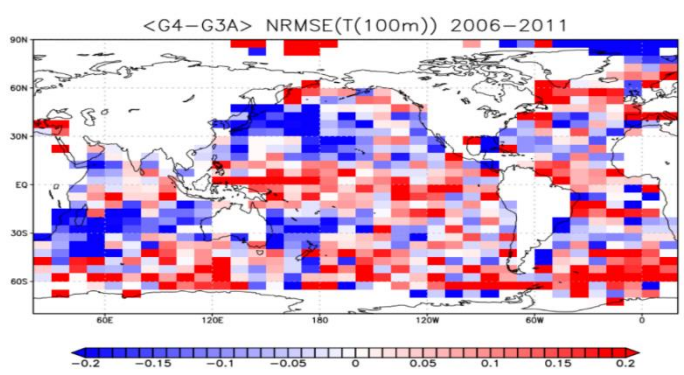




T at 100m



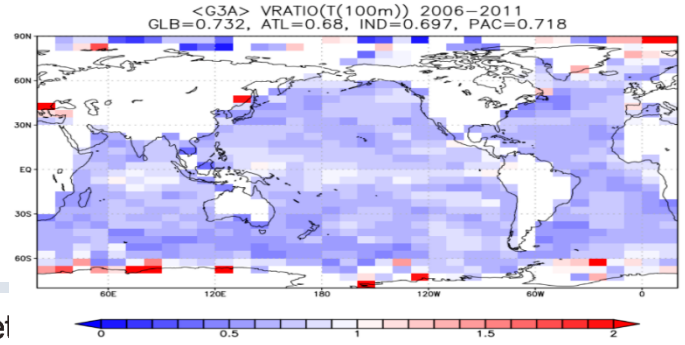


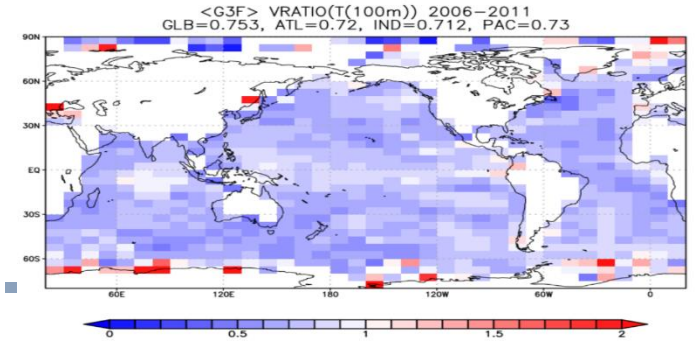


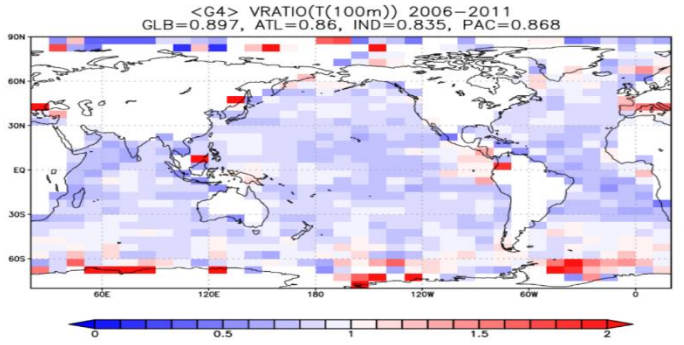
Impact on temperature variance

variance ratio (= STDV[Analysis anomaly] / STDV[Observed anomaly], verified assimilated Argo data)

G3A (Current 4DVAR System) | G3F (current downscaled system) | Tested System



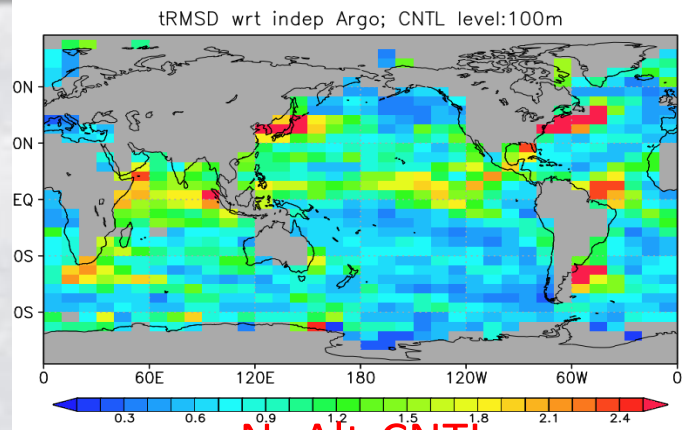




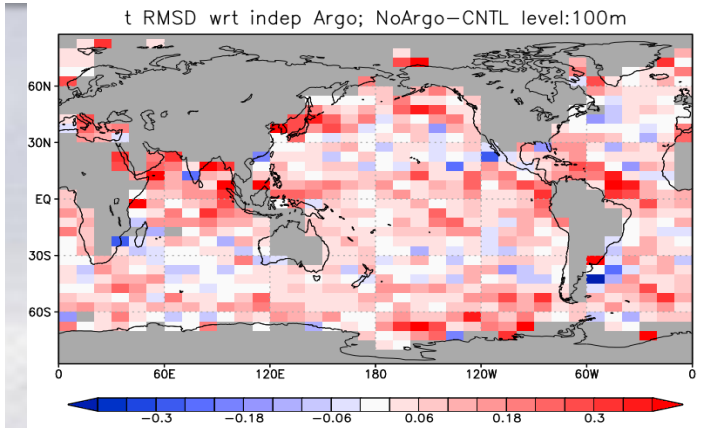
Synergistic Observing Network for Ocean Prediction (SynObs)

- **SynObs** is the Project of **the United Nations (UN) Ocean Decade** to seek the way to get maximum synergy from the combination among various observation platforms in ocean predictions.
- SynObs is now promoting a coordinated OSEs using various ocean prediction systems.
- JMA has currently been conducting the OSEs for the SynObs coordinated OSE activity.
- The figure shows the RMSEs of 100 m temperature fields of OSEs not assimilating the altimetry (NoAlt), Argo (NoArgo), and mooring data (NoMoor), as well as the control run (CNTL).

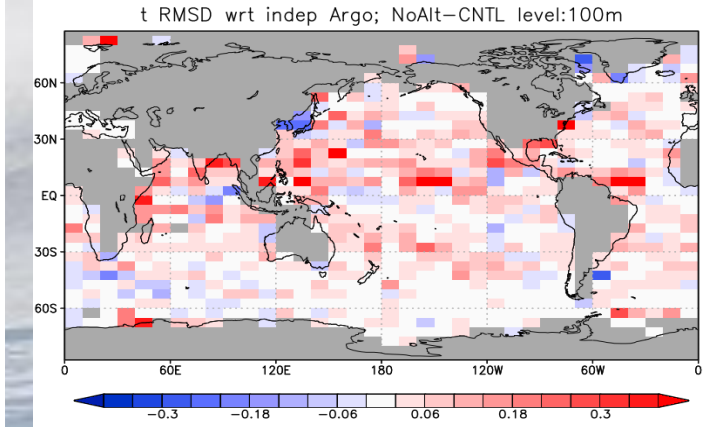
CNTL



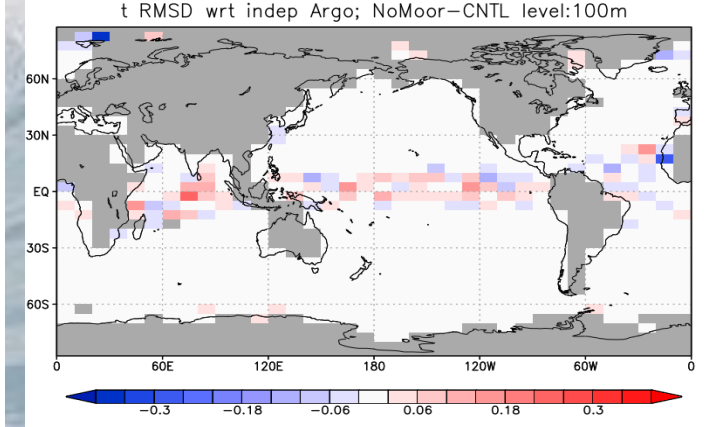
NoArgo-CNTL



NoAlt-CNTL



NoMoor-CNTL



- RMSEs are evaluated for each 5˚x10˚ box using independent Argo data.
- Argo data has significant impacts in the global ocean, but altimetry and mooring data still have some positive impacts complimentary to Argo data.

4. Concluding Remarks

☆ Concluding Remarks

- A better SST representation likely improves both uncoupled and coupled predictions!
- Oceanic 4DVAR and dedicated bias correction can improve the SST analysis, resulting in better coupled forecasts.
- Using SST predicted by a coupled prediction system can improve the uncoupled atmospheric forecasts.

- JMA/MRI are currently conducting OSEs for the SynObs coordinated muti-system OSE project, and NOAA/CPC and EMC and NASA/GMAO plan to join the project.
- Please mail to SynObs **(synobs@mri-jma.go.jp)** or visit the web page to join the SynObs activities. (We share the information on the activity through the SynObs mailing list and the SynObs web meetings.)

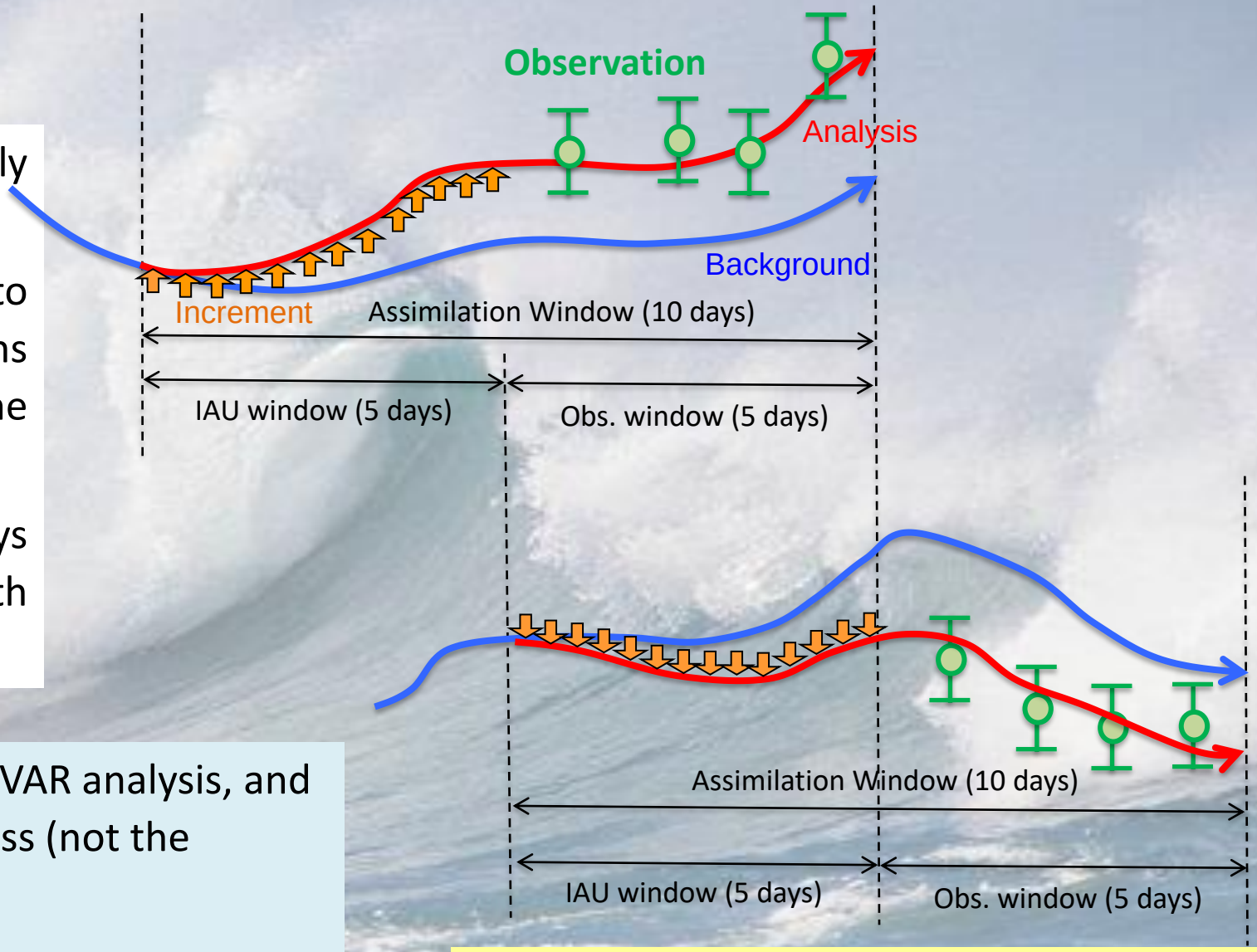
SynObs Webpage:
https://oceanpredict.org/un-decade-of-ocean-science/synobs-2/

Thank you!!

Supplemental Materials

★ IAU-4DVAR

- Model fields are modified by gradually adding TS increments for 5 days by IAU.
- The TS increments are optimized so as to fit the model trajectory to observations through the iterative calculation of the forward and adjoint model.
- The observation window is shifted 5 days after the IAU window, and overlapped with the IAU window in the next analysis cycle.



- the system performs 3DVAR before the 4DVAR analysis, and the result of 3DVAR is used as the first guess (not the background fields) of the 4DVAR.
  - ➢ To reduce the computational time
  - ➢ To grantee the accuracy similar to 3DVAR even if the number of the iterations are insufficient.

- ➢ We regard the trajectory connecting model fields in the second half of the assimilation window in each analysis as the analysis fields.

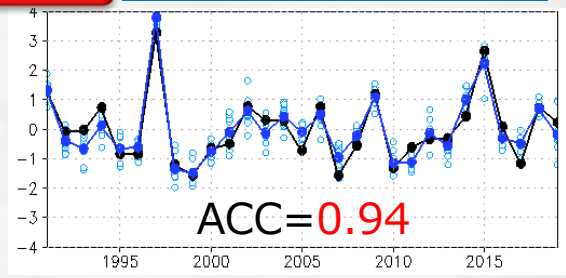
★ Improvement of SST Predictions

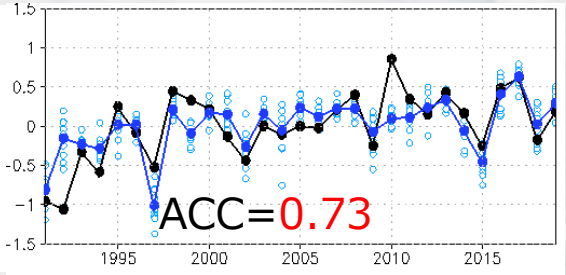
Evaluation Period: 1990-2019

Winter NINO3 SST Predictions from ends of Julys

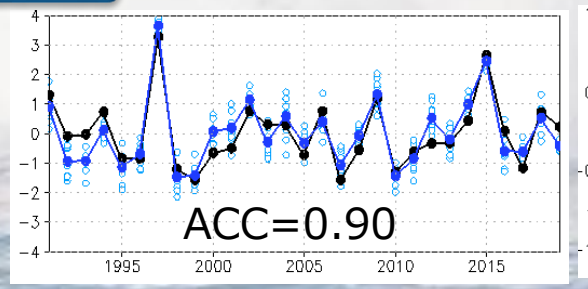
Winter Far Western EqPac SST Predictions from ends of Julys

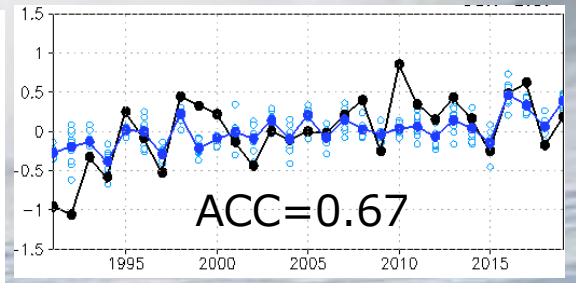
New





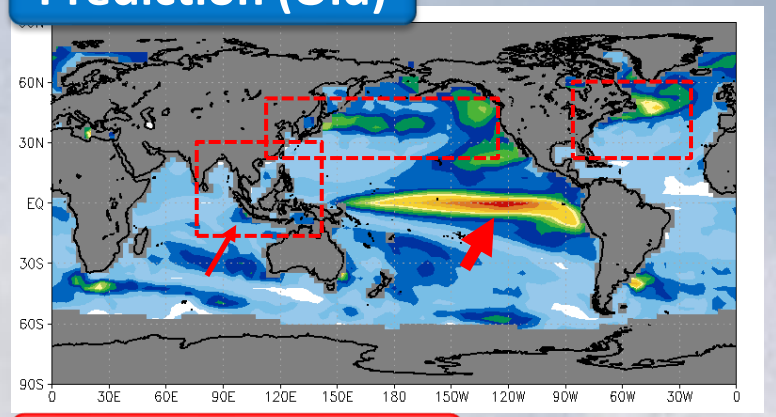
Old



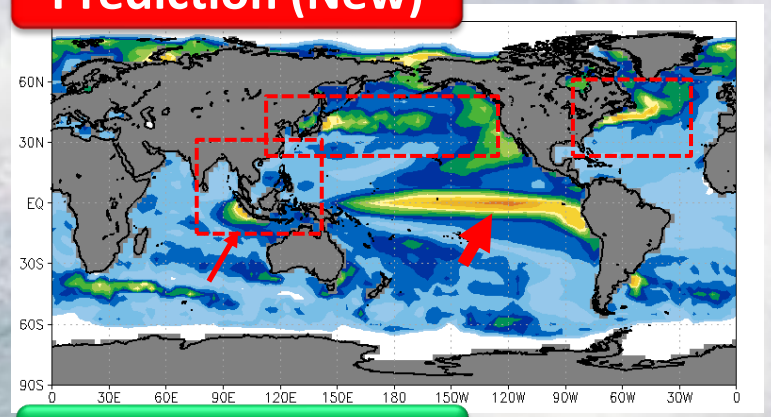


Global distribution of the standard deviation from that time average of winter SST predictions from ends of Julys.

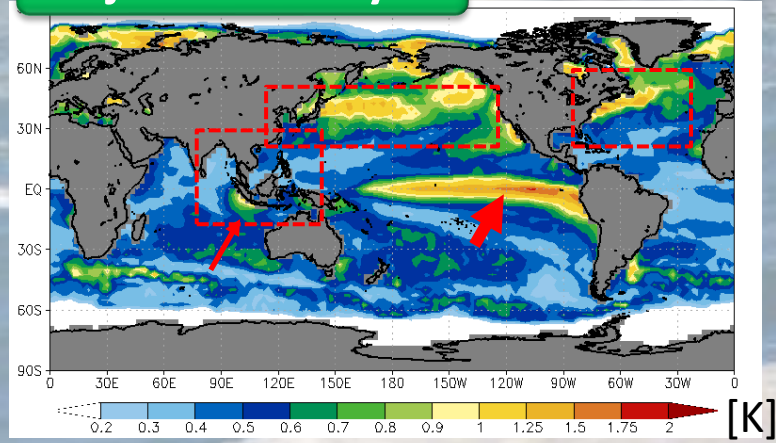
Prediction (Old)



Prediction (New)



Objective Analysis



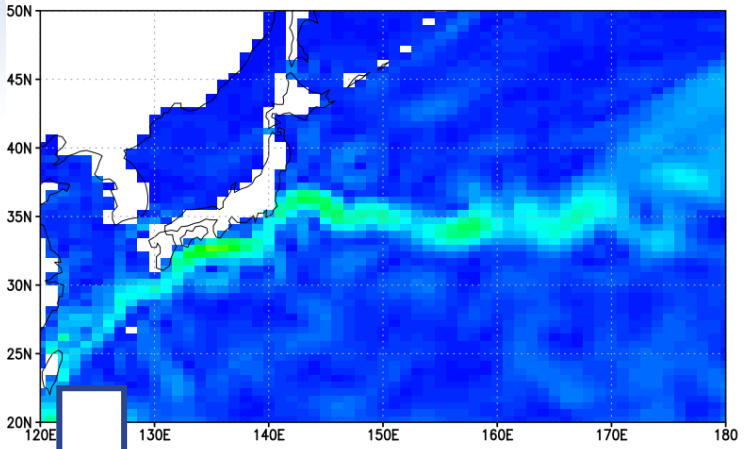
● Objective Analysis
● Ensemble mean
○ Each Member

- Prediction Scores related to ENSO are generally improved.
- Variabilities are suppressed in the eastern equatorial Pacific, and enhanced in the eastern equatorial Indian Ocean.
- Variabilities are increased in the mid-latitude frontal zones.

High-resolution ocean 4DVAR

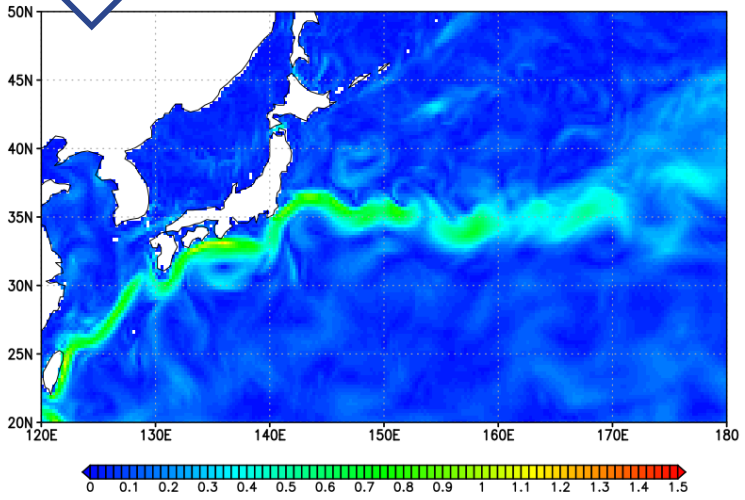
CPS3

G3A-4DVAR (1.0deg)

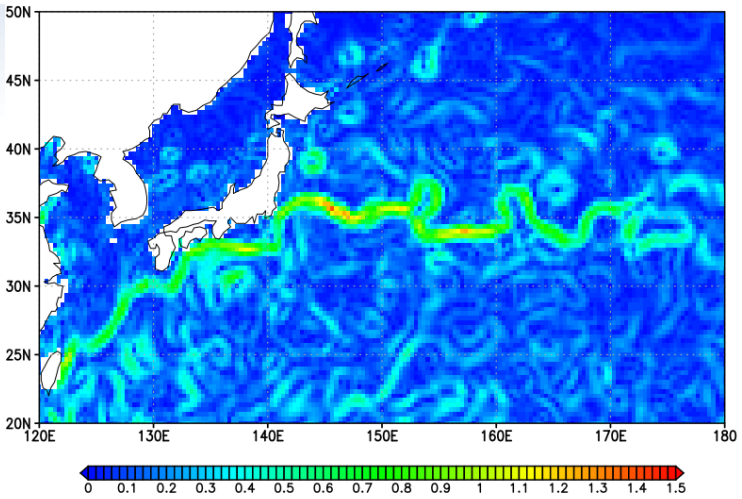


Downscaling

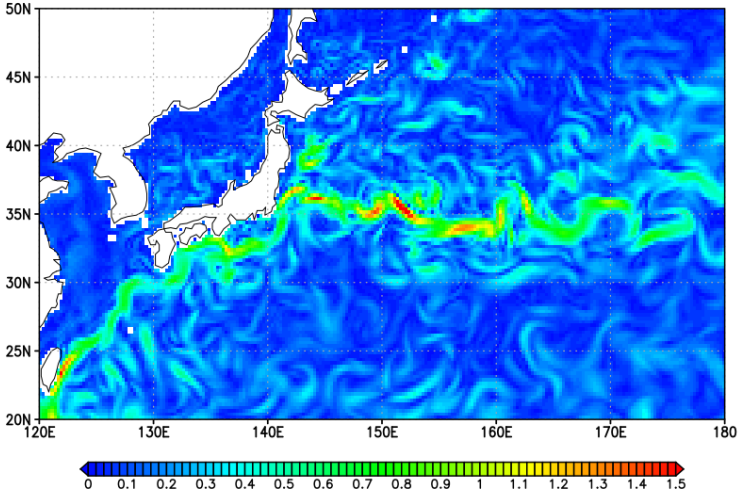
G3F-IAU (0.25deg)



OSCAR Surface Current Analysis (1/3deg)



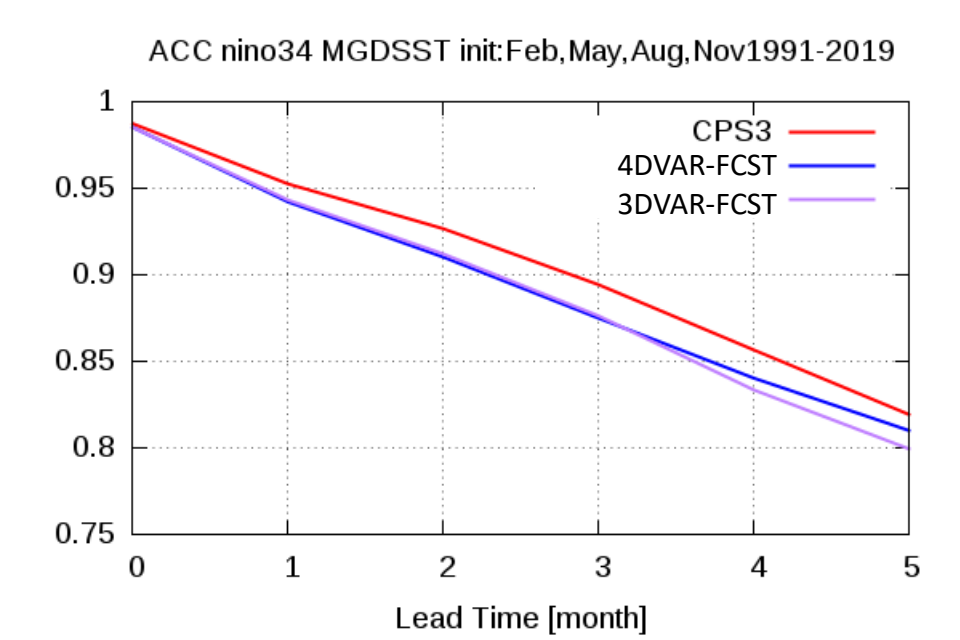
TEST-4DVAR (0.25deg)



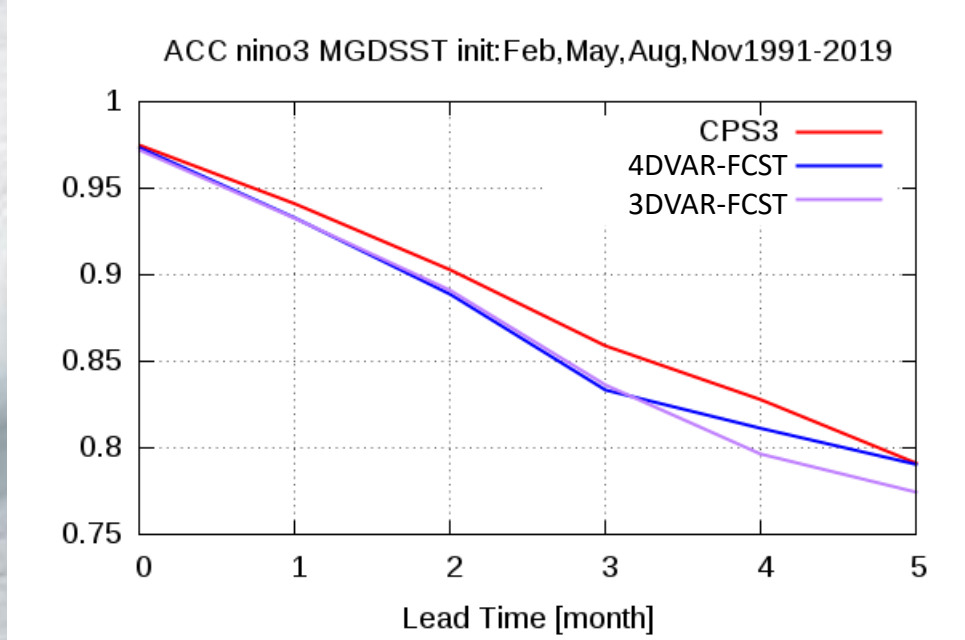
- Currently using the combination of low resolution 4D-Var (1.0x0.3-0.5deg.) and high-resolution IAU (0.25deg.)
- Only large-scale features such as mainstream of the Kuroshio are resolved by the current 4D-Var system.
- Finer resolution (0.25deg) Ocean 4DVAR is currently under development (, but is not targeted on CPS4)

☆ Comparison of the prediction scores of ENSO indices

ACC for NINO3.4 Index



ACC for NINO3 Index

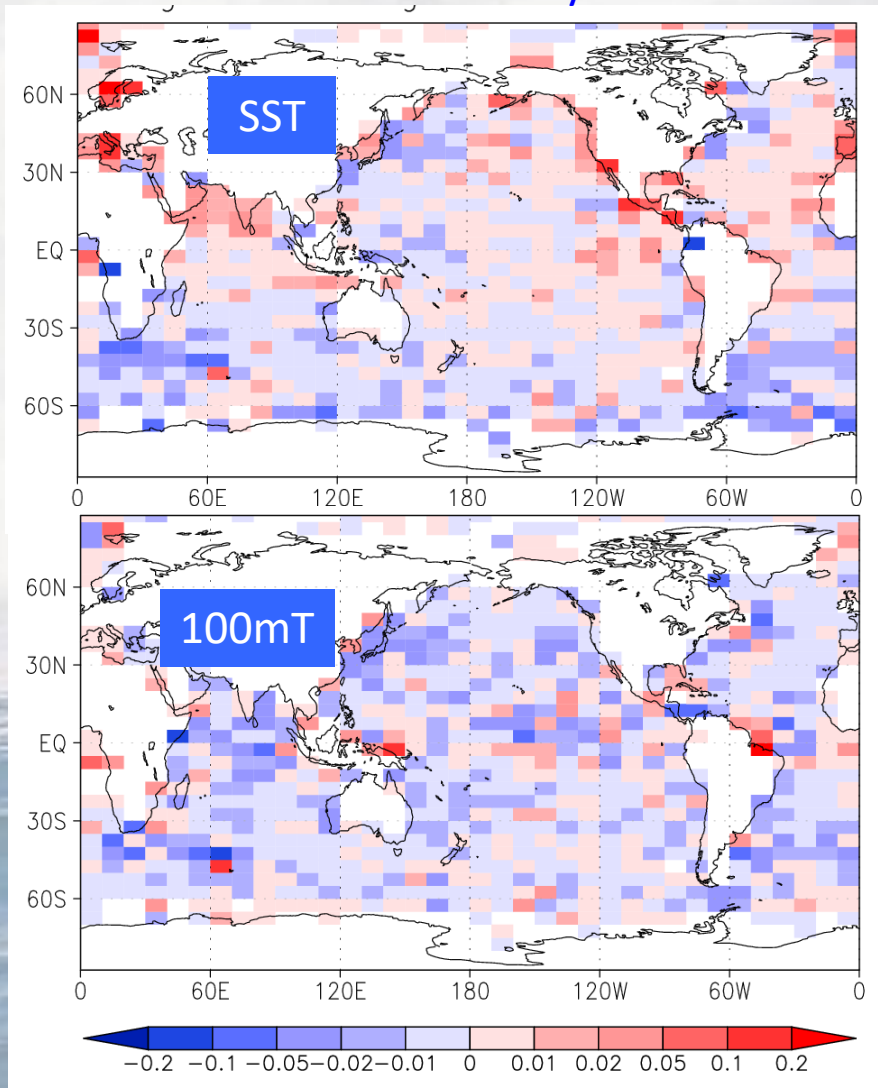


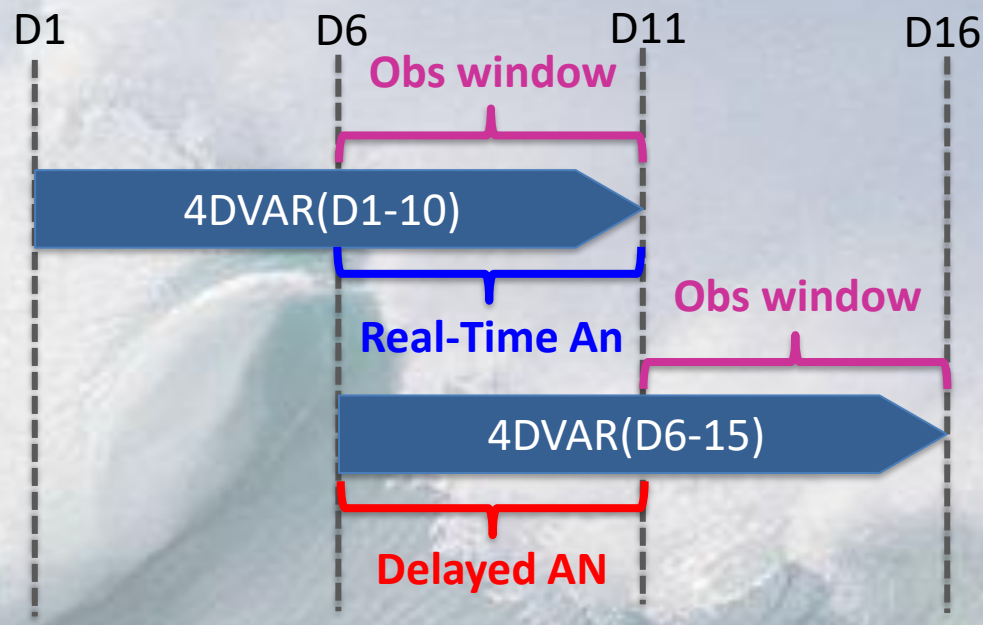
- The better scores of the operational system (CPS3) are due to its higher resolutions.
- 4DVAR-FCST has better scores for 4 to 5 months predictions.
  - Maybe due to the smaller bias and RMSD around the equatorial thermocline in the 4DVAR ocean data assimilation system (G3A-CTL).

★ Capacity of improving the analysis fields using future observations

Difference of RMSD against indep. Argo between delayed and real-time Ans

Blue: Delayed An is better





- The real-time analysis are further improved by assimilating observations in the next five days in the delayed analysis, especially for 100-m temperature.
- SST is not so improved because sufficient SST observation data have already constrained the real-time analysis.
- 4DVAR has a capacity of improving the analysis fields using future observations.

Synergistic Observing Network for Ocean Prediction

UN Ocean Decade Project

Led by OceanPedict OS-Eval TT

- Objective

  SynObs will seek the way to extract maximum benefits from the combination among various observation platforms, typically between satellite and in situ observation data, in ocean predictions.

- Strategy

  SynObs aims to identify the optimal combination of different ocean observation platforms through observing system design/evaluation, and to develop assimilation methods with which we can draw synergistic effects.

2021 2030 United Nations Decade of Ocean Science for Sustainable Development

SynObs Contact

SynObs Co-Chairs: Y. Fujii (JMA/MRI), Elisabeth Remy (Moi)

E-Mail: synobs@mri-jma.go.jp

https://oceanpredict.org/un-decade-of-ocean-science/synobs-2/

Mailing List

SynObsML@googlegroups.com

Please mail to synobs@mri-jma.go.jp for joining

☆ Plan of SynObs Flagship OSEs/OSSEs

SynObs plans to implement OSEs/OSSEs using various ocean prediction systems with a common setting.

Why?

- In order to remove system dependency by averaging the results with various systems

Systems participating in the OP OSEs

Center	System	Area	Res. (Deg.)
UK MetOffice	FOAM	Global	1/12
NOAA/NCEP	RTOFS-DA	Global	0.08
ECMWF	ORAS5/6	Global	1/4
NASA/GMAO	GEO-S2S V3	Global	1/4
JMA/MRI	MOVE-G3F	Global	1/4
ECCC	GIOPS	Global	1/4
NOAA/NCEP	GLORe	Global	1
NOAA/QUOSAP	MOM6	Global	?
JAMSTEC-APL	JCOPE-FGO	Semi-glob.	0.1
JMA/MRI	MOVE-NP	N Pac.	1/10x1/11
Pukyong Uni.	KOOS-OPEM	N. Pac	1/24
REMO-UFBA	HYCOM-RODAS	S. Atl.	1/12
MetService, NZ	MetService, NZ	S. Pac.	1/24

OSEs requested in the OP OSEs and S2S OSEs

1	CNTL	Ocean Model		SST	Argo 80%	Mooring	Other TS	Alt. (optional)
2	NoAlt	Ocean Model		SST	Argo 80%	Mooring	Other TS	
3	NoArgo	Ocean Model		SST		Mooring	Other TS	Alt. (optional)
4	NoMoor	Ocean Model		SST	Argo 80%		Other TS	Alt. (optional)
5	NoSST	Ocean Model			Argo 80%	Mooring	Other TS	Alt. (optional)
6	NoInsitu	Ocean Model		SST				Alt. (optional)
7	SSTonly	Ocean Model		SST				
8	Free	Ocean Model						
9	HalfArgo	Ocean Model		SST	Argo 40%	Mooring	Other TS	Alt. (optional)
10	Oper	Ocean Model	Oper. Setting	SST	Argo 100%	Mooring	Other TS	Nadir Altimeter

- **Ocean Prediction OSEs**
  - Reanalysis: Jan. 2020-Dec. 2020 (Dec. 2022)
  - 10-day predictions: Started from every pentad
- **S2S OSEs** (with lower resolution systems)
  - Reanalysis: 2003-2022
  - 1-month predictions: Once a month
  - 4-month predictions: Twice a year
- **Ocean Prediction OSSEs**
  - Use GEOS/NASA coupled simulation as the Nature Run