Balanced Upper Ocean Circulation & its Reconstruction in the Context of SWOT Mission

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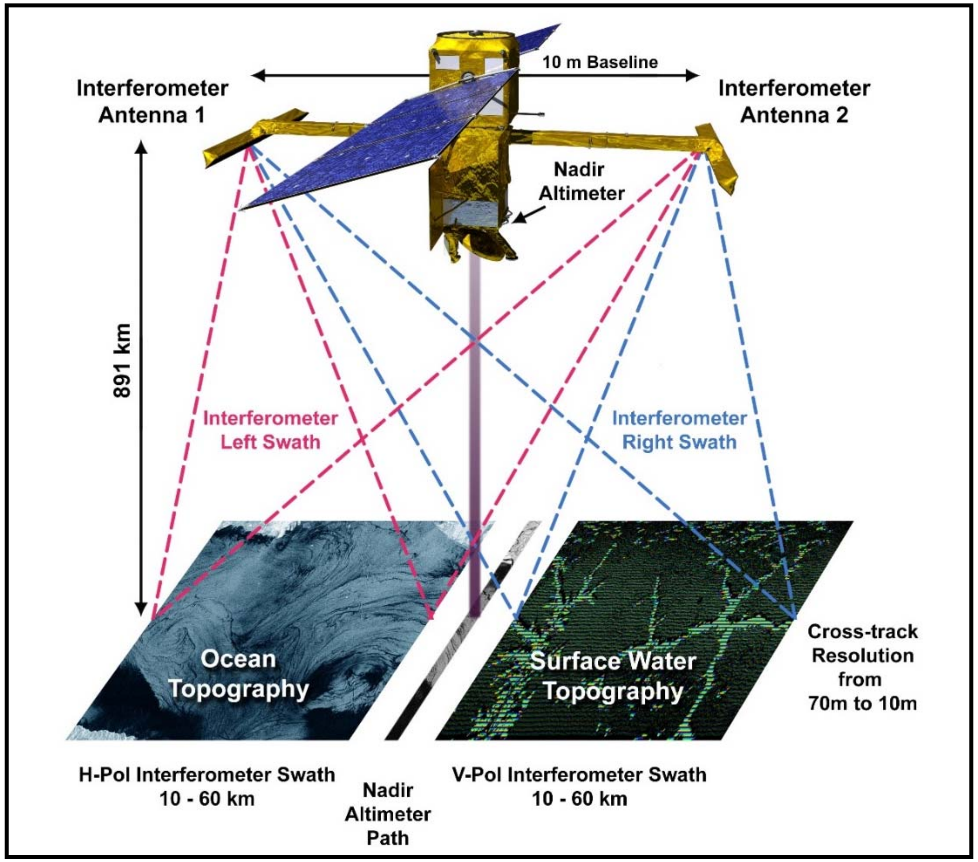

SWOT 4th Science Team Meeting, Bordeaux, France, 17-20 June 2019

Background:

- Like horizontal velocity u/v field (geostrophic, Ekman, tidal, Stokes drift, …), vertical velocity w has many components resulting from different dynamical processes

- Also like u/v field, not all components of w are retrievable from SSH measurements, and nor are they of equal dynamical importance

- Recent studies based on MITgcm LLC4320 have shown that it is the balanced w that is most relevant to the upper ocean vertical heat transport (Su et al. 2018)

- Our goal of the study is to explore the reconstructability of the balanced w in the context of SWOT mission (i.e., considering sampling + measurement errors)

- Effective SQG (eSQG) model of Lapeyre & Klein (2016) is adopted for reconstruction

- **Decompose w through the primitive-equation (PE) omega equation (e.g., Giordani et al. 2006):**

$$f^2 \frac{\partial^2 \omega}{\partial z^2} + \nabla_h (N^2 \cdot \nabla_h \omega) = \nabla_h \cdot \mathbf{Q}$$

where

$$\mathbf{Q} = \mathbf{Q}_{th} + \mathbf{Q}_{dm} + \mathbf{Q}_{tw} + \mathbf{Q}_{dag} + \mathbf{Q}_{dr}$$

- **Dynamical processes generating the w velocity:**

$$\mathbf{Q}_{th} = -\frac{g}{\rho_0} \nabla_h \left(\frac{\partial F_{x_i}}{\partial x_i} \right)$$ forcing by turbulent buoyancy fluxes

$$\mathbf{Q}_{dm} = -\frac{f}{\rho_0} \frac{\partial}{\partial z} \left(\mathbf{k} \times \frac{\partial \boldsymbol{\tau}_{x_i}}{\partial x_i} \right)$$ forcing by turbulent momentum fluxes

$$\mathbf{Q}_{tw} = \frac{2g}{\rho_0} (\nabla_h \mathbf{u})^T \cdot \nabla_h \rho$$ forcing by kinematic deformation

$$\mathbf{Q}_{dag} = -f \left[\nabla_h (\mathbf{k} \times \mathbf{u}) \right]^T \cdot \frac{\partial \mathbf{u}_{ag}}{\partial z}$$ deformation by thermal wind imbalance

$$\mathbf{Q}_{dr} = -f \, \mathbf{k} \times \frac{D}{Dt} \left(\frac{\partial \mathbf{u}_{ag}}{\partial z} \right)$$ forcing by material derivative of TWI

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forcing by turbulent momentum fluxes

$$\mathbf{Q}_{tw} = \frac{2g}{\rho_0} (\nabla_h \mathbf{u})^T \cdot \nabla_h \rho$$

forcing by kinematic deformation

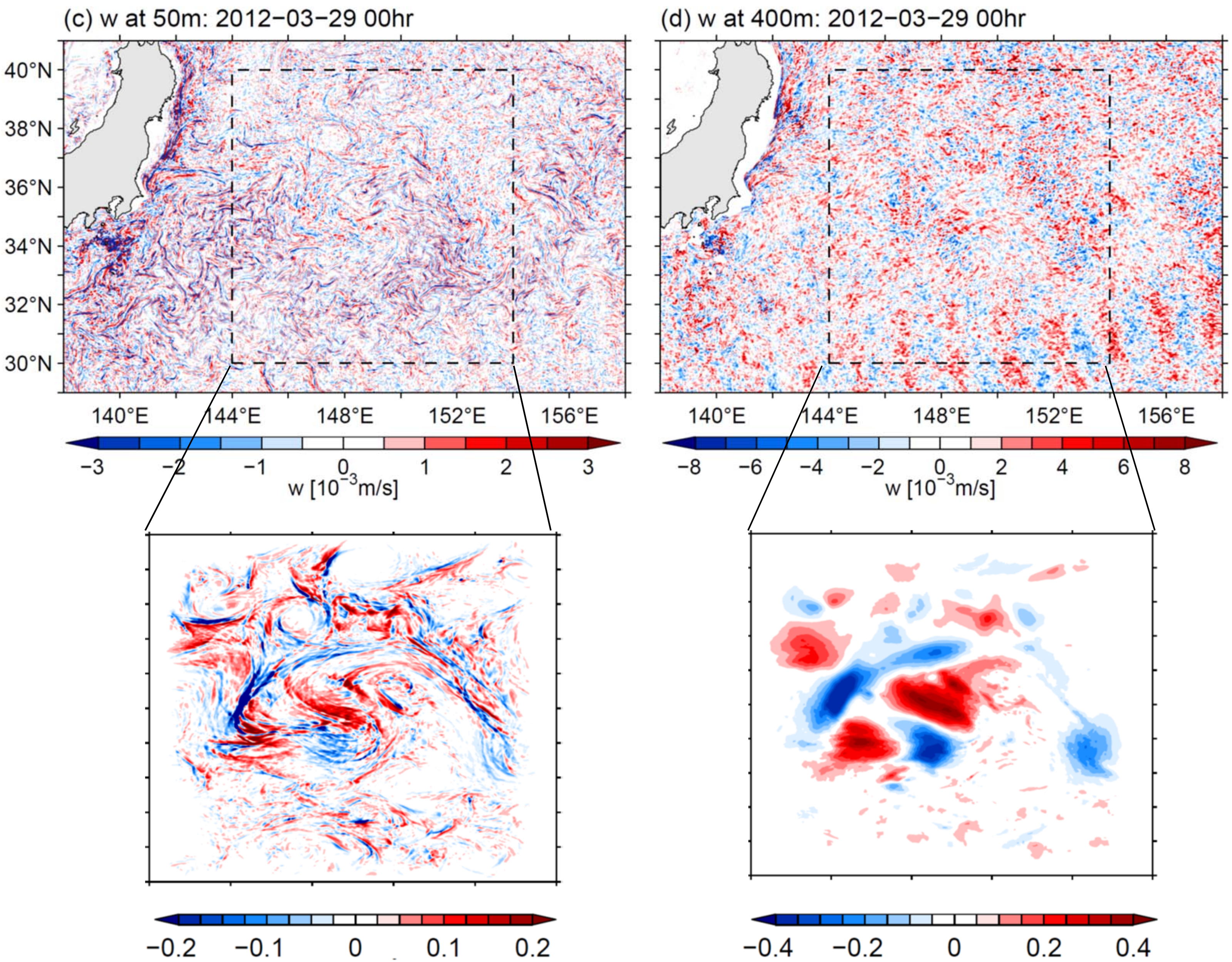
induces the "balanced" w

$$\mathbf{Q}_{dag} = -f \left[\nabla_h (\mathbf{k} \times \mathbf{u}) \right]^T \cdot \frac{\partial \mathbf{u}_{ag}}{\partial z}$$

deformation by thermal wind imbalance

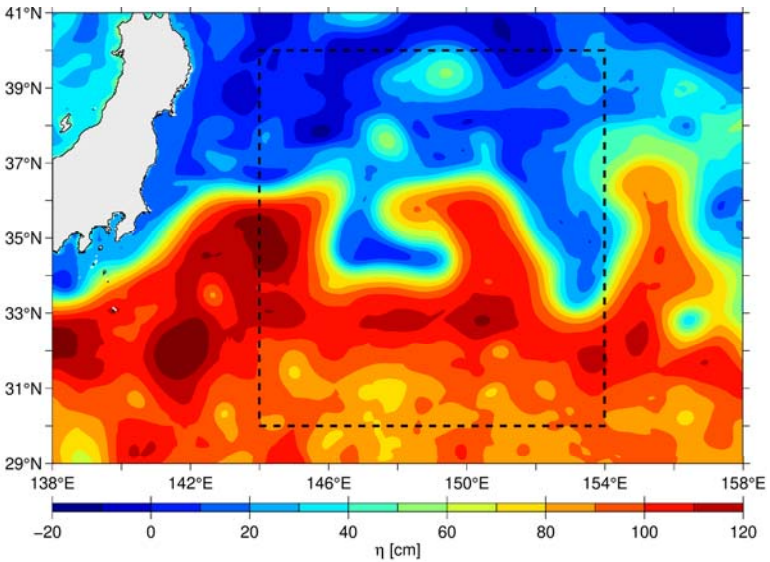
$$\mathbf{Q}_{dr} = -f \, \mathbf{k} \times \frac{D}{Dt} \left(\frac{\partial \mathbf{u}_{ag}}{\partial z} \right)$$

forcing by material derivative of TWI



kinematic deformation-induced balanced w field: reconstruction target

Typical winter sub-inertial η field in LLC4320



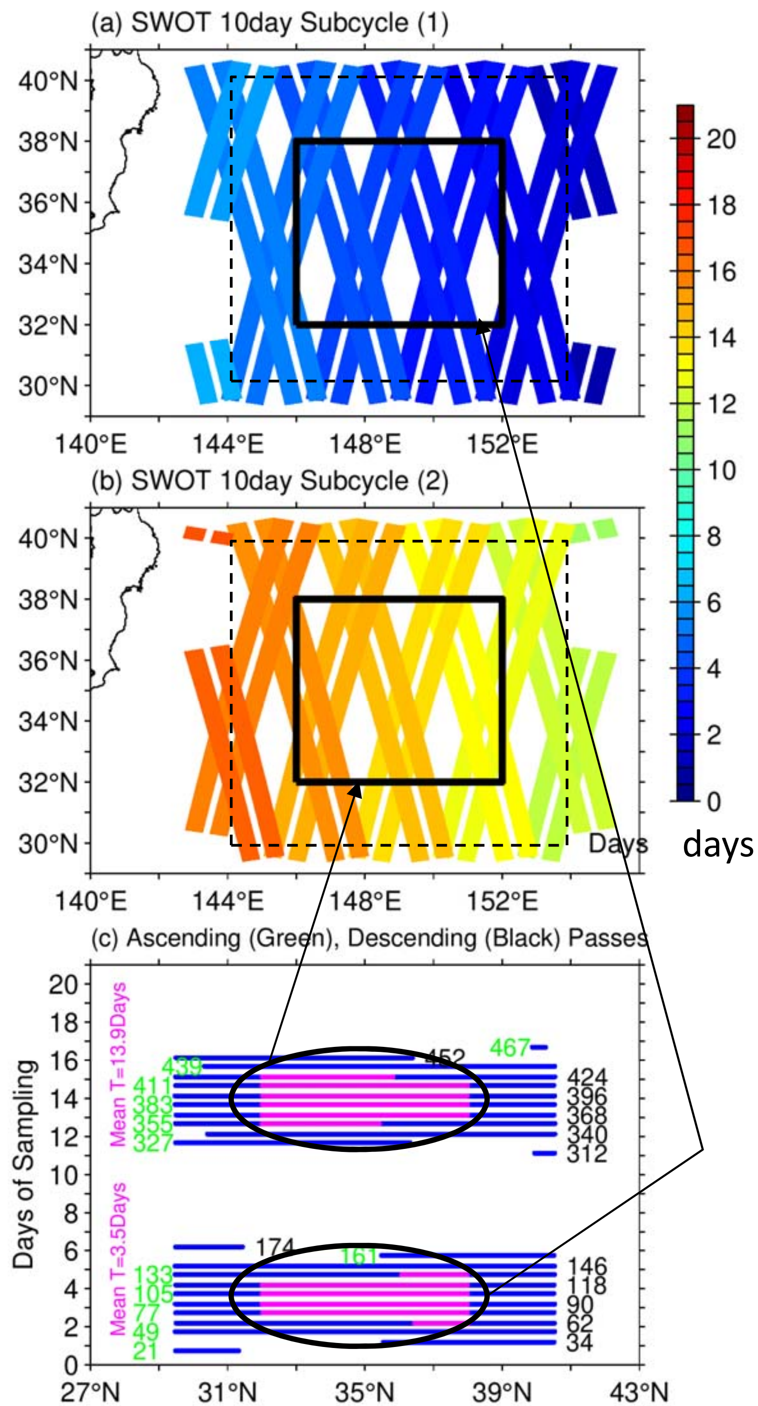
SWOT sampling: two sub-cycles in each 20.86-day repeat cycle

Due to fast evolution of meso-submeso-scale features, it does not help to bring in η data from neighboring sub-cycles

"Best scenario": input of sub-inertial η field

"SWOT scenario": input of time-varying along-swath, hourly, η data + SWOT Simulator-generated measurement errors

Target: balanced w (& ζ) in 1000m upper ocean



Effective surface quasi-geostrophic theory of Lapeyre & Klein (2006):

- **Under assumption that upper ocean PV is correlated to the surface PV anomalies, the geostrophic streamfunction anomaly ψ becomes related to the SSH anomaly η :**

$$\hat{\psi}(\mathbf{k}, z) = \frac{g}{f_o}\hat{\eta}(\mathbf{k}) \exp\left(\frac{N_o}{f_o}kz\right)$$

where ^ : horizontal Fourier transform, k : horizontal wavenumber, &
N_0 : effective upper ocean buoyancy frequency

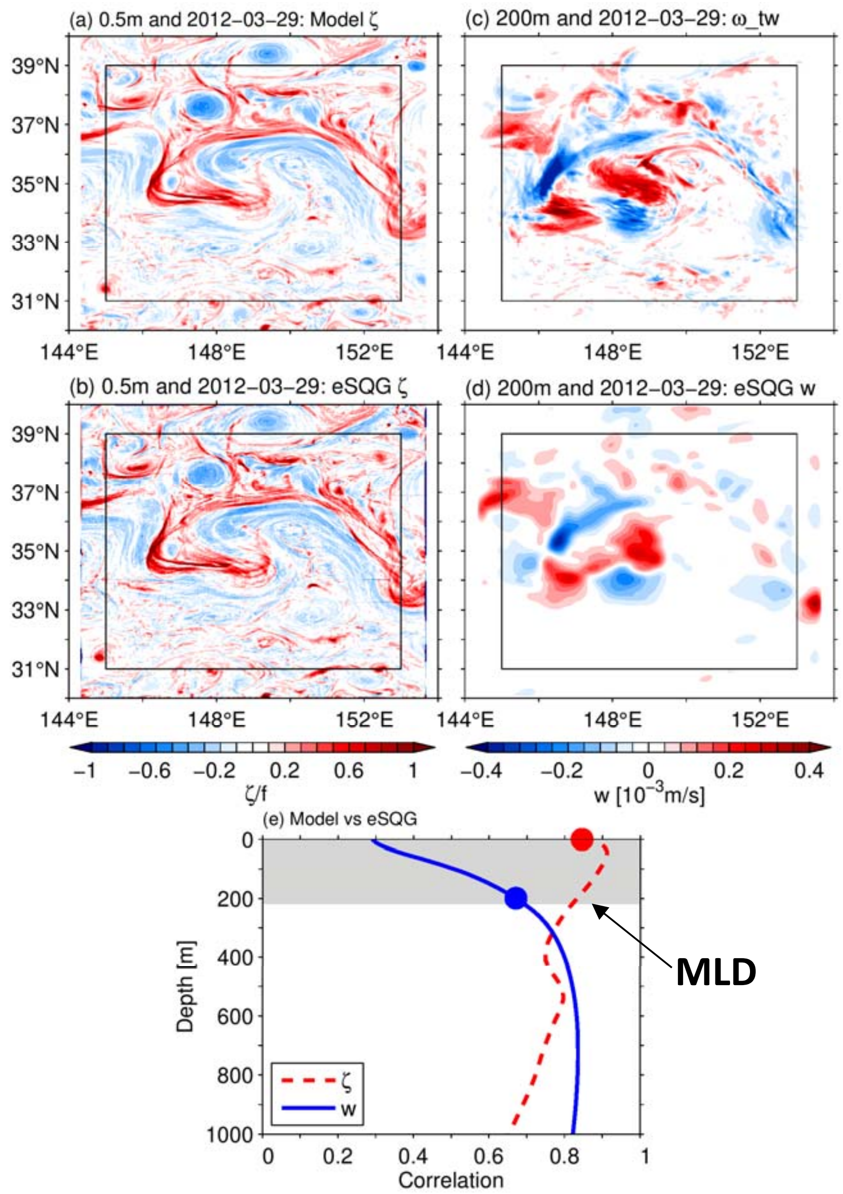
- **Once ψ is specified, 3-D fields of relative vorticity, buoyancy, & vertical velocity can be deduced from geostrophy, hydrostaticity, & advective buoyancy equation, respectively :**

$$\hat{\zeta}(\mathbf{k}, z) = -k^2\hat{\psi}(\mathbf{k}, z),$$

$$\hat{b}(\mathbf{k}, z) = \frac{N_o k}{c}\hat{\psi}(\mathbf{k}, z),$$

$$\hat{w}(\mathbf{k}, z) = -\frac{c^2}{N_o^2}\left[-\widehat{J(\psi_s, b_s)} \exp\left(\frac{N_o}{f_o}kz\right) + \widehat{J(\psi, b)}\right]$$

typical winter example: surface ζ & 200m w

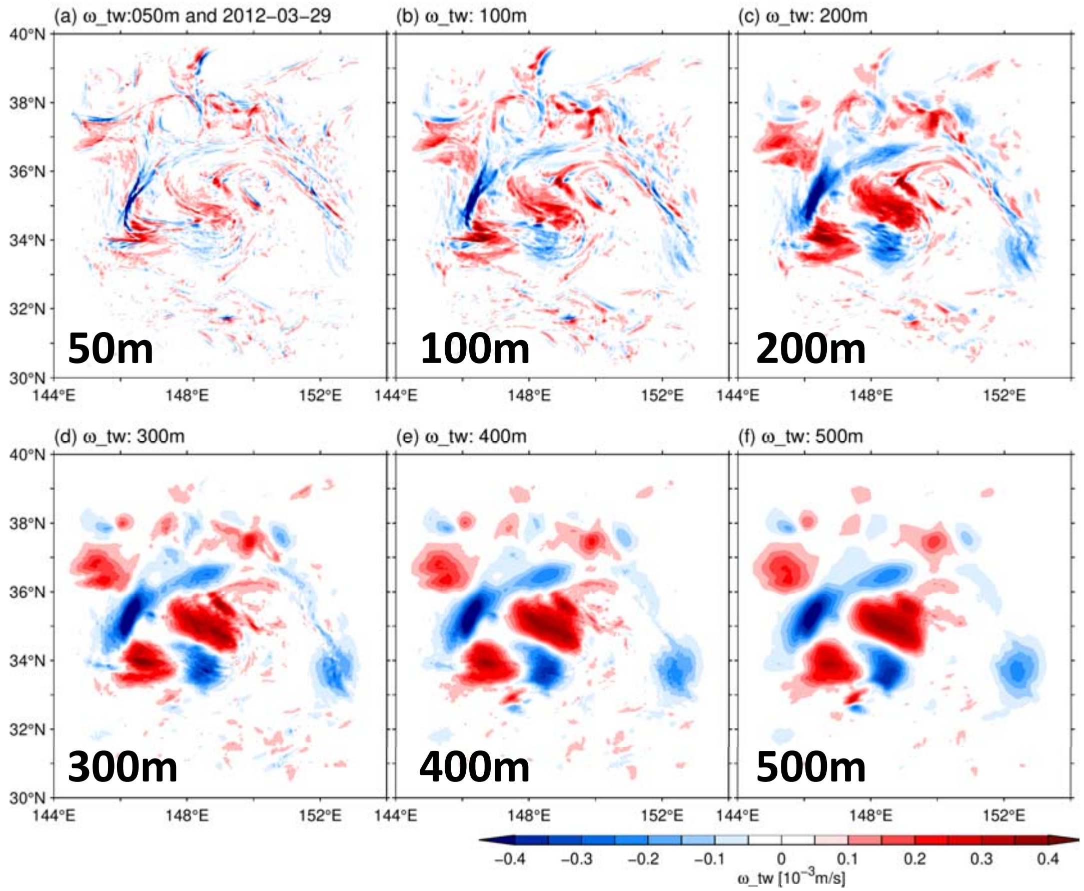


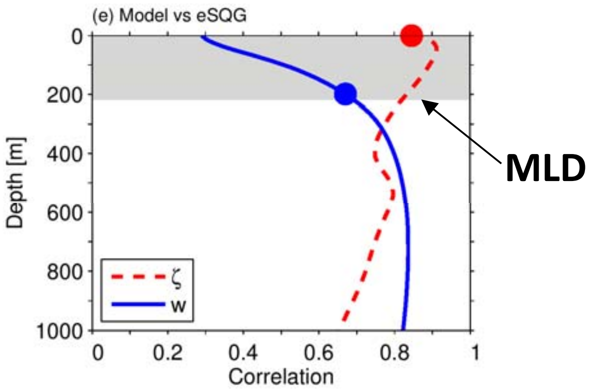
target ζ & w field

best scenario reconstruct

- **Reconstructed ζ is favorable near surface, but degenerates with depth**
- **Reconstructed w is fair within ML, but improves below the ML**

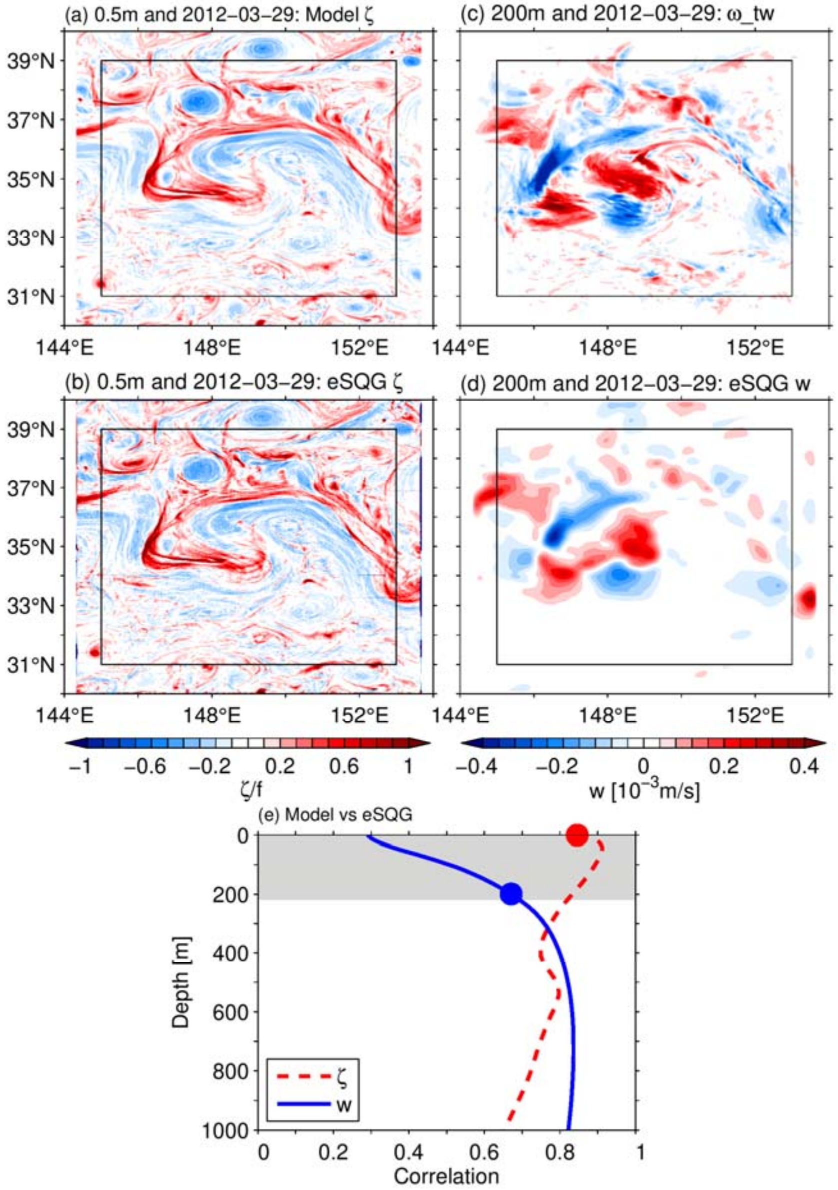
Targeted w field at different depths



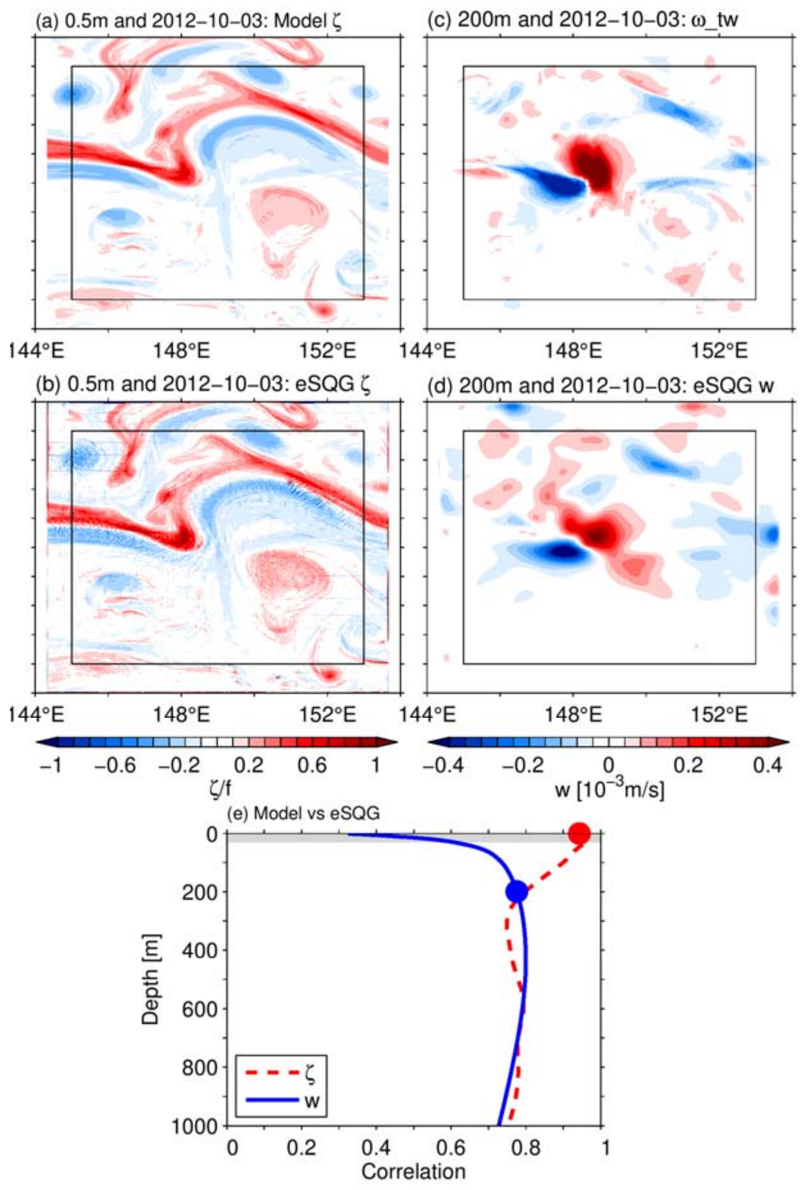


- Reconstructed ζ is favorable near surface, but degenerates with depth
- Reconstructed w is fair within ML, but improves below the ML **due to reduction in submesoscale signals & increase in balanced w amplitude**

typical winter example



typical summer example

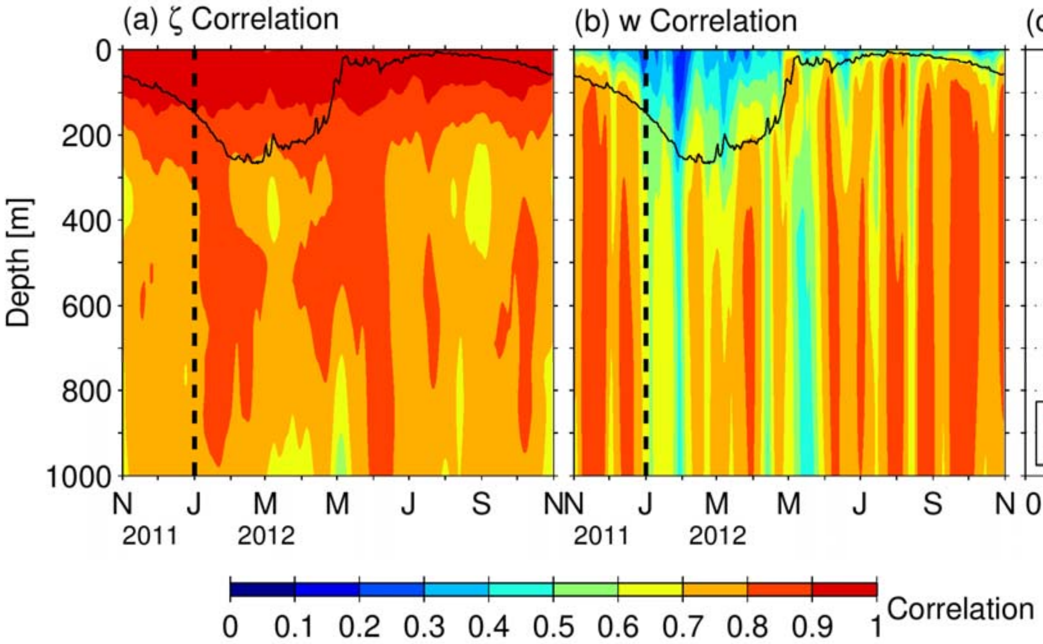


target ζ & w field

best scenario reconstruct

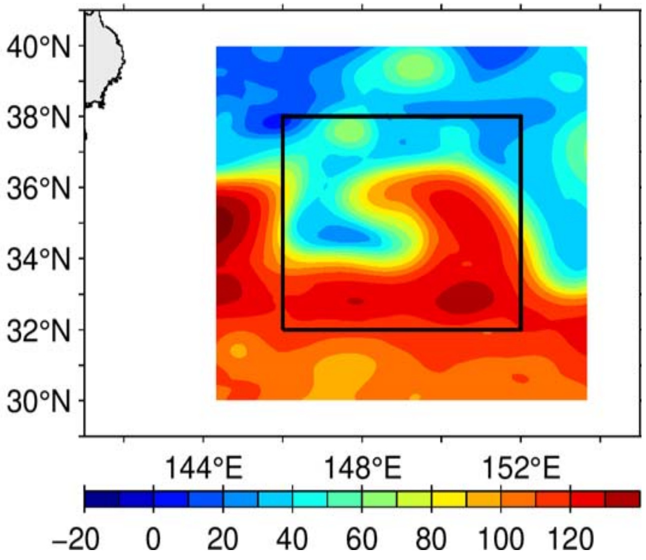
- **Better reconstruction in summer due to weaker submesoscale signals**

Reconstructed w & ζ correlations as a function of time



Best scenario reconstruct

target η field



Comments on mapping of η field:

A non-trivial issue !!

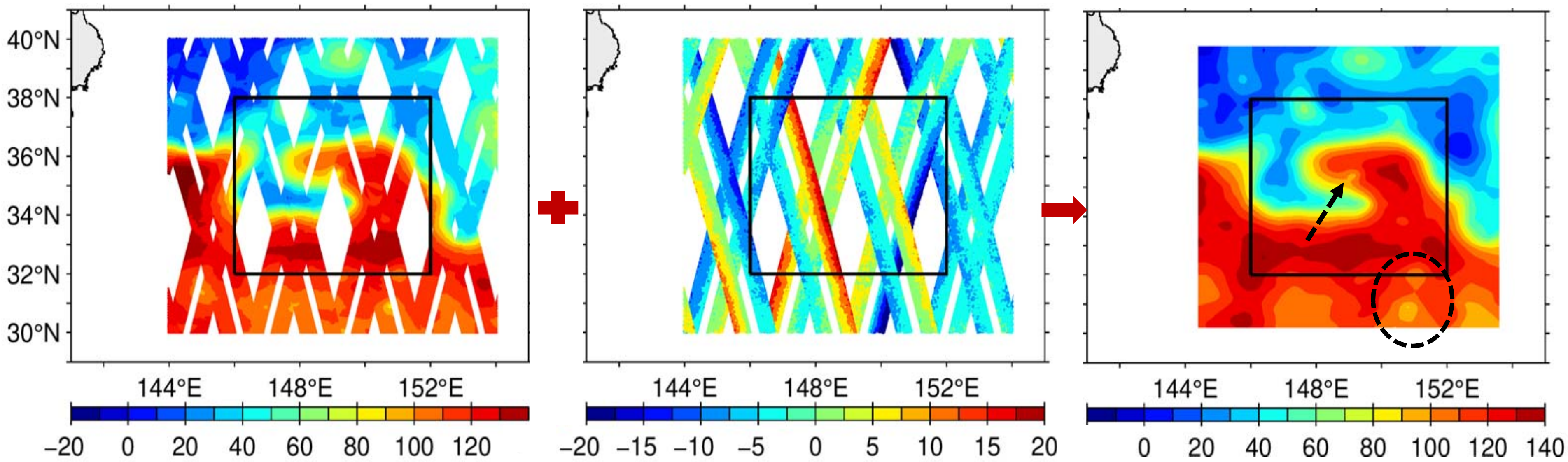
Used simulator-sampled η data (+ errors) within a sub-cycle (±3 days) in 10° x 10° box

Determined "optimal" temporal-spatial mapping scales; see Qiu et al. (2016)

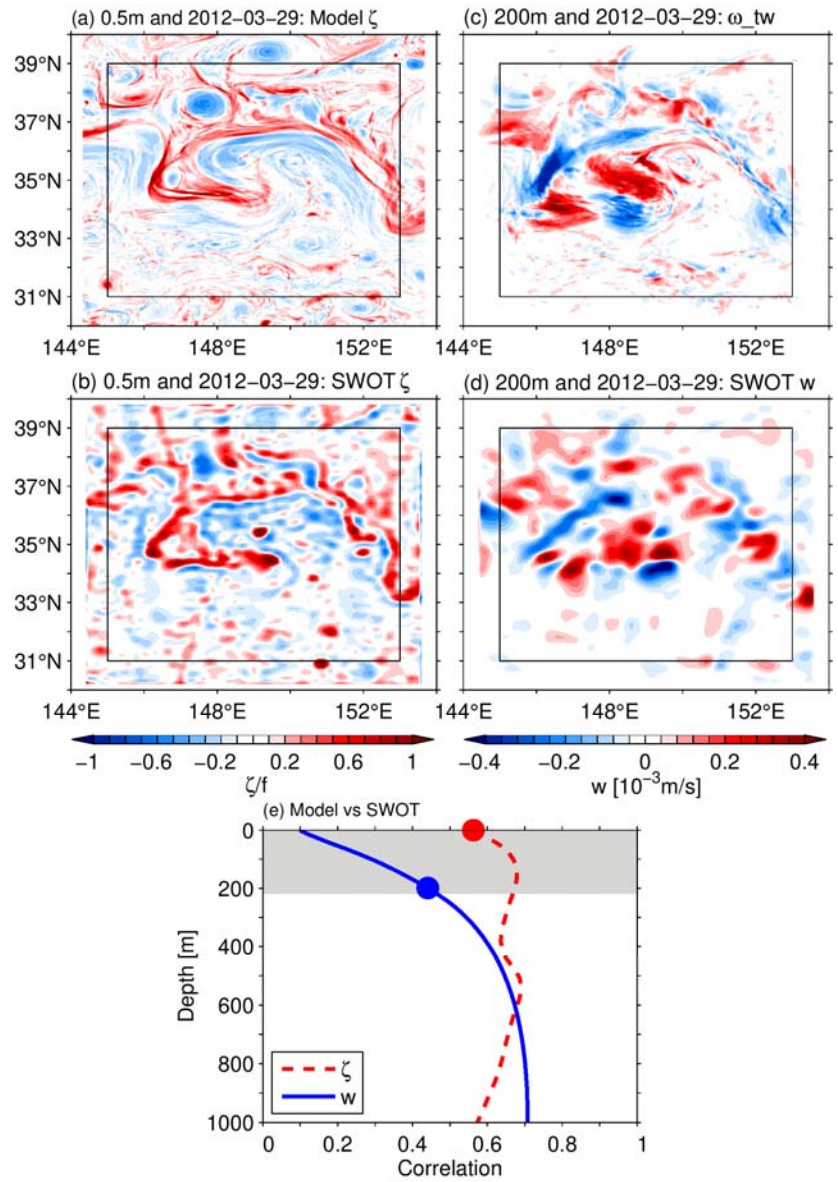
simulator-sampled hourly η field

simulator-generated η errors

mapped η with optimal scales



typical winter example: surface ζ & 200m w

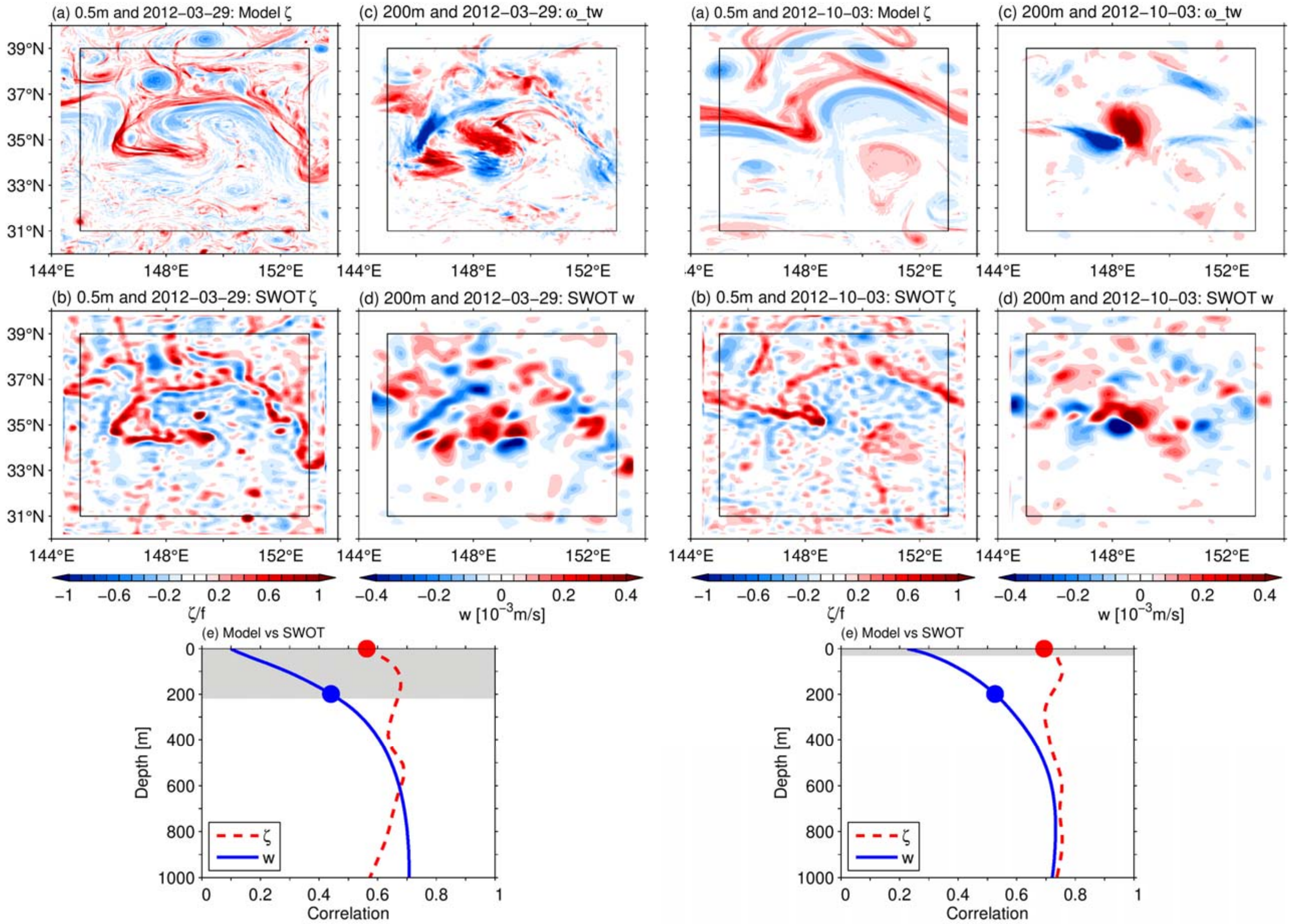


target ζ & w field

SWOT scenario reconstruct

- **Reconstructed ζ & w appear speckled due to interleaved ground-tracks & OI**
- **Compared to "best scenario", there is an overall 20% reduction in correlation for both ζ & w**

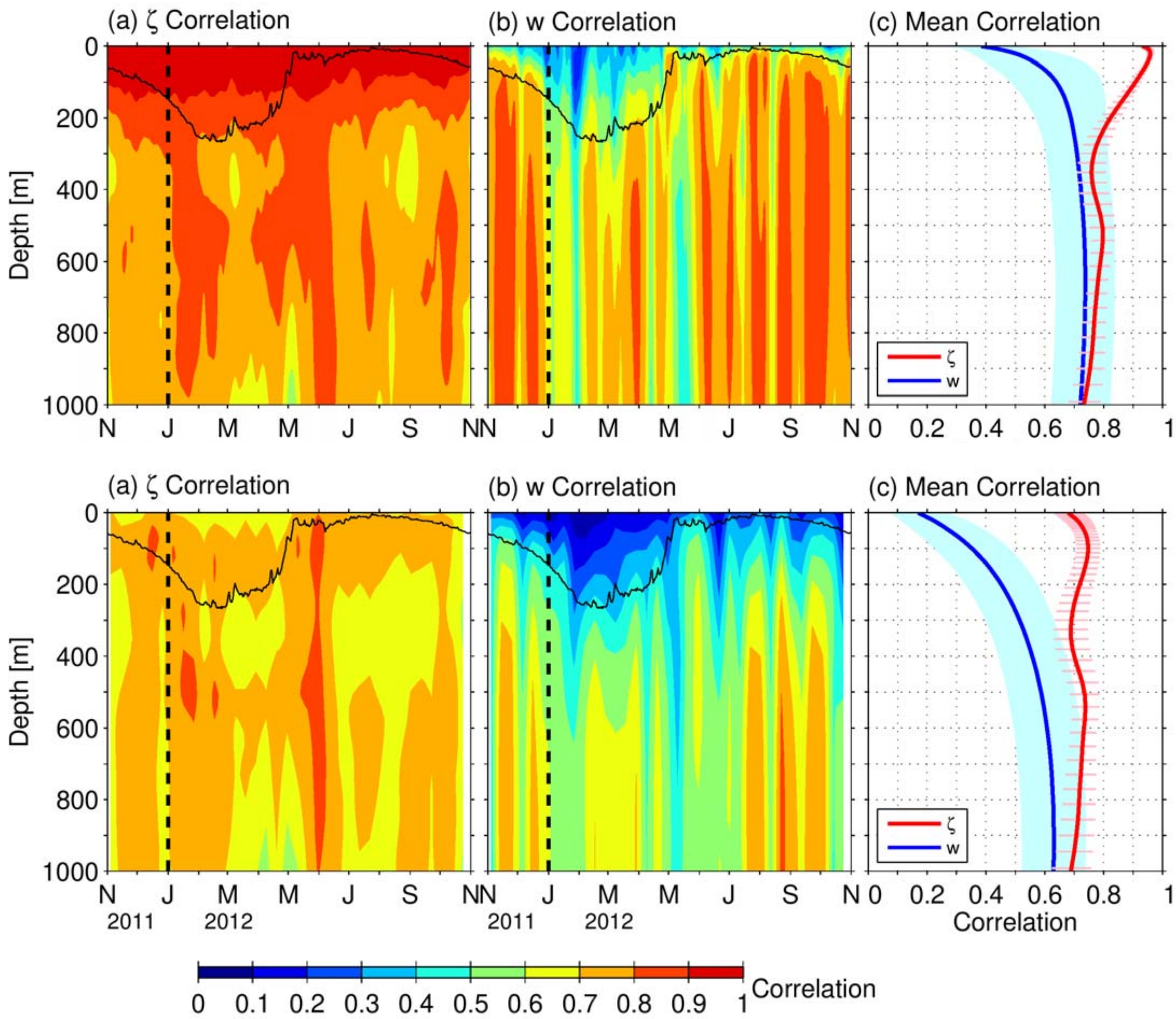
typical winter example **typical summer example**



target ζ & w field

best scenario reconstruct

Reconstructed w & ζ correlations as a function of time

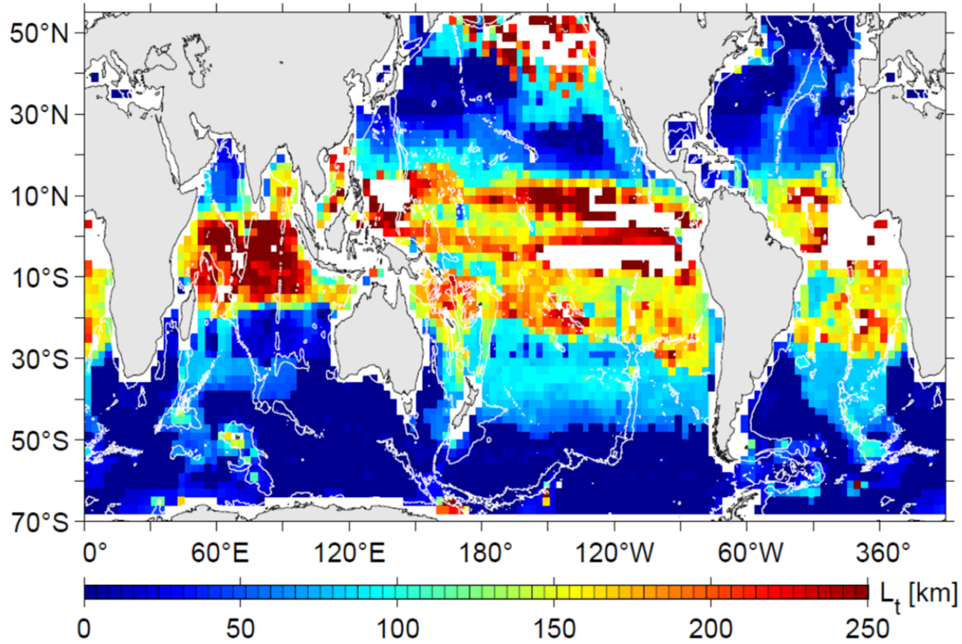


Best scenario reconstruct

SWOT scenario reconstruct

Concluding Remarks

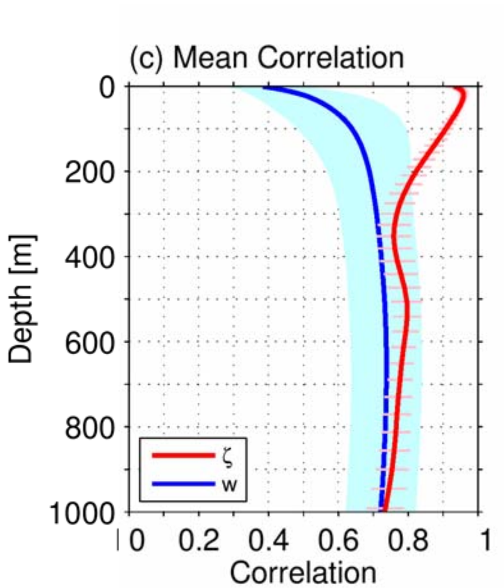
- **Effective SQG is a useful framework for reconstructing 3-D circulation field, including balanced w, from SWOT SSH measurements in high-EKE oceans**



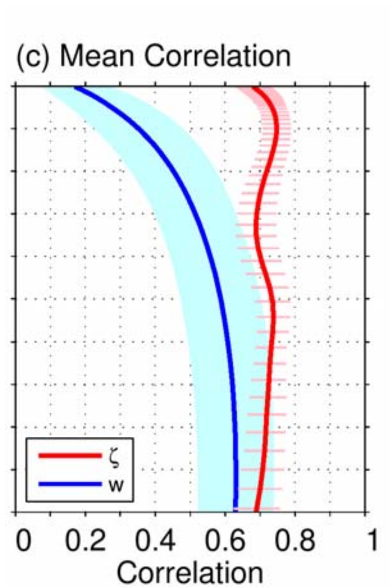
LLC4320-based transition scale Lt (Qiu et al. 2018)

Concluding Remarks

- **Much of the reconstruction deterioration, especially for w, is due to the 2-D mapping error; measurement error is of secondary importance. Improved mapping schemes are needed.**



Best scenario reconstruct



SWOT scenario reconstruct

Proposed methodology to reconstruct vertical velocities at submesoscale from space

in collaboration with Bo Qiu and Shuiming Chen (Univ. Hawaii)

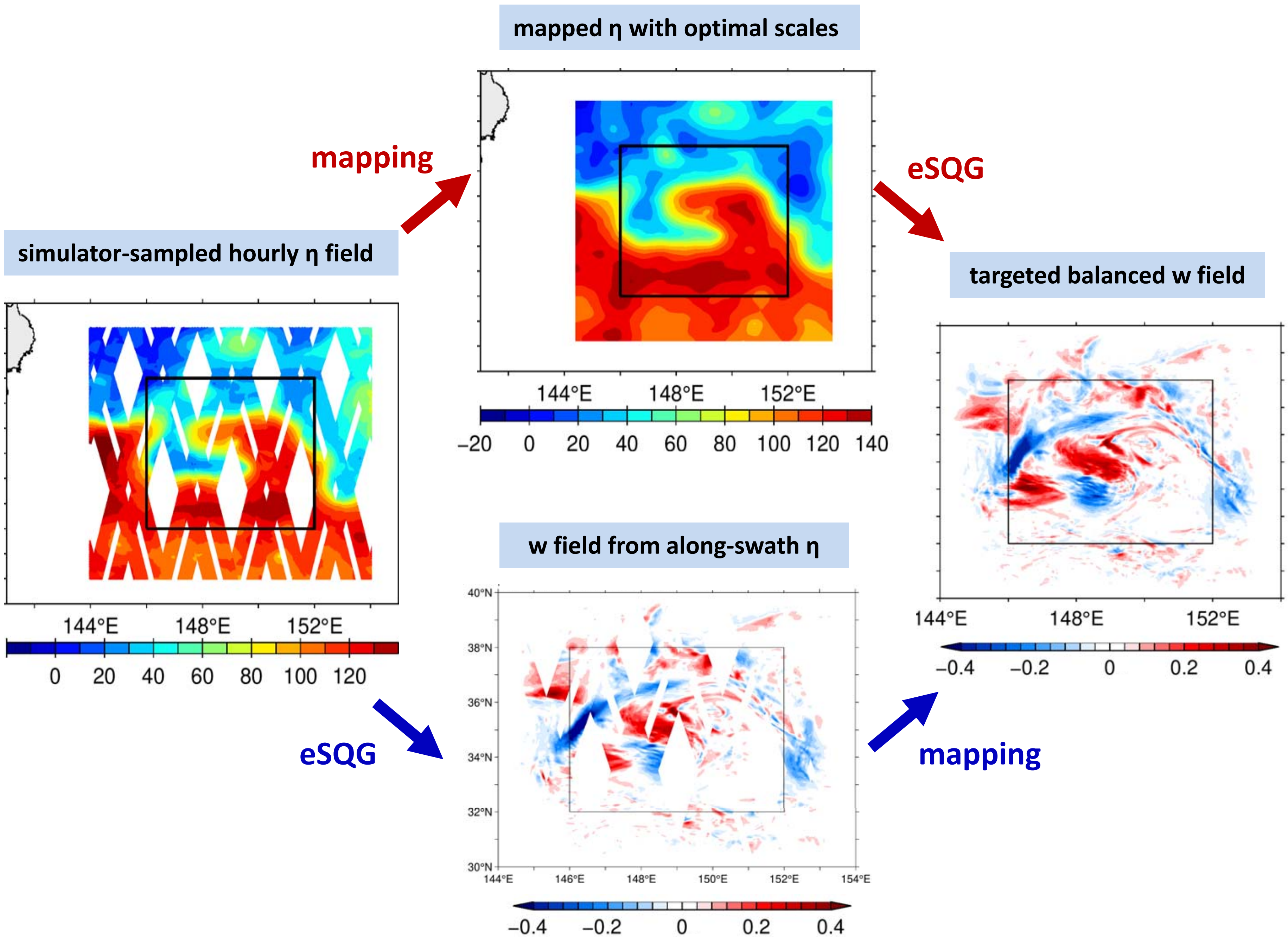
1. E-sqg method -> mesoscale density and (u,v) fields at depth

2. Calibrate the density gradient field at depth:
   advect density with (u,v) from e-sqg-> creation of fronts by the direct cascade of PE
   calibrate the fronts with FSLE derived from altimetry

3. Use the omega equation to retrieve w

$$N^2 w_{xx} + f^2 w_{zz} = 2(u_x b_x)_x$$

Slide from Lia Siegelman & Patrice Klein



mapped η with optimal scales
mapping
eSQG
simulator-sampled hourly η field
targeted balanced w field
144°E
148°E
152°E
–20
0
20
40
60
80
100
120
140
w field from along-swath η
eSQG
mapping
–0.4
–0.2
0
0.2
0.4
40°N
38°N
36°N
34°N
32°N
30°N
144°E
146°E
148°E
150°E
152°E
154°E