Virtual European Physical Oceanography and Shelf Sea Seminars

On Thermocline Mixing at Low Latitudes

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Talley et al. (2011)

海洋中的流动处于湍流状态

The Turbulent Ocean

Huang (2012)
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

\[
\frac{\partial k}{\partial t} + \frac{u_j}{\partial x_j} \frac{\partial k}{\partial x_j} = \frac{1}{\rho_0} \frac{\partial u_i' p'}{\partial x_i} - \frac{1}{2} \frac{\partial u_i' u_j' u_i'}{\partial x_i} + \nu \frac{\partial^2 k}{\partial x_j^2} - \frac{u_i' u_j'}{\partial x_j} \frac{\partial u_i}{\partial x_j} - \nu \frac{\partial u_i'}{\partial x_j} \frac{\partial u_i'}{\partial x_j} - \frac{g}{\rho_0} \frac{\rho' u_i' \delta_{i3}}{\delta_{i3}}
\]

- Local derivative
- Advection
- Pressure diffusion
- Turbulent transport \( \mathcal{T} \)
- Molecular viscous transport
- Production \( \mathcal{P} \)
- Dissipation \( \varepsilon_k \)
- Buoyancy flux \( b \)

Energy-containing scale | Inertial subrange | Dissipation subrange
---|---|---
\( \phi(k) \) [m² s⁻² cpm]

\( k \) (cpm)

\( \varepsilon_{\text{ADV}} = 1.5 \times 10^{-7} \) W kg⁻¹

\( \varepsilon_{\text{MSS}} = 1.8 \times 10^{-8} \) W kg⁻¹

Liu (2009)

“Duality” of Ocean Turbulence

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

Lozovatsky et al. (2017)
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 $\varepsilon$, the dissipation rate of turbulent kinetic energy, as a function of resolvable properties (in measurements/model), i.e.

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

**Garrett (2003)**

**Polzin et al. (2014)**
Fine-scale Parameterization of Ocean Turbulence

Whalen et al. (2015)

Average Dissipation Rate 250–500m [Wkg⁻¹]

Gregg et al. (2003)

Yang et al. (2014)

10⁻⁶ m² s⁻¹

>10⁻⁴ m² s⁻¹
Thermocline Mixing at Low Latitudes

Geophysical Research Letters

RESEARCH LETTER

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

10.1002/2017GL075210
Thermocline Mixing in the North Pacific LLWBCs
Thermocline Mixing in the North Pacific LLWBCs
Thermocline Mixing in the North Pacific LLWBCs

(a) South Flank
(b) Background/Core
(c) North Flank

Thermocline Mixing

South Flank: 3.0 \times 10^{-8} \text{ W kg}^{-1}
Background/Core: 4.4 \times 10^{-10} \text{ W kg}^{-1}
North Flank: 4.2 \times 10^{-9} \text{ W kg}^{-1}

South Flank: 2.9 \times 10^{-5} \text{ m}^2 \text{ s}^{-1}
Background/Core: 0.83 \times 10^{-6} \text{ m}^2 \text{ s}^{-1}
North Flank: 5.9 \times 10^{-6} \text{ m}^2 \text{ s}^{-1}
Thermocline Mixing in the North Pacific LLWBCs

(a) M10 $v$ (m s$^{-1}$)

(b) M10 $\log_{10}[S^2$ (s$^{-2}$)]

(c) M10 $\log_{10}[\rho^2$ (kg m$^{-3}$)]

(d) M10 $\log_{10}[\text{Ri}^{-1/4}]$

(e) M10 $\log_{10}[\kappa$ (m$^2$ s$^{-1}$)]

(f) M10 $\log_{10}[\kappa$ (m$^2$ s$^{-1}$)]

East Flank 2.0 x 10$^{-9}$ W kg$^{-1}$

Background/Core 4.4 x 10$^{-10}$ W kg$^{-1}$

West Flank 2.9 x 10$^{-9}$ W kg$^{-1}$

$\langle \varepsilon \rangle$

$\langle K_\rho \rangle$

East Flank 1.4 x 10$^{-6}$ m$^2$ s$^{-1}$

Background/Core 0.83 x 10$^{-6}$ m$^2$ s$^{-1}$

West Flank 2.4 x 10$^{-6}$ m$^2$ s$^{-1}$
Thermocline Mixing in the North Pacific LLWBCs

\[ \kappa_\rho = \kappa_0 + \kappa_m (1 + \frac{\text{Ri}}{\text{Ri}_c})^{-1} \]

\[ \kappa_0 = 2.1 \times 10^{-6} \text{ m}^2 \text{ s}^{-1} \]

\[ \kappa_m = 1.9 \times 10^{-4} \text{ m}^2 \text{ s}^{-1} \]

\[ \text{Ri}_c = 0.25 \]

IW Breaking + Shear Turbulence
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.
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\(^1\)

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 \(K_p\). The formula is in the form of

\[
K_p = K_0 + K_m \cdot (1 + Ri/R_{c})^{-1},
\]

where \(R_{c} = 1/4\) 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 \(K_p\) when choosing \(K_0 = 2.1 \times 10^{-6} \text{ m}^2 \text{ s}^{-1}\) and \(K_m = 1.9 \times 10^{-4} \text{ m}^2 \text{ s}^{-1}\) (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

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

Zhiwei Zhang¹, Zhiyu Liu², Kelvin Richards³, Gong Shang¹, Wei Zhao¹, Jiwei Tian¹, Xiaodong Huang¹, and Chun Zhou¹

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

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 Niño 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

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

Chuanyu Liu¹,²,³,⁴ ID, Xiaowei Wang¹,²,³,⁴ ID, Armin Köhl⁵ ID, Fan Wang¹,²,³,⁴ ID, and Zhiyu Liu⁶ ID

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
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The Subsurface Mode Tropical Instability Waves in the Equatorial Pacific Ocean and Their Impacts on Shear and Mixing
Chuanyu Liu¹,²,³,⁴, Liyuan Fang¹,²,³,⁴, Armin Köhl⁵, Zhiyu Liu⁶, William D. Smyth⁷, and Fan Wang¹,²,³,⁴

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…
Take-home Message

- Thermocline mixing at low latitudes sustained by breaking of background internal waves is generally weak, due to inefficient energy transfer through internal wave-wave interactions;

- Additional mixing is due to shear turbulence fertilized by sheared currents, eddies (surface & subsurface), and waves (e.g., tropical instability waves of different types/modes/frequencies);

- Mixing parameterization incorporating impacts of both internal wave breaking and shear turbulence to characterize variability of thermocline mixing at low latitudes is developed;

- The resulting parameterization can be easily adopted into regional (& global) ocean and climate models.
Thank you!

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