Bi-directional Kinetic Energy Cascades from Repeat Ship-Board ADCP Observations in the North Pacific Ocean

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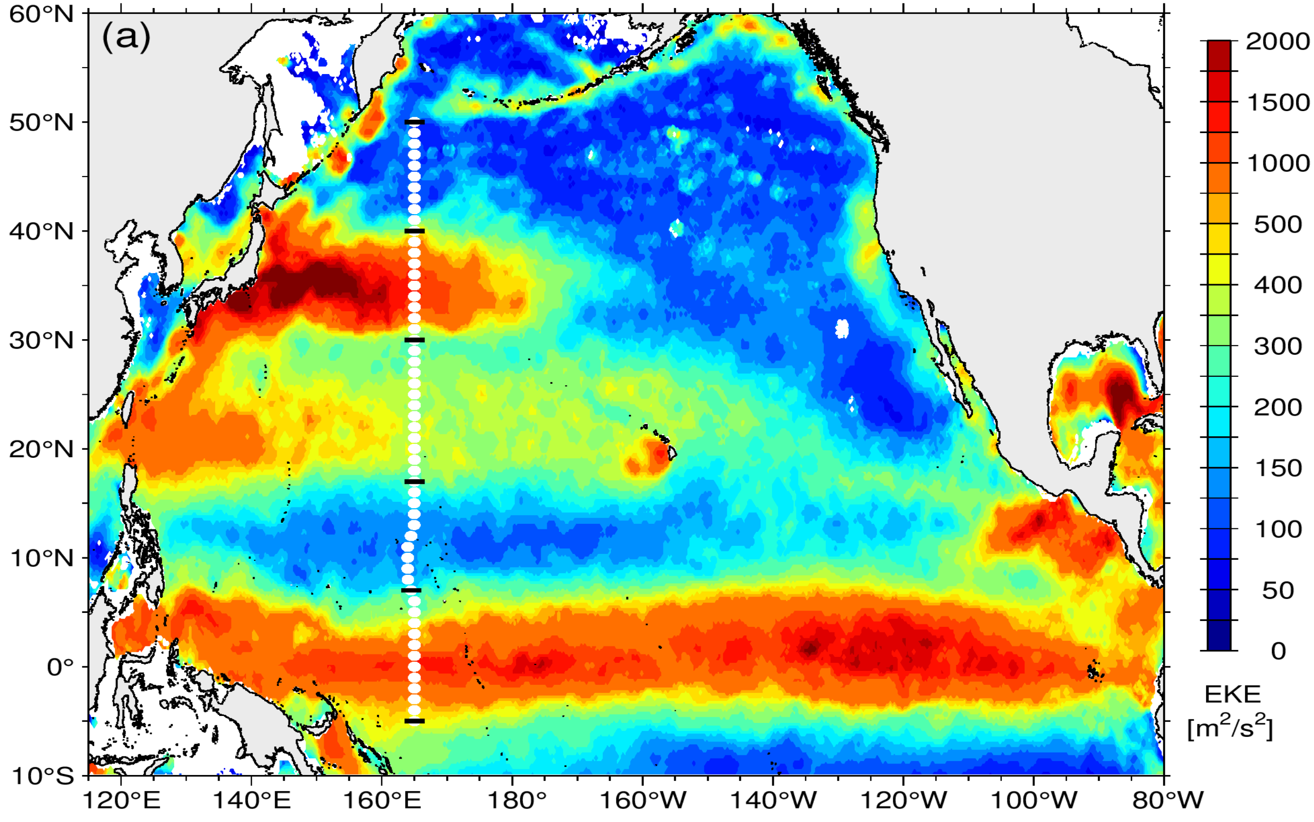

Surface ocean EKE map based on surface drifter data (Laurindo et al. 2017)

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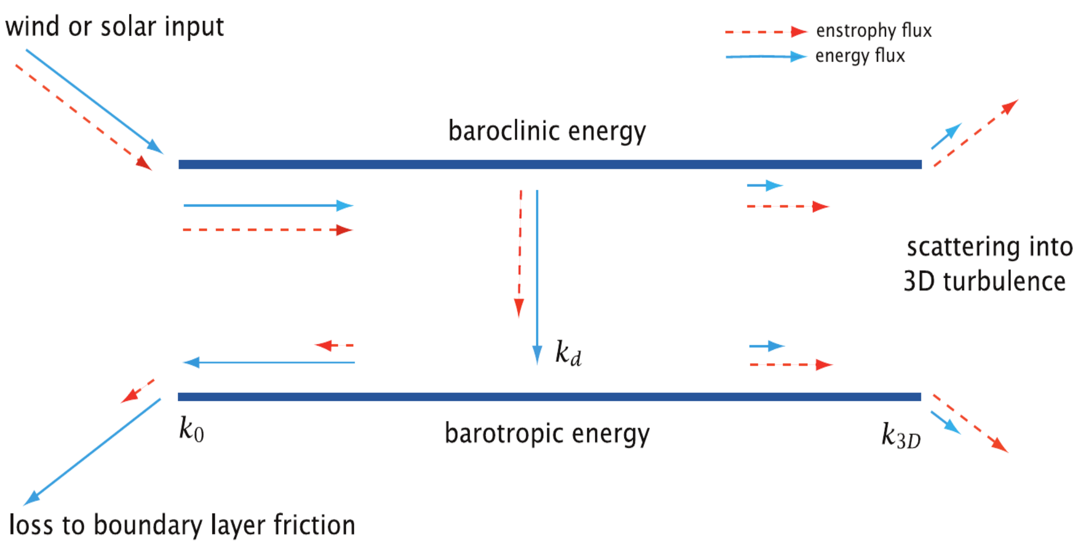
Background

- Ocean circulation receives its input energy at basin scales while dissipates it at mixing scale of O(1 cm); How this energy is transferred across scales is important to ocean circulation equilibration/changes
- QG dynamics predicts forward & inverse KE cascades separate at the baroclinic deformation radius L_R (e.g., Vallis 2017)



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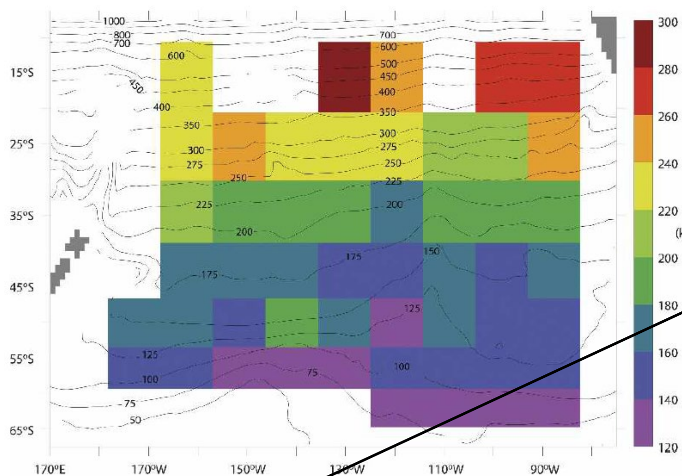
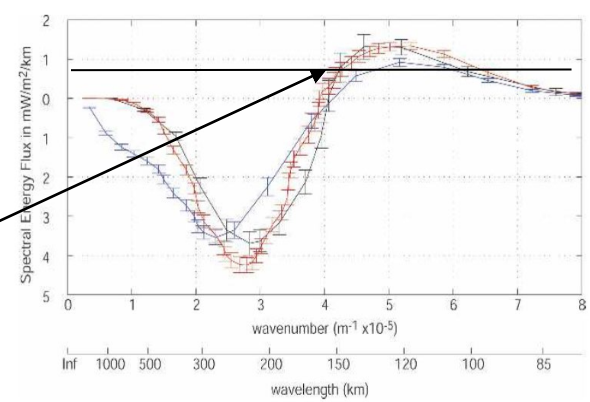
- Scott & Wang (2005) confirmed bi-directional KE cascades by evaluating spectral KE flux: $\Pi_K \equiv \langle \mathbf{u}_K^{\lesssim} \cdot (\mathbf{u}_K^{\lesssim} \cdot \nabla \mathbf{u}_K^{\gtrsim}) \rangle + \langle \mathbf{u}_K^{\lesssim} \cdot (\mathbf{u}_K^{\gtrsim} \cdot \nabla \mathbf{u}_K^{\gtrsim}) \rangle$ based on gridded AVISO SSH data:



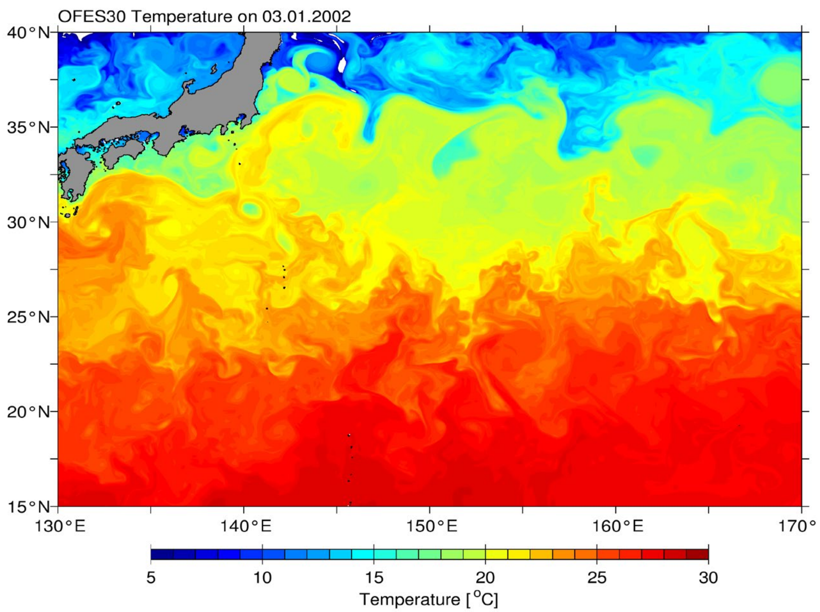
Scales where $\Pi(k) = 0$ from AVISO SSH data in South Pacific

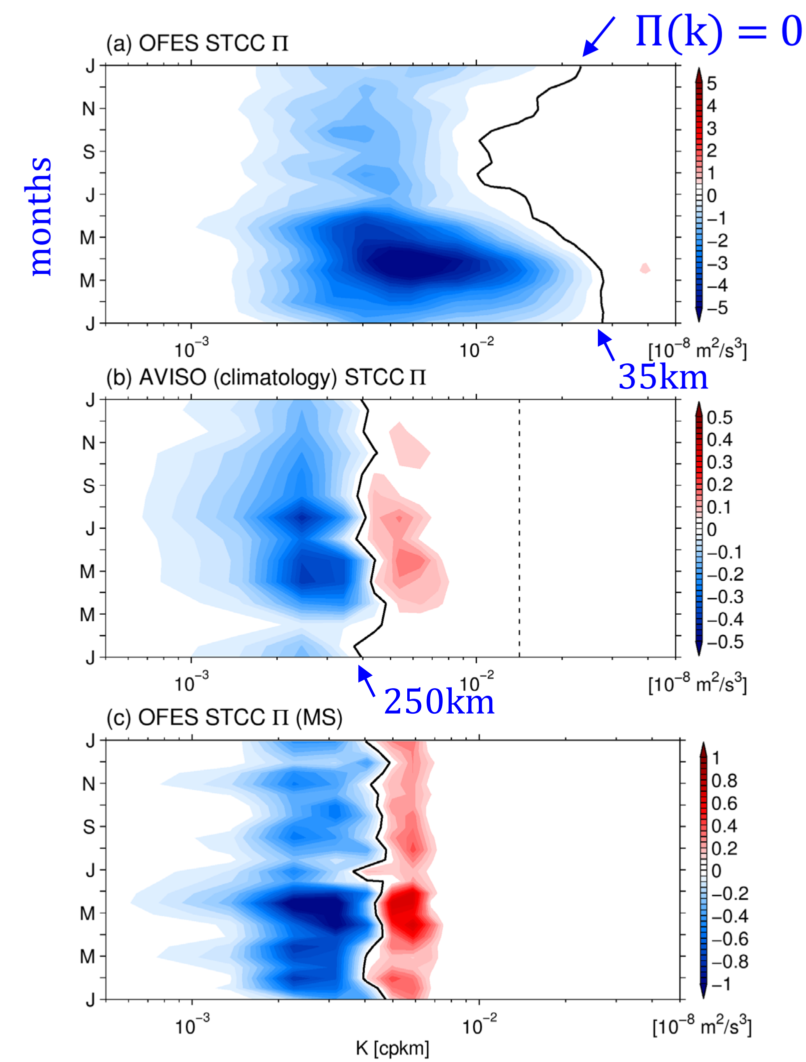
$\Pi(k)$



Typical spectral KE flux $\Pi(k)$; inverse cascade: $\Pi(k) < 0$ & forward cascade: $\Pi(k) > 0$

- This classical QG paradigm is put into question by submesoscale-permitting OGCM simulations in *two* regards. First, inverse KE cascade from high-res. OGCM simulations is found to occur at a much shorter lengthscale





- 3-km OFES spectral KE flux in STCC band

- Unlike in AVISO, separation scale L_S has a clear seasonal cycle: small in winter & large in summer due to mixed layer instability

- When OFES-SSH output is coarse-grained to AVISO level, $\Pi(k)$ recovers the AVISO result

Qiu et al. (2014, JPO)

- Second, and more subtly, balanced & unbalanced motions co-exist in the O(10-100km) range; while the former favors inverse cascade, the latter supports forward cascade → the KE cascade direction at a particular scale depends on relative strengths of the balanced vs. unbalanced motions!

- We used JMA repeat ship-board ADCP data of 2004-2020 to quantify KE cascade based on 2^{nd}- & 3^{rd}-order velocity structure functions (SF)

- For homogeneous/isotropic turbulent flows, 2^{nd}-order SF is related to the kinetic energy spectrum, *E(k),* where *r* is separation distance:

$$D2(r) = 4\int_0^\infty E(k)\,[1 - J_0(kr)]\,dk$$

For QG turbulence:	$E(k) \sim k^{-3}$ →	$D2(r) \sim r^2$
For ML instability & GM turbulence:	$E(k) \sim k^{-2}$ →	$D2(r) \sim r$

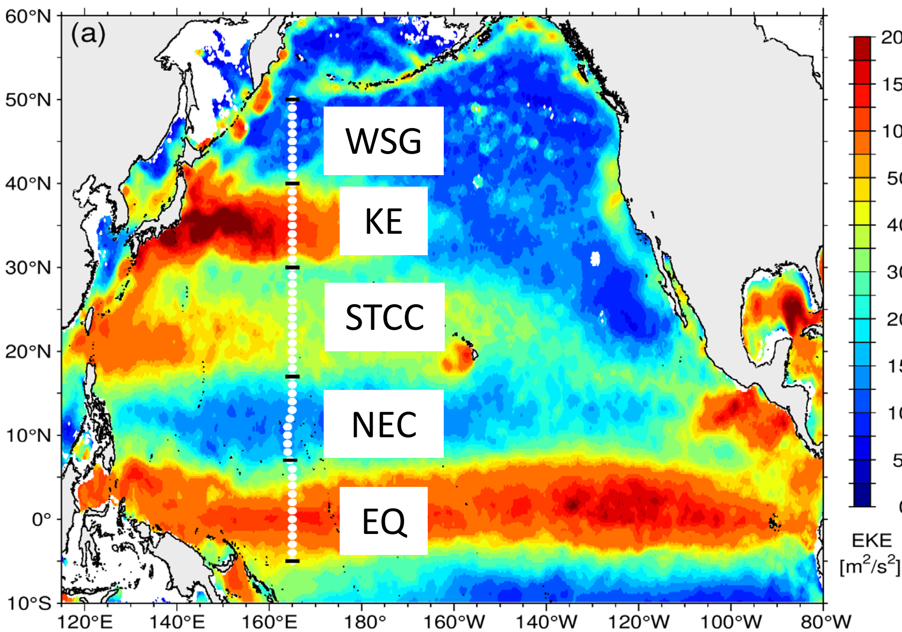
- For quasi-2D turbulence, 3^{rd}-order SF is related to spectral KE flux, $\Pi(k)$:

$$D3_L(r) = \langle\, \delta u_L(r)[\,\delta u_L^2(r) + \delta u_T^2(r)]\,\rangle = -2Fr$$

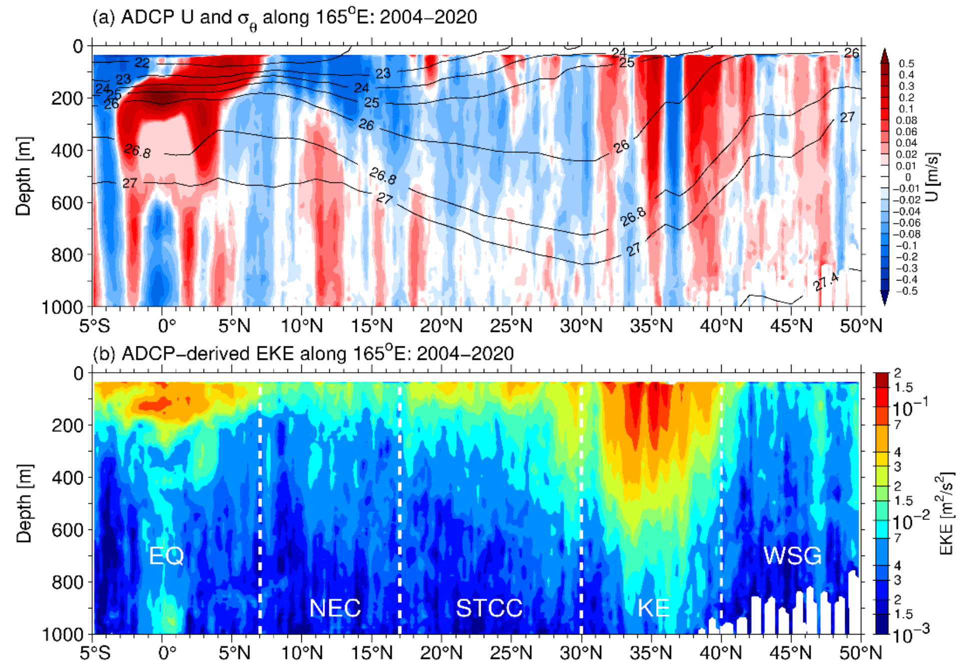
$F > 0$ (< 0) implies a forward (an inverse) cascade & the *F* value provides the KE dissipation rate ε

- To ensure dynamic homogeneity, ADCP u/v data are sub-divided into 5 geographic bands & energy cascades in each band are quantified by using 2nd- & 3rd-order SFs

JMA 165°E ADCP section (white dots) & EKE from surface drifter data (color)

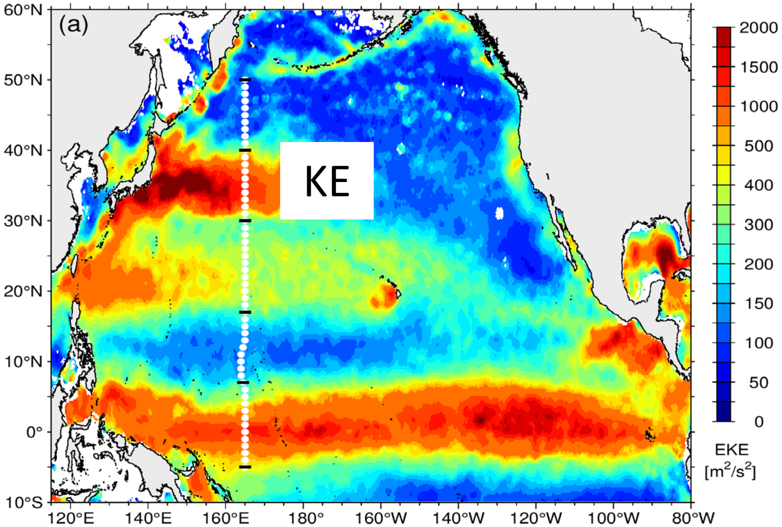


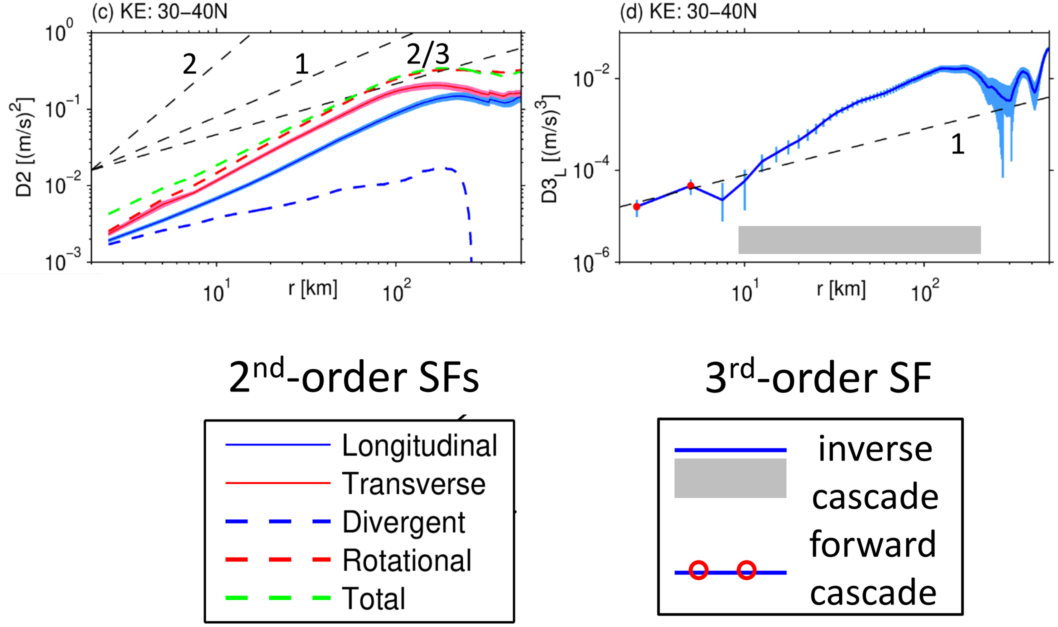
Time-mean U(y,z)/σ_θ(y,z) (top) & EKE(y,z) (bottom) along 165°E



Equatorial | North Eq. Current | Subtropical Counter Current | Kuroshio Extension | Western Subarctic Gyre

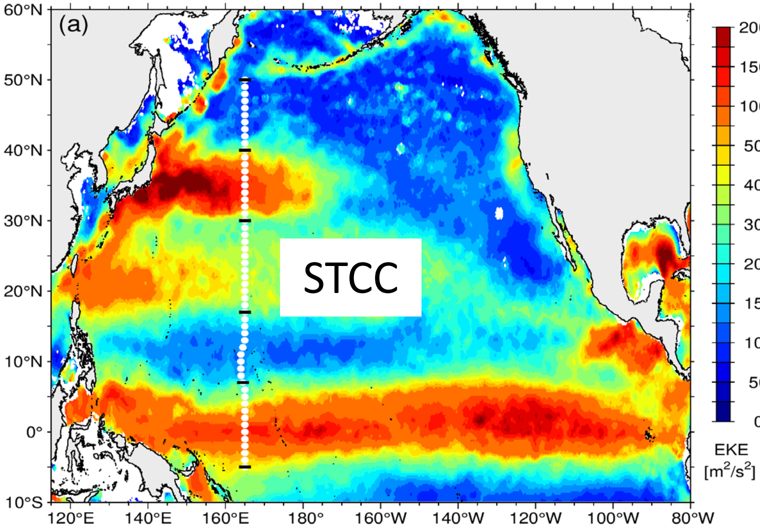
- Qiu, B., T. Nakano, S. Chen, and P. Klein, 2022: Bi-directional energy cascades in the Pacific Ocean from equator to subarctic gyre. Geophys. Res. Lett., 49, e2022GL097713.

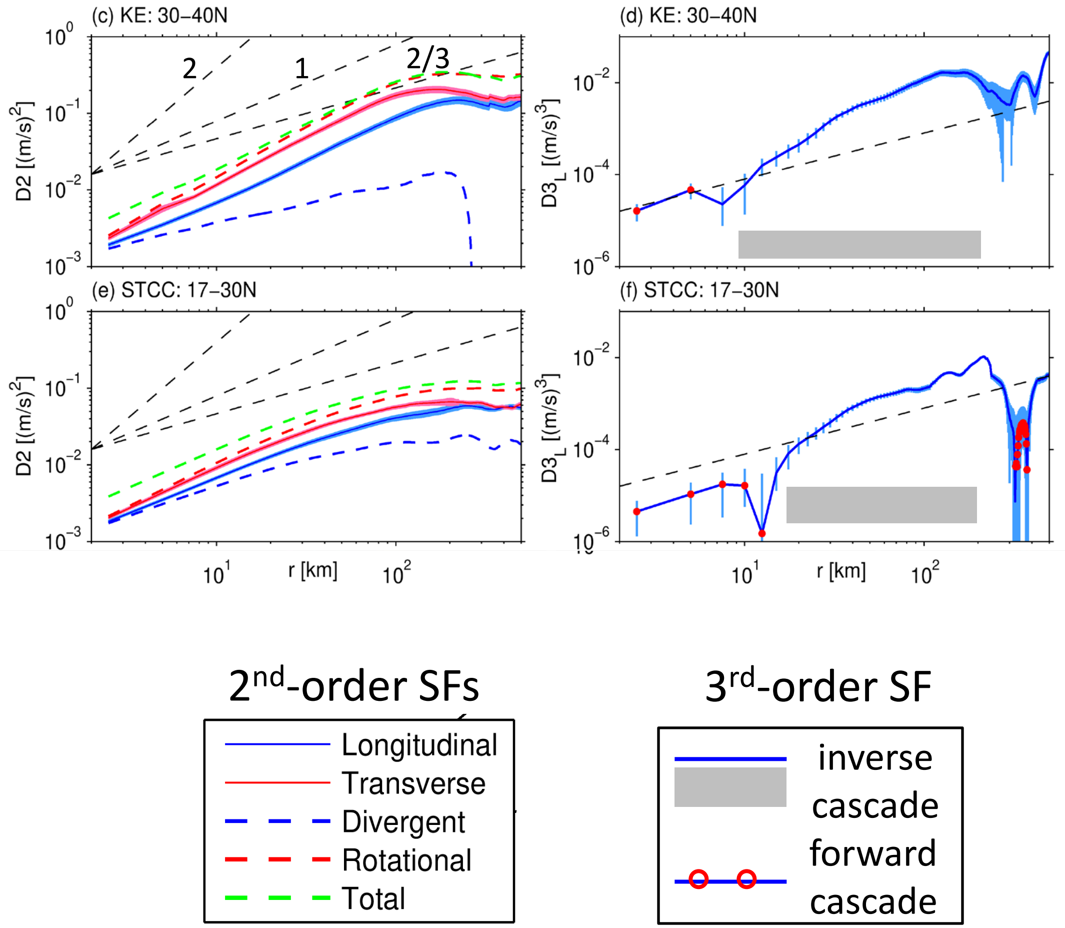




Kuroshio Extension band

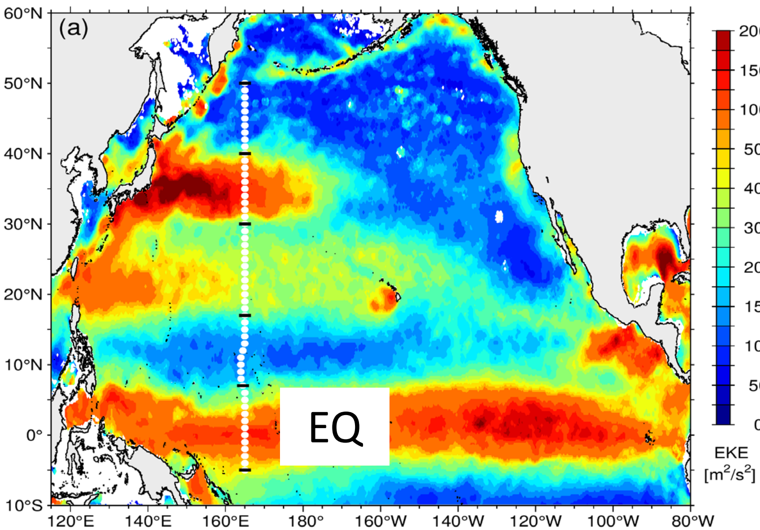
- $D2_r >> D2_d$; balanced motion dominates over unbalanced one
- $D2_r \sim r^{1.6}$ → SQG/QG mixture
- Bi-directional cascade separation occurs near r = 8km; inverse cascade ($D3_l < 0$) at r > 10 km; cf. L_R = 30~40 km
- There is hint that inverse cascade weakens when r > 200 km





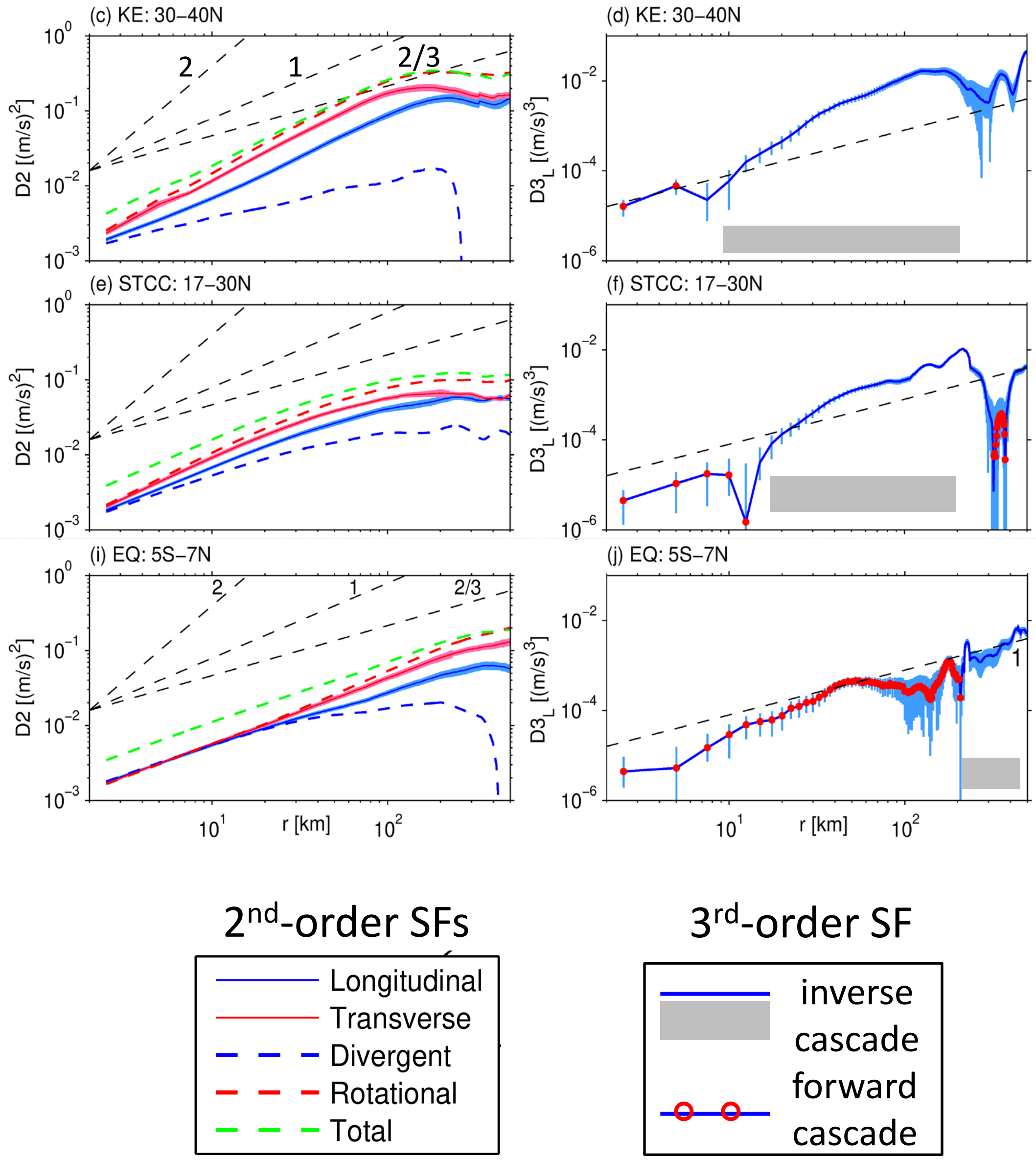
Subtropical Countercurrent band

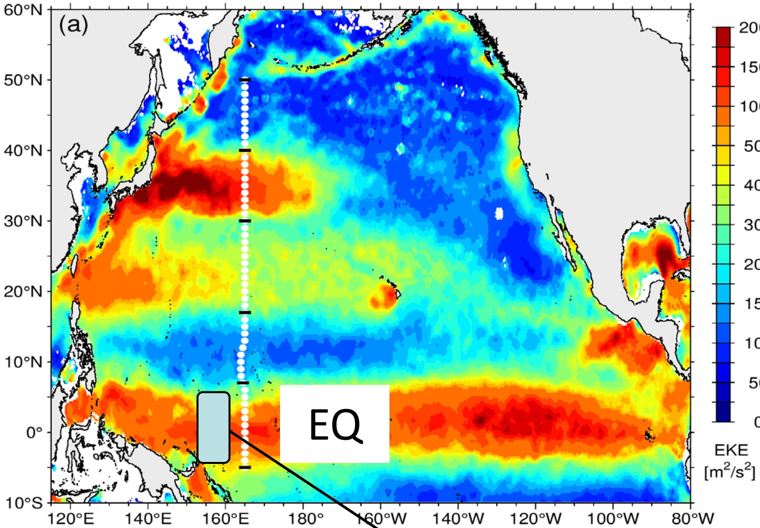
- Balanced motion dominates over unbalanced one to lesser extent
- $D2_r \sim r^1$ → SQG dynamics
- Inverse cascade occurs within r = 30~200 km; cf. L_R = 40~70 km
- What determines the large r scale of the inverse cascade window?

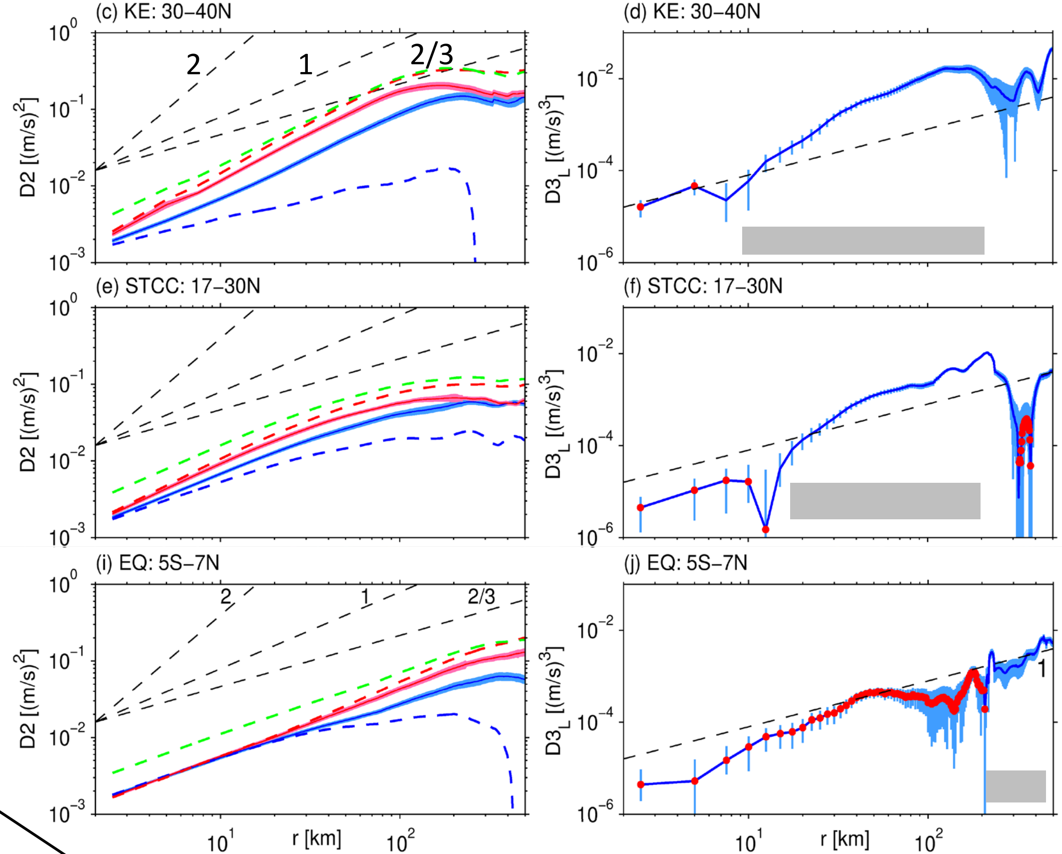


Equatorial band

- Balanced & unbalanced motions have comparable amplitudes
- $D2_r \sim r^1 \rightarrow E(k) \sim k^{-2}$: dominated by GM & SQG turbulence (?)
- Inverse cascade occurs when $r \geq 200$km; cf. $L_R \geq 200$km

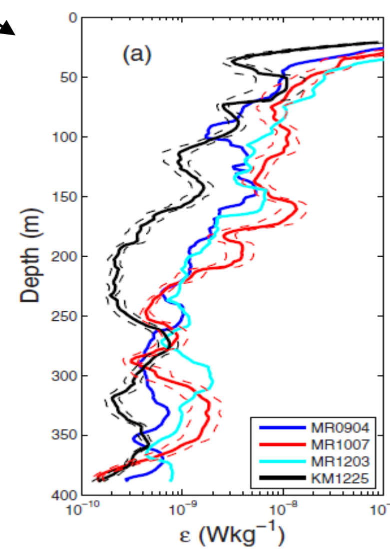




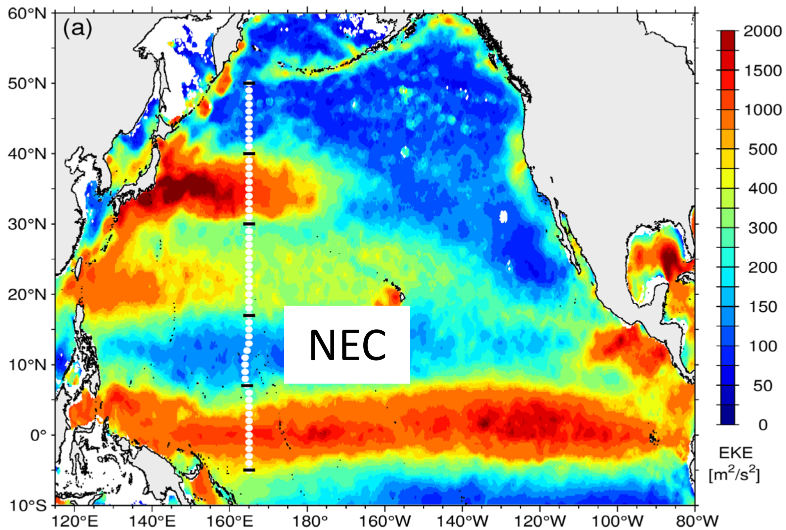


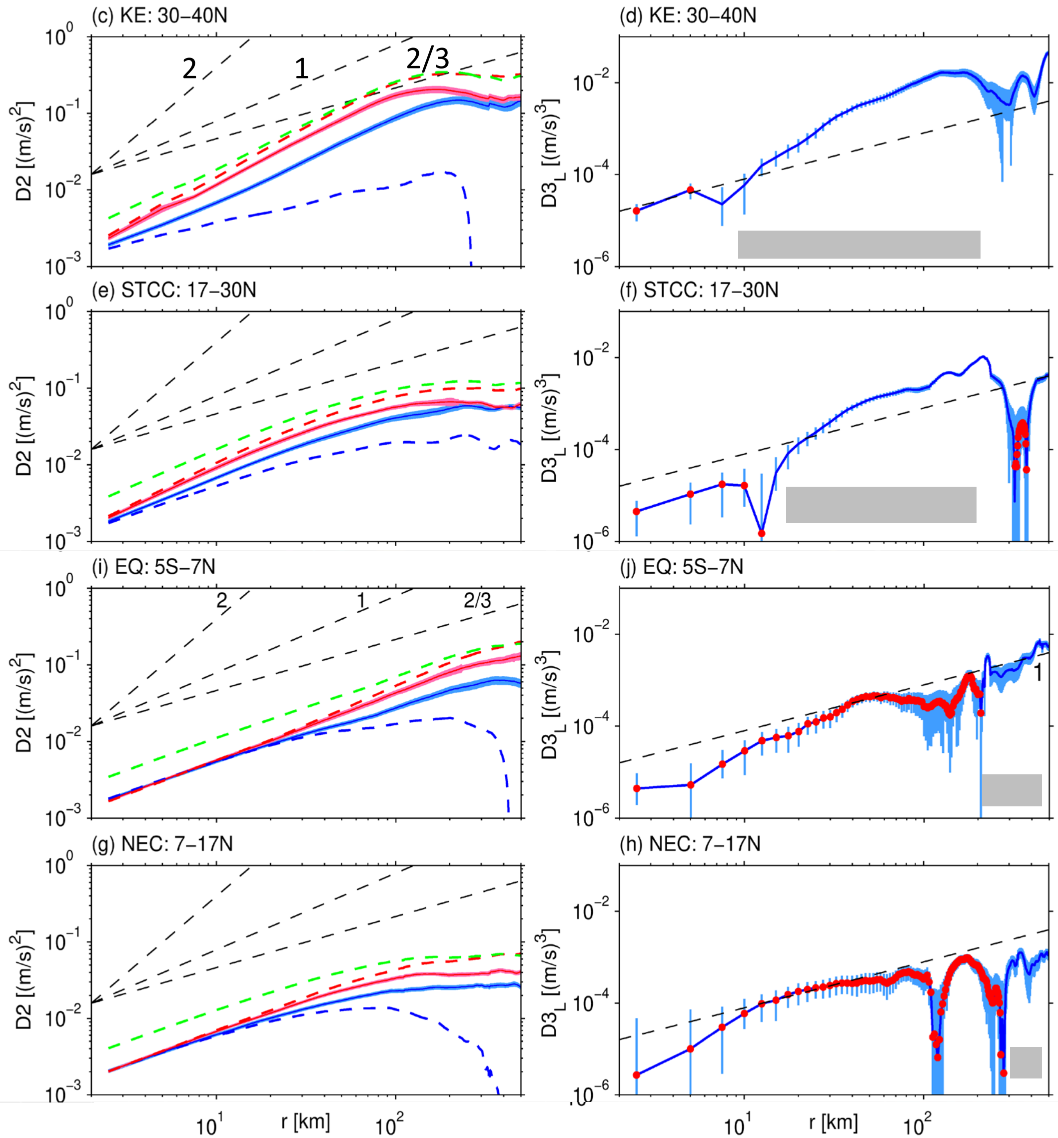
Equatorial band

- Balanced & unbalanced motions have comparable amplitudes
- $D2_r \sim r^1 \rightarrow E(k) \sim k^{-2}$: dominated by GM & SQG turbulence (?)
- Inverse cascade occurs when $r \geq$ 200km; cf. $L_R \geq$ 200km
- KE dissipation rate: $\varepsilon = -D3l(r)/2r \sim 3 \times 10^{-9}\ m^2/s^3$ → consistent with microstructure measurements



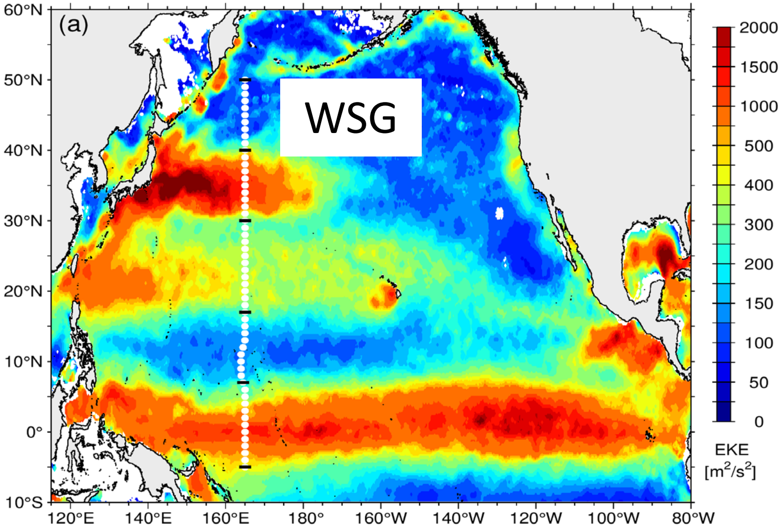
Richards et al. (2015, JGR)

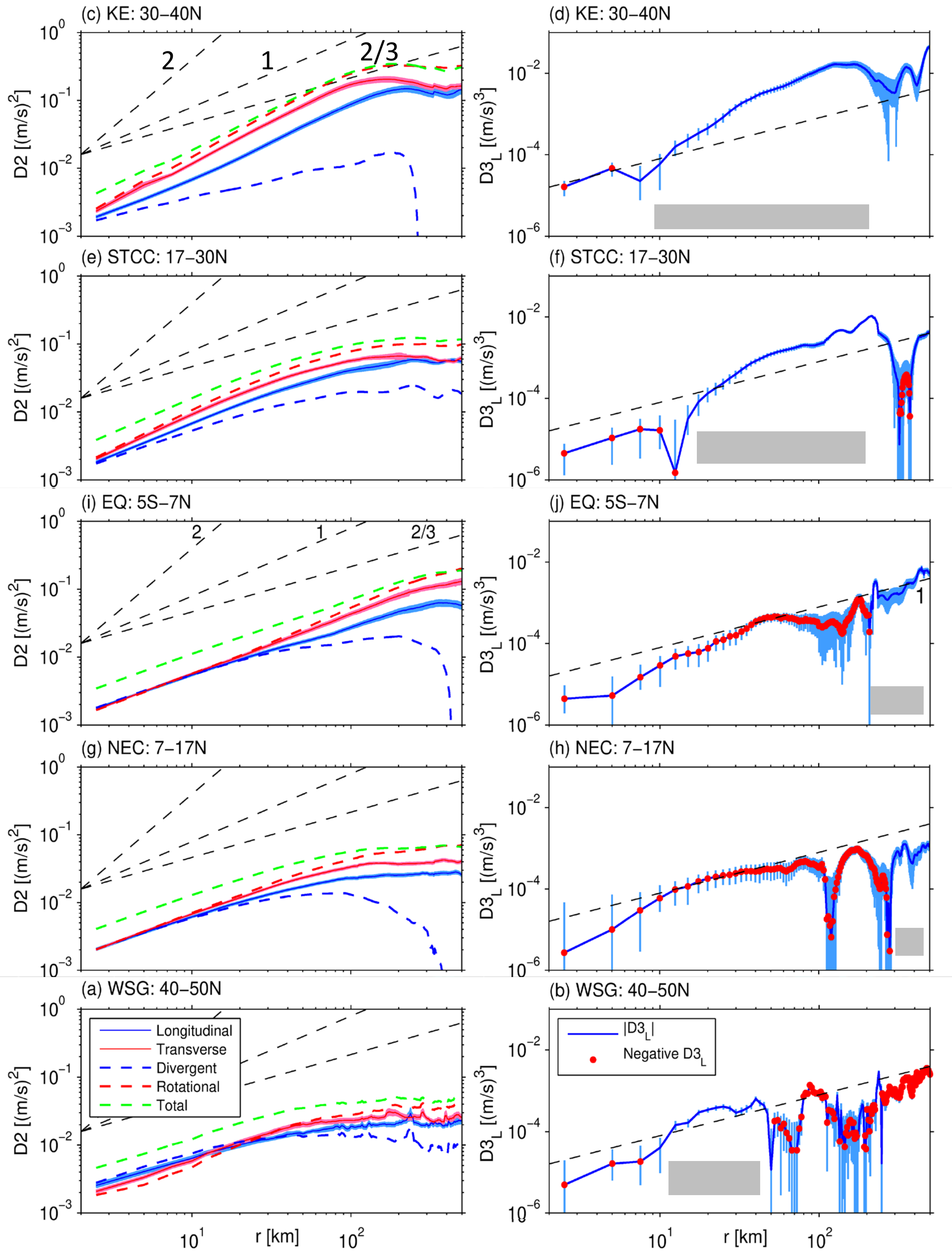




North Equatorial Current band

- Low EKE level, inverse cascade occurs when $r \geq 300$km; cf. L_R = 70~200km
- Despite being more constrained by rotation than Eq. band, inverse cascade window is narrower due to lack of balanced eddy motion
- KE dissipation rate ε is similar to Eq. band: ~ 3×10^{-9} m^2/s^3 ← ε is more dictated by UM than BM





Western Subarctic Gyre band

- Lowest EKE band; unbalanced motion is largely wind-forced & can exceed balanced motion
- Inverse cascade occurs in narrow r = 10~50 km window; cf. $L_R \approx 25$km
- Caused possibly by interaction between wind-forced NIWs & balanced zonal flows

Takeaway Message

- Due to co-existence of balanced & unbalanced motions, the scale separating the bi-directional KE cascades do NOT scale with L_R
- Inverse KE cascade can extend down to km-scales in regions where interior & mixed layer instabilities prevail
- Relative importance between the balanced-unbalanced motions & their interactions control the range an inverse KE cascade occurs
- To capture the bi-directional KE cascade globally, there is a need to observe both balanced & unbalanced motions down to O(1~10km)
- A better understanding of cross-scale interaction in the meso- & submesoscale range is critical for upper ocean processes relevant to phytoplankton growth & ecosystems

PICES WG-50: Sub-mesoscale Processes and Marine Ecosystems

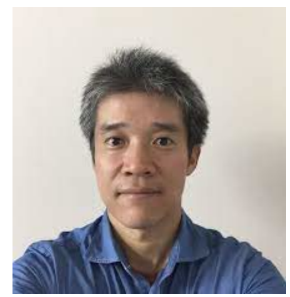
Motivation: Sub-mesoscale processes are relevant to ocean primary productivity because they support large vertical velocity with timescale similar to the phytoplankton growth, which will ultimately influence the upper trophic levels and food chain.

Goals: To improving our essential knowledge on the sub-mesoscale processes by integrating the sub-mesoscale-permitting observation dataset, developing and evaluating the high-resolution coupled model in the North Pacific, particularly in the coastal areas and others with important living resources".

WG members:

A. Bracco

S. Y. Kim



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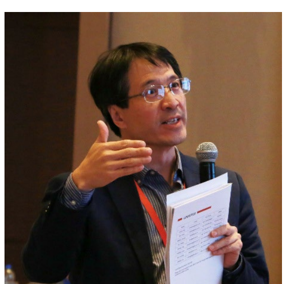

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