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A new method for estimating steric mean sea surface dynamic height in MOVE system combining in-situ profiles and sea level anomalies

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1. Ocean data assimilation system: MOVE

- ✓ **MOVE**: MRI Multivariate Ocean Variational Estimation
  - ✓ Ocean data assimilation system in MRI/JMA
  - ✓ Variational method (3D-Var/4D-Var)
  - ✓ Vertical coupled TS-EOF mode (Fujii and Kamachi 2003)
    - ✓ TS: Temperature and Salinity
  - ✓ Control variables: amplitude of the TS EOF modes
- ✓ Cost function J(z) is calculated by using observations and is minimized
  - ✓ In-situ TS profiles
  - ✓ Sea surface temperature (SST)
  - ✓ Sea level anomalies(SLAs)

MOVE system can optimize the TS fields as baroclinic structures.

When assimilate SLAs, **a mean surface dynamic height (MSDH) is required**. However, **satellite-based SLAs includes not only steric (baroclinic) but also non-steric components**.
Thus, corrections of the non-steric components should be applied to reduce analysis errors.

→ **Need baroclinic component of the MSDH for MOVE system**

Background term / Observation term (Temperature / Salinity) / Observation term (SLA)

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

$$J_{SLA}(\mathbf{z}) = \frac{1}{2\sigma_h^2}\sum_i^N \left[h_i(\mathbf{x}_i(\mathbf{z})) - \bar{\mathbf{h}} - \left(\mathbf{y}_i^{SLA} - \boldsymbol{\eta}_i^{NS}\right)\right]^T \left[h_i(\mathbf{x}_i(\mathbf{z})) - \bar{\mathbf{h}} - \left(\mathbf{y}_i^{SLA} - \boldsymbol{\eta}_i^{NS}\right)\right]$$

model-based SSDH: $\boldsymbol{h}(\mathbf{x}) = -\int_0^{z_m} \frac{\Delta\rho(T,S,p)}{\rho_s} dz$

MSDH(1993-2012)

SLA from altimeter: $\mathbf{y}^{SLA} = \boldsymbol{\eta}^{dyn} + \boldsymbol{\eta}^{bt} + \boldsymbol{\eta}^{mass}$

Non-steric correction term

Barotropic response to wind forcing: $\eta^{bt} = \frac{p_b - \overline{p_b}}{\rho_b g}$

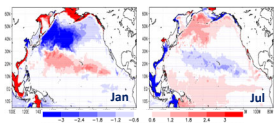


Fig. 1 Seasonal change of the wind-induced barotropic variation estimated by free-run simulation

Area averaged mass variation: $\eta^{mass} \sim \frac{1}{A}\iint |y^{SLA} - y^{dyn}_{in-situ}| dxdy$

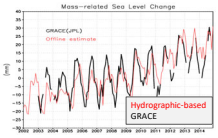


Fig. 2 Mass variation averaged over the North Pacific

h : sea surface dynamic height (SSDH)
$\bar{h}$: mean surface dynamic height (MSDH)
y^{SLA}: sea level anomaly (SLA)
η^{dyn}: steric component of SLA
η^{NS}: non-steric component of SLA
η^{bt}: barotropic response to wind forcing
η^{mass}: mass variation
$y^{dyn}_{in-situ}$: SSDH at the in-situ profiles
p_b: bottom pressure
$\overline{p_b}$: time averaged bottom pressure
g: gravitational acceleration

2. Making method for MSDH

2.1. Conventional method (CNTL)

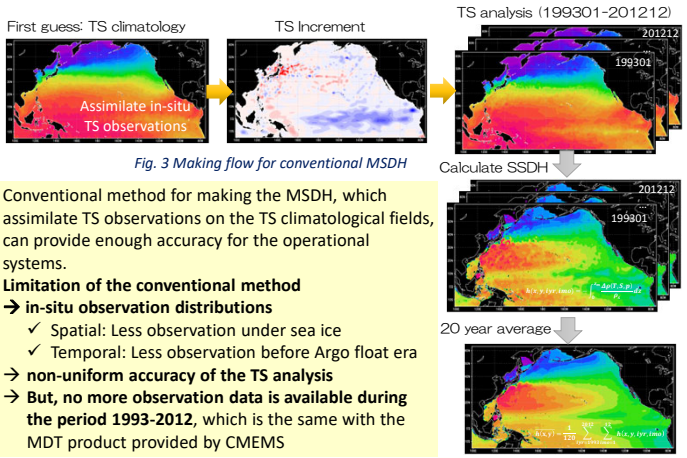


Fig. 3 Making flow for conventional MSDH

Conventional method for making the MSDH, which assimilate TS observations on the TS climatological fields, can provide enough accuracy for the operational systems.

Limitation of the conventional method

→ **in-situ observation distributions**
- ✓ Spatial: Less observation under sea ice
- ✓ Temporal: Less observation before Argo float era

→ **non-uniform accuracy of the TS analysis**

→ **But, no more observation data is available during the period 1993-2012**, which is the same with the MDT product provided by CMEMS

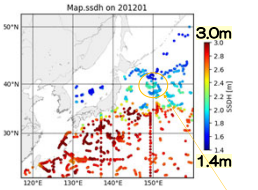
This study intends to give a new approach for making the baroclinic MSDH for MOVE system.

2.2. New method combining in-situ profiles and SLAs (TEST)

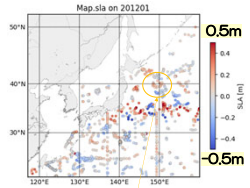
$$\mathbf{y}^{dyn}_{in-situ,i} = \boldsymbol{\eta}^{dyn}_i + \bar{\mathbf{h}}_i$$
$$\downarrow$$
$$\bar{\mathbf{h}}_i = \mathbf{y}^{dyn}_{in-situ,i} - \left(\mathbf{y}^{SLA}_i - \boldsymbol{\eta}^{BT}_i - \boldsymbol{\eta}^{MASS}\right)$$

The idea is similar to Rio et al., (2004). They used the dynamic height from the hydrographic data and SLAs to estimate the mean dynamic topography (MDT). However, the corrections of non-steric components are required in this study.

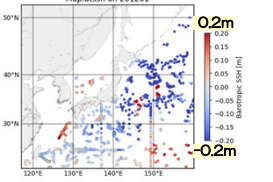
SSDH: $y^{dyn}_{in-situ,i}(x,y,t)$
In-situ profiles (WOD, GTSPP)
Reference level: 600m – 2000m



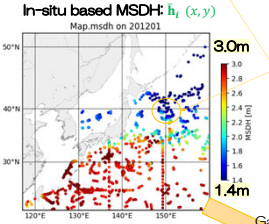
SLA $y^{SLA}(x,y,t)$
SEALEVEL_GLO_PHY_L3_MY_008_062-DGF



Barotropic correction $\eta^{BT}(x,y,t)$
Estimate from the free-run in the North Pacific
5-days interval → interpolate to daily data



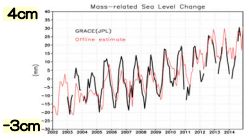
In-situ based MSDH: $\bar{h}_i\ (x,y)$



Positive SDH anomalies are removed as the non-steric variations
↓
Estimate MSDH at the location of the in-situ observations

Fig. 4 Example of the in-situ based MSDH referred to the 2000 m depth in January 2012

Mass correction $\eta^{MASS}(t)$
Regional balance
Monthly data



Gather in-situ MSDHs from 1993 to 2017, then interpolate on the grids (1/11×1/10)

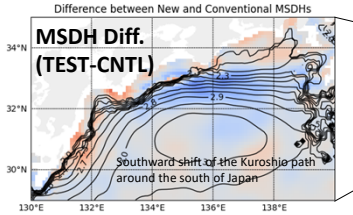


Fig.7 Same as Fig. 6, but around the south of Japan

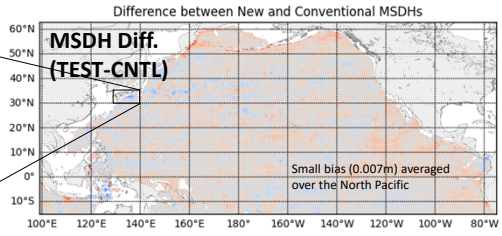


Fig.6 MSDH difference between conventional (CNTL) and new (TEST) methods

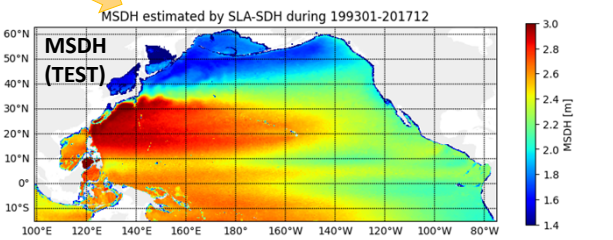


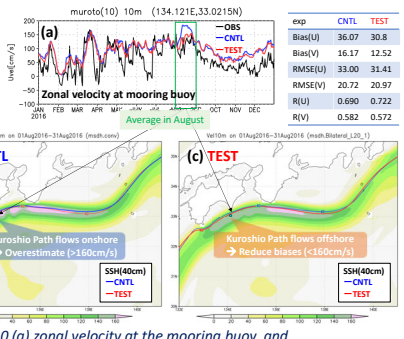
Fig. 5 MSDH map based on the in-situ hydrographic data

3. Assimilation experiments

Settings:
- Model domain: North Pacific
- Horizontal Resolution: 1/11 x 1/10
- Assimilation: 3DVAR
- Observation
  - In-situ TS profiles
  - Sea surface temperature (MGDSST)
  - Along-track SLAs
- Forcing:
  - JRA55-do (Tsujino etal., 2018),
  - Runoff (Suzuki et al., 2018)

Experiments:
- **CNTL**: Conventional MSDH
- **TEST**: In-situ based MSDH
- Assimilation window: 10 days
- Period: 2016.1.1 – 2016.12.31

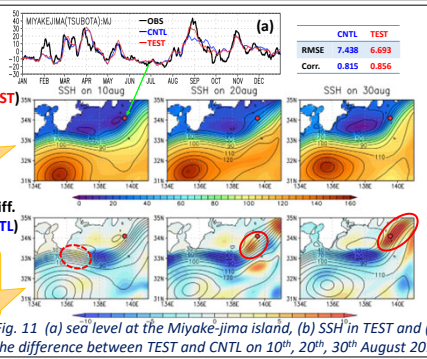
Validation (Velocity)



exp	CNTL	TEST
Bias(U)	36.07	30.8
Bias(V)	16.17	12.52
RMSE(U)	33.00	31.41
RMSE(V)	20.72	20.97
R(U)	0.690	0.722
R(V)	0.582	0.572

Fig. 10 (a) zonal velocity at the mooring buoy, and velocity averaged in August in (b) CNTL and (c) TEST

Validation (sea level)



	CNTL	TEST
RMSE	7.438	6.693
Corr.	0.815	0.856

At Miyake-jima island, TEST reproduce the SSH increase in August associated with the meander of the Kuroshio path.

Small disturbances along the Kuroshio path gradually developed, and propagated downstream. It improve the increase of SSH in August.

Fig. 11 (a) sea level at the Miyake-jima island, (b) SSH in TEST and (c) the difference between TEST and CNTL on 10th, 20th, 30th August 2016

Impact of the MSDH for the mean SSH in 2016

The patterns of SSH difference correspond to that of MSDH difference

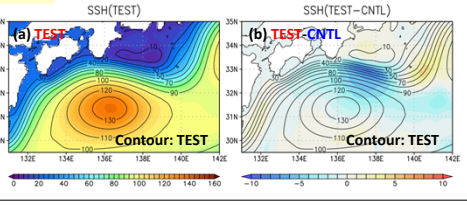


Fig. 8 (a) SSH averaged in 2016 in TEST and (b) the difference between TEST and CNTL

4. Summary

- New method for making the mean surface dynamic height (baroclinic component)
  - Combine in-situ profiles and SLAs with the correction of non-steric variations
  - Bias of the MSDH based on the in-situ profiles is small in the North Pacific
  - However, there is a significant difference along the Kuroshio path.
- The zonal velocity bias was reduced as the Kuroshio path separated from the coast.
- The effect of this improvement was propagated downstream as seen at the tide-gauge station.