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Assimilation of high-resolution sea surface temperature into an eddy-resolving ocean model with a weak-constraint 4D-Var method

Norihisa Usui, Yosuke Fujii, Nariaki Hirose, Ichiro Ishikawa

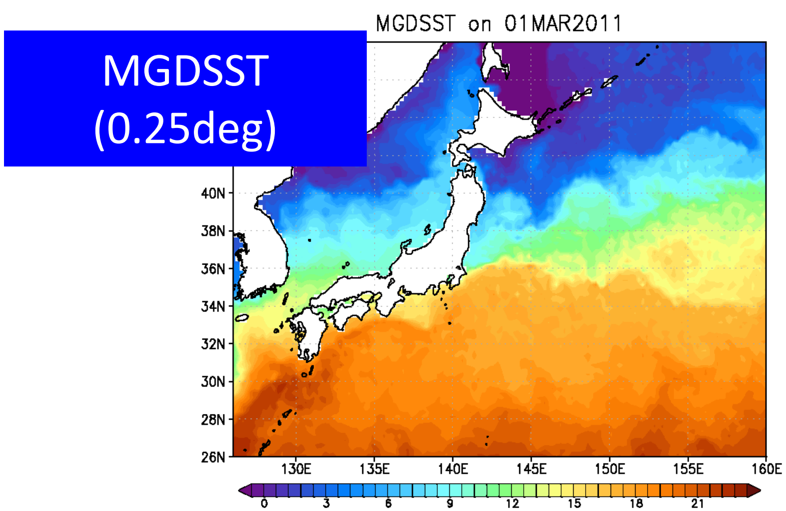
Japan Meteorological Agency / Meteorological Research Institute

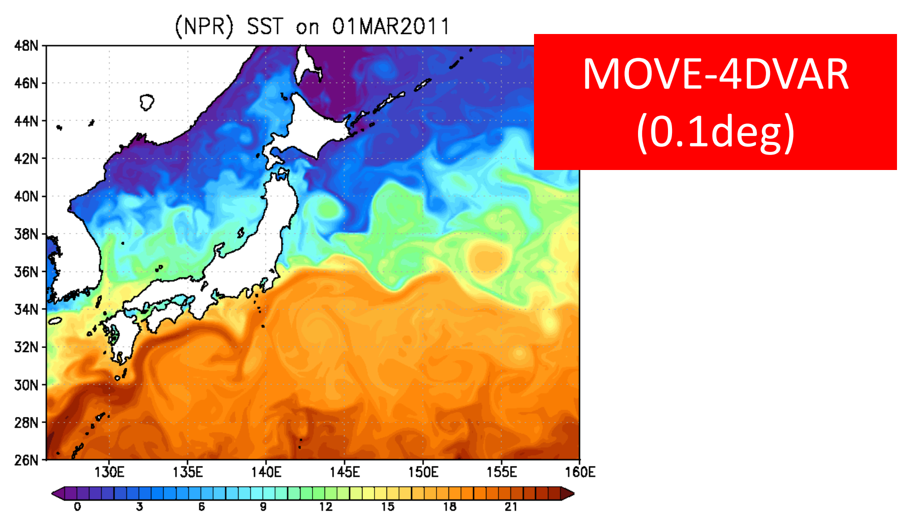
Introduction

- Sea Surface Temperature (SST)
  - Essential ocean variable
  - Plays a crucial role in heat, freshwater, and momentum exchange at the ocean-atmosphere interface
- Gridded SST products
  - Based on satellite (Infrared, microwave) and in-situ observations
  - Typical resolution: daily, 0.25deg x 0.25deg
  - Produced by objective analysis method such as the optimum interpolation
- SST assimilation in ocean DA systems
  - Gridded SSTs are utilized for assimilation in many systems
  - It is desirable for high-resolution DA systems to assimilate satellite L2 data directly because gridded SSTs are spatially and temporally smoothed

JMA's operational system (MOVE-4DVAR)

- North Pacific, 0.1deg x 0.1deg
- 4D-Var assimilation method
  - 10-day window
  - Control variables are TS increments to the initial condition (strong-constraint 4D-Var)
- SST assimilation in MOVE-4DVAR
  - MGDSST: JMA's SST product, 0.25deg
  - Temporal mean SSTs averaged over the 10-day assimilation window are used due to the temporally smoothed feature of MGDSST

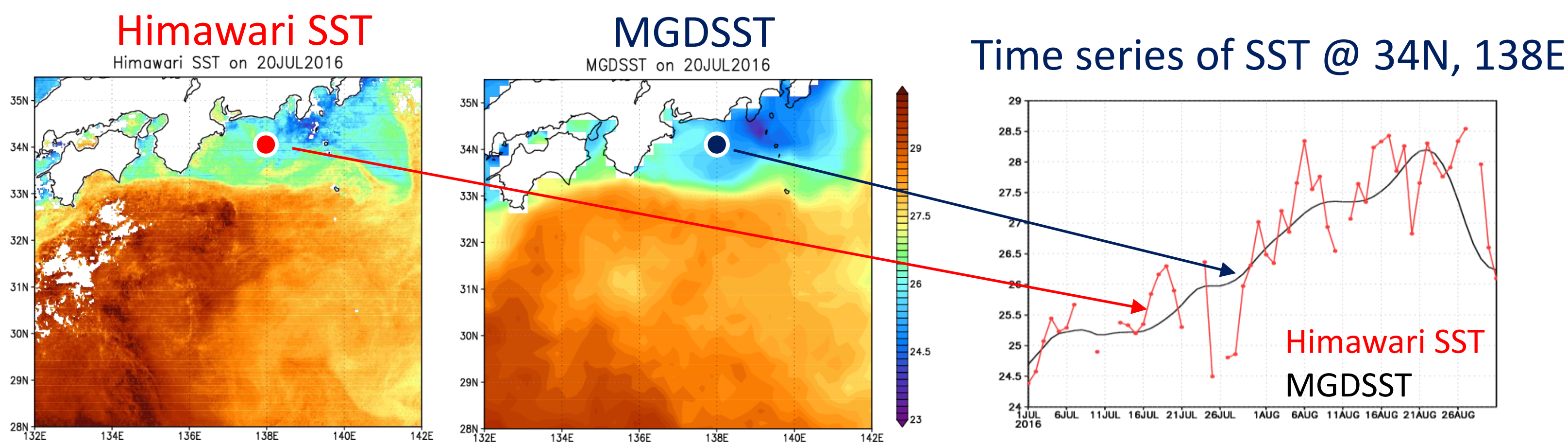




Toward improvement of SST analysis and forecast

- It is desirable to assimilate satellite L2 SST instead of gridded products such as MGDSST
- The 10-day window is too long to analyze the short-term SST variations with the strong-constraint 4D-Var

  → We introduce weak-constraint 4D-Var to overcome this issue



Objective of this study

- Weak-constraint 4D-Var is introduced to reproduce detailed spatial-temporal variations of SST with the present setting of the 10-day assimilation window

- Assimilation experiments using high-resolution satellite SST are conducted and impacts of the weak-constraint 4D-Var scheme are evaluated

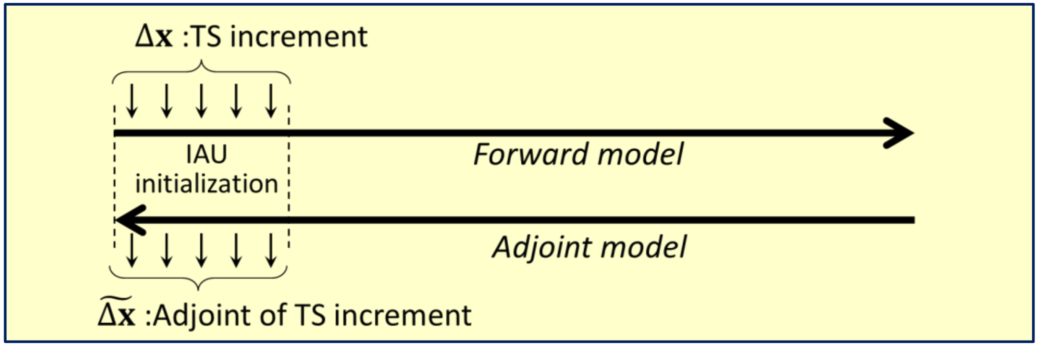
4D-Var scheme in MOVE

$$J(\mathbf{z}) = \frac{1}{2}\mathbf{z}^T\mathbf{B}_H^{-1}\mathbf{z} + \frac{1}{2}\sum_i^N \left[\mathbf{H}_i\mathbf{x}_i(\mathbf{z}) - \mathbf{y}_i\right]^T \mathbf{R}^{-1}\left[\mathbf{H}_i\mathbf{x}_i(\mathbf{z}) - \mathbf{y}_i\right]$$

- TS increment: $\Delta\mathbf{x} = \mathbf{SU\Lambda z}$
- Forward model: $\mathbf{x}_t = M(\mathbf{x}_{t-1}) + \underbrace{\Delta\mathbf{x}/N_{\mathrm{IAU}}}$

IAU initialization term

$\mathbf{z}$:Amplitude of vertically coupled T-S EOFs (control variable)
$\mathbf{S}$:Diagonal matrix of background standard errors
$\mathbf{U}$:Orthogonal matrix composed of dominant TS EOF modes
$\mathbf{\Lambda}$:Diagonal matrix of singular vectors for TS EOFs
$\mathbf{H}$:Observation operator
$\mathbf{y}$:Observations
$\mathbf{B}_H$:Horizontal correlation matrix for background errors
$\mathbf{R}$:Observation error covariance matrix



Schematic of the 4D-Var scheme with IAU initialization

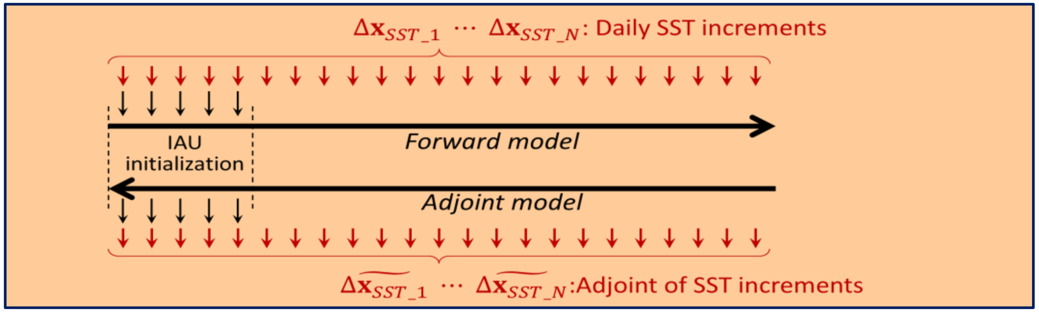
Extension of control variables: introduction of weak-constraint 4D-Var

$$J(\mathbf{w}) = \frac{1}{2}\mathbf{w}^T\mathbf{B}_{\mathrm{w}}^{-1}\mathbf{w} + \frac{1}{2}\sum_{i}^{N}\left[\mathbf{H}_i\mathbf{x}_i(\mathbf{w}) - \mathbf{y}_i\right]^T\mathbf{R}^{-1}\left[\mathbf{H}_i\mathbf{x}_i(\mathbf{w}) - \mathbf{y}_i\right]$$

$$= \frac{1}{2}\mathbf{z}^T\mathbf{B}_H^{-1}\mathbf{z} + \underbrace{\frac{1}{2}\sum_{i}^{N}\mathbf{z}_{SST\_i}^T\mathbf{B}_{SST\_i}^{-1}\mathbf{z}_{SST\_i}}_{\text{BG term for SST}} + \frac{1}{2}\sum_{i}^{N}\left[\mathbf{H}_i\mathbf{x}_i(\mathbf{w}) - \mathbf{y}_i\right]^T\mathbf{R}^{-1}\left[\mathbf{H}_i\mathbf{x}_i(\mathbf{w}) - \mathbf{y}_i\right]$$

- Control variable: $\mathbf{w} = \big(\mathbf{z}^T\ \underbrace{\mathbf{z}_{SST\_1}^T\ \mathbf{z}_{SST\_2}^T \cdots \mathbf{z}_{SST\_N}^T}_{\text{Daily SST increments (normalized)}}\big)^T$
- SST increment at *i*-th day: $\Delta\mathbf{x}_{SST\_i} = \mathbf{S}_{SST\_i}\mathbf{z}_{SST\_i}$
- Forward model: $\mathbf{x}_t = M(\mathbf{x}_{t-1}) + \Delta\mathbf{x}/N_{\mathrm{IAU}} + \underbrace{\Delta\mathbf{x}_{SST\_i}/N_{\mathrm{IAU}}^{\mathrm{sst}}}_{\text{IAU term for SST}}$
- B matrix: $\mathbf{B}_{\mathrm{w}} = \begin{pmatrix} \mathbf{B}_H & & & 0 \\ & \mathbf{B}_{SST\_1} & & \\ & 0 & \ddots & \\ & & & \mathbf{B}_{SST\_N} \end{pmatrix}$

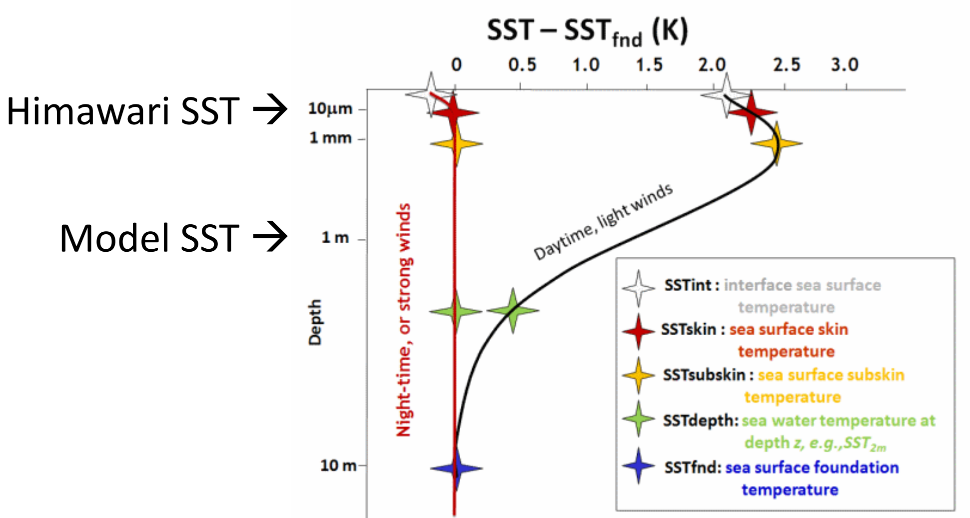
BG errors for initial condition and SST are assumed to be independent



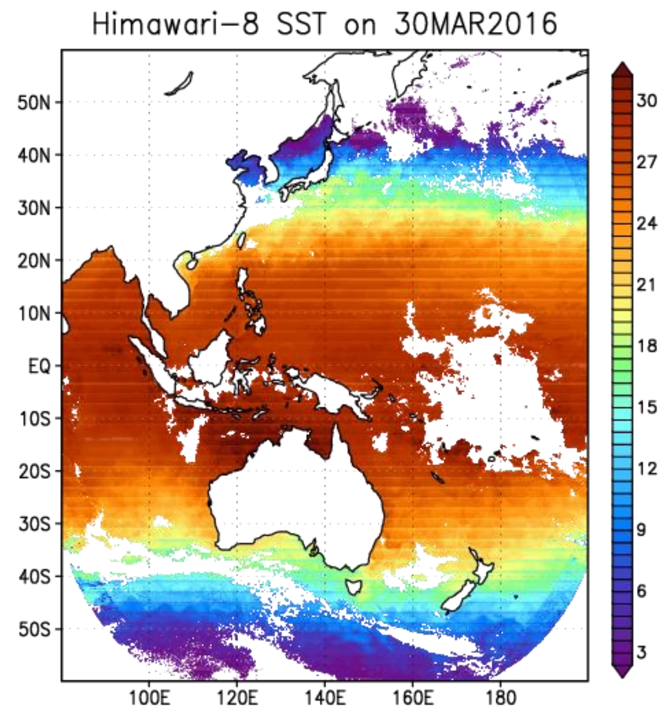
Schematic of the new 4D-Var scheme

Himawari SST

- Himawari-8
  - Geostationary meteorological satellite
  - Launched in October 2014
  - Location: 140.7E at the equator
  - Coverage: 60S-60N, 80E-160W
- Himawari SST
  - Observed by Infrared sensors
  - Horizontal resolution: 2km
  - Observation frequency: 10 min
  - Skin SST (≠ bulk SST ≒ model SST)
    → Need correction of Himawari SST



Typical temperature profiles near the surface (GHRSST, 2012)



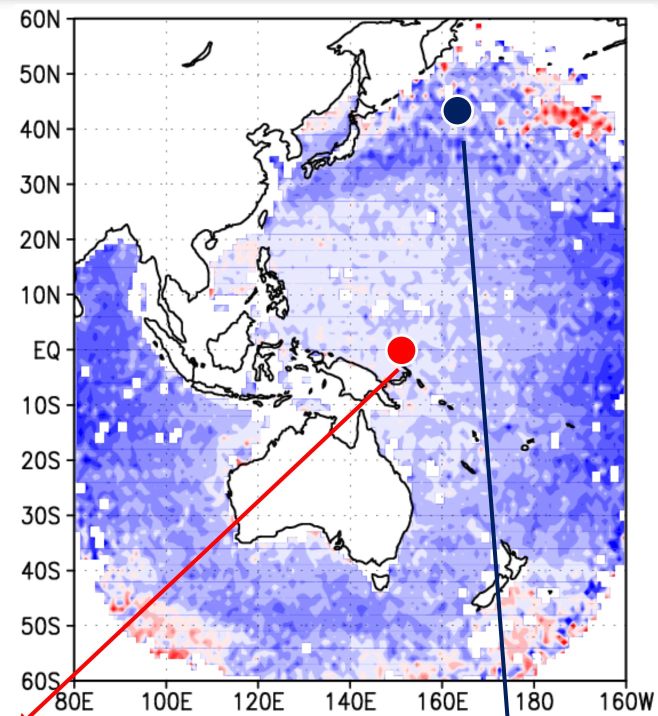
Example of Himawari SST

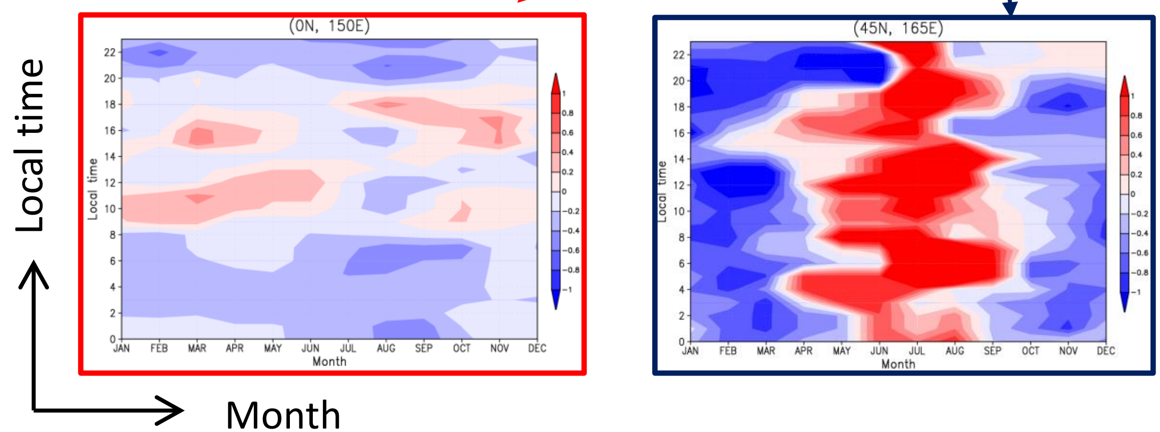
Correction of Himawari SST

Bias Table

- Every 2-degree x 2-degree box
- Function of local time and month
- Correction values are calculated from a match-up b/w in-situ T and hourly Himawari SST

- Daily data of the Himawari SST for assimilation were produced by taking the daily average of the corrected hourly data





Example of the bias table

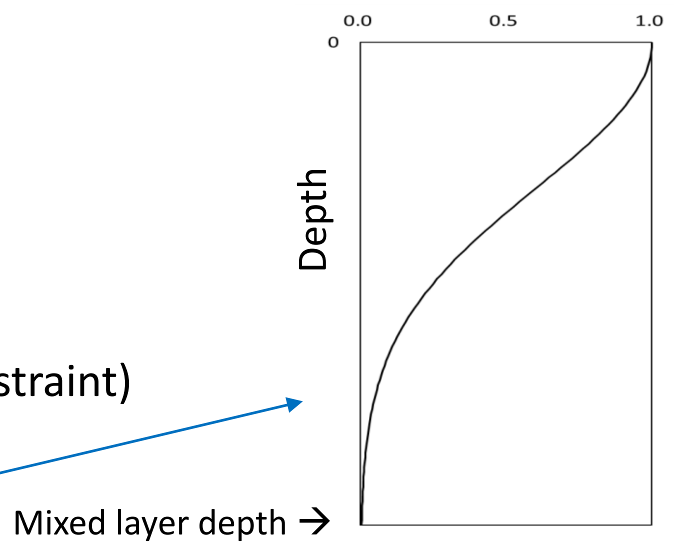
Assimilation experiments

<u>Common setting:</u>

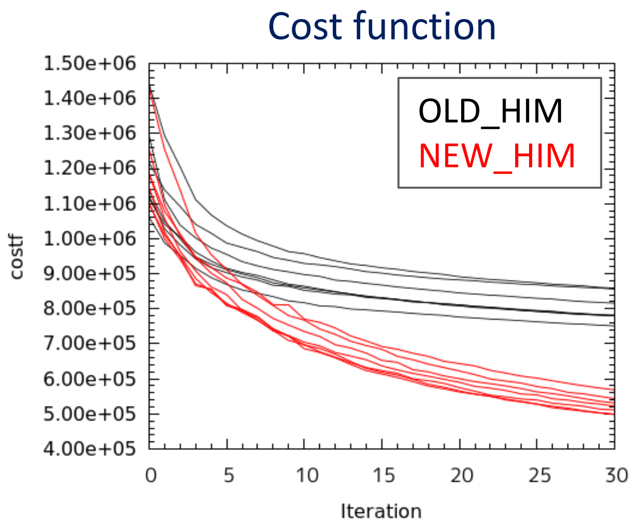
- DA system: MOVE/MRI.COM-4DVAR
  - North Pacific, 10km
- Period: 1 Jan– 9 Jul 2016
- Assimilation window: 10 days
- Assimilated observations other than SST
  - Along track SLAs (Jason-2, Cryosat-2, Altika)
  - In-situ temperature and salinity profiles

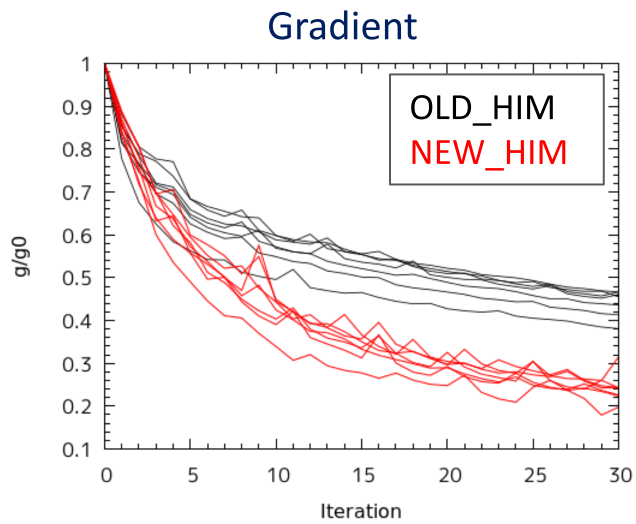
<u>Experiments:</u>

- “**CTRL**” (same as the setting of the present operational system)
  - 4D-Var method: Original version (strong constraint)
  - Assimilated SST: MGDSST (10-day average)
- “**OLD_HIM**”
  - 4D-Var method: Original version (strong constraint)
  - Assimilated SST: Himawari SST (daily)
- “**NEW_HIM**”
  - 4D-Var method: Newly developed version (weak constraint)
  - Assimilated SST: Himawari SST (daily)
  - SST increments are projected down to MLD



Comparison b/w OLD_HIM and NEW_HIM

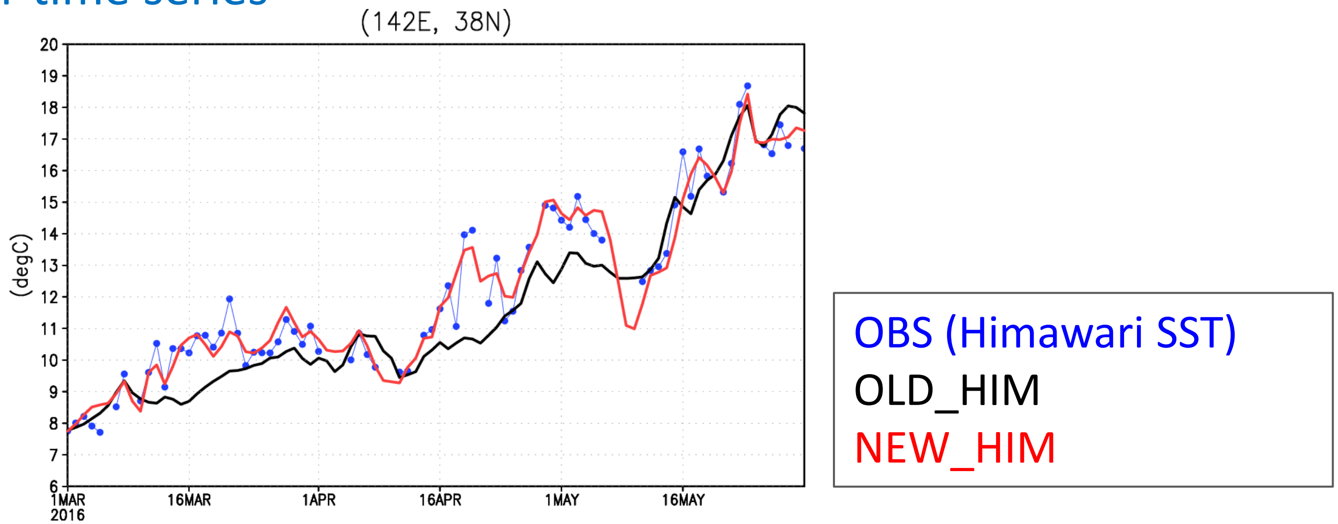




- In OLD_HIM and NEW_HIM, the same observations are used.
- The cost function and its gradient in NEW_HIM decrease steadily with iterations, while their decreasing rate are obviously slow in OLD_HIM.
- This is because:
  - Short-term variations in Himawari SST are well represented by the newly added daily SST increments in NEW_HIM.
  - The short-term variations of SST are not controlled by only increments to the initial condition (OLD_HIM).

Comparison b/w OLD_HIM and NEW_HIM

SST time series



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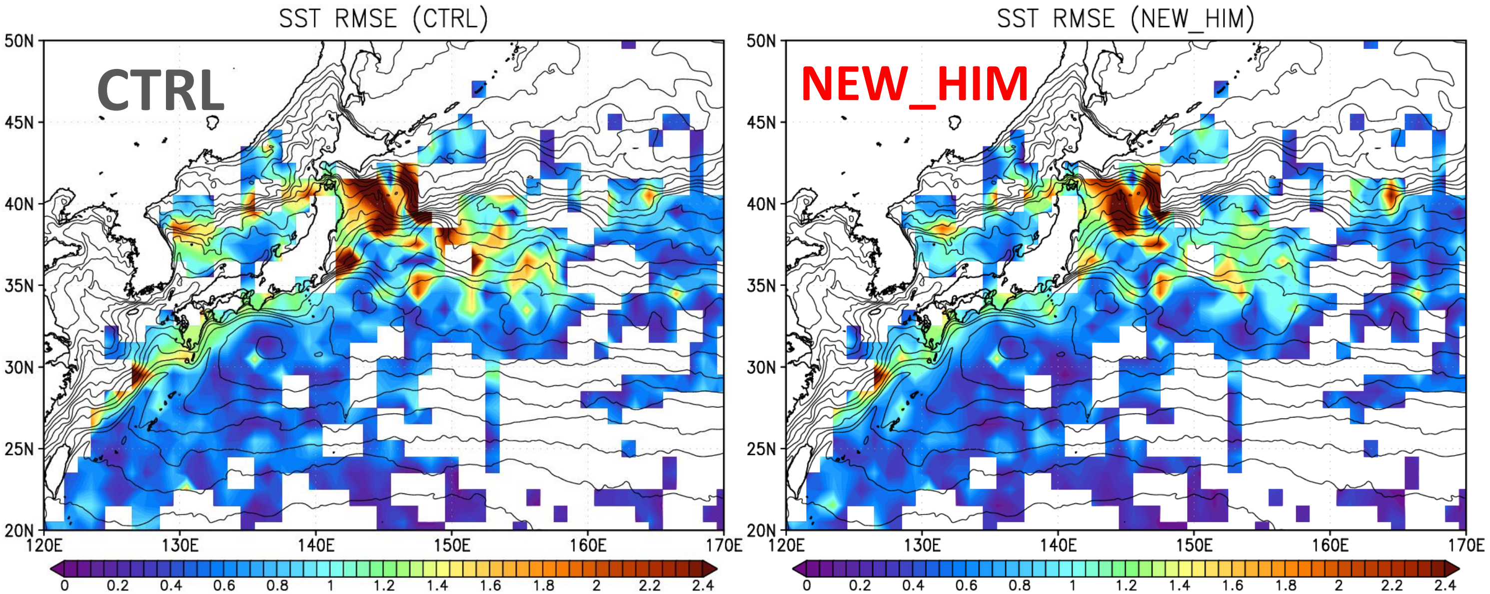
SST RMSE: CTRL and NEW_HIM

- First-guess fields (forecast from the previous cycle) are evaluated using in-situ data
- RMSE is relatively large in SST frontal regions



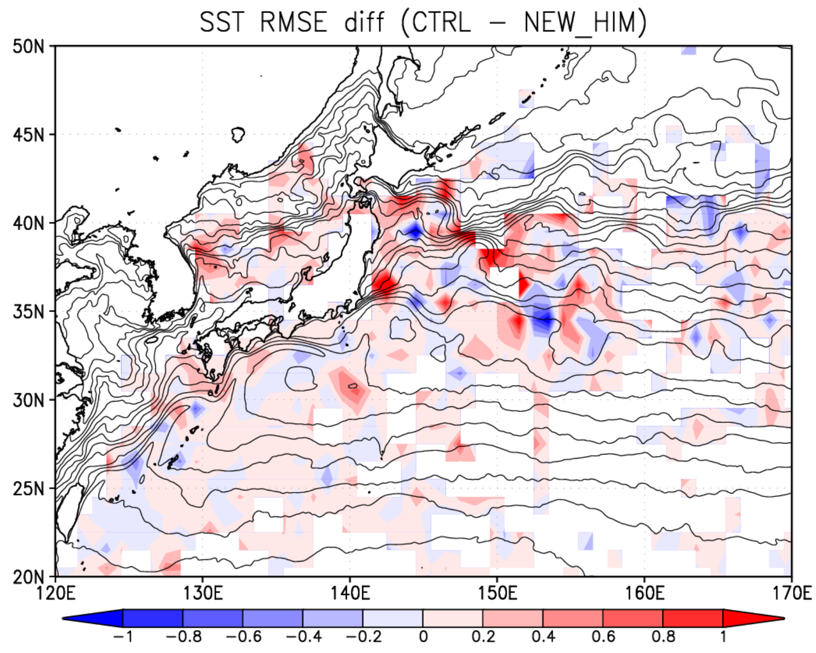
Shade: SST RMSE
Contour: mean SST

RMSEs of (first-guess) SST

SST RMSE: CTRL and NEW_HIM

- First-guess fields (forecast from the previous cycle) are evaluated using in-situ data
- RMSE is relatively large in SST frontal regions
- RMSEs for NEW_HIM are improved in most areas of the western North Pacific

RMSE difference
(CTRL – NEW_HIM)

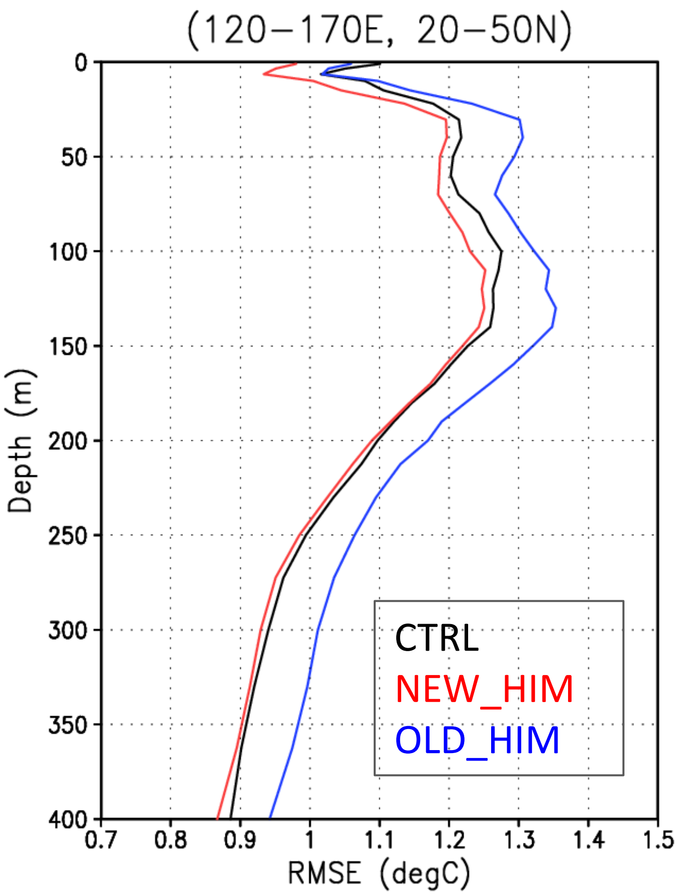


Worsen Improve

Shade: RMSE difference
Contour: mean SST

Impact on subsurface temperature

- Improvements in RMSE for NEW_HIM are seen up to around 150m.
- In OLD_HIM, subsurface temperature is degraded compared to CTRL.
- The slow convergence of the cost function might lead to the degradation of the analysis results in OLD_HIM.



Summary

- We have developed a new 4D-Var scheme based on weak-constraint 4D-Var to assimilate high-resolution SST.
- Daily SST increments are added to control variables to represent short-term variations.
- The result of assimilation experiments suggest that the new scheme works well and short-term variations in Himawari SST are well represented.
- Future works:
  - Further evaluation of the new scheme with longer assimilation experiments
  - Tuning/optimization of assimilation parameters such as:
    - Observation error for Himawari SST
    - Background error for SST
    - Vertical projection of SST increments