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Development of coupled atmosphere-ocean data assimilation: Achievements and Perspective

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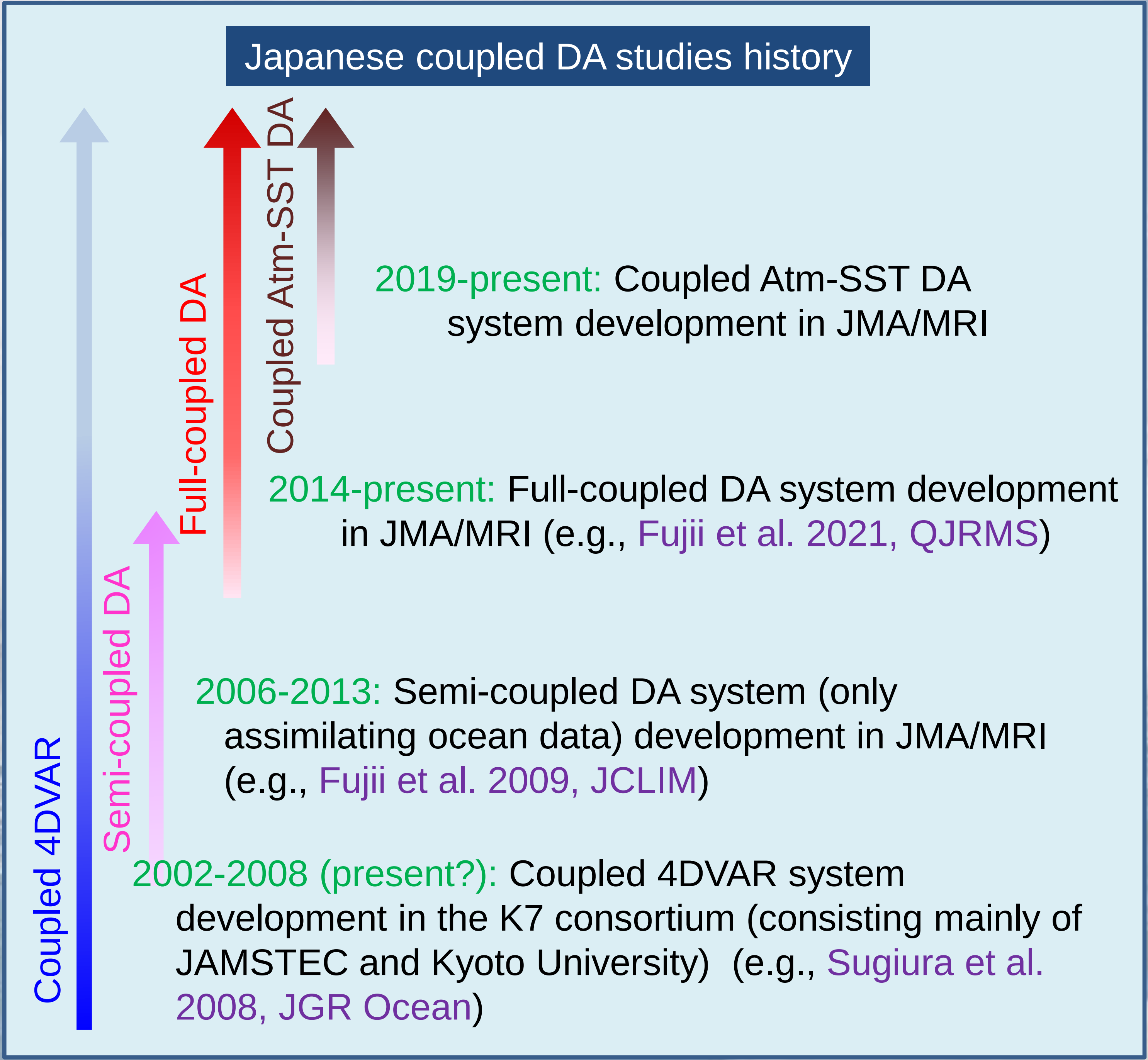
Outline of this presentation

- Classification and advantages of Coupled DA
- Review of coupled DA studies in Japan
  - Coupled 4DVAR
  - Semi-coupled DA
  - Full-coupled DA
  - Coupled Atmosphere-SST DA
- Future perspective and development plan



Classification of coupled DA

Full-coupled DA

Both **atmospheric and ocean obs** are assimilated.

Coupled Atm-SST DA

SST is optimized together with atm variables in atm analysis

E.g., Akella et al. (2017)

Semi-coupled DA

Only ocean obs are assimilated to reproduce **slow variations** of the coupled system

E.g., Fujii et al. (2009)

Strongly coupled DA

- Information of observations propagates across the sea surface in an analysis step.
- E.g., coupled 4DVAR or coupled EnKF

Quasi-strongly coupled DA (e.g., ECMWF-CERA)

- Although atmosphere and ocean analyses are performed separately, information of atmosphere and ocean obs can affects the analysis fields across the sea surface.
- E.g., outer-loop coupling

Weakly coupled DA (e.g, NCEP-CFSR)

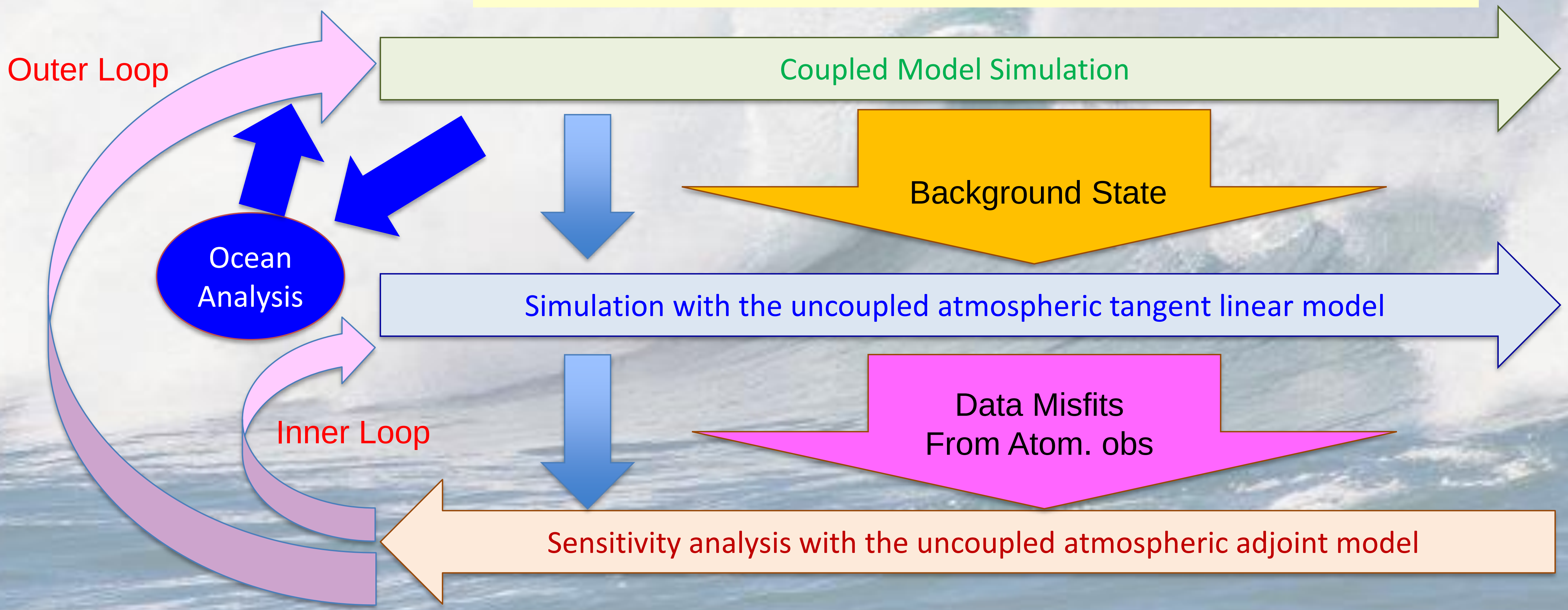
- Information of observations does not propagate across the sea surface in an analysis step.
- Uncoupled atmosphere and ocean DA systems are typically used with only small changes.

See, Penny et al. (2017)

Outer-Loop coupling with an atmospheric 4DVAR System (Quasi-Strongly Coupled DA)

See, Laloyaux et al., 2016,
DOI:10.1007/s00382-015-2705-z, 2016.

Observation information propagates across the sea surface during the coupled model integration

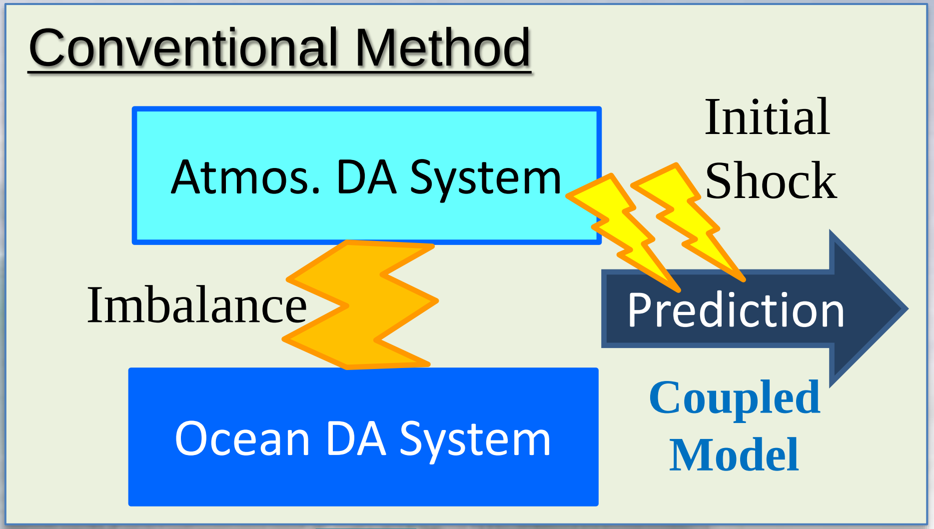


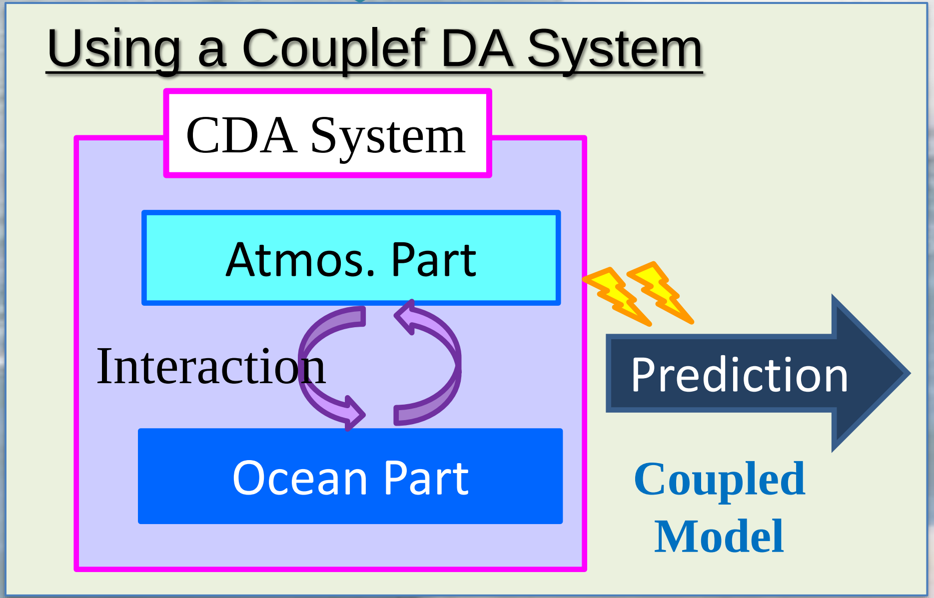
Atmosphere and ocean analysis routines are used almost as they are, but the observation information propagate across the sea surface in an analysis step.

★ Technical Advantages of Coupled DA

1. Coupled DA may reduce initial shocks due to imbalance between the atmosphere and ocean in weather and climate predictions with a coupled model.
   - ➢ Very suitable for Seamless Prediction

2. Information of observation data associated with the atmosphere-ocean interface may be able to be assimilated more effectively.
   - ➢ Satellite Brightness Temperature (SST)
   - ➢ Satellite Scatterometer (Surface Winds and Currents)
   - ➢ Ocean wave observations
   - ➢ Sea Ice Observations
   - ➢ etc.



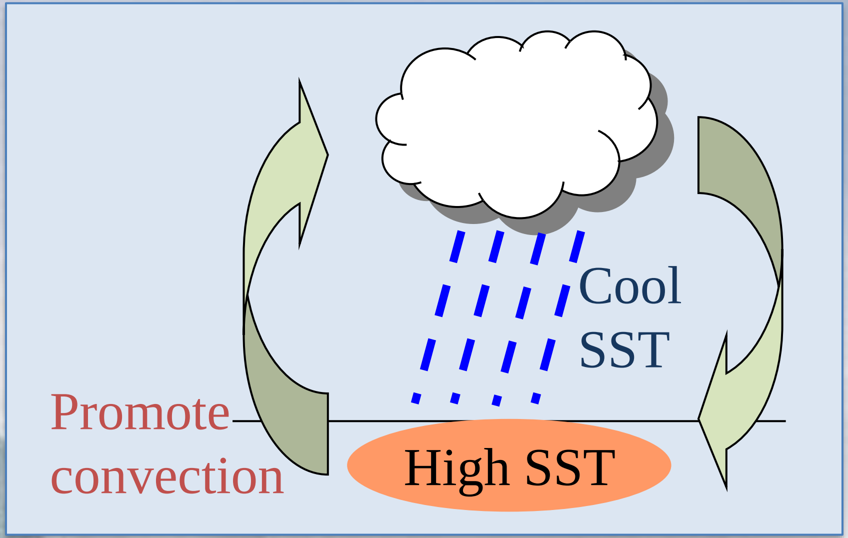


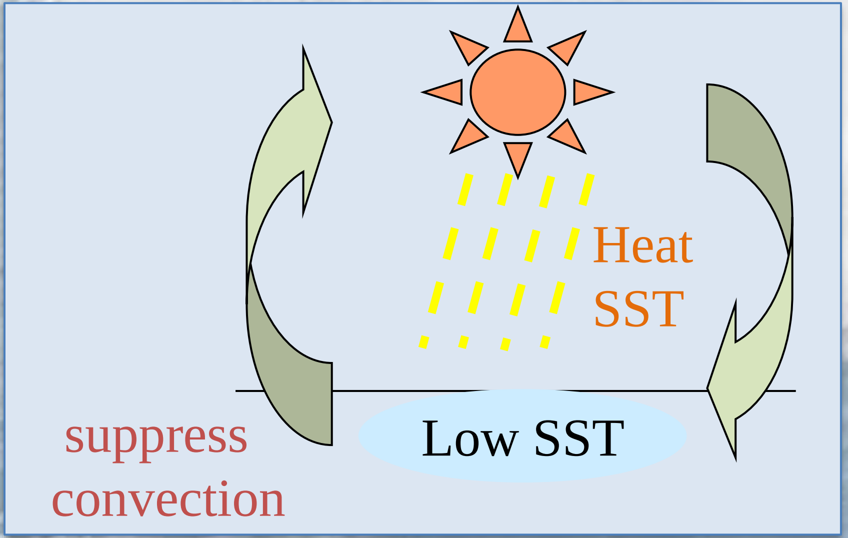
☆ Scientific Advantages of Coupled DA

◆ CDA may be able to represent atmosphere and ocean interaction more realistically.

- ➢ Negative feedback between SST and precipitation (Convection)
- ➢ Diurnal Cycle of SST
- ➢ Development of tropical cyclones
- ➢ Madden Julian Oscillation (MJO)
- ➢ Coupled Atmosphere-Ice-Ocean processes (e.g., Polynyas)
- ➢ Coastal weather (e.g., sea fogs)
- ➢ Extreme rainfall (e.g., atmospheric river)

■ Potential to generate Coupled Reanalysis



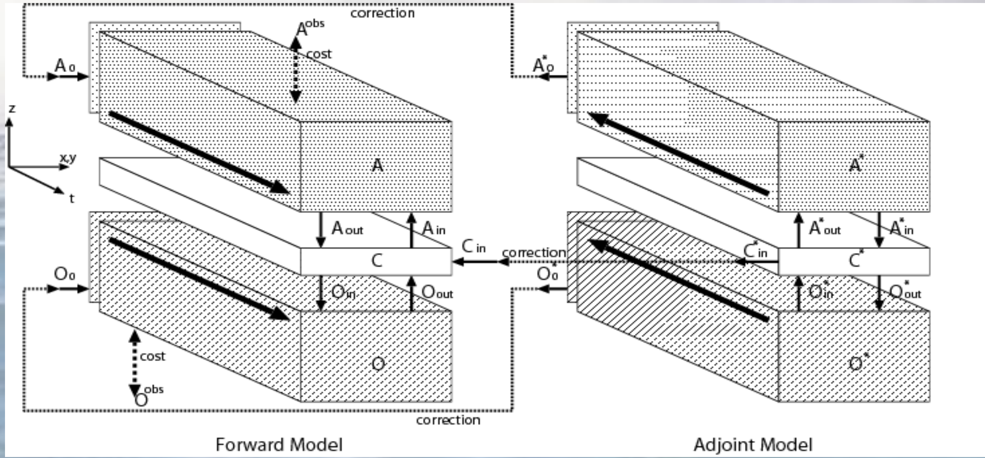


This feedback adjusts precipitation, (avoids the continuous rainfall over high SST).

Coupled 4DVAR Development

Development of a Coupled A-O 4DVAR System by Japan K7 consortium in the early 2000s.

- In early 2000s, Japan manufactured the Earth Simulator (ES), which is the world fastest supercomputer at the time.
- To make effective use of the ES, the Japanese K7 consortium developed an adjoint code of a coupled model and a coupled strong-constraint 4DVAR system, and generated a coupled state estimation dataset.



Sugiura et al. (2008), DOI:10.1029/2008JC004741

Setting of the coupled state estimation

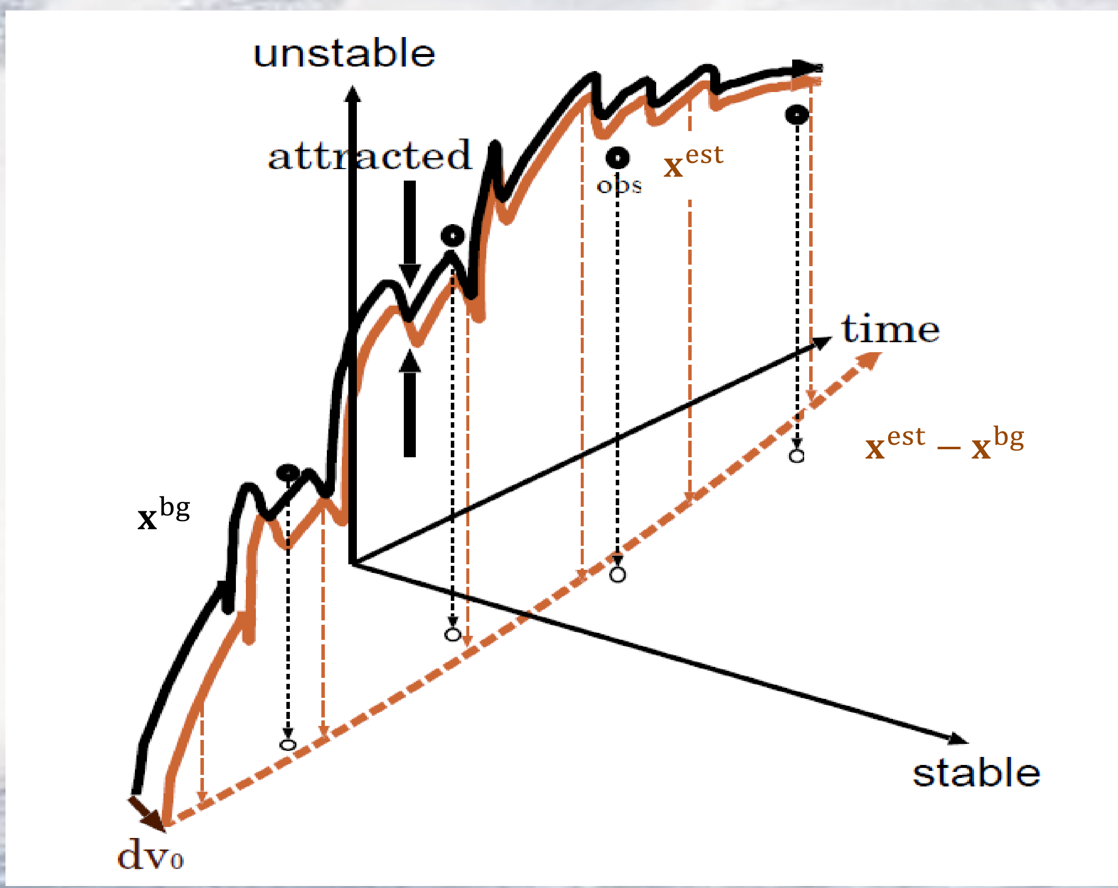
- Prediction model (Coupled model)
  - AGCM: AFES (T42L24)
  - OGCM: MOM3 (1x1˚, L45)
  - IARC Sea ice model, MATSIRO Land Model
- Assimilated observation data
  - NCEP's BUFR data U,V,T,Q (10daily)
  - SSM/I sea wind scalar x ERA40 wind direction (10daily)
  - Satellite sea surface heigh anomaly data(10daily)
  - Reynolds SST (10daily)
  - WOD2001 data T,S (monthly) (+ TS from ODA result)
- 9-month assimilation windows (with 3 month overlapping)
- The bulk adjustment factor in the flux bulk formula are optimized, as well as initial conditions, in the coupled 4DVAR system.

$$F_{\mathbf{v}} = -\rho \alpha_M C_M |\mathbf{v}| \mathbf{v}$$

$$F_{\theta} = \rho c_p \alpha_H C_H |\mathbf{v}| \left(\theta_g - \theta\right)$$

$$F_q = \rho \alpha_E C_E |\mathbf{v}| \left(q_g - q\right)$$

How to prevent divergence of the atmospheric adjoint model in the 9-month calculation



Outer Model: $\frac{\partial \mathbf{x}^{bg}}{\partial t} = M(\mathbf{x}^{bg})$ — Damping Term

Inner Model: $\frac{\partial (\mathbf{x}^{est})}{\partial t} = M(\mathbf{x}^{est}) - \boldsymbol{\Gamma}(\mathbf{x}^{est} - \mathbf{x}^{bg})$

Time evolution of the first variation:

$$\frac{\partial\{\delta(\mathbf{x}^{est} - \mathbf{x}^{bg})\}}{\partial t} = (\mathbf{M} - \boldsymbol{\Gamma})\,\delta(\mathbf{x}^{est} - \mathbf{x}^{bg})$$

If this operator has no growing modes, the adjoint model will not diverse through the long integration.

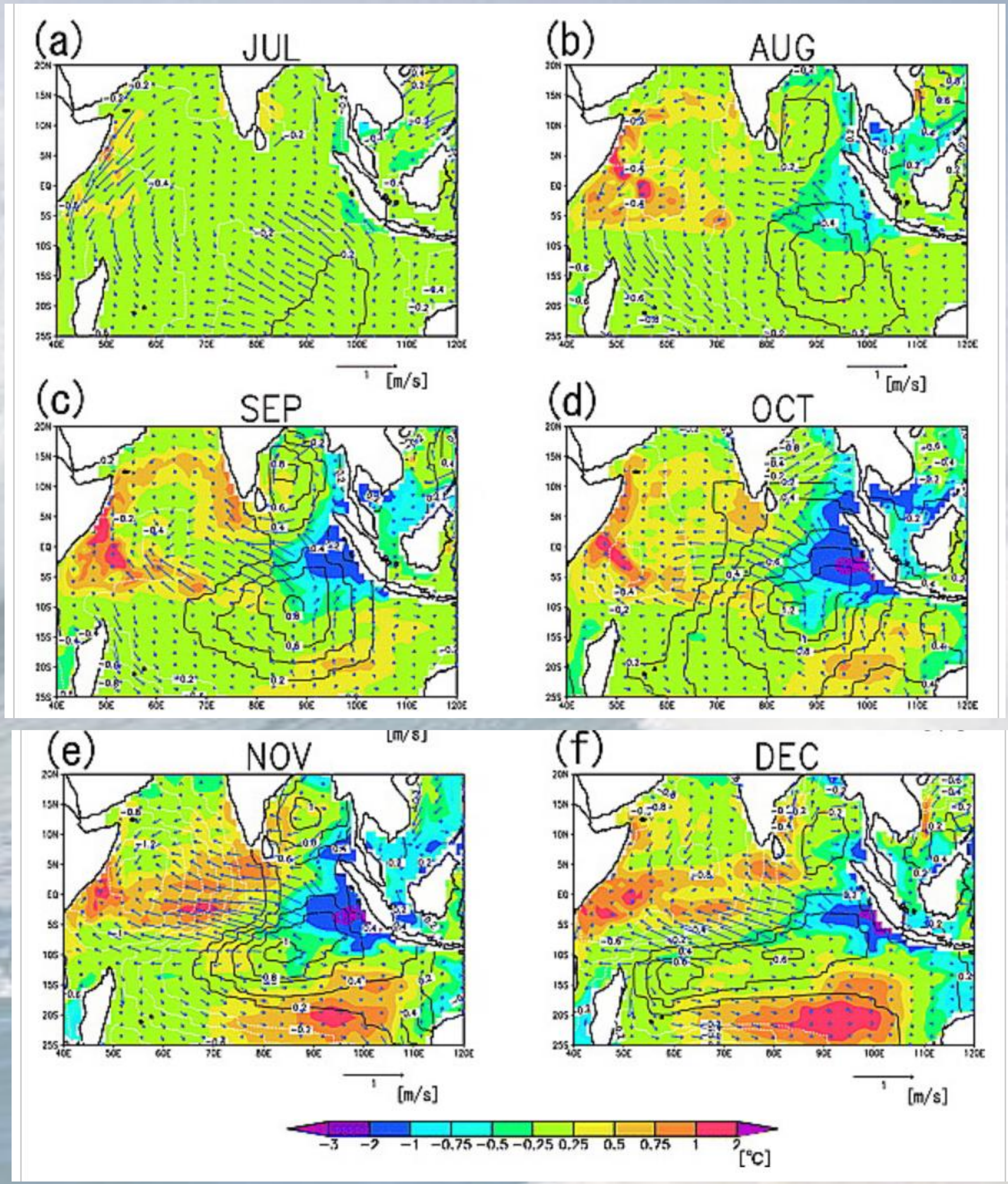
$\mathbf{x}^{bg}$: Background state time-evolved by the outer model
$\mathbf{x}^{est}$: 4DVAR estimation time-evolved by the inner model
$\mathbf{M}$: Tangent linear operator of the model M
$\boldsymbol{\Gamma}$: Damping Operator

The model state is modified only in the stable direction (slow manifold) by using the attractive (nudging) term to the background state in the inner model.
See Sugiura et al. 2013 (DOI: 10.1175/MWR-D-12-00231.1) for the theoretical Background.

- The University of Hamburg group recently uses similar approach in their coupled 4DVAR (e.g., Lyu et al., 2018, DOI:10.1002/2017MS001194)

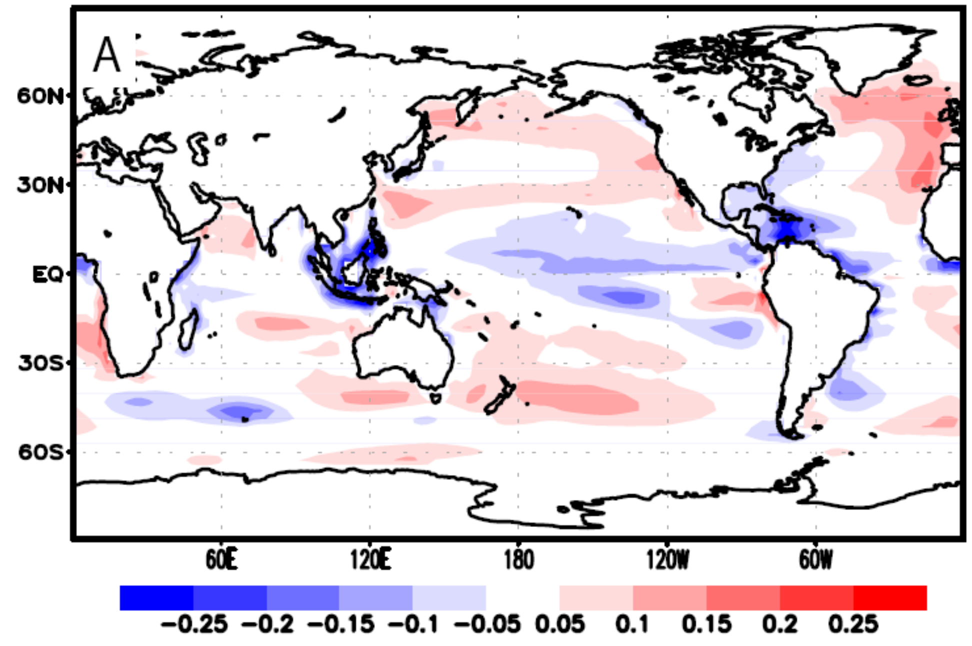
Impact of the flux bulk coefficient adjustment on the Indian Dipole Mode

- Difference of SST, Sea Level Pressure, and the wind stress between the coupled model prediction run from Jul 1997 with the optimized ocean initial condition and flux bulk coefficient parameters and the run with the initial condition alone.
- The run with the adjusted bulk coefficients well represents the development of the Indian Dipole Mode event, which is not developed in the run without the adjusted coefficients.
- The relation between westward wind stress and the decrease of SST in the eastern equatorial Indian ocean is properly represented in the run with the adjusted bulk coefficients.
- Thus, adjustment of the bulk coefficients effectively reproduce the coupled variation of the atmosphere and ocean fields in the coupled 4DVAR system.

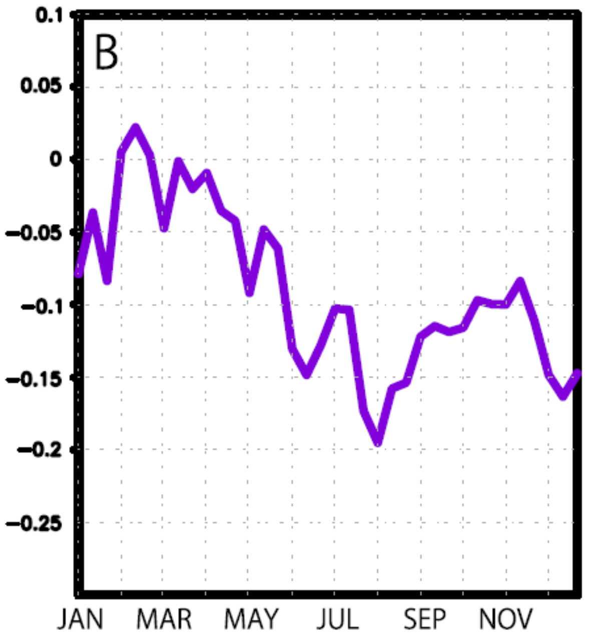


Bulk adjustment factor for momentum optimized by the Coupled 4DVAR system

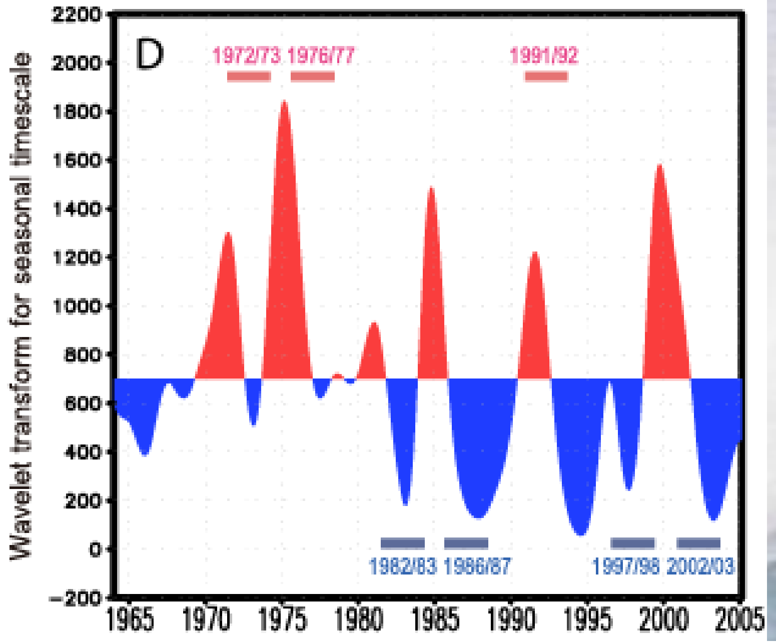
The bult factor averaged for 1970-2010 (log scale)



Climatological seasonal cycle of the bulk factor averaged in the NINO3 region (log scale)



Seasonal cycle amplitude of the mean perturbation wind power



From Masuda et al. (2015)

- The 4DVAR system tends to weaken the momentum coupling in the equatorial Pacific.
- Momentum coupling tends to be weakened in the second half of years.
- The modulation of the seasonal cycle is related to the interannual variation of the bulk adjustment factor.

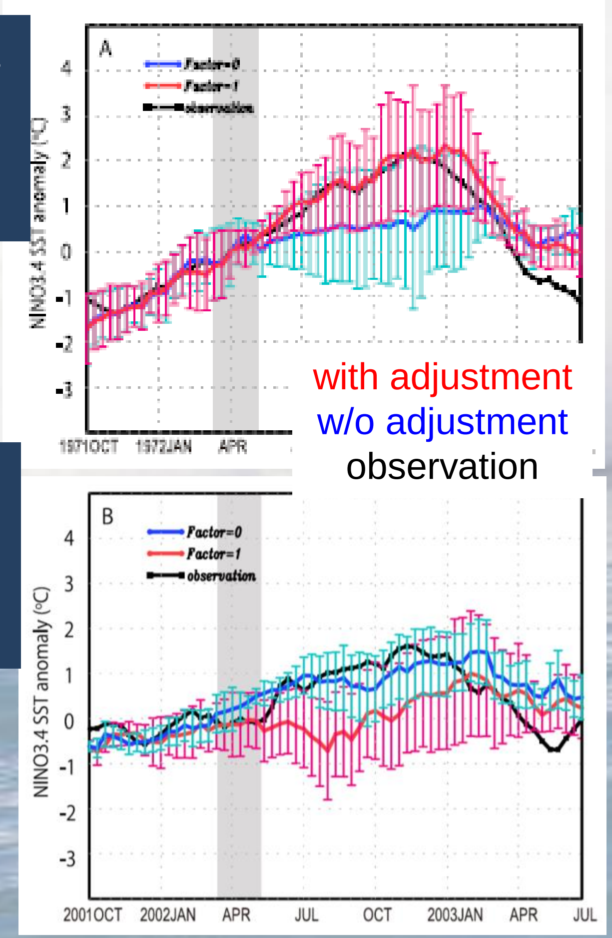
Impact of the bulk adjustment factor in the ENSO forecasts

The forecasts were better with (without) the bulk adjustment factor in the period of a large (small) seasonal cycle of the wind perturbation power.

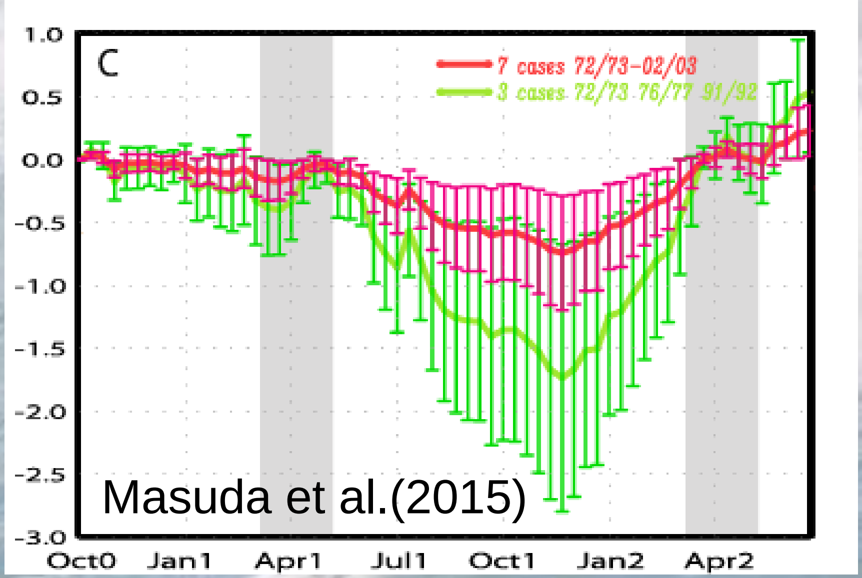
- ➢ Diagnose the strength of the seasonal cycle amplitude before forecasting.
- ➢ perform the forecasts with switching on (off) the seasonally varying bulk adjustment factor.

Case of a large seasonal amplitude

Case of a small seasonal amplitude



NINO3.4 SST Index Error Reduction from the forecast w/o the seasonal bulk adjustment

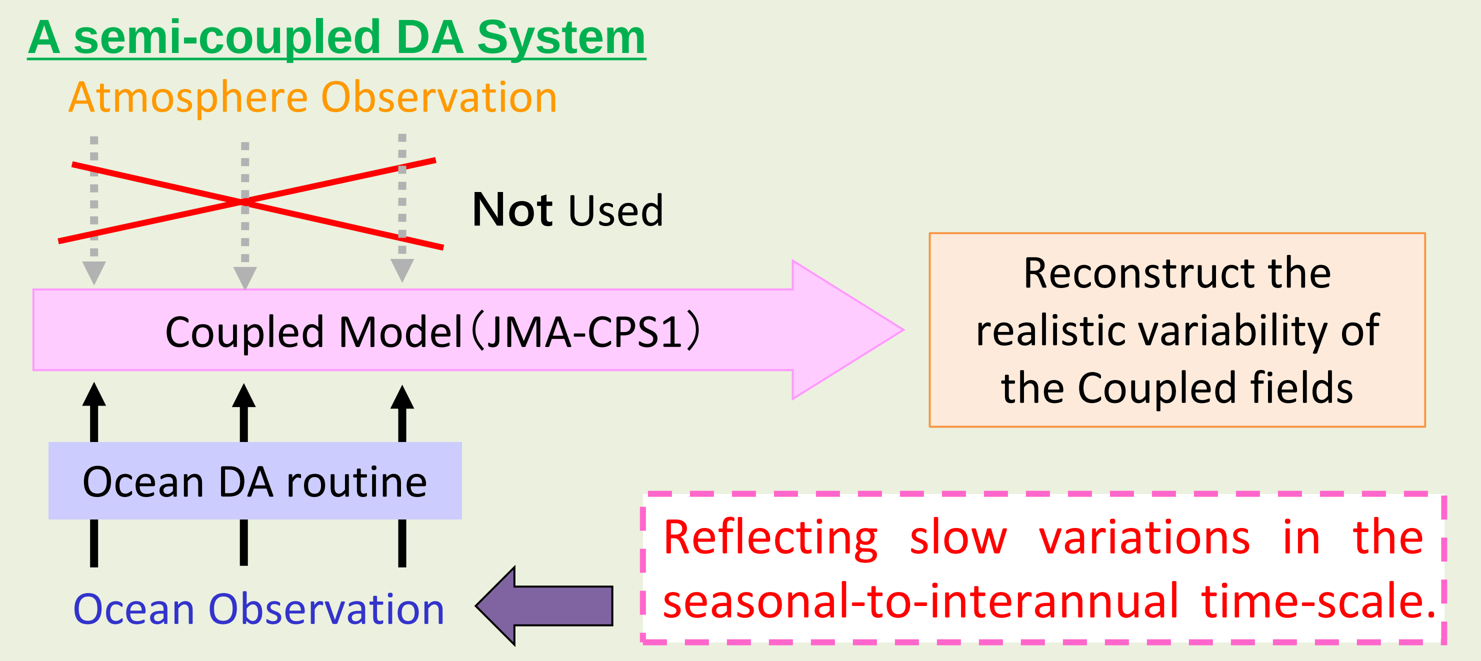


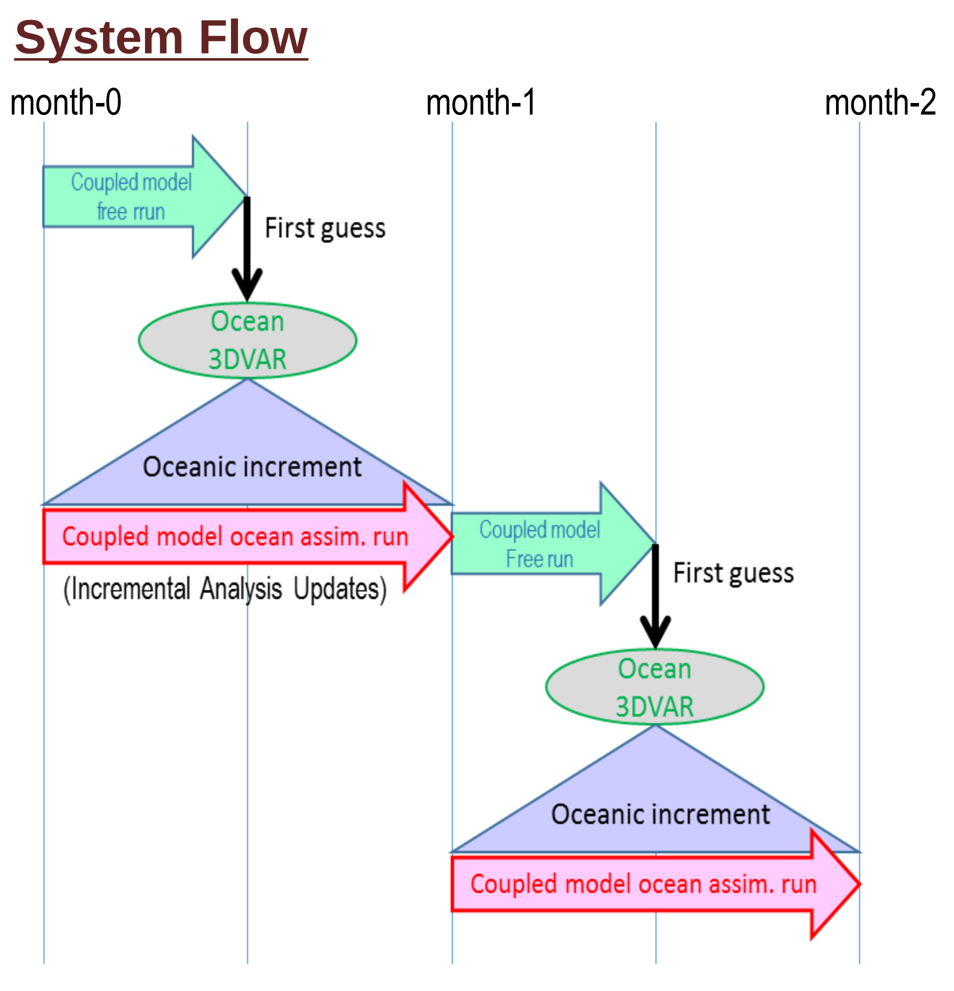
- ◆ The ENSO forecast error is reduced especially after the spring barrier.
- ◆ **Thus, the bulk adjustment factor estimated by the CDA system can be used for improving the ENSO Forecasts!!**

Results of Semi-Coupled Data Assimilation

Stimulated by the coupled 4DVAR development by the K7 consortium, JMA/MRI also began developing a semi-coupled DA system (i.e., weekly CDA without atmospheric data assimilation).

Development of a Semi-coupled DA System in JMA/MRI





- ➢ the coupled 4DVAR study indicated that slow variations of coupled atmosphere-ocean fields can be largely controlled by constraining only ocean component by DA.
- ➢ JMA/MRI developed a system in which data assimilation is applied only to the ocean component of the coupled model.

- ✓ Incremental Analysis Updates (IAU) with an analysis interval of 1 month.
- ✓ Short time-scale variabilities like the weather modes are not constrained in the system.

Precipitation Improvement of Semi-coupled DA over the AMIP Run

We compared the semi-coupled DA result with an AMIP run (i.e., **uncoupled atmospheric model** simulation forced by observation-based daily SST mapping.)

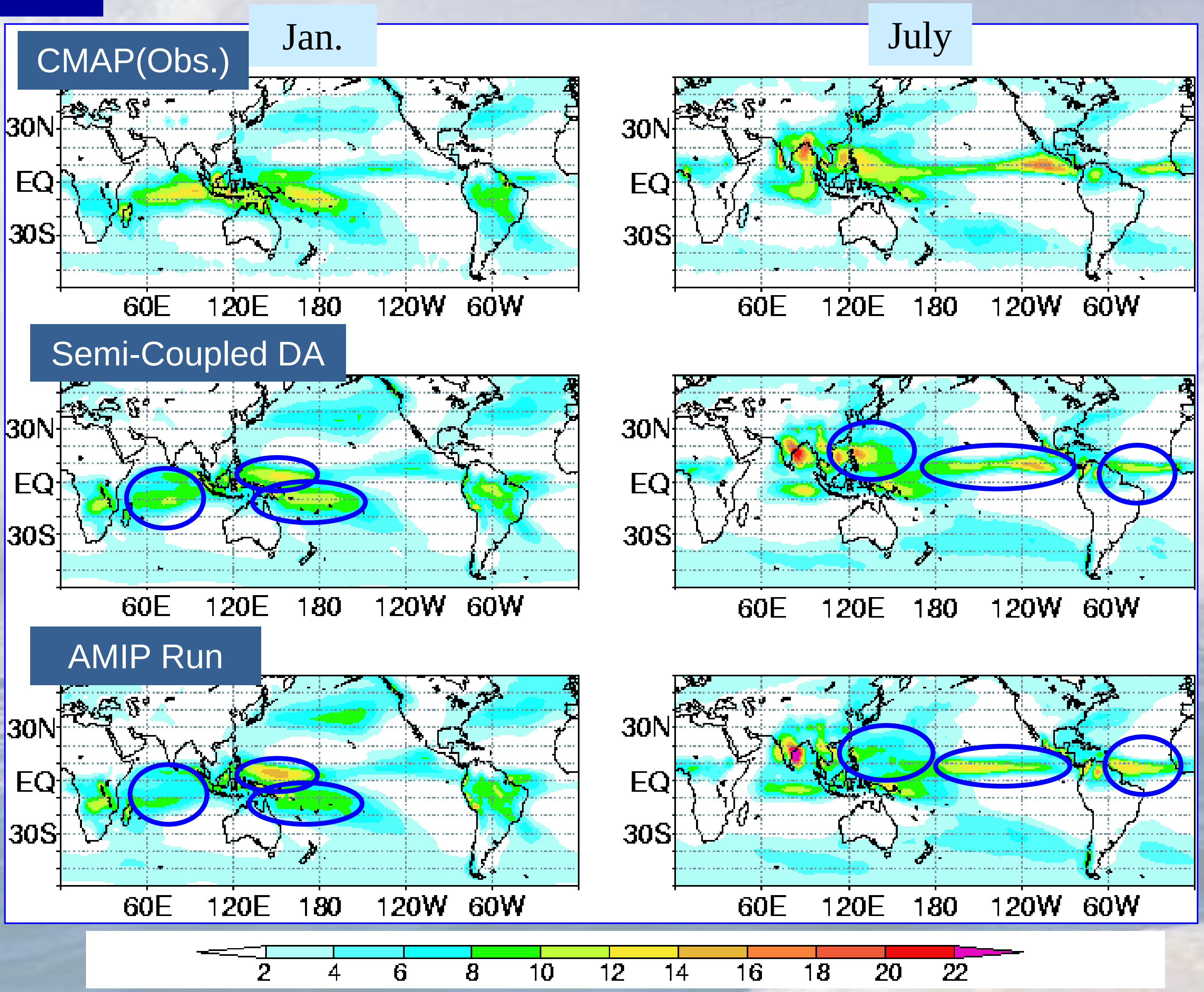
In the AMIP run, the atmosphere was forced by the **observed SST itself**.

In contrast, the SST field in the semi-coupled DA system had some **deviations from the observed SST.**

Therefore, it was natural that the atmospheric field in the AMIP run **is better than** that in the semi-coupled DA system.

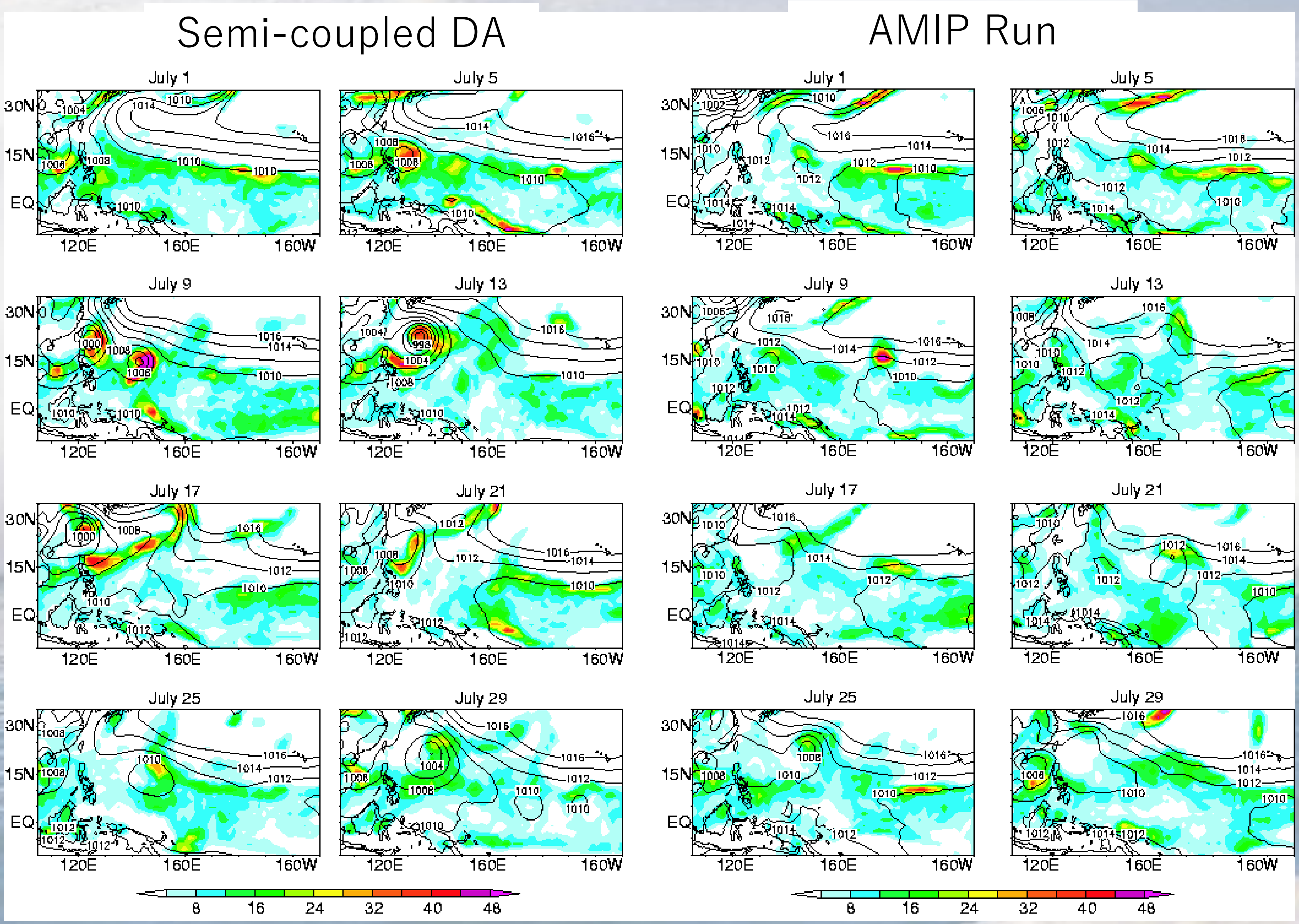
However, the monthly climatological precipitation field had **clear improvements in the semi-coupled DA.**

Monthly Climatological Precipitation



Difference of TC development between semi-coupled DA and AMIP Run

Daily SLP and Precipitation Fields (July, 1997)



In this month, the precipitation in the Philippine sea is largely underestimated in the AMIP run.

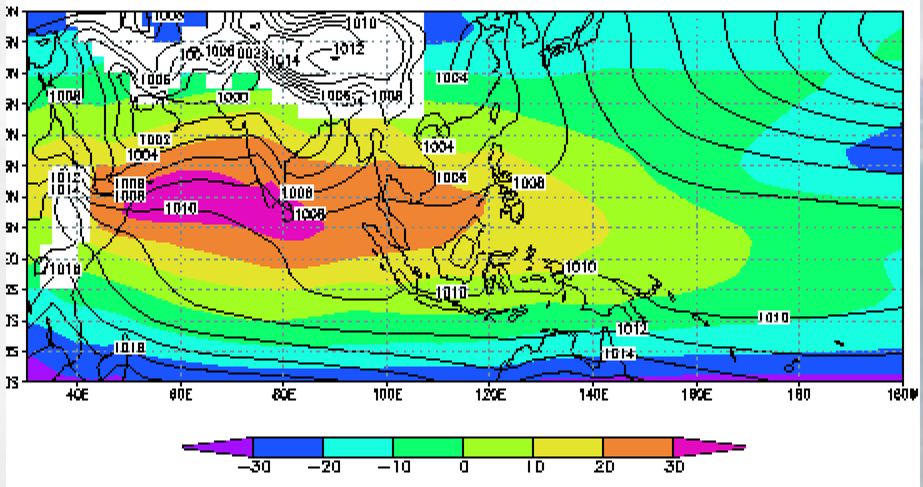
Although some tropical cyclones (TCs) are developed in the semi-coupled DA, there is no TC in the AMIP Run.

Intensification of the Walker Circulation between semi-coupled DA

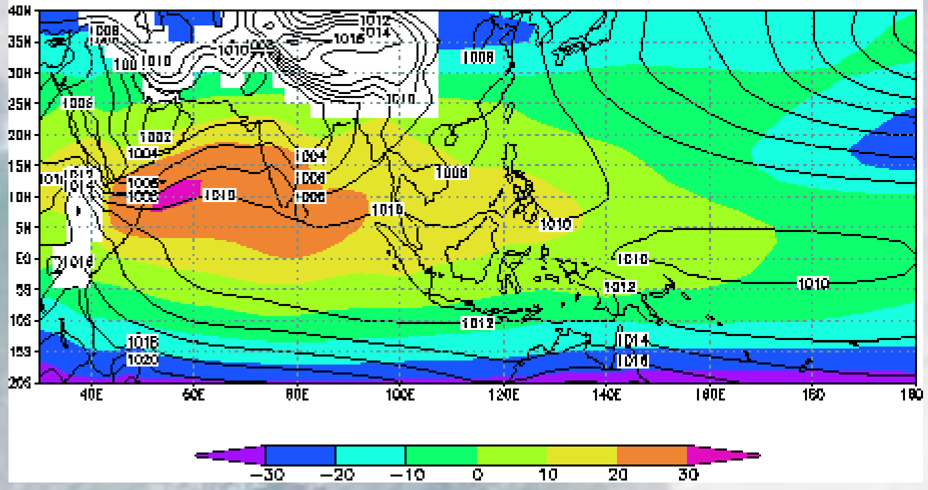
Climatological SLP, vertical sheer of zonal winds (Jun.-Aug. Clim.)

Vertical sheer of zonal winds : U(850hPa)-U(200hPa)

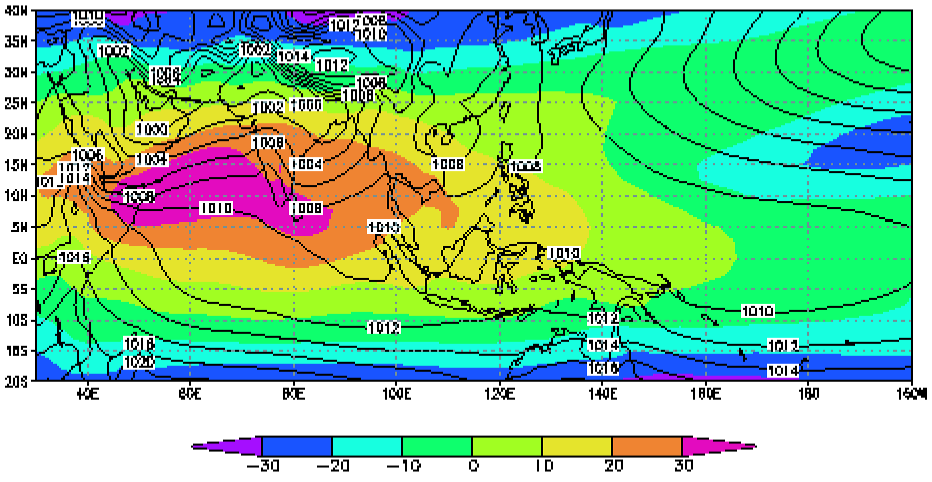
Semi-coupled DA



AMIP Run

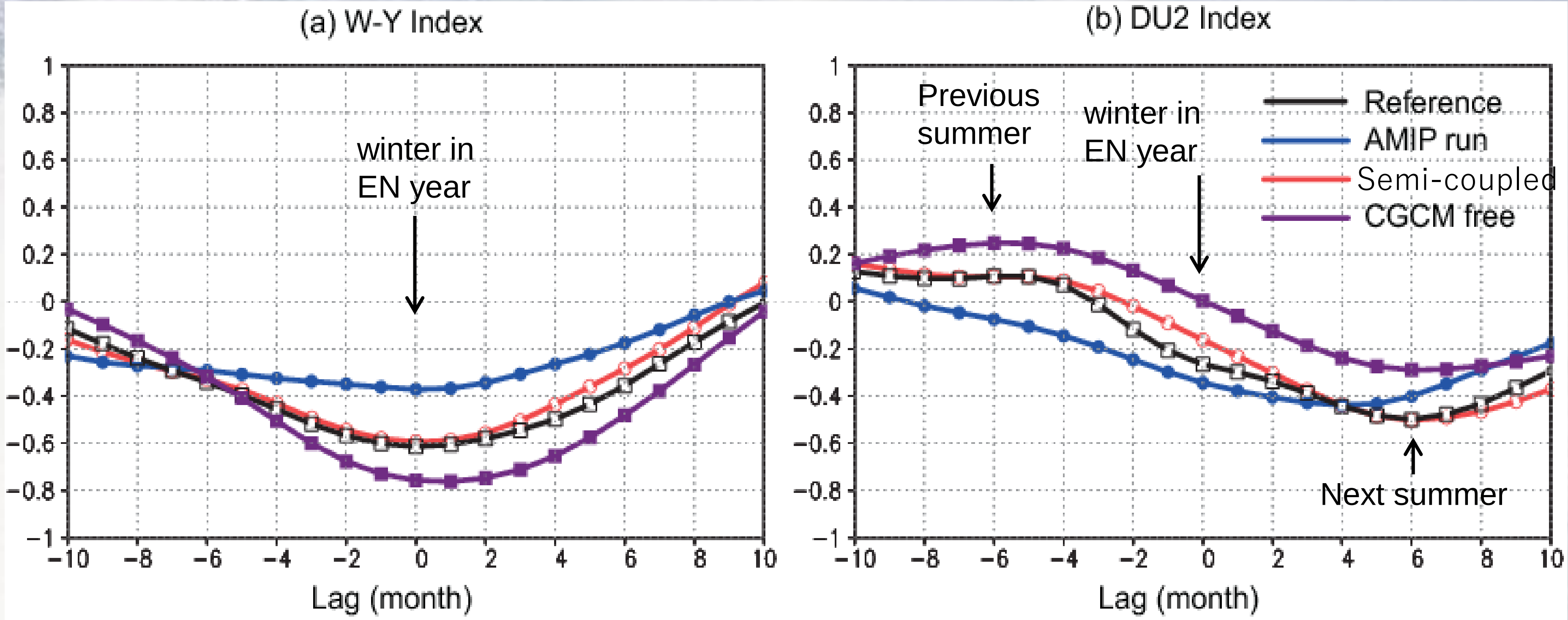


JRA-25 (Obs.)

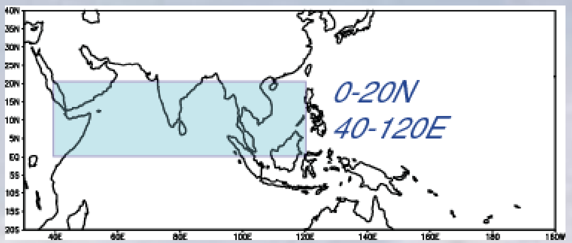


- The semi-couped DA properly represent the monsoon trough, but the trough is weak in the AMIP run.
- The zonal Walker circulation is underestimated in the AMIP Run, but it is improved in the semi-coupled DA.

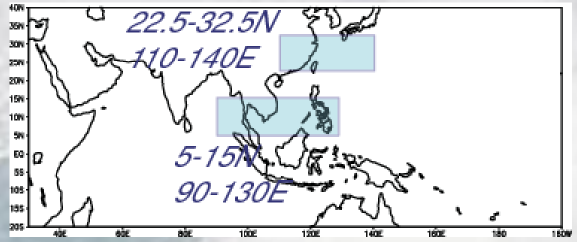
Lagged Correlation between NINO3 and W-Y/DU2 indices



W–Y Index (U, 850hPa–200hPa)



DU2 Index (U 850hP, diff of 2 boxes)



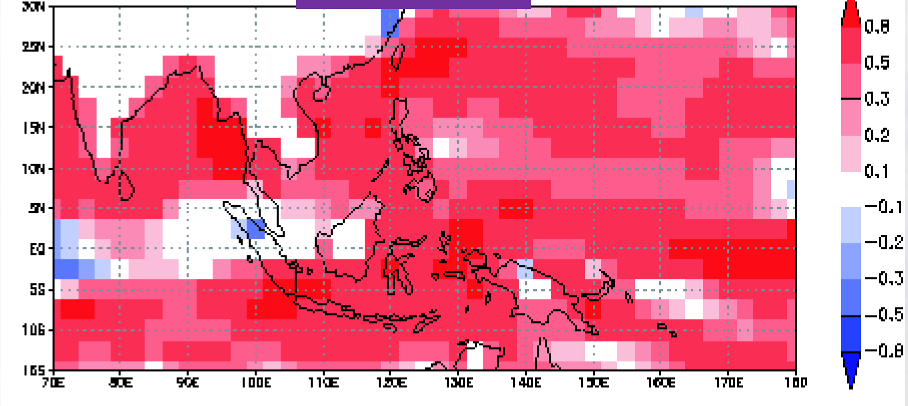
Plots of the correlation coefficients of (a) W-Y index (for the variation of the Walker circulation), (b) DU2 index (for the variation of the monsoon trough), with the NINO3 index against the lag (month) of the W-Y or DU2 indices for JRA-25 (black), AMIP run (Blue), Semi-coupled DA (Red), and CGCM Free run (purple).

- ✓ The walker circulation is weakened at the winter peak of the El Nino, which is underestimated in the AMIP run, but well reproduced in the semi-coupled DA.
- ✓ The monsoon trough is almost neutral in the previous summer, and gradually weakened until the next summer. The minimum of the correlation is attained earlier in the AMIP run, but the strength of correlation and timing is well reproduced in the semi-coupled DA.

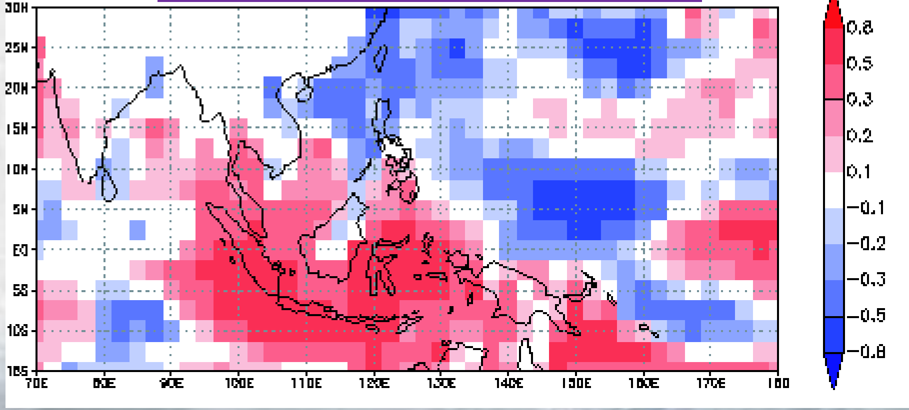
Improvement of the index for the Walker Circulation

Correlation between SST and PRC in Jun.-Aug.

AMIP Run



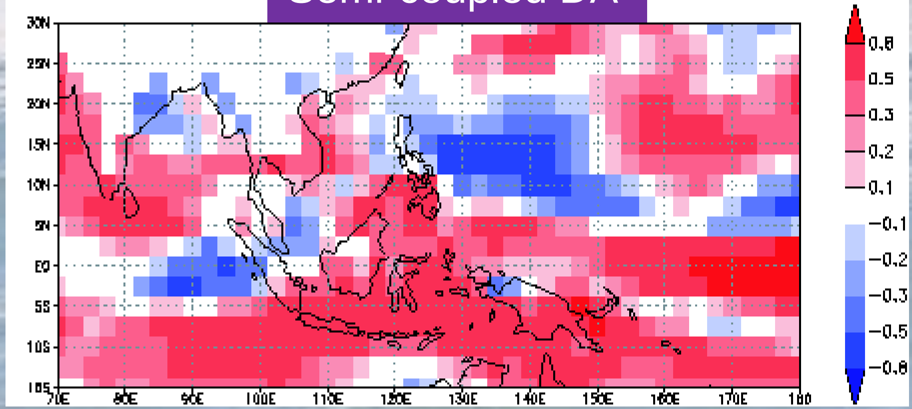
CMAP-COBESST （Obs.)



AMIP Run: PRC is strongly coupled with SST.

Real World (CMAP-COBESST): The coupling is not so strong because the negative feedback decouples them.

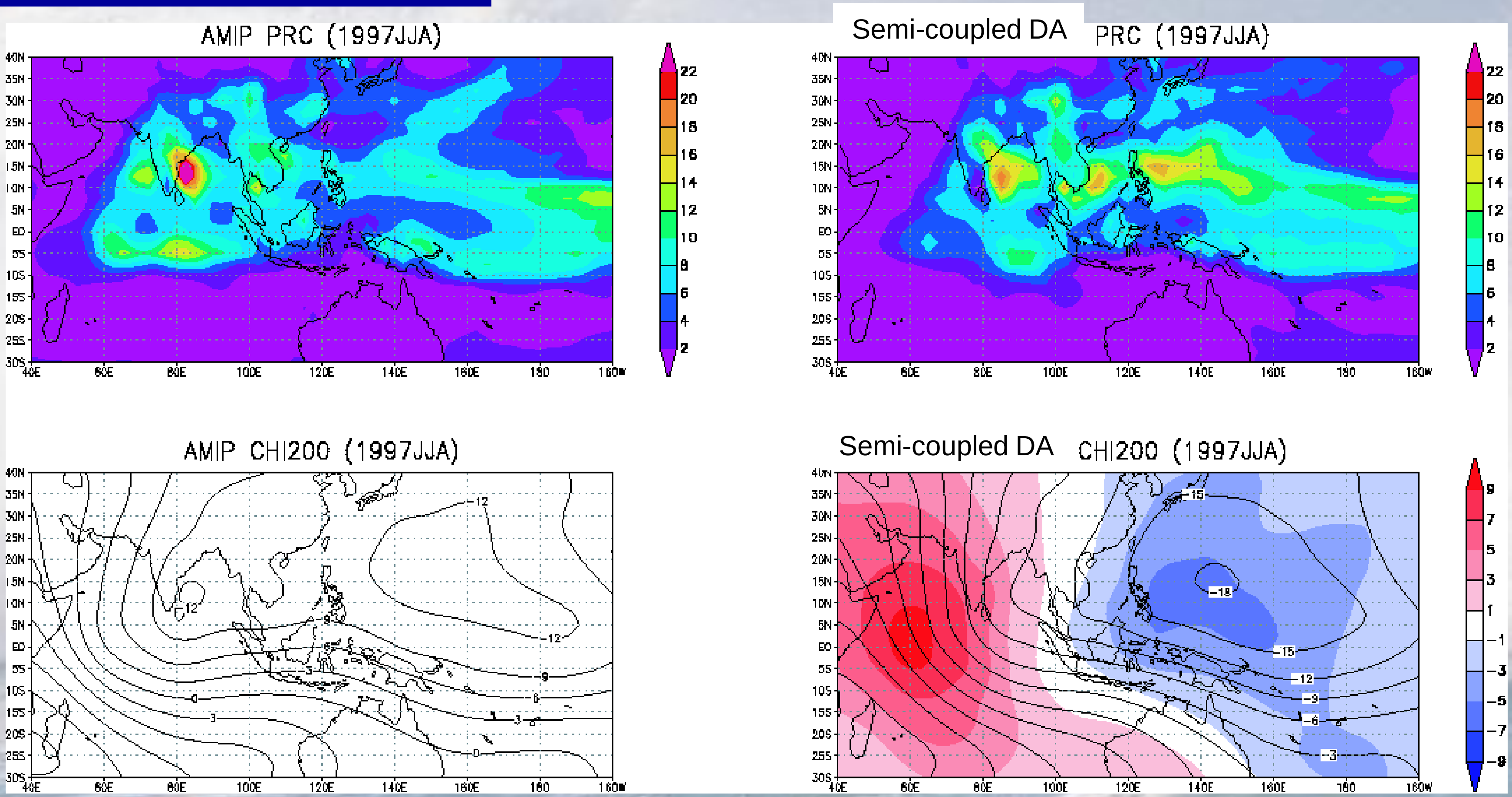
Semi-coupled DA



Semi-coupled DA: The feature above is better estimated in semi-coupled DA because the negative feedback is reproduced. The low correlation in the western tropical Pacific and Bay of Bengal are represented.

Why the monsoon trough is enhanced in the semi-coupled DA?

PRC and Velocity Potential at 200hPa (Jun-Aug, 97)



Color: Difference (Semi-CDA – AMIP)

In the AMIP run, the peak of the divergence at the east of the India suppresses the convection in the western tropical Pacific

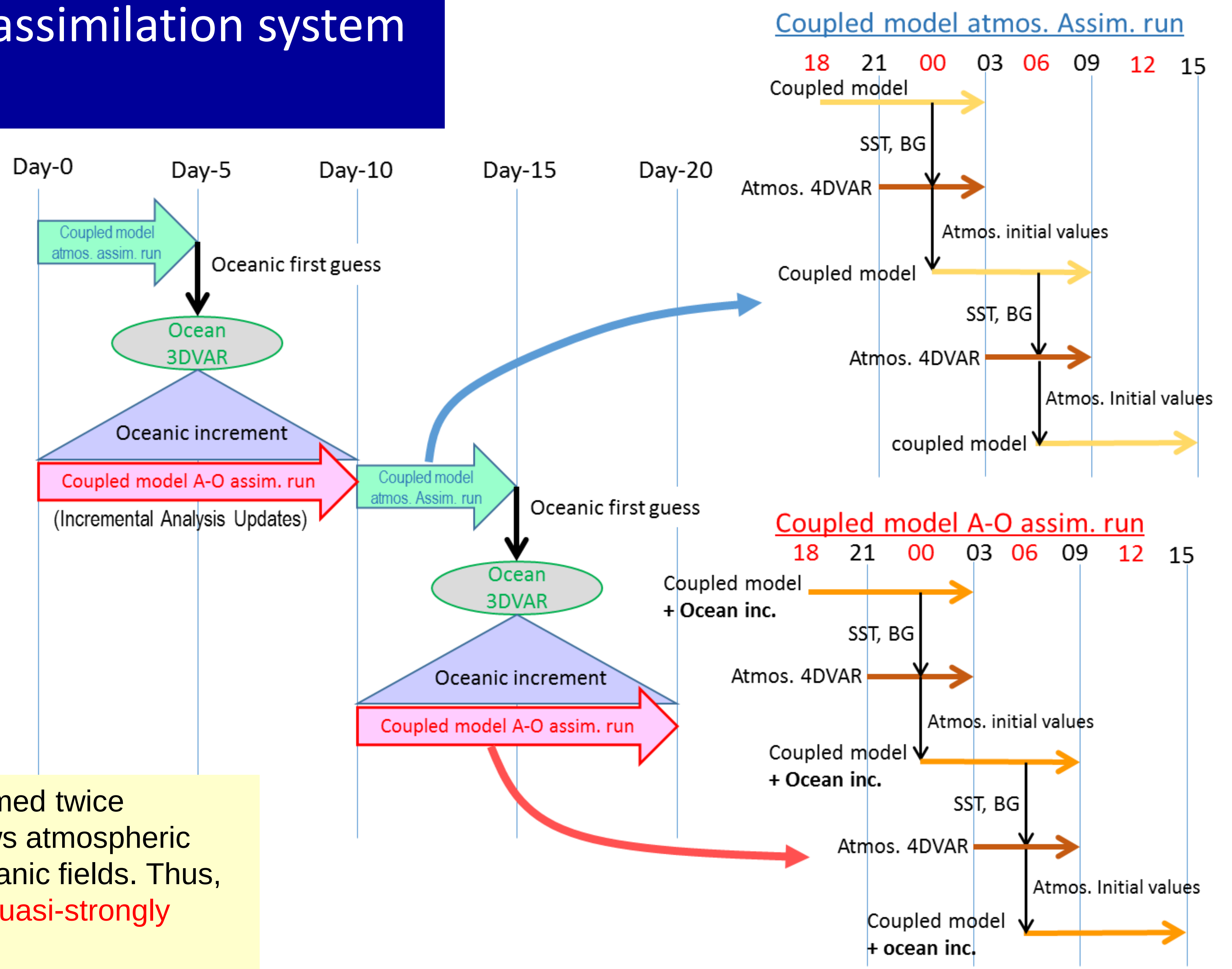
The zonal contrast is intensified in the semi-coupled DA. Thus, the zonal Walker circulation is intensified, and the atmospheric circulation is improved.

Development of a full coupled Data Assimilation Using existing atmospheric and ocean DA components

After confirming the significant potential of the semi-coupled assimilation system, the Meteorological Research Institute began developing a full coupled data assimilation system.

JMA/MRI coupled data assimilation system version 1 (MRI-CDA1)

- ◆ Based on the JMA's operational atmosphere and ocean DA systems (NAPEX and MOVE-G2) and the operational coupled model (JMA/MRI-CGCM2) at the time.
- ◆ The system uses different intervals for data assimilation cycles of the atmosphere (6 hours) and ocean (10 days.)
- ➢ Ocean 3DVAR results are inserted into the coupled model by IAU with 10-day interval. But the model integrations in the IAU scheme are substituted by alternate integrations of the coupled model and atmospheric 4DVAR.



- ◆ The atmospheric 4DVARs are performed twice between Day-0 and Day-5. This allows atmospheric fields to adjust to the assimilated oceanic fields. Thus, this system can be considered as a quasi-strongly coupled DA system.

Reanalysis Experiment

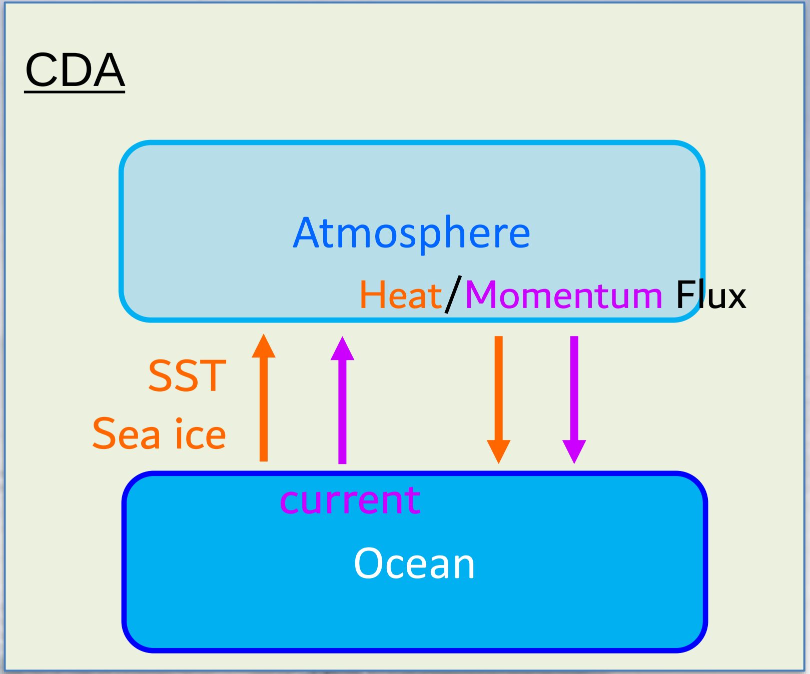
- Reanalysis experiments are performed for the period from 28 October 2013 to 31 December 2015.
  - CDA: Regular reanalysis run of the coupled data assimilation system, MRI-CDA1
  - UCPL: All delivery of oceanic data (SST, sea ice, surface current) to the atmospheric model is stopped. Observation-based gridded SST is used for the ocean surface condition of the atmospheric component.

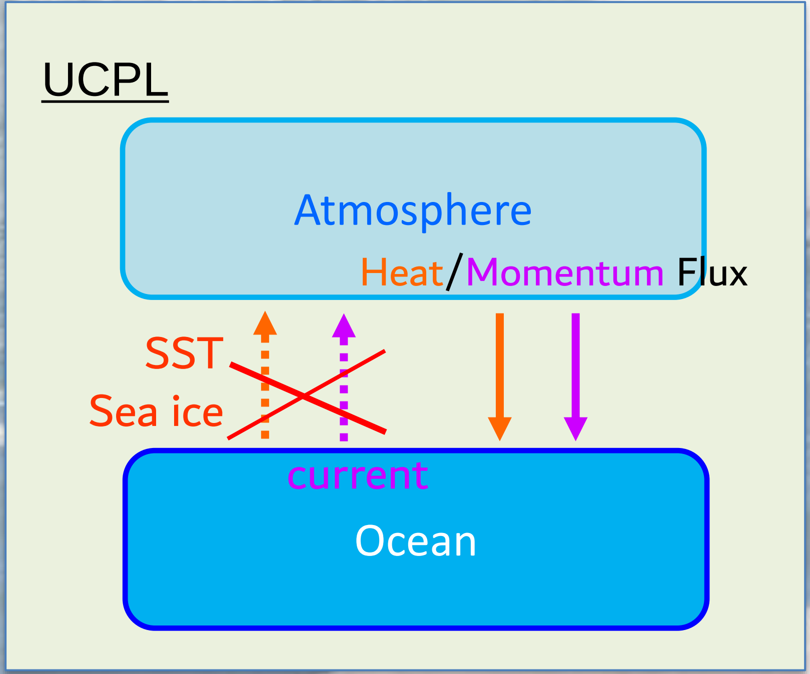
- Reference data

✓ JRA-55: JMA's Atmospheric Reanalysis Data by 4DVAR. The atmospheric model is different from those in MRI-CDA1.

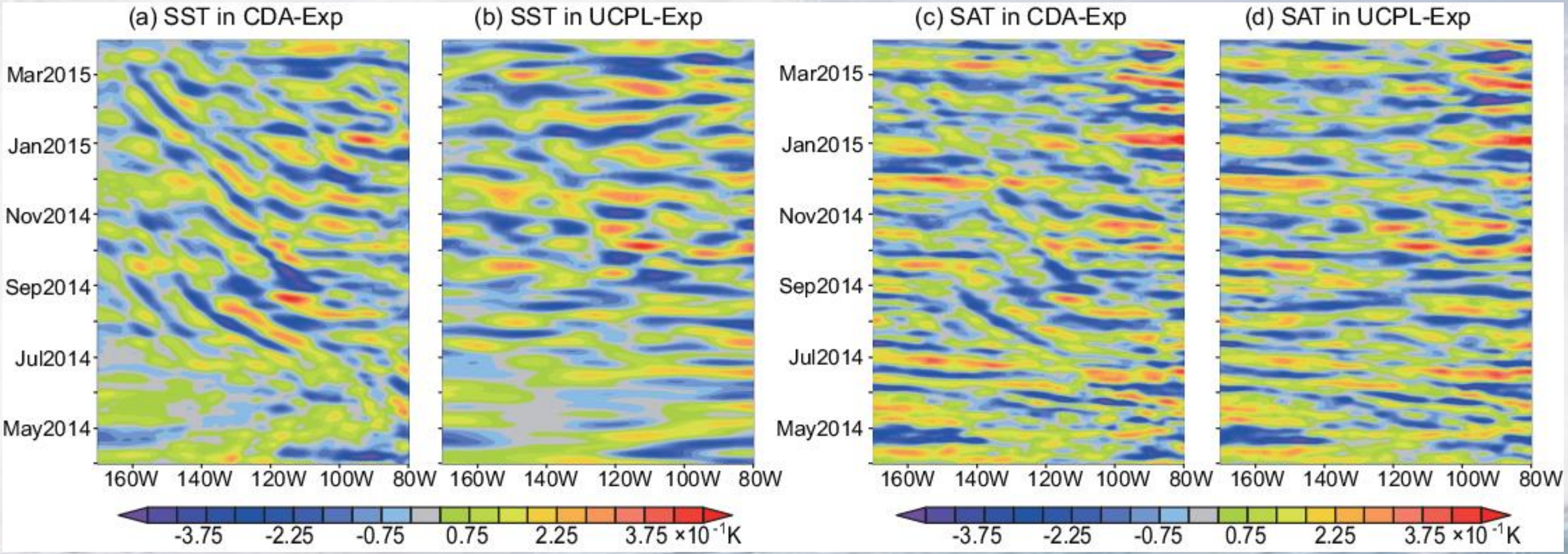
✓ GPCP (Objective Daily Precipitation Map)

✓ COBE-SST (Objective SST Map for climate analyses in JMA)



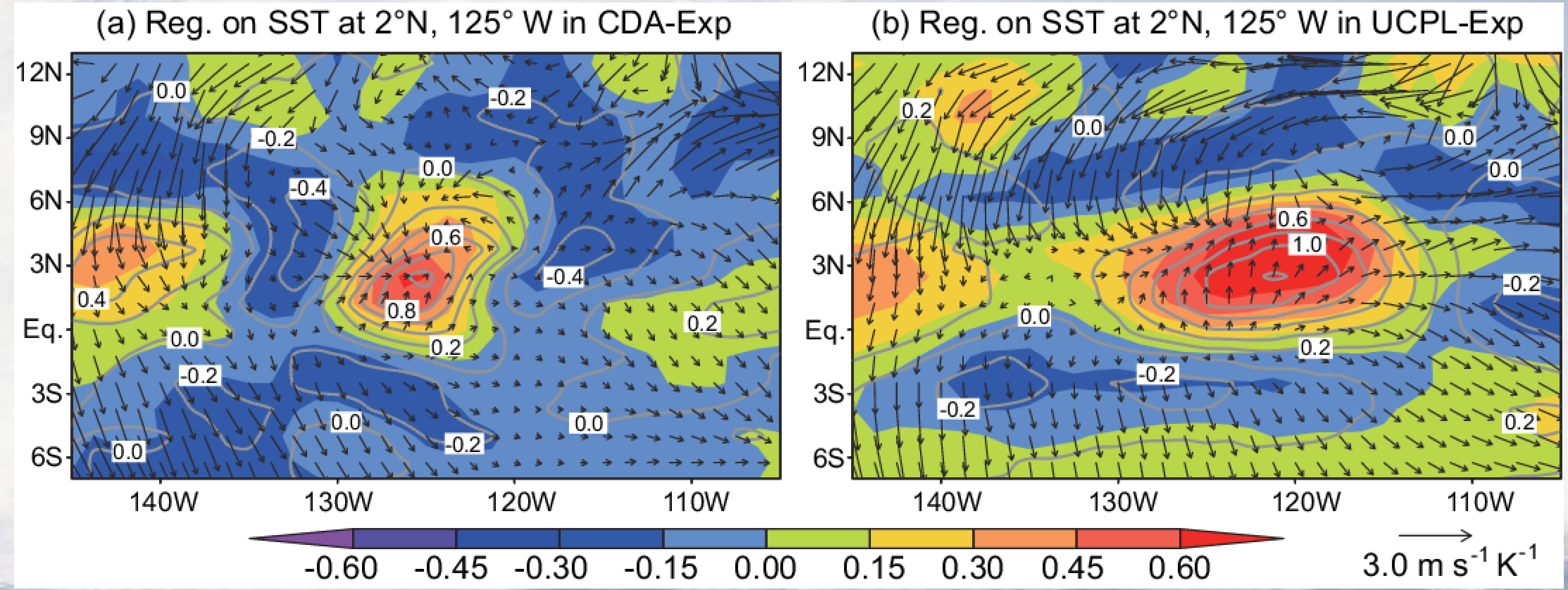


Hovmöller diagram of SST and SAT between 1-6N



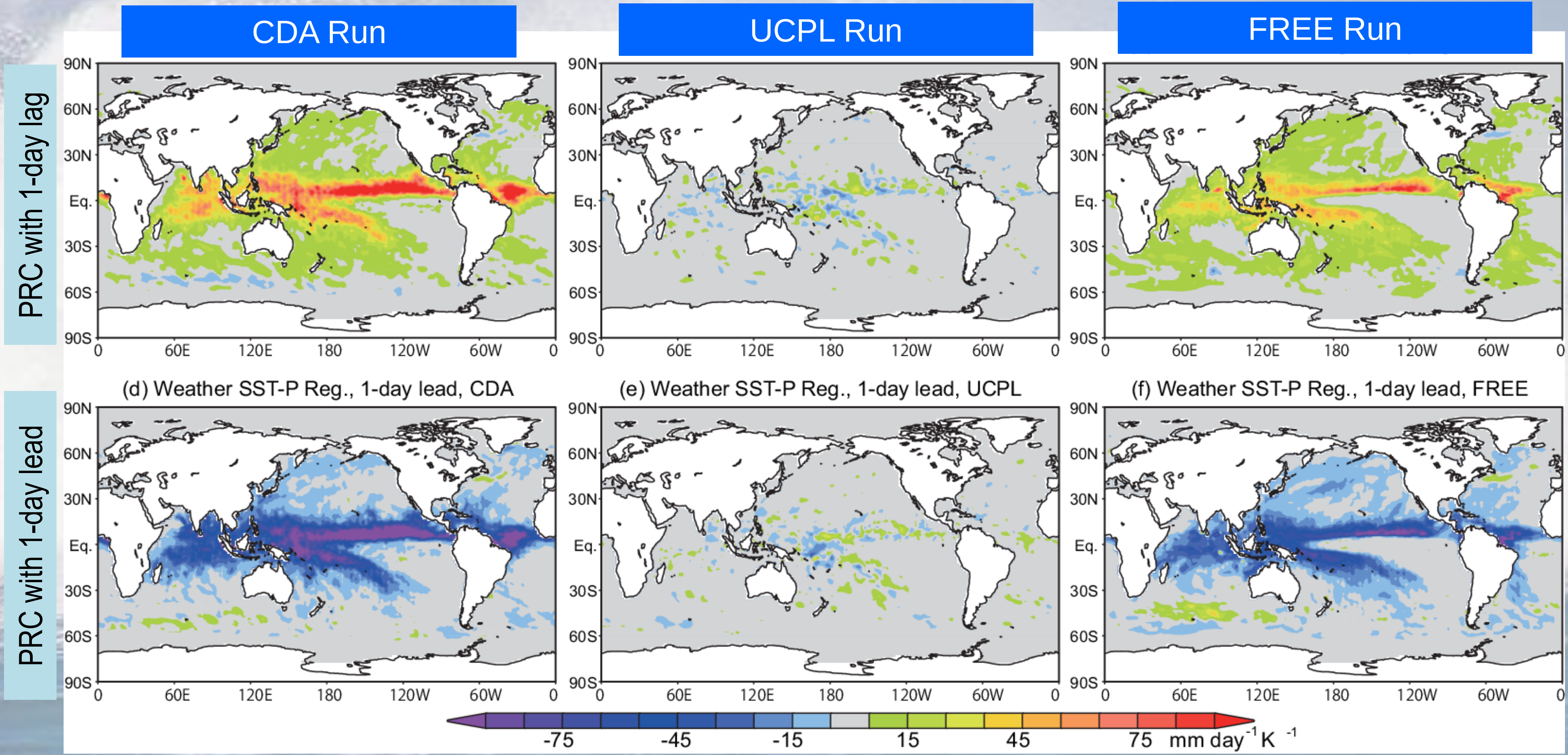
- ✓ Figure (a) shows SST variations associated with TIWs in CDA, and Figure (c) shows the adjustment of SAT to the SST variation
- ✓ SST variations associated with TIWs are not clearly represented in the prescribed SST in UCPL. Thus, the propagation of SAT variations is hardly seen in UCPL.

Regression of SST, SAT, and surface winds on SST at 2N and 125W



- ✓ The regression maps of SST and SAT properly reflect the zonal scale of TIWs in CDA. Winds blowing into the peak of SST are also reproduced.
- ✓ In contrast, the positive regression area of SST and SAT is extended zonally in UCPL, which means that SST and SAT variations related to TIWs are not properly reproduced. And northerly winds are dominated at the north of 3N.

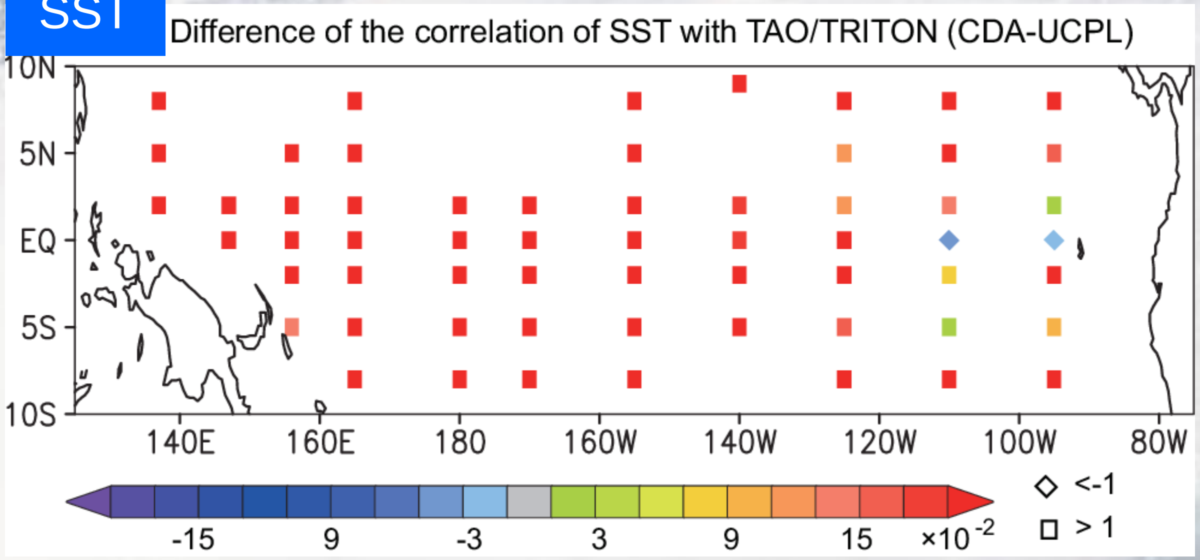
Maps of PRC Lagged Regression on SST (Time scale: 1-10 days)



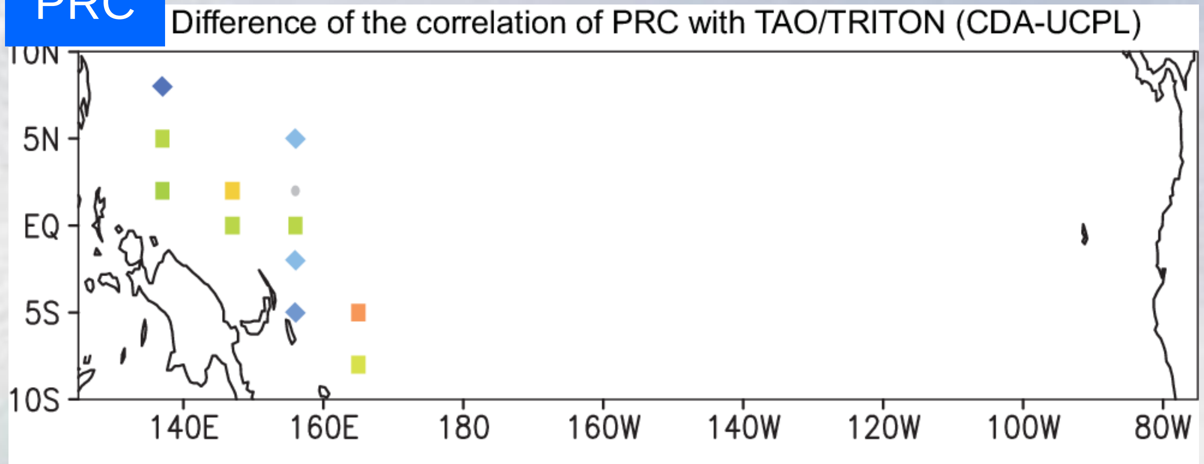
- ✓ Regressions in CDA and Free indicate that the feedback between SST and precipitation adequately works.
- ✓ UCPL shows no significant relationship between SST and PRC.

ACC of SST, PRC, SAT with TAO/TRITON on 1-10 days time scale

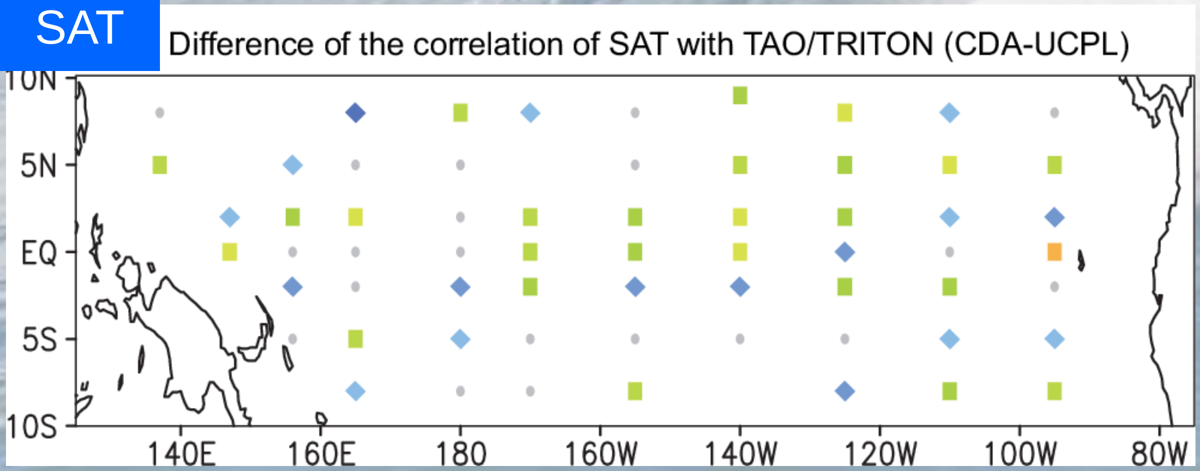
SST



PRC



SAT

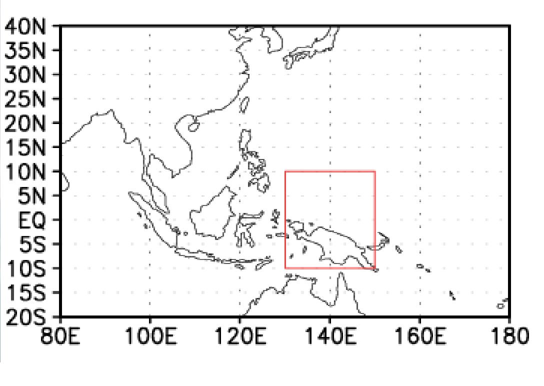


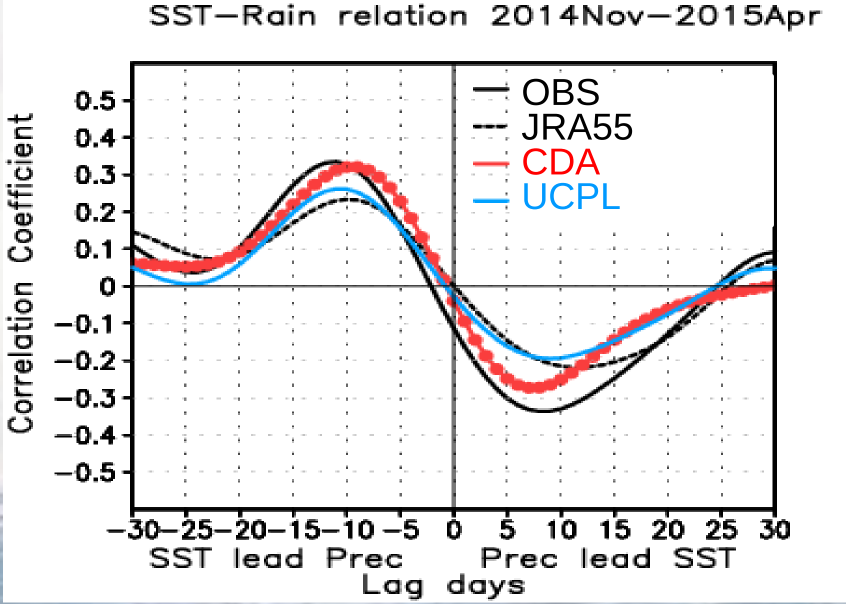
- ✓ Coupled data assimilation (CDA) well improves SST variation on the daily time scale over the prescribed SST in UCPL.
- ✓ As the result, PRC and SAT variations are also improved in many positions.
- ✓ Thus, coupled DA has some potential to improve near-surface representations.

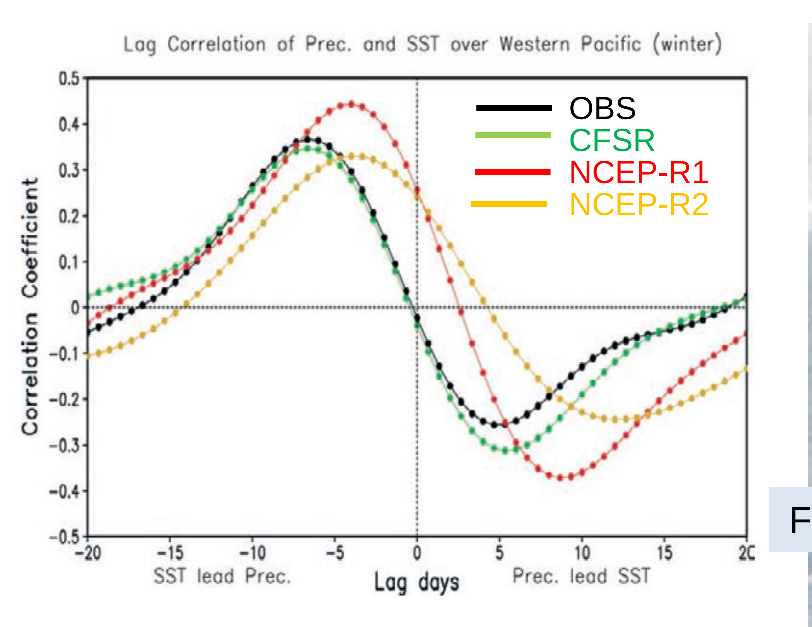
Comparison of the Lagged correlation between SST and precipitation

Kobayashi et al., 2021, Clim. Dyn

- ✓ Time series of SST and precipitation averaged in 10ºS-10ºN, 130-150ºE are used.
- ✓ The time series are bandpass-filtered for 20 to 100 days





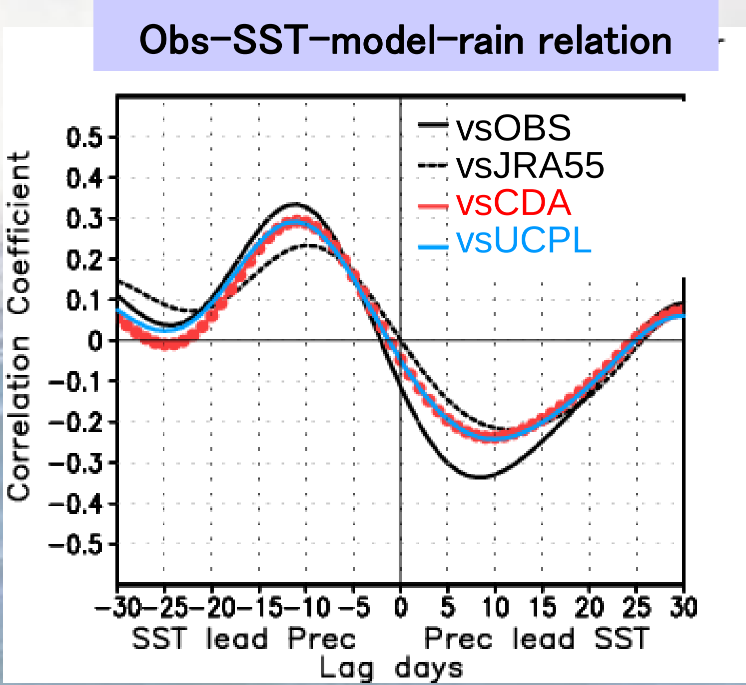


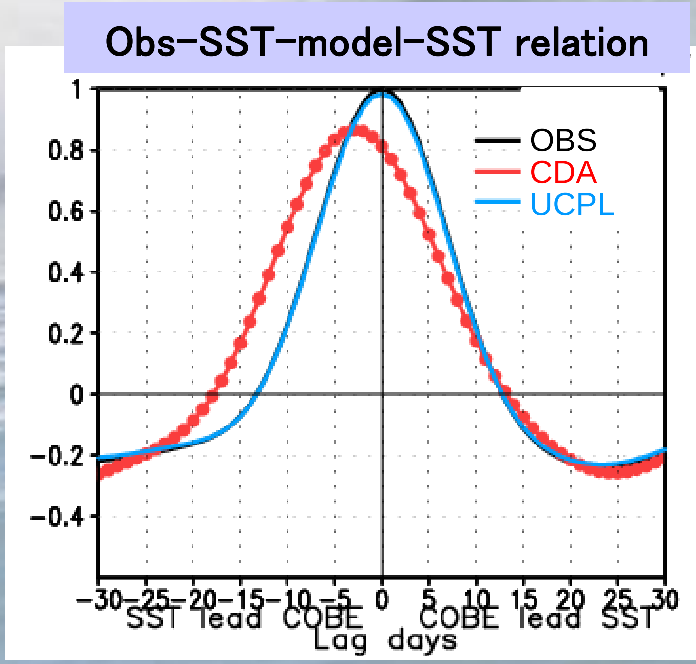
From Saha et al. (2010)

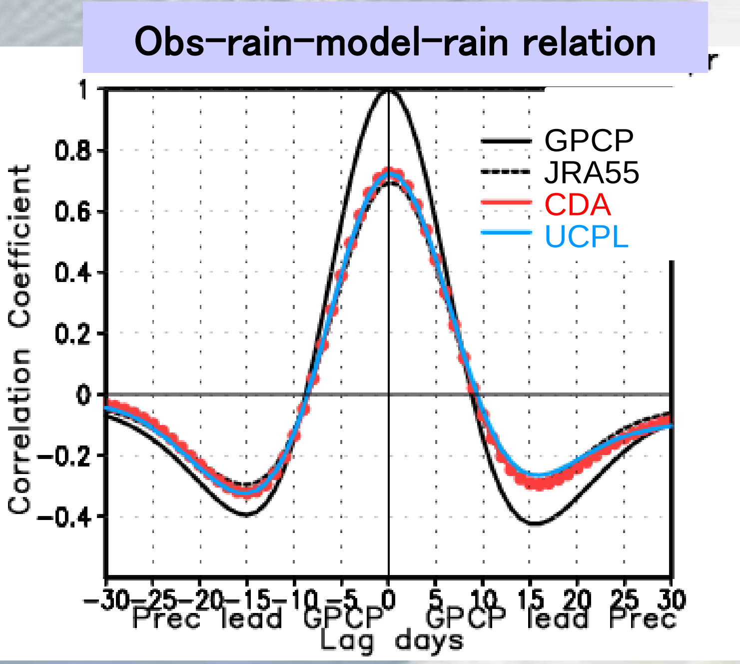
- ✓ CDA reproduces lagged correlation between SST and precipitation (precipitation lags about 10 days behind SST) better than UCPL and JRA-55.
- ✓ A similar result based on NCEP reanalyses is also reported by Saha et al. (2010).

How the lagged correlation is reproduced?

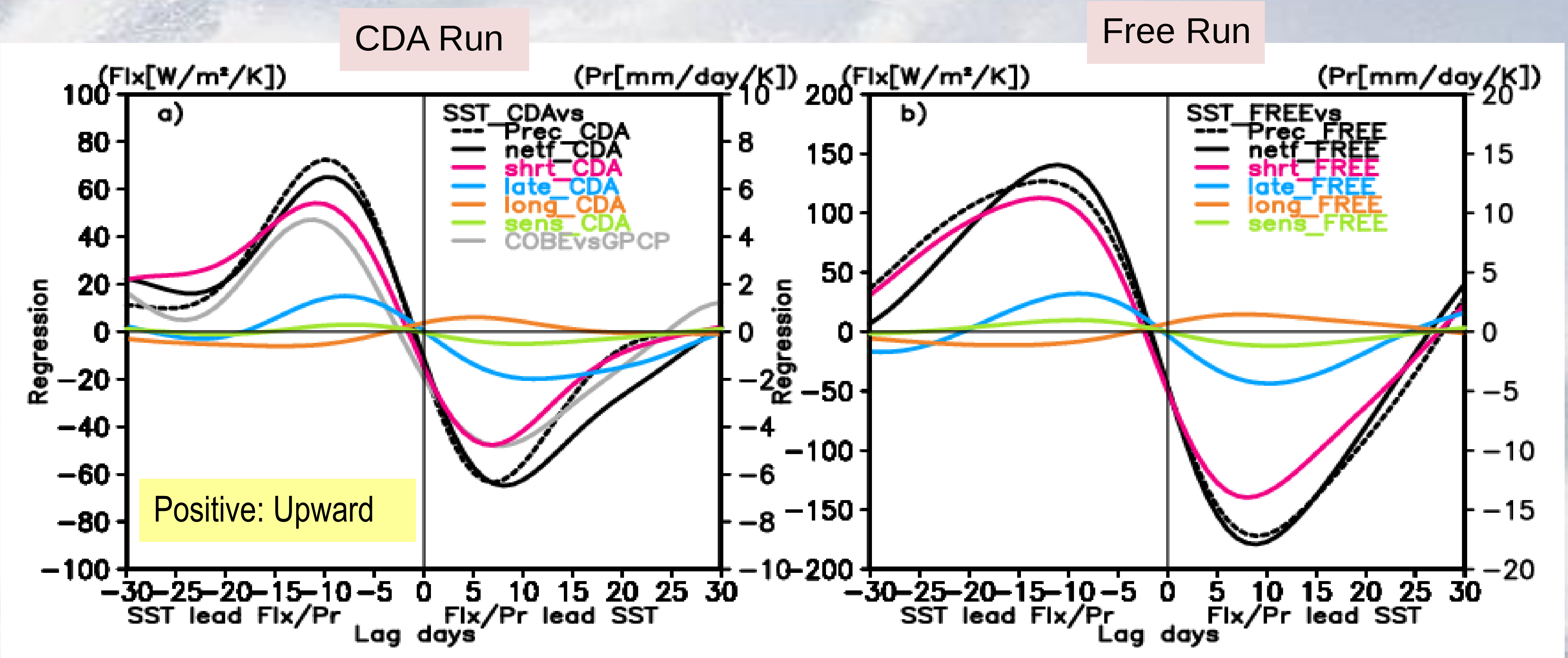
- ✓ However, time series of precipitation in CDA is almost in phase with UCPL and JRA-55.
- ✓ Therefore, if we examine correlation of PRC in CDA and UCPL with independent SST, the difference between CDA and UCPL disappears.
- ✓ The same result based on NCEP reanalyses was reported by Kumar et al. (2013).
- ✓ Because the constraint of the atmospheric fields by data assimilation is too strong, the precipitation field cannot be adjusted to the SST field.
- ✓ The SST field is adjusted to the atmospheric fields instead.







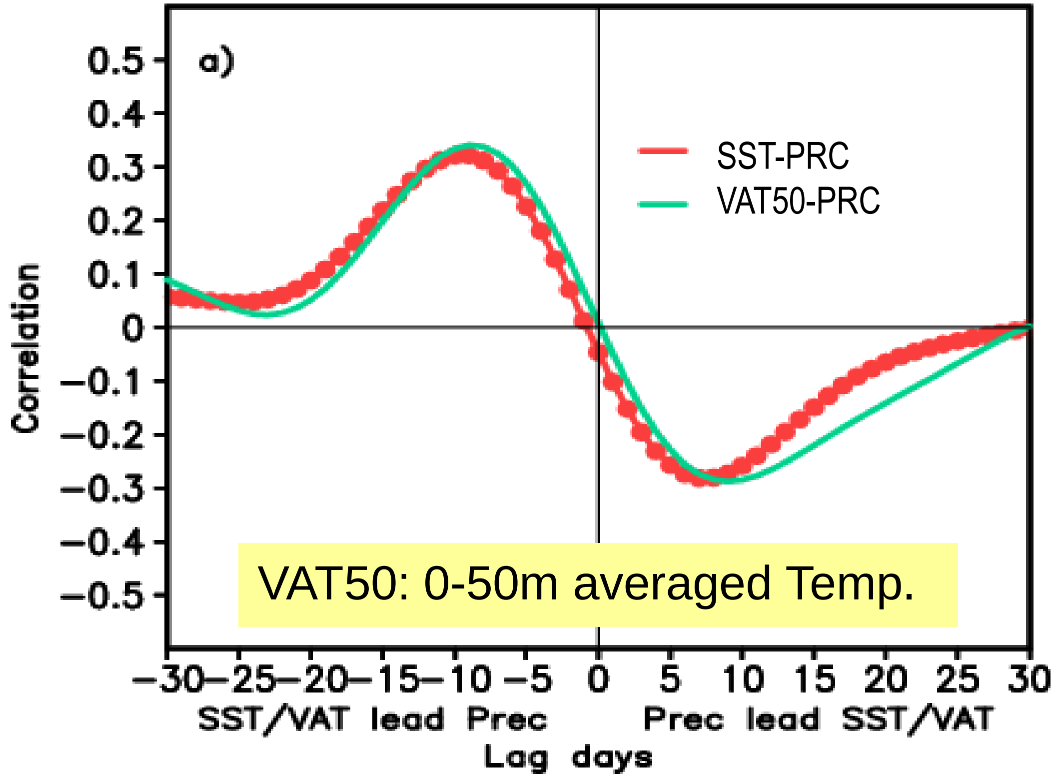
Lagged correlations between SST and heat flux components



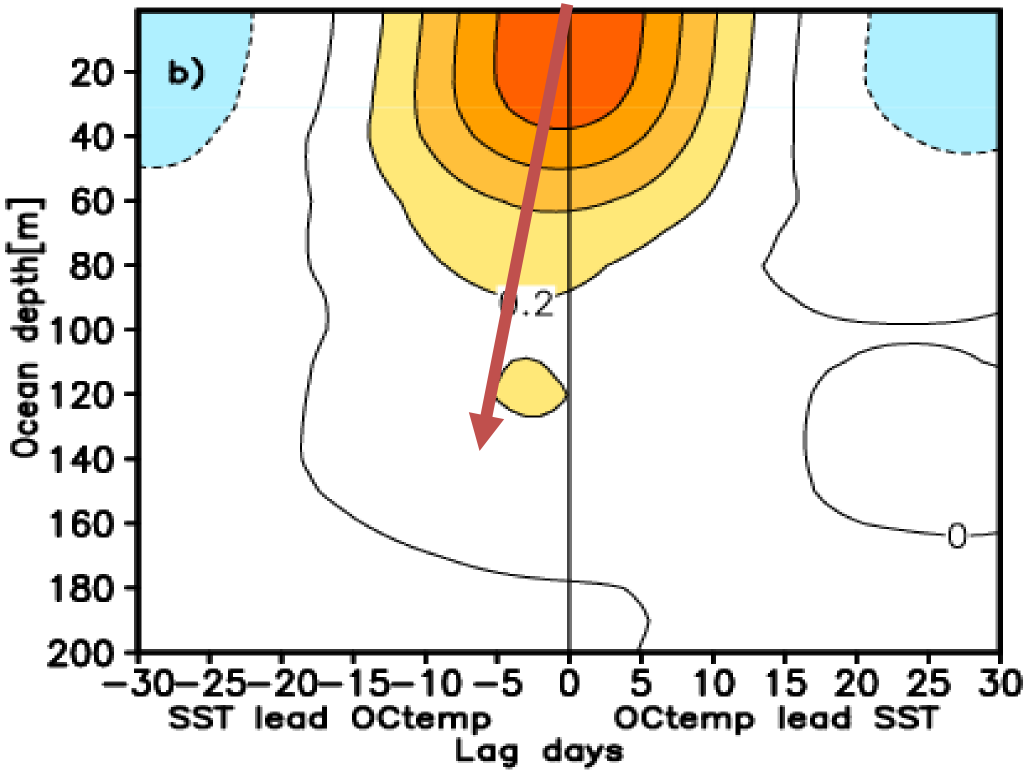
- ✓ The short wave flux is dominant in the heat budget at the surface. Latent heat flux plays a marginal role.
- ✓ PRC variation is in phase with the short wave flux and consequently with the net heat flux variation. Thus, SST-PRC lagged correlation reflects the correlation between SST and the net heat flux.
- ✓ But, the no lag correlation between SST and precipitation is negative, and the timing of changing the sign of precipitation anomaly from negative to positive delays from the peak of SST.

Ocean vertical mixing Effect on the SST Variation (10ºS-10ºN, 130-150ºE)

Lagged correlation
SST-PRC vs VAT50-PRC



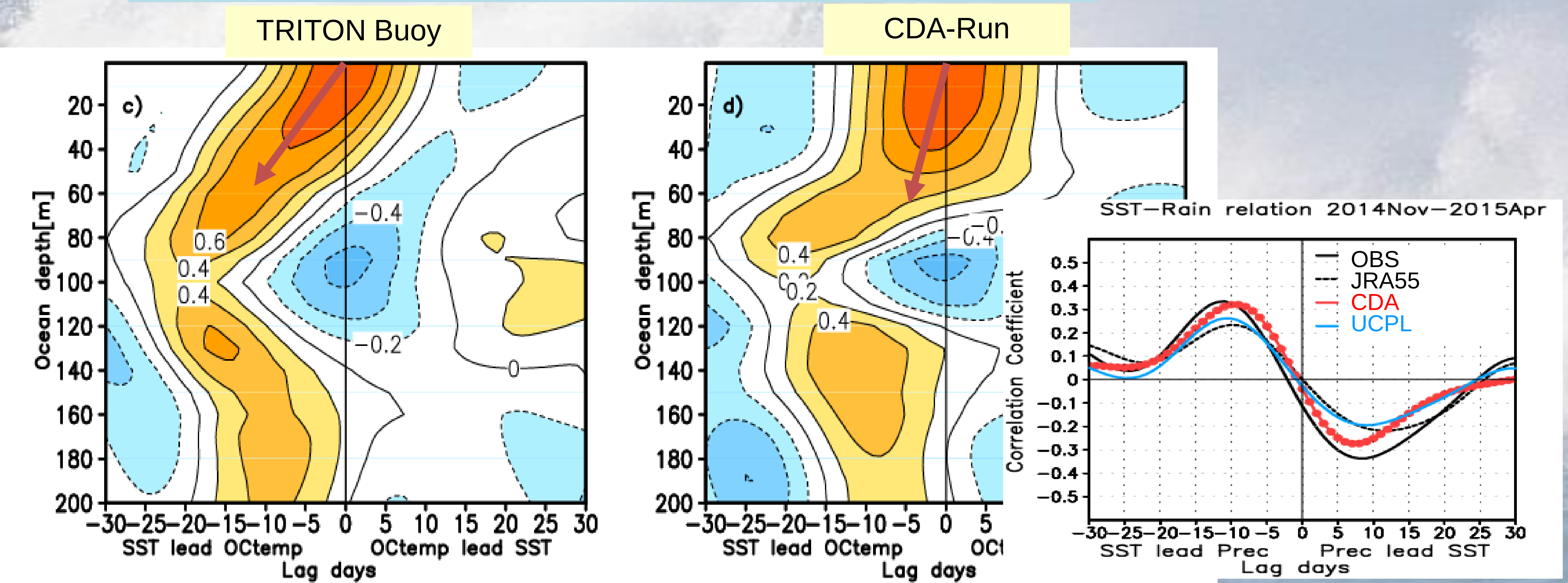
Lagged Correlation between SST and ocean interior temperature (CDA)



- ✓ Lags of ocean interior temperature behind SST indicates downward heat transfer in the mixed layer.
- ✓ This downward heat transfer significantly affects the SST variation.
- ✓ Variation of VAT50 goes across zero at no lag like this, because heat transfer across 50 m depth is not significant, and the heat budget for upper 50 meter layer is closed.

Comparison of downward heat transfer at eq.-147ºE between CDA and Obs.

Lagged Correlation between SST and ocean interior temperature



- ✓ The downward heat transfer in the mixed layer in CDA is faster than that observed by the buoys.
- ✓ This discrepancy causes smaller deviation of the timing that the net heat flux changes the sign from the peaks of temperature in CDA compared to observation data.

Recent study on the coupled atmosphere-SST DA

Coupled Atm-SST DA: formulation

E.g., Akella et al. (2017), Frrolov et al. (2020), Massart et al (2021)

$$\delta \mathbf{x} = \begin{pmatrix} \delta \mathbf{x}_a \\ \delta \mathbf{x}_s \end{pmatrix} = \mathbf{B}\mathbf{H}^T\mathbf{D}^{-1}\mathbf{d}$$

Add SST to the analysis variables in the atmospheric DA

$$\mathbf{D} = \mathbf{H}\mathbf{B}\mathbf{H}^T + \mathbf{R}$$

$$= \begin{pmatrix} \mathbf{B}_{a,a} & \mathbf{B}_{a,s} \\ \mathbf{B}_{s,a} & \mathbf{B}_{s,s} \end{pmatrix} \begin{pmatrix} \mathbf{H}_{pa,a} & \mathbf{H}_{pa,s} \\ \mathbf{H}_{ps,a} & \mathbf{H}_{ps,s} \end{pmatrix}^T \begin{pmatrix} \mathbf{D}_{pa,pa} & \mathbf{D}_{pa,ps} \\ \mathbf{D}_{ps,pa} & \mathbf{D}_{ps,ps} \end{pmatrix}^{-1} \begin{pmatrix} \mathbf{d}_{pa} \\ \mathbf{d}_{ps} \end{pmatrix}$$

Extended Background Covariance Matrix

Extended Tangent Linear Model+Obs Operator

Capable to assimilate obs with SST sensitivity

$$\begin{pmatrix} \mathbf{H}_{pa,a} & \mathbf{H}_{pa,s} \\ \mathbf{H}_{ps,a} & \mathbf{H}_{ps,s} \end{pmatrix} = \begin{pmatrix} \mathbf{h}_{pa,a} & \mathbf{h}_{pa,s} \\ \mathbf{h}_{ps,a} & \mathbf{h}_{ps,s} \end{pmatrix} \begin{pmatrix} \mathbf{M}_{a,a} & \mathbf{M}_{a,s} \\ \mathbf{M}_{s,a} & \mathbf{M}_{s,s} \end{pmatrix}$$

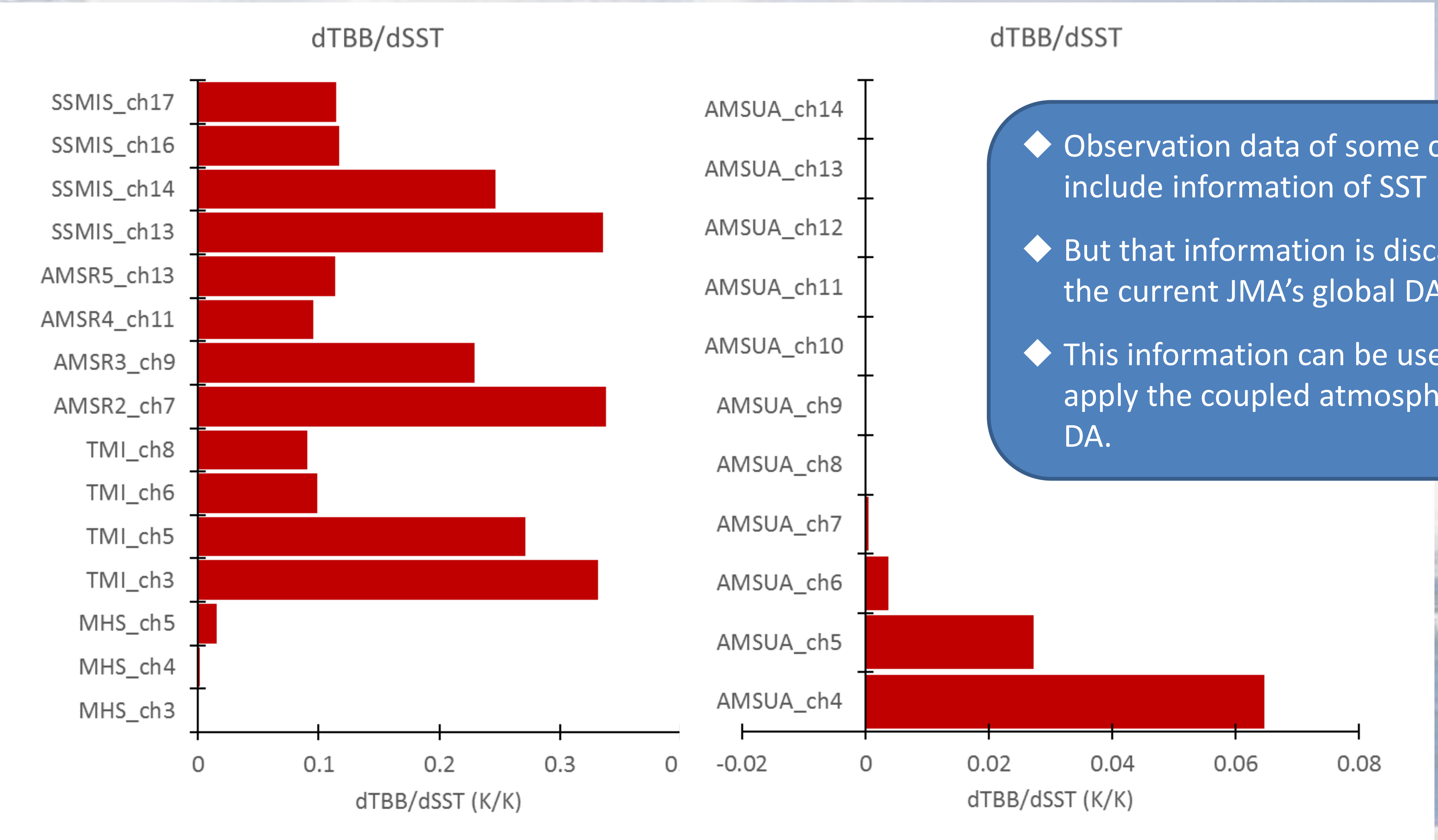
Model+Obs Operator

a=Atm variables
s= Sea Surface (SS) variables
pa=Atm obs
ps=SS obs

$$\mathbf{B} \approx \begin{pmatrix} \mathbf{B}_{aa} & 0 \\ 0 & \mathbf{B}_{ss} \end{pmatrix} \qquad \mathbf{M} \approx \begin{pmatrix} \mathbf{M}_{a,a} & 0 \\ 0 & \mathbf{I}_{s,s} \end{pmatrix}$$

Approximation

Sensitivity of SST to the microwave channels assimilated in the JMA global DA



- Observation data of some channels include information of SST
- But that information is discarded in the current JMA's global DA.
- This information can be used if we apply the coupled atmosphere-SST DA.

Forecast RMSE changes Coupled Atm-SST DA vs CNTL (No additional obs)

- TEST=Coupled Atm-SST DA
  - Obs data is the same as CNTL
- CNTL=JMA global NWP routine
- Validation term：Jun 11-Jul 11, 2020

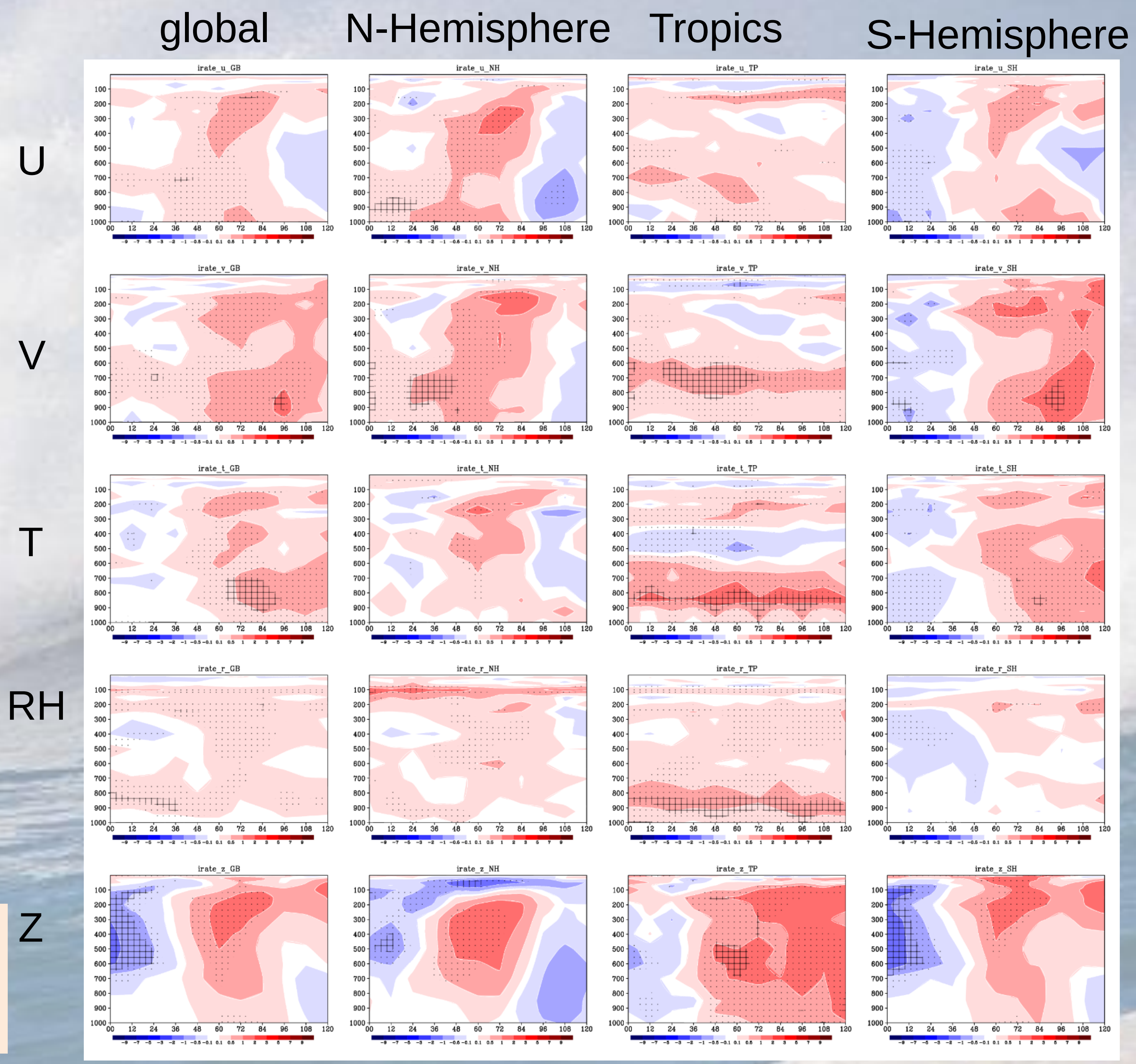
Pressure level [1000-1hPa]

RMSE change rate:

$$\frac{RMSE_{cntl} - RMSE_{test}}{RMSE_{cntl}} \ (\%)$$

Forecast time 0-5 days

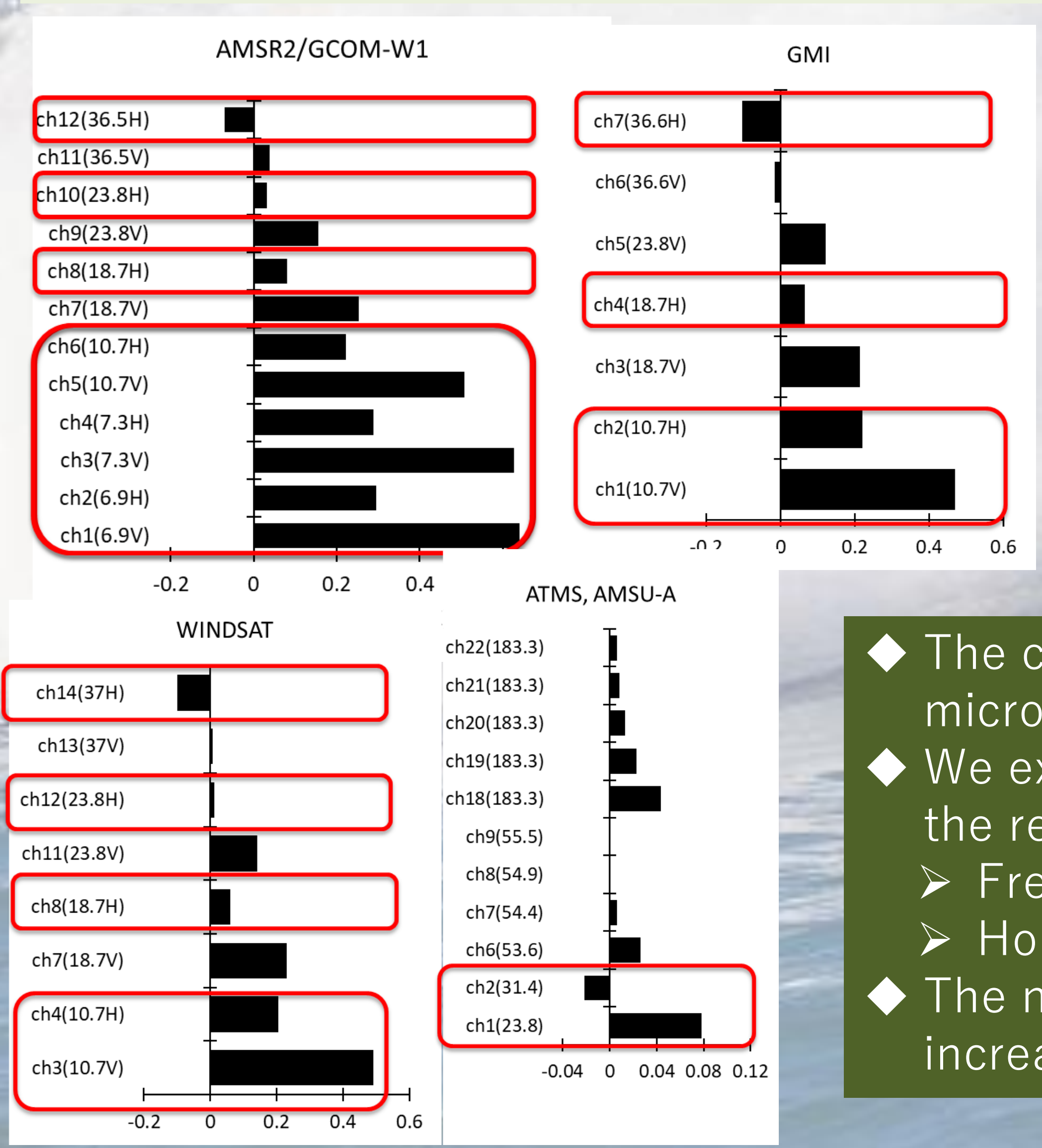
＊TRUTH=ERA5



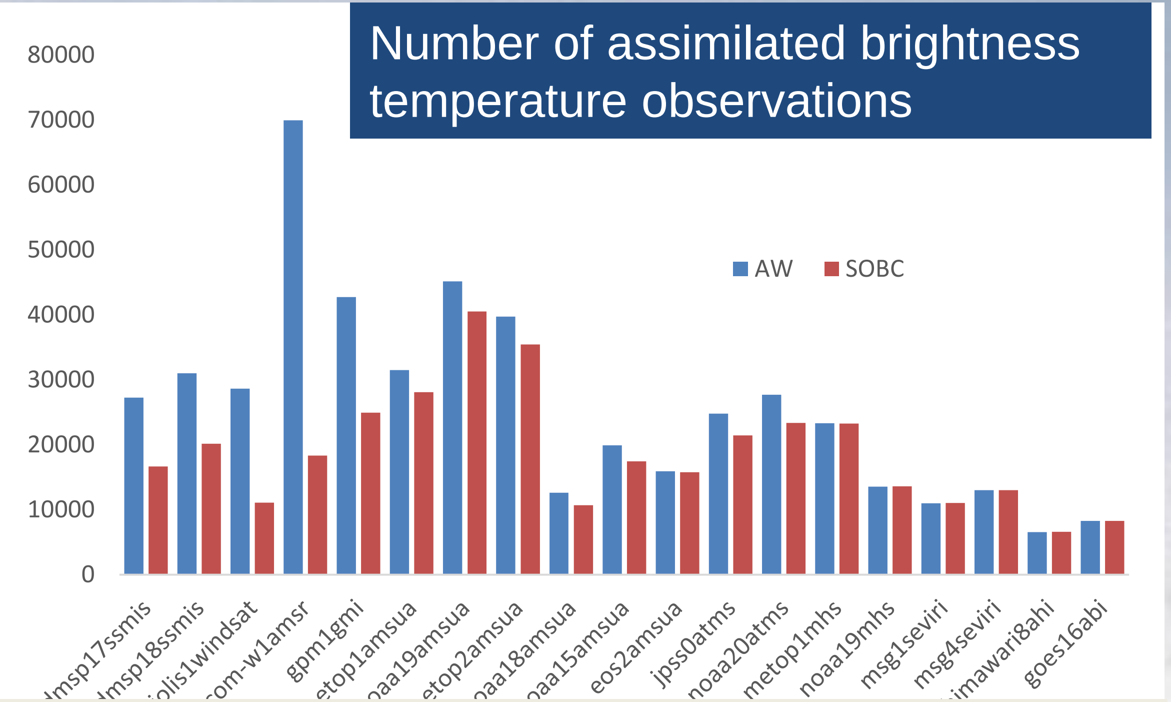
The predicted atmospheric variables are clearly improved, especially for the north-hemisphere and the tropics.

Microwave data adding experiment

dTBB/dSST and added channels (in red lines)



Number of assimilated brightness temperature observations



Blue：Coupled Atm-SST DA + Additional obs （492,470）
Red：CNTL （359,600）

- The coupled Atm-SST DA enables us to assimilate low frequency microwave channels.
- We examine the impacts of additionally assimilating the channels in the red lines in the left figure.
  - Frequency<10.7GHz
  - Horizontal Polarized wave channels, 18GHz<Frequency<38GHz
- The number of satellite brightness temperature data being assimilated increased by a factor of 1.4.

Forecast RMSE changes Coupled Atm-SST DA vs CNTL (with additional obs)

- TEST=Coupled Atm-SST DA
  - Low frequency microwave radiance data are added.
- CNTL=JMA global NWP routine
- Validation term：Jun 11-Jul 11, 2020

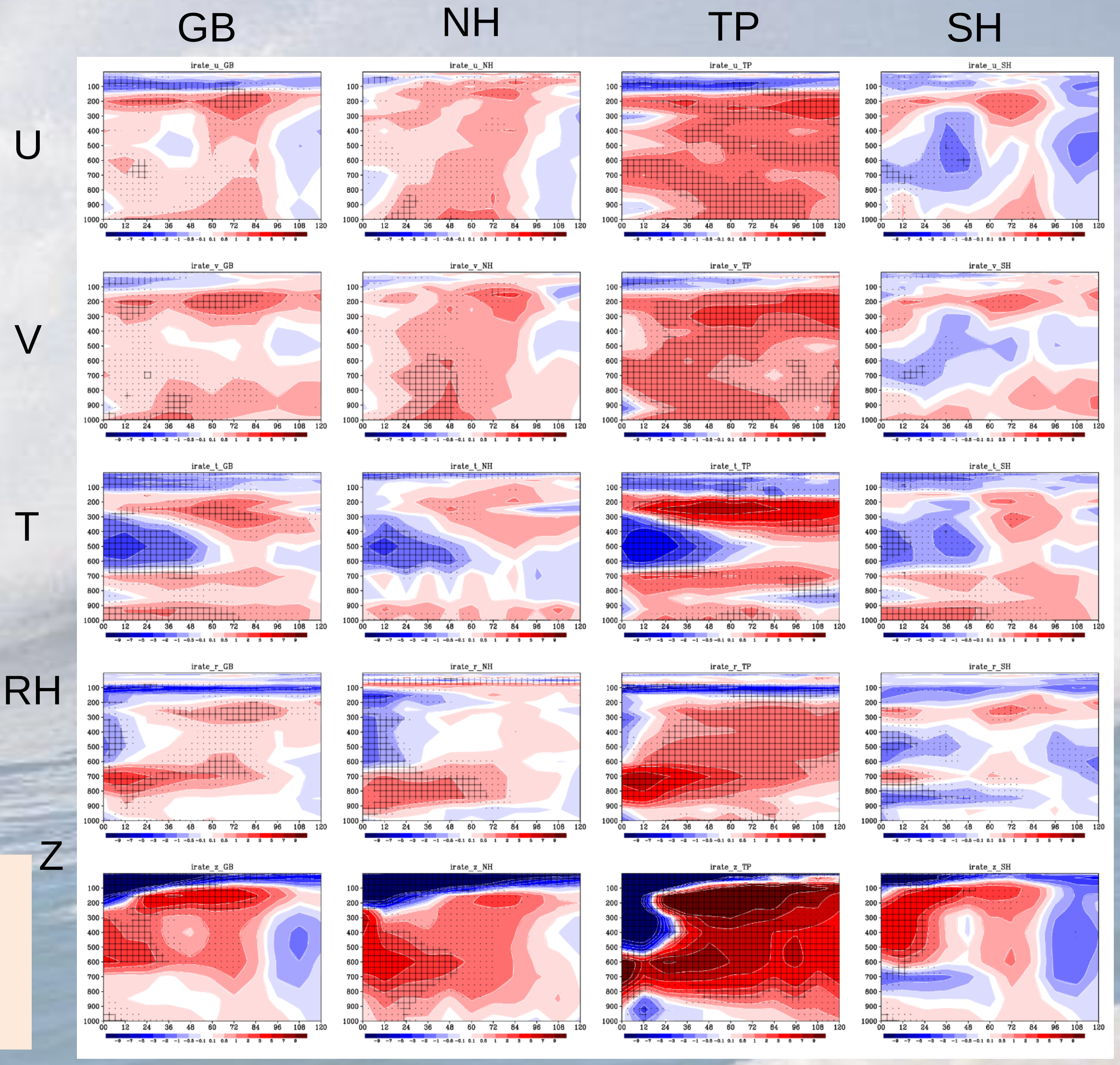
Pressure level [1000-1hPa]

RMSE change rate:

$$\frac{RMSE_{cntl} - RMSE_{test}}{RMSE_{cntl}} \quad (\%)$$

Forecast time 0-5 days

＊TRUTH=ERA5



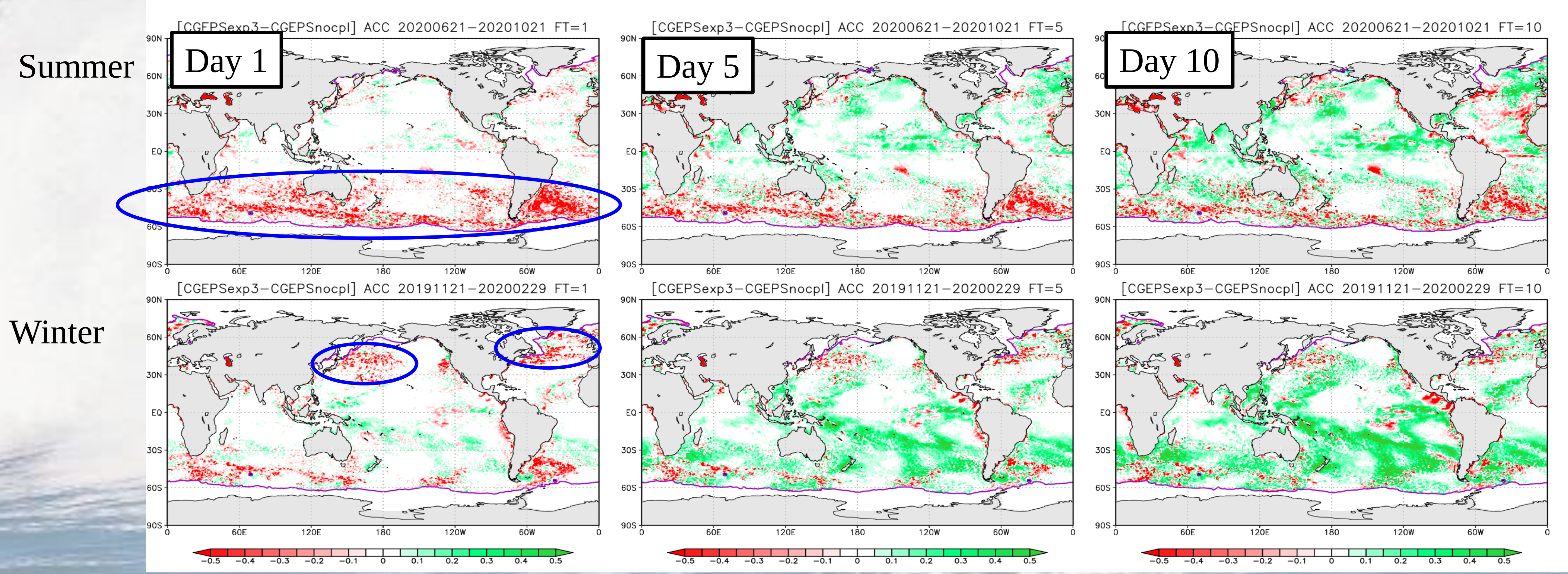
- The positive impacts are increased in the tropics.
- Impacts in the north and south hemispheres do not appear to have increased much.

Perspective and the future plan

Requirement of resolving oceanic eddies for coupled predictions

- Ref.: MGDSST by JMA
- (Exp. using JMA systems)

Predicted SST ACC Score Difference (uncoupled atm. PR－coupled PR from uncoupled DAs)

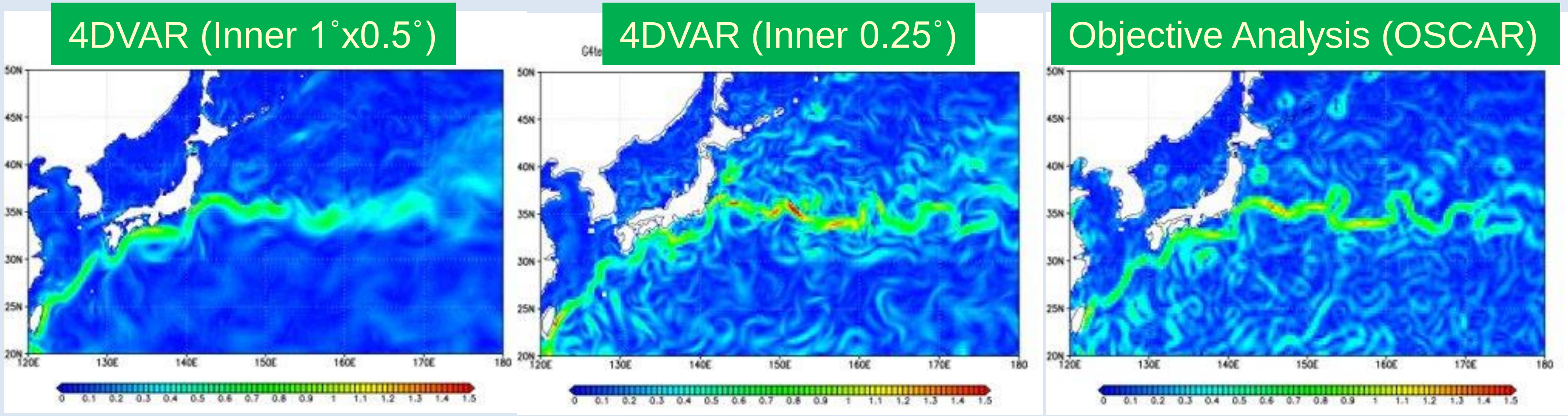


The coupled prediction improved SST forecasts for 10-day lead times, but degraded SST in areas with oceanic eddies for 1-day lead time. (Resolution of current ocean DA is not sufficient for resolving eddies.

⇒ It is preferable to use the eddy-resolving resolution for the oceanic DA part of the coupled DA system.

Improving Oceanic Representation in the coupled DA

- We need to improve the oceanic representation to further exploit the advantages of coupled DA.
  - Higer resolution ocean analysis (It is preferable to resolve ocean eddies.) ⇒ JMA plans to introduce oceanic 4DVAR with 0.25˚x0.25˚ resolution for the future coupled DA system.



Test of the oceanic 4DVAR with different resolutions. Showing the current speed at the surface on 21 Mar. 2011.

  - Reproducibility of SST variations in the ocean model should be improved.
    - SST diurnal cycle is not reproduced by current ocean models due to the low vertical resolution ⇒ Need to introduce skin SST procedure.
    - Our study on the coupled reanalysis showed that inaccuracies in vertical heat transfer in the mixed layer prevent accurate reproduction of SST variations.⇒ Need to improve the mixing parameterization
  - Sea Ice representation is also important. Former studies reported that sea ice has significant impact in coupled DAs (e.g., Browne et al., 2019)

Incorporating the coupled Atm-SST DA into the full coupled DAs

- We plan to incorporate the coupled Atm-SST DA into the current full coupled DA system (in the atmospheric DA component).
  - Coupled Atm-SST DA is promising. It enables us to use satellite data with sea surface information more effectively.
  - Need to improve the SST time evolution model (skin SST model?) and coupled Atm-SST statistics
  - Is it possible to assimilate SST data both in the atmosphere and ocean DA components?
    - It may be OK because the targeted time scales of the Atmospheric and oceanic DAs are much different (Increments of both DAs are likely independent.)

$$2J = \delta\mathbf{x}_{Atm}^{T}\mathbf{B}_{Atm}^{-1}\delta\mathbf{x}_{atm} + \delta\mathbf{x}_{Ocn}^{T}\mathbf{B}_{Ocn}^{-1}\delta\mathbf{x}_{Ocn} + \{\mathrm{H}(\mathbf{x}^{b} + \delta\mathbf{x}_{atm} + \delta\mathbf{x}_{Ocn}) - \mathbf{y}\}^{T}\mathbf{R}^{-1}\{\mathrm{H}(\mathbf{x}^{b} + \delta\mathbf{x}_{atm} + \delta\mathbf{x}_{Ocn}) - \mathbf{y}\}$$

$$\partial J/\partial(\delta\mathbf{x}_{Ocn}) = \mathbf{B}_{Ocn}^{-1}\delta\mathbf{x}_{Ocn} + \mathbf{H}^{T}\mathbf{R}^{-1}\{\mathrm{H}(\mathbf{x}^{b} + \delta\mathbf{x}_{atm} + \delta\mathbf{x}_{Ocn}) - \mathbf{y}\} = 0$$

$$\delta\mathbf{x}_{Ocn} \approx \mathbf{B}_{Ocn}\mathbf{H}^{T}(\mathbf{H}\mathbf{B}_{Ocn}\mathbf{H}^{T} + \mathbf{R})^{-1}\{\mathrm{H}(\mathbf{x}^{b} + \delta\mathbf{x}_{atm}) - \mathbf{y}\}$$ Increment of Atm DA

(Also see, Souopgui et al. 2020, DOI:10.1016/j.ocemod.2020.101683)

  - Is a special method to reflect SST increments from the coupled Atm-SST DA to the ocean component necessary?
    - It may not be necessary because SST adjusts to the modified heat fluxes from the atmosphere.

Toward the strongly coupled DA

- The best way to get the analysis fields consistent between the atmosphere and ocean(?)
- Coupled 4DVAR? ⇒ Development of a coupled adjoint model requires considerable human resource.
- EnKF and EnVar are more promising?
  - It is difficult to obtain reasonable correlations between atmosphere and ocean mainly due to large difference of the time scale.
  - How do we obtain the cross correlations?
    - Take the correlation of the ocean variables with the time-averaged atmospheric variables.

$$\overline{\mathbf{K}} = \mathrm{Cov}\langle \mathbf{x}_{\mathrm{ocn}}, \overline{\mathbf{Hx}_{\mathrm{atm}}} \rangle \{ \mathrm{Cov}\langle \overline{\mathbf{Hx}_{\mathrm{atm}}}, \overline{\mathbf{Hx}_{\mathrm{atm}}} \rangle + \mathrm{Cov}\langle \overline{\mathbf{y}_{\mathrm{atm}}}, \overline{\mathbf{y}_{\mathrm{atm}}} \rangle \}^{-1}$$

$$\delta \mathbf{x}_{\mathrm{atm\ to\ ocn}} = \overline{\mathbf{K}} (\overline{\mathbf{y}_{\mathrm{atm}}} - \overline{\mathbf{Hx}_{\mathrm{atm}}})$$

(See, Lu et al., 2015, DOI: 10.1175/MWR-D-14-00322.1)

    - Sophisticated localization. E.g., cutoff the correlation according to the prescribed statistics from the preliminary ensemble (or long-term) simulations (e.g., Yoshida et al., 2018, DOI: 10.1175/MWR-D-17-0365.1, Necker ey al, 2023, DOI:10.5194/npg-30-13-2023)
    - Use machine learning.
    - Other methods?

Example of Localization using statistical cutoff estimated by a neural network

Yoshida (2019), PhD Thesis, https://drum.lib.umd.edu/items/6012edb4-5551-4c1d-8216-7d690522fc2d

Kalnay el al. (2023), doi:10.5194/npg-30-217-2023

Attributes of analysis variable x_i

- Analysis variable type
- Latitude φ_{anl}
- Altitude z_{anl}

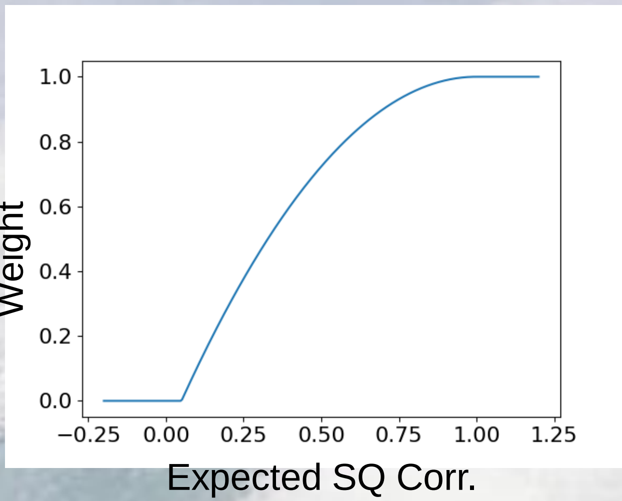
Attributes of observable y_j

- Observation type
- Horizontal distance r (from x_i)
- Altitude z_{obs}

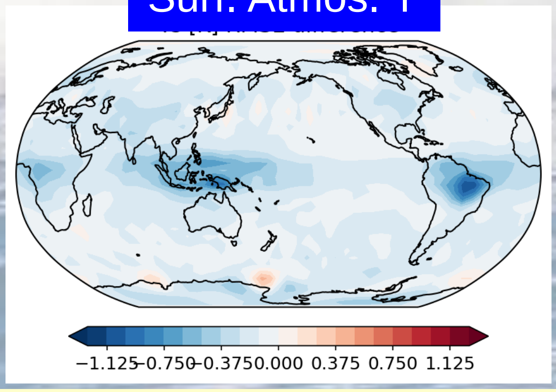
→ Neural Network ⇄ Preliminary Ensemble Simulation

→ Expected Squared BG Correlation

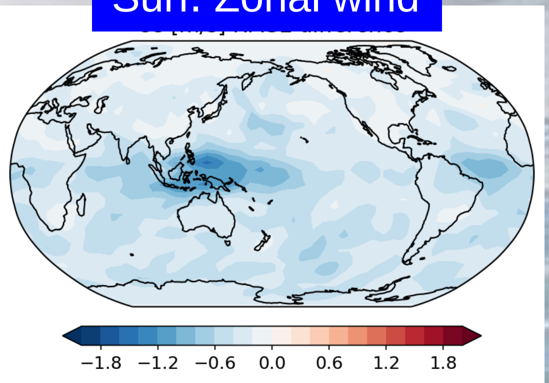
→ Weight for the localization



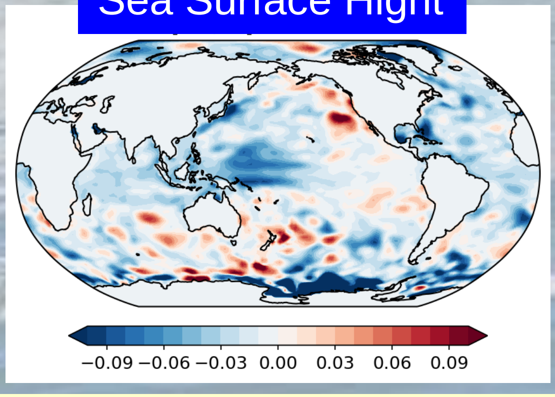
Surf. Atmos. T



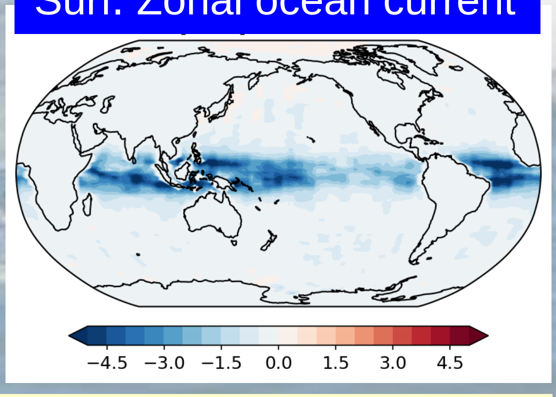
Surf. Zonal wind



Sea Surface Hight



Surf. Zonal ocean current



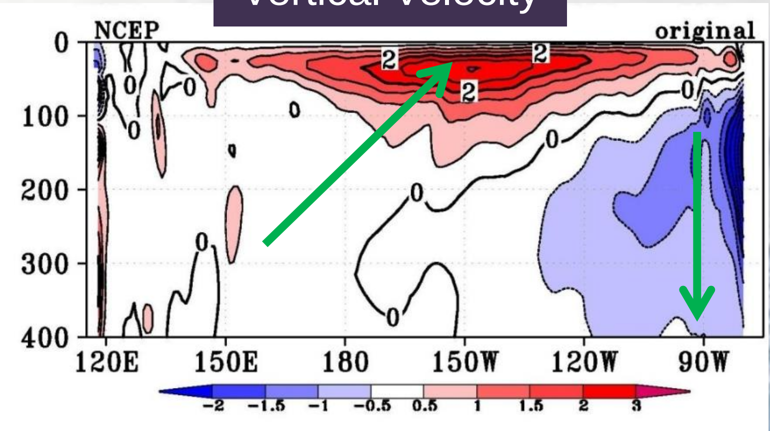
RMSE increase (red)/ decrease (blue) of the strongly coupled DA using the statistical localization based on the NN from the case using the standard localization according to the distance.

THANK YOU

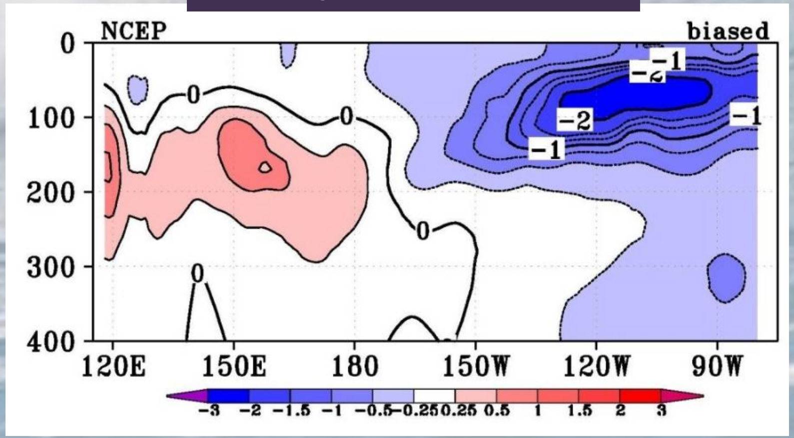
Incorporating the coupled Ocn-Atm boundary layer DA into the full coupled DAs

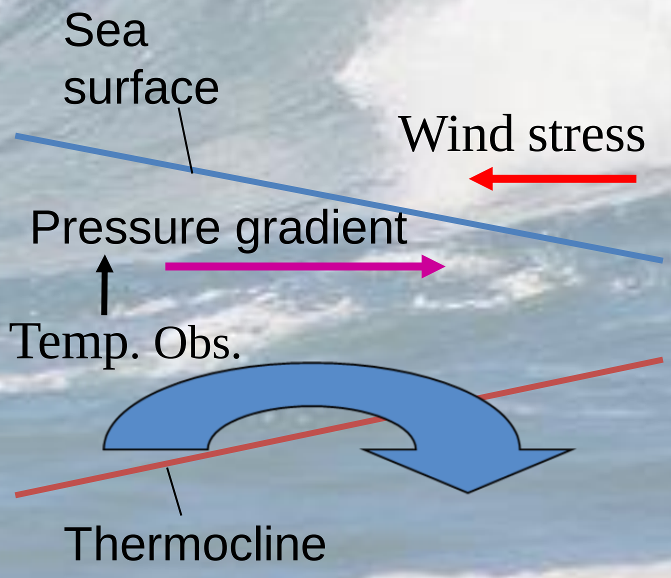
- Uncoupled Ocean DA tends to generate imbalance between the wind stress and the pressure gradient.
  - This imbalance should be modified by correcting the atmospheric forcing in the coupled Ocn-Atm boundary layer (AtmBL) DA (e.g., Storto et al. 2018).
- Coupled Ocn-AtmBL DA may also improve the atmosphere-SST relation.
- This is the oceanic counterpart of the coupled Atm-SST DA.
- Coupled Ocn-AtmBL DA can also be incorporated in the current full coupled DA.
  - If we do so, we need to consider how to reflect the increments on the BL to the atmospheric component.

Vertical Velocity



Analysis Increment





Vertical velocity and the analysis increments in an uncoupled ocean DA forced by the NCEP-R1 wind stress fields (weak trade winds)

Introduction of SynObs

SynObs

UN Ocean Decade Project

Synergistic Observing Network for Ocean Prediction

Led by OceanPedict OS-Eval TT

Ocean Prediction Capacity of the Future

ForeSea

2021 2030 United Nations Decade of Ocean Science for Sustainable Development

- 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.

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

☆ Outline of SynObs Activity Plan

1. Collaboration for evaluation and design

- Collaboration on a Multi-System OSE and OSSE (SynObs flagship OSEs/OSSEs)
- Establish a best practice based on the collaboration above.

2. Supporting DA scheme development

- Share the information on the development of DA schemes
- Planning of observation campaigns for DA scheme development

3. Providing information from ocean prediction systems in real time

- Explore the methods to evaluate observing system status in real-time

4. OS-Eval showcase and reporting

- Introduce OS-Eval examples to demonstrate its potential (Special collection in Frontier Marine Science, Science Session in Ocean Science Meeting 2024, Showcase webpage, etc.)
- Contributing to WMO Observation Impacts workshop and Rolling Review of Requirement (RRR)

☆ 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 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

Self Introduction

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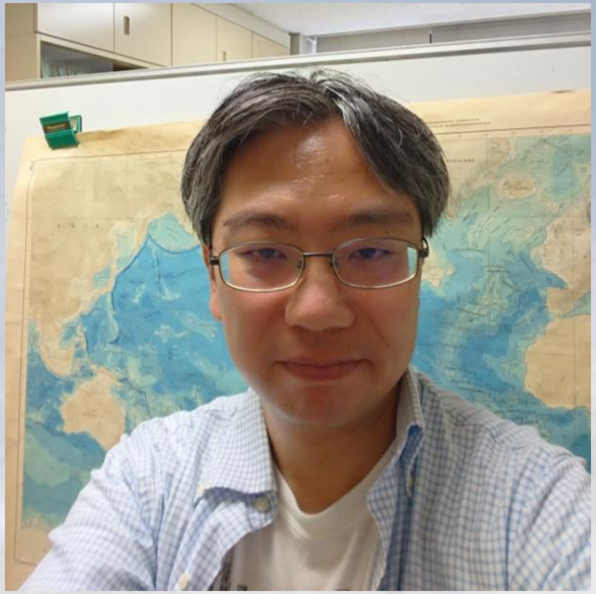
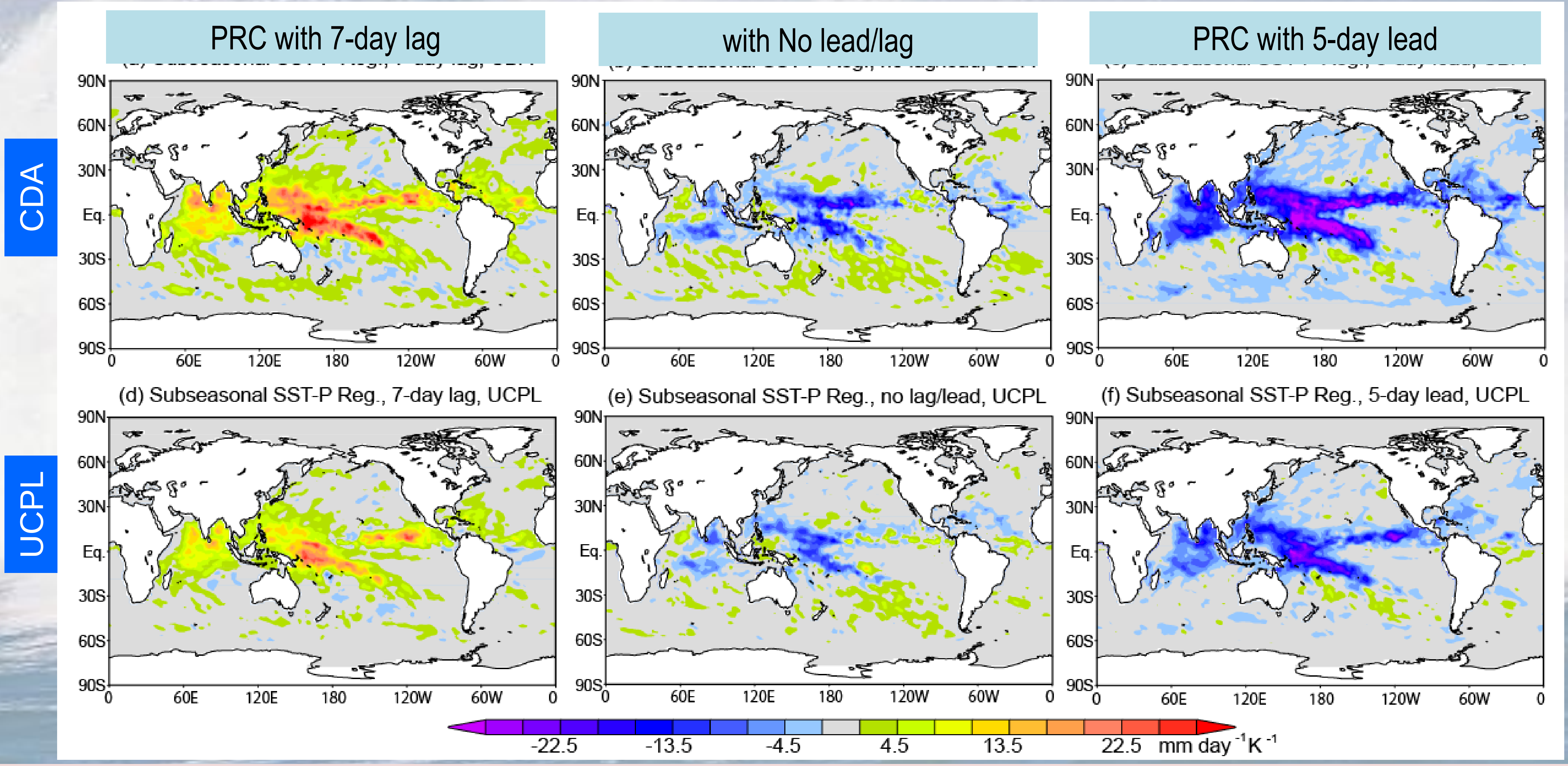


Research Fields

- Development of JMA's Oceanic 3DVAR/4DVAR System
  - Introductive paper of the current JMA's global oceanic 4DVAR System (Fujii et al. 2022, doi:10.3389/fclim.2022.1019673)
- Coupled DA (DA: Data Assimilation)
  - Semi-coupled DA (Fujii et al. 2009, doi:10.1175/2009JCLI2814.1)
  - Full-coupled DA with outer-loop coupling (Fujii et al., 2021, doi:10.1002/qj.3973)
- Evaluation of ocean observation impacts in ocean/coupled prediction systems
  - Co-chair of OceanPredict Observing System Evaluation Task Team
  - Co-chair of UN Ocean Decade Project SynObs

☆ Maps of PRC Lagged Regression on SST (Time scale: 10-60 days)

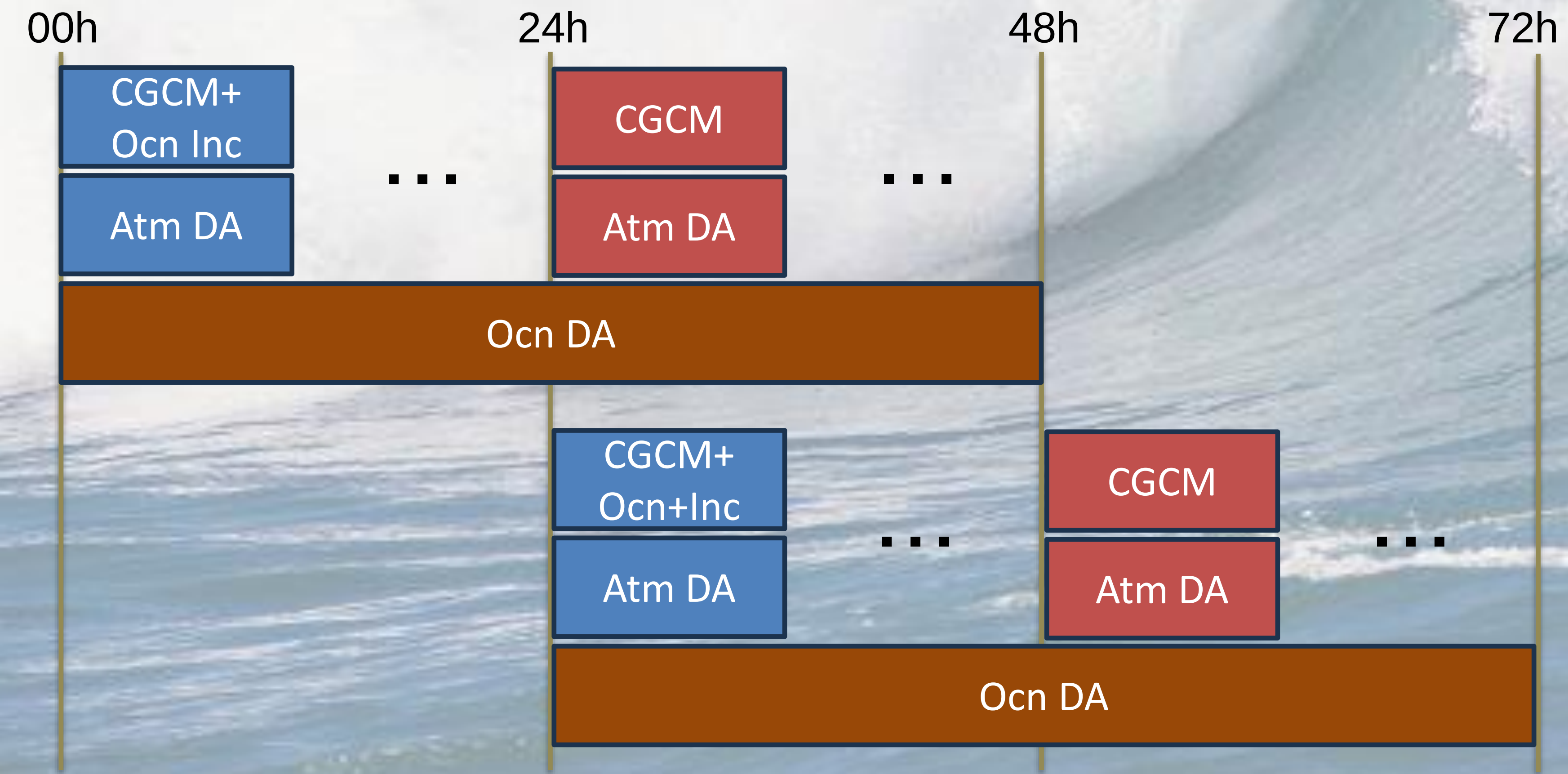


- ✓ It should be noted that the regression of PRC on SST is negative in the tropical area.
- ✓ The positive regression with 7-day lag and the negative one with 5-day lead are amplified in CDA.

Configuration of MRI-CDA2

Comp.	MRI-CDA1	MRI-CDA2
CGCM	Atm: TL159 (〜110km) Ocn: 0.5˚ x 1˚	Atm: TL959 (〜20km) Ocn: 0.25˚ x 0.25˚
Atm DA	4DVAR (every 6h) Inner: TL159 (〜110km)	4DVAR (every 6h) Inner: TL319 (〜60km)
Ocn DA	3DVAR (every 10d) Inner: 0.5˚ x 1˚	4DVAR (every 1d) Inner: 0.5˚ x 1˚

System Flow



- Higher resolution
- Ocean 4DVAR
- More frequent ocean analysis
- Still Weakly coupled DA

- Currently performing the coupled reanalysis for 2020 with this system

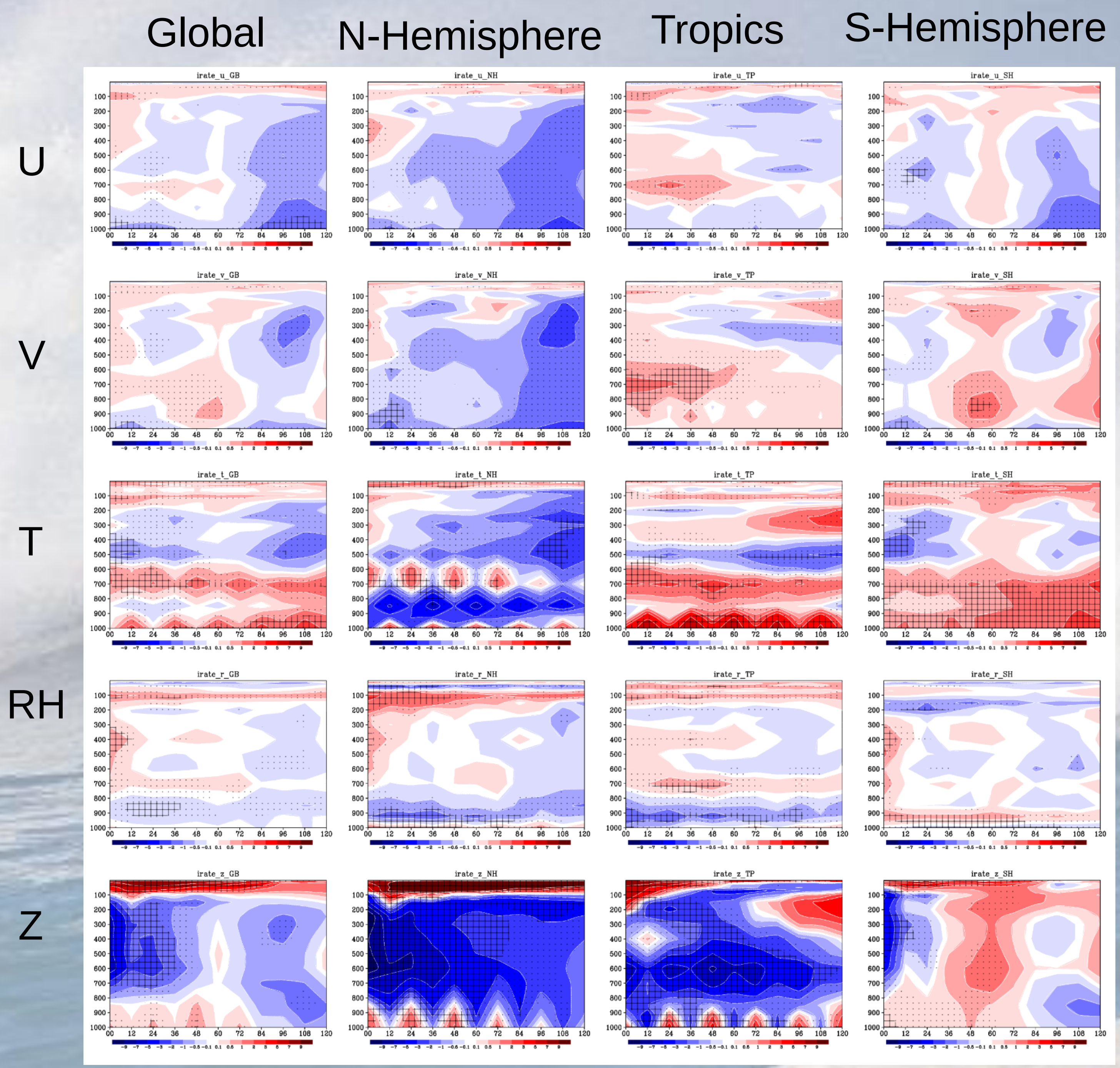
Forecast RMSE changes MRI-CDA2 vs CNTL

- TEST=MRI-CDA2 + Prediction by the coupled model
- CNTL=JMA global NWP routine (uncoupled DA and Prediction)
- Validation term：Jun 11-Jul 11, 2020

Pressure level [1000-1hPa]

RMSE change rate: $\frac{RMSE_{cntl} - RMSE_{test}}{RMSE_{cntl}}$ (%)

Forecast time 0-5 days



＊TRUTH=ERA5