Development of a four-dimensional variational assimilation system with a high-resolution coastal ocean model

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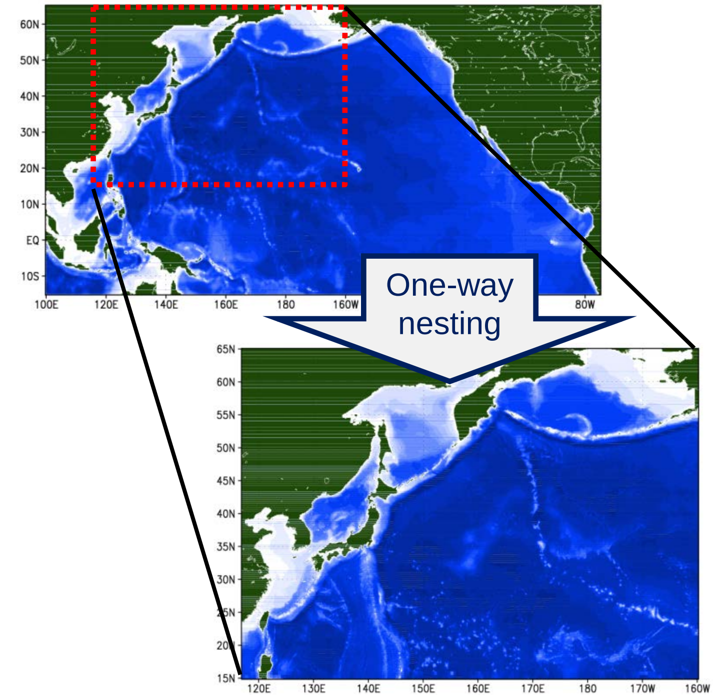
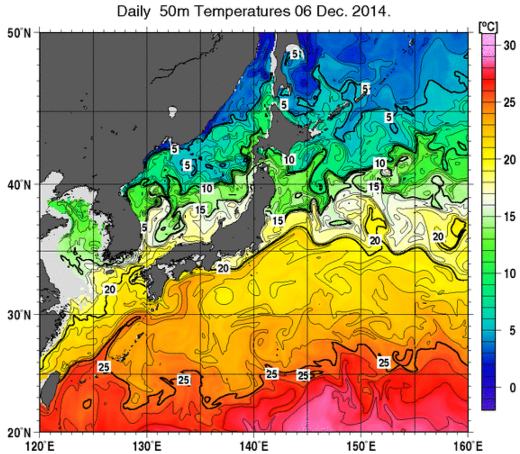
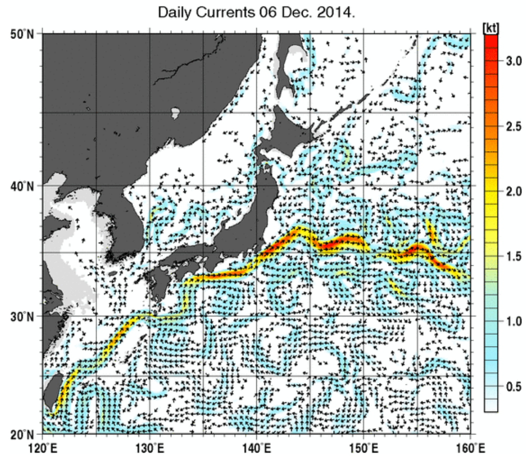
JMA operational ocean forecast system

MOVE/MRI.COM-WNP

- operated since 2008
- western North Pacific model
- **10km** resolution
- data assimilation with **3DVAR**
- targeting mesoscale phenomena in the open ocean (Kuroshio, Oyashio, mesoscale eddies,…)
- **cannot resolve coastal processes**

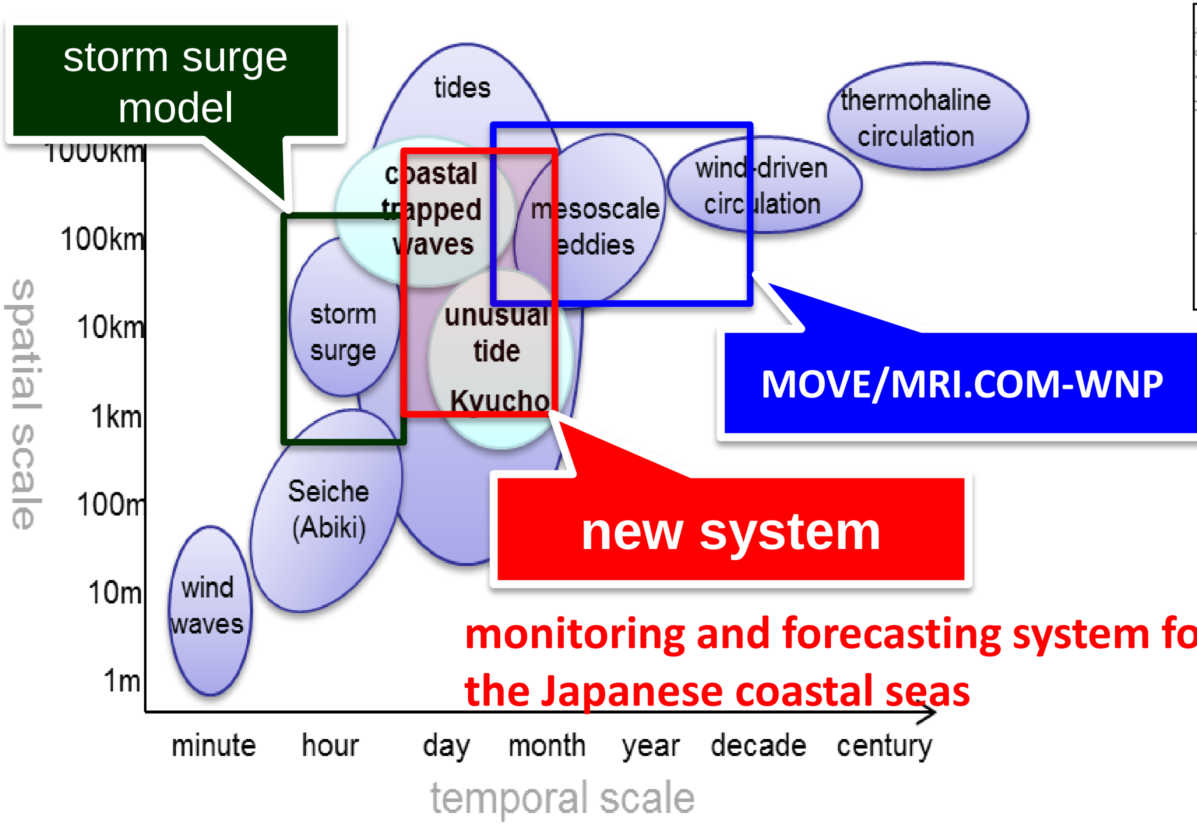




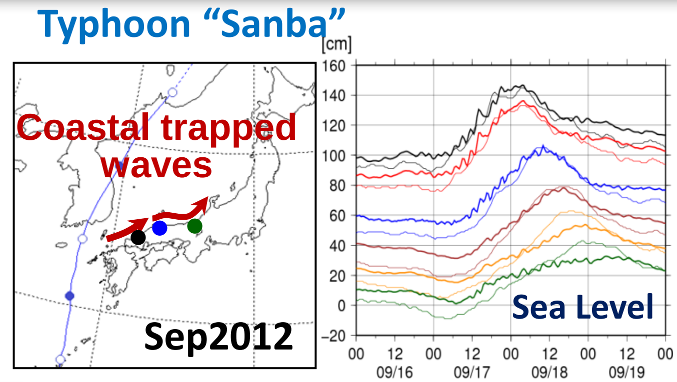


http://www.data.jma.go.jp/gmd/kaiyou/shindan/index.html

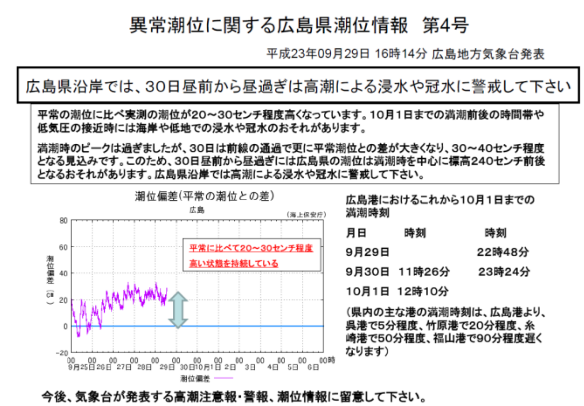
Need for coastal system



monitoring and forecasting system for the Japanese coastal seas



Sea-level information (Hiroshima local meteorological office)



異常潮位に関する広島県潮位情報　第4号

平成23年09月29日 16時14分 広島地方気象台発表

広島県沿岸では、30日昼前から昼過ぎは高潮による浸水や冠水に警戒して下さい

平常の潮位に比べ実測の潮位が20～30センチ程度高くなっています。10月1日までの満潮前後の時間帯や低気圧の接近時には海岸や低地での浸水や冠水のおそれがあります。

満潮時のピークは過ぎましたが、30日は前線の通過で更に平常潮位との差が大きくなり、30～40センチ程度となる見込みです。このため、30日昼前から昼過ぎには広島県の潮位は満潮時を中心に標高240センチ前後となるおそれがあります。広島県沿岸では高潮による浸水や冠水に警戒して下さい。

潮位偏差(平常の潮位との差)

広島　(海上保安庁)

平常に比べて20～30センチ程度高い状態を持続している

潮位偏差

広島港におけるこれから10月1日までの満潮時刻

月日	時刻	時刻
9月29日		22時48分
9月30日	11時26分	23時24分
10月1日	12時10分	

(県内の主な港の満潮時刻は、広島港より、呉港で5分程度、竹原港で20分程度、糸崎港で50分程度、福山港で90分程度遅くなります)

今後、気象台が発表する高潮注意報・警報、潮位情報に留意して下さい。

Observations used for ocean data assimilation

☐ Satellite altimeter

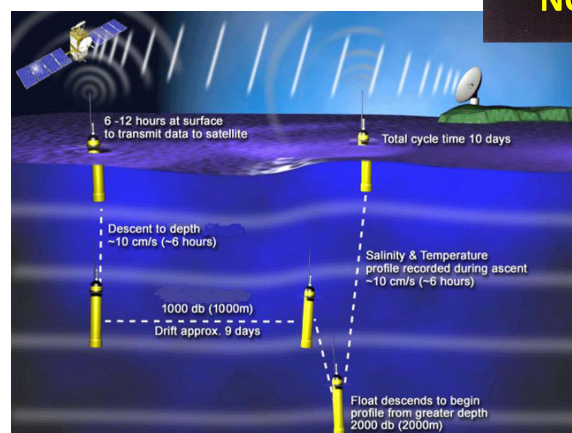
- TOPEX/Poseidon, Jason-1/2/3
- ERS-1/2, Envisat, Cryosat-2
- GFO, SARAL/AltiKa, HY-2

☐ Satellite SST

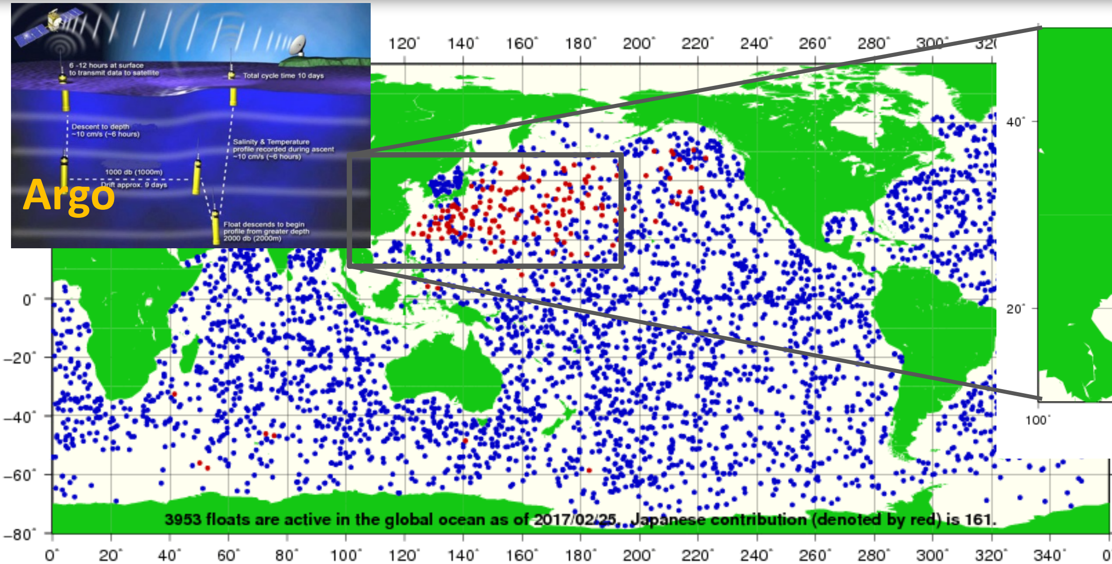
- NOAA/AVHRR
- AQUA/AMSR-E
- Himawari/AHI

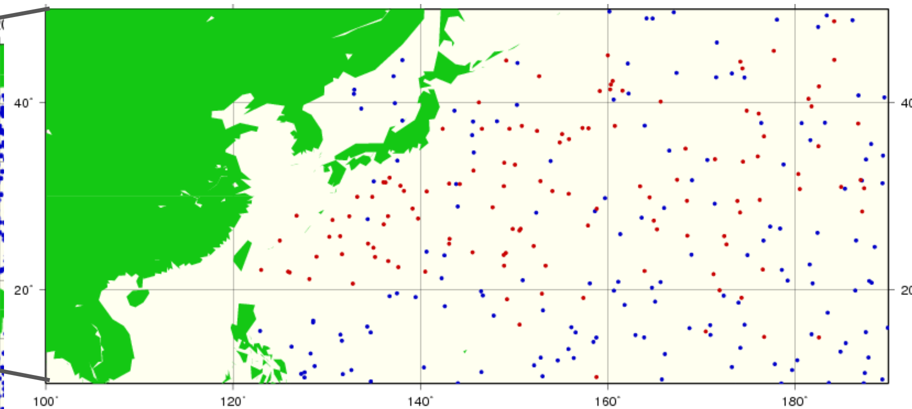
☐ In-situ observations (T and S)

- Argo
- Ship
- Buoy
- …



Observations used for ocean data assimilation

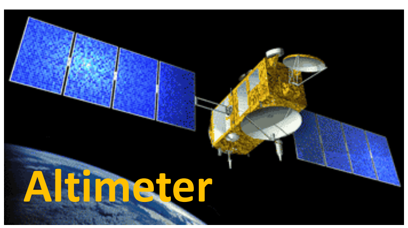


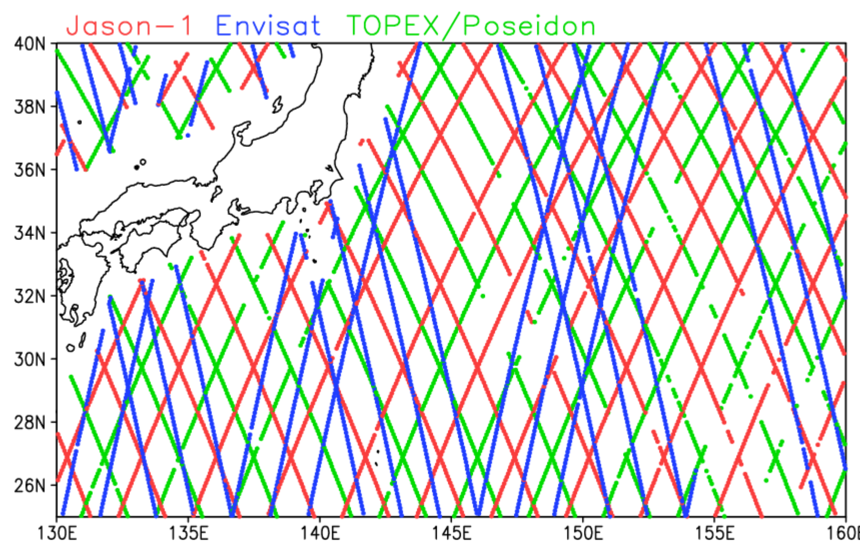


Positions of floats (Feb 25, 2017)

http://ds.data.jma.go.jp/gmd/argo/data/indexJ.html

Few observations in coastal waters





Jason-1
Envisat
T/P

(11-20AUG2004)

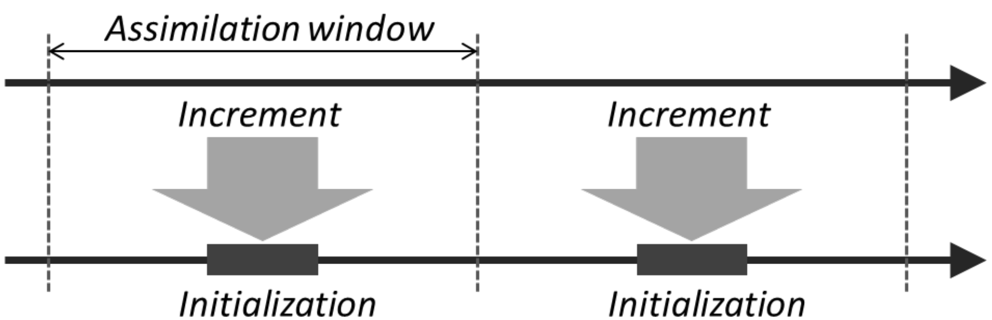
A strategy for a coastal system

- **Analysis model**
  - Basin-scale model with a **10km** resolution (eddy-resolving)
  - **4D-Var** assimilation scheme (upgrade from the previous 3D-Var)
    - Aims at improving **short-term mesoscale** variability
- **Forecast model**
  - High resolution (~**2km**) coastal model
  - Use of up-to-date schemes
  - **Initialized** with analysis model results

Assimilation cycle:

Analysis model (10km)

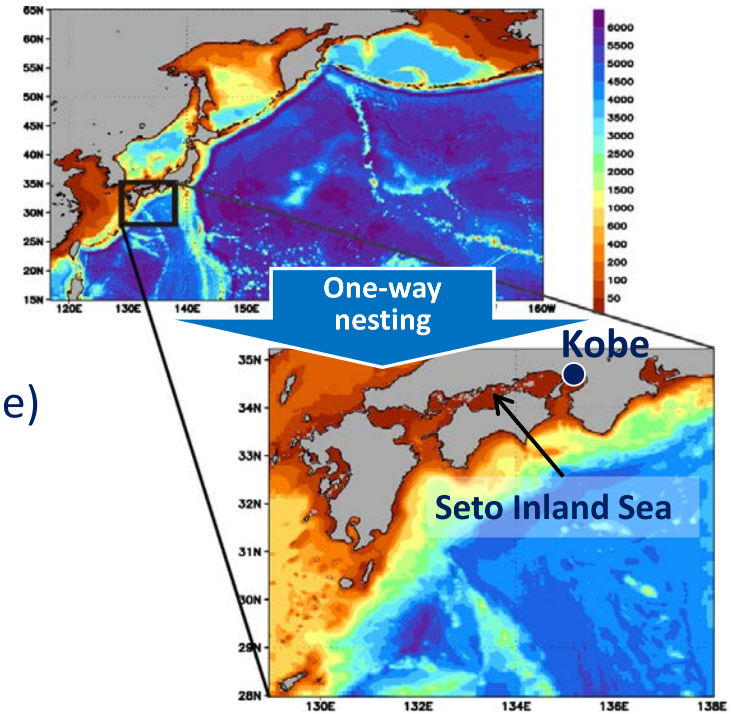
Forecast model (2km)



Plan for development of coastal systems

Target area:

- **Seto Inland Sea (MOVE/MRI.COM-Seto)**
  - **2km** coastal model (MRI.COM-Seto)
  - **4DVAR** analysis model with 10km grid in the western North Pacific (MOVE-4DVAR-WNP)
  - implemented at JMA in June 2016 (now trial phase)



Roadmap

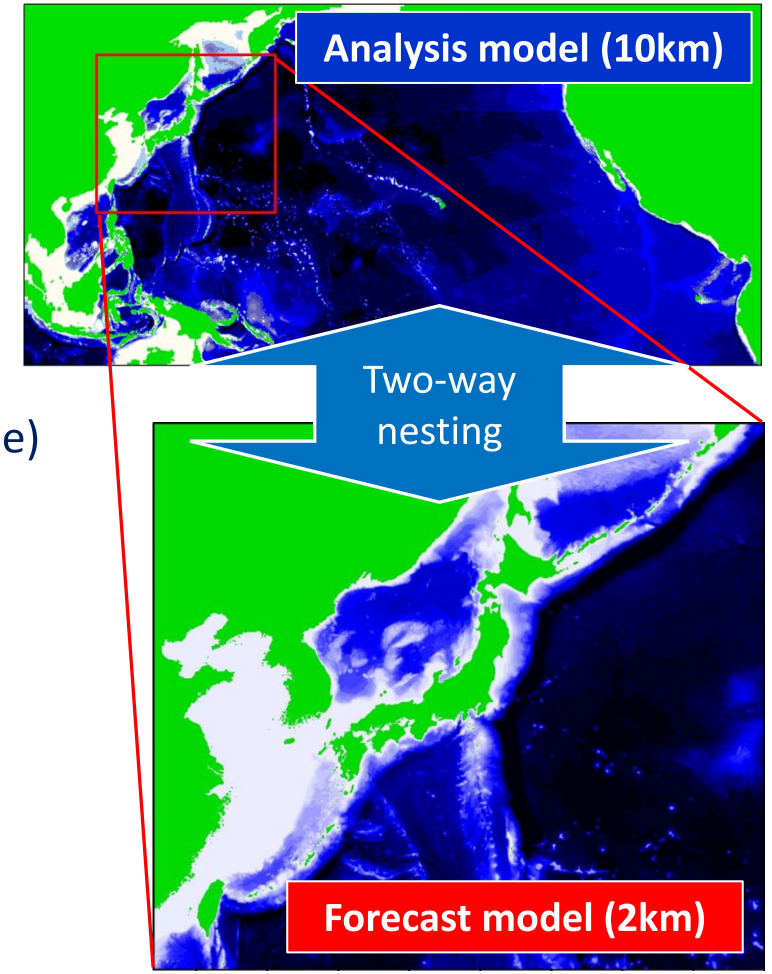
June 2016-

MOVE/MRI.COM-Seto

Plan for development of coastal systems

Target area:

- **Seto Inland Sea (MOVE/MRI.COM-Seto)**
  - **2km** coastal model (MRI.COM-Seto)
  - **4DVAR** analysis model with 10km grid in the western North Pacific (MOVE-4DVAR-WNP)
  - implemented at JMA in June 2016 (now trial phase)
- **Whole coastal regions of Japan (MOVE/MRI.COM-Jpn)**
  - Model Japan with **2km** resolution (MRI.COM-Jpn)
  - **4DVAR** analysis model in the North Pacific (MOVE-4DVAR-NP)



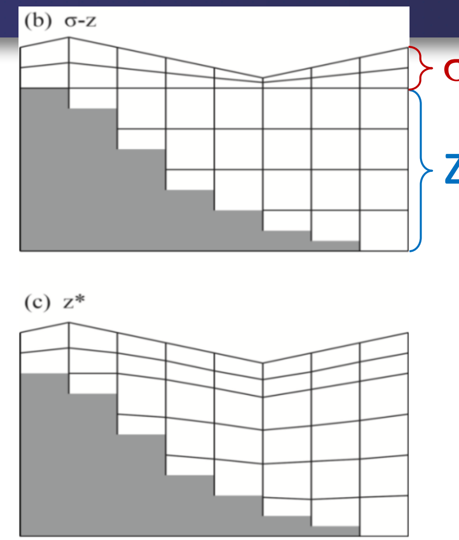
Roadmap

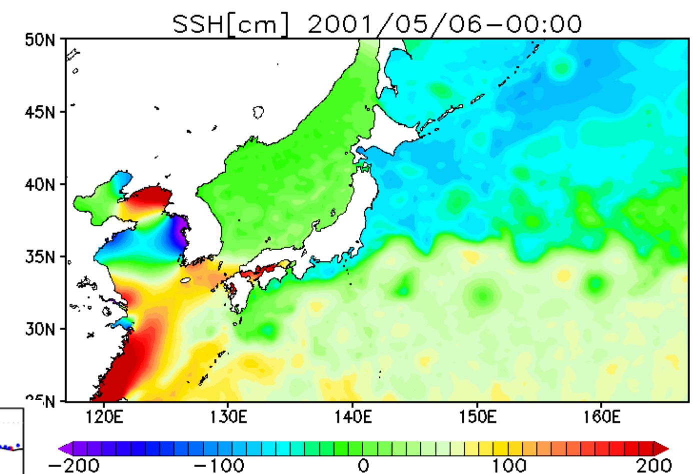
June 2016- MOVE/MRI.COM-Seto

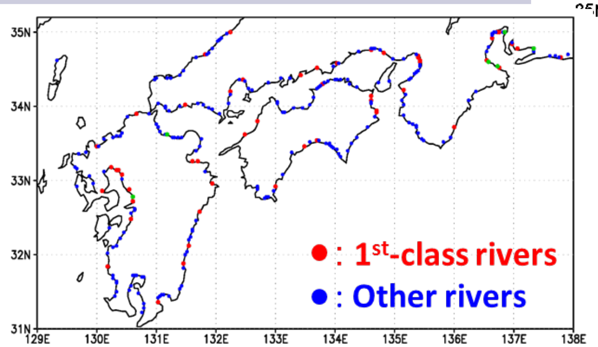
Several years later MOVE/MRI.COM-Jpn

Coastal Ocean Model

Model	MRI Community Ocean Model ver. 4 (MRI.COM; Tsujino et al. 2011)
Coordinates	free surface, z*-coordinate
Hori. resolution	1/33° ×1/50° (~2km)
Vert. resolution	2-700m (60 levels)
Tracer advection	Second-order Momentum closure (Prather 1986)
Hori. mixing	Smagrosinky bi-harmonic
Vert. mixing	Generic length-scale (GLS; Umlauf and Burchard 1999)
Tides	Explicit tidal forcing (Sakamoto et al. 2013)
Nesting	Online two-way nesting
River run-off	JMA Runoff Index (JMARI)
Sea ice	Multi-category sea ice model







Location of river mouths

3DVAR scheme in MOVE/MRI.COM-WNP

3DVAR with vertically coupled temperature-salinity (T-S) EOF modes

- **Cost function:**

$$J(\mathbf{z}) = \frac{1}{2}\mathbf{z}^T \mathbf{B}_H{}^{-1}\mathbf{z} + \frac{1}{2}\left[\mathbf{Hx}(\mathbf{z}) - \mathbf{y}^{\mathrm{TS}}\right]^T \mathbf{R}^{-1}\left[\mathbf{Hx}(\mathbf{z}) - \mathbf{y}^{\mathrm{TS}}\right] + \frac{1}{2\sigma_h^2}\left[\mathcal{H}(\mathbf{x}(\mathbf{z})) - \mathbf{y}^{\mathrm{SLA}}\right]^T \left[\mathcal{H}(\mathbf{x}(\mathbf{z})) - \mathbf{y}^{\mathrm{SLA}}\right] + J_c$$

Deviation from first guess

Deviation from T S observation

Deviation from altimetry data

Constraints

→Optimize T and S fields

$\mathbf{z}$	Amplitudes of vertically coupled T-S EOF modes ← control variables
$\mathbf{x}$	Temperature and salinity analyses
$\mathbf{B}_H$	Horizontal correlation matrix for background errors
$\mathbf{R}$	Observation error covariance matrix for in-situ T-S profiles
σ_h	Observation error for altimeter-derived sea-level anomalies
$\mathbf{y}^{\mathrm{TS}}$	T-S profile data
$\mathbf{y}^{\mathrm{SLA}}$	Altimeter-derived sea level anomaly

Background error covariance matrix

Background term: $J_b = \frac{1}{2}\mathbf{z}^T \mathbf{B}_H{}^{-1}\mathbf{z}$

Background error covariance matrix: $\mathbf{B}$

$$\frac{1}{2}\Delta\mathbf{x}^{\mathrm{T}}\overbrace{[\mathbf{SU\Lambda B}_H\mathbf{\Lambda US}]}^{\mathbf{B}}{}^{-1}\Delta\mathbf{x}$$

$$= \frac{1}{2}\underbrace{\left(\mathbf{\Lambda}^{-1}\mathbf{U}^{\mathrm{T}}\mathbf{S}^{-1}\Delta\mathbf{x}\right)}_{=\mathbf{z}}{}^{\mathrm{T}}\mathbf{B}_H^{-1}\underbrace{\left(\mathbf{\Lambda}^{-1}\mathbf{U}^{\mathrm{T}}\mathbf{S}^{-1}\Delta\mathbf{x}\right)}_{=\mathbf{z}}$$

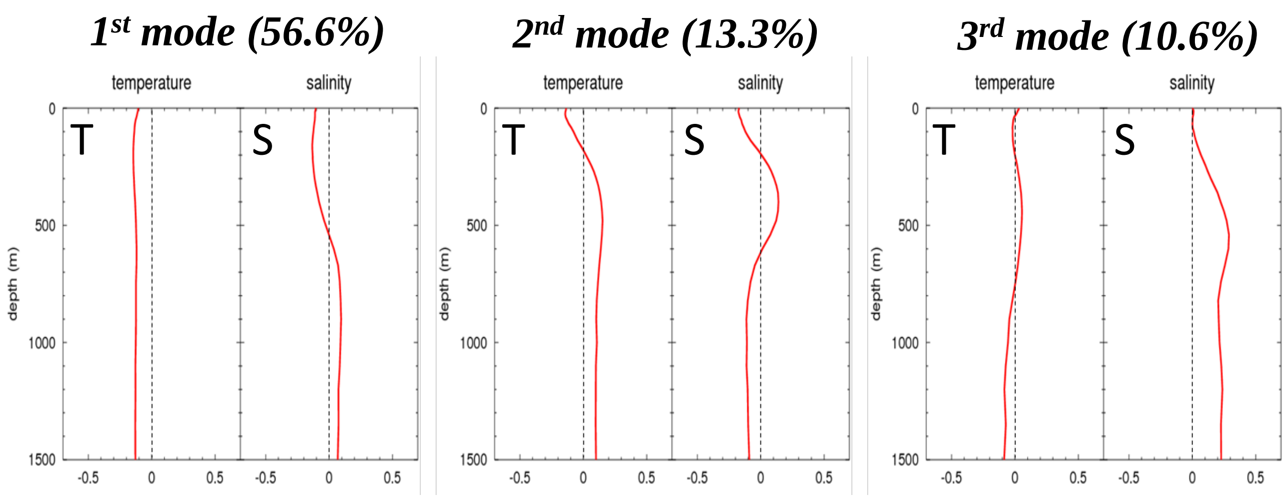
→ Analysis increment (T and S):

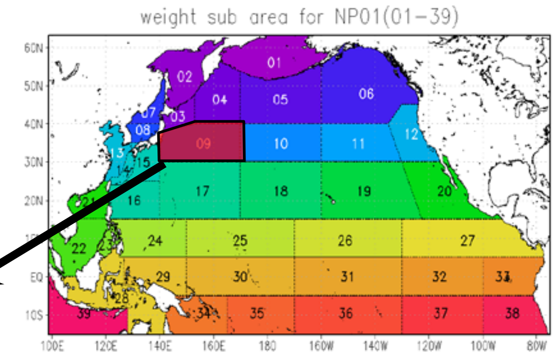
$$\Delta\mathbf{x} = \mathbf{x} - \mathbf{x}^b$$
$$= \mathbf{SU\Lambda z}$$

$\mathbf{z}$	Amplitudes of **vertically coupled T-S EOF modes** ← **control variables**
$\Delta\mathbf{x}$	T-S increments (= $\mathbf{x} - \mathbf{x}^b$)
$\mathbf{B}_H$	Horizontal correlation matrix for background errors
$\mathbf{S}$	Diagonal matrix composed of background standard errors
$\mathbf{U}$	Orthogonal matrix composed of dominant **T-S EOF modes**
$\mathbf{\Lambda}$	Diagonal matrix composed of singular values for **T-S EOF modes**

Background error covariance matrix

■ Vertical direction → Vertically coupled T-S EOF modes



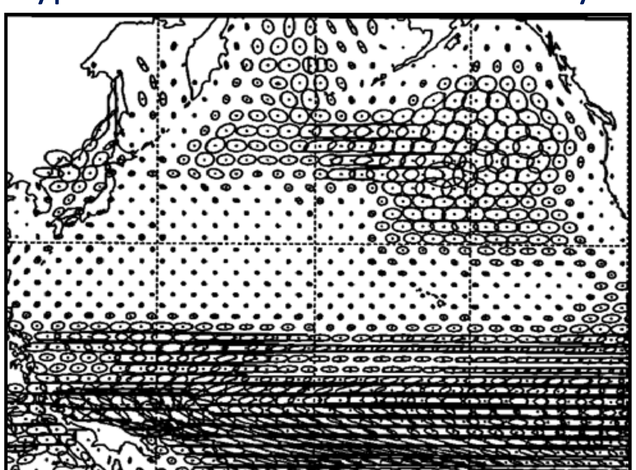


Subareas for T-S EOFs

■ Horizontal direction → Gaussian function

- Gaussian ellipsoid model with parameters of zonal and meridional correlation scales
- Correlation scales are determined each subregion

Typical scale of oceanic variability



Kuragano and Kamachi (2000)

Extension of 3D-Var to 4D-Var

3D-Var

$$J(\mathbf{z}) = \frac{1}{2}\mathbf{z}^T\mathbf{B}_H{}^{-1}\mathbf{z} + \frac{1}{2}\left[\mathbf{Hx}(\mathbf{z}) - \mathbf{y}^{\mathrm{TS}}\right]^T \mathbf{R}^{-1}\left[\mathbf{Hx}(\mathbf{z}) - \mathbf{y}^{\mathrm{TS}}\right] + \frac{1}{2\sigma_h^2}\left[\mathcal{H}(\mathbf{x}(\mathbf{z})) - \mathbf{y}^{\mathrm{SLA}}\right]^T\left[\mathcal{H}(\mathbf{x}(\mathbf{z})) - \mathbf{y}^{\mathrm{SLA}}\right] + J_c$$

$$\Delta\mathbf{x} = \mathbf{x} - \mathbf{x}^b = \mathbf{SU\Lambda z}$$

4D-Var

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

$$\mathbf{x}_i = M_{i-1}(\mathbf{x}_{i-1}) + \underbrace{g_i\Delta\mathbf{x}}_{\text{correction term}} \qquad g_i = \begin{cases} 1/\tau & (0 < i \le \tau) \\ 0 & (\tau < i) \end{cases}$$

$$\Delta\mathbf{x} = \mathbf{SU\Lambda z}$$

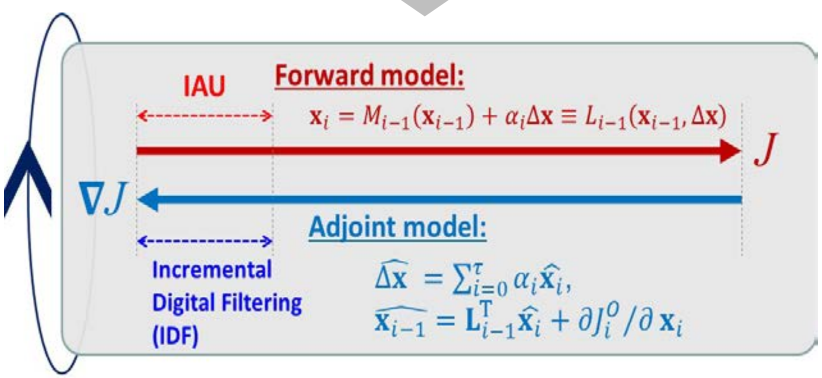
(τ : Initialization period)

- Control variables are $\boldsymbol{z}$ (amplitude of vertically coupled T-S EOF modes)
  → Same **B** matrix as that in the 3DVAR system
- Incorporates an initialization scheme of Incremental Analysis Update (IAU)

Combination use of 3D-Var and 4D-Var

Standard 4D-Var

Initial increment : $\Delta\mathbf{x} = \mathbf{0}$



Optimal increment : $\Delta\mathbf{x}^a$

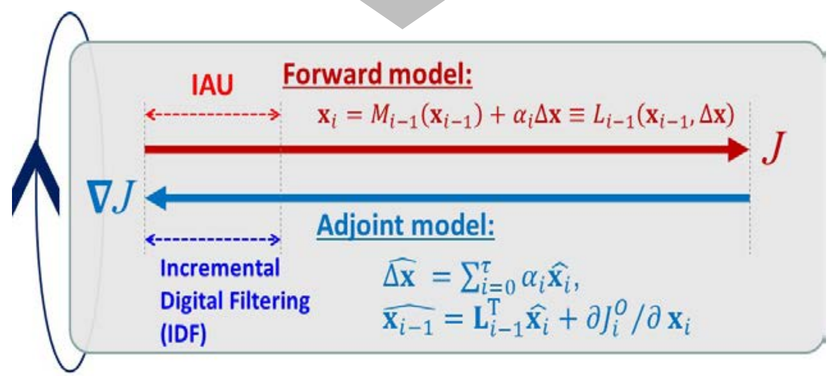
Analysis value :

$$\mathbf{x}_i^a = M_{i-1}(\mathbf{x}_{i-1}) + g_i \Delta\mathbf{x}^a$$

4D-Var starting with 3D-Var

Perform 3D-Var

Initial increment : $\Delta\mathbf{x}_{\mathrm{3DVAR}}$



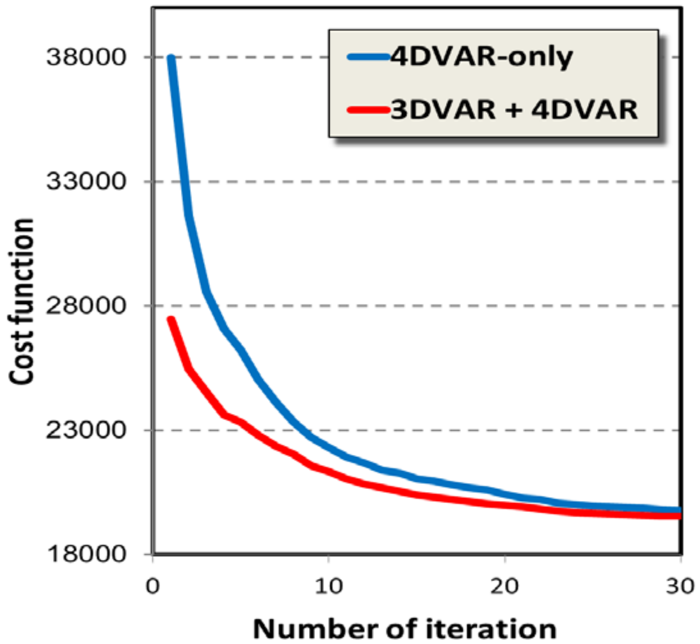
Optimal increment : $\Delta\mathbf{x}^a$

Analysis value :

$$\mathbf{x}_i^a = M_{i-1}(\mathbf{x}_{i-1}) + g_i \Delta\mathbf{x}^a$$

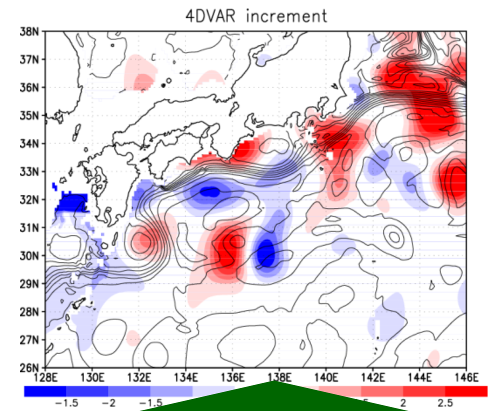
Combination use of 3D-Var and 4D-Var

Cost function

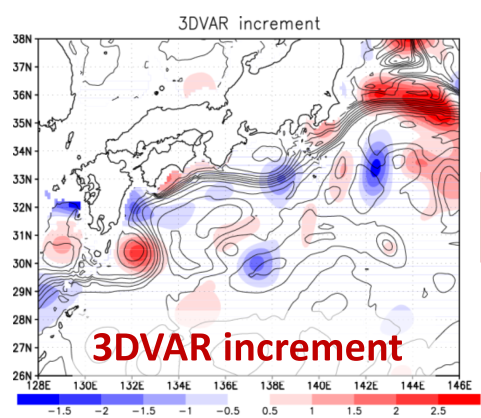


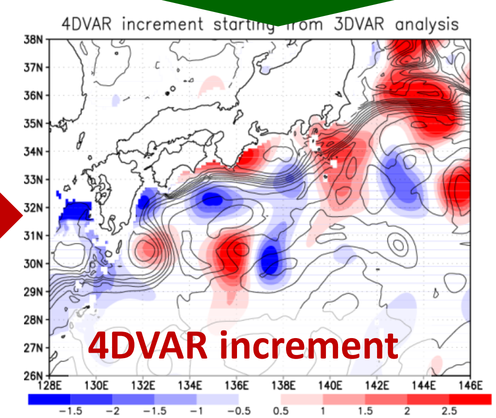
Analysis increment for T400

4DVAR-only

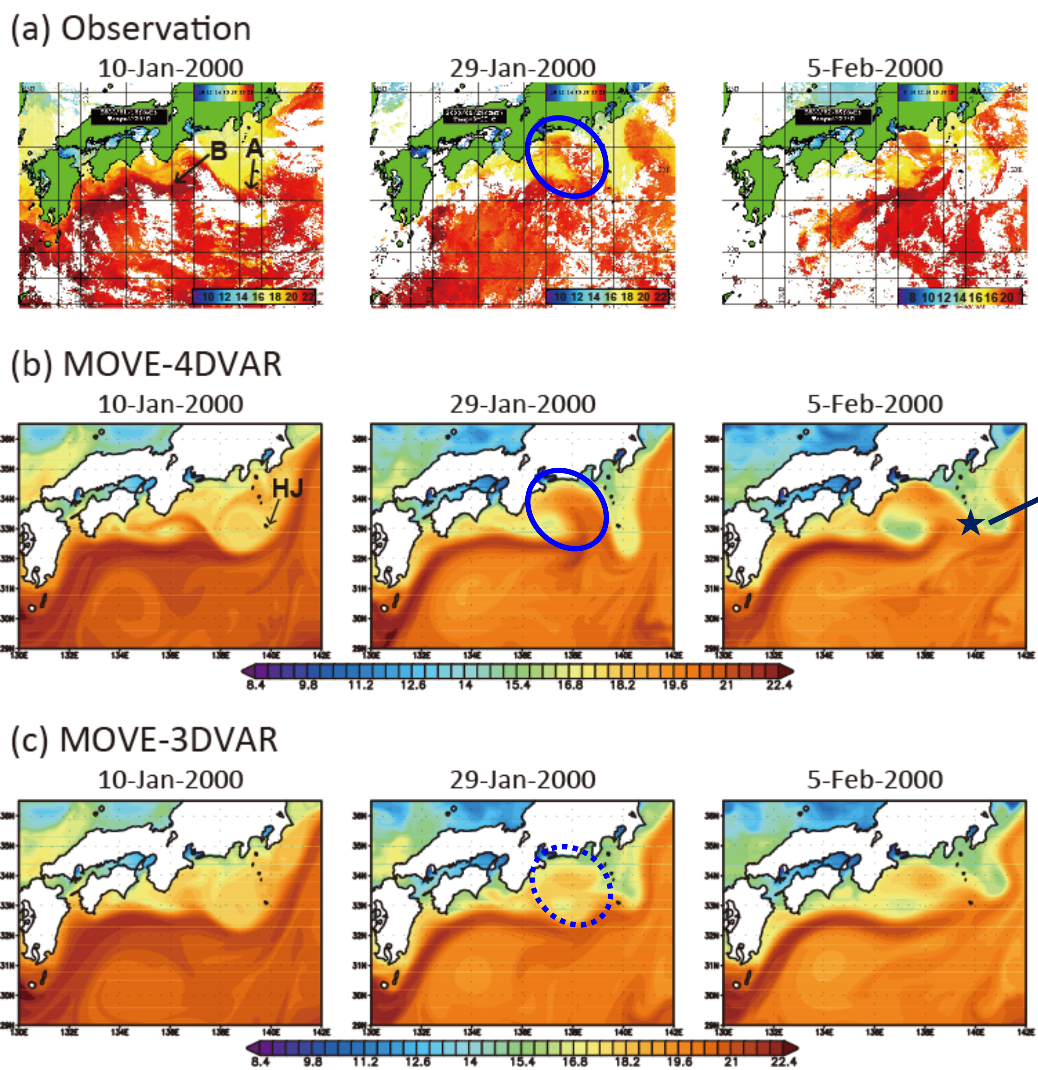


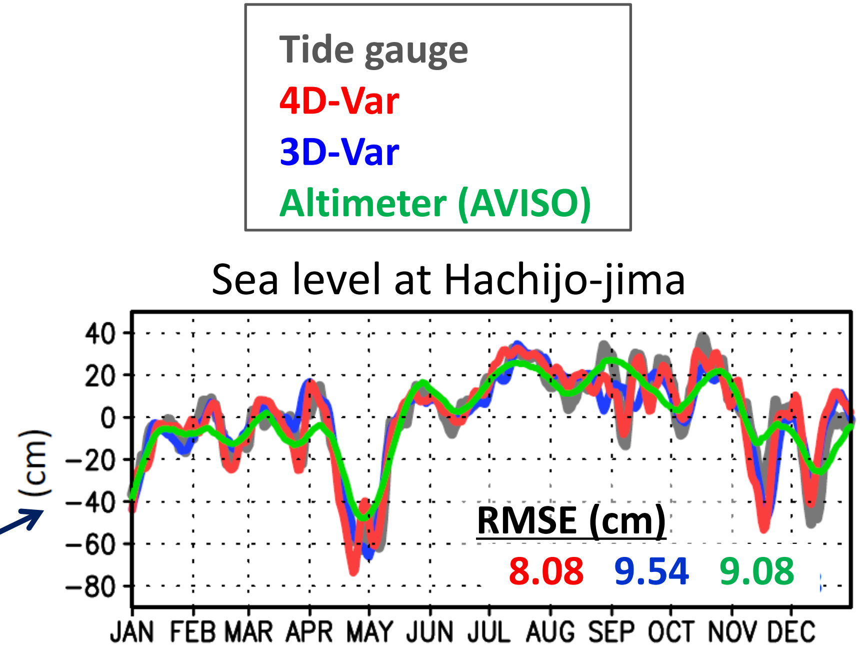
3DVAR + 4DVAR



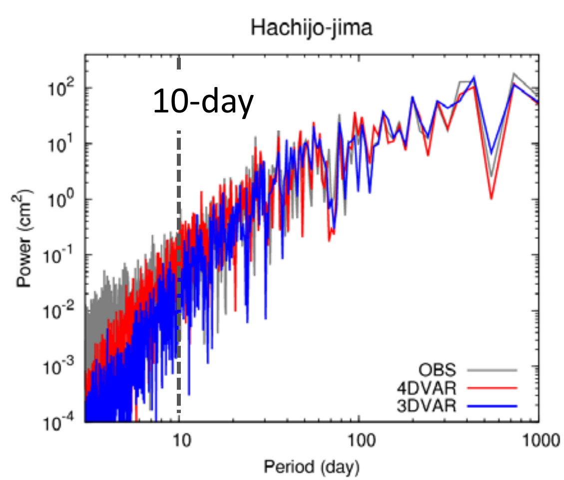


Comparison of 3D-Var and 4D-Var





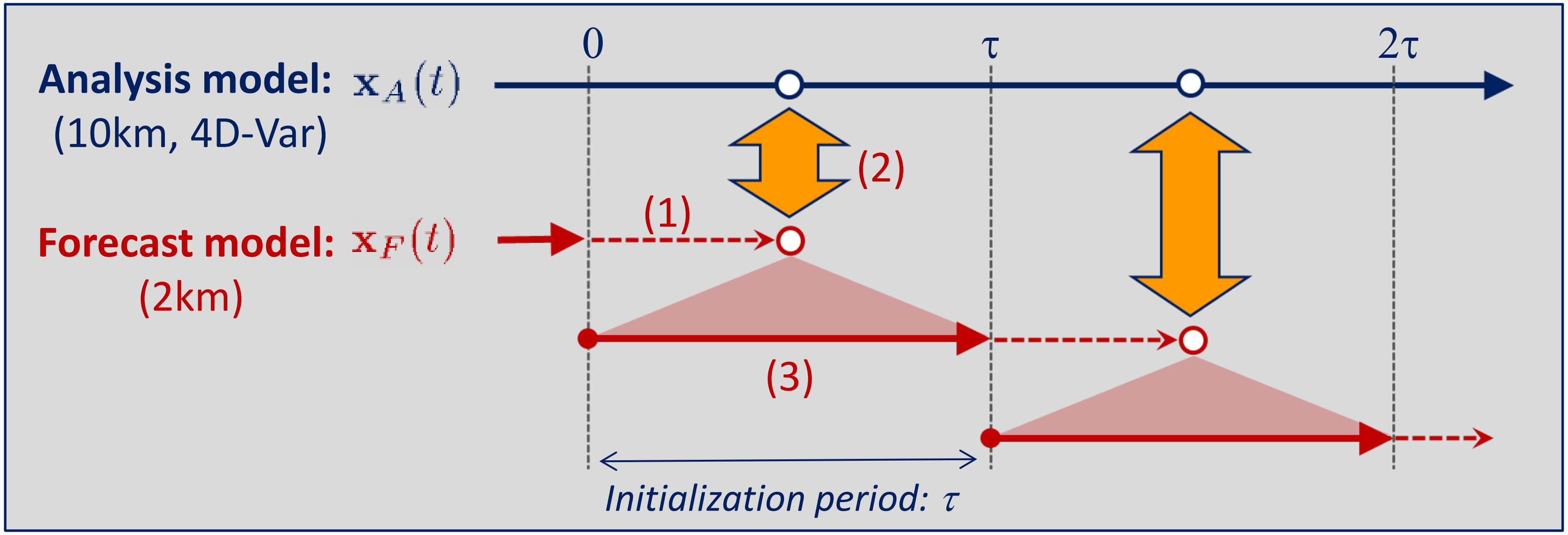
Usui et al (2016)



Usui et al (2015)

Initialization of the forecast model

Incremental Analysis Update (IAU; Bloom et al. 1996)



(1) Integrate the forecast model during [0, τ/2]

$$\frac{\partial \mathbf{x}_F(t)}{\partial t} = \mathcal{M}\left[\mathbf{x}_F(t)\right]$$

(2) Take model-analysis misfit after a spatial interpolation of $\mathbf{x}_A$ and determine increment

$$\Delta \mathbf{x}_F = \frac{\tilde{\mathbf{x}}_A(\tau/2) - \mathbf{x}_F(\tau/2)}{\tau}$$

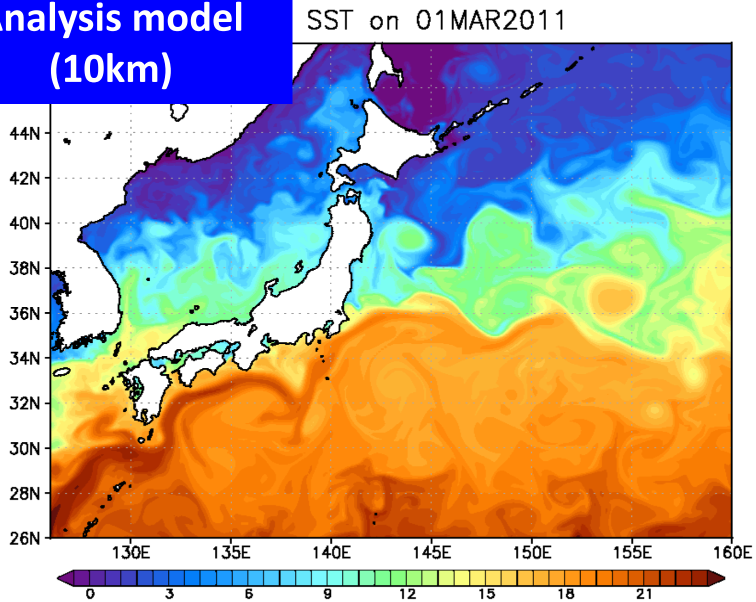
$\tilde{\mathbf{x}}_A$: interpolated to $\mathbf{x}_F$ space

(3) Again integrate the forecast model with correction term during [0, τ]

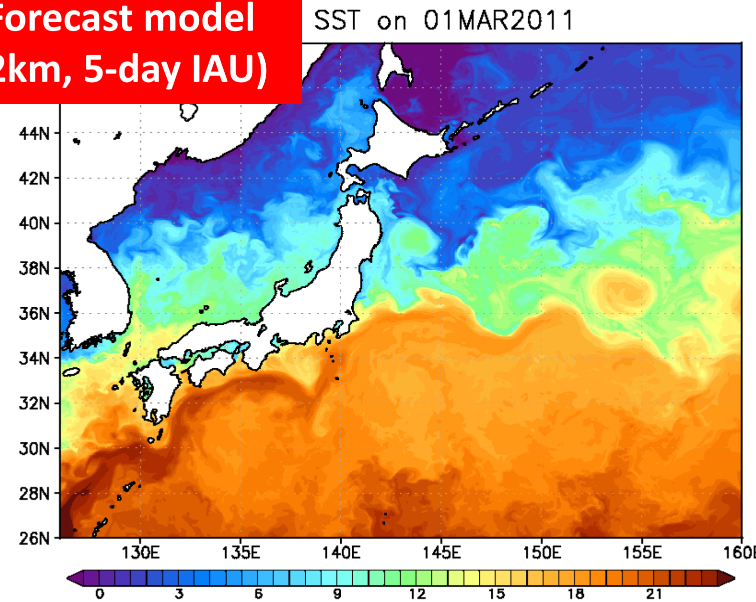
$$\frac{\partial \mathbf{x}_F(t)}{\partial t} = \mathcal{M}\left[\mathbf{x}_F(t)\right] + \Delta \mathbf{x}_F$$

Comparison of SST fields

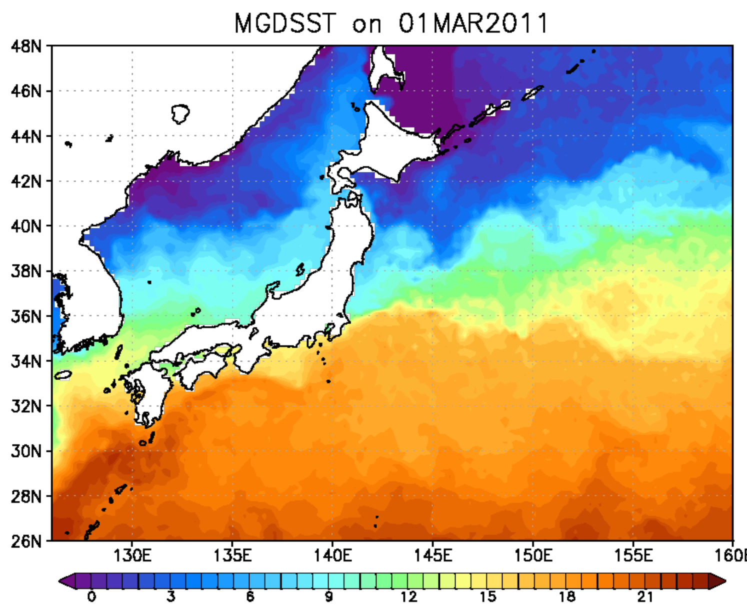
Analysis model (10km)



Forecast model (2km, 5-day IAU)

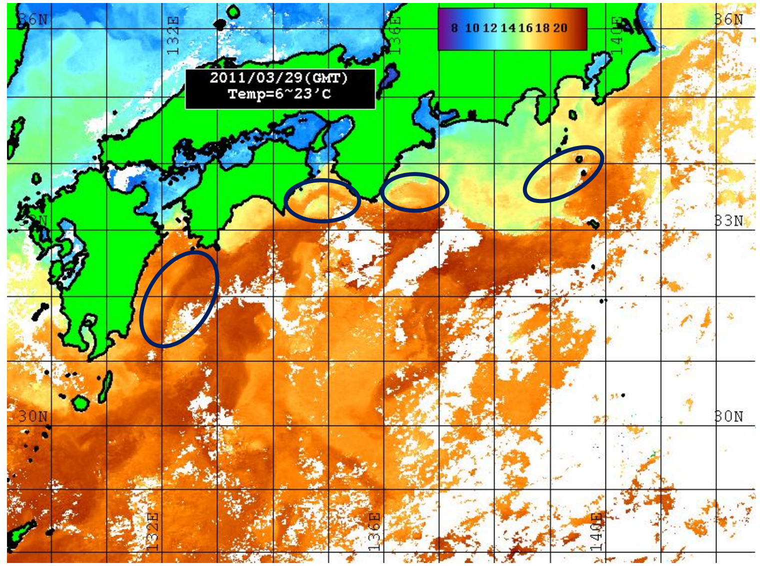


Satellite-based SST map (MGDSST ~25km)



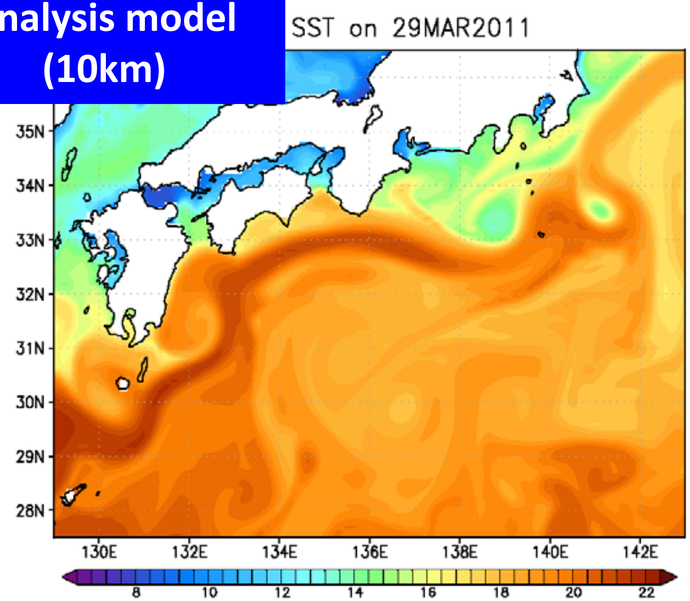
Comparison of snapshot SST

Satellite SST image (NOAA/AVHRR)

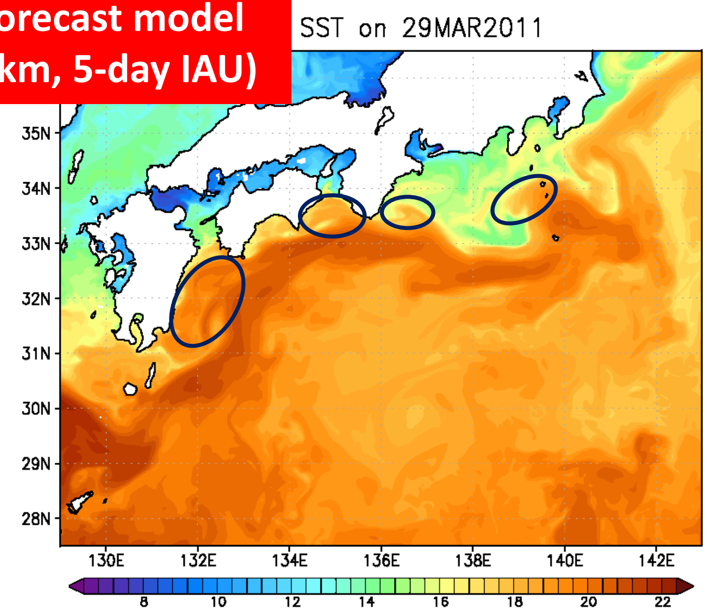


http://www.mpstpc.pref.mie.lg.jp/sui/kaikyo/detail.htm

Analysis model (10km)

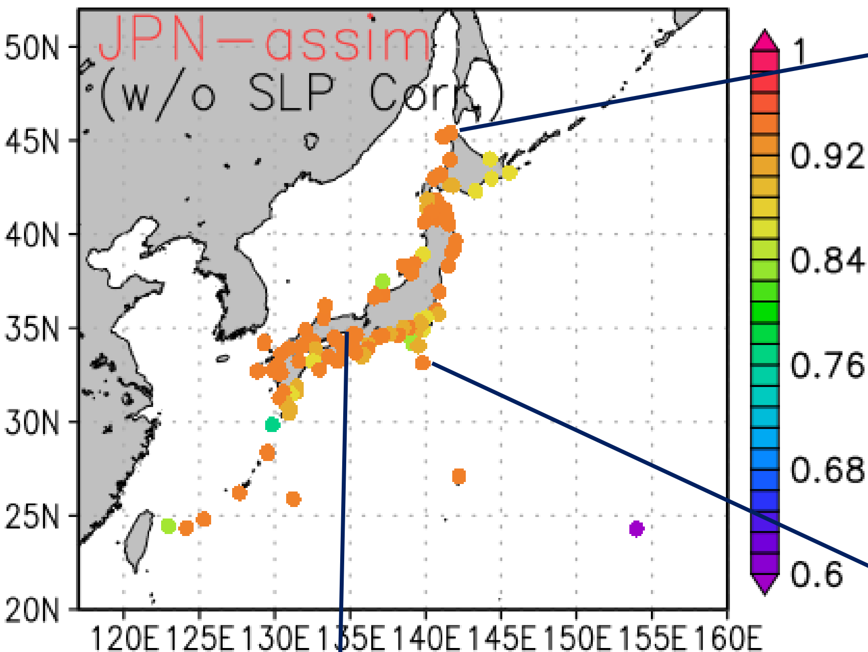


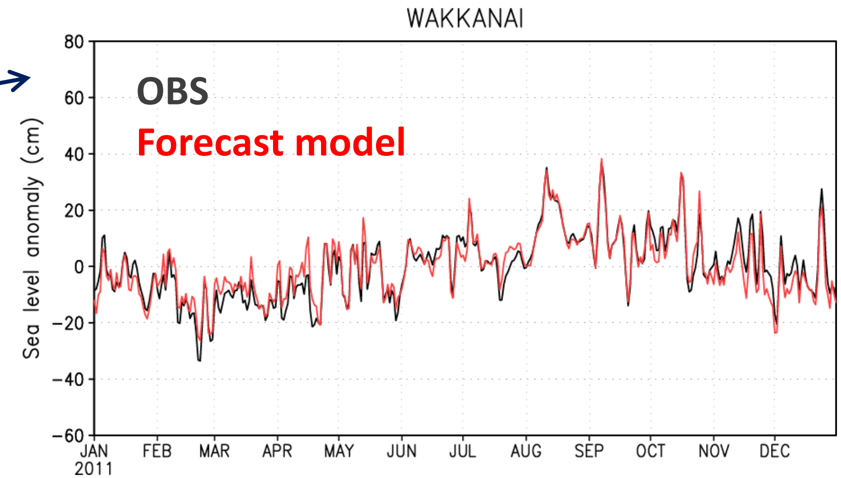
Forecast model (2km, 5-day IAU)

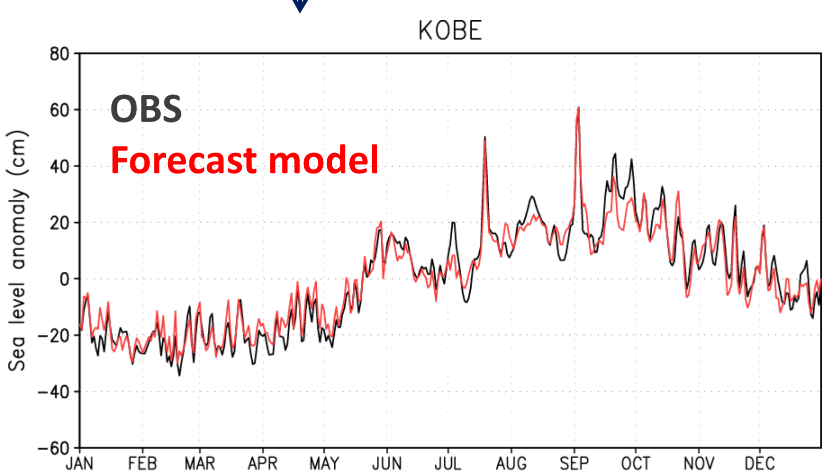


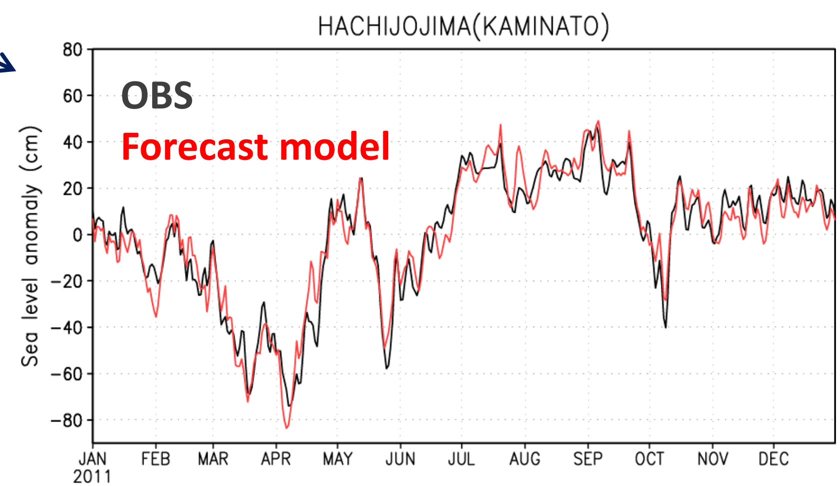
Coastal Sea Level

Correlation with tide-gauge data







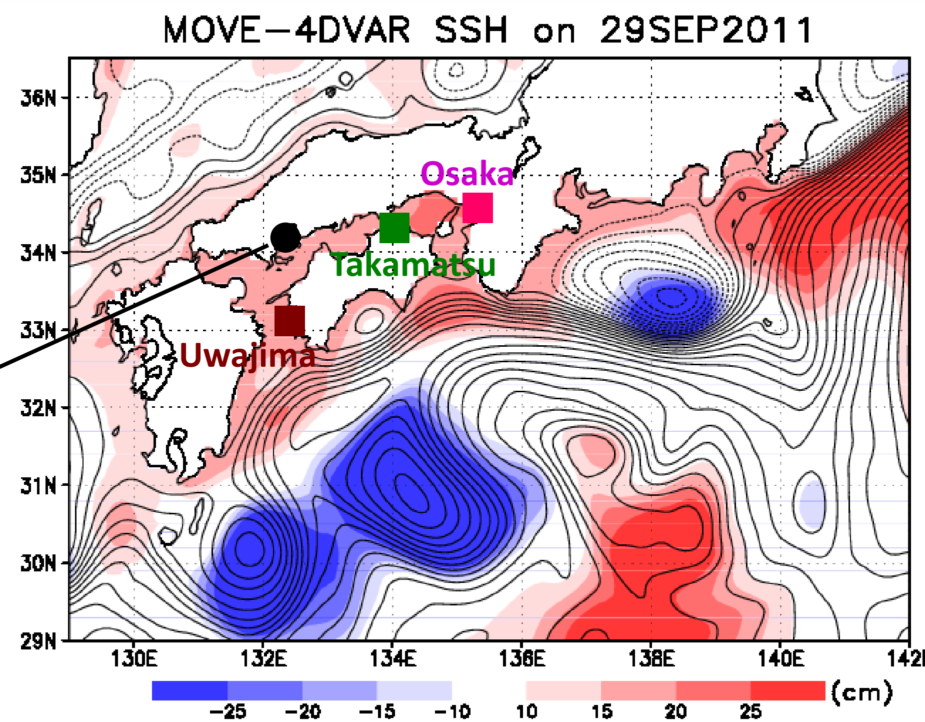


Tide-gauge data are not assimilated

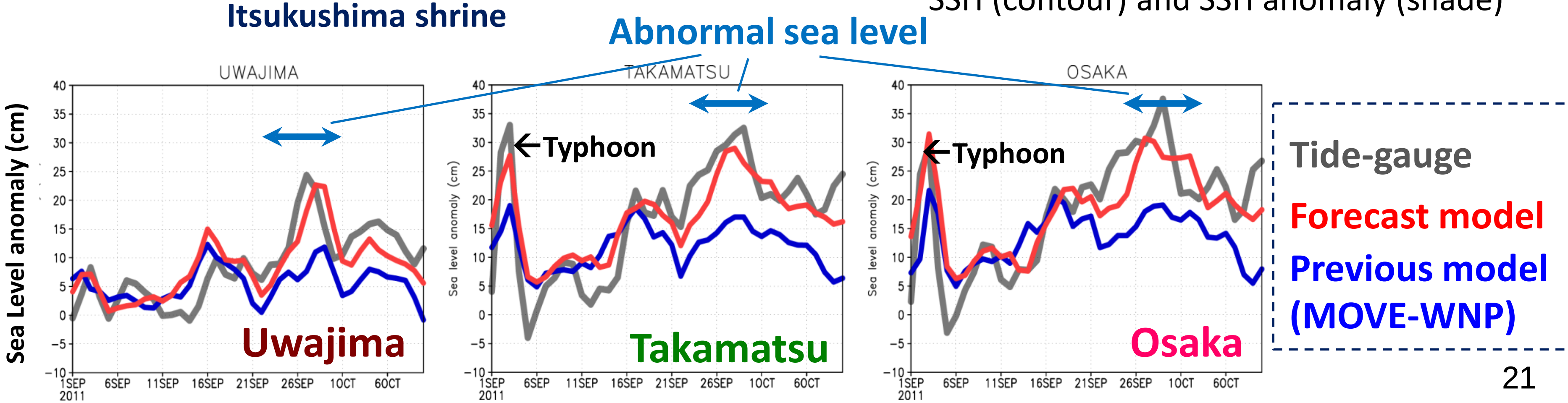
Abnormal high sea level in September 2011

- SLAs exceed 30cm at south coast of Japan in the end of Sep 2011

Itsukushima shrine

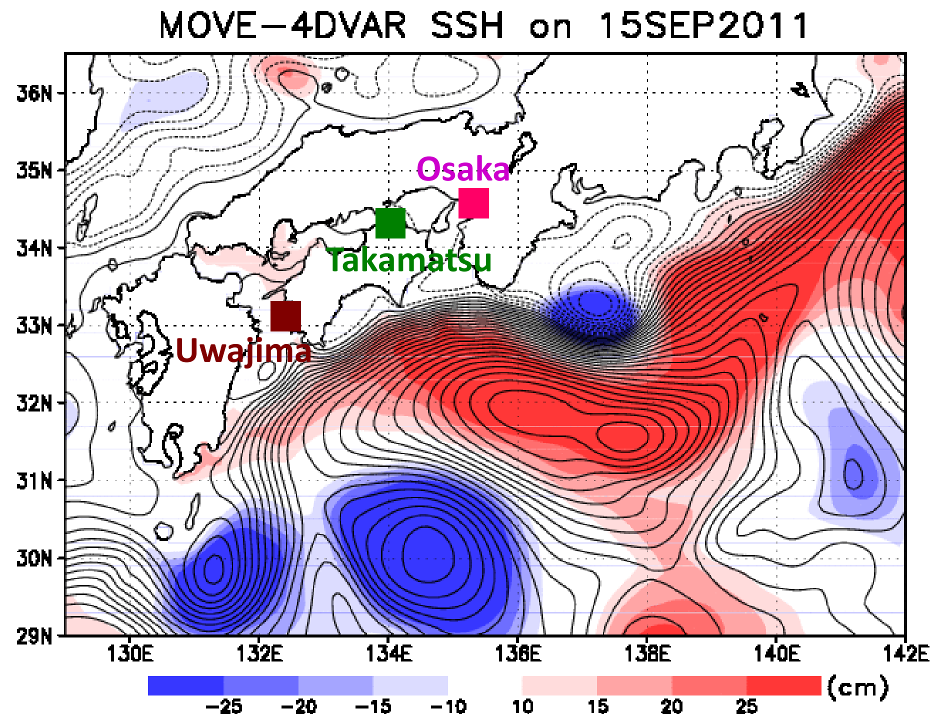


SSH (contour) and SSH anomaly (shade)

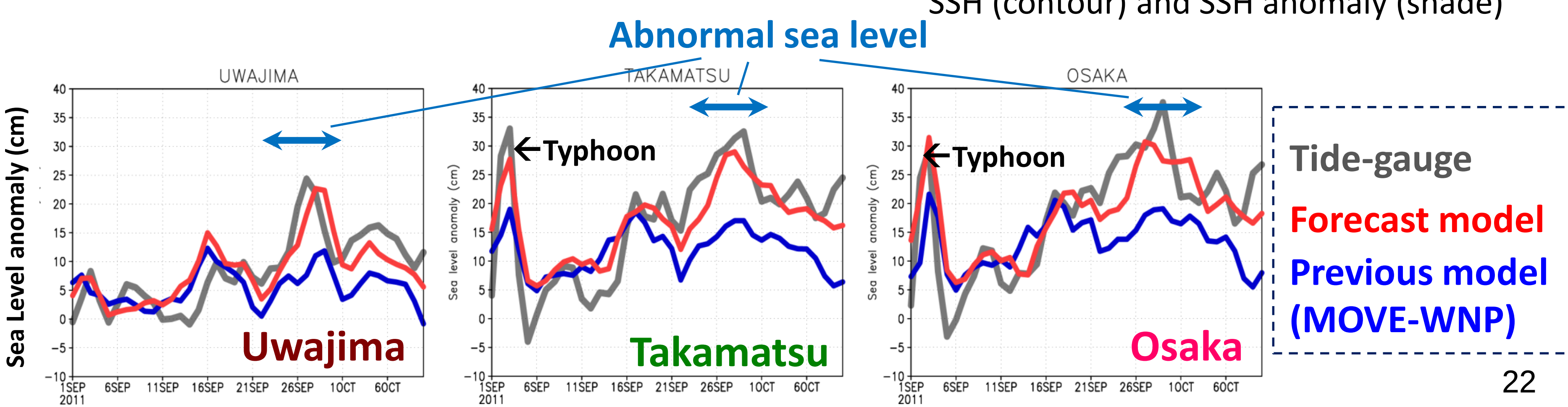


Abnormal high sea level in September 2011

- SLAs exceed 20cm at south coast of Japan in the end of Sep 2011
- The forecast model succeeded in reproducing this event
- The sea-level rise was caused by coastal trapped waves induced by a Kuroshio path fluctuation



SSH (contour) and SSH anomaly (shade)



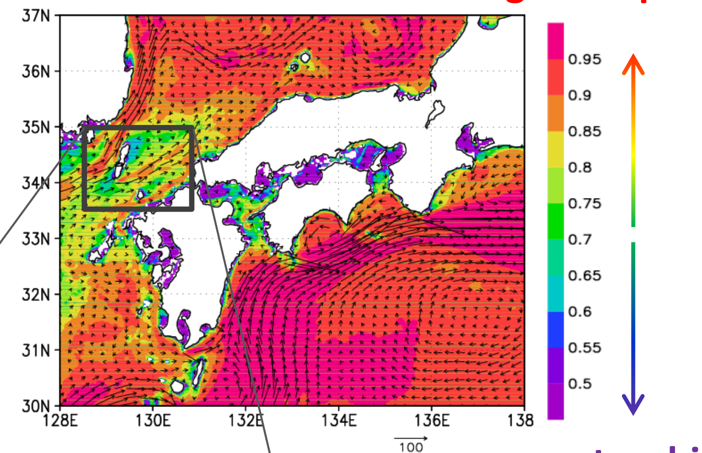
Toward coastal scale DA

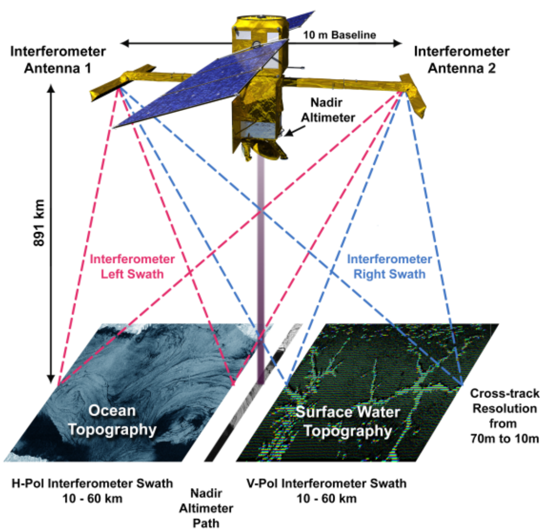
- Relative importance of different observations
  - **Mesoscale (O(100km): T and S obs are effective**
  - **Coastal scale (O(10km)): Velocity obs are effective**
    - **→ enable to estimate ageostrophic currents**

- Velocity observations for coastal scale DA:
  - HF radars
  - High-resolution 2D SSH (SWOT, COMPIRA)

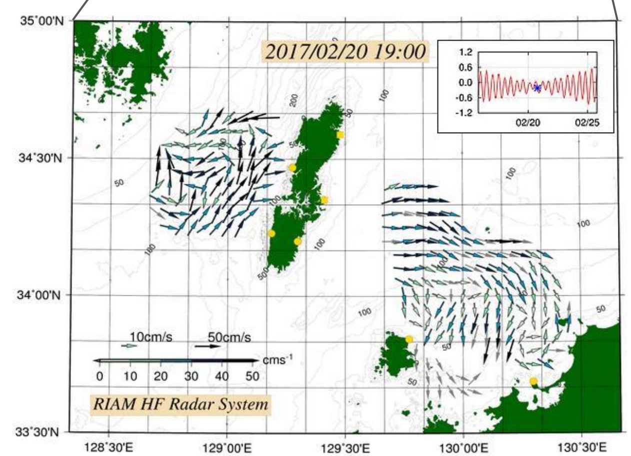
Vector correlation between v and v_g

$$\mathbf{v} = \mathbf{v}_g + \mathbf{v}_{ag}$$





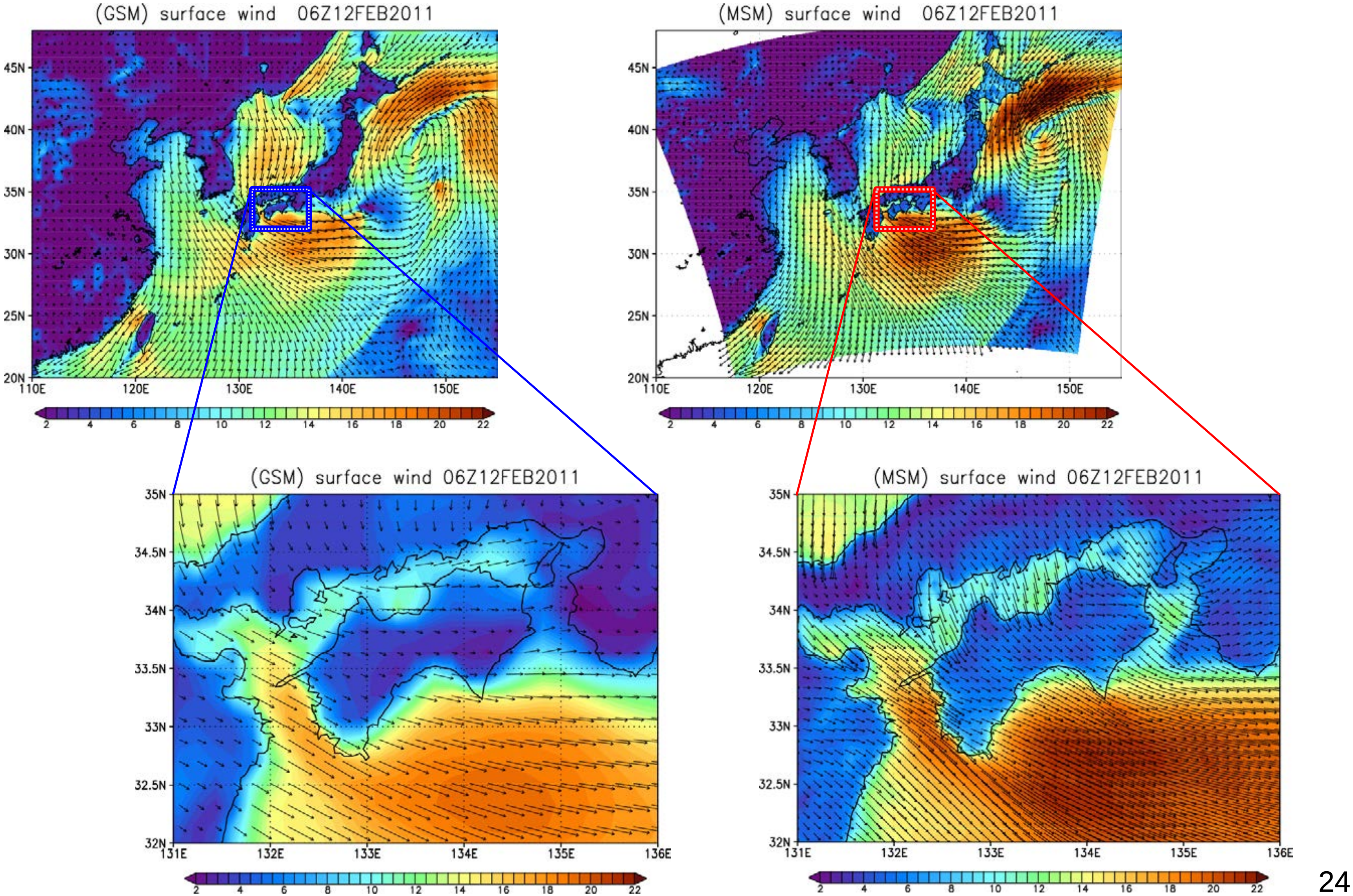
https://swot.jpl.nasa.gov/



http://le-web.riam.kyushu-u.ac.jp/radar/

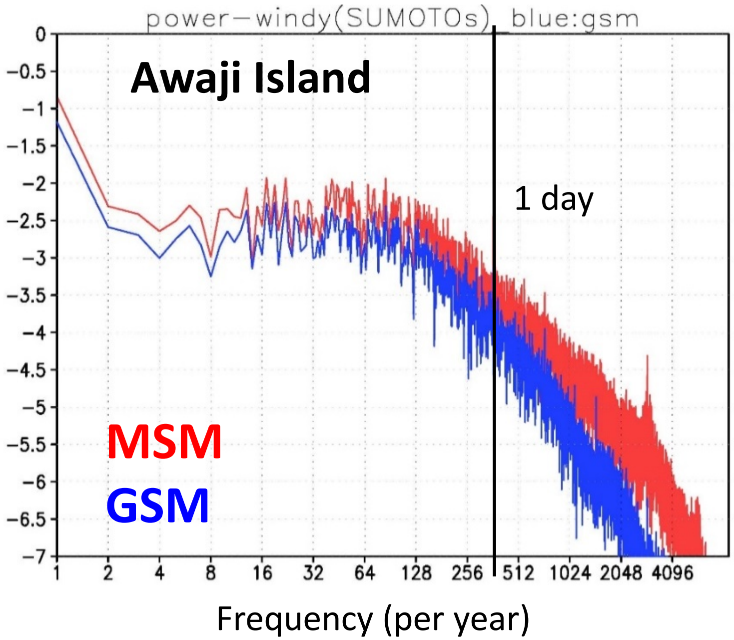
Uncertainty in forcing: wind

GSM (TL959 ~ 20km) **MSM (~5km)**

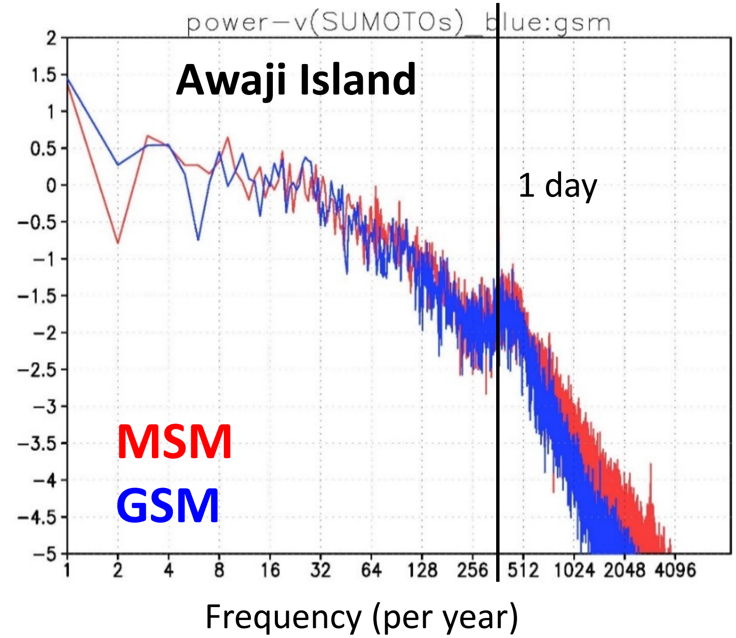


Uncertainty in forcing: wind

Wind stress (meridional)



Surface current (meridional)



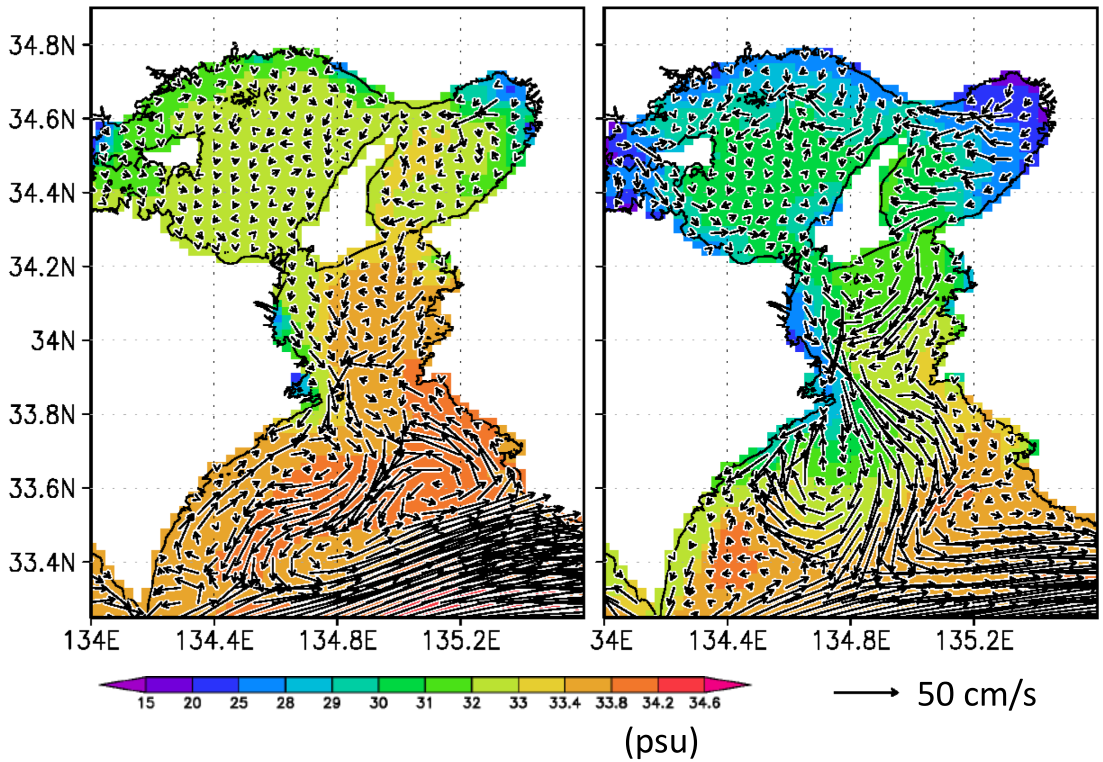
- High-resolution wind field is indispensable for a coastal system
- There is still large uncertainty in wind field in coastal areas with complex coastal topography

→ **To correct atmospheric forcing as one of control variables would be a possible approach to improve coastal circulation**

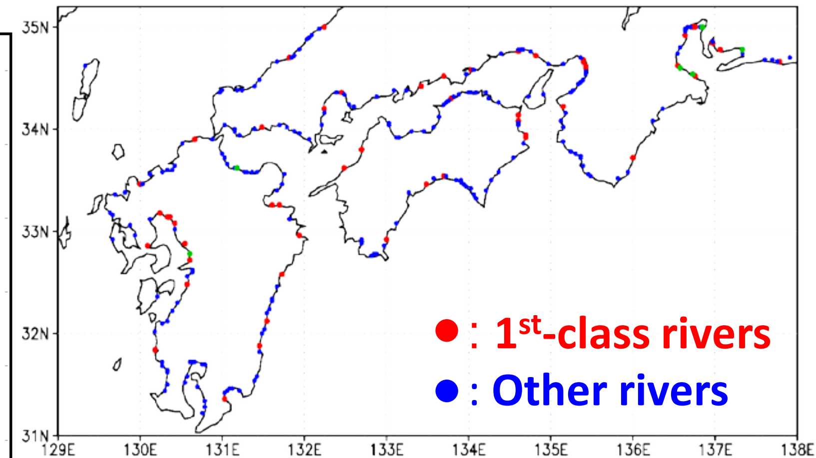
Uncertainty in forcing: river discharge

Surface Salinity and Surface Current (23SEP2011)

CLIM **JMARI**

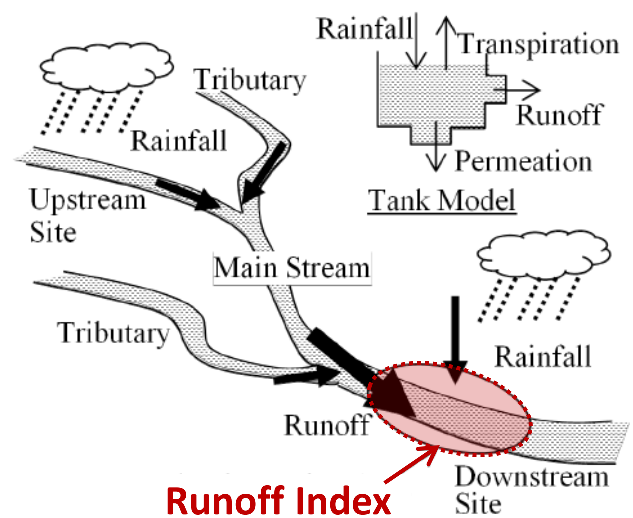


Mouths of major rivers



- **Climatology of 1st-class rivers**

- **JMA Runoff Index (JMARI)**
- **Calculated by a hydrological model using precipitation**
- **Covers 3,986 rivers**

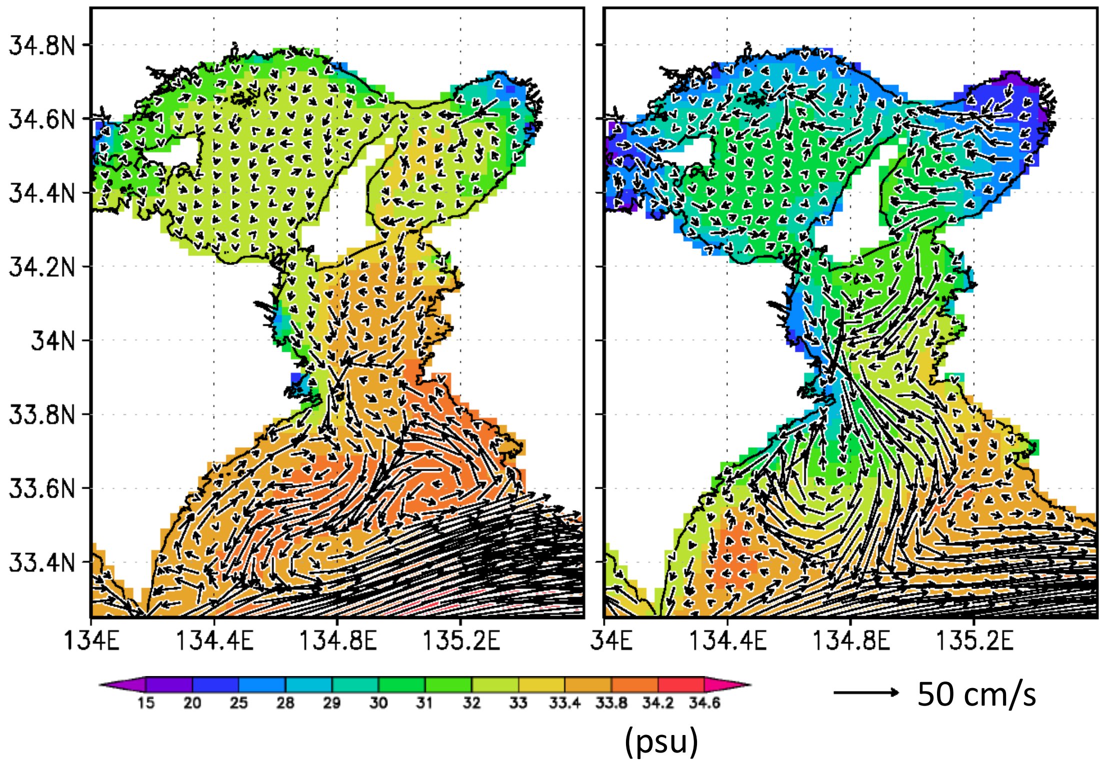


Kitagami et al. (2016)

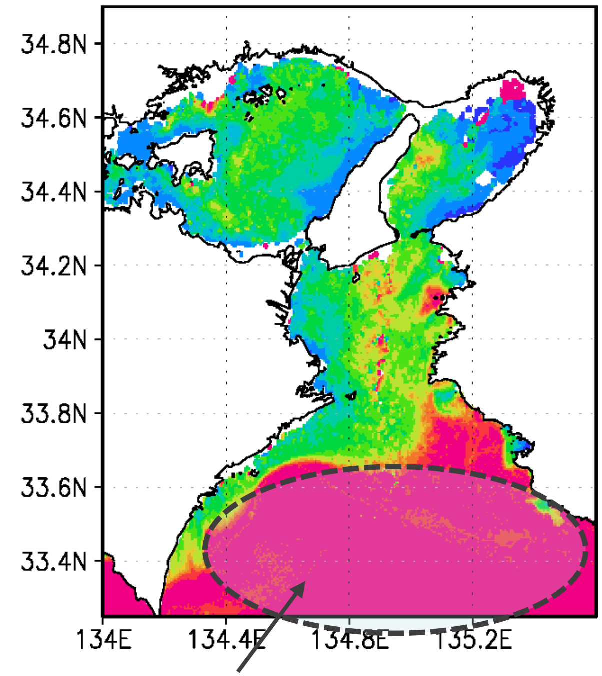
Uncertainty in forcing: river discharge

Surface Salinity and Surface Current (23SEP2011)

CLIM **JMARI**



Surface Salinity retrieved from Ocean Color Imager (GOCI/COMS)

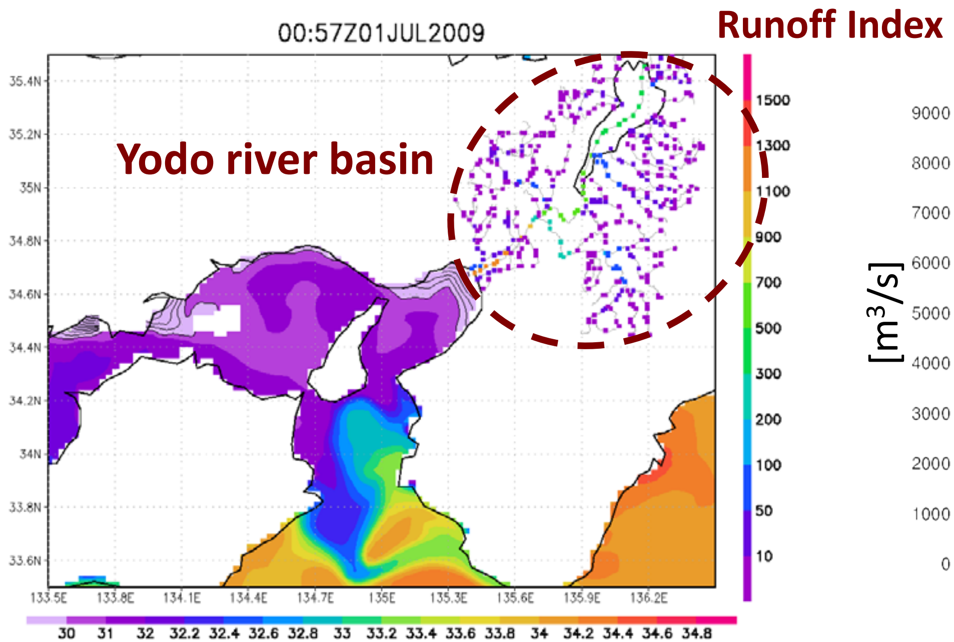


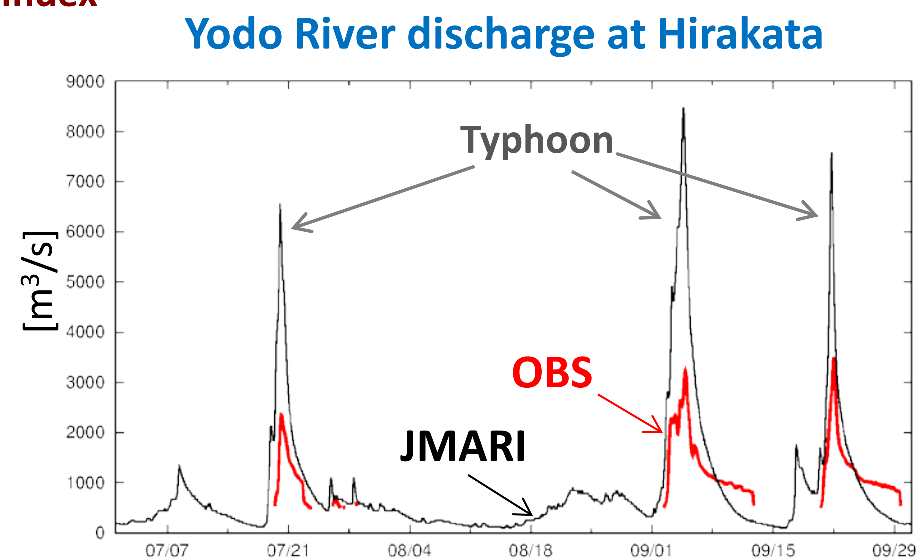
High salinity bias originated from retrieval algorithm

- JMARI qualitatively well captures observed features in surface salinity
- CLIM has a high salinity bias

Uncertainty in forcing: river discharge

Surface Salinity and JMARI in the Yodo river basin





- Timing of river discharge is in good agreement with observation
- But the maximum discharge is overestimated

→ **One possible approach would be to correct the run off data using ocean observations such as salinity data.**

Summary

- Coastal system (MOVE/MRI.COM-Jpn)
  - Forecast model: high resolution coastal model (MRI.COM-Jpn)
    - Up-to-date schemes
      (Z* coordinate, online two-way nesting, tidal scheme, river runoff …)
    - IAU initialization using 4DVAR analysis field
  - Analysis model: 4DVAR assimilation model (MOVE-4DVAR-NP)
    - Vertical TS-EOF mode for B matrix
    - Combination algorithm of 3D-Var and 4D-Var
    - Improve short-term mesoscale variability from 3D-Var
- Toward coastal scale DA
  - Importance of assimilation of velocity observations
  - Uncertainty in forcing
    - Surface wind
    - River discharge