Virtual European Physical Oceanography and Shelf Sea Seminars

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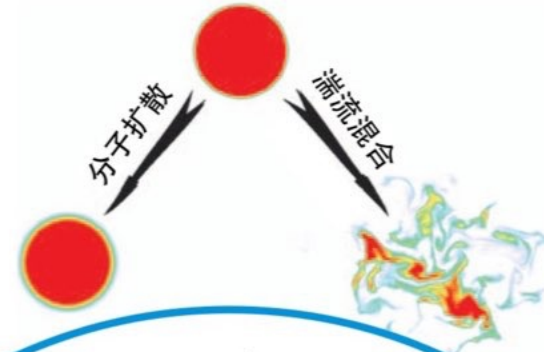
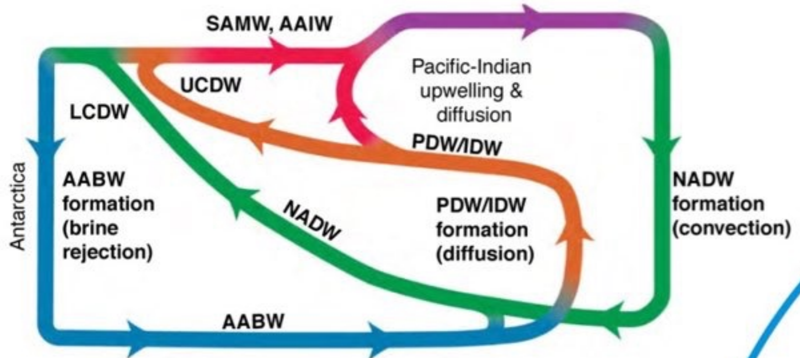
水体混合

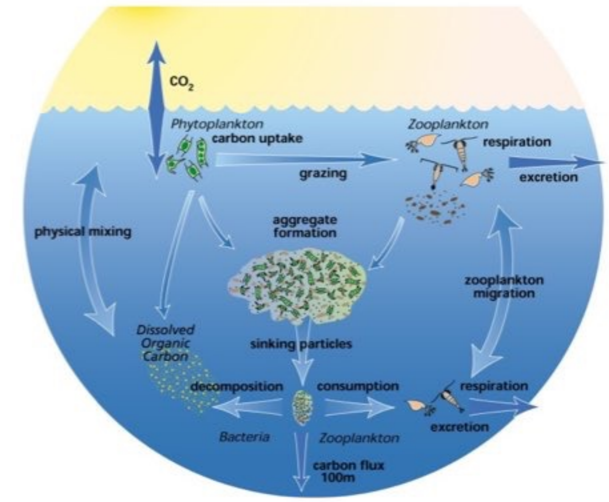


气候|热盐分布、海洋环流



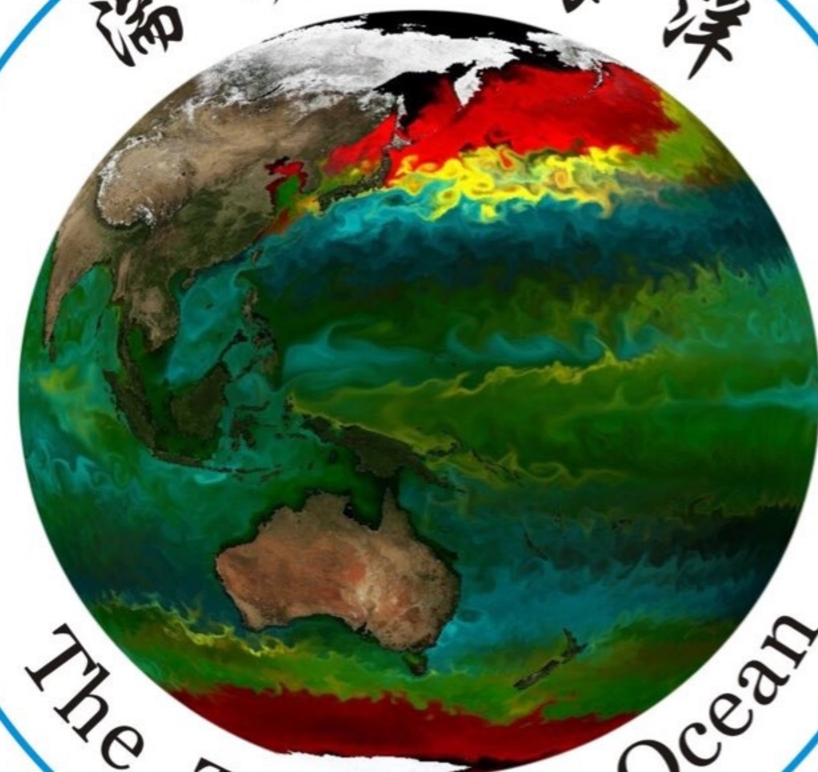
Talley et al. (2011)

生源要素分布|生态



U.S. JGOFS

湍动的海洋

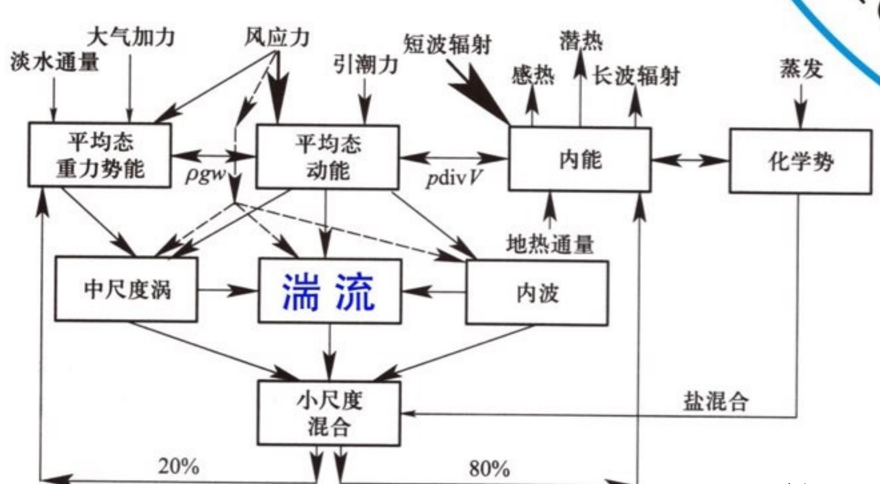


The Turbulent Ocean

湍流: 流体的一种运动状态

海洋中的流动处于湍流状态

能量平衡

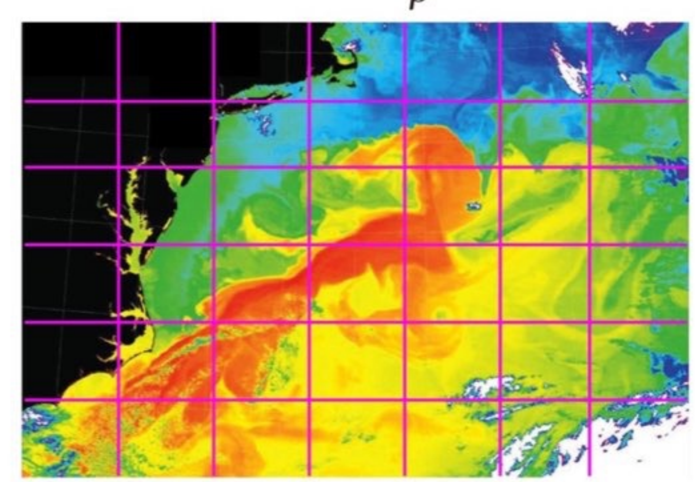


Huang (2012)

动量输运

$$\partial \mathbf{V}/\partial t + \mathbf{V}\cdot\nabla\mathbf{V} = -\frac{1}{\rho}\nabla p + \nu\nabla^2\mathbf{V}$$

次网格效应



Relevance of Theory?

AGU Advances

COMMENTARY
10.1029/2019AV000129

Key Points:
- Theory remains an essential cornerstone of geophysical sciences
- Researchers should resist the temptation to prioritize matching models to observations over getting the physics right
- Parameterizations firmly grounded in sound theory and tested against observations should remain a vital part of global modeling for some time

The Relevance of Theory for Contemporary Research in Atmospheres, Oceans, and Climate

Kerry Emanuel[1]

[1]Lorenz Center, Massachusetts Institute of Technology, Cambridge, MA, USA

Abstract Dealing with large data sets and complex computational codes demands increasing time and effort by researchers in atmospheres, oceans, and climate. The author argues for a more balanced approach to using models, observations, and theory to advance basic understanding.

Parameterizations firmly grounded in sound theory and tested against observations should remain a vital part of global modeling for some time.

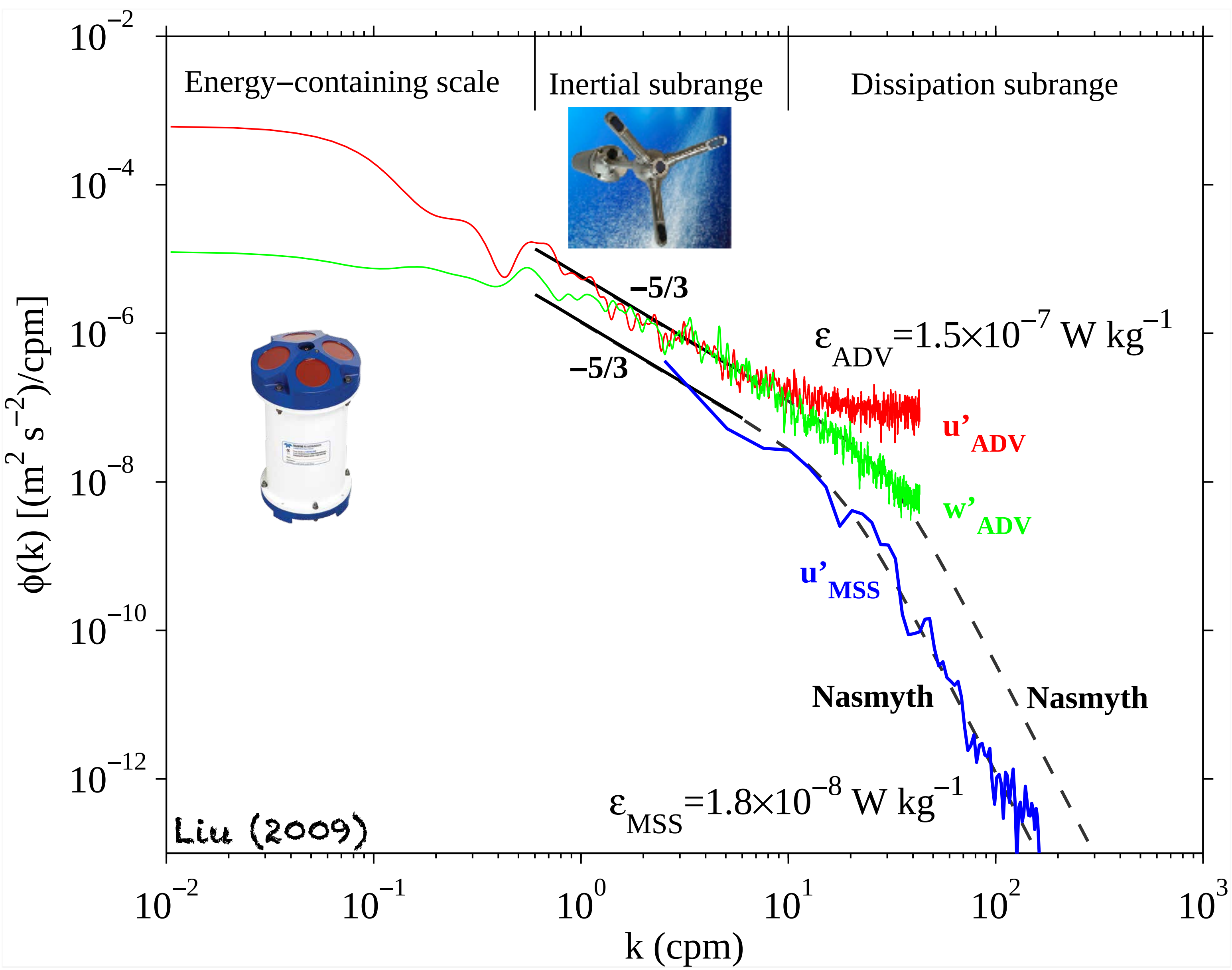
Yet there are signs of some weaknesses in this endeavor, and it is natural to focus on these to further accelerate progress. Some that come to mind include our poor understanding of the processes leading to the generation of tropical cyclones, the underlying physics of the Madden-Julian Oscillation and equatorially trapped disturbances, the nature and importance of vertical mixing in driving the circulation of the oceans, the possible influence of stratospheric processes on weather, and the role of clouds in climate and climate change. On longer time scales, we lack a comprehensive understanding of such essential processes as the behavior of large ice sheets and the carbon cycle in general. All of these problems are being addressed by

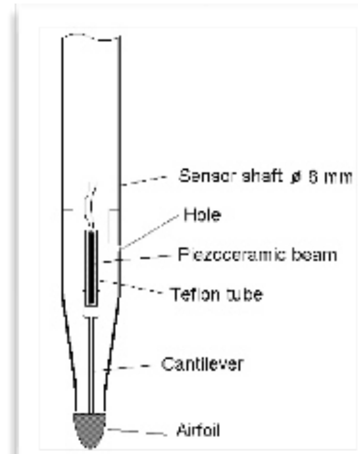
Quantifying Small-Scale Turbulence in the Ocean

Mixing efficiency?

$$\underbrace{\frac{\partial k}{\partial t}}_{\text{Local derivative}} + \underbrace{\overline{u}_j \frac{\partial k}{\partial x_j}}_{\text{Advection}} = -\underbrace{\frac{1}{\rho_o}\frac{\partial \overline{u_i' p'}}{\partial x_i}}_{\text{Pressure diffusion}} - \underbrace{\frac{1}{2}\frac{\partial \overline{u_j' u_j' u_i'}}{\partial x_i}}_{\substack{\text{Turbulent transport} \\ \mathcal{T}}} + \underbrace{\nu \frac{\partial^2 k}{\partial x_j^2}}_{\text{Molecular viscous transport}} \underbrace{- \overline{u_i' u_j'}\frac{\partial \overline{u_i}}{\partial x_j}}_{\substack{\text{Production} \\ \mathcal{P}}} - \underbrace{\nu \overline{\frac{\partial u_i'}{\partial x_j}\frac{\partial u_i'}{\partial x_j}}}_{\substack{\text{Dissipation} \\ \varepsilon_k}} - \underbrace{\frac{g}{\rho_o}\overline{\rho' u_i'}\delta_{i3}}_{\substack{\text{Buoyancy flux} \\ b}}$$

estimate!
(with local isotropy assumption)





"Duality" of Ocean Turbulence

- Deterministic (dynamics)
- Stochastic (lognormal, Burr)

Lozovatsky et al. (2017)

Internal Wave Driven Mixing

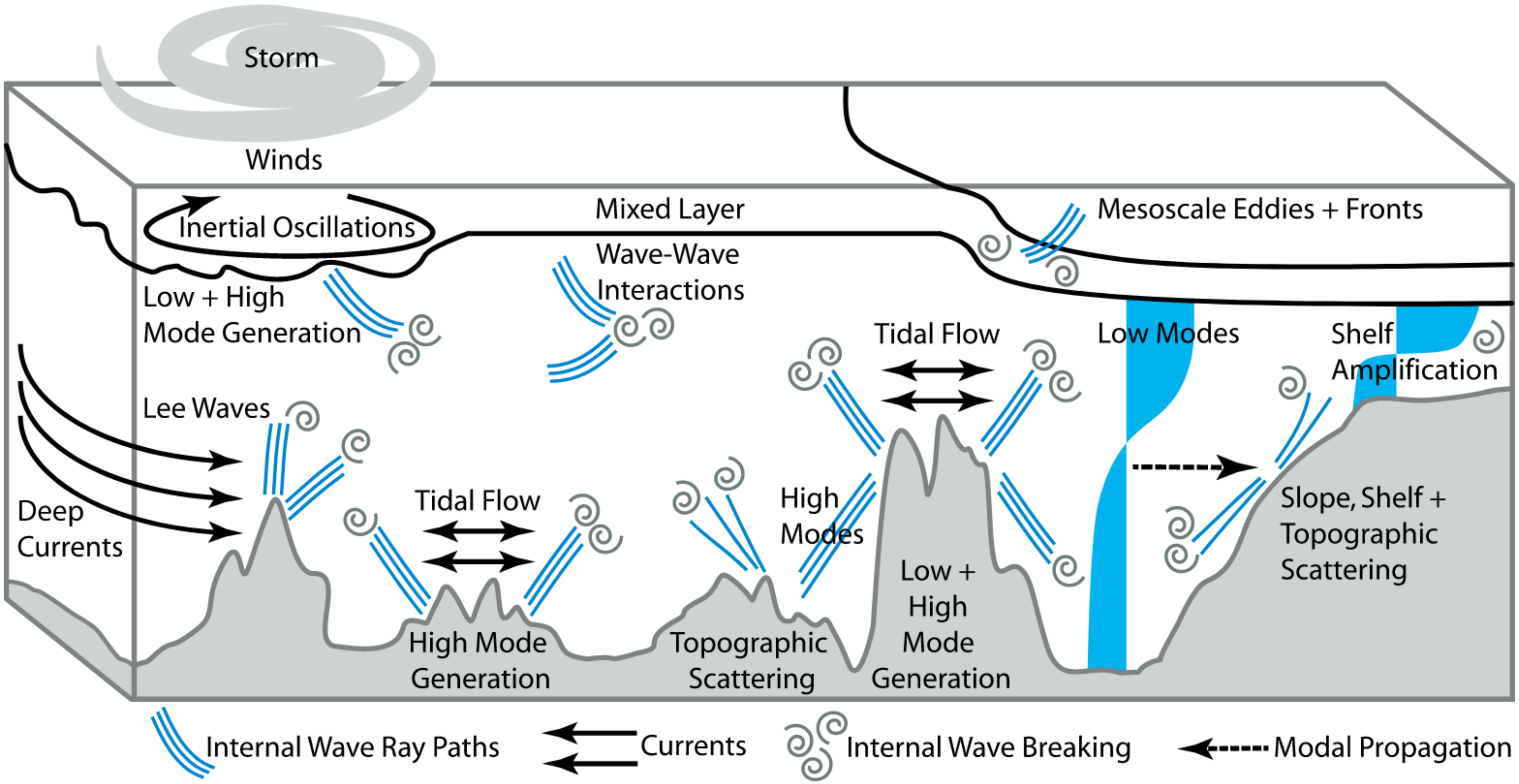


Fig. 1. Schematic of internal wave mixing processes in the open ocean that are considered as part of this CPT. Tides interact with topographic features to generate high-mode internal waves (e.g., at midocean ridges) and low-mode internal waves (e.g., at tall steep ridges such as the Hawaiian Ridge). Deep currents flowing over topography can generate lee waves (e.g., in the Southern Ocean). Storms cause inertial oscillations in the mixed layer, which can generate both low- and high-mode internal waves (e.g., beneath storm tracks). In the open ocean, these internal waves can scatter off of rough topography and potentially interact with mesoscale fronts and eddies until they ultimately dissipate through wave–wave interactions. Internal waves that reach the shelf and slope can scatter or amplify as they propagate toward shallower water.

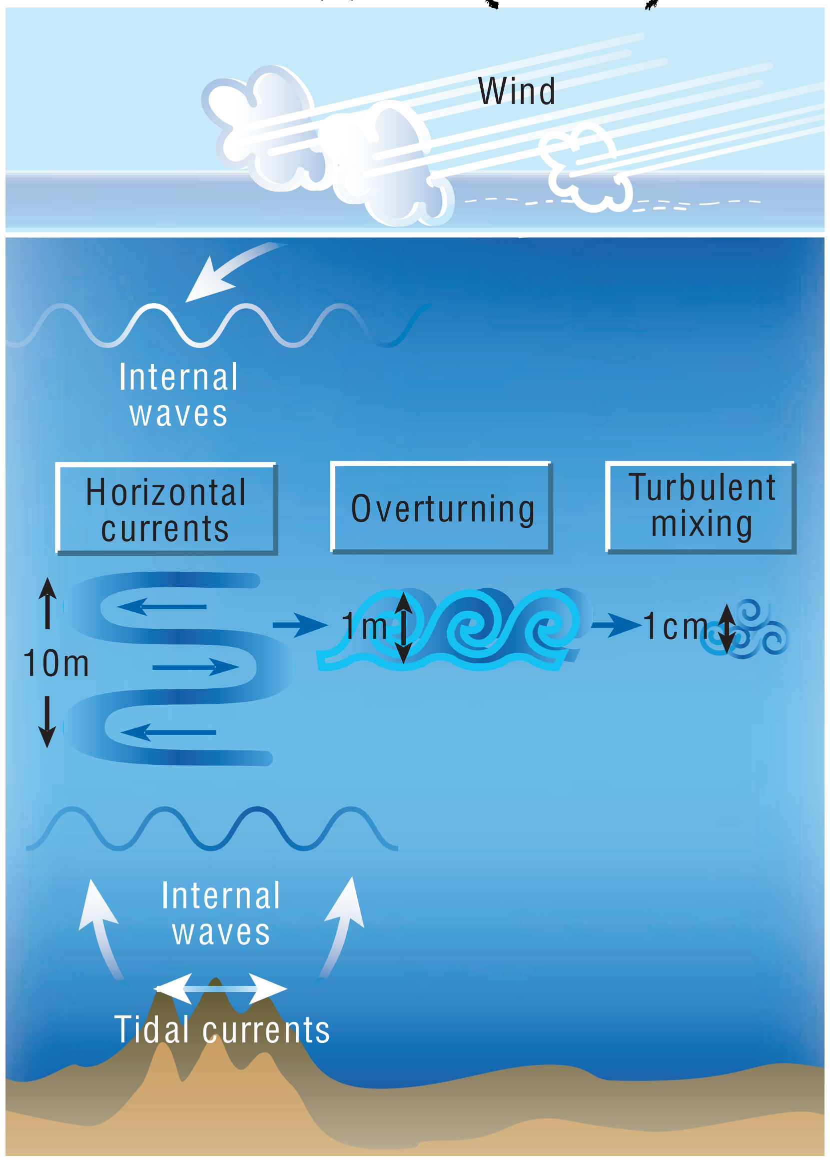
MacKinnon et al. (2017)

Fine-scale Parameterization of Ocean Turbulence

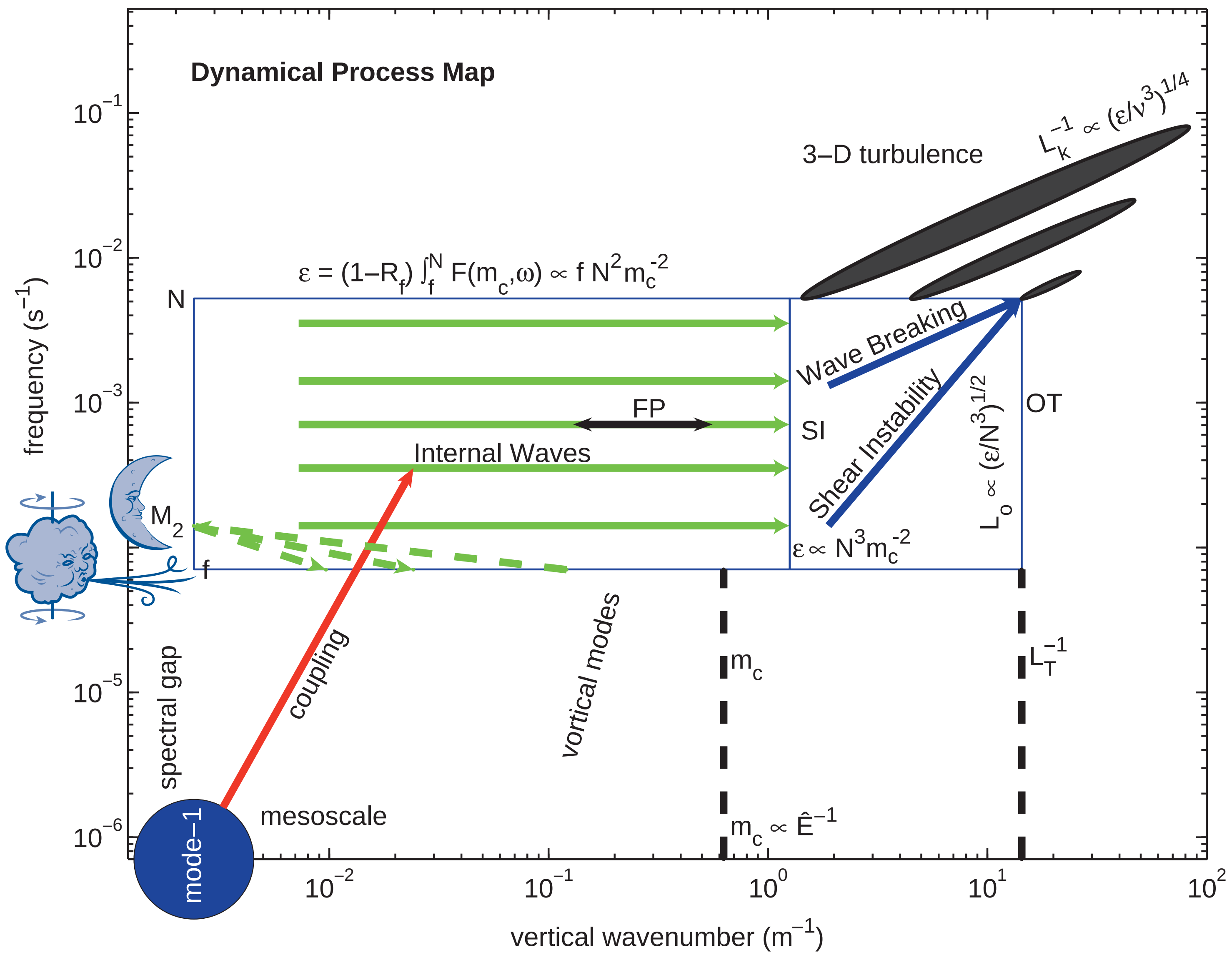
Based on theories of nonlinear internal wave-wave interactions, semi-empirical formulas have been devised to parameterize ε, the dissipation rate of turbulent kinetic energy, as a function of resolvable properties (in measurements/model), i.e.

$$\varepsilon = \varepsilon(N, f, S, \xi_z, ...),\ \kappa_\rho = \Gamma\varepsilon/N^2$$

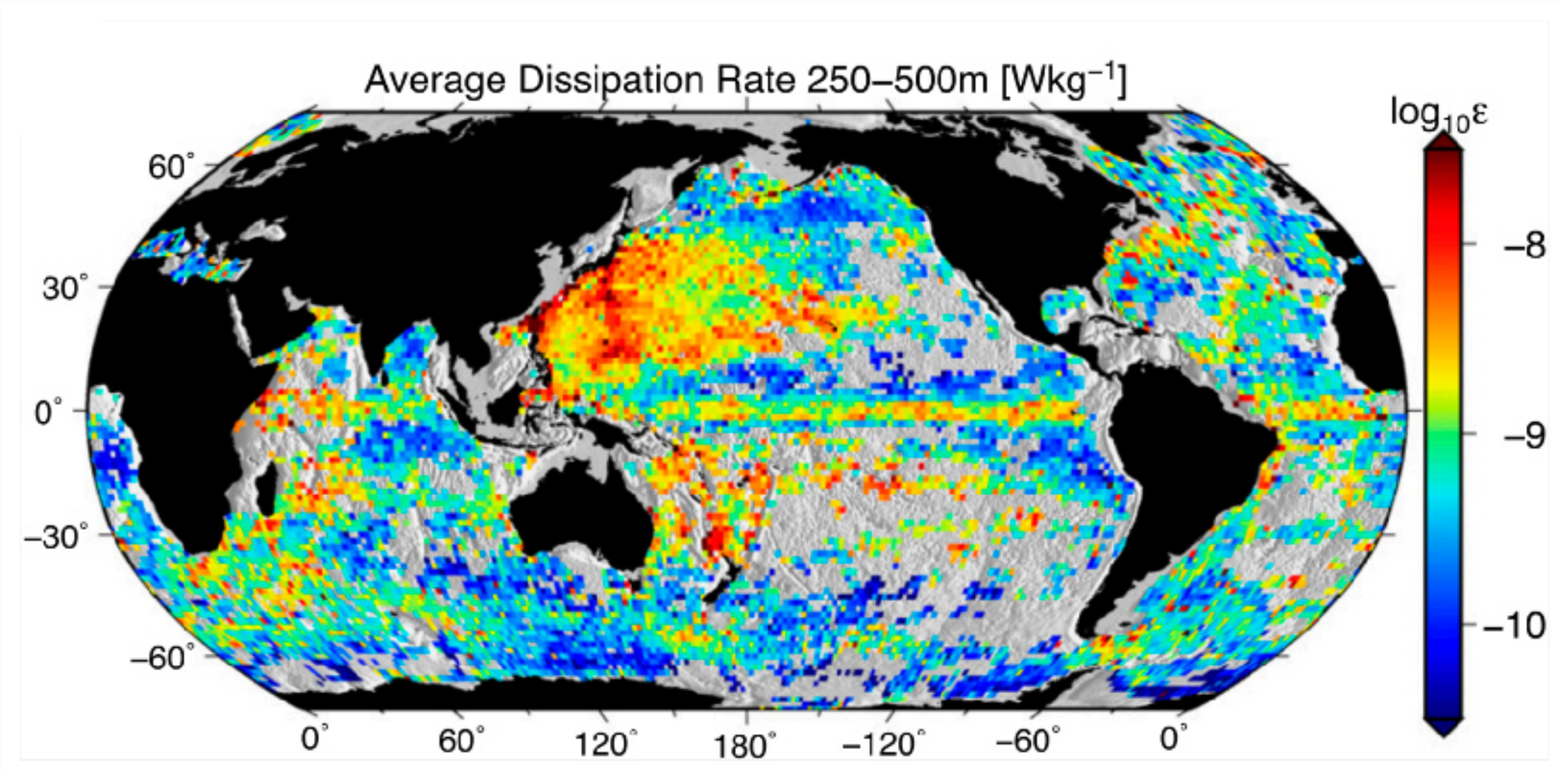
Garrett (2003)



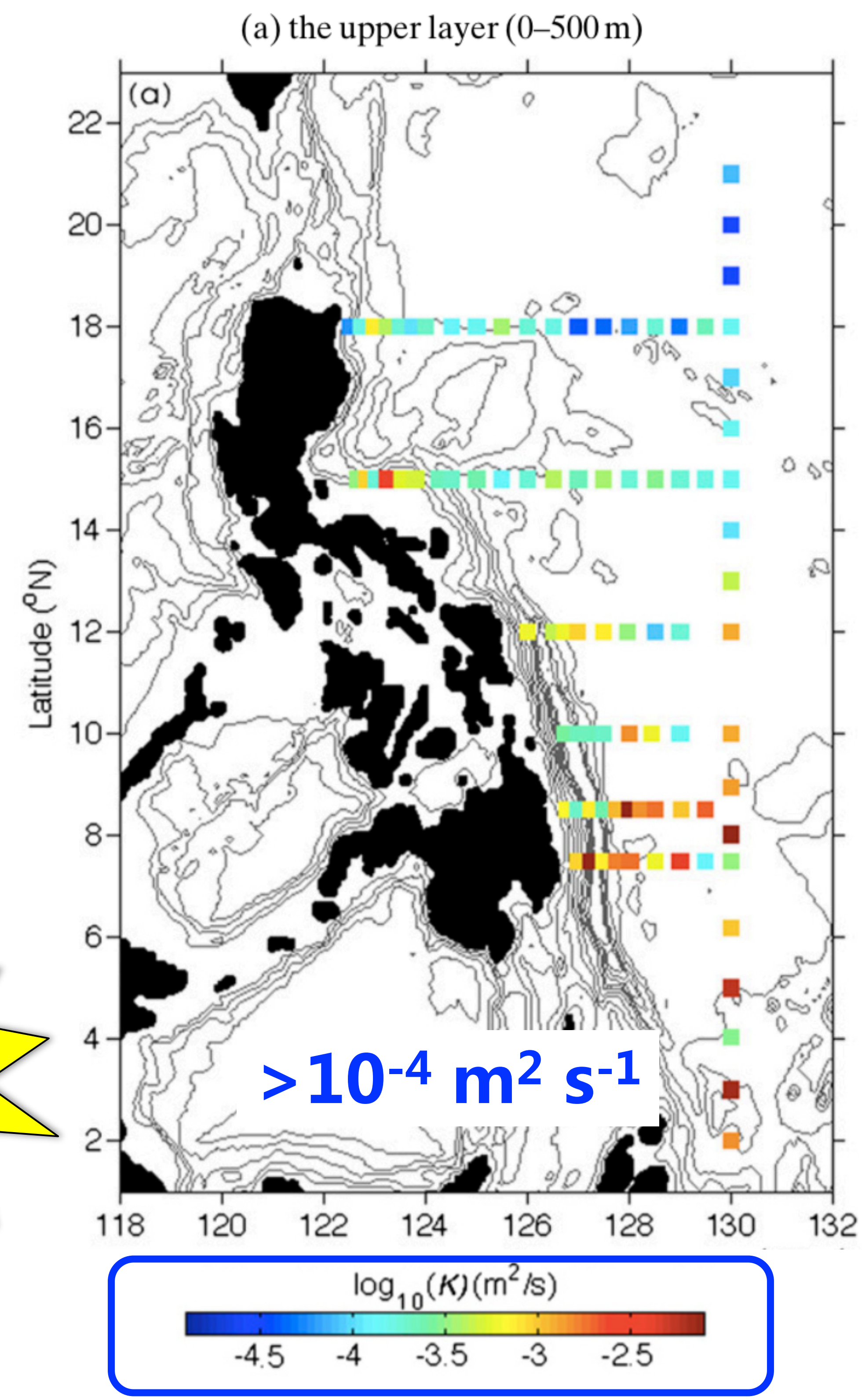
Polzin et al. (2014)



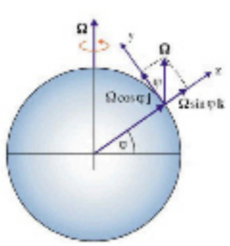
Fine-scale Parameterization of Ocean Turbulence

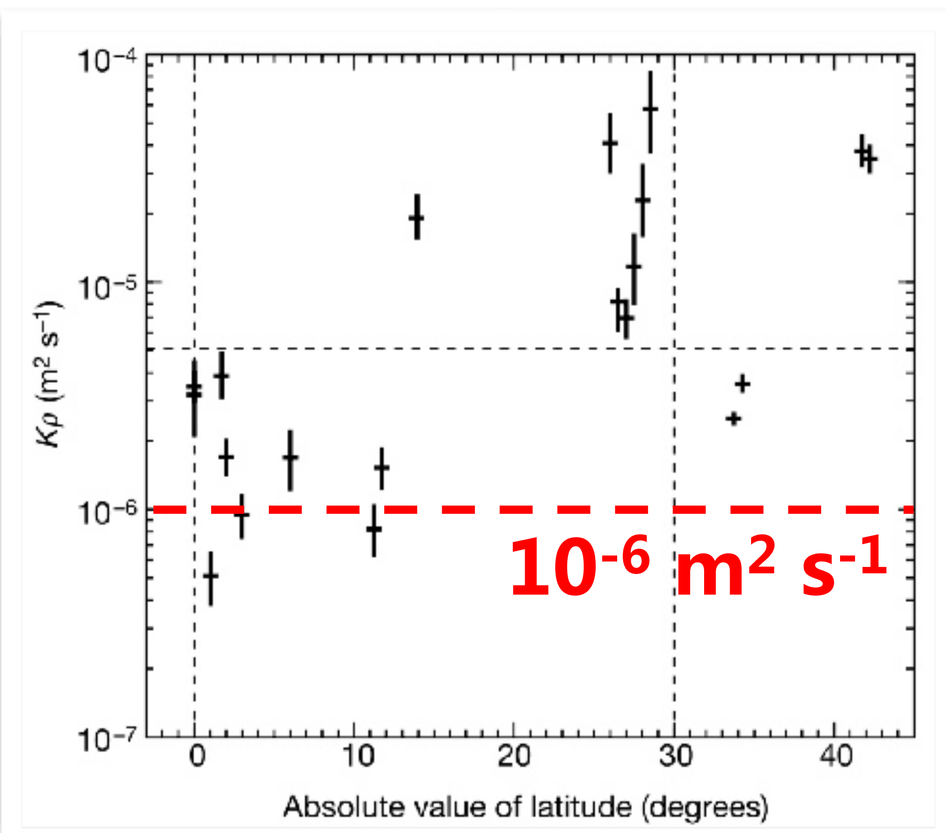


Whalen et al. (2015)



Yang et al. (2014)





Gregg et al. (2003)

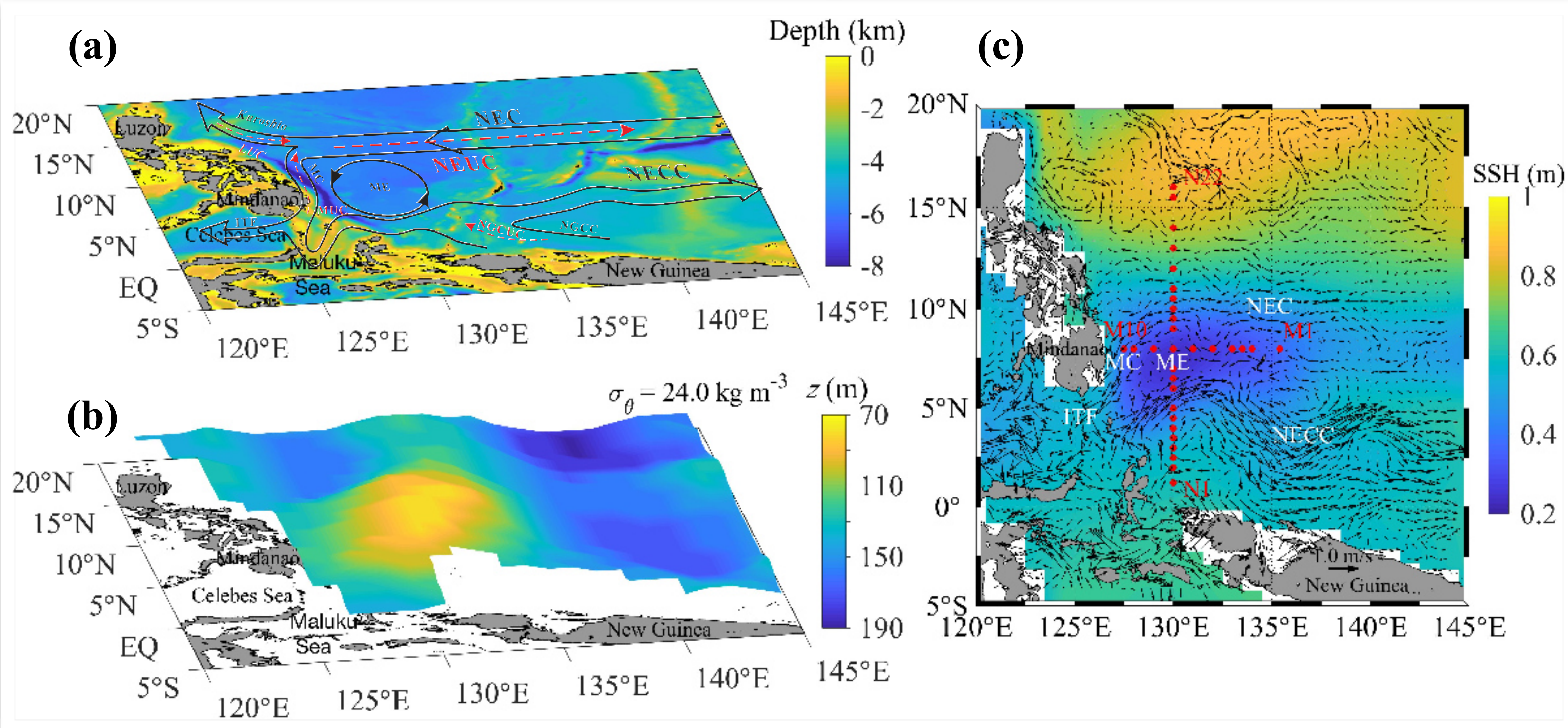
Thermocline Mixing at Low Latitudes

Geophysical Research Letters

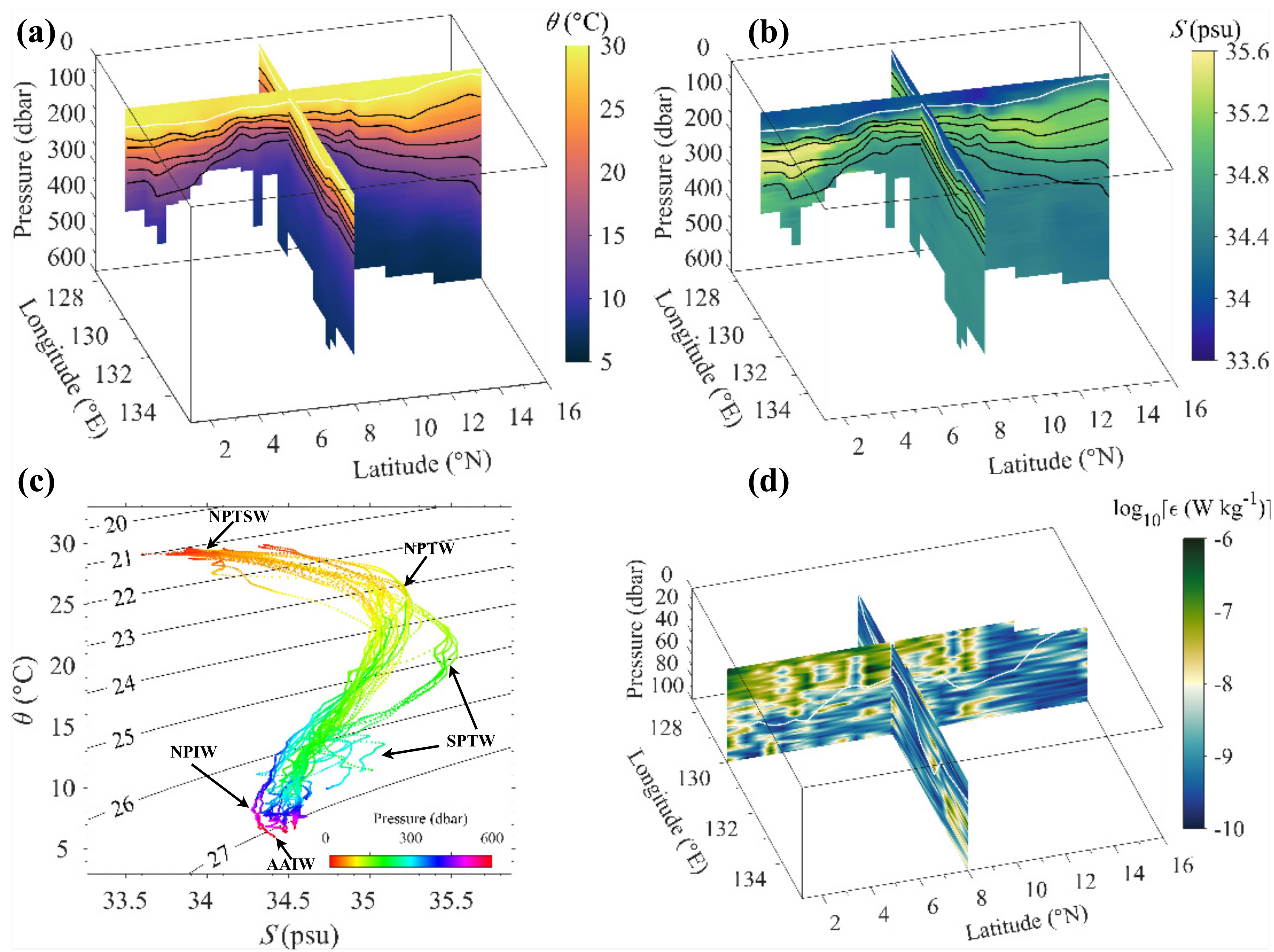
RESEARCH LETTER
10.1002/2017GL075210

Weak Thermocline Mixing in the North Pacific Low-Latitude Western Boundary Current System

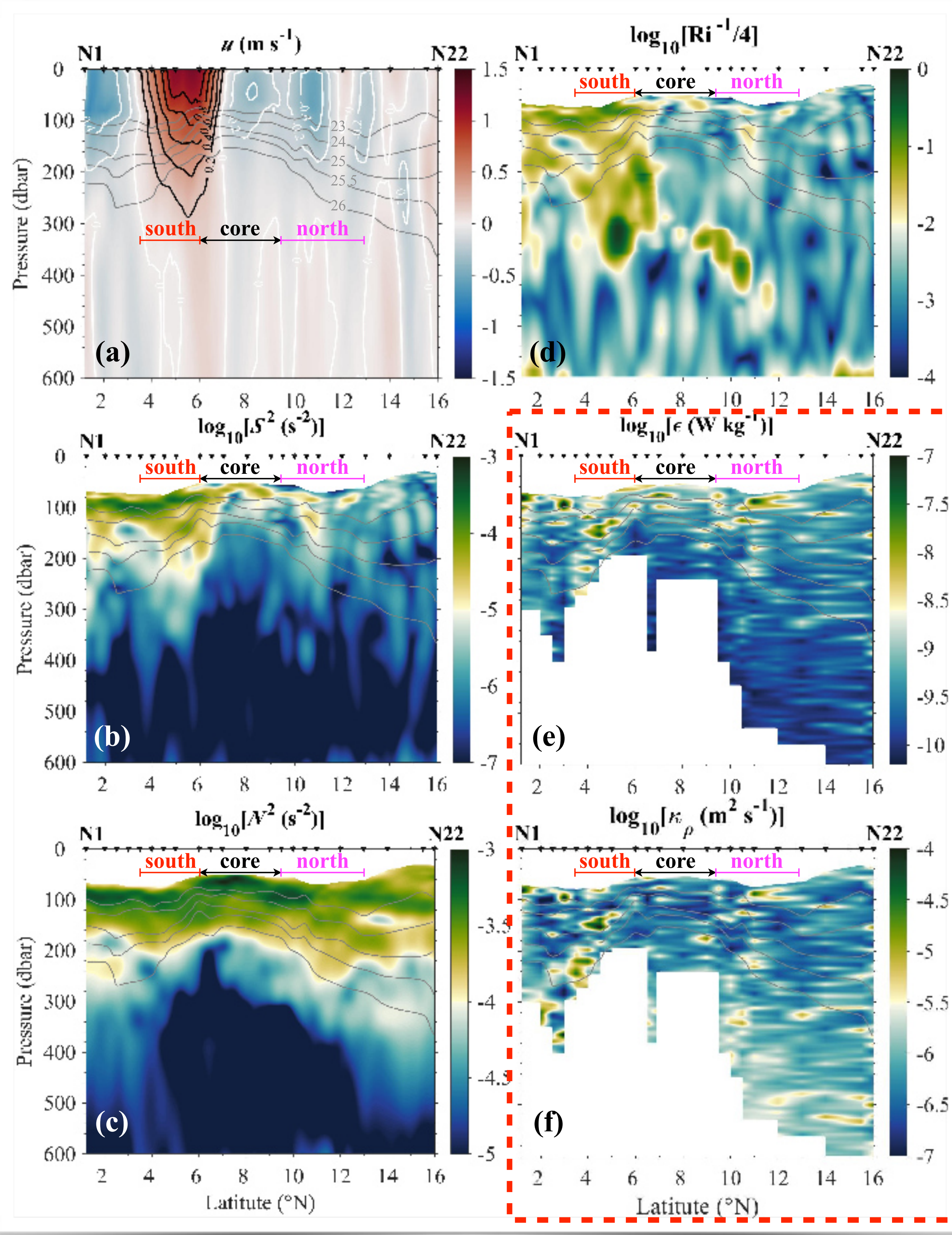
Thermocline Mixing in the North Pacific LLWBCs

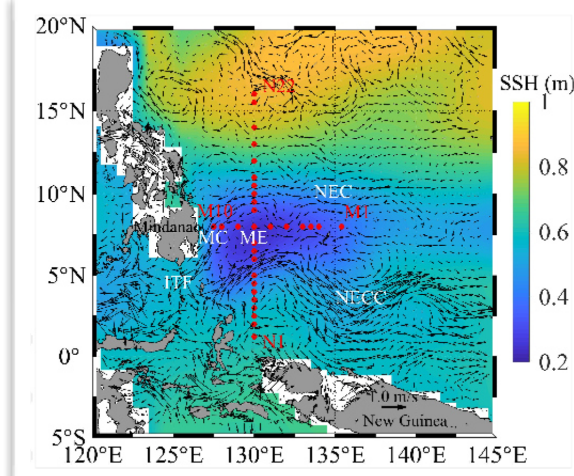


Thermocline Mixing in the North Pacific LLWBCs



Thermocline Mixing in the North Pacific LLWBCs





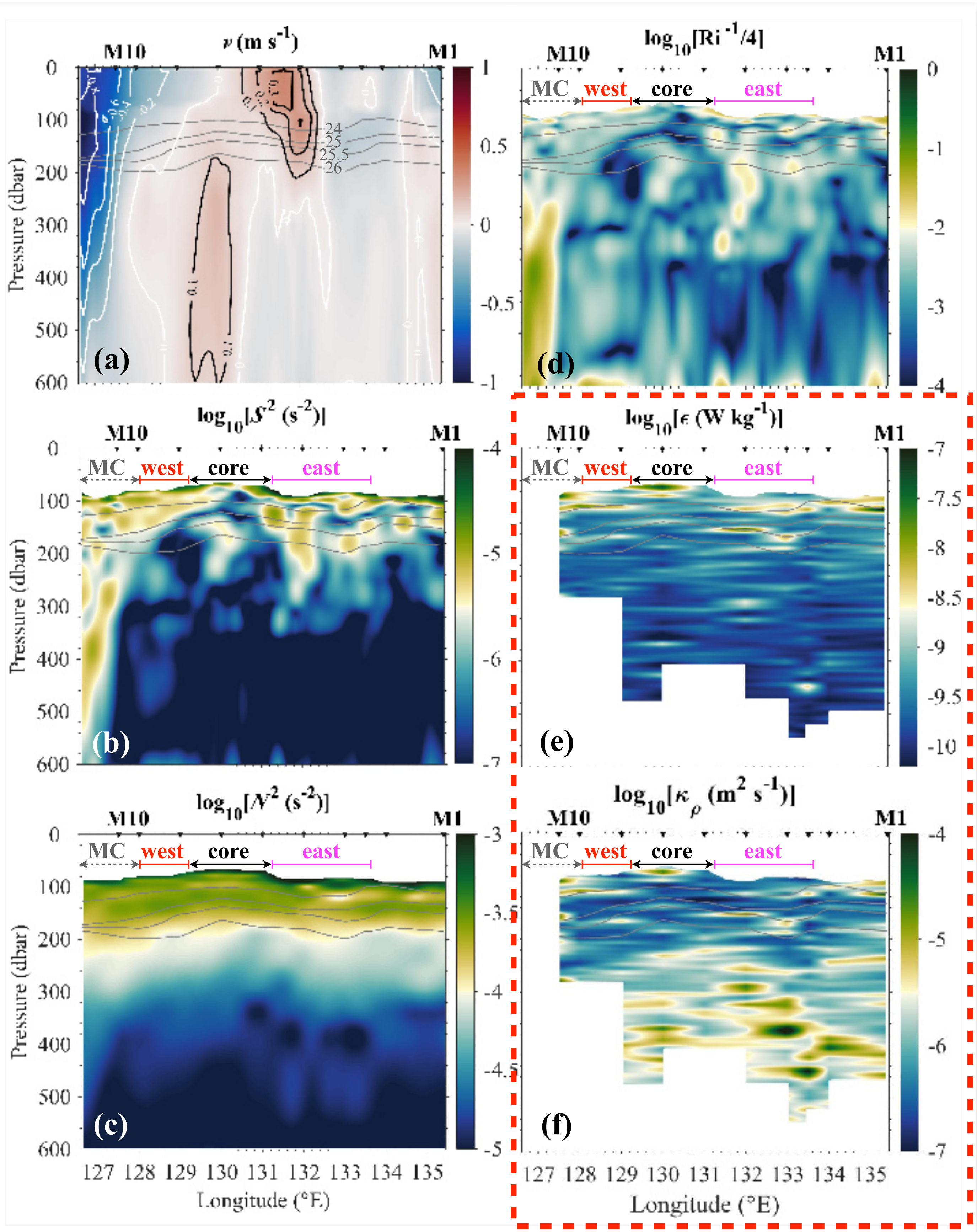
$< \varepsilon >$

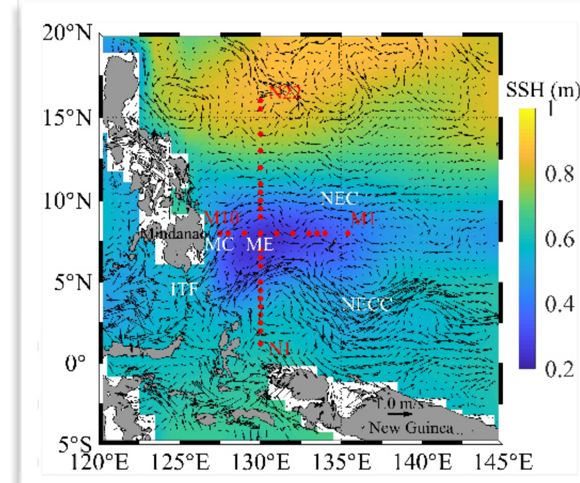
South Flank	3.0×10^{-8} W kg^{-1}
Background/Core	4.4×10^{-10} W kg^{-1}
North Flank	4.2×10^{-9} W kg^{-1}

$< \kappa_\rho >$

South Flank	2.9×10^{-5} m^2 s^{-1}
Background/Core	0.83×10^{-6} m^2 s^{-1}
North Flank	5.9×10^{-6} m^2 s^{-1}

Thermocline Mixing in the North Pacific LLWBCs





$< \varepsilon >$

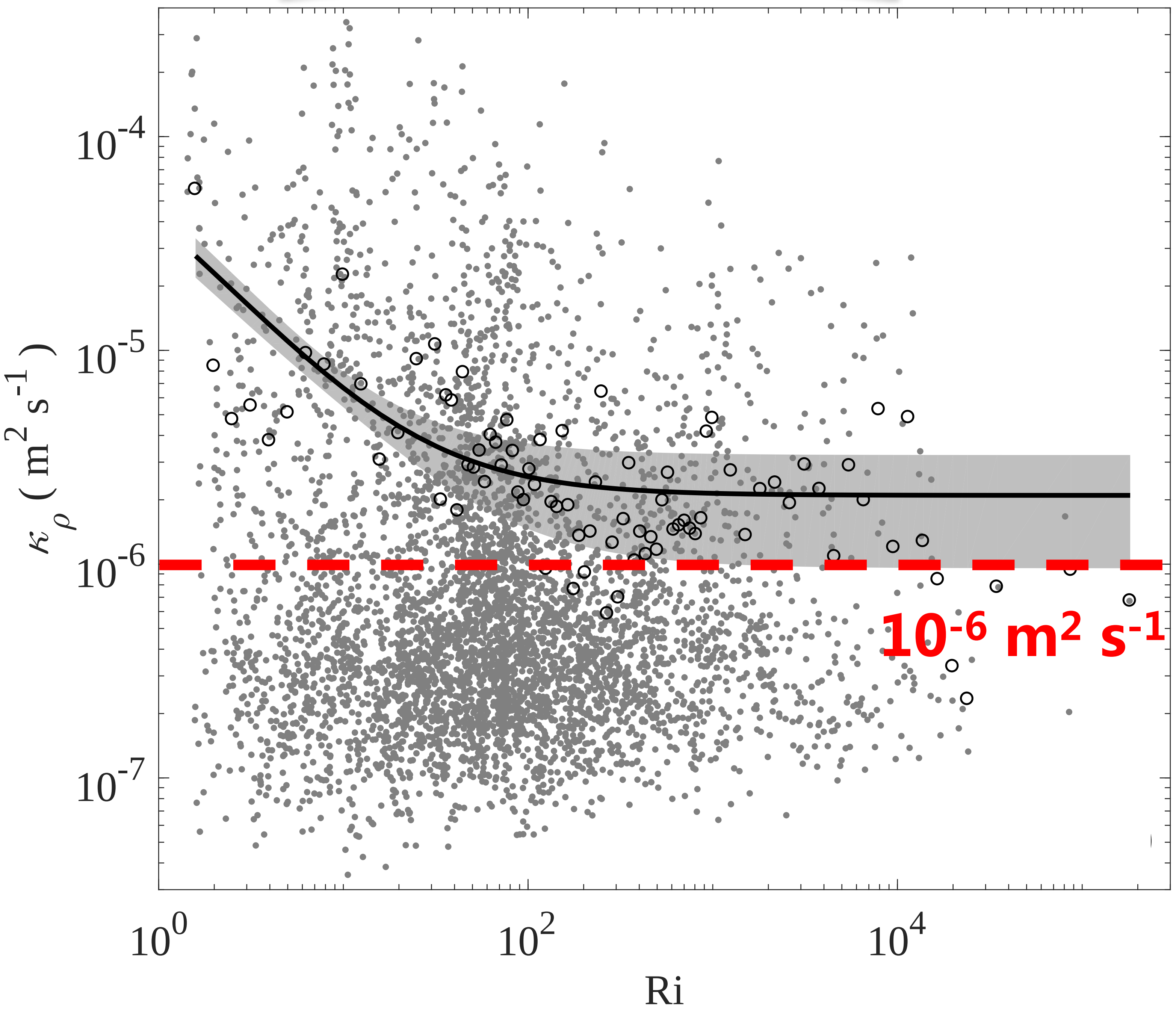
East Flank	2.0×10^{-9} W kg^{-1}
Background/Core	4.4×10^{-10} W kg^{-1}
West Flank	2.9×10^{-9} W kg^{-1}

$< \kappa_\rho >$

East Flank	1.4×10^{-6} m^2 s^{-1}
Background/Core	0.83×10^{-6} m^2 s^{-1}
West Flank	2.4×10^{-6} m^2 s^{-1}

Thermocline Mixing in the North Pacific LLWBCs

$$\kappa_\rho = \kappa_0 + \kappa_m (1 + \mathrm{Ri}/\mathrm{Ri}_c)^{-1}$$



$$\kappa_0 = 2.1 \times 10^{-6}\ \mathrm{m}^2\ \mathrm{s}^{-1}$$

$$\kappa_m = 1.9 \times 10^{-4}\ \mathrm{m}^2\ \mathrm{s}^{-1}$$

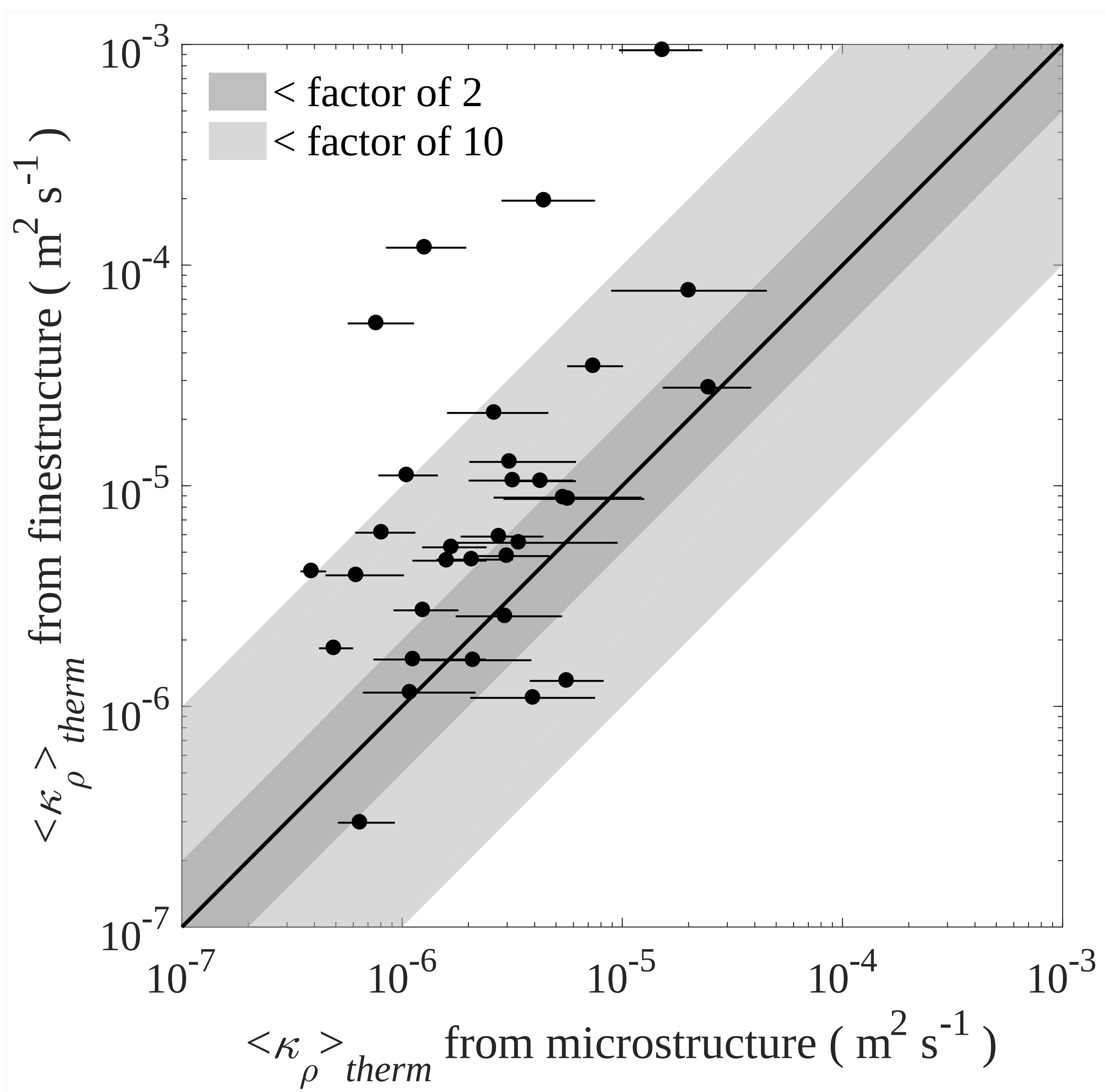
$$\mathrm{Ri}_c = 0.25$$

IW Breaking

+

Shear Turbulence

Thermocline Mixing in the North Pacific LLWBCs



Thermocline Mixing in the North Pacific LLWBCs

Key Points:

- Thermocline mixing in the North Pacific low-latitude western boundary current system is overall very weak
- Thermocline mixing at the south and north flanks of the Mindanao Eddy was elevated by an order of magnitude due to eddy-induced shear
- The oft-used fine-scale parameterization of turbulence seems to generally overestimate thermocline mixing in the North Pacific LLWBC

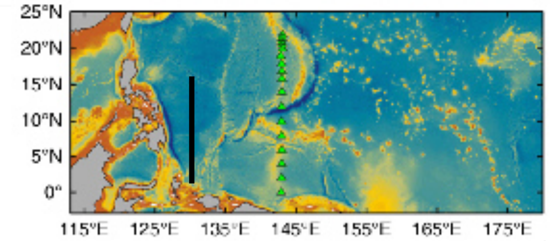
RESEARCH LETTER
10.1002/2017GL075210

Weak Thermocline Mixing in the North Pacific Low-Latitude Western Boundary Current System

Thermocline Mixing in the Tropical-Extratropical Pacific

nature COMMUNICATIONS

DOI: 10.1038/s41467-018-06260-8 OPEN



Latitude-dependent finescale turbulent shear generations in the Pacific tropical-extratropical upper ocean

Zhiwei Zhang[1], Bo Qiu[2], Jiwei Tian[1], Wei Zhao[1] & Xiaodong Huang[1]

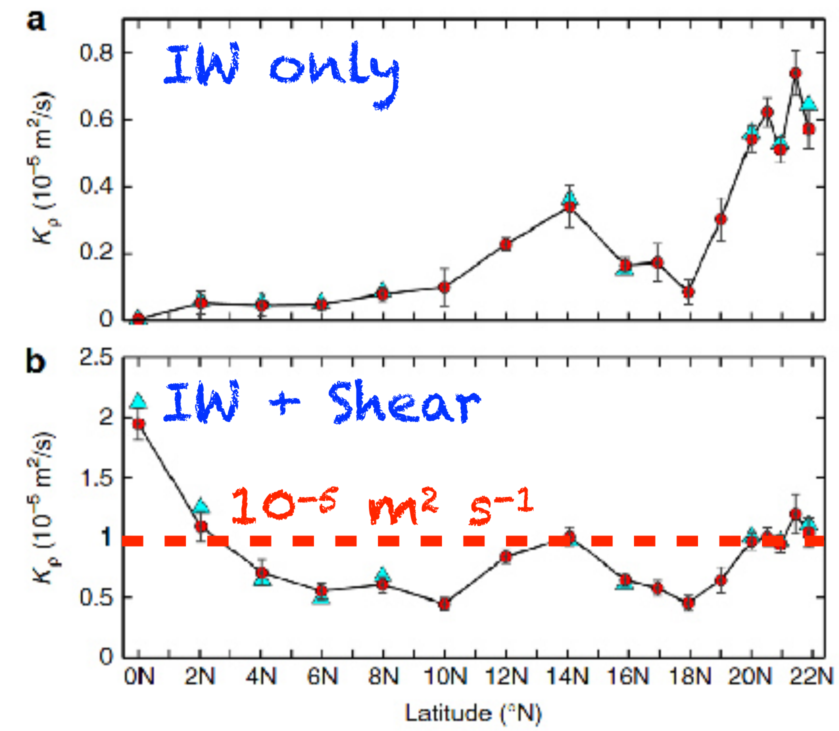


Fig. 8 Latitudinal distribution of the finescale parameterized K_ρ. **a** and **b** are the upper layer-averaged K_ρ estimated from the GHP and *Ri*-based methods, respectively.

Given that the GHP parameterization may be invalid for the equatorial region where turbulent mixing is closely related to the strongly sheared sub-inertial currents rather than the breaking of internal waves, we also adopted a straightforward Richardson number-based parameterization method[50,70] to independently estimate K_ρ. The formula is in the form of

$$K_\rho = K_0 + K_m \cdot (1 + Ri/Ri_c)^{-1}, \quad (5)$$

where $Ri_c = 1/4$ is the critical *Ri* value for shear instability, K_0 and K_m are the constant background diffusivity and maximum diffusivity, respectively. By analyzing dozens of microstructure profiles in the low-latitude northwestern Pacific, the recent study of Liu et al.[50] demonstrated that this finescale *Ri*-based parameterization can well approximate the observed K_ρ when choosing $K_0 = 2.1 \times 10^{-6}$ m² s^{-1} and $K_m = 1.9 \times 10^{-4}$ m² s^{-1} (determined by nonlinear least-square fit). Here, the same parameters proposed by Liu et al.[50] were used considering our similar study region. Similar to the results from the GHP method, using the

potential shear instabilities is found here (recall Fig. 4). These results are actually consistent with Liu et al.'s[50] analysis that in the equatorial region the turbulent shear (also mixing) is dominantly caused by the sub-inertial currents (recall Fig. 2), and therefore the principle of the GHP parameterization based on the internal wave-wave interaction theory is violated there. Con-

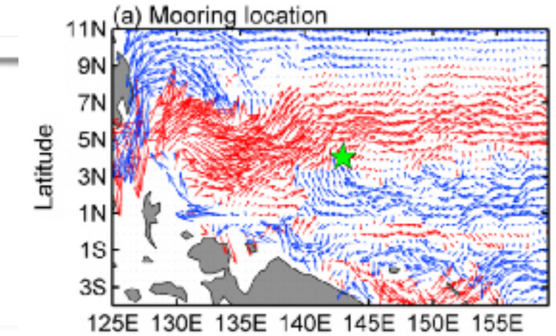
Thermocline Mixing in the Western Equatorial Pacific

Geophysical Research Letters

RESEARCH LETTER
10.1029/2018GL081512

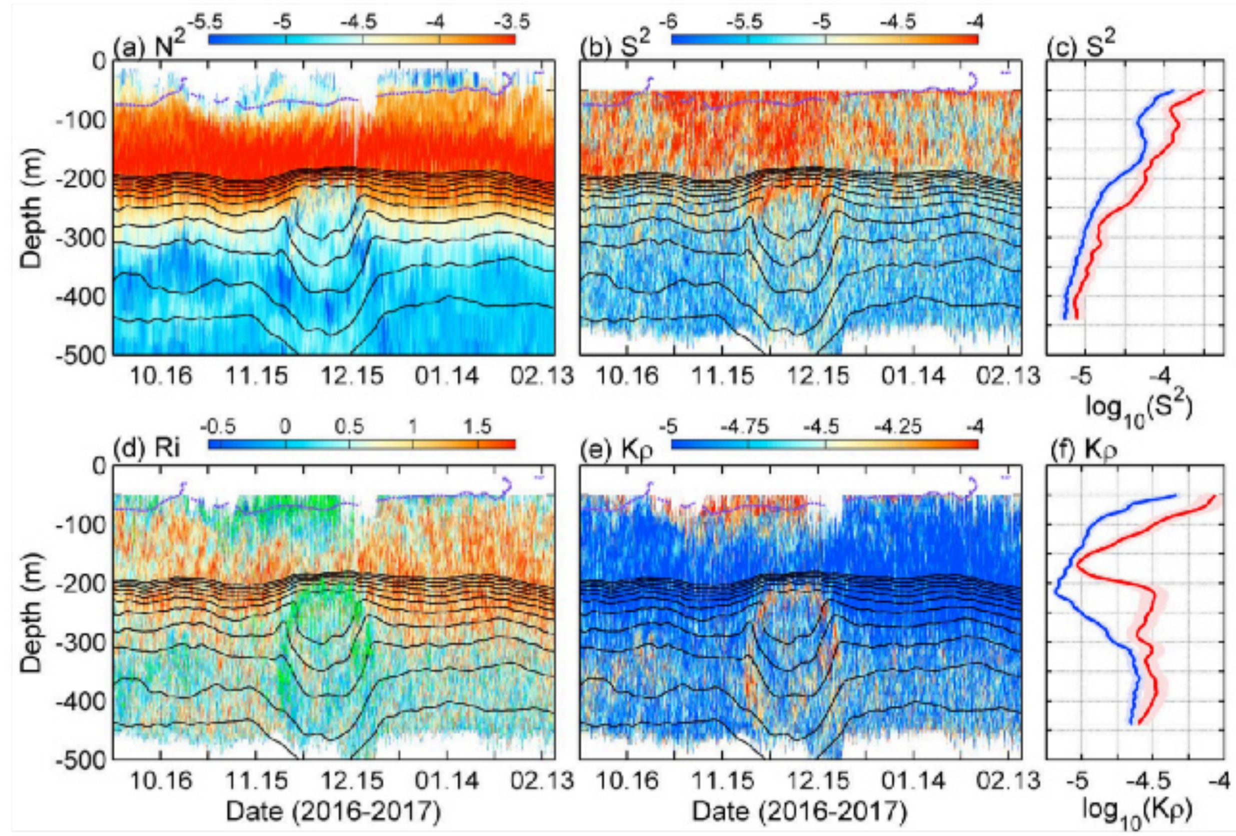
Elevated Diapycnal Mixing by a Subthermocline Eddy in the Western Equatorial Pacific

Zhiwei Zhang[1], Zhiyu Liu[2], Kelvin Richards[3], Gong Shang[1], Wei Zhao[1], Jiwei Tian[1], Xiaodong Huang[1], and Chun Zhou[1]



Key Points:

- An anticyclonic subthermocline eddy was documented by a mooring in the western equatorial Pacific
- The subthermocline eddy significantly elevated the thermocline mixing through shear instability with *Ri* < 1/4
- The subthermocline eddy acted as dynamic barrier for the downward penetration of wind-generated near-inertial energy



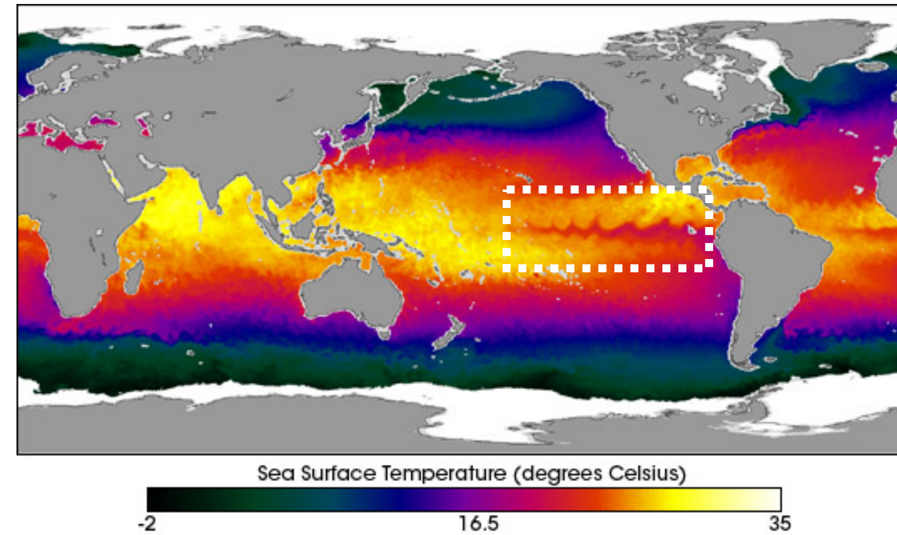
Thermocline Mixing in the Eastern Equatorial Pacific

nature COMMUNICATIONS

DOI: 10.1038/ncomms11576 OPEN

Deep-reaching thermocline mixing in the equatorial pacific cold tongue

Chuanyu Liu[1,2,3], Armin Köhl[1], Zhiyu Liu[4], Fan Wang[2,3] & Detlef Stammer[1]



Vertical mixing is an important factor in determining the temperature, sharpness and depth of the equatorial Pacific thermocline, which are critical to the development of El Ninõ and Southern Oscillation (ENSO). Yet, properties, dynamical causes and large-scale impacts of vertical mixing in the thermocline are much less understood than that nearer the surface. Here, based on Argo float and the Tropical Ocean and Atmosphere (TAO) mooring measurements, we identify a large number of thermocline mixing events occurring down to the lower half of the thermocline and the lower flank of the Equatorial Undercurrent (EUC), in particular in summer to winter. The deep-reaching mixing events occur more often and much deeper during periods with tropical instability waves (TIWs) than those without and under La Niña than under El Niño conditions. We demonstrate that the mixing events are caused by lower Richardson numbers resulting from shear of both TIWs and the EUC.

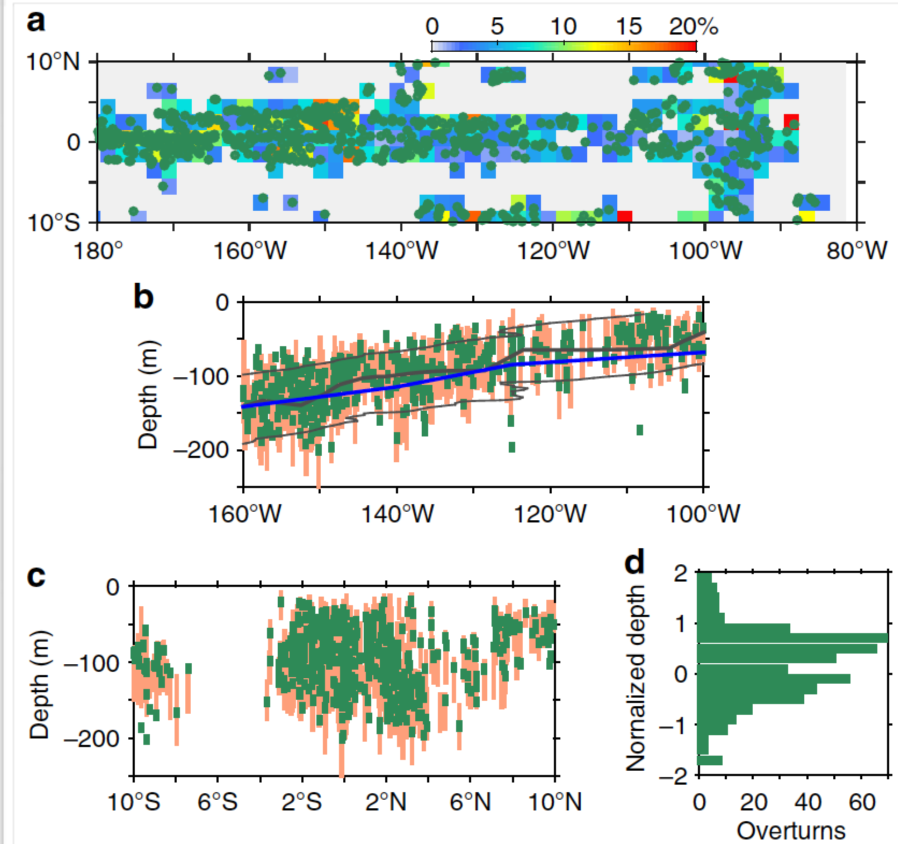


Figure 1 | Spatial distribution of detected density overturns in the equatorial Pacific cold tongue.

Thermocline Mixing in the Eastern Equatorial Pacific

Geophysical Research Letters

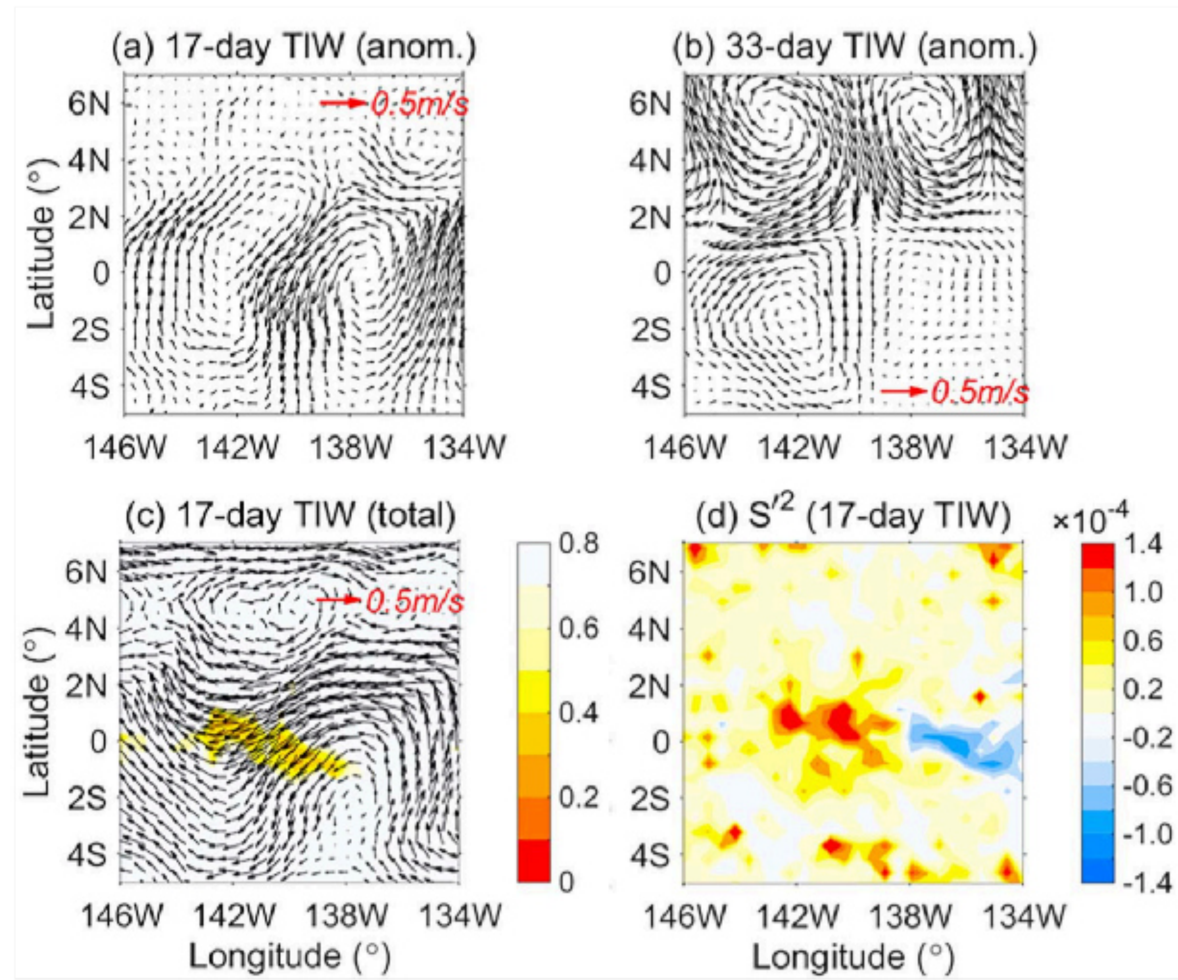
RESEARCH LETTER
10.1029/2018GL080226

The Northeast-Southwest Oscillating Equatorial Mode of the Tropical Instability Wave and Its Impact on Equatorial Mixing

Chuanyu Liu[1,2,3,4], Xiaowei Wang[1,2,3,4], Armin Köhl[5], Fan Wang[1,2,3,4], and Zhiyu Liu[6]

Key Points:

- At the equator, zonal velocity oscillations of the 17-day TIW are identified, in complement to the well-known meridional oscillations
- The resulting NE-SW oscillating, equatorial mode TIW differs from both the Yanai wave at the equator or the TIV north of the equator
- The westward anomalous velocities induce the strongest vertical shear in the subsurface ocean, favoring the equatorial turbulent mixing



Thermocline Mixing in the Eastern Equatorial Pacific

Geophysical Research Letters

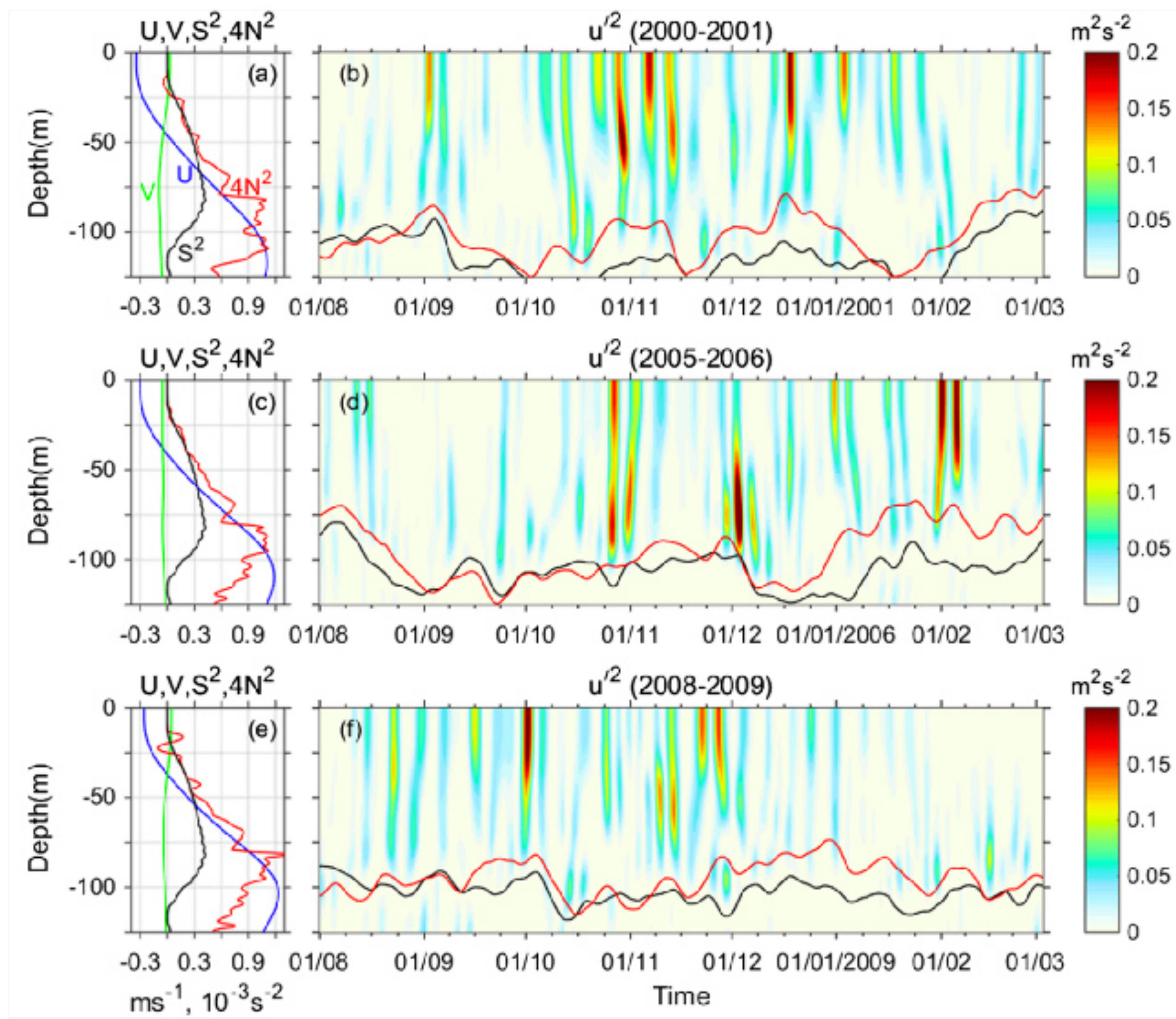
RESEARCH LETTER
10.1029/2019GL085123

The Subsurface Mode Tropical Instability Waves in the Equatorial Pacific Ocean and Their Impacts on Shear and Mixing

Chuanyu Liu[1,2,3,4], Liyuan Fang[1,2,3,4], Armin Köhl[5], Zhiyu Liu[6], William D. Smyth[7], and Fan Wang[1,2,3,4]

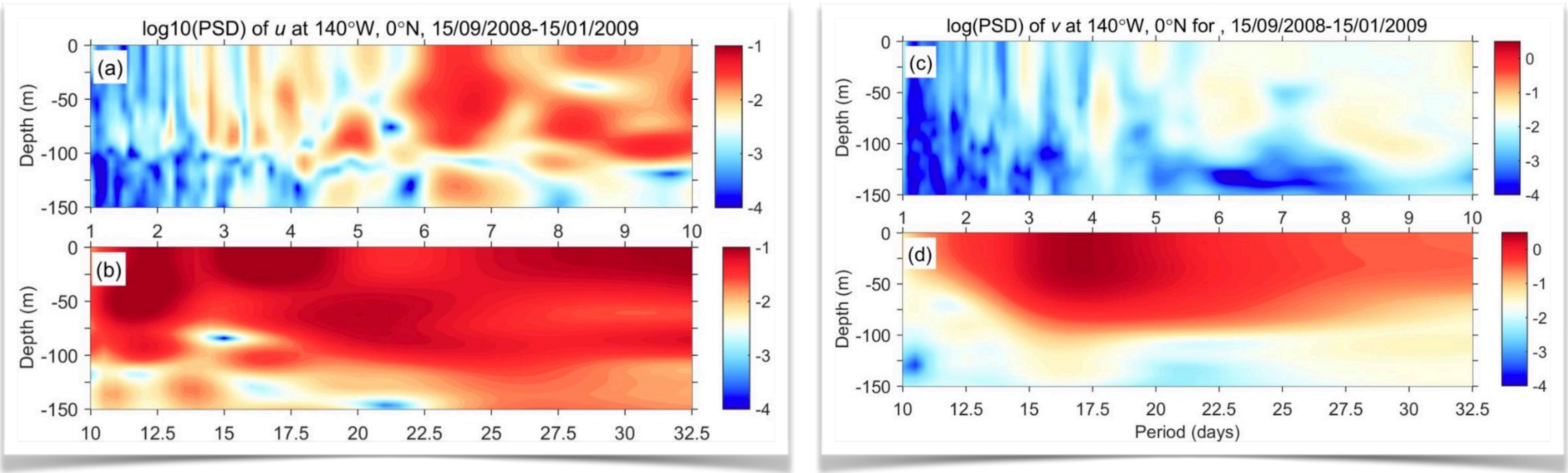
Key Points:

- Subsurface tropical instability waves, with zonal velocity oscillation peaking at 70–90 m, are identified in the eastern equatorial Pacific
- The waves have periods of 5–20 days and amplitudes of 0.1–0.2 m/s and can persist for 3–7 months from July to the following February
- The waves can induce periodically enhanced and reduced shear and hence mixing at ~50 m and above the core of the Equatorial Undercurrent



To Be Continued…

Interplays of multi-timescale equatorial waves



Take-home Message

Thermocline mixing at low latitudes

is generally

weak

Additional mixing is due to shear turbulence

Mixing parameterization

is developed

parameterization can be easily adopted

into

models


Thank you!
TAN KAH KEE
Zhiyu Liu (zyliu@xmu.edu.cn)