Submesoscale Transition from Geostrophic Flows to Unbalanced Motions in ADCP Data and 1/48° MITgcm: Implications for the SWOT Mission

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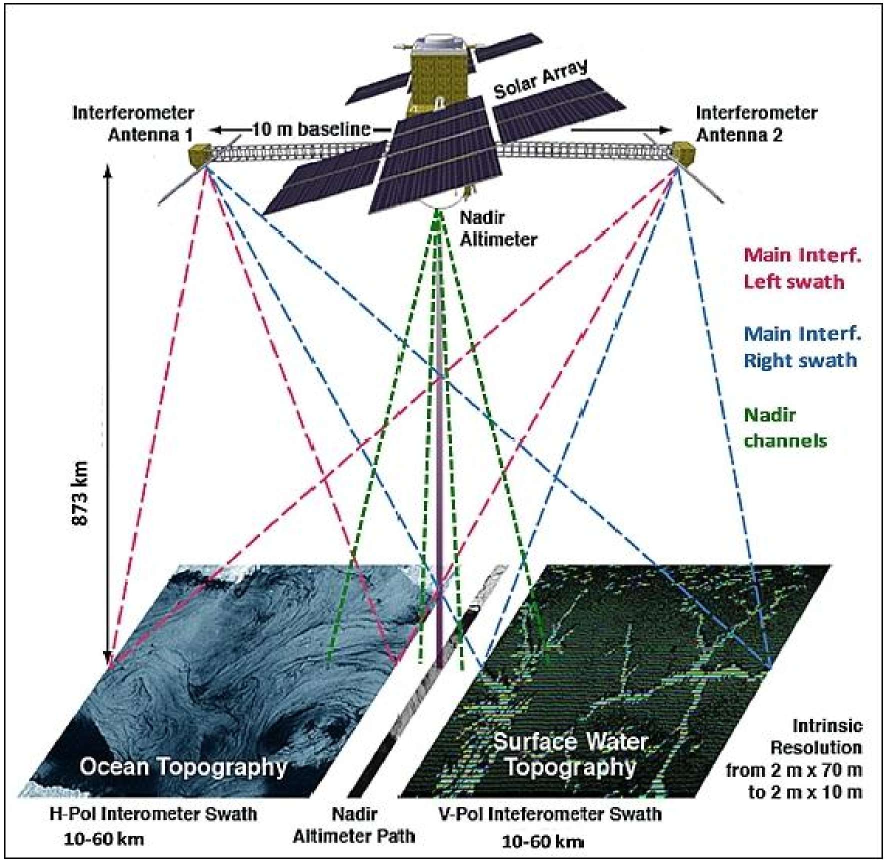
Collaborators: S. Chen, P. Klein, J. Wang, L.-L. Fu, D. Menemenlis & T. Nakano

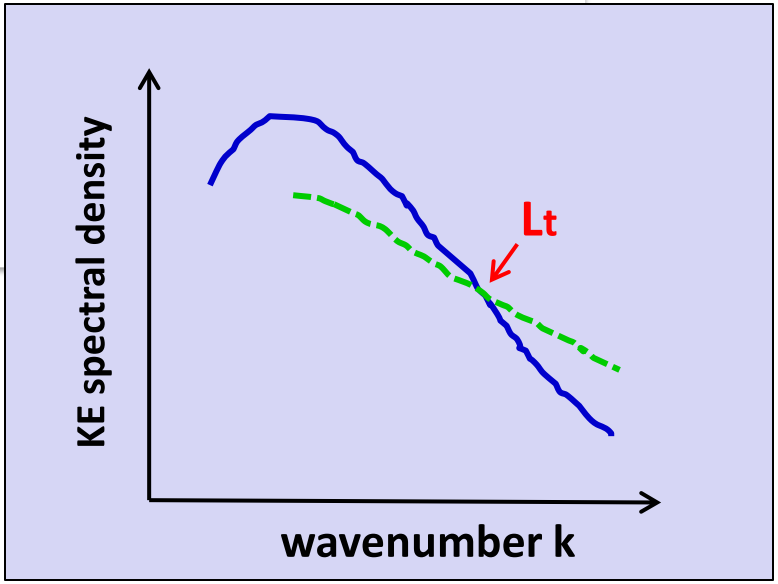


2[nd] SWOT Science Team Meeting

Toulouse, France, 26-28 June 2017

Background

- For mesoscales with $2\pi/k > 200$km, balanced geostrophic flow dominates and altimeter-derived SSH can be readily used to infer surface geostrophic velocities
- As the geostrophic flow weakens at $k^{-2} \sim k^{-3}$, unbalanced wave motions can overtake in the 10-200km meso-submesoscale range
- For SWOT mission, it is important to identify the length scale at which the geostrophic flow loses its dominance & is overtaken by unbalanced wave motions
- This study explores this transition scale Lt from both the ADCP data in NW Pacific & global 1/48^o MITgcm output



Evaluate transition scale L_t

- **As SSH contains admixture of geostrophic and internal wave motions, it is difficult to effectively separate the two. Use of observed u/v data, on the other hand, helps this separation**

- **Under the isotropic condition, Helmholtz decomposition allows**

  $$(u, v) = (-\psi_y + \phi_x , \psi_x + \phi_y)$$

  be separated into rotational ψ and irrotational ϕ components.
  In spectral space: $S^u(k)$, $S^v(k)$ → $S^\psi(k)$, $S^\phi(k)$ (references below)

Bühler, O., Callies, J. & Ferrari, R., 2014: Wave-vortex decomposition of one-dimensional shiptrack data. *J. Fluid Mech*., 756, 1007-1026.

Callies, J., Ferrari, R., Klymak, J.M. & Gula, J., 2015: Seasonality in submesoscale turbulence. *Nature Commun*., 6, 6862.

Rocha, C.B., Chereskin, T.K., Gille, S.T. & Menemenlis, D., 2016: Mesoscale to submesoscale wavenumber spectra in Drake Passage. *J. Phys. Oceanogr*., 46, 601–620.

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- By definition, geostrophic flow has ψ only (i.e., $S^\phi_g(k) = 0$) and KE spectrum for ϕ is completely set by wave motions: $S^\phi_w(k) = S^\phi(k)$

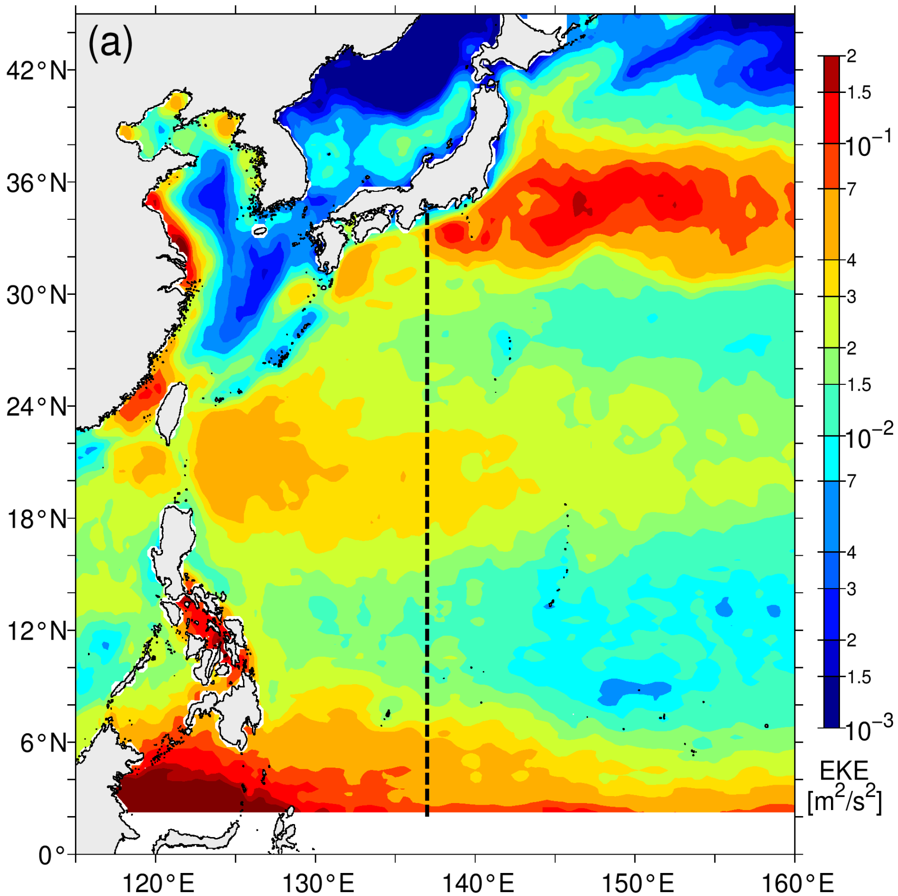
- Assuming internal waves in open ocean follow the Garrett-Munk spectrum, rotational part of $S^\psi(k)$ for the internal waves becomes:

  $$S^\psi_w(k) = f^2 S^\phi_w(k) / \omega_*^2$$

- 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 $S^\psi_g(k) = S^\psi_w(k) + S^\phi_w(k)$

AVISO eddy KE map in NW Pacific Ocean



R/V Ryofu Maru of JMA

- **Repeat ship-board ADCP surveys along 137°E were carried out by Japan Meteorological Agency**
- **Utilized 33 surveys spanning four seasons of 2004-2016**
- **Near-surface u/v data (40-100m) are QC-processed, averaged to 2.5km grid & analyzed for Lt evaluation**

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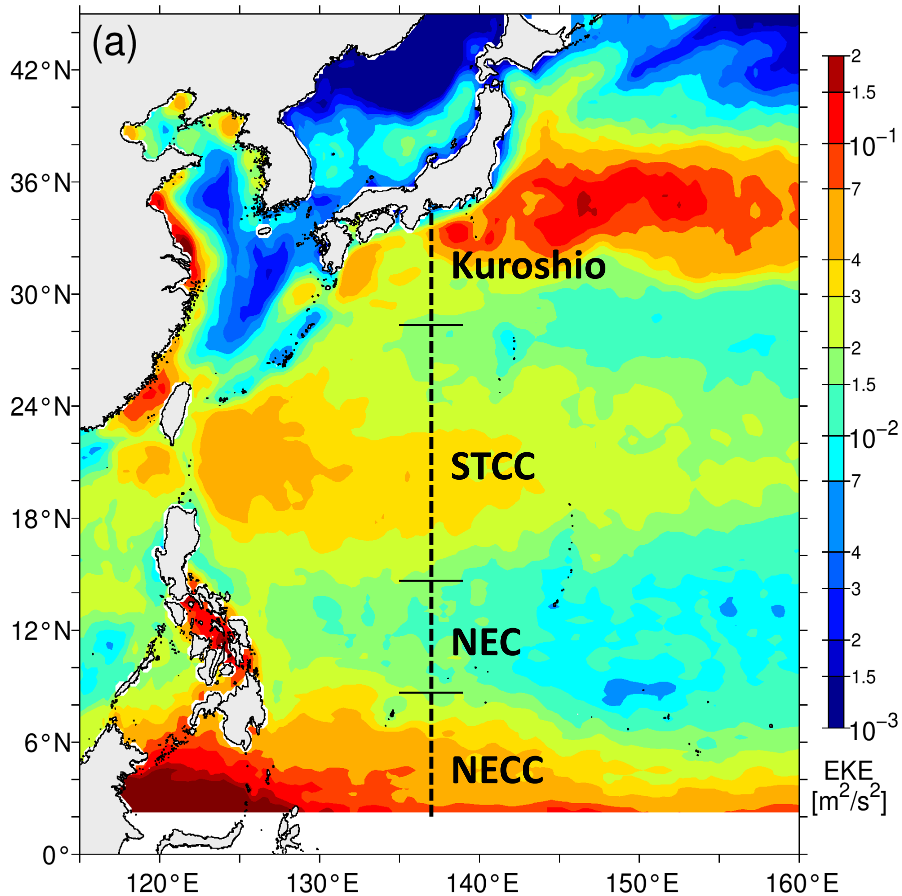
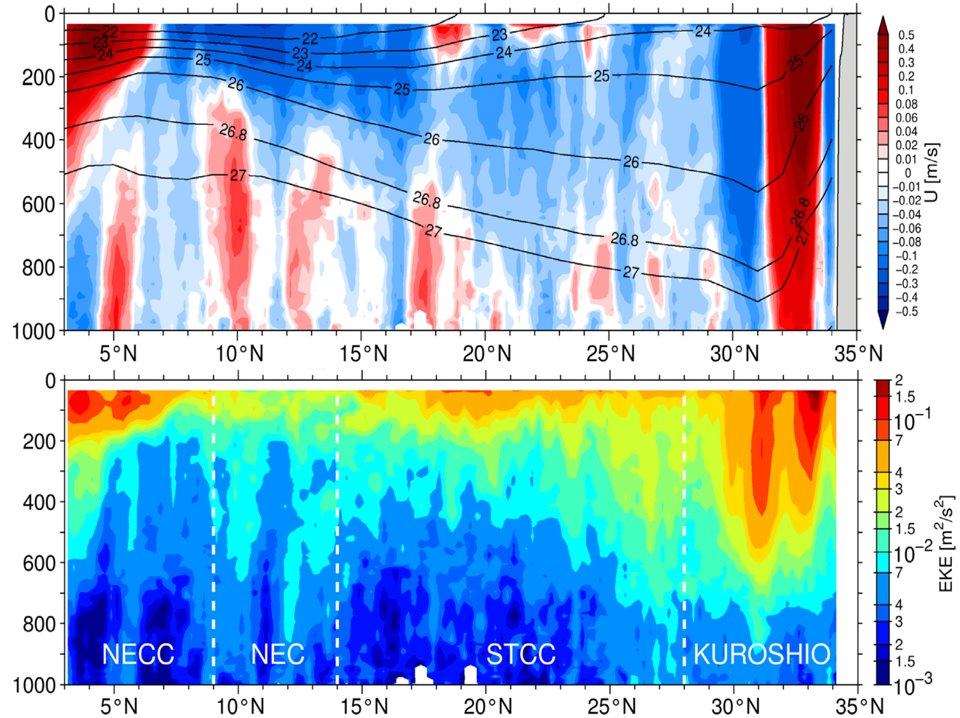
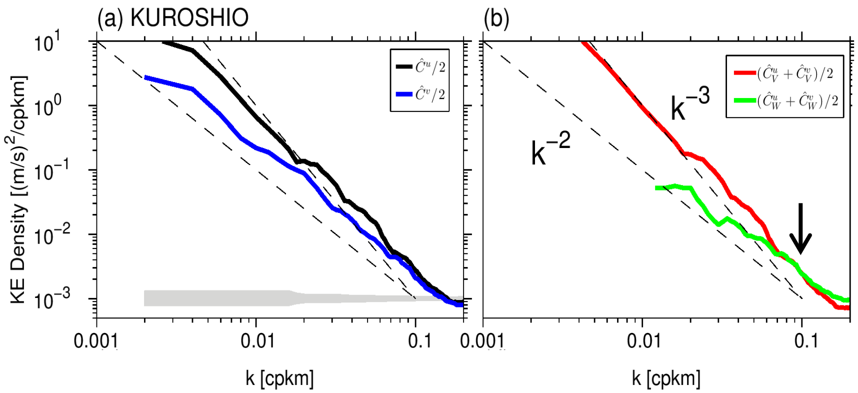


ADCP-mean U & eddy KE along 137°E



- **Kuroshio:** WBC/recirculation gyre, deep-reaching, intense baroclinic instability
- **Subtropical Countercurrent:** Shallow, vertically-sheared, moderately unstable
- **North Equatorial Current:** Intense westward flow, largely stable
- **North Equatorial Countercurrent:** Intense eastward flow, barotropically unstable



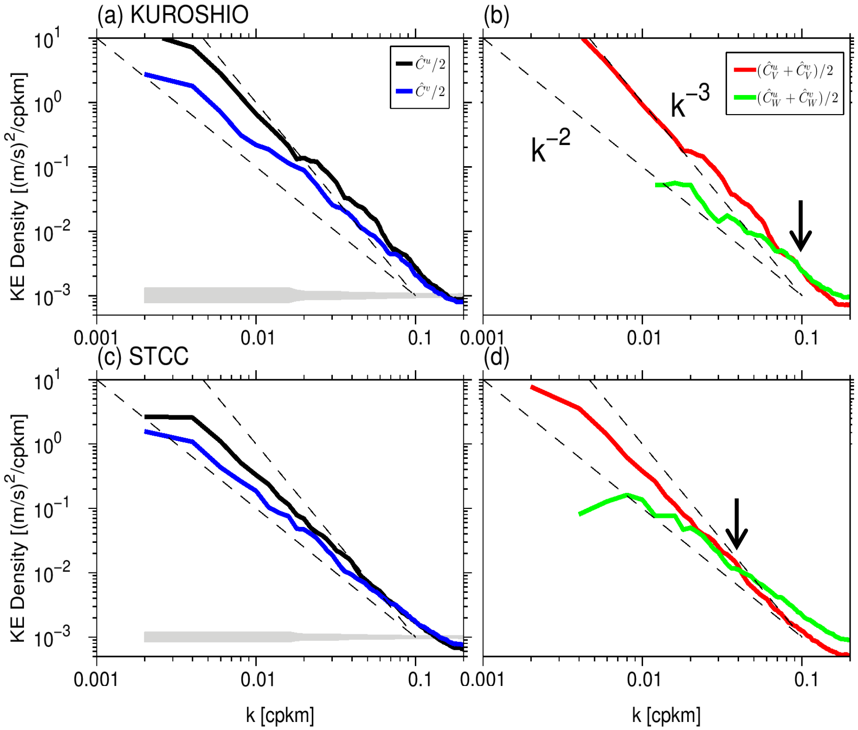
spectra for original u & v

spectra for geostrophic & wave motions

- **Kuroshio: WBC/recirculation gyre, deep-reaching, intense baroclinic instability**

  Geostrophic motions overpower wave motions; Lt = 12 km

Qiu, B., T. Nakano, S. Chen, and P. Klein, 2017: Submesoscale transition from geostrophic flows to internal waves in the northwestern Pacific upper ocean. *Nature Commun.*, 8, 14055.



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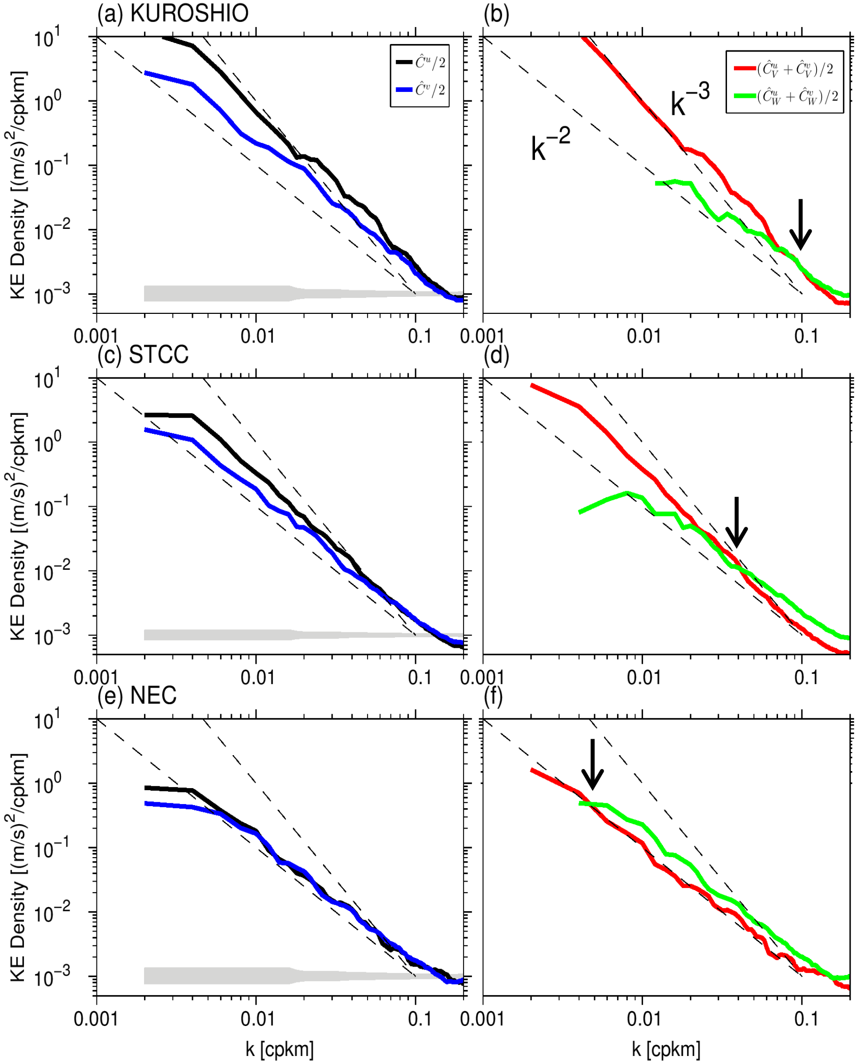

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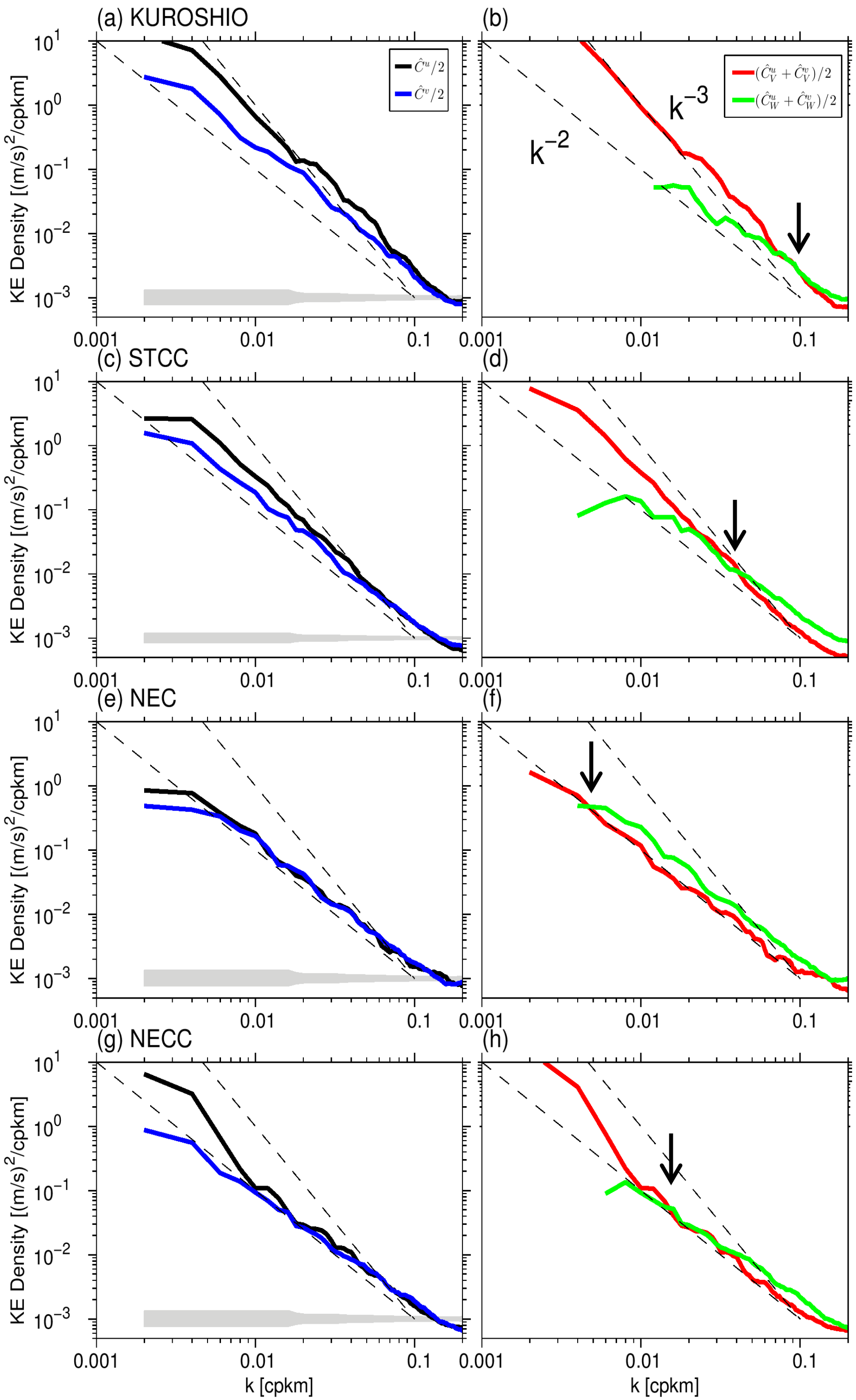
  Geostrophic motions drop significantly & overtaken by wave motions; Lt = 250km



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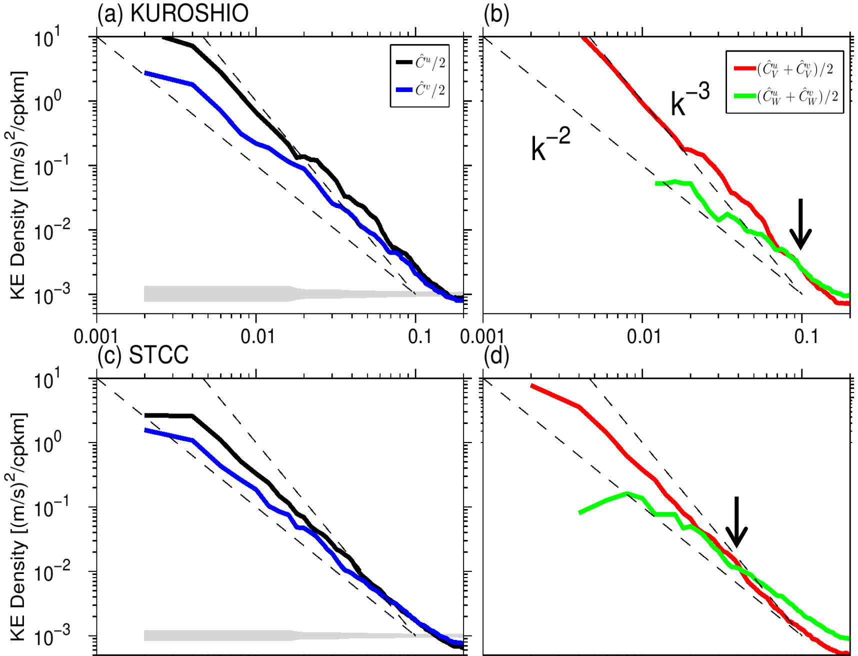
- **North Equatorial Countercurrent:** **Intense eastward flow, barotropically unstable**

  Large-scale geostrophic eddy motions enhance; Lt = 80km



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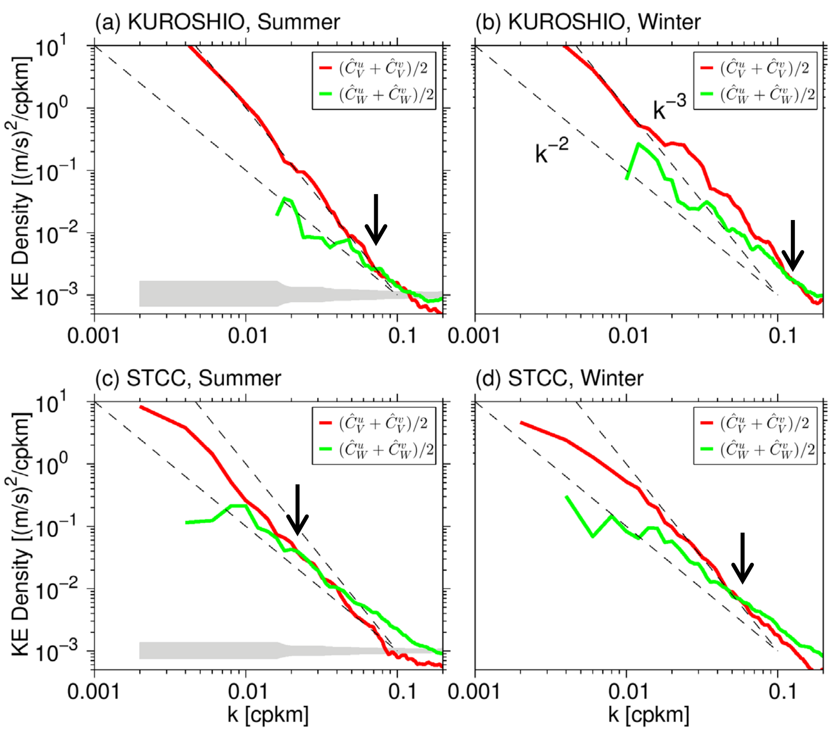
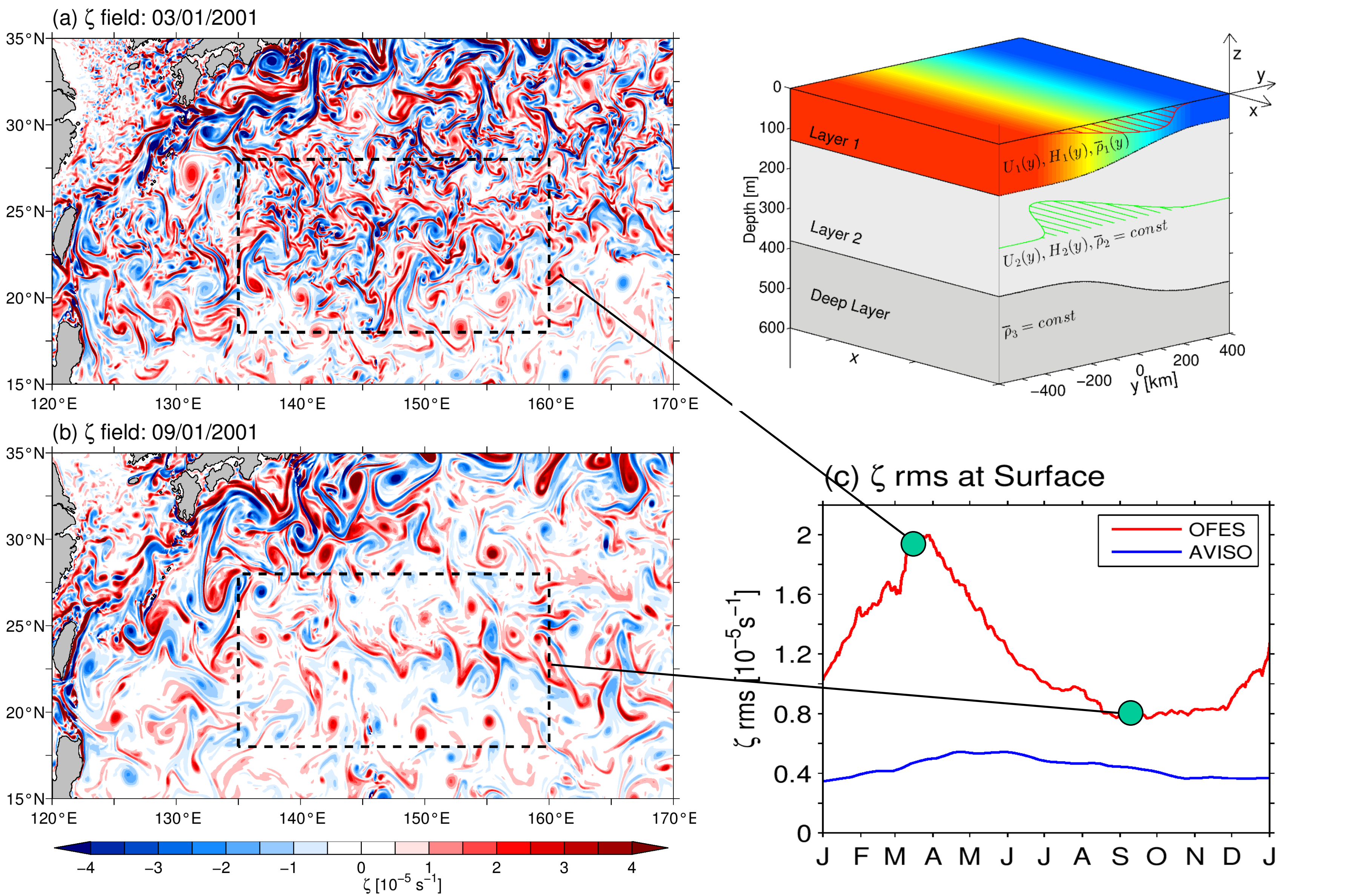


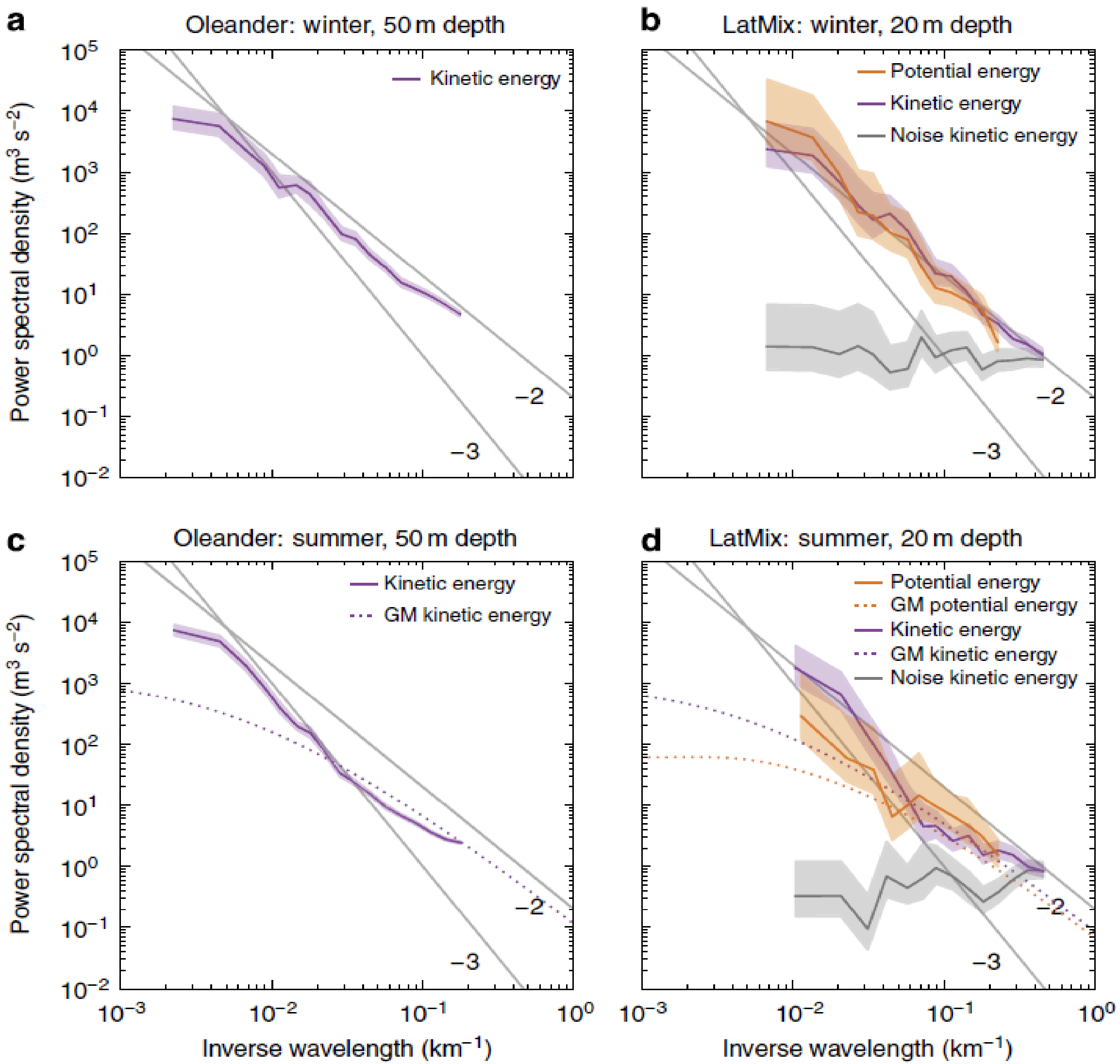
- **For both Kuroshio & STCC, Lt is smaller in winter (<10km & 18km) than in summer (20 km & 50km) due to enhanced submesoscale variability**

Instantaneous surface ζ maps from 1/30° OFES simulation: March vs. September



Qiu, B., S. Chen, P. Klein, H. Sasaki, and Y. Sasai, 2014: Seasonal mesoscale and submesoscale eddy variability along the North Pacific Subtropical Countercurrent. *J. Phys. Oceanogr.*, 44, 3079-3098.

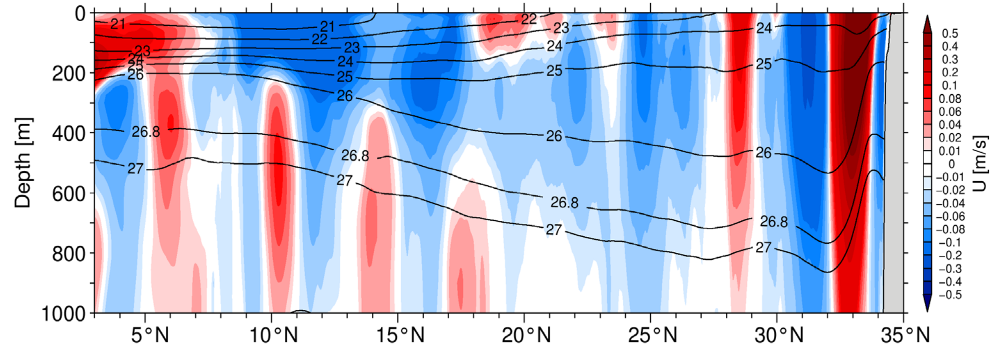
ADCP-derived KE spectra in NW Atlantic detect winter submesoscale enhancement

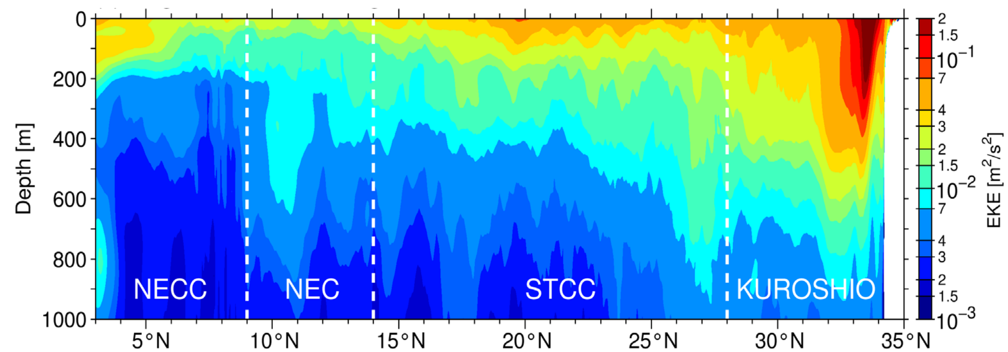


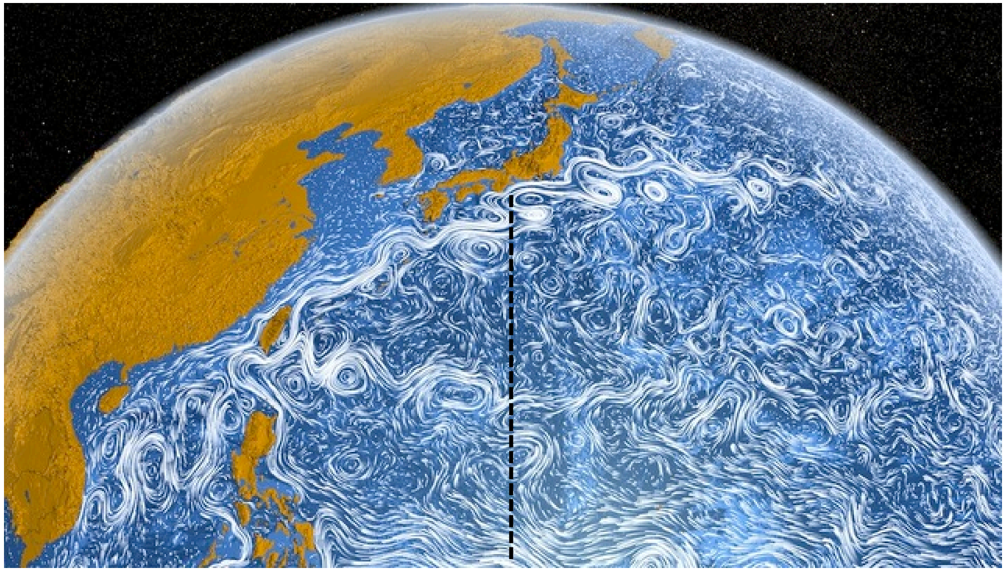
Callies, J., R. Ferrari, J.M. Klymak, & J. Gula, 2015: Seasonality in submesoscale turbulence. *Nature Commun*., 6, 6862.

MITgcm-mean U & eddy KE along 137°E

- MITgcm llc 4320: global ocean & sea ice configuration; 16-component tidal forcing
- 1/48° horizontal resolution & 90 vertical levels
- Hourly output from 1 October 2011 to 30 September 2012 (366 days)







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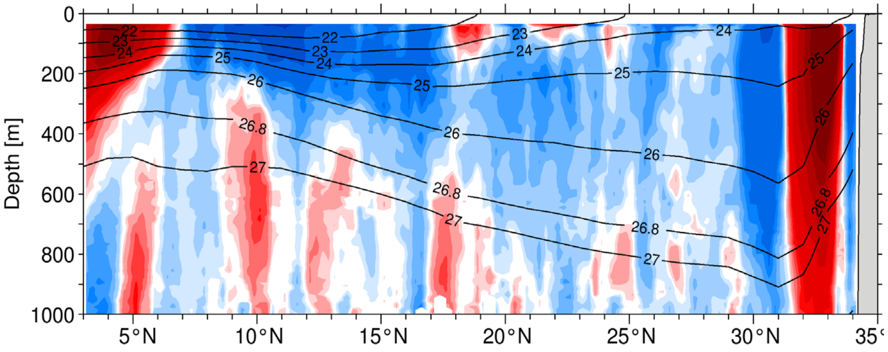
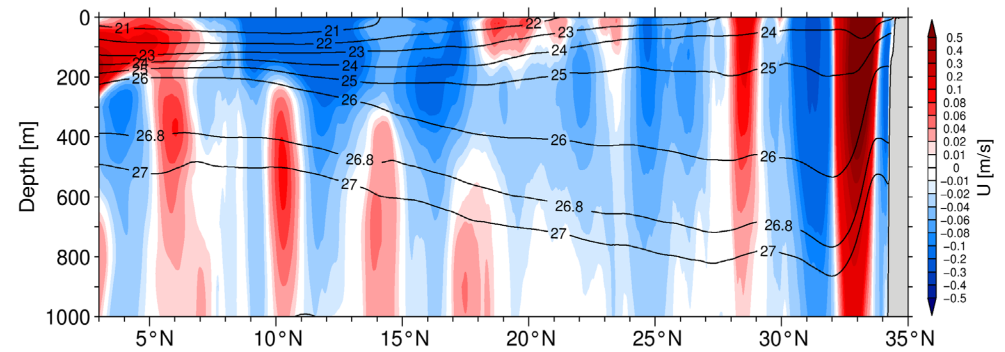
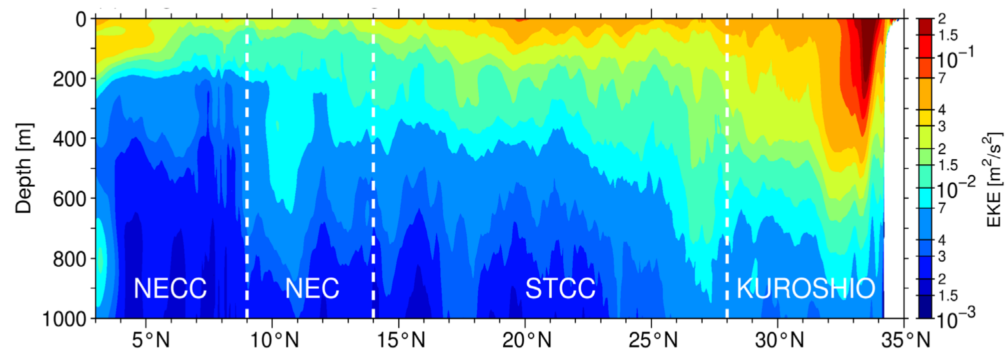
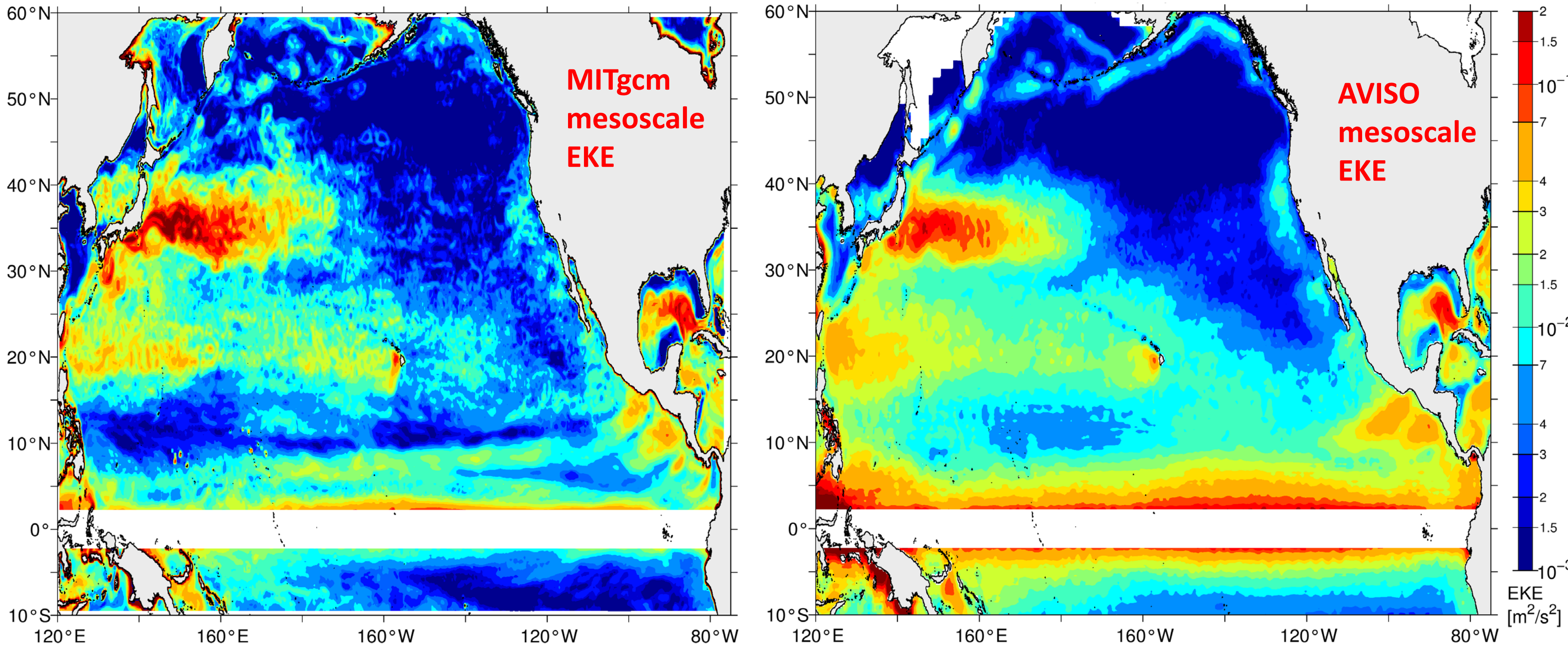


MITgcm-mean U & eddy KE along 137°E



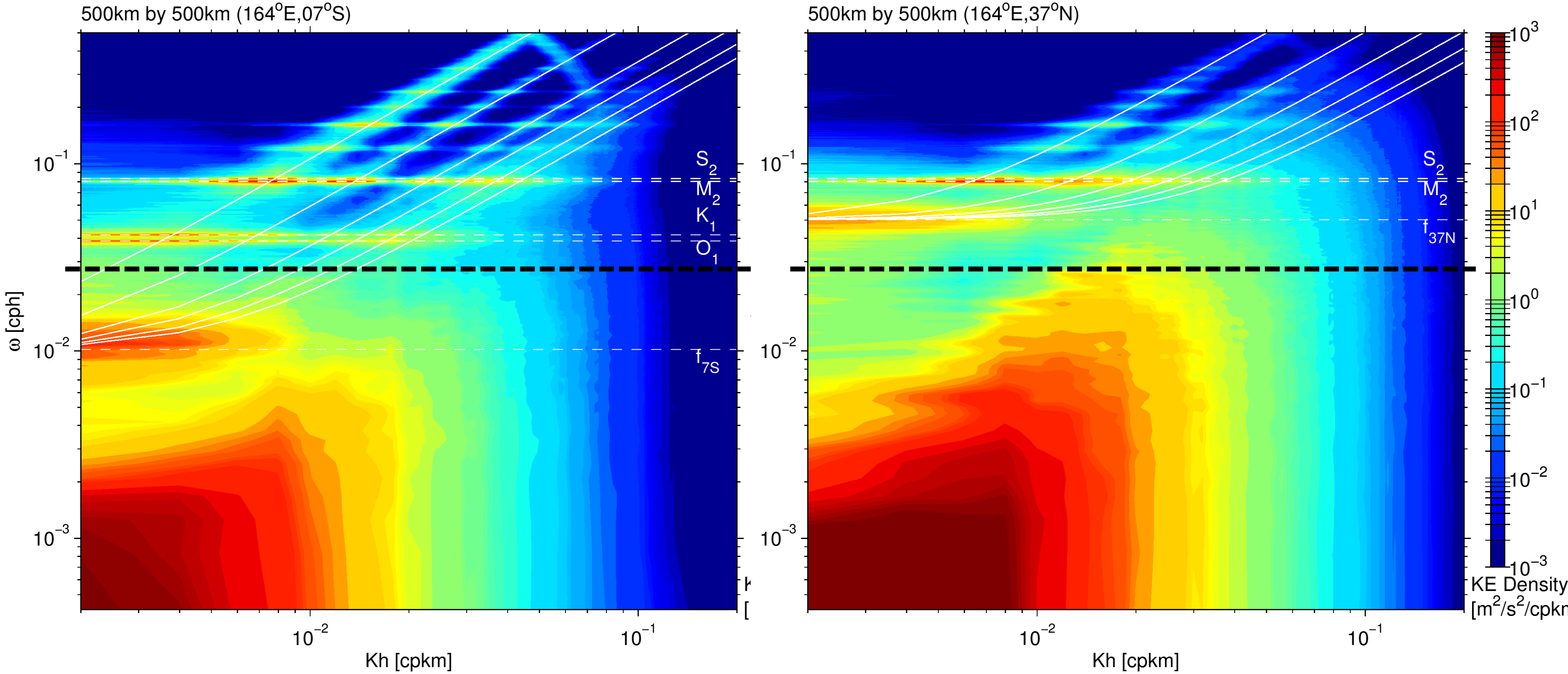


- MITgcm simulates favorably the time-mean circulation in NW Pacific, including sub-thermocline zonal jet features



- MITgcm simulates favorably the time-mean circulation in NW Pacific, including sub-thermocline zonal jet features
- For eddy variability, it performs well in Kuroshio/STCC bands, but under-estimates in the NECC region
- This under-estimation is due to short integration (i.e., no interannual variability), which affects tropical Lt evaluation

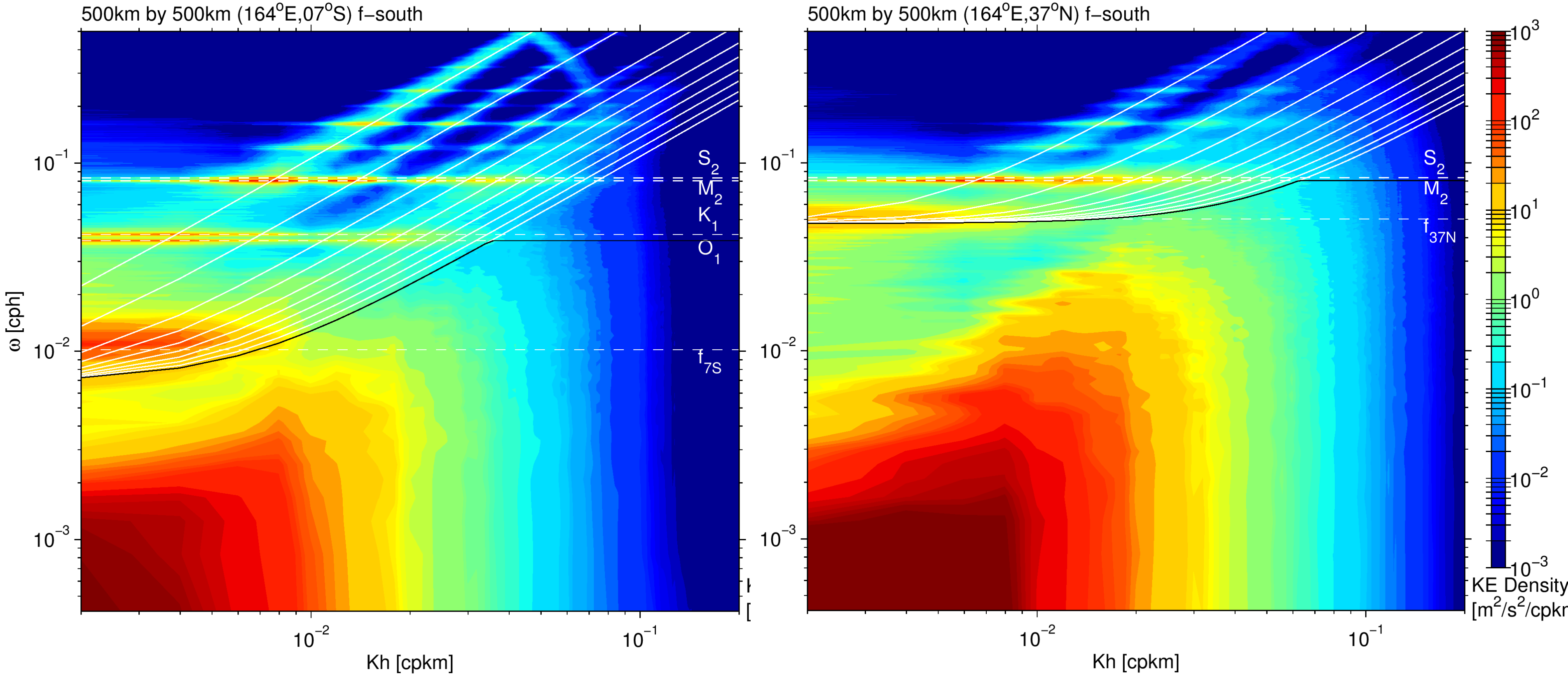
Delineation of balanced geostrophic vs. unbalanced wave motions



Single frequency filtering: **e.g., 36-hour low- & high-pass filter**

Unsuitable for global Lt study !

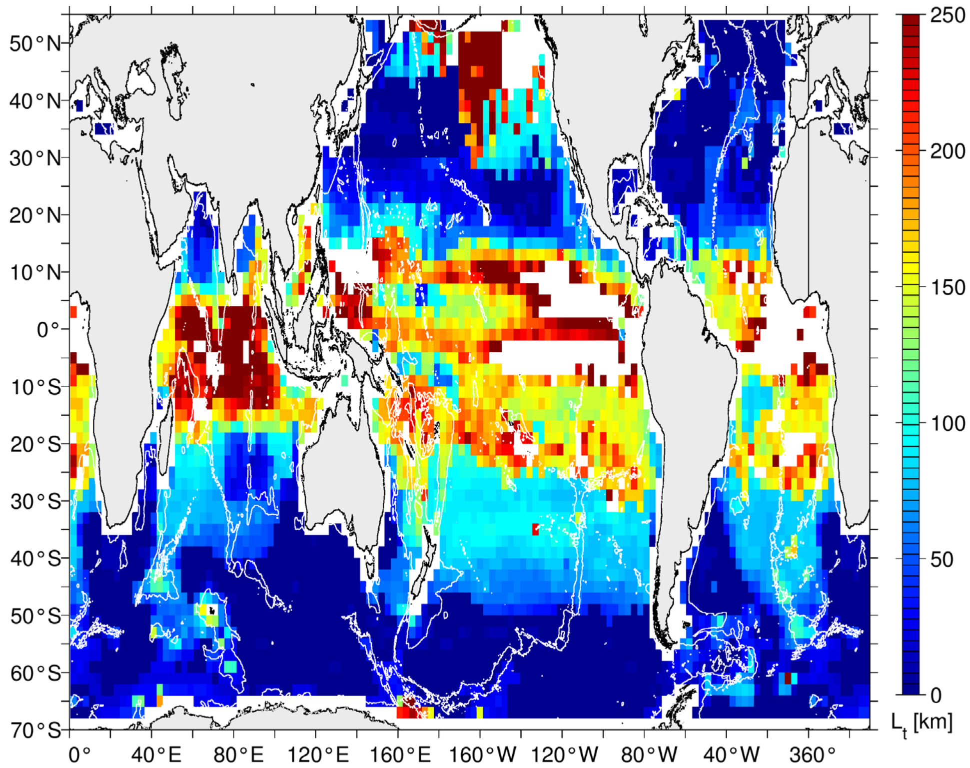
Delineation of balanced geostrophic vs. unbalanced wave motions



Dynamical filtering: delineated by the lower frequency boundary of either the local IGW dispersion curve or the permissible tides

(Solid white lines denote dispersion curves for the first 10 baroclinic IGW modes)

Global Lt inferred from dynamical delineation



- Consistent with ADCP estimates in NW Pacific; Lt in the NECC band is biased high

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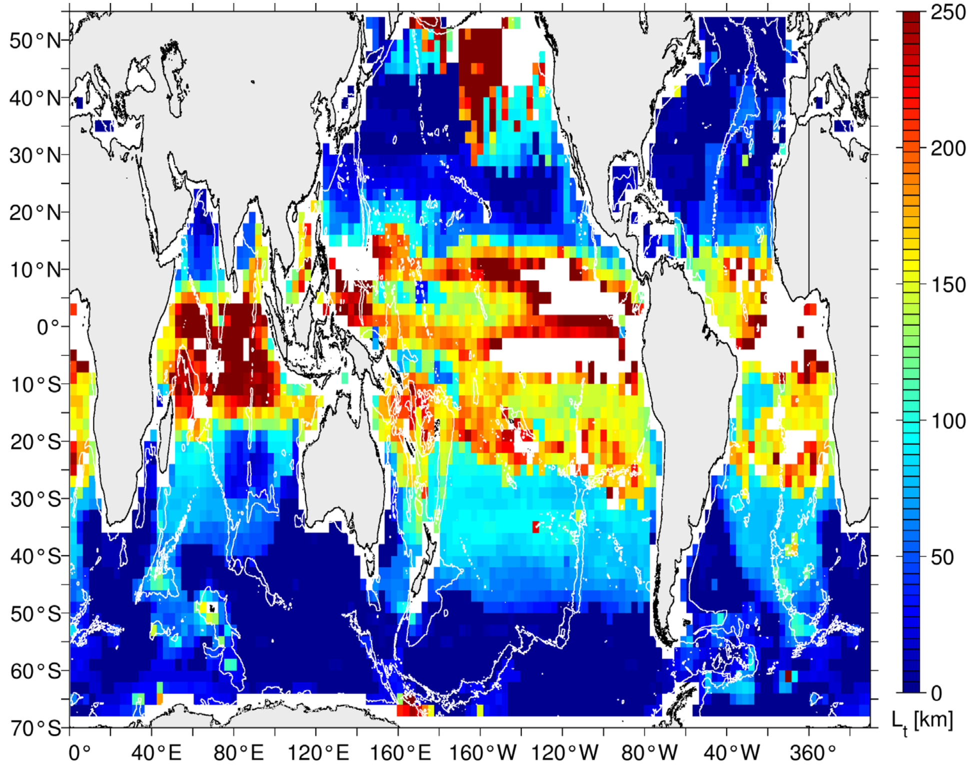
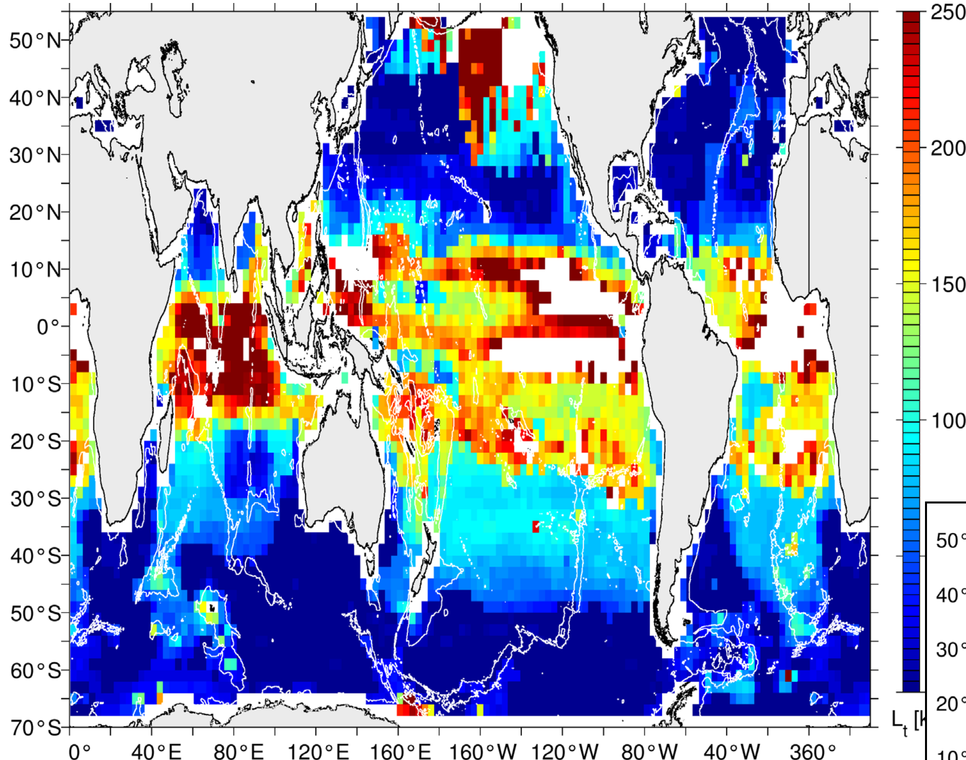


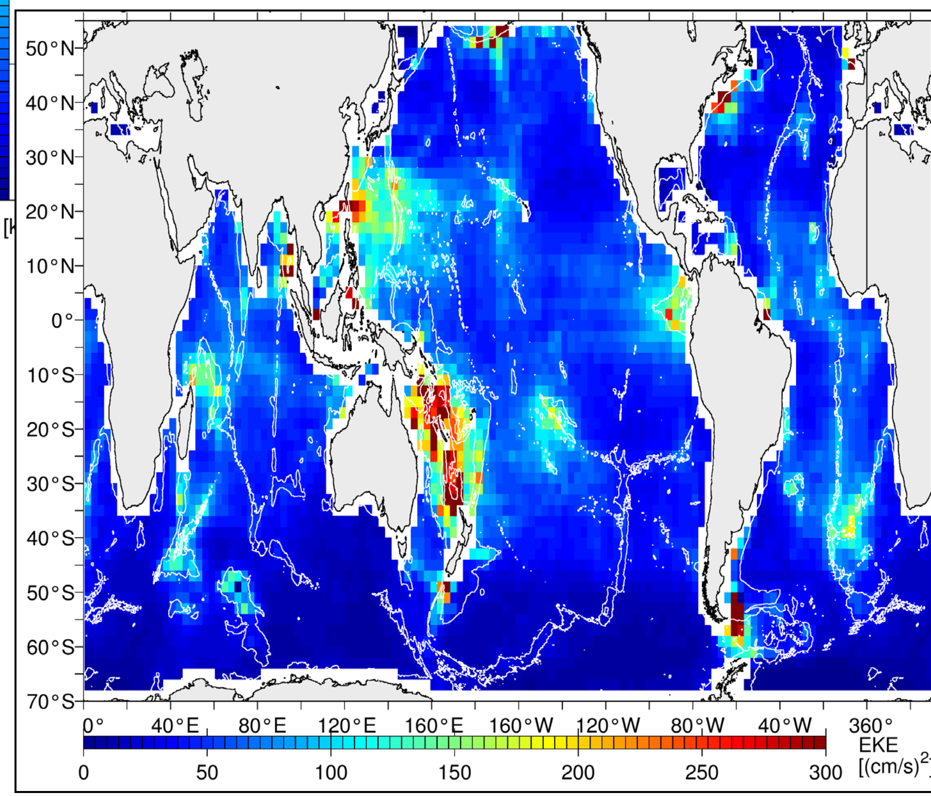
- Consistent with ADCP estimates in NW Pacific; Lt in the NECC band is biased high

- 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 dynamical delineation

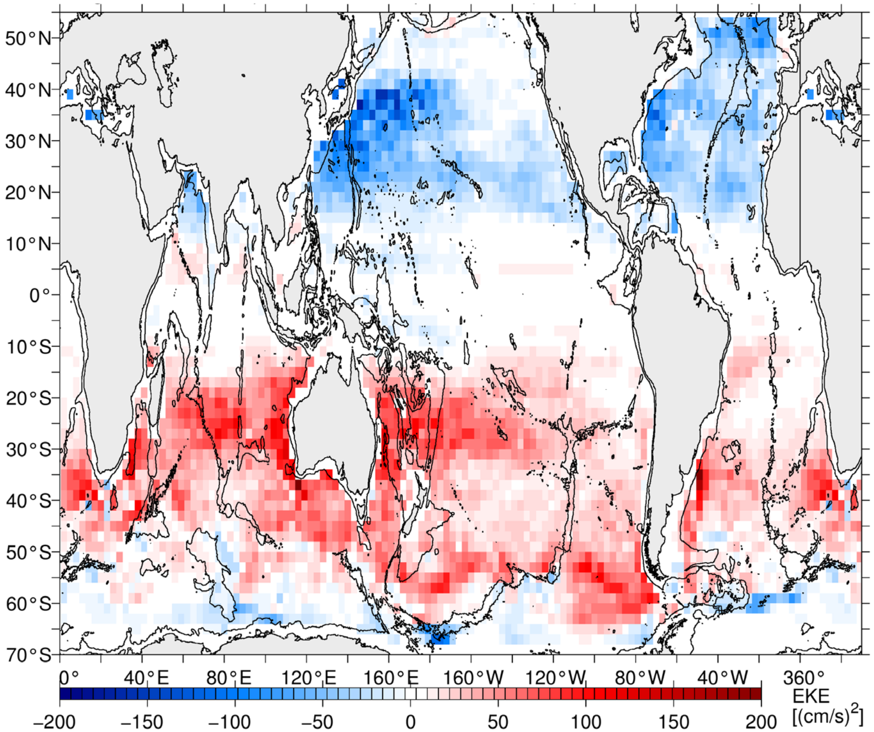


EKE level of unbalanced wave motions



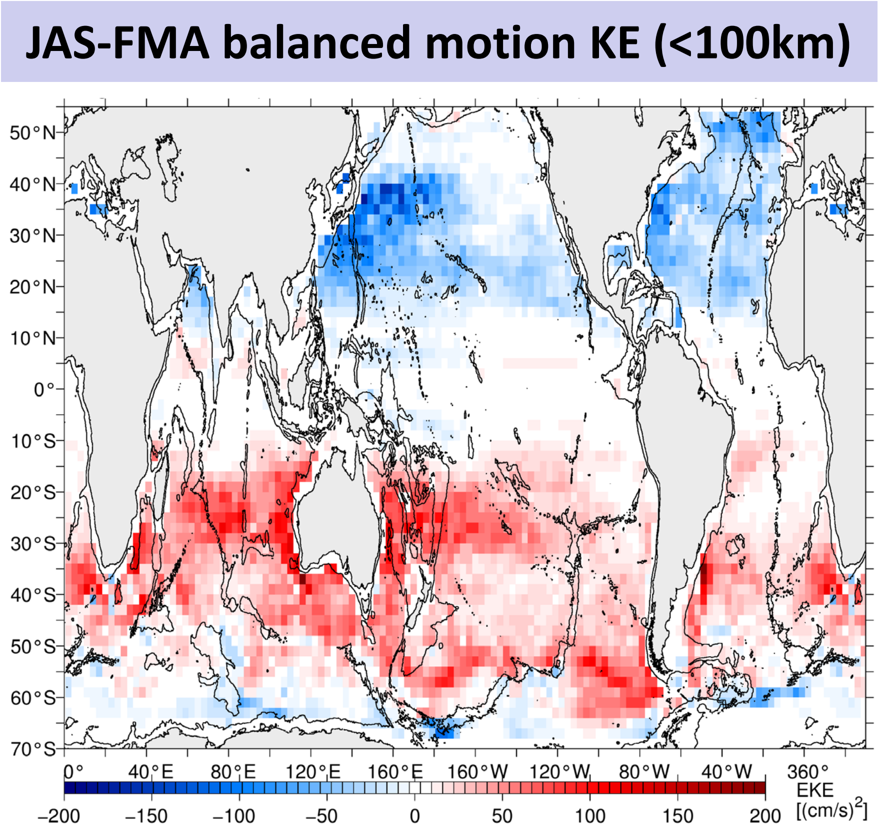
- **Regional mesoscale eddy variability is only one determinant for Lt**
- **Energy level for unbalance wave motions is spatially non-uniform; it affects Lt in regions like EAC & along the ACC path**

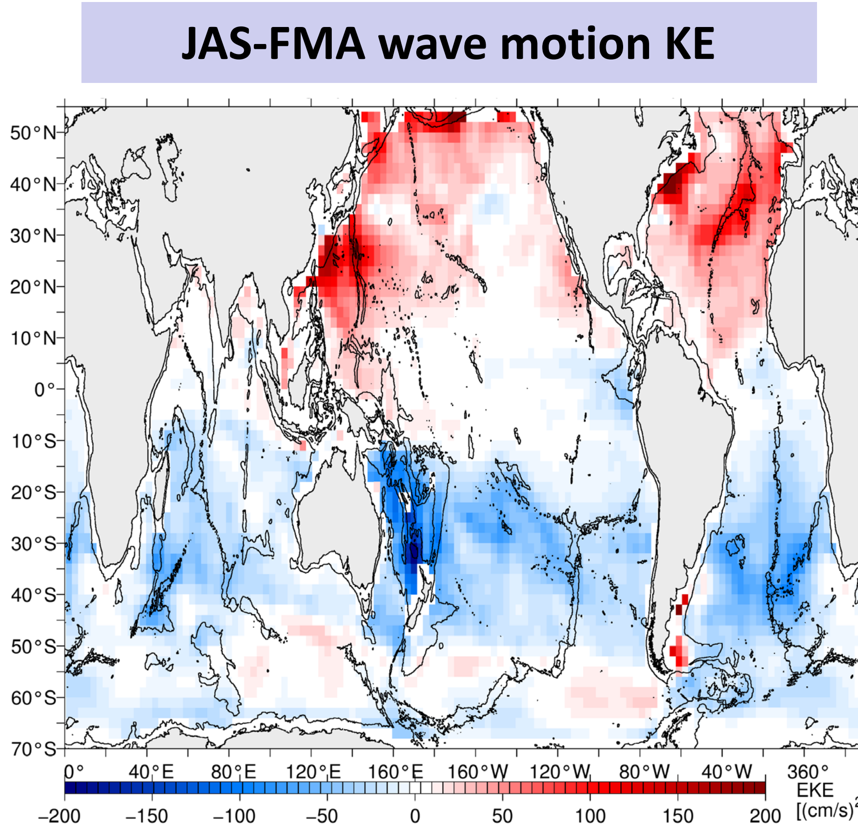
JAS-FMA balanced motion KE (<100km)



Seasonal Changes in Lt

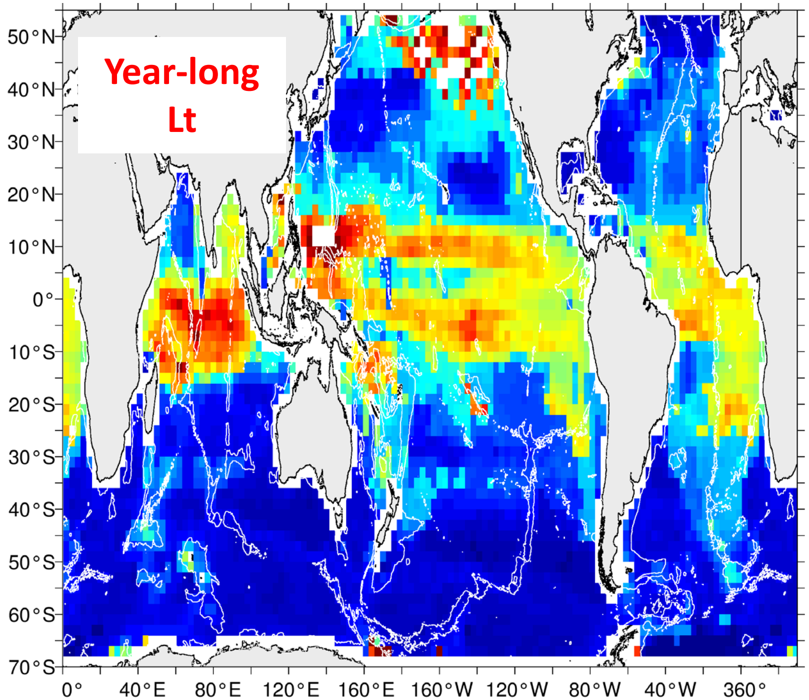
- **Like in ADCP data, small-scale balanced motion KE in MITgcm is higher in winter than summer**
- **This helps to reduce Lt in winter**

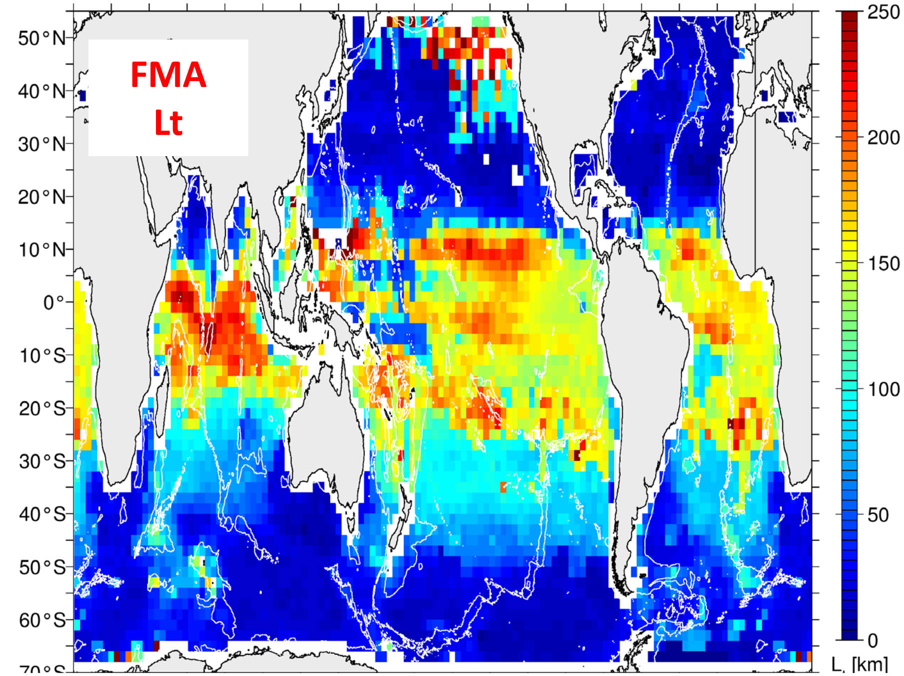


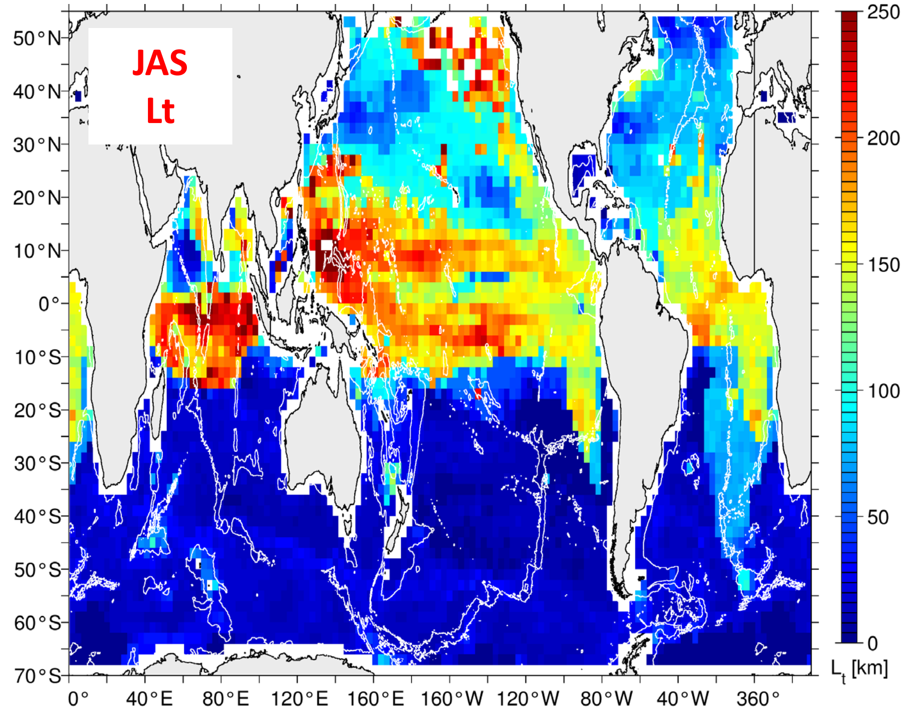


- **Like in ADCP data, small-scale balanced motion KE in MITgcm is higher in winter than summer**
- **This works to reduce Lt in winter**

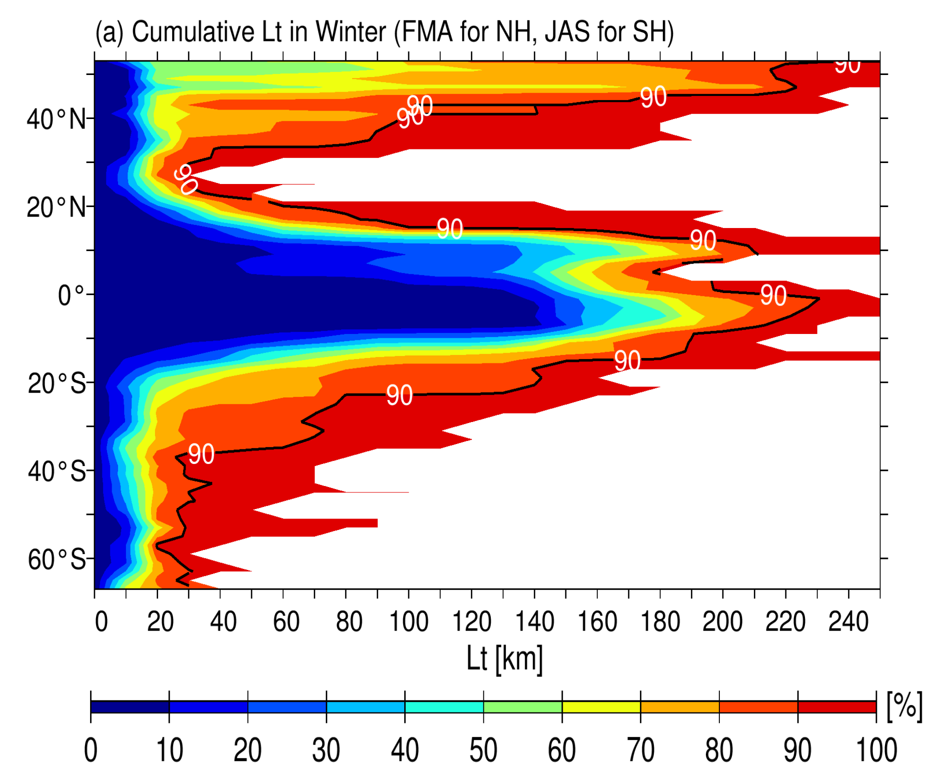
- **Menwhile, wave-motion KE is higher in summer than winter, further helping to reduce Lt**
- **Large density jump across the shallow ML base is suggested for enhanced wave KE in summer (Rocha et al. 2016)**

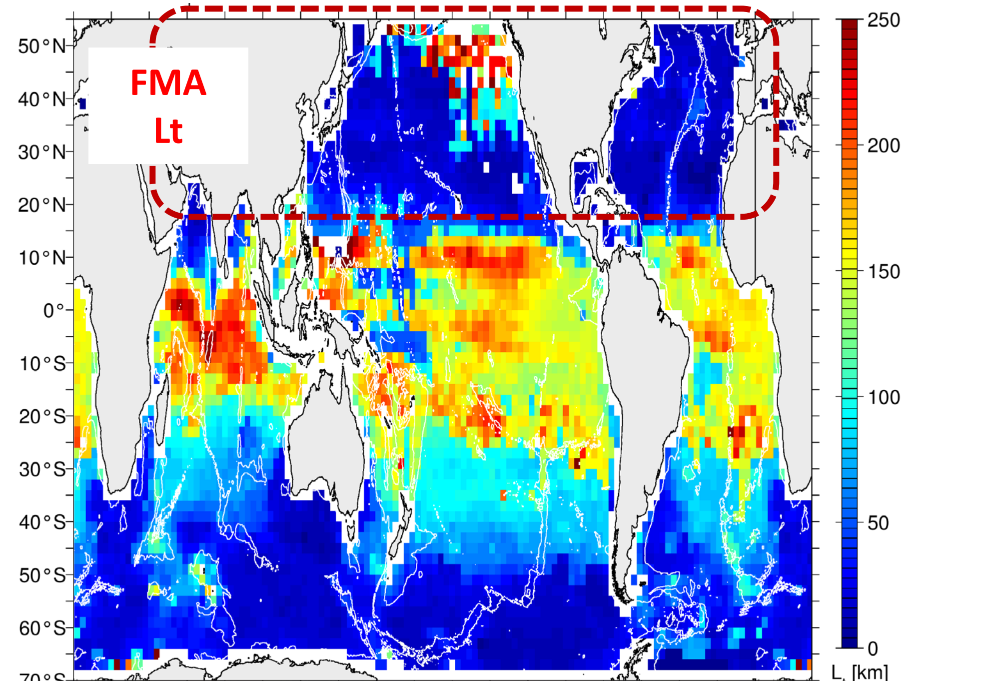


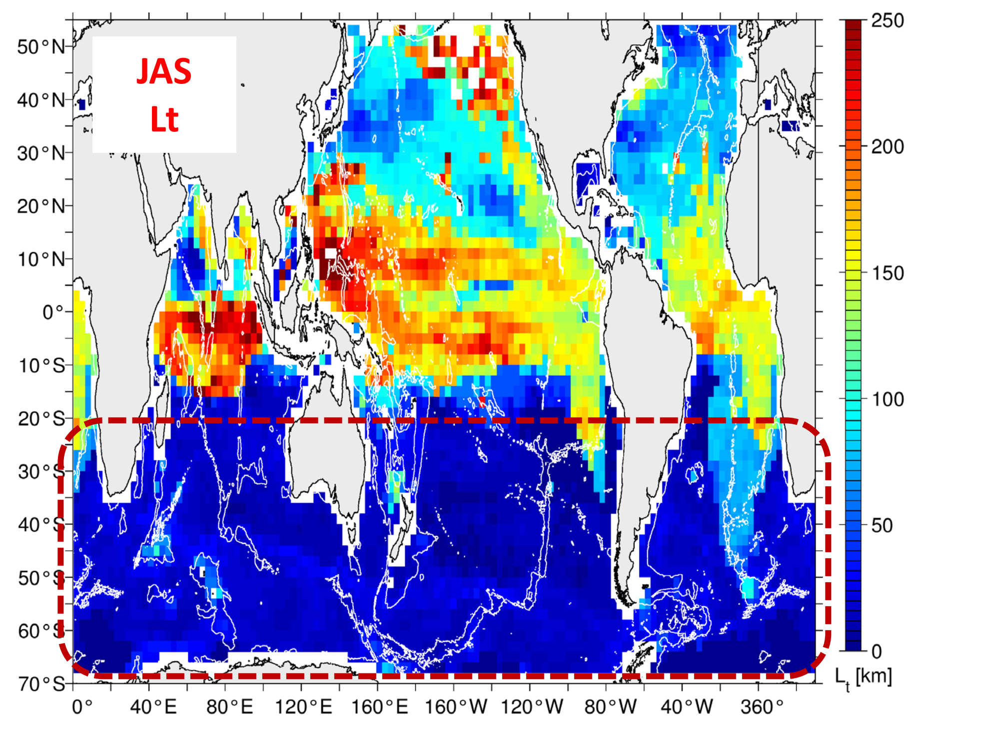




- Lt is much shorter in winter than summer







- Lt is much shorter in winter than summer
- Poleward of 20°lat in both NH & SH (excluding Alaskan Gyre), most Lt < 40km in winter

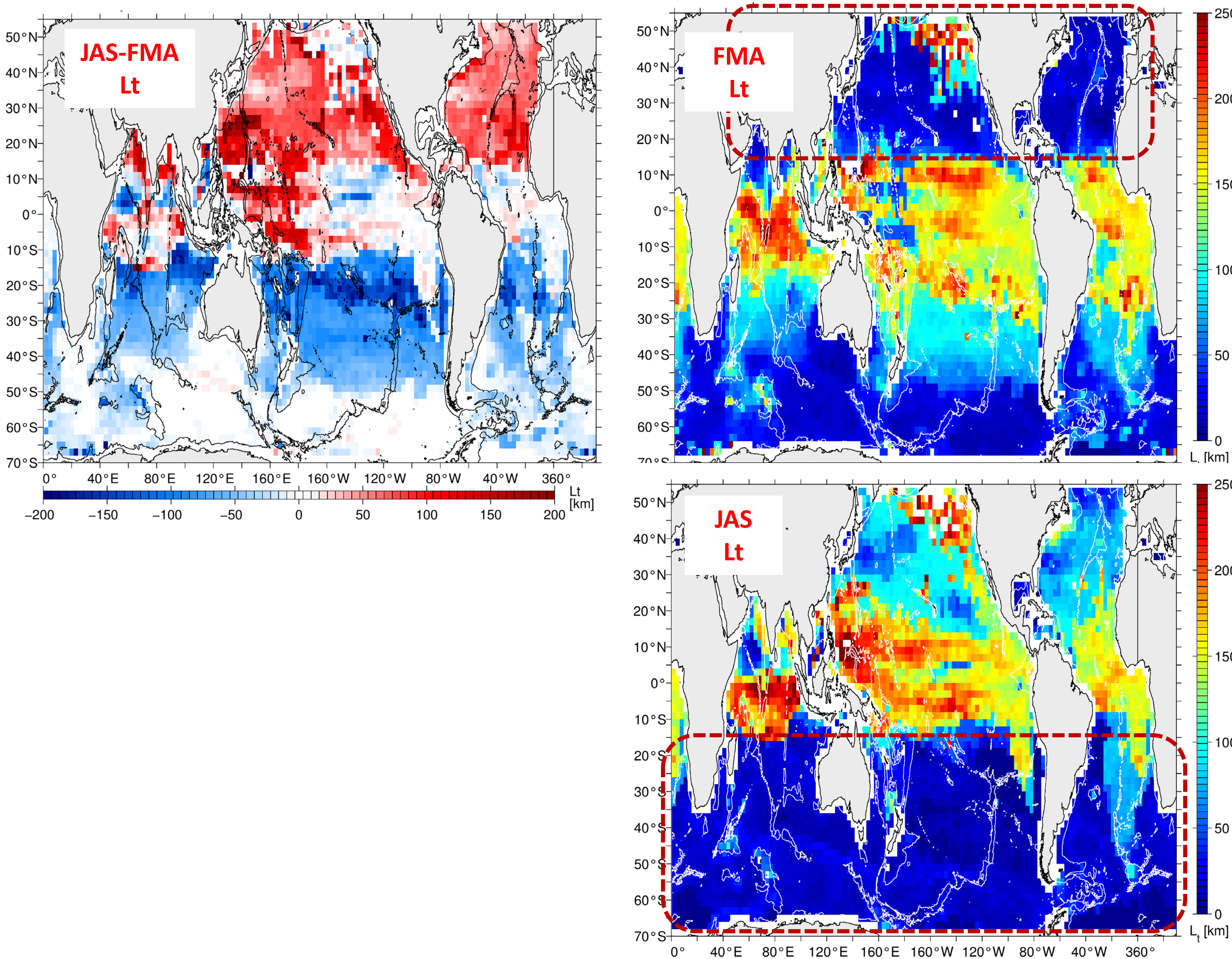
Summary

- **As length scale decreases from meso- to submeso-scales, geostrophic motions can have comparable, or even lower, KE level as those of unbalanced motions**

- **Transition scale Lt between these two motions depends on both the intrinsic mesoscale variability of background circulation & the local KE level of unbalanced motion**

- **ADCP & MITgcm results indicate time-mean Lt ≤ O(50 km) in WBC and ACC regions, 50~100km in STCC bands, & exceed O(200km) in the tropics**

- **Lt is strongly seasonally dependent; it drops to below 40km in winter in most of the global ocean poleward of 20° lat., allowing SWOT data be used to explore submesoscale variability when it is seasonally maximum**


JAS-FMA
Lt
FMA
Lt
JAS
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50°N
40°N
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10°S
20°S
30°S
40°S
50°S
60°S
70°S
0°
40°E
80°E
120°E
160°E
160°W
120°W
80°W
40°W
360°
−200
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Lt [km]
250
200
150
100
50
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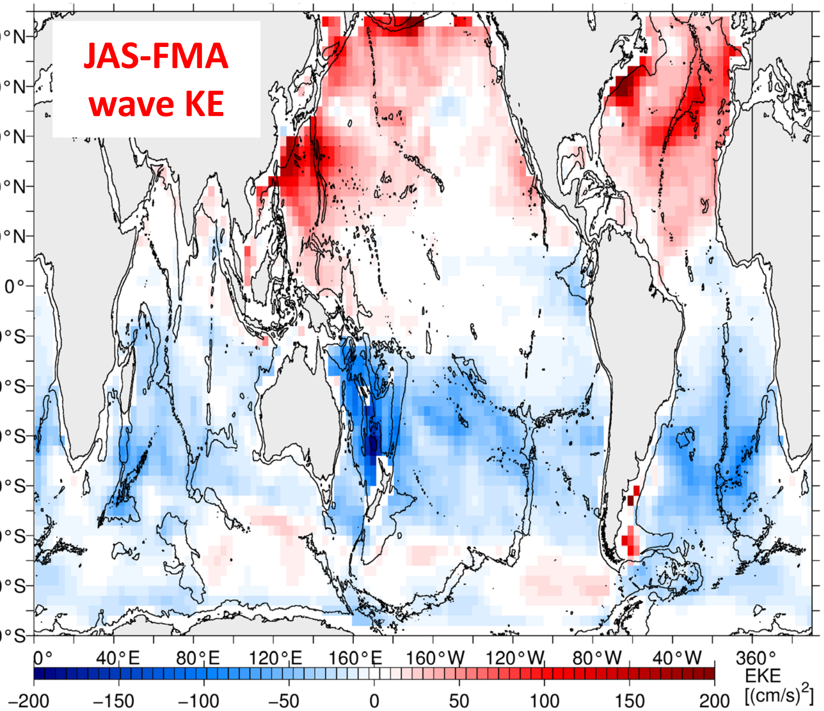
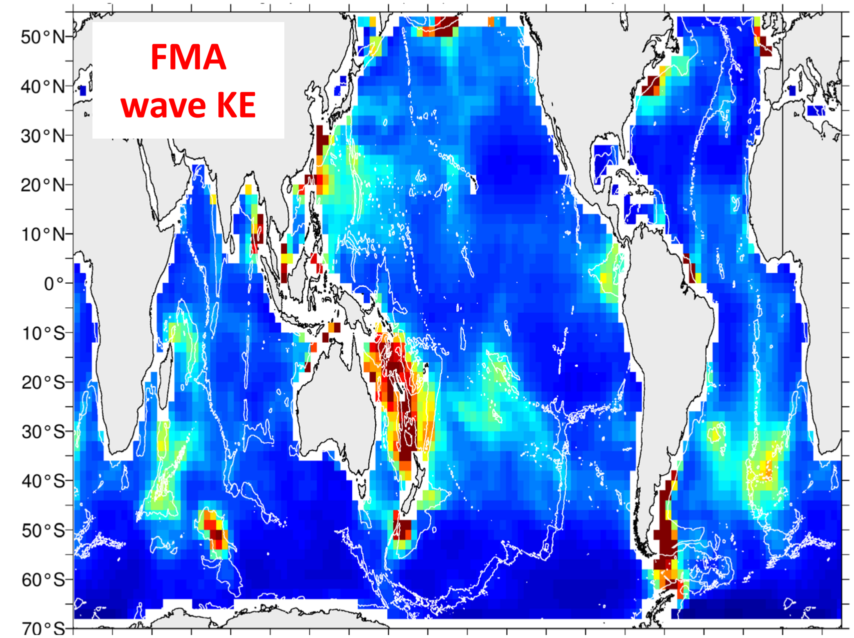
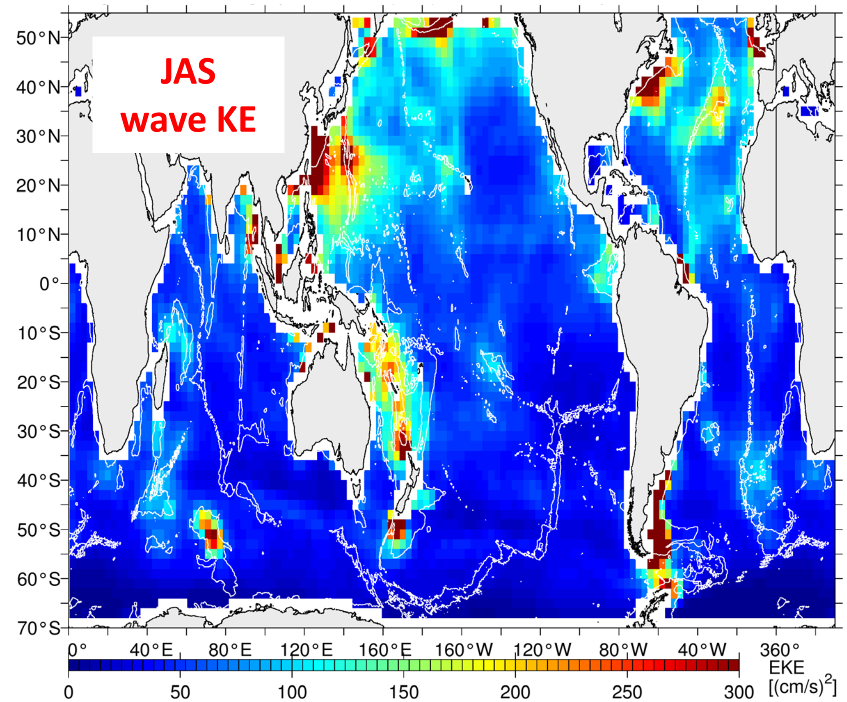
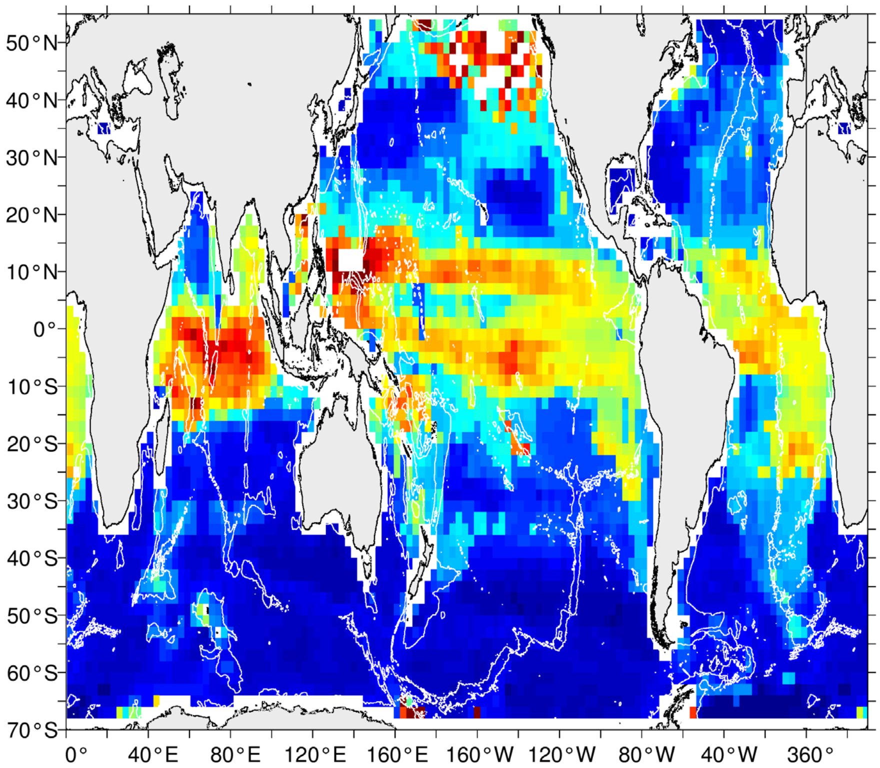


- **Lt** is shorter in winter than summer
- This is due to enhanced internal wave motions and reduced geostrophic flows in summer
- Observational confirmation & dynamical understanding of the seasonal changes are required

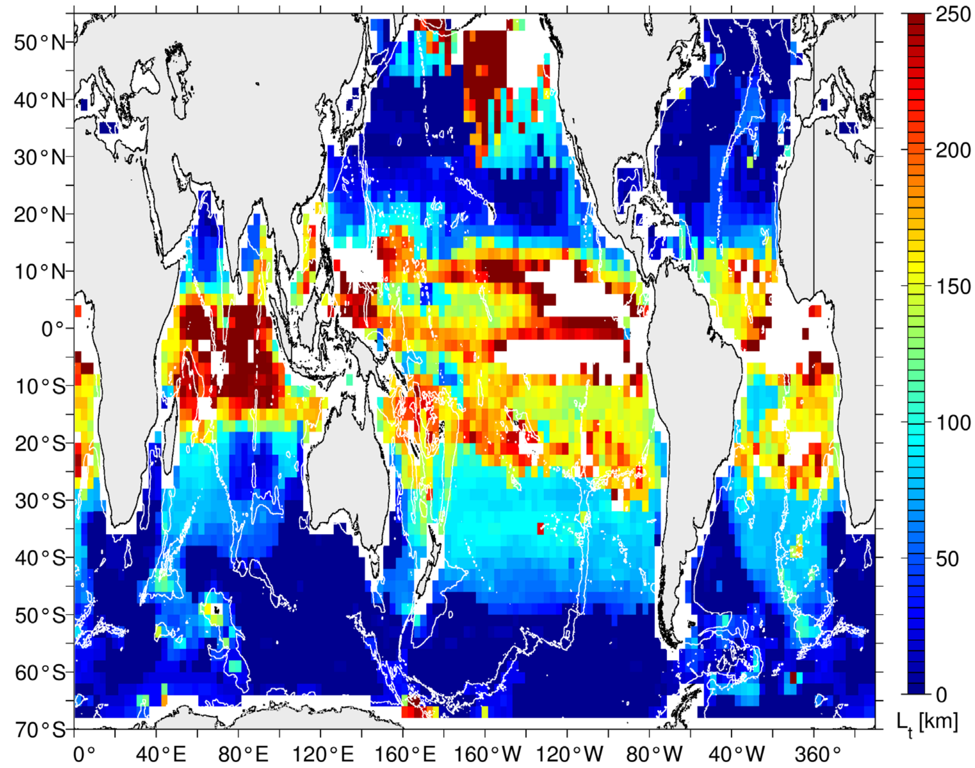




Lt (KE) based on 36-hour filtering

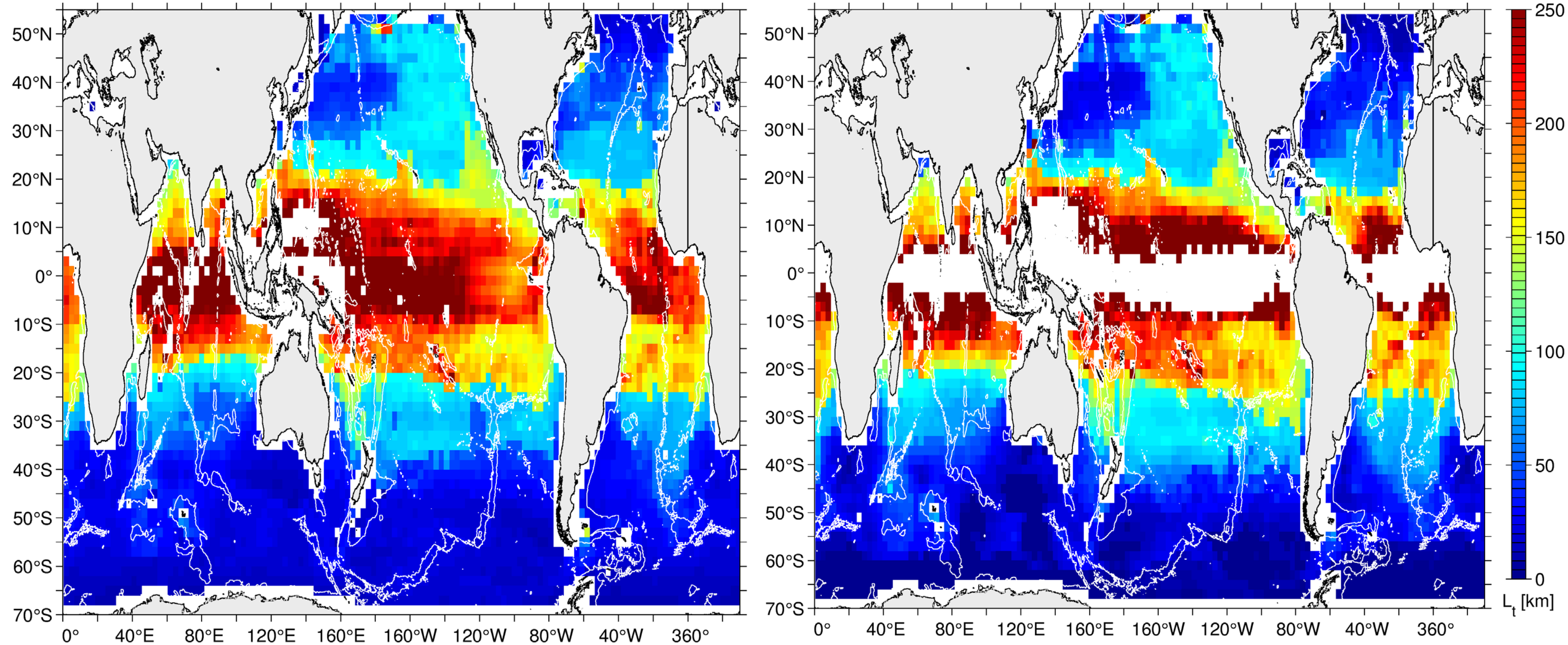


Lt (KE) based on dynamic delineation

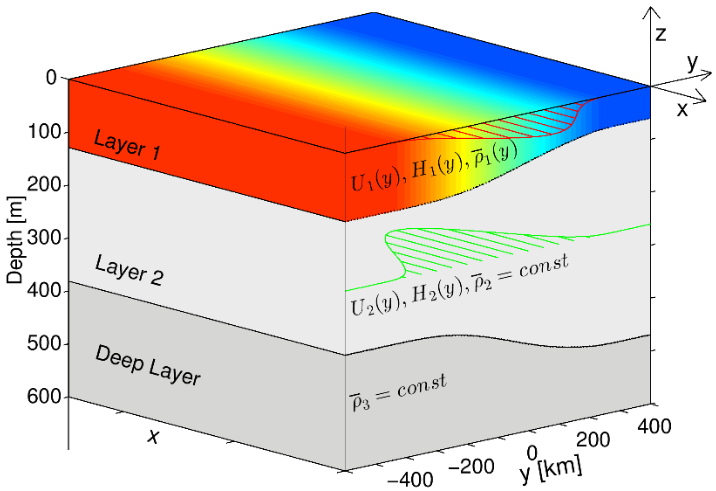


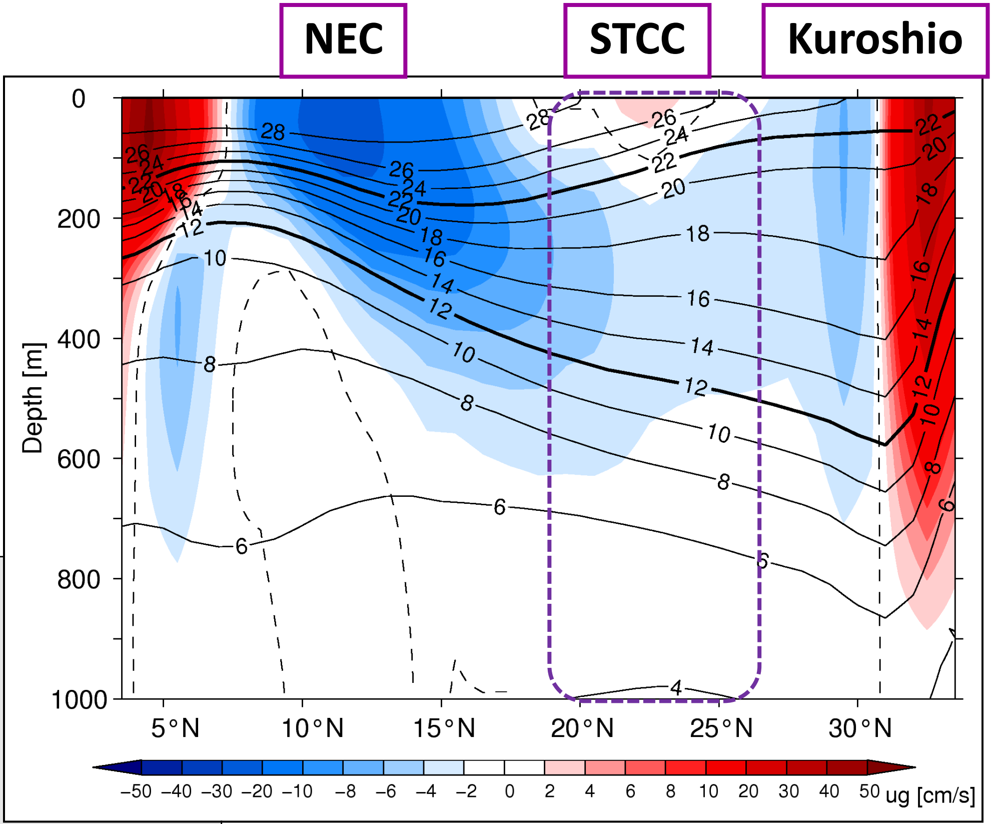
Lt (SSH) based on 36-hour filtering

Lt (SSH) based on dynamic delineation

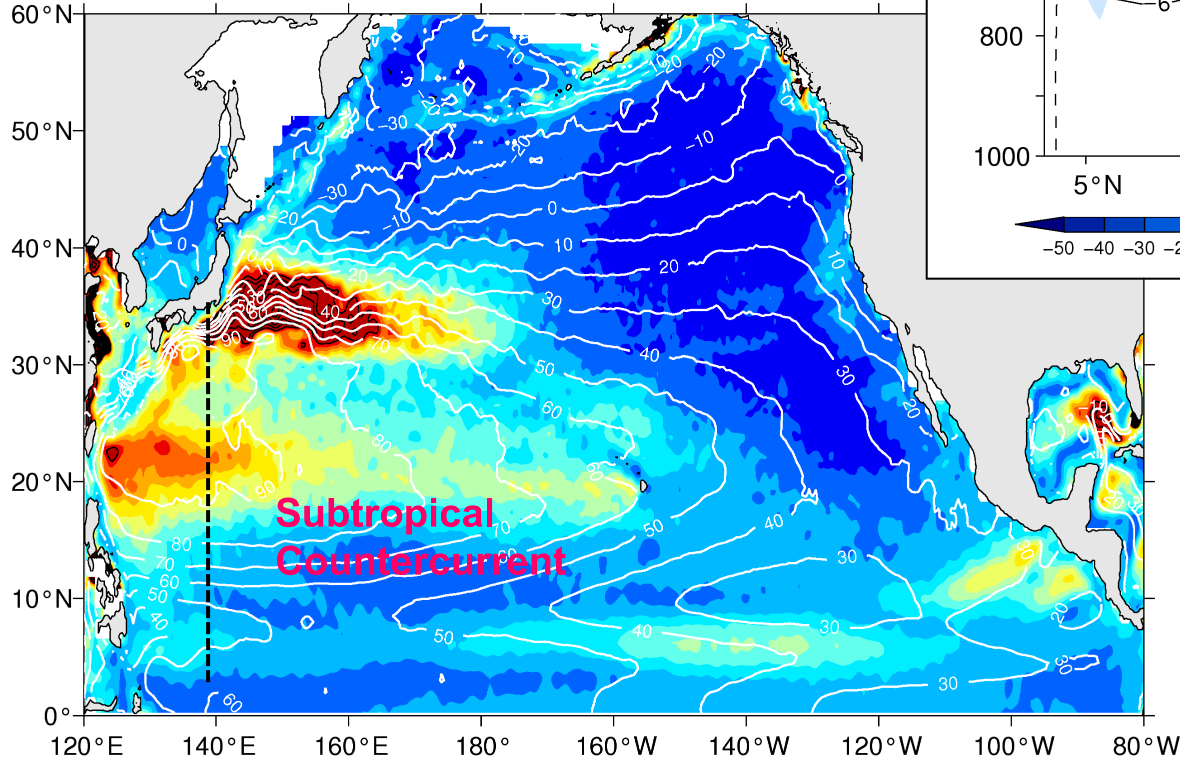


Enhanced STCC variability due to ML vs. interior baroclinic instability



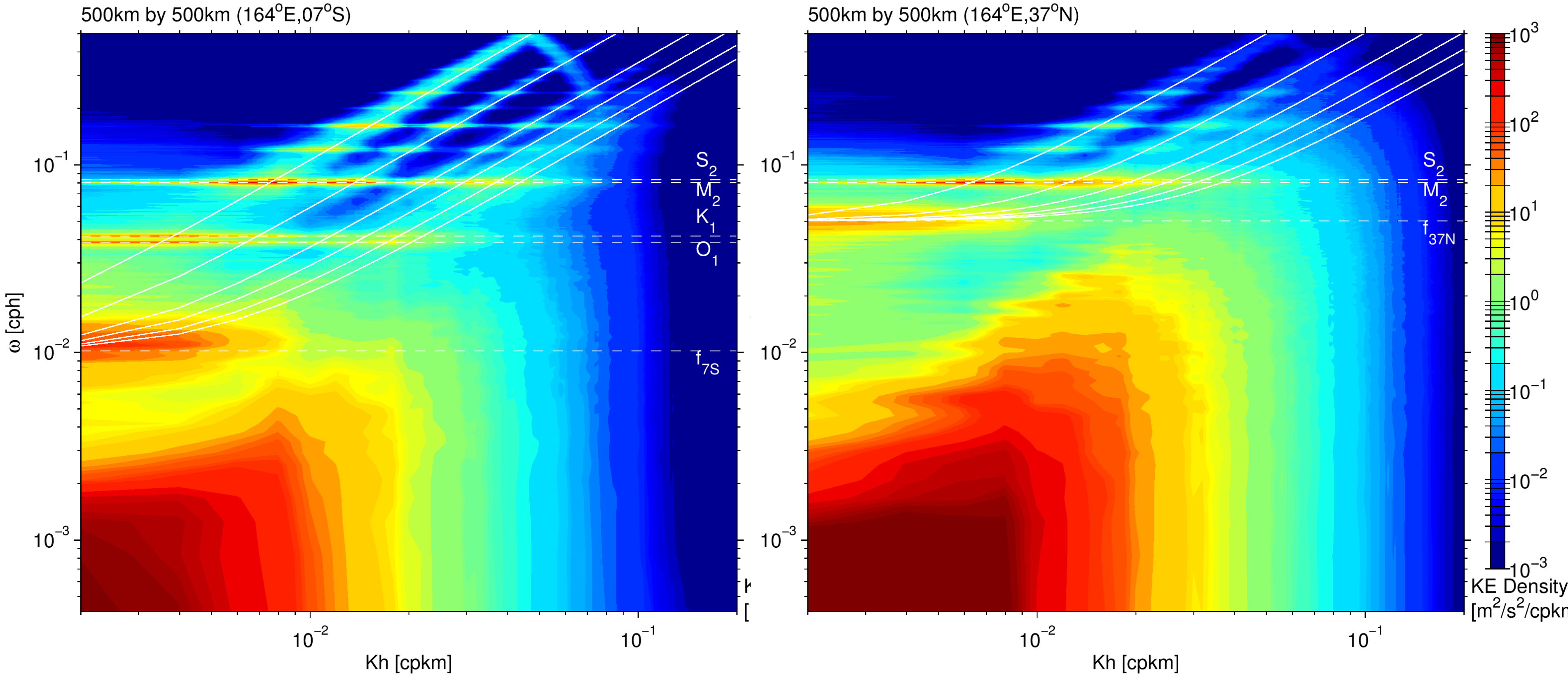


JMA temperature and Ug section along 137°E (1993-2008 mean)



AVISO rms SSH variability in N Pacific

Typical low- vs. mid-latitude wavenumber-frequency KE spectra from MITgcm



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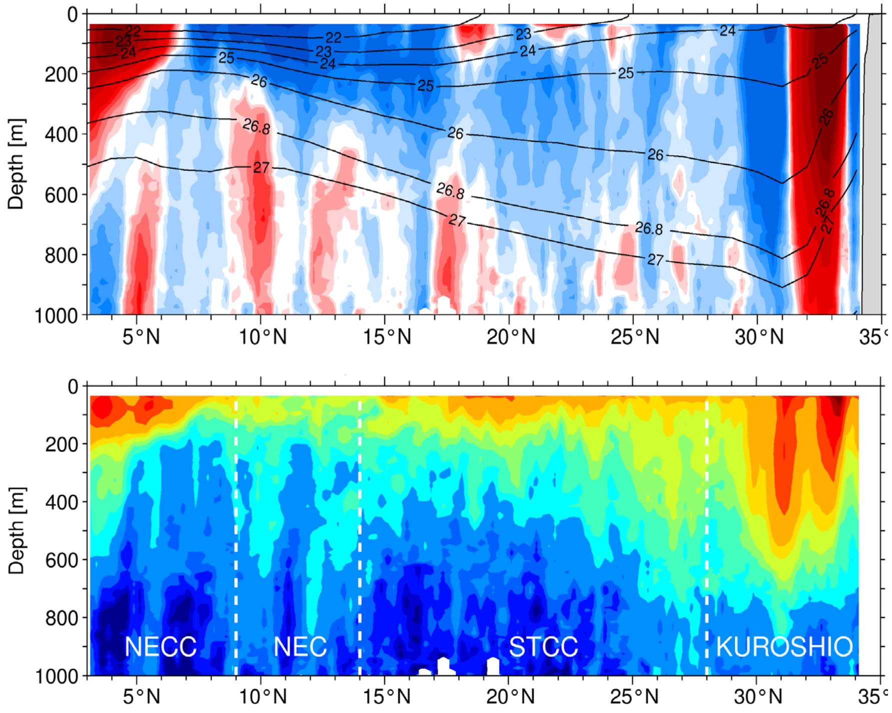
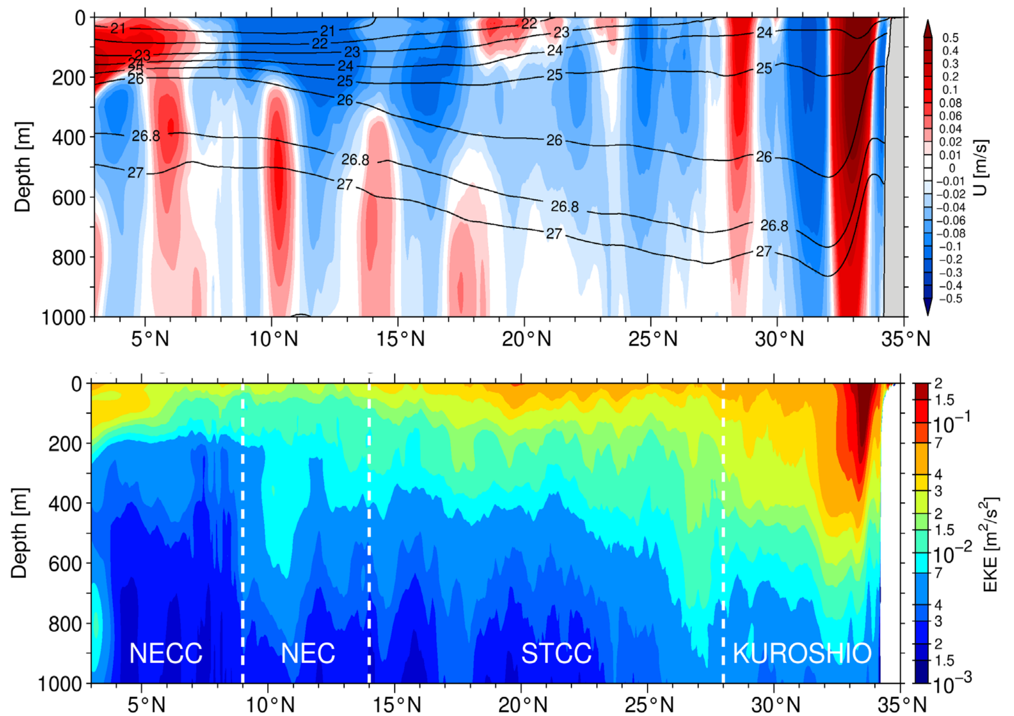


MITgcm-mean U & eddy KE along 137°E



- MITgcm simulates favorably the time-mean circulation in NW Pacific, including sub-thermocline zonal jet features
- For eddy variability, it performs well in Kuroshio/STCC bands, but under-estimates in the NECC region
- This under-estimation is due to short integration (i.e., no interannual variability), which affects tropical Lt evaluation