Oceanic Variability from Mesoscale to Submesoscale

-- Dynamics, Opportunities & Challenges

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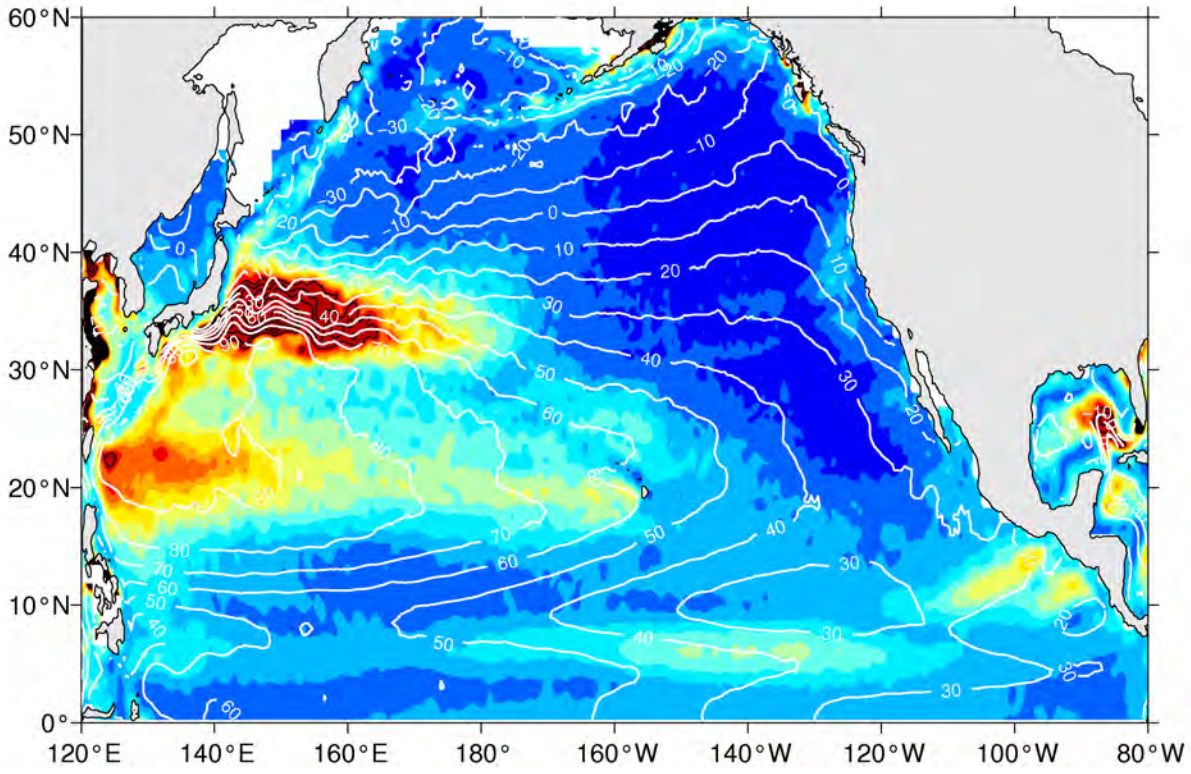
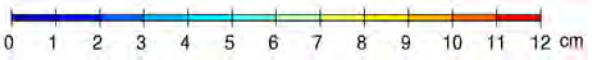
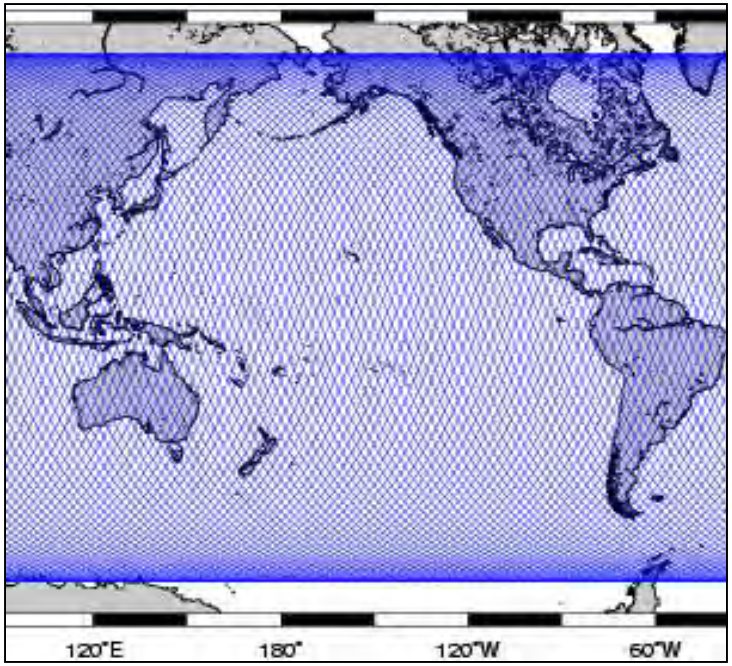


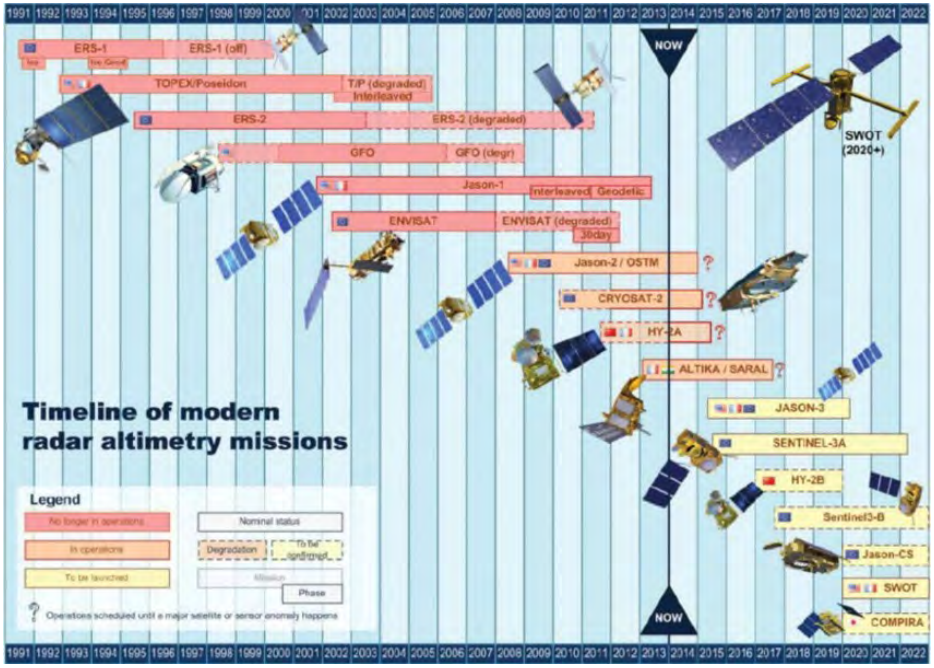
AVISO rms SSH variability in the North Pacific



PICES-2018 Annual Meeting, Yokohama, 10/30/2018

Satellite altimetry missions & their typical ground tracks

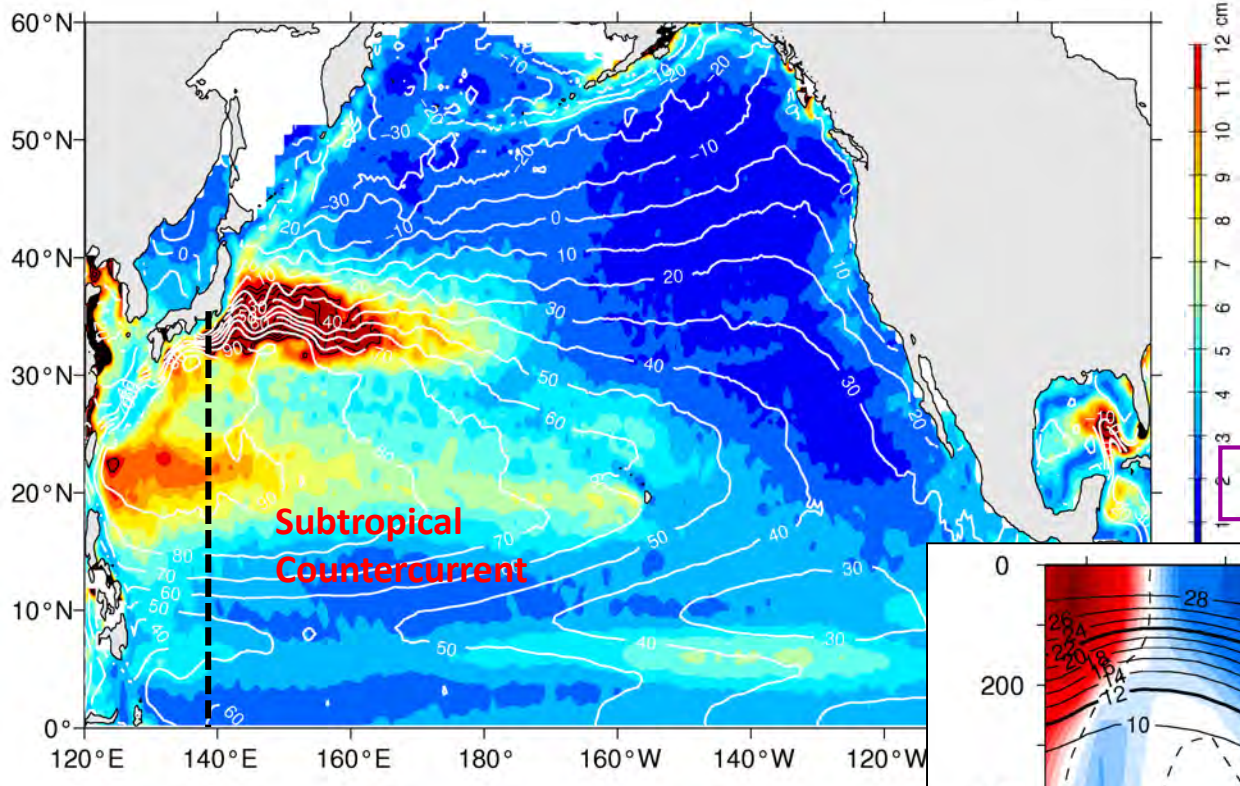




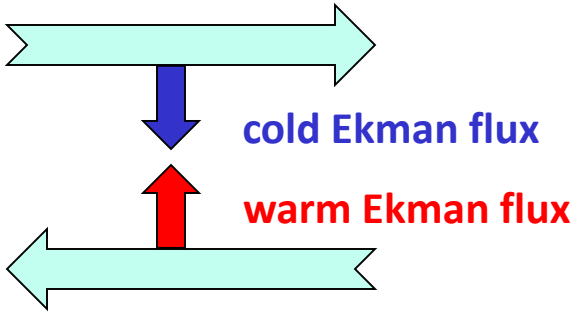
Le Traon et al. (2015, JOO)

- Ground track separation at equator is ~ 135 km with an exact repeat cycle of 9.9 days
- Multiple concurrent missions have been achieved since 1993
- With 2-3 missions, the resolved oceanic features (by, e.g., the weekly AVISO product) are on the order of 100-150 km

Time-mean STCC is generated by convergent Ekman heat fluxes in upper ocean

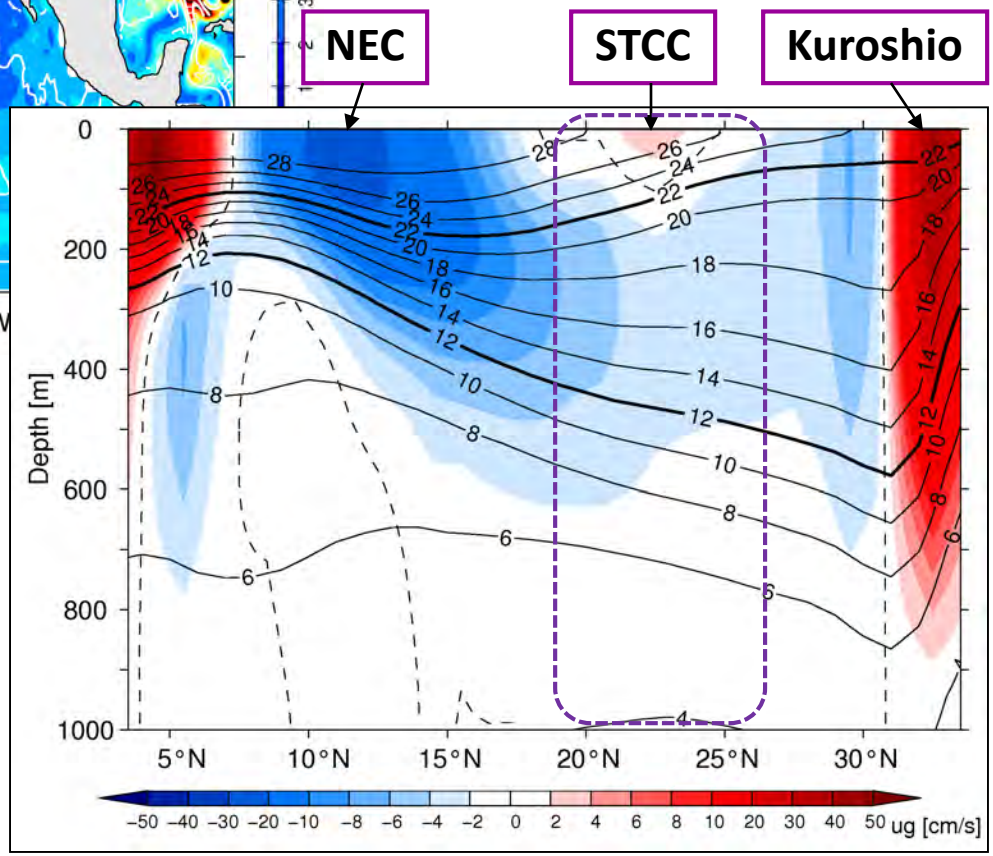


mid-latitude westerly winds

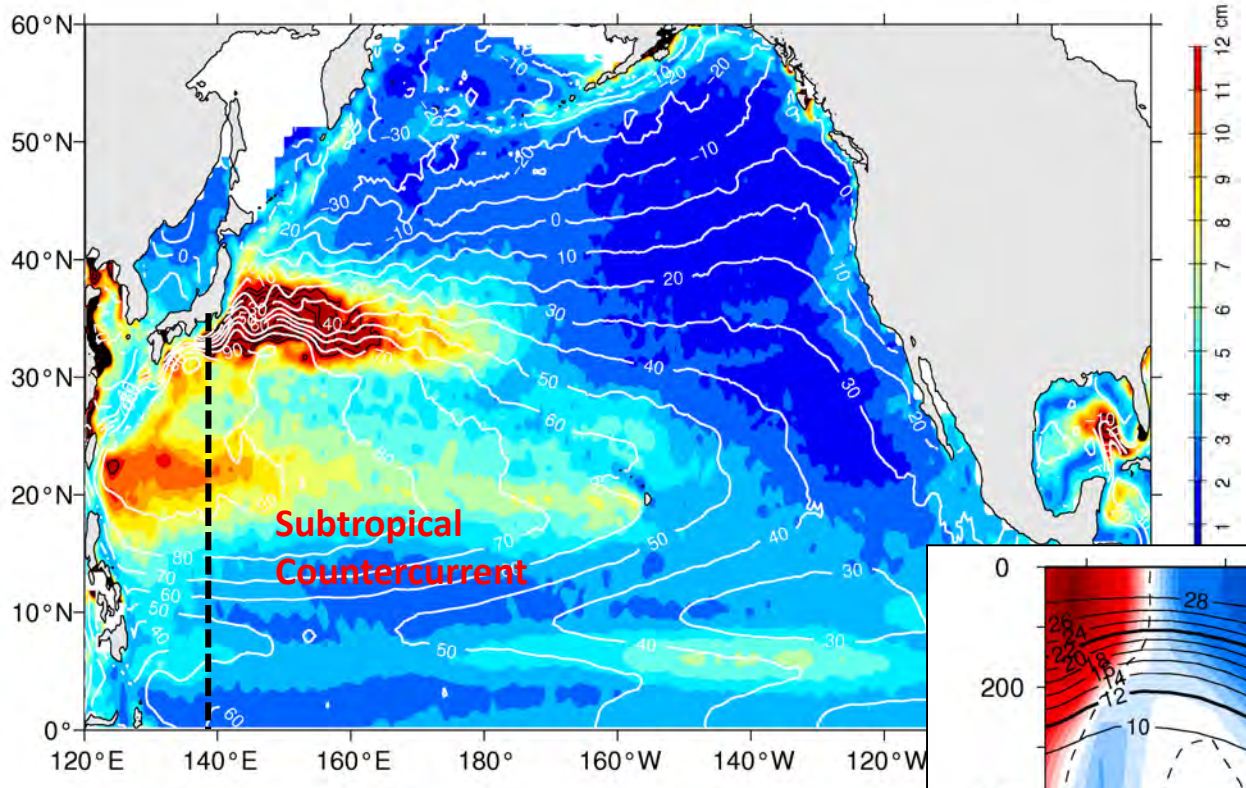


tropical trade winds

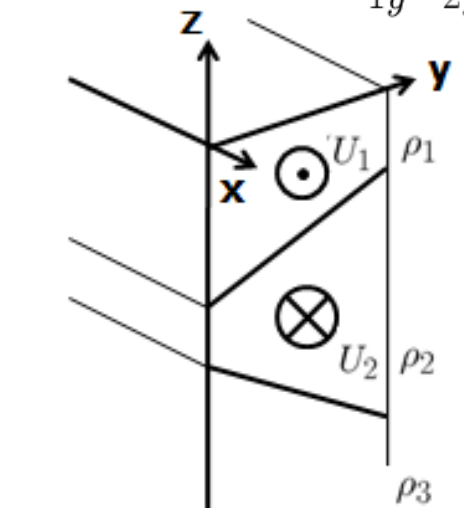
JMA temperature and Ug section along 137°E (1993-2008 mean)

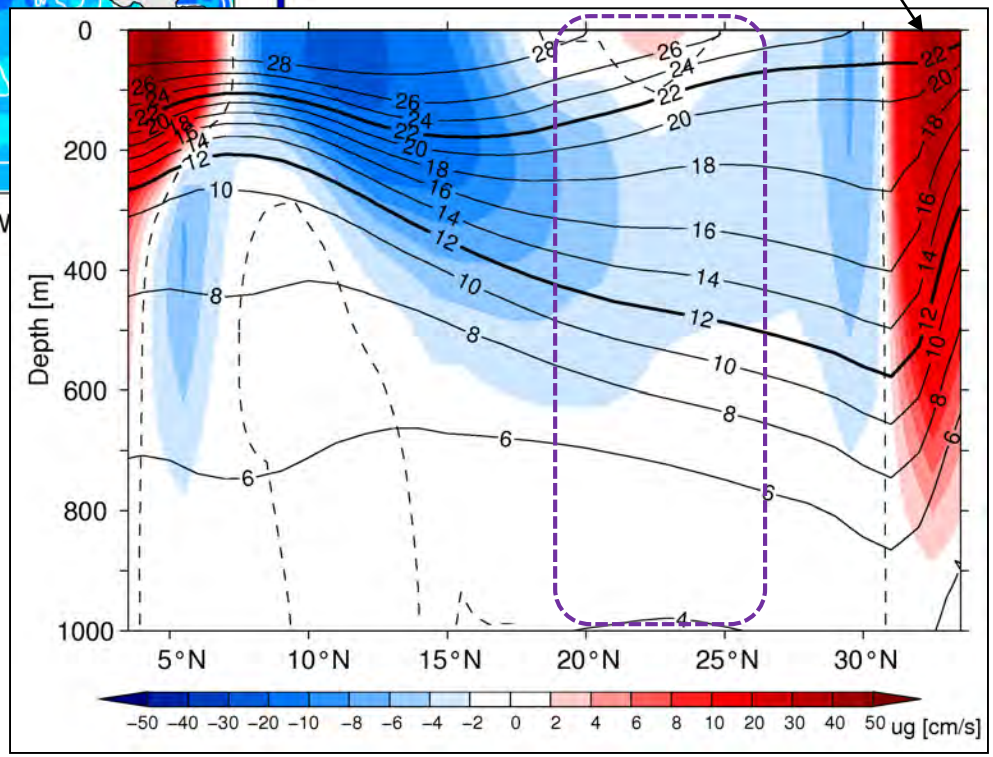


STCC band has the 2nd highest EKE level in the North Pacific



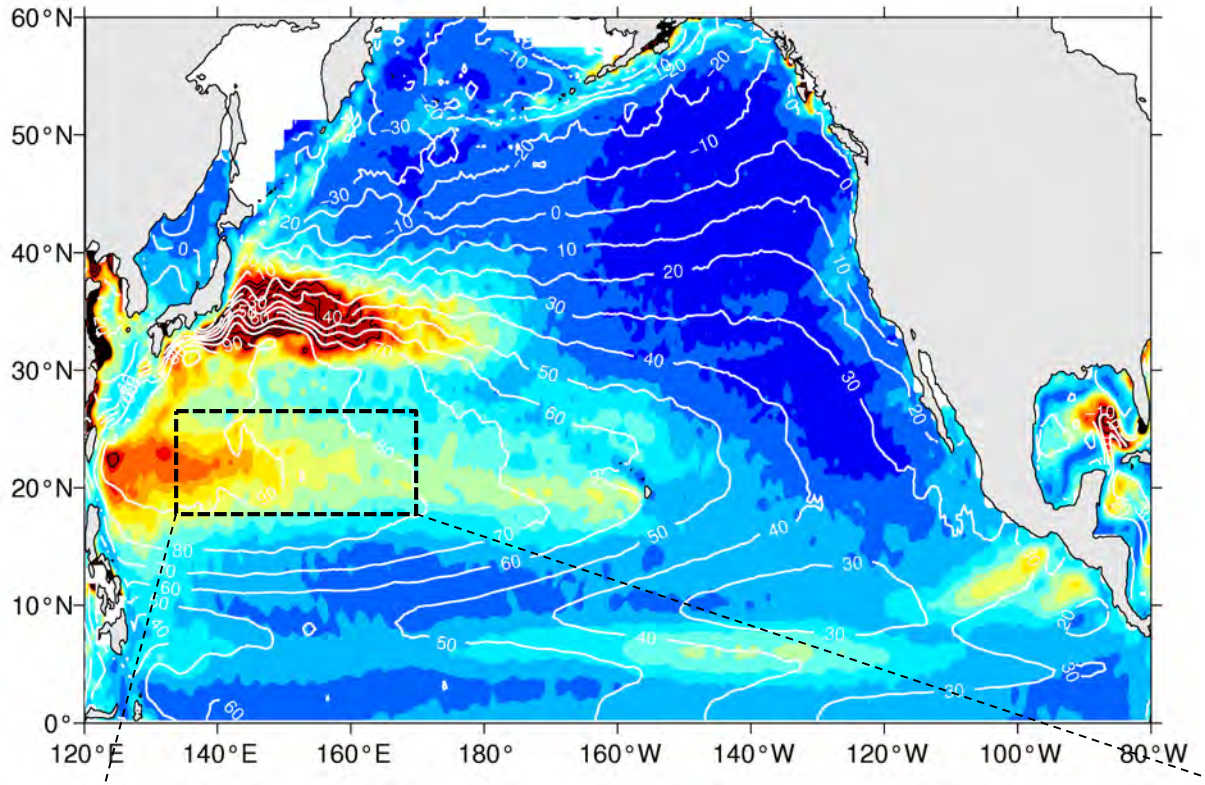
$\Pi_{1y}\Pi_{2y}<0$

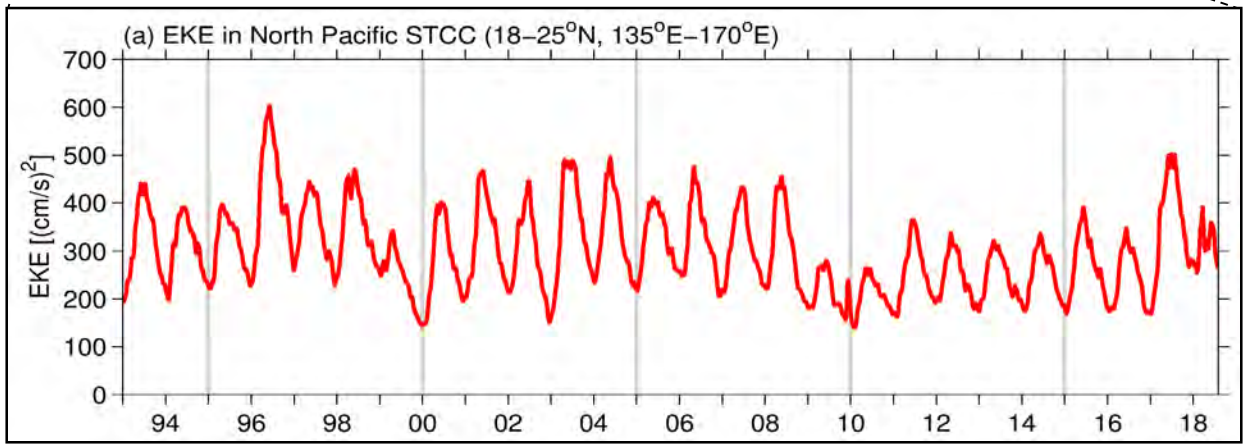




Meridional PV gradient in the upper seasonal thermocline has opposite sign to that in the lower main thermocline, satisfying the condition for baroclinic instability

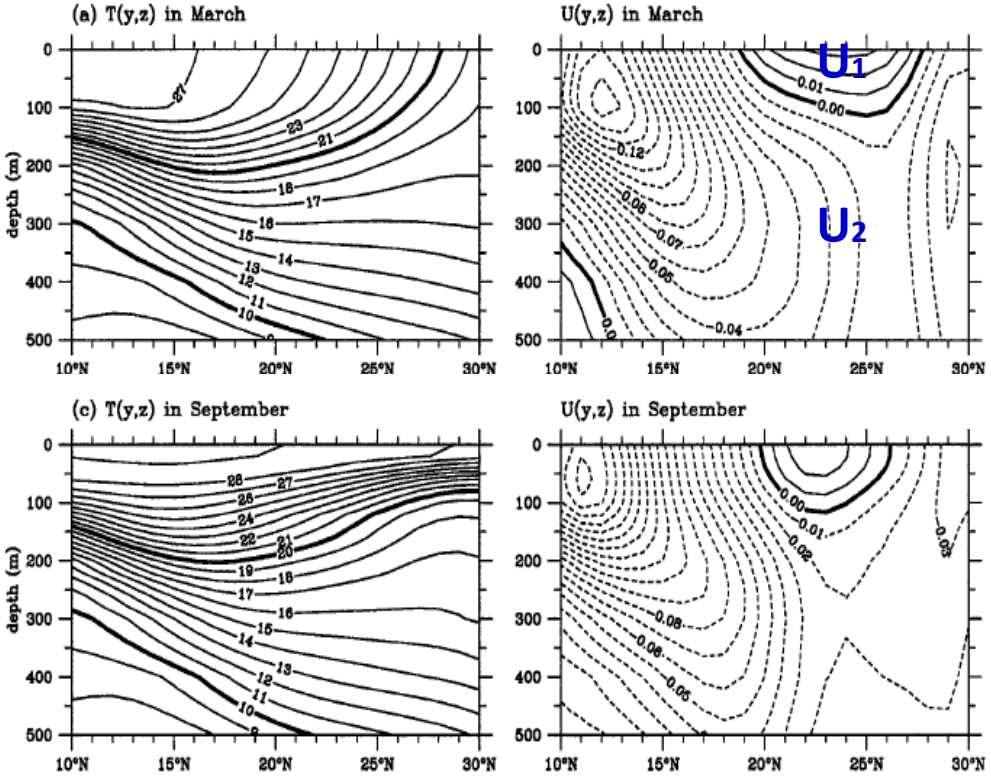
AVISO-based EKE time series in the STCC band: 18°-25°N, 135°-170°E



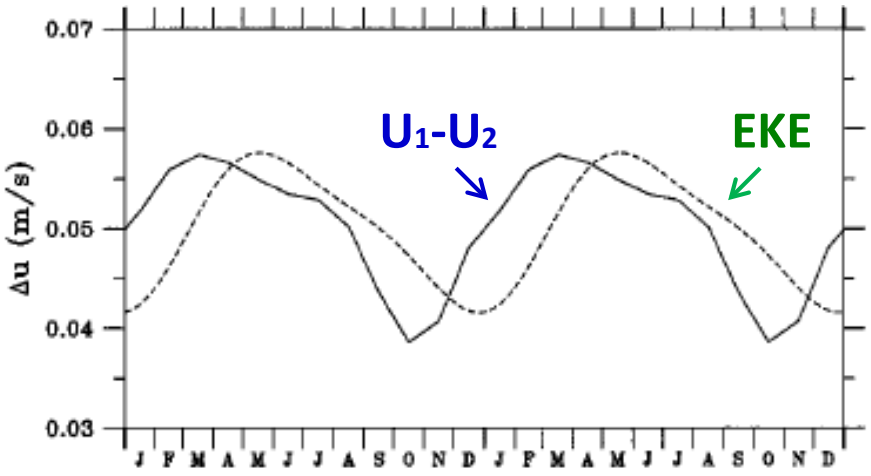


- **well-defined annual EKE cycle: May max & January min**

T(y,z) & U(y,z) in March vs. September

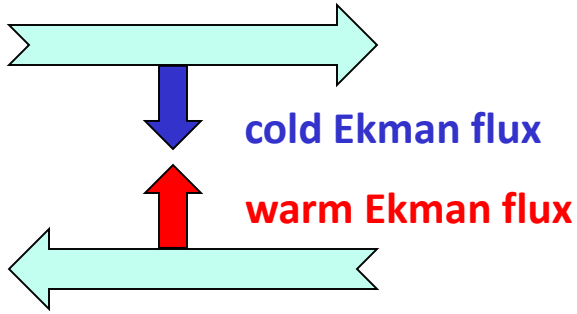


Annual cycle of U_1-U_2 vs. EKE



- **March: stronger STCC/NEC shear + weaker surface N^2**
- **Mean flow shear annual cycle leads that of EKE by ~ 2 months**

mid-latitude westerly winds

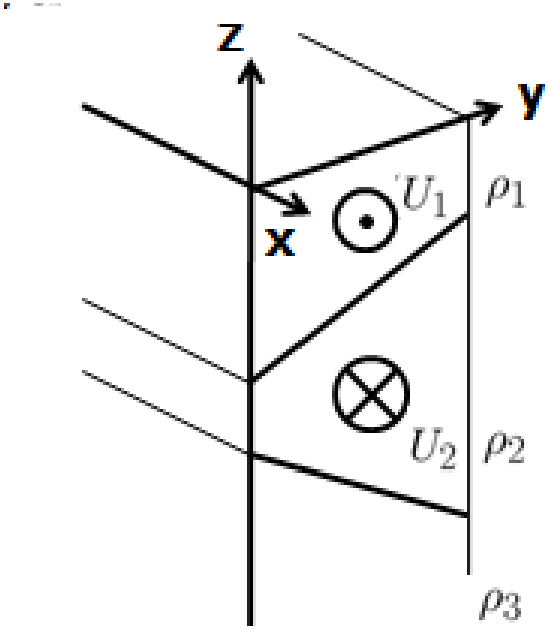


cold Ekman flux

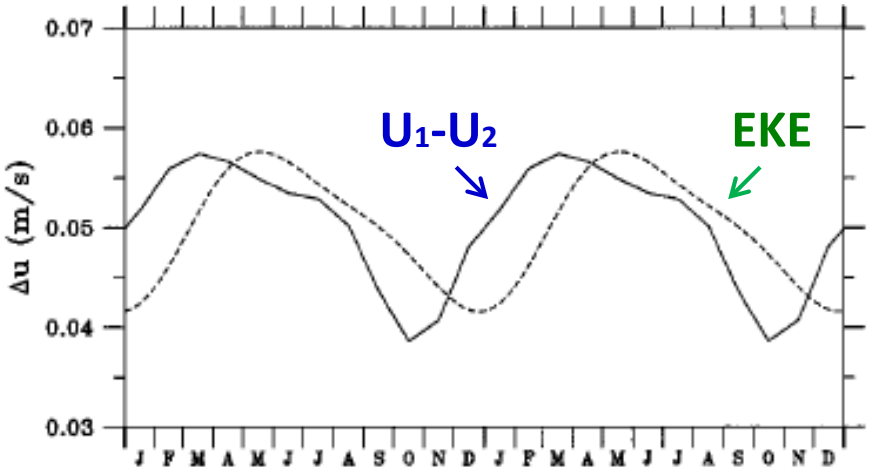
warm Ekman flux

tropical trade winds

Sheared STCC-NEC system in a 2.5-layer RG model

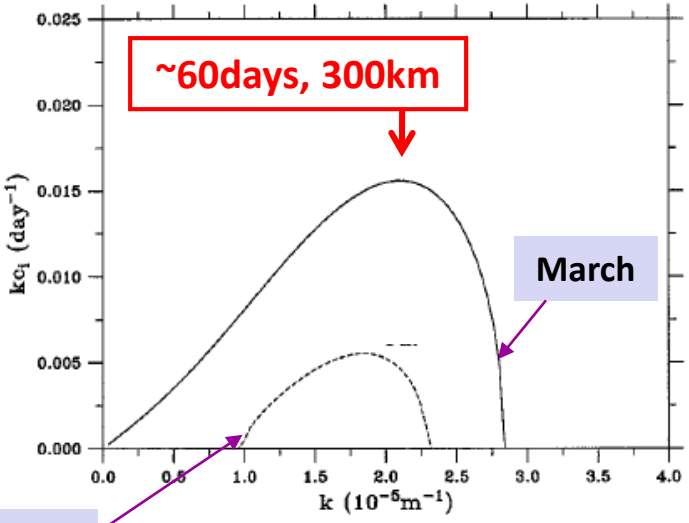


Annual cycle of U_1-U_2 vs. EKE



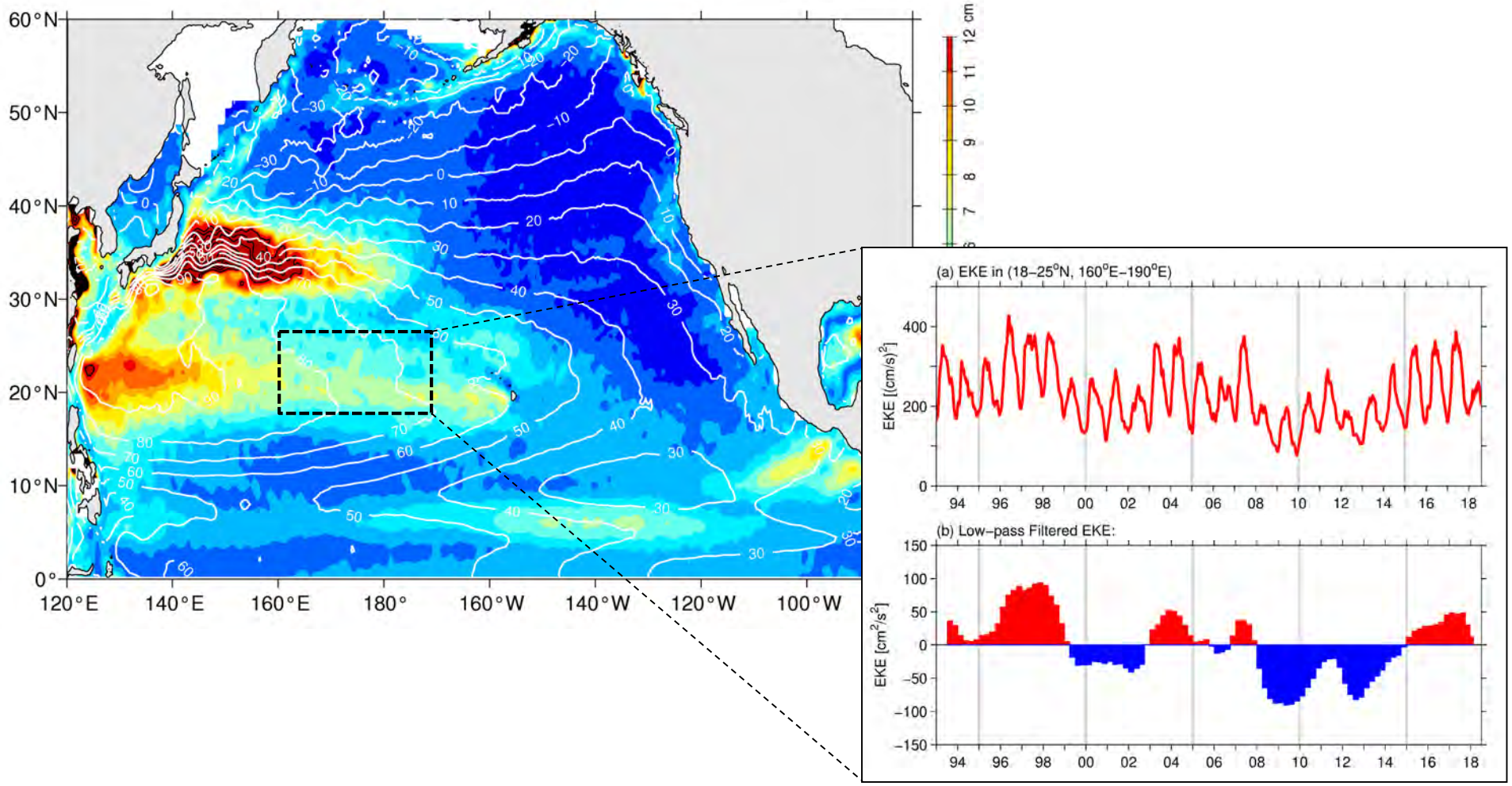
- **March: stronger STCC/NEC shear + weaker surface N^2**
- **Mean flow shear annual cycle leads that of EKE by ~ 2 months**
- **2.5-layer model predicts an e-folding growth scale of ~60 days, explaining the 2-month EKE delay behind U_1-U_2**

growth rate

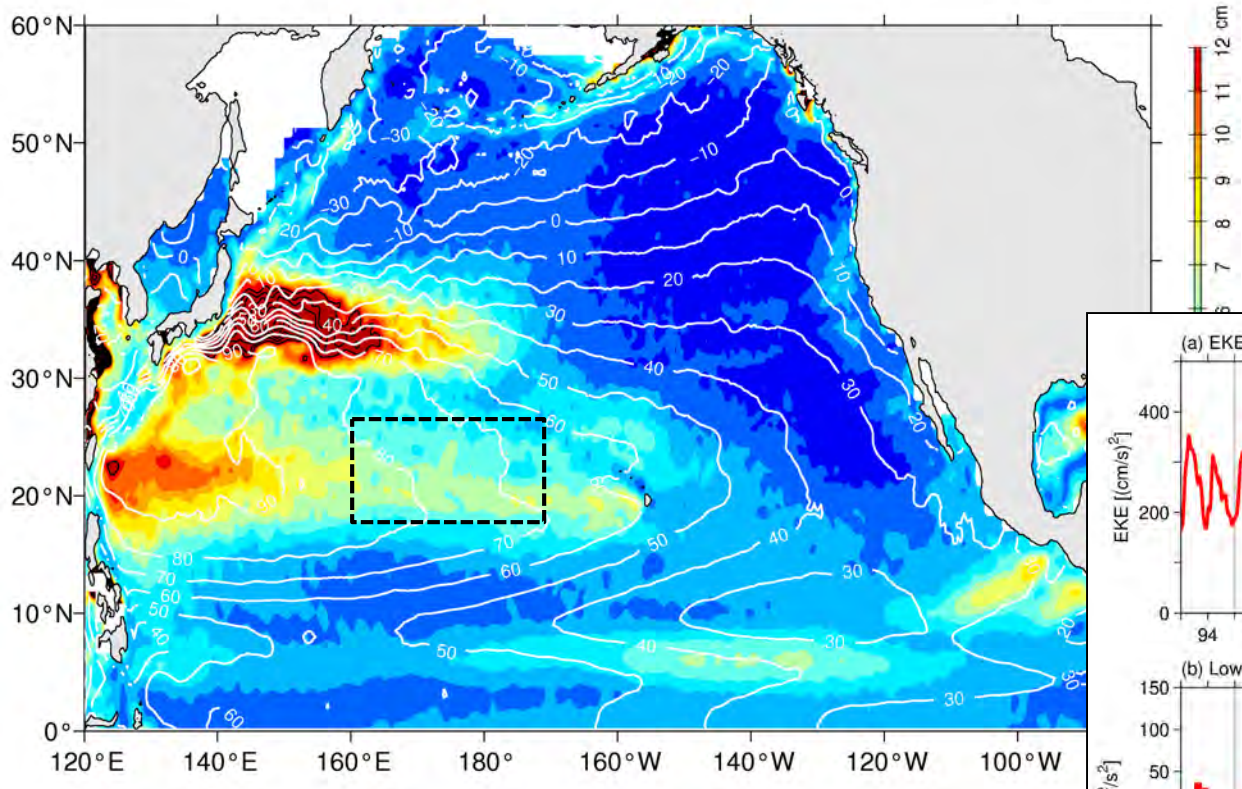


Qiu (1999, JPO)

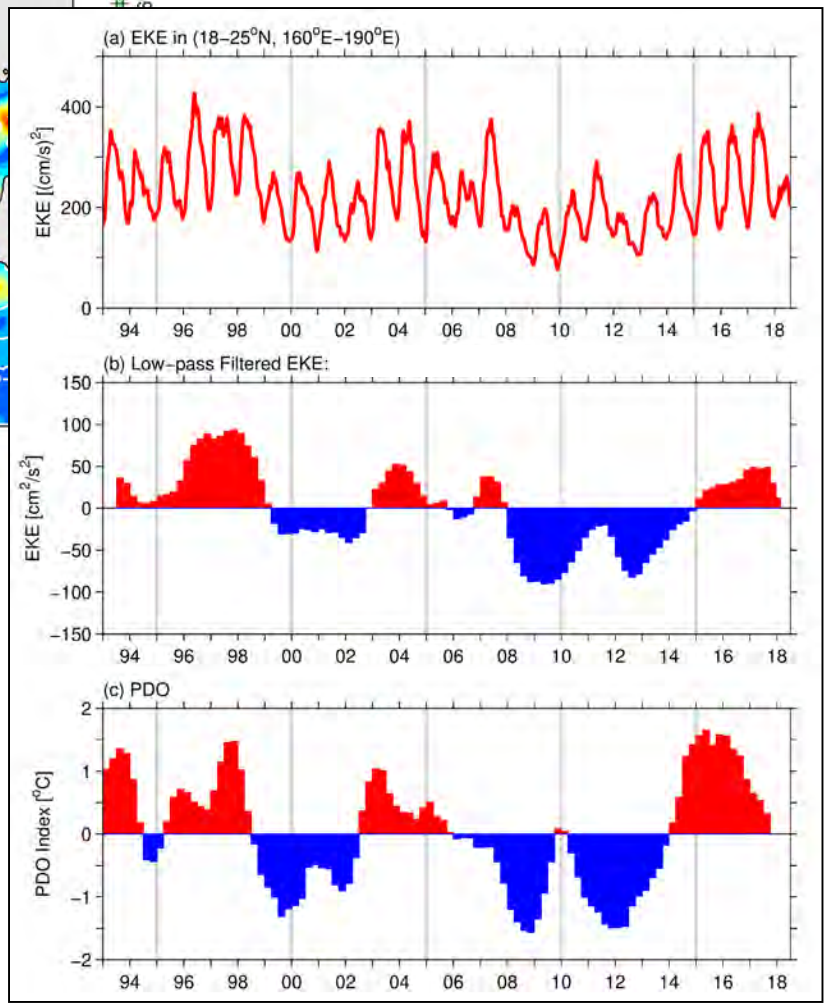
STCC's EKE level also has prominent interannual-decadal modulations



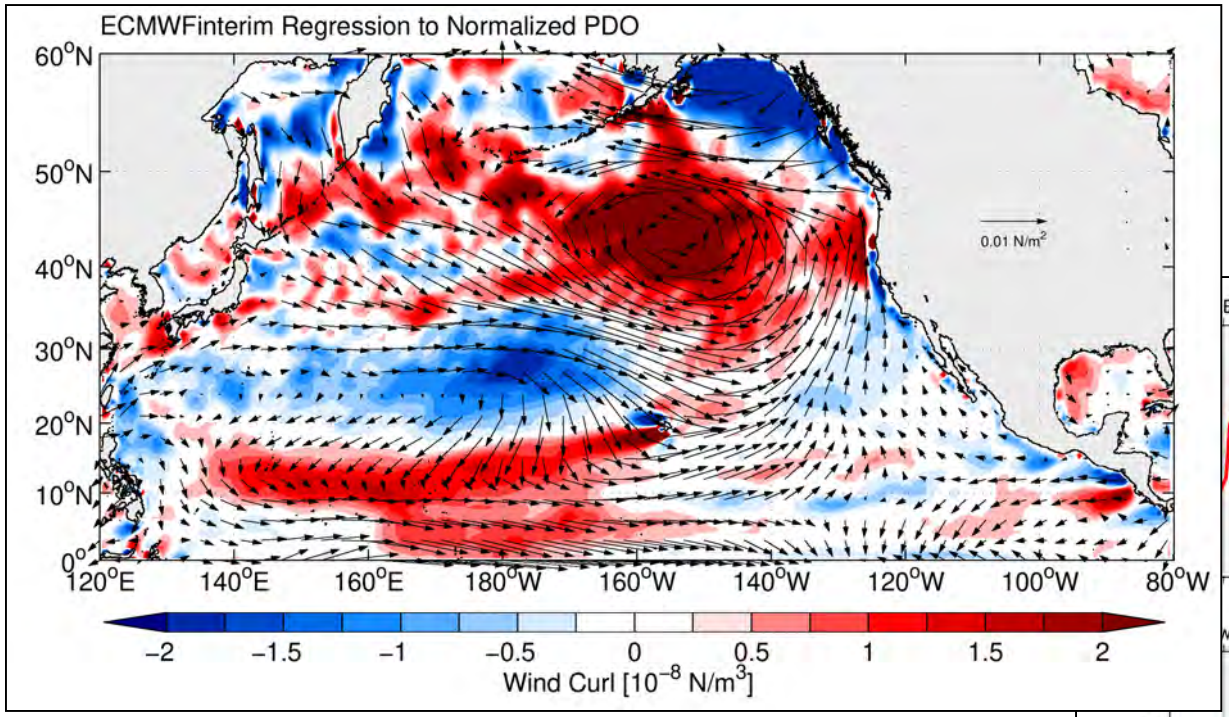
STCC's low-frequency EKE variability corresponds well to the PDO index

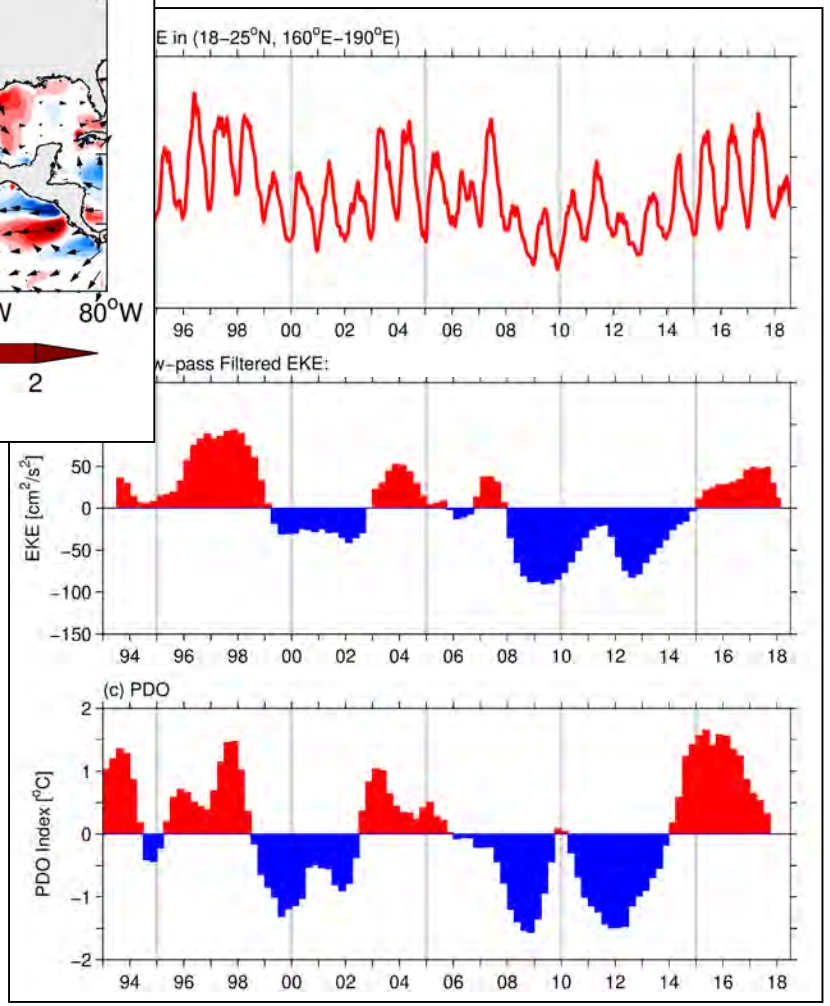


R = 0.69



Wind stress vector & curl (in color) regressed to the PDO index

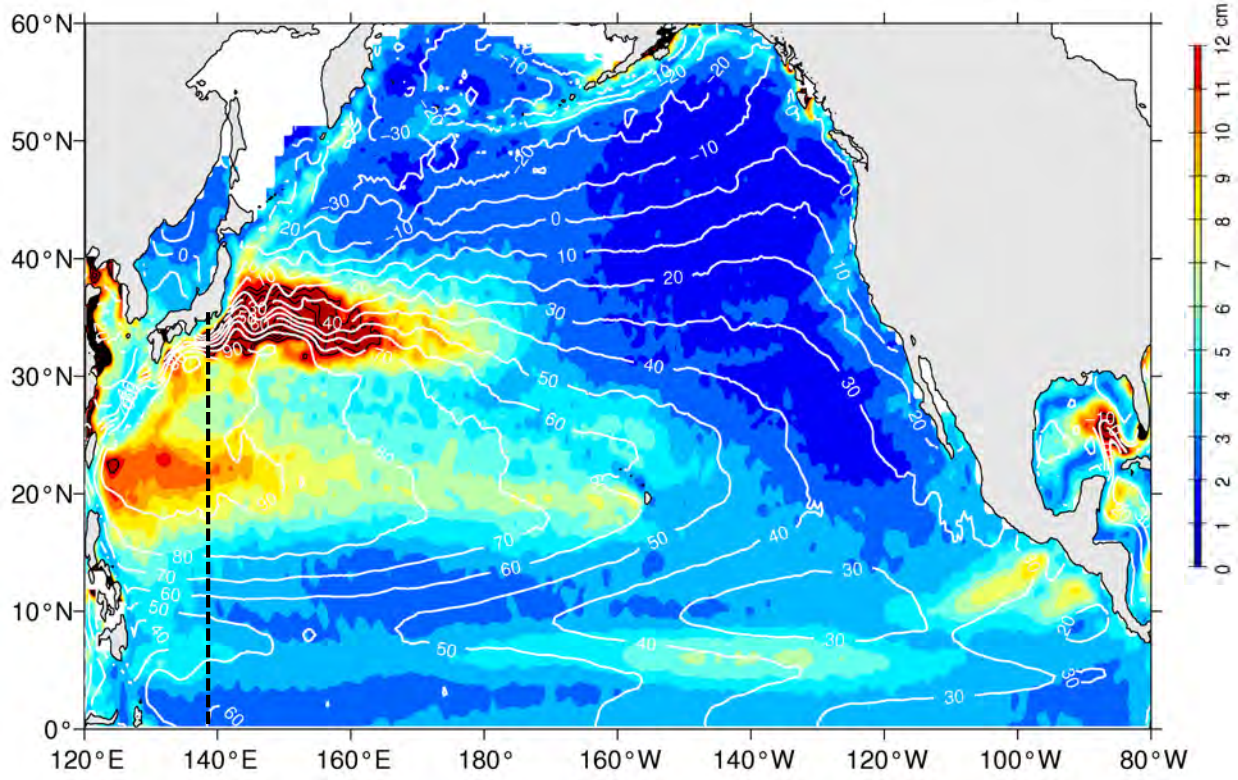




- When PDO index is positive, both trades & westerlies intensify, enhancing Ekman temperature flux convergence along STCC
- This increases STCC's baroclinicity & results in more intense instability & eddy generation

Qiu & Chen (2013, JPO)

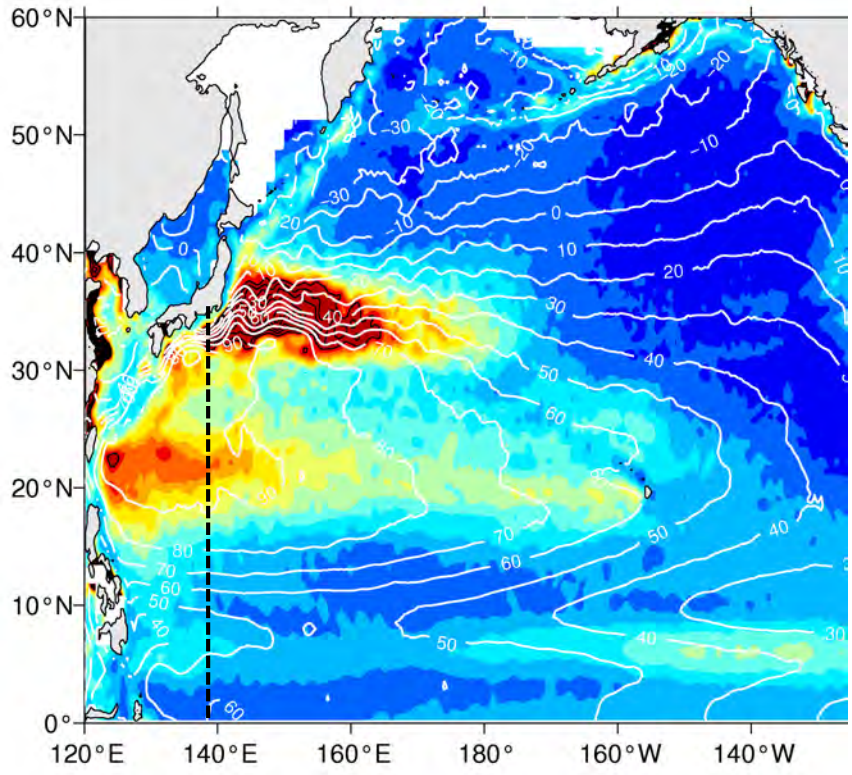
What are missing from the AVISO-derived STCC variability?

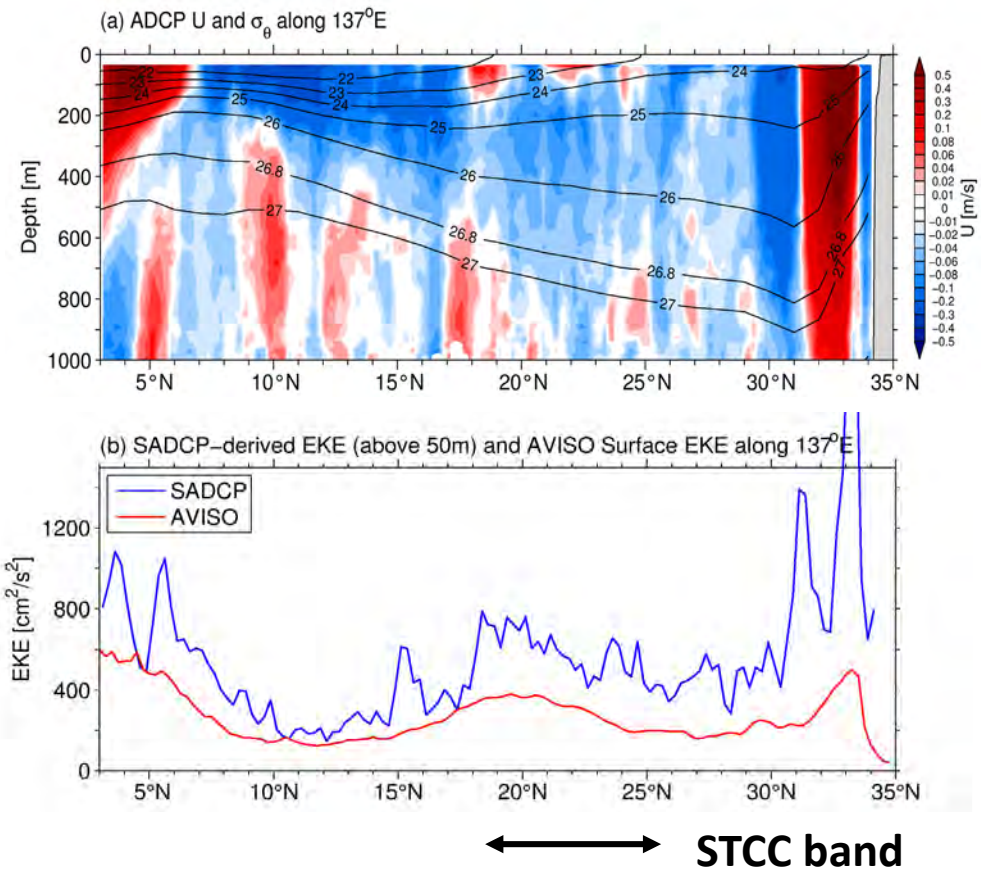


R/V Ryofu Maru of JMA

- Repeat ship-board ADCP surveys along 137°E have been carried out by Japan Meteorological Agency
- Analyzed 33 surveys spanning 2004-16
- Upper ocean u/v data (40-1000db) are QC-processed & averaged to a 2.5km grid

Comparison between ADCP- vs. AVISO-derived EKE level

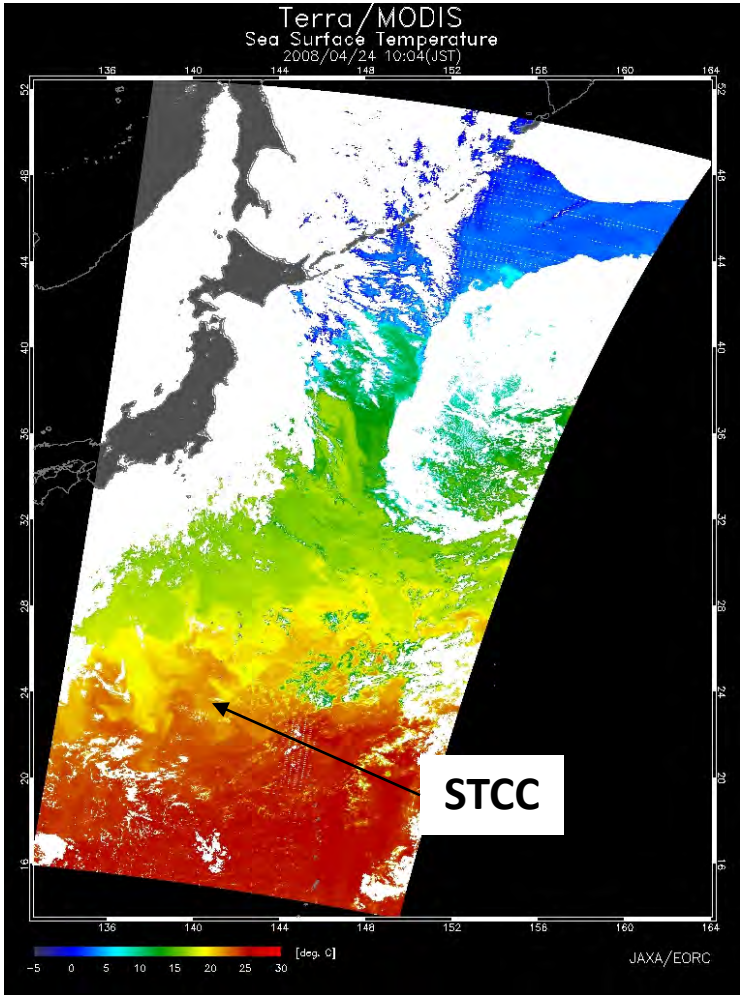


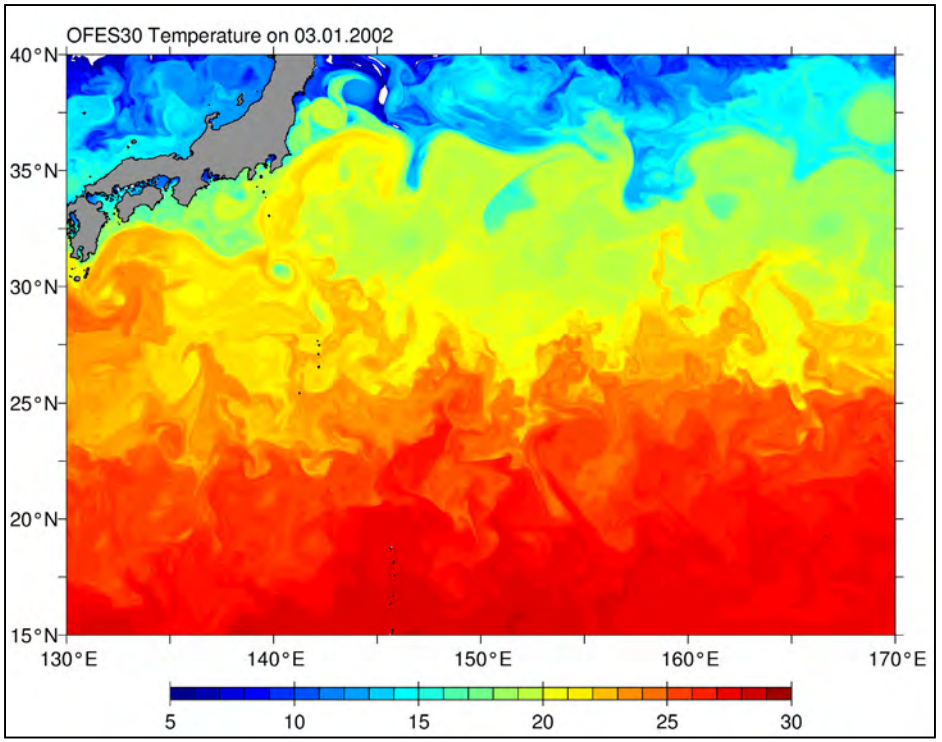


- **Except for the stable NEC band, AVISO-derived EKE level significantly under-estimates the ADCP-derived EKE level**

OFES 1/30° N Pacific OGCM Simulation:

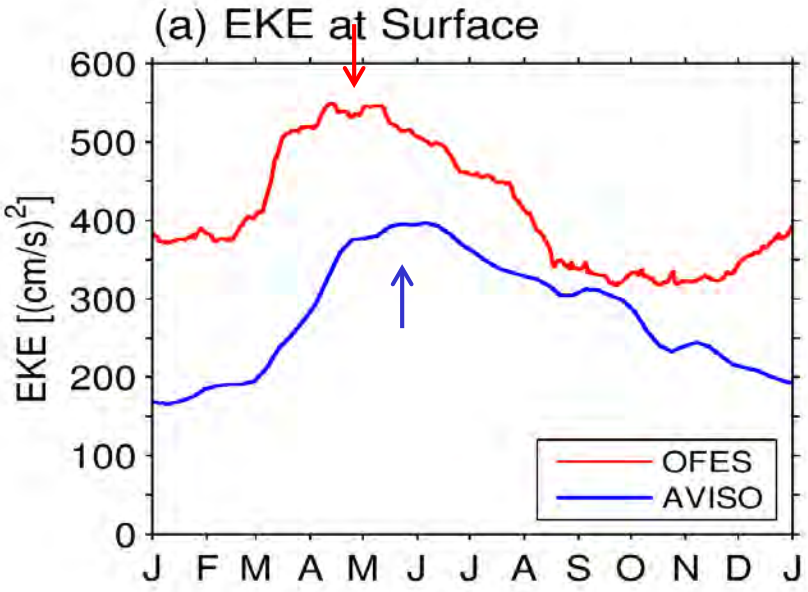
- 3-km horizontal grid resolution (100 vertical levels)
- Model domain 100°E-70°W, 20°S-66°N
- Forced by JRA-25 1°x1° 6-hourly reanalysis data





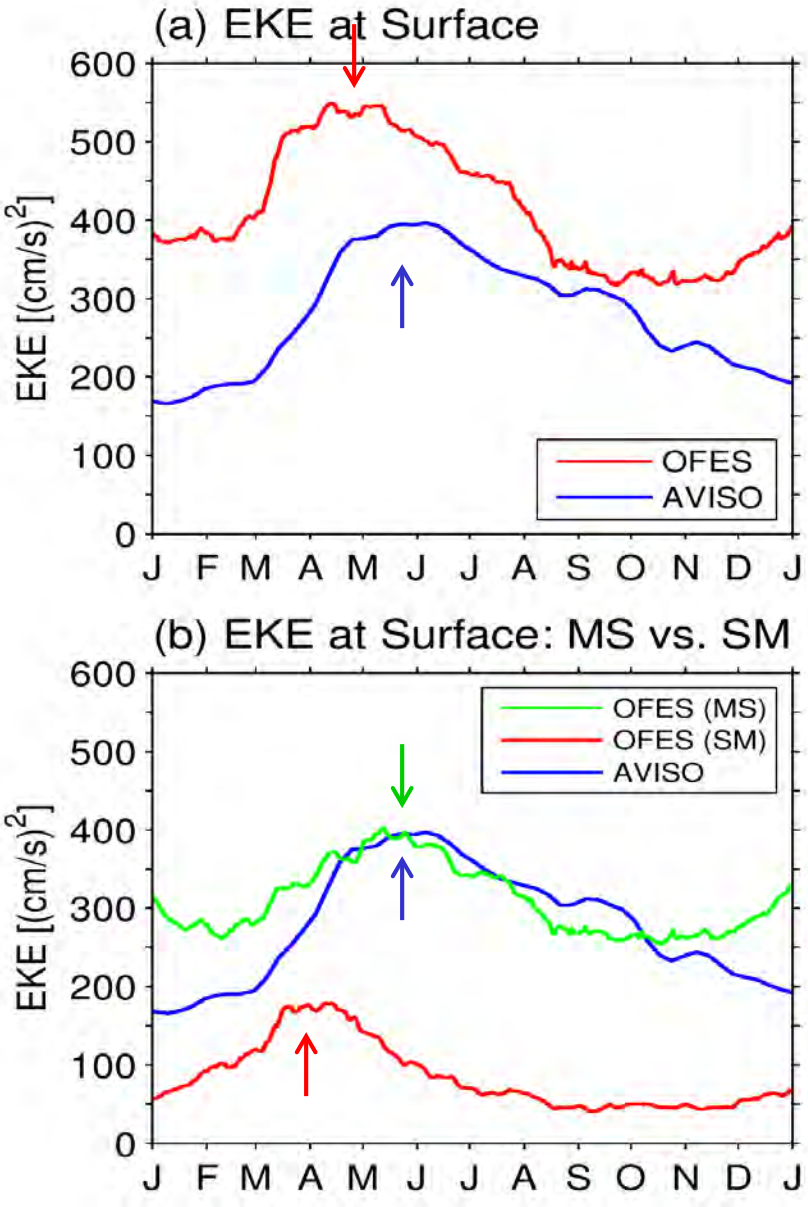
Sasaki, Klein, Qiu & Sasai (2014)

AVISO vs. OFES30 EKE time series in the STCC band: 18°-25°N, 135°-160°E



- **Aside from the energy level, modeled EKE peak precedes the AVISO peak by ~1 month**

AVISO vs. OFES30 EKE time series in the STCC band: 18°-25°N, 135°-160°E



- **Aside from the energy level, modeled EKE peak precedes the AVISO peak by ~1 month**

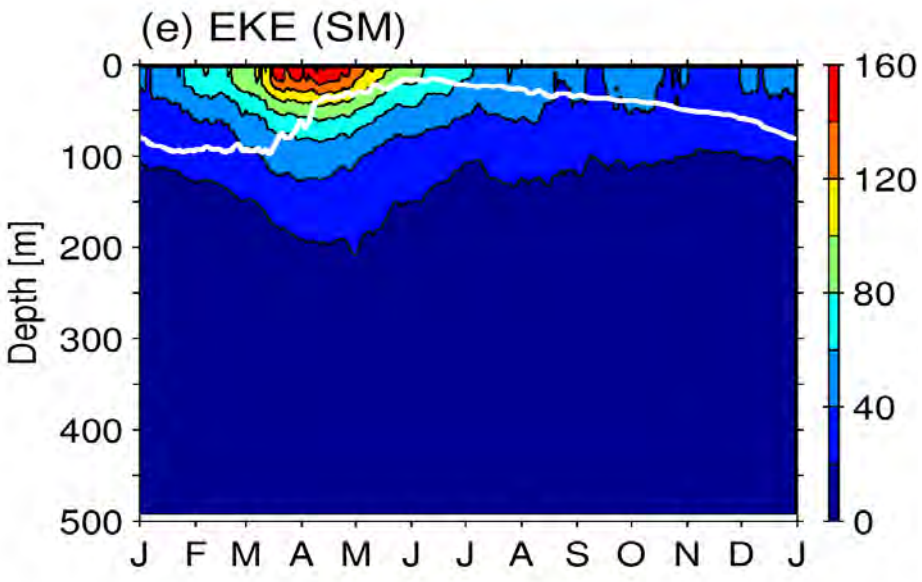
$\eta' = \eta'_{MS} + \eta'_{SS}$

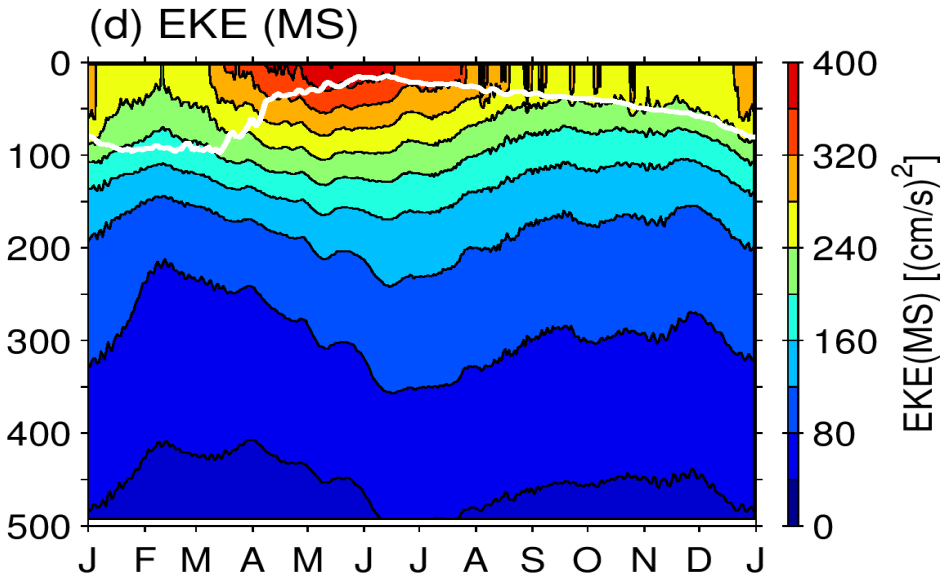
η'_{MS} : **mesoscale SSH signals resolved by AVISO; $2\pi/K > 150$ km**

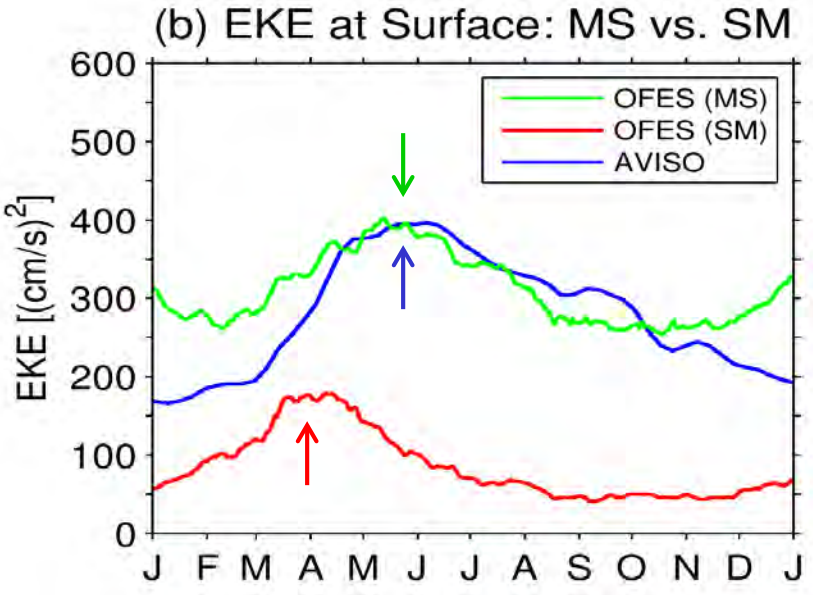
η'_{SS} : **submesoscale SSH signals unresolved by AVISO; $2\pi/K < 150$ km**

- **Mesoscale OFES EKE seasonal amplitude/phase are similar to AVISO**
- **Submesoscale EKE peaks in late March**

OFES30 vertical EKE time series in the STCC band: 18°-25°N, 135°-160°E

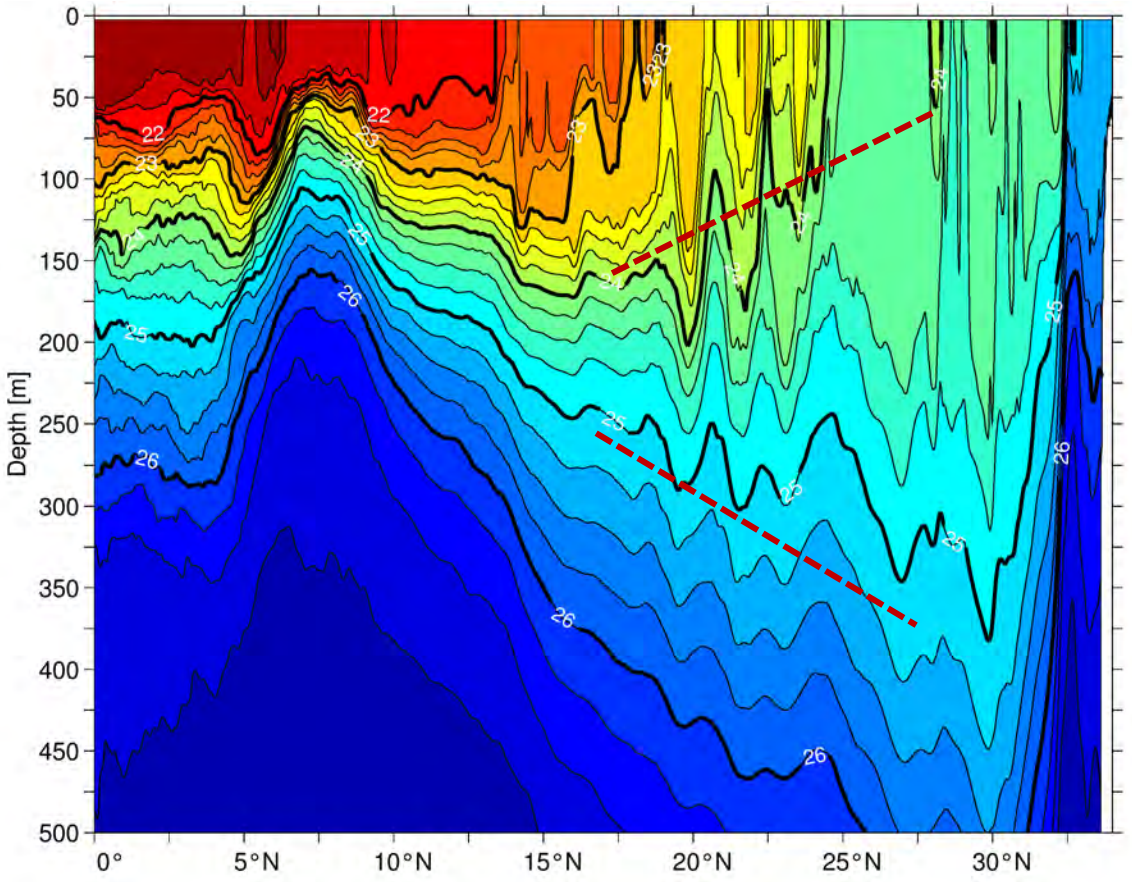


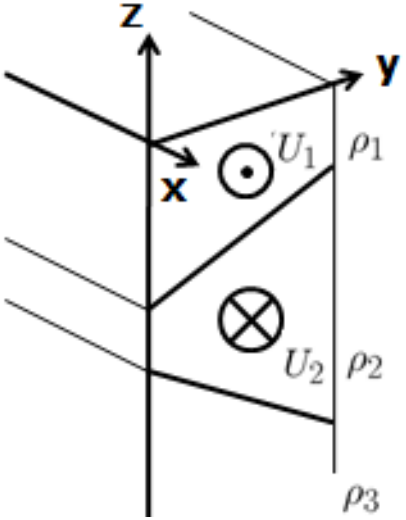




- **Vertically, submesoscale EKE is largely trapped within the surface ML (white curve)**
- **Mesoscale EKE has deeper expressions and its seasonal peak lags with increasing depth**

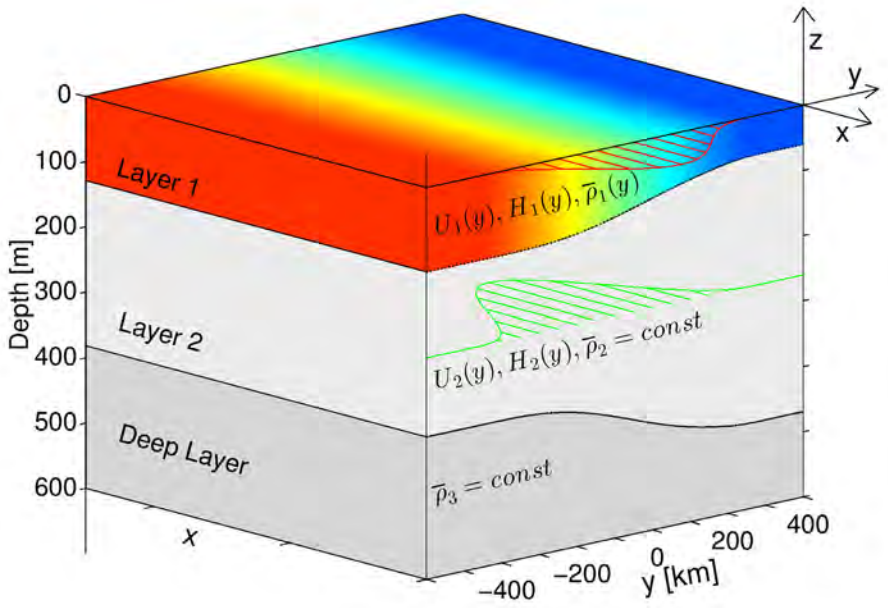
OFES30 σ_θ(y,z) section along 135°E on 1 March 2002

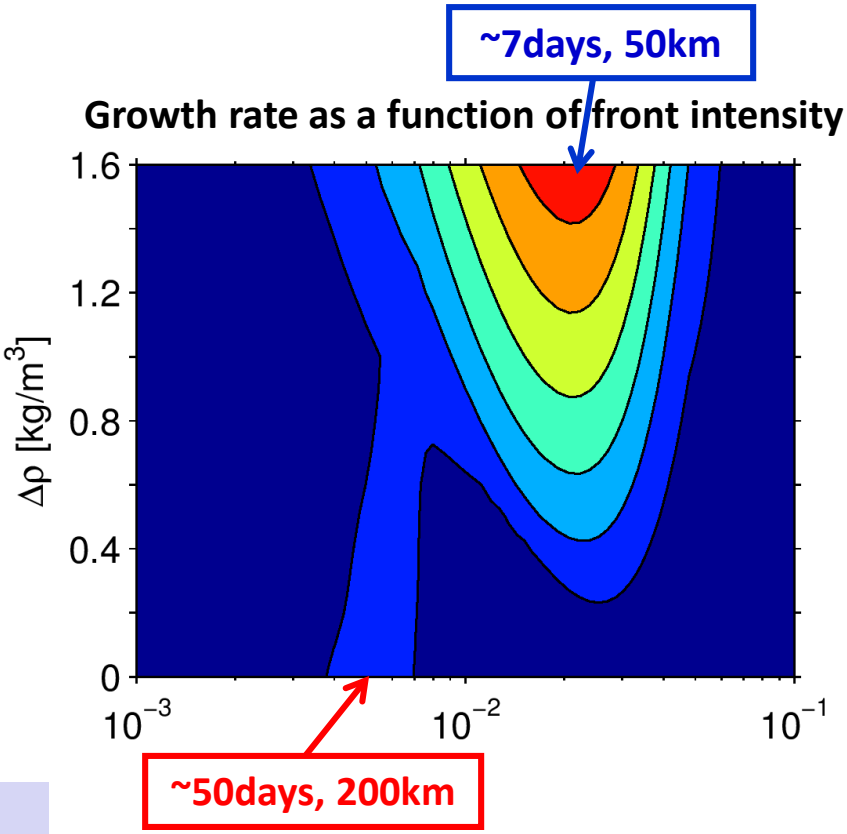




- **In addition to the vertical STCC/NEC shear that generates interior baroclinic instability, steep density gradients in the mixed layer lead to submesoscale ML instability**

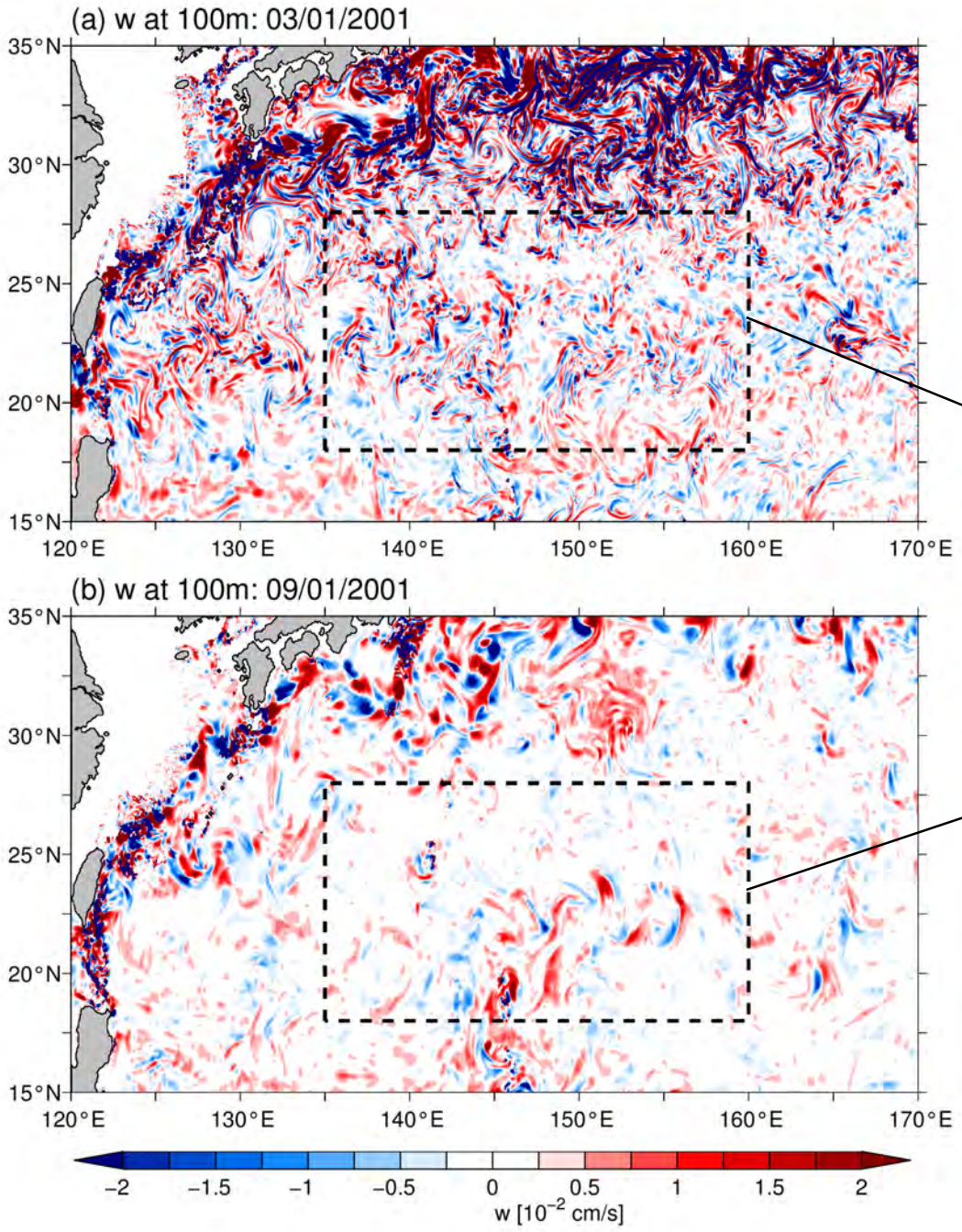
An extended 2.5-layer RG model with density front embedded in upper layer



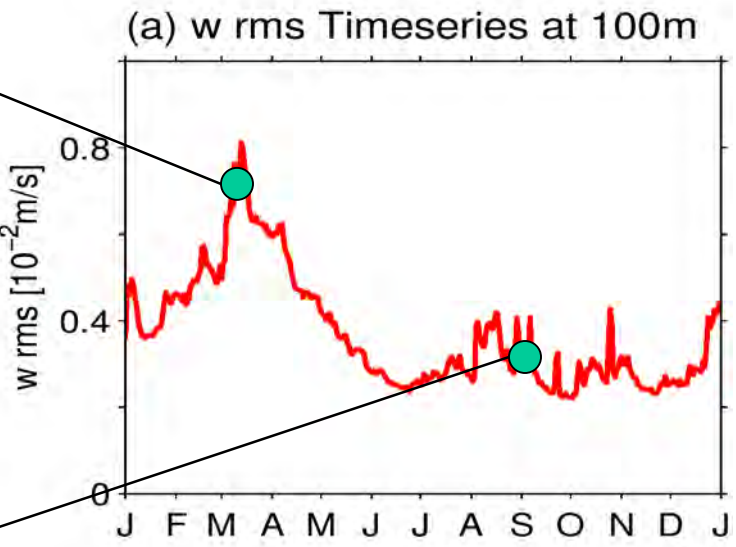


- When $\Delta\rho = 0$ (no upper layer density front), the analysis recovers the interior QG instability
- When $\Delta\rho \neq 0$, ML frontal instability occurs
- ML instability has faster growth rate & shorter most unstable wavelength

Qiu et al. (2014, JPO)

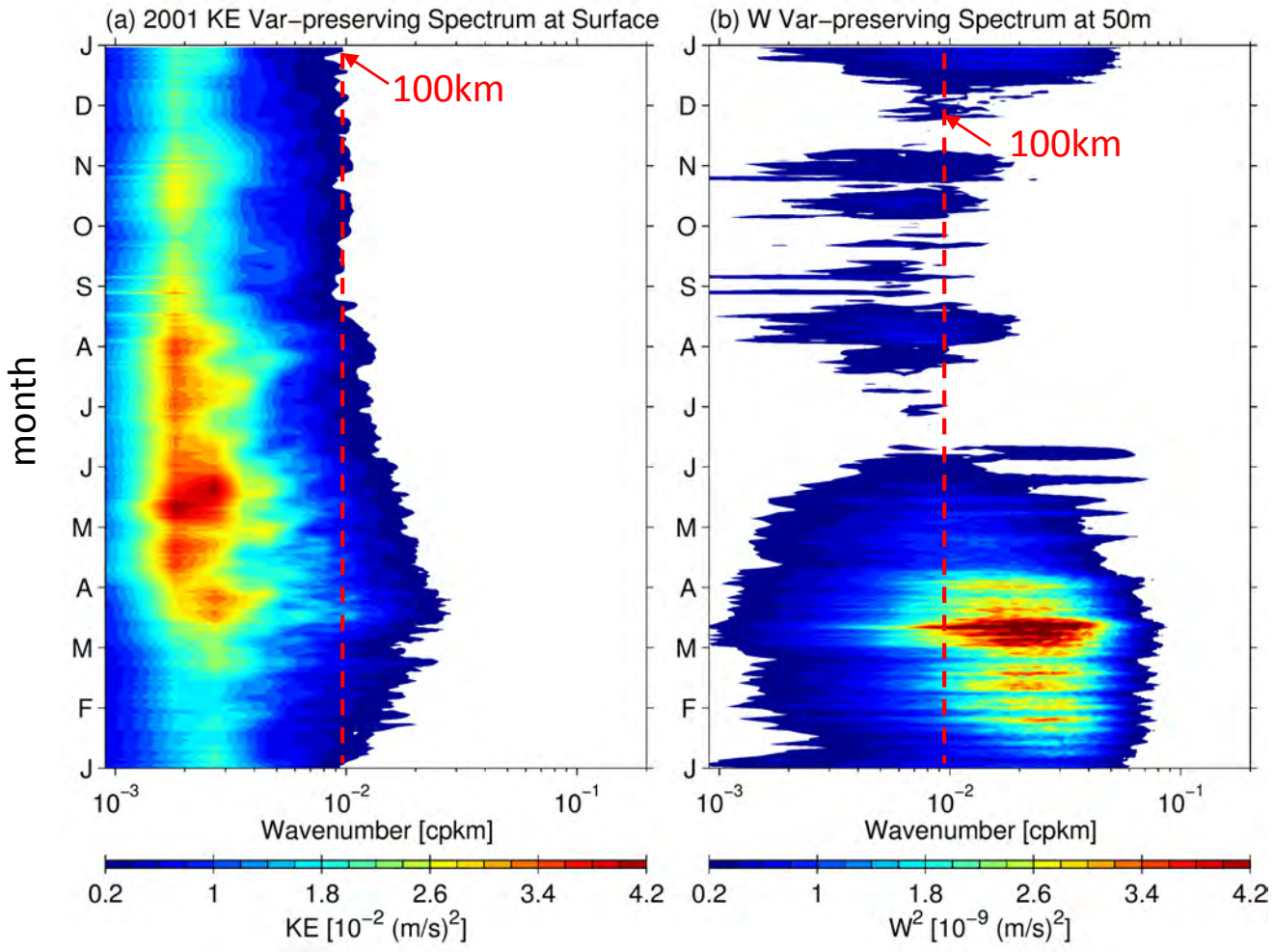


Instantaneous 100m vertical velocity maps from the 1/30° OFES: March vs. September



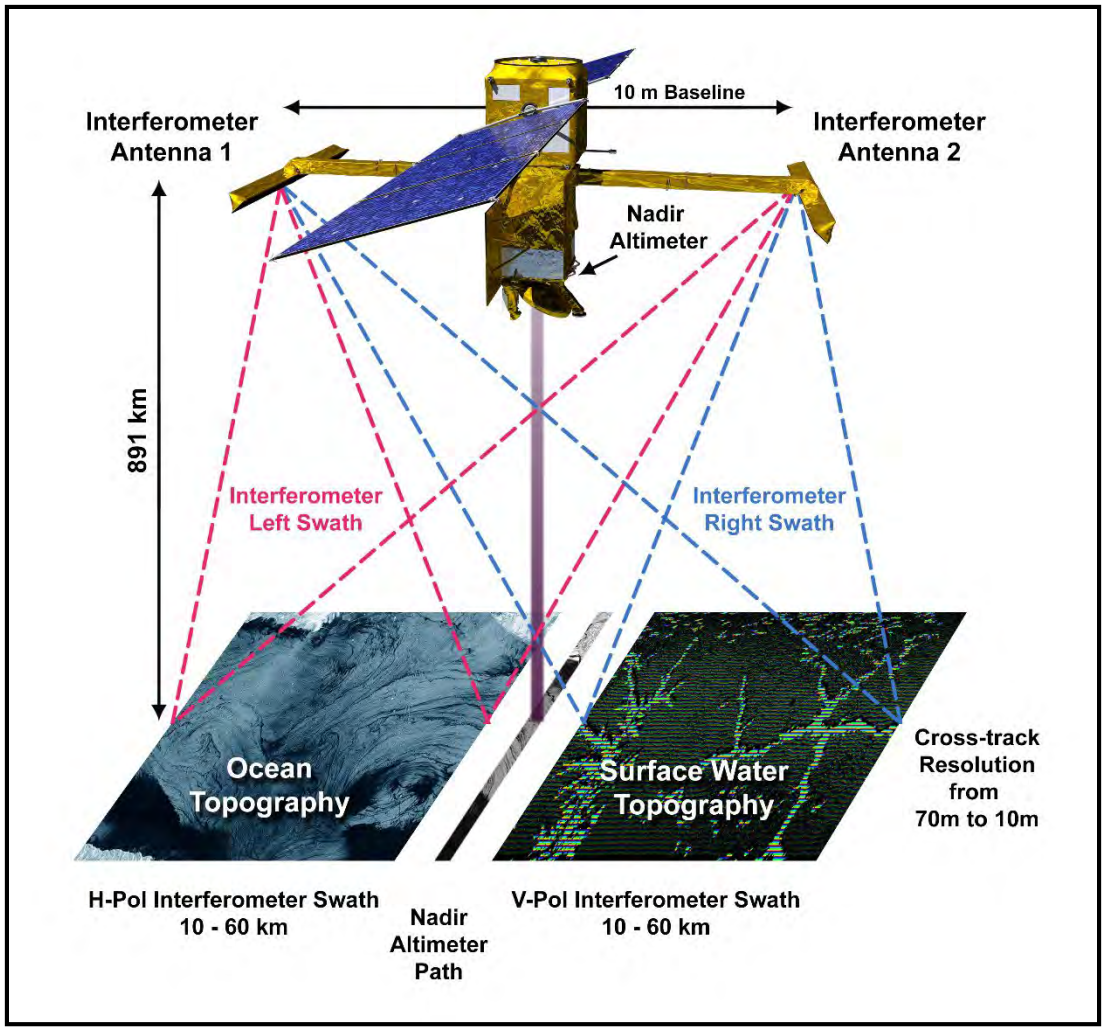
- **Submesoscale variability controls the w signals!**

OFES30 horizontal (z=0) vs. vertical velocity (z=50m) spectra



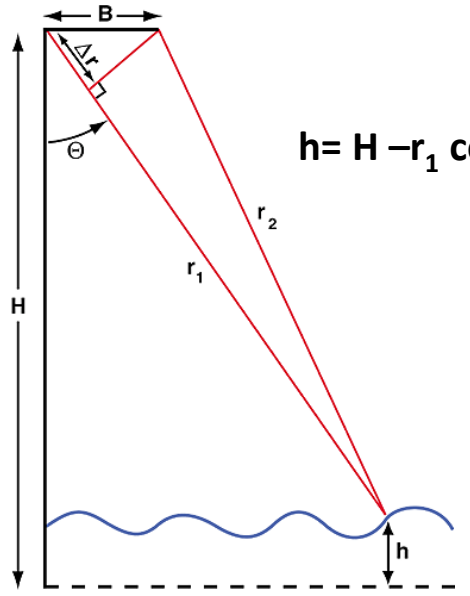
- **While mesoscale eddy variability controls the horizontal circulation changes, submesoscale variability controls the w amplitude/seasonality**

NASA-CNES Surface Water and Ocean Topography (SWOT) Mission



https://swot.jpl.nasa.gov

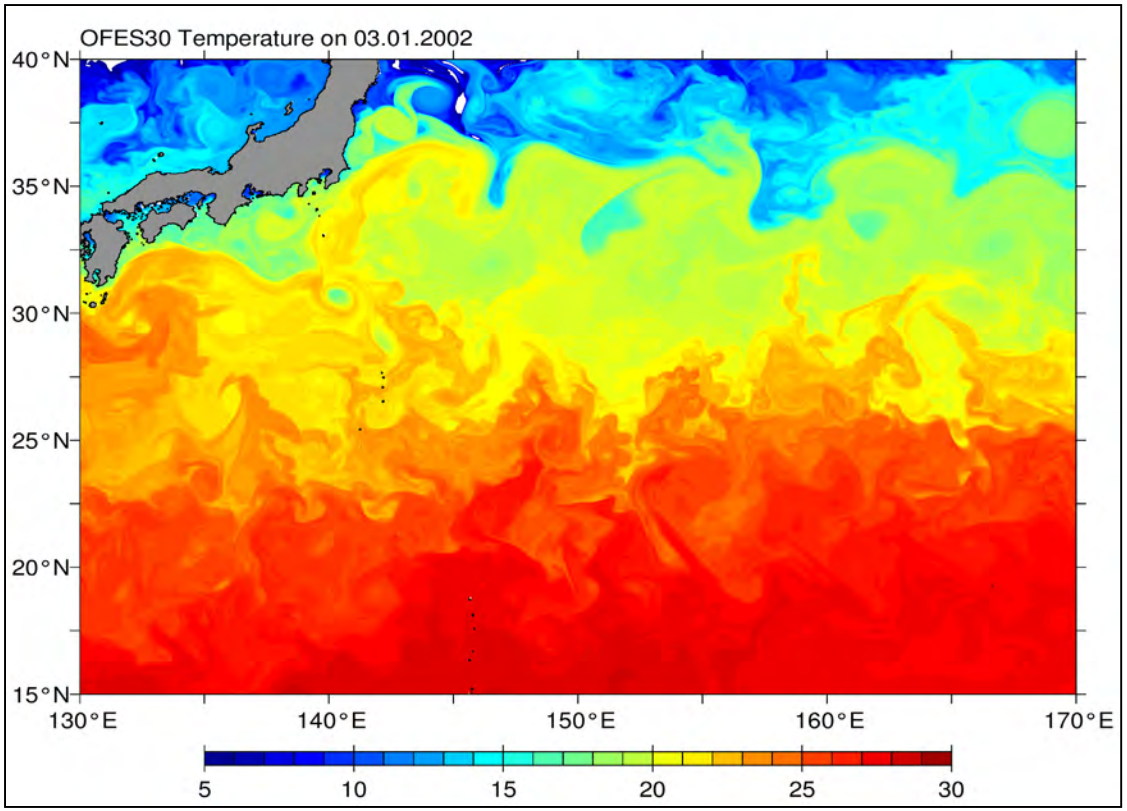
- Point vs 120km-wide swath measurements
- O(150~200km) vs O(15km) resolution; cf. L_R = O(50km)
- Planned launch: Sept. 2021
- Ka-band radar Interferometer measurement (see below)



$h = H - r_1 \cos(\Theta)$

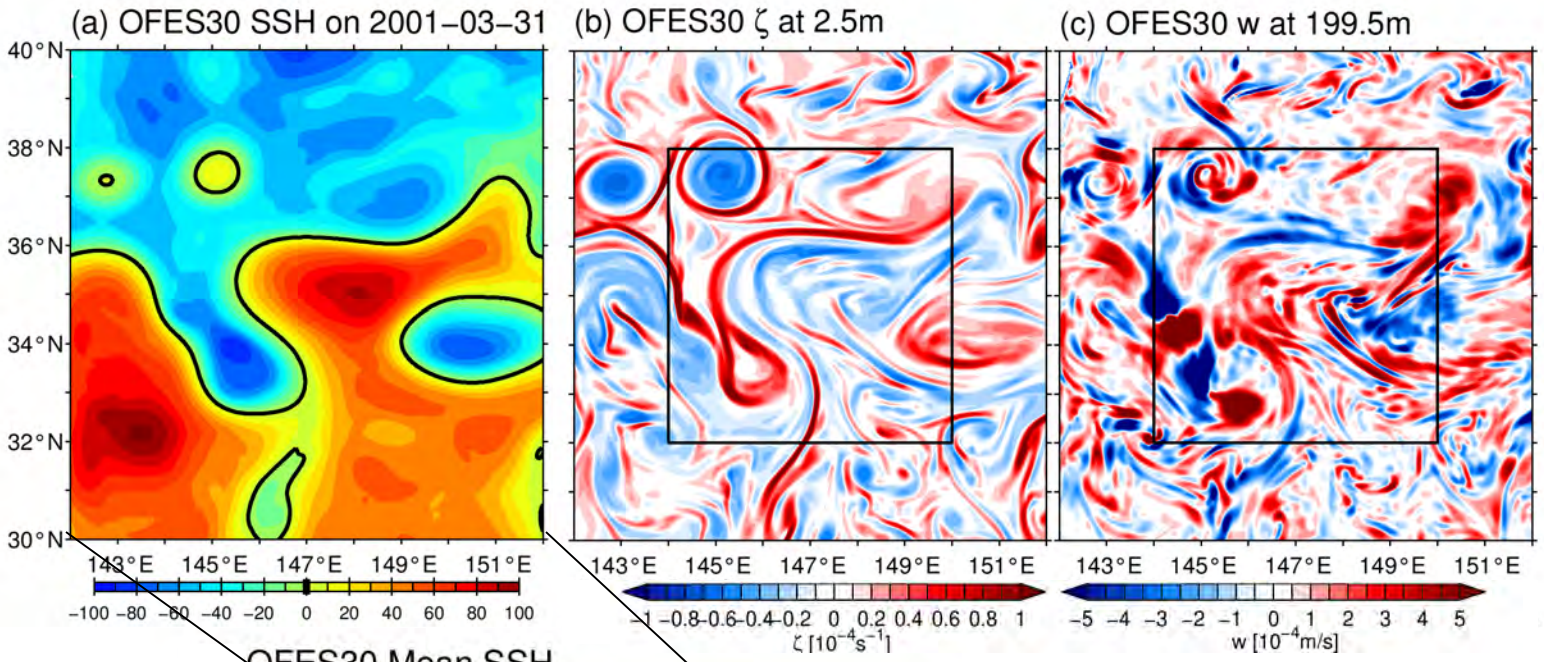
Opportunities from the SWOT Mission: an Example

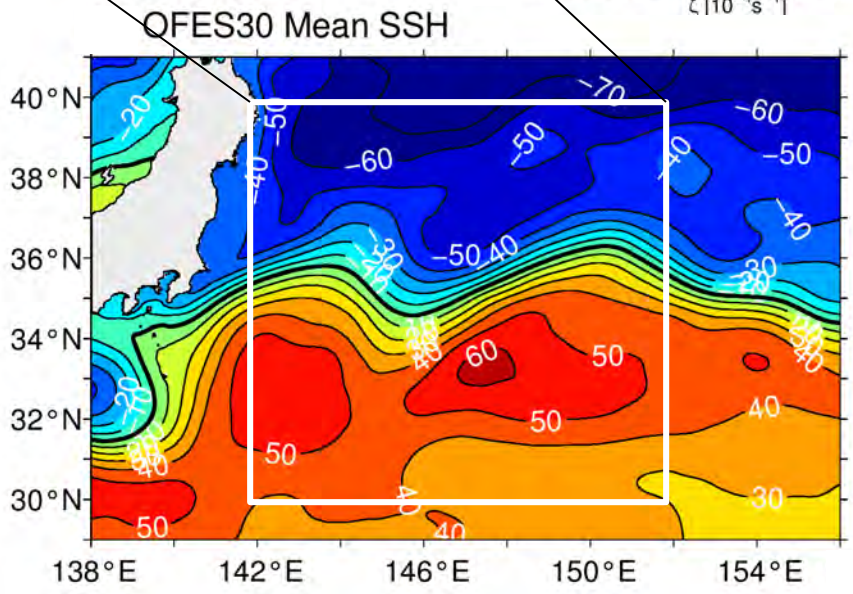
- **Submesoscale features tend to be advected by the mesoscale circulation in which they're imbedded**
- **This opens the possibility of reconstructing the 3D upper ocean circulation structures, including w field, using the high-resolution SSH data from SWOT**



Sasaki et al. (2014)

Case study in the Kuroshio Extension region: March 31, 2001





OFES original

Input: 10°x10° SSH η field (upper left)

Target: 6°x6° relative vorticity ζ field (upper middle)

6°x6° vertical velocity w field (upper right)

(a smaller target box is chosen to avoid edge effect)

Effective surface quasi-geostrophic (SQG) theory: Lapeyre and Klein (2006)

- **Under the assumption that surface & subsurface PV anomalies are correlated, the geostrophic streamfunction anomaly ψ can be functionally related to the SSH anomaly η by :**

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

where ^ : horizontal Fourier transform, k : horizontal wavenumber, and N_0 : effective buoyancy frequency.

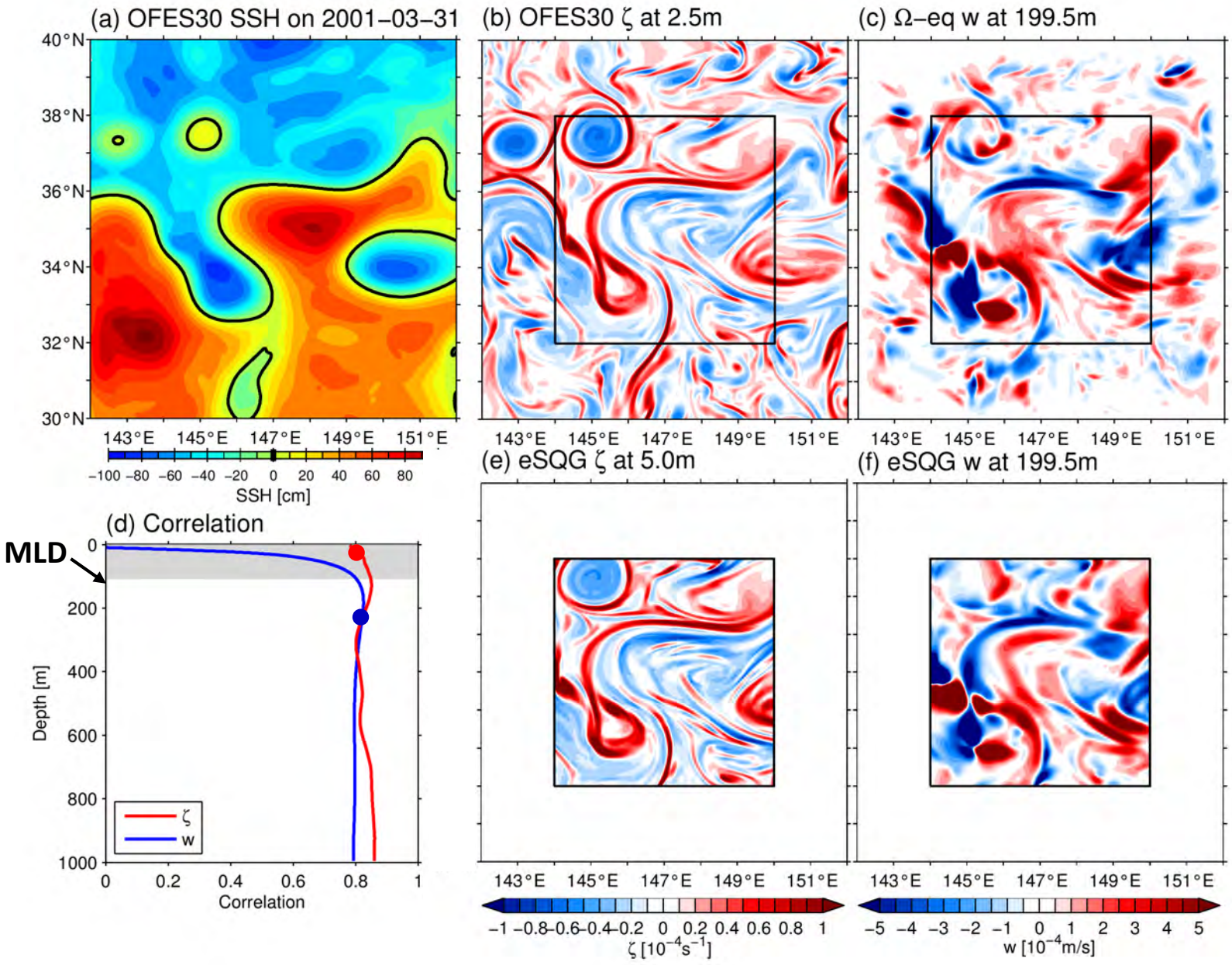
- **Once ψ is specified, 3-D fields of relative vorticity, buoyancy, & vertical velocity can be deduced from geostrophy, hydrostaticity, & advective buoyancy equation, respectively :**

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

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

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

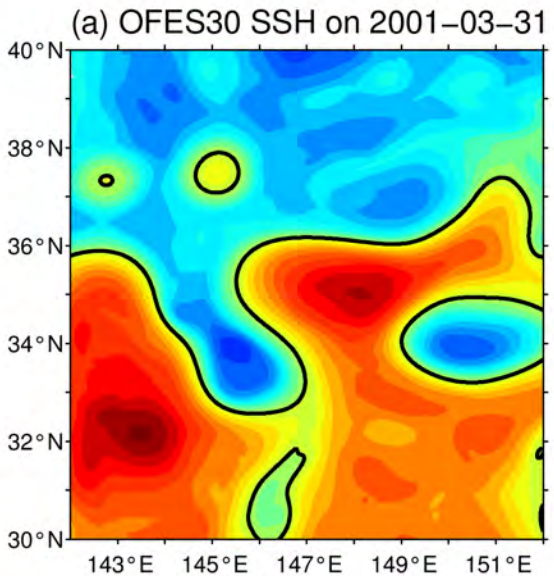
Best reconstruction: modeled η as input, no swath gaps/measurement errors

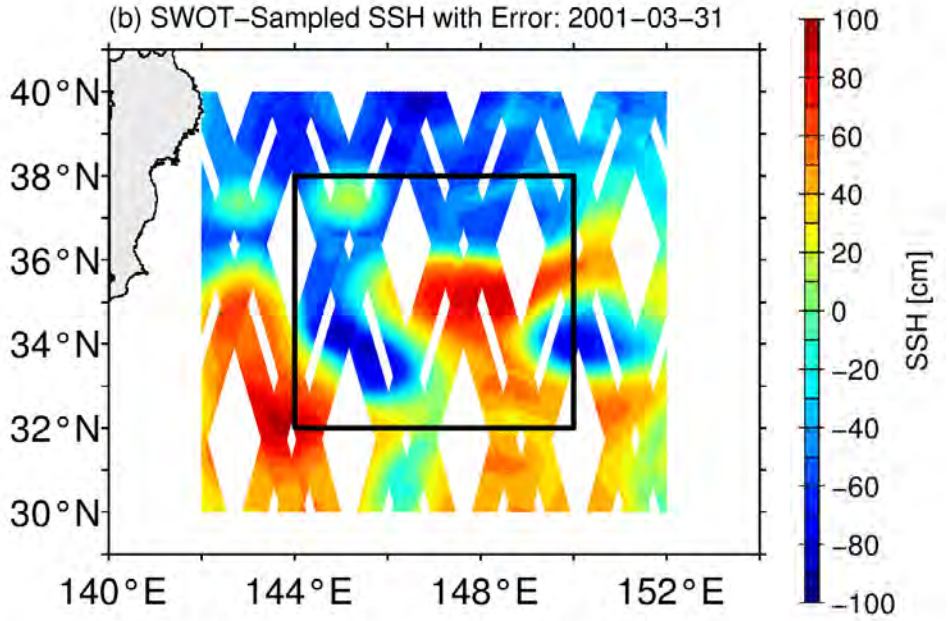


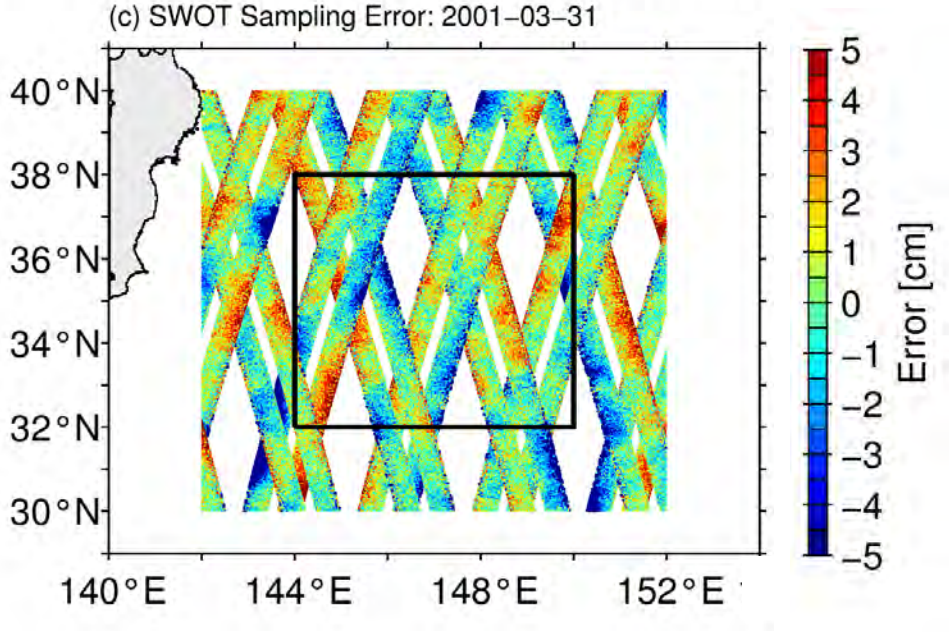
OFES original (balanced w)

eSQG reconstruct

SWOT simulator-sampled SSH field in a sub-cycle centered on March 31

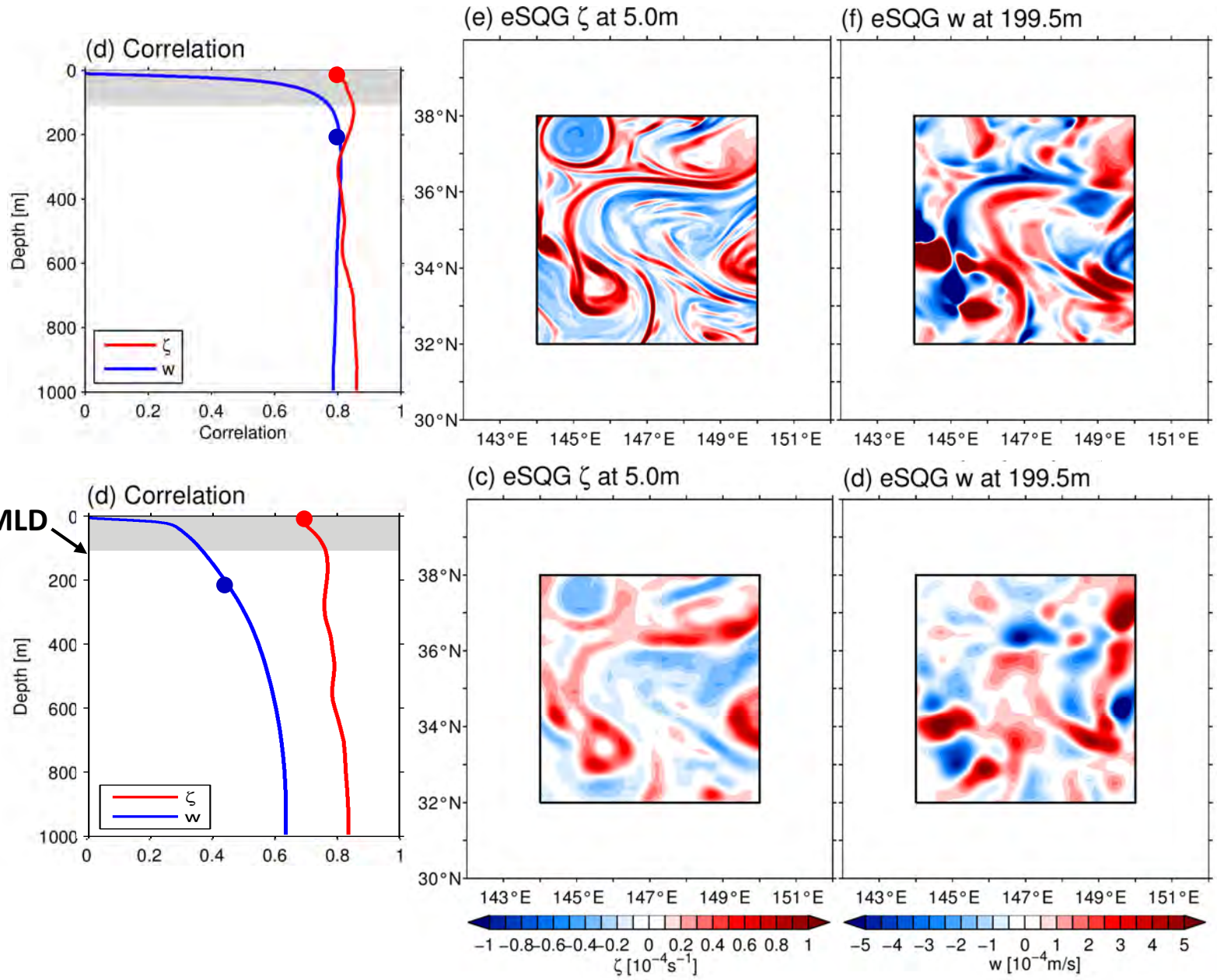






- **Spatial η discontinuities due to swath time difference and larger measurement errors toward edges**
- **Measurement errors have a larger impact on small-scale η signals due to larger noise-to-signal ratio**

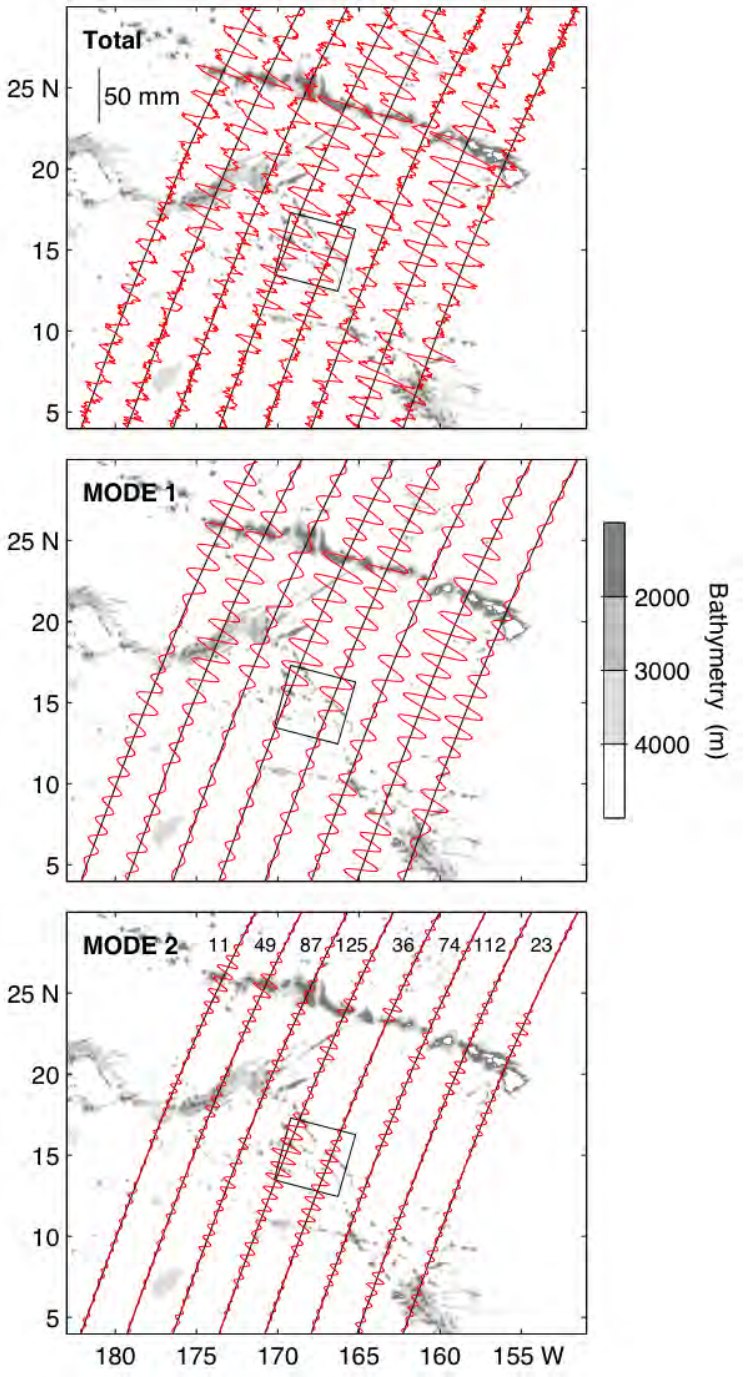
Reconstruction comparisons with simulated vs. mapped SSH field as input



eSQG original reconstruct

eSQG SWOT reconstruct

Qiu et al. (2016, JPO)

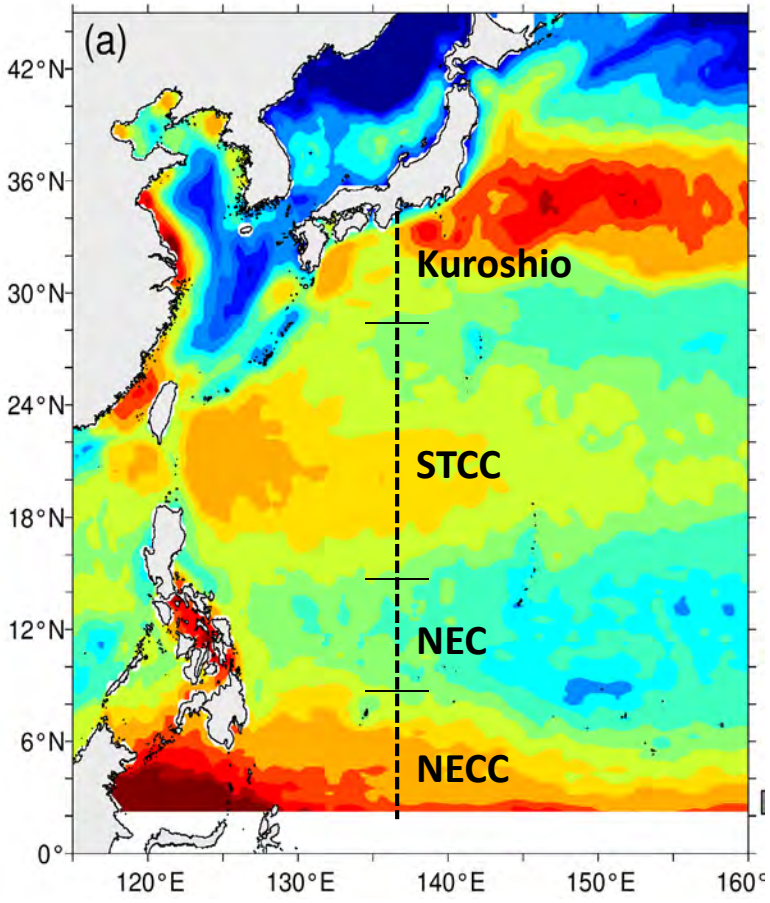


- SSH signals associated with the coherent M_2 internal tides around Hawaiian Islands
- Mode-1 has a wavelength of ~150km & an amplitude of ~5cm

Challenges

- For mesoscales with $2\pi/k > 150$km, balanced geostrophic flow dominates and altimeter-derived SSH can be readily used to infer surface geostrophic velocities
- As the geostrophic flow weakens as $k^{-2} \sim k^{-3}$, unbalanced wave motions can overtake in the 10-150km meso-submesoscale range
- For SWOT mission, it is important to identify the length scale Lt at which geostrophic flow loses its dominance & is overtaken by unbalanced wave motions

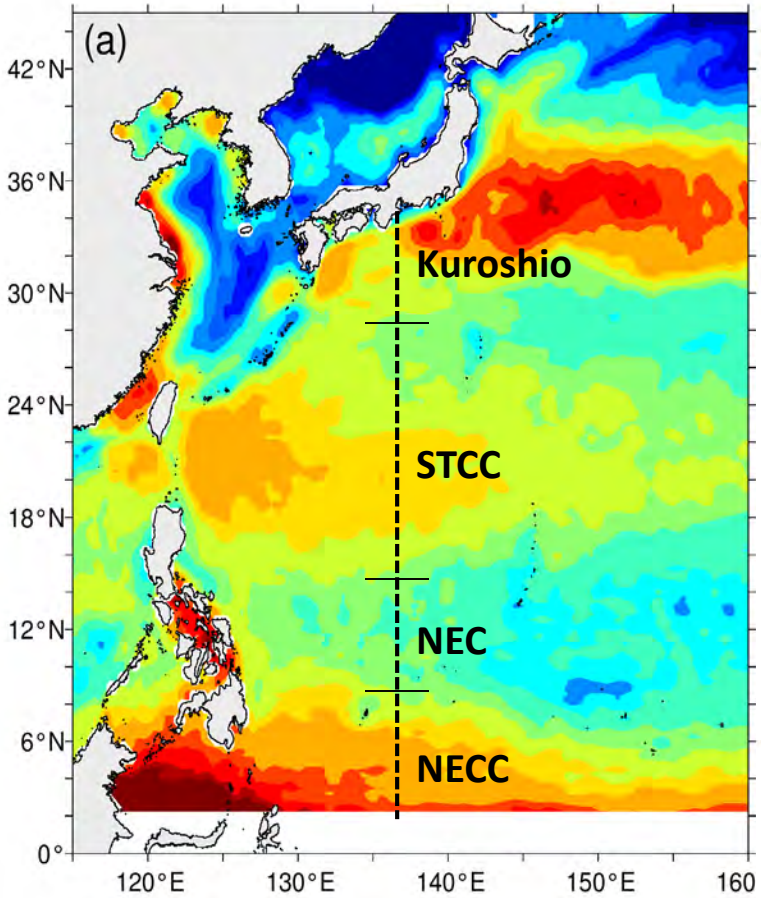
JMA repeat S-ADCP surveys along 137°E



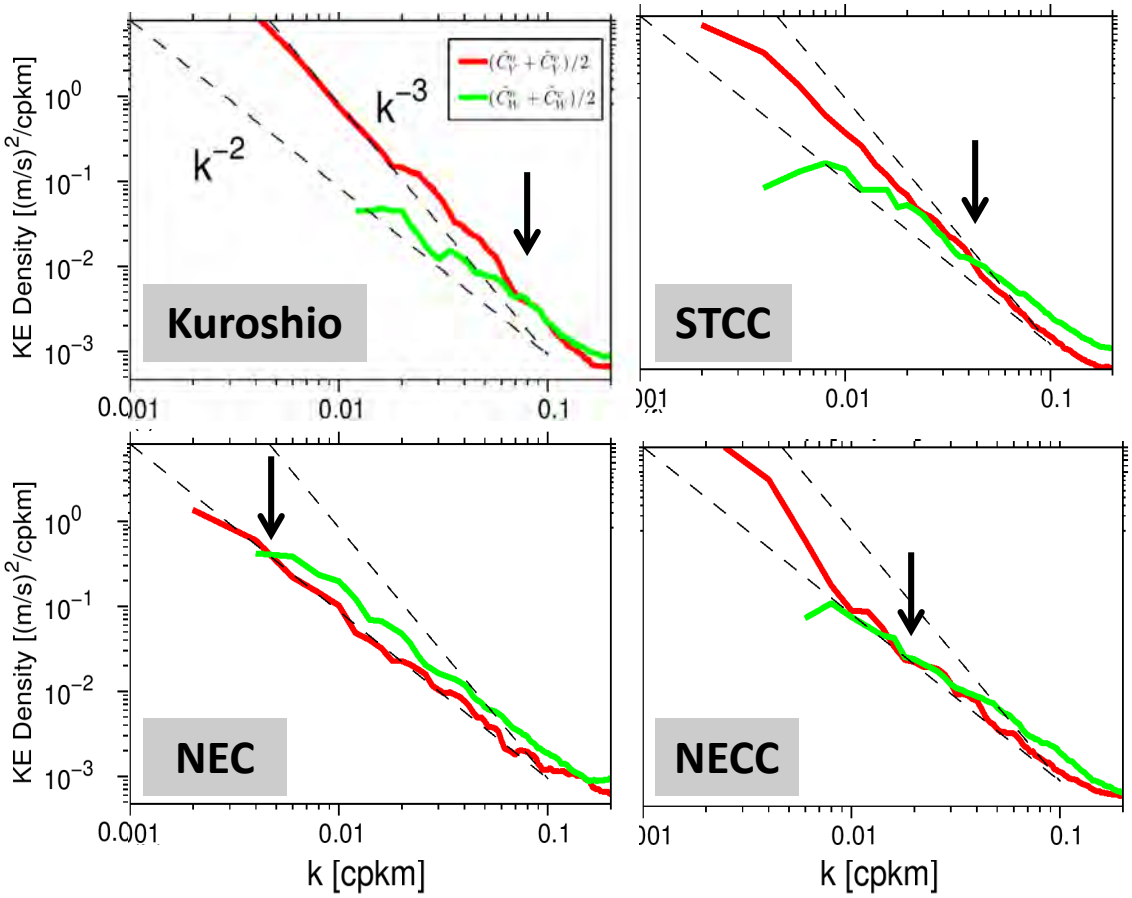
Separating balanced vs. unbalanced motions:

- Under isotropic condition, Helmholtz decomposition allows $(u, v) = (-\psi_y + \phi_x, \psi_x + \phi_y)$ be separated into rotational ψ & irrotational ϕ components. In spectral space: $S^u(k), S^v(k) \rightarrow S^\psi(k), S^\phi(k)$ (Bühler et al. 2014)
- By definition, geostrophic flow has ψ only (i.e., $S^\phi_g(k) = 0$) & KE spectrum for ϕ is completely set by wave motions: $S^\phi_w(k) = S^\phi(k)$
- Assuming internal waves in open ocean follow the Garrett-Munk spectrum, rotational part of $S^\psi(k)$ for the internal waves becomes: $S^\psi_w(k) = f^2 S^\phi_w(k) / \omega_*^2$
- Given $S^\psi_w(k)$, geostrophic KE spectrum is $S^\psi_g(k) = S^\psi(k) - S^\psi_w(k)$
- Transition scale Lt is defined at where $S^\psi_g(k) = S^\psi_w(k) + S^\phi_w(k)$

JMA repeat S-ADCP surveys along 137°E



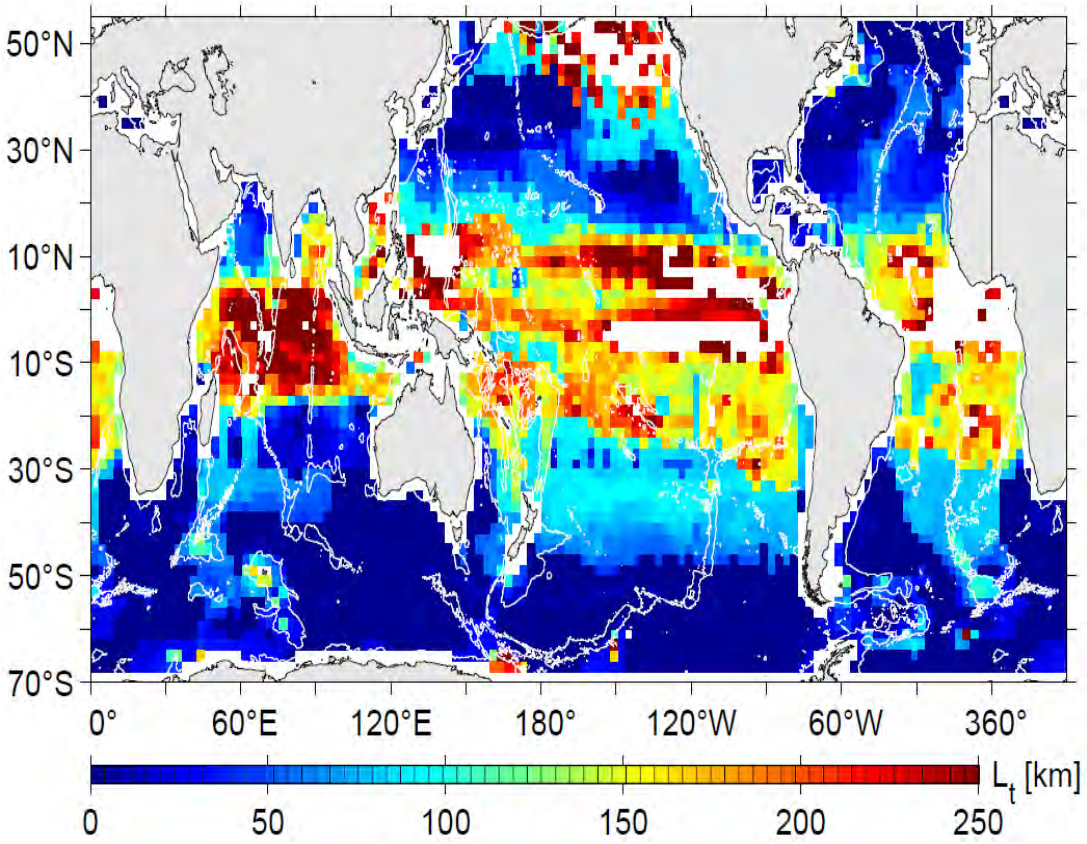
- **Kuroshio: Lt = 12km**
- **Subtropical Countercurrent: Lt = 25km**
- **North Equatorial Current: Lt = 250km**
- **North Equatorial Countercurrent: Lt = 80km**



KE spectra for geostrophic vs. wave motions

Qiu et al. (2017, Nat Com)

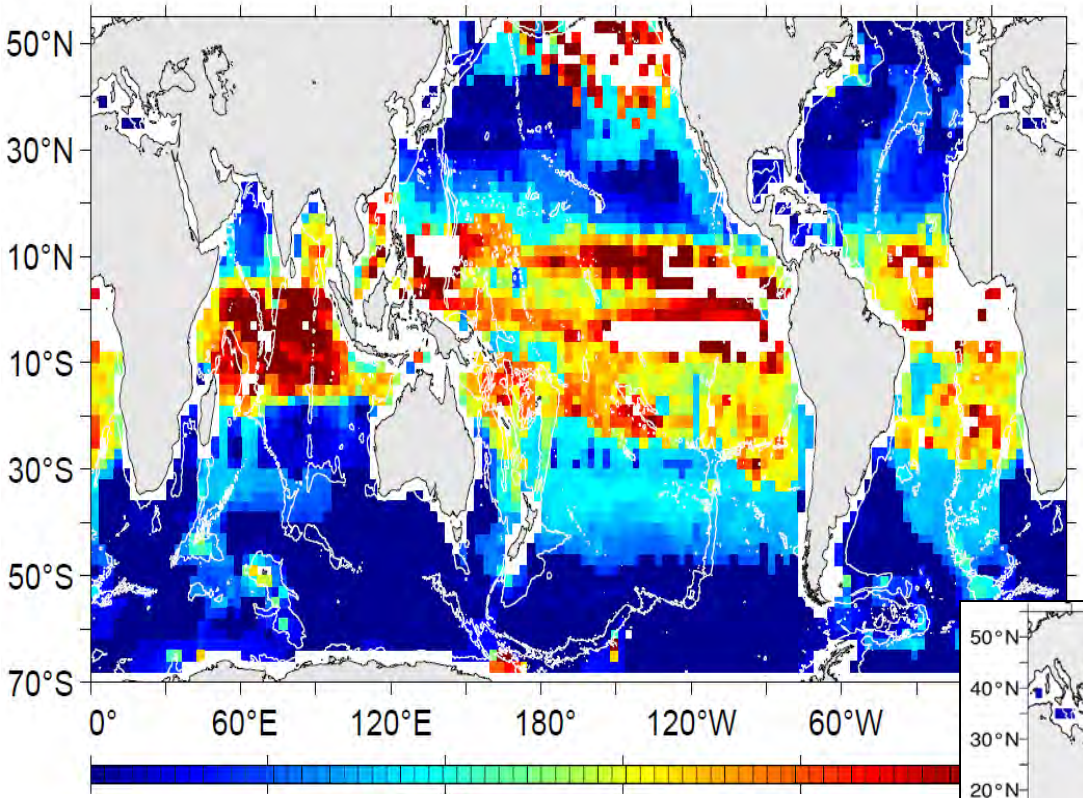
Global Lt inferred from 1/48° MITgcm



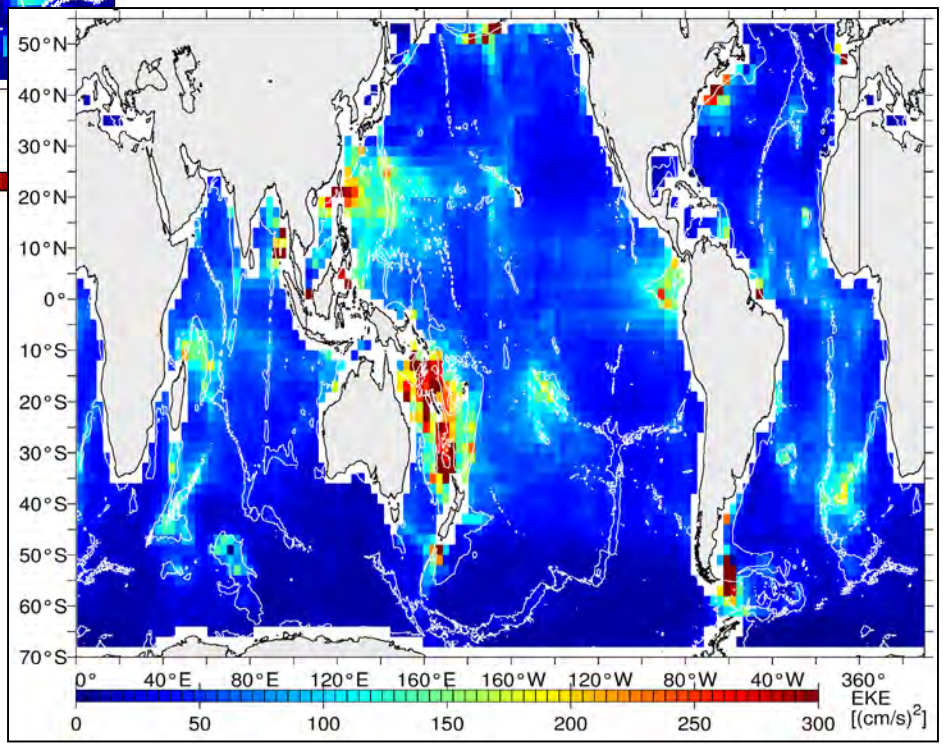
- Consistent with ADCP estimates in NW Pacific

- Globally, Lt < 30km in WBC regions & ACC; exceptions appear in EAC & in ACC areas with prominent topographic features
- In temperate latitudes (i.e., STCC bands), Lt = 50~100km
- Lt > 150km in most of tropics & the Alaskan Gyre

Global Lt inferred from 1/48° MITgcm



EKE level of unbalanced wave motions



- Regional mesoscale eddy variability is only **one determinant** for **Lt**
- Energy level for unbalance wave motions is **spatially non-uniform**; it affects **Lt** in regions like EAC & along ACC path

Qiu et al. (2018, JPO)

Concluding Remarks

- Current altimetry measurements only capture mesoscale variability with spatial scales > 150km
- Interior and ML baroclinic instabilities occur concurrently along STCC. Interior instability is deep-reaching, slowly-growing & controls the seasonal evolution of horizontal KE field
- ML instability is confined to wintertime ML, fast-growing & diminishes after April. It generates submesoscale variability & dictates the seasonal evolution of w field
- SWOT SSH measurements have the potential to allow us to infer the 3D upper ocean circulation, including w field, on a repetitive & global scale
- Disentangling the balanced geostrophic & unbalanced wave motions in the SWOT-measured, submesoscale-resolving, SSH data poses a challenge