Turbulent mixing in the Indonesian throughflow exit passages, the Lesser Sunda waters

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November 24, 2022

Abstract

Turbulent kinetic energy dissipation rates in the Indonesian throughflow (ITF) exit passages to the Indian Ocean, the Lesser Sunda waters, are inferred from archived CTD measurements and recent high-resolution time series data sets. Dissipation rates from archived data sets are inferred using an improved Thorpe scale method validated against microstructure measurements. Elevated dissipation rates ~[10-6-10-7] m2s-3 were observed in the straits, where internal tides are generated. Tidal variations seemingly influence the dissipation rates and diffusivities as has been suggested from the yoyo profiling data sets. The spatial pattern of dissipation rates inferred from the high-resolution 3D hydrodynamics model output of Nagai et al (2015) shows a general agreement with the observations in the location of the mixing hot spots and suggests that the M2 internal tide is the dominant factor driving the turbulent kinetic dissipation rates in this region. The bias in the model is possible due to the lack of representation of the ITF and mesoscale circulation in the model.

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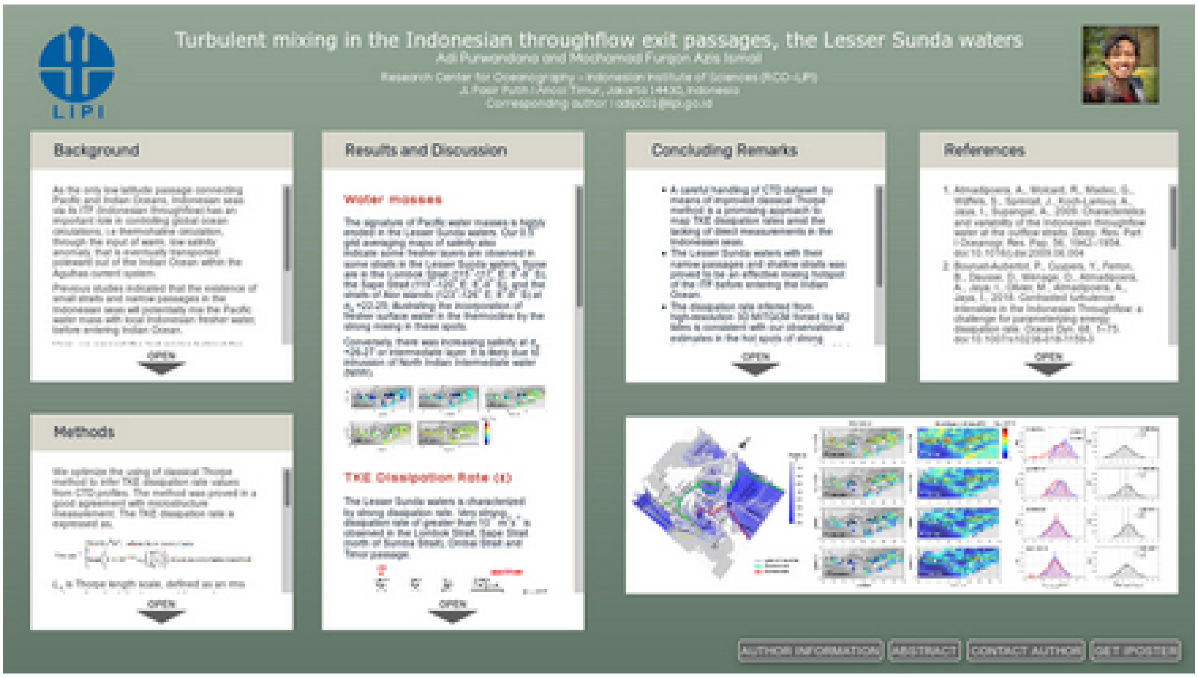

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PRESENTED AT:

JpGU - AGU Joint Meeting 2020
For a Borderless World of Geoscience
Japan Geoscience Union, American Geophysical Union

BACKGROUND

As the only low latitude passage connecting Pacific and Indian Oceans, Indonesian seas via its ITF (Indonesian throughflow) has an important role in controlling global ocean circulations, i.e thermohaline circulation, through the input of warm, low salinity anomaly, that is eventually transported poleward out of the Indian Ocean within the Agulhas current system.

Previous studies indicated that the existence of small straits and narrow passages in the Indonesian seas will potentially mix the Pacific water mass with local Indonesian fresher water, before entering Indian Ocean.

Here, we present the last mixing hotspot for the ITF before entering the Indian Ocean, i.e the Lesser Sunda waters which is the exit passages of the ITF.

Lack of direct turbulence measurements in the Indonesian seas has led us to apply an indirect Thorpe scale method to infer dissipation rates and diapycnal diffusivities using CTD profiles obtained from annual RCO-LIPI cruises.

METHODS

We optimize the using of classical Thorpe method to infer TKE dissipation rate values from CTD profiles. The method was proved in a good agreement with microstructure measurement. The TKE dissipation rate is expressed as,

$$\varepsilon_{Th-GM} = \begin{cases} 0.64{L_T}^2N^3, & \text{when there is overturn} \\ \max\left(1\times10^{-10}, \varepsilon_0\left(\frac{N^2}{{N_0}^2}\right)\right), & \text{when no overturn observed} \end{cases}$$

L_T is Thorpe length scale, defined as an rms value of vertical displacement for each turbulent patch to gain gravitationally stable density profile, N is buoyancy frequency, 1×10^{-10} is the lowest dissipation rate, defined based on the typical minimum dissipation rate observed by microstructure measurements, $\varepsilon_0 = 7\times10^{-10}$ m^2 s^{-3} and $N_0 = 3$ cph are the canonical Garret and Munk dissipation rate and respected buoyancy frequency reference, respectively. The final dissipation rate termed as $\varepsilon_{Th\text{-}GM}$ will give a continuous profile of the dissipation rate as opposed to the standard Thorpe method.

Once the dissipation rate is estimated, turbulent diffusivity can be determined as,

$$K_{\rho\,Th-GM} = \Gamma\frac{\varepsilon_{Th-GM}}{N^2}$$

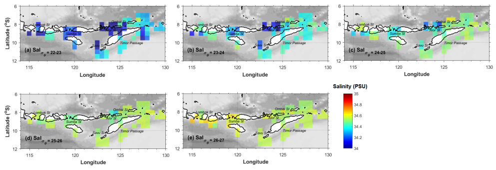
To inspect the spatial variability of hydrography and turbulent kinetic energy dissipation rates which is related to the potency of mixing events, we built maps by gridding horizontally the data over 0.5° and by vertical averaging over several depth intervals of 50-300 m, 300-500 m, 500-800 m, 800-1000 m, which represent the upper thermocline, lower thermocline, intermediate layer, and deeper layer.

RESULTS AND DISCUSSION

Water masses

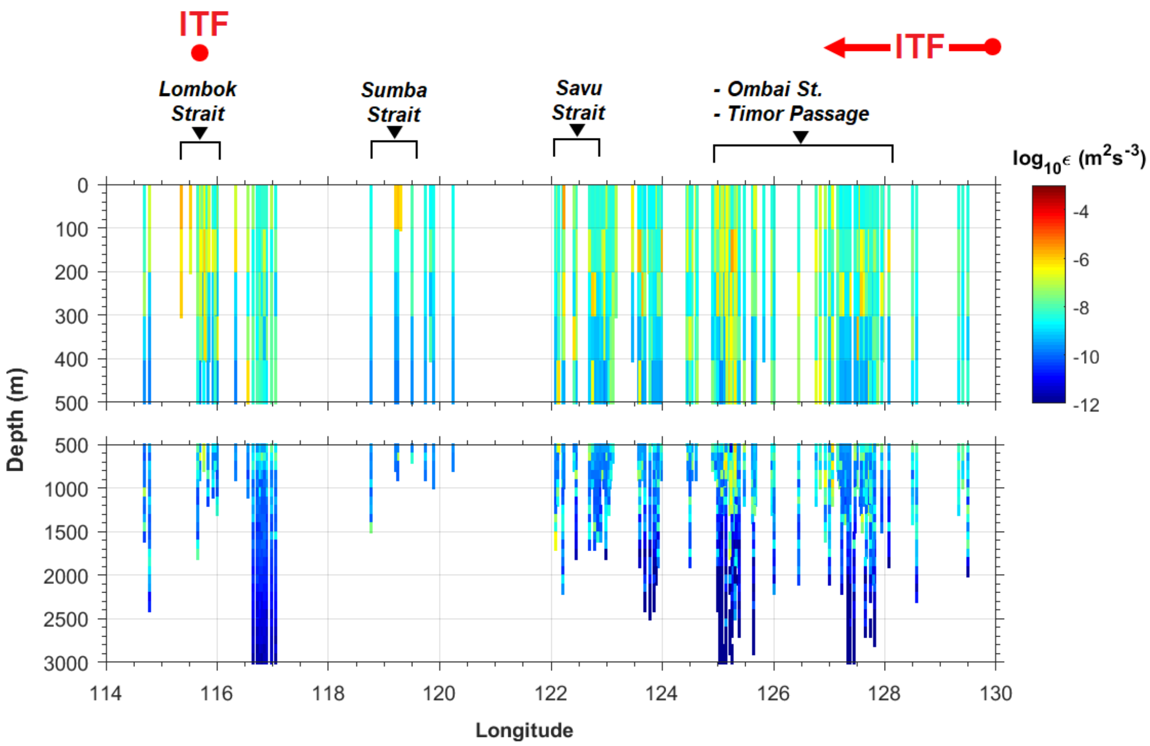
The signature of Pacific water masses is highly eroded in the Lesser Sunda waters. Our 0.5^o grid averaging maps of salinity also indicate some fresher layers are observed in some straits in the Lesser Sunda waters, those are in the Lombok Strait (115^o-117^o E; 8^o-9^o S), the Sape Strait (119^o-120^o E; 8^o-9^o S), and the straits of Alor islands (123^o-126^o E; 8^o-9^o S) at σ_θ =22-25; illustrating the incorporation of fresher surface water in the thermocline by the strong mixing in these spots.

Conversely, there was increasing salinity at σ_θ=26-27 or intermediate layer. It is likely due to intrussion of North Indian Intermediate water (NIIW).

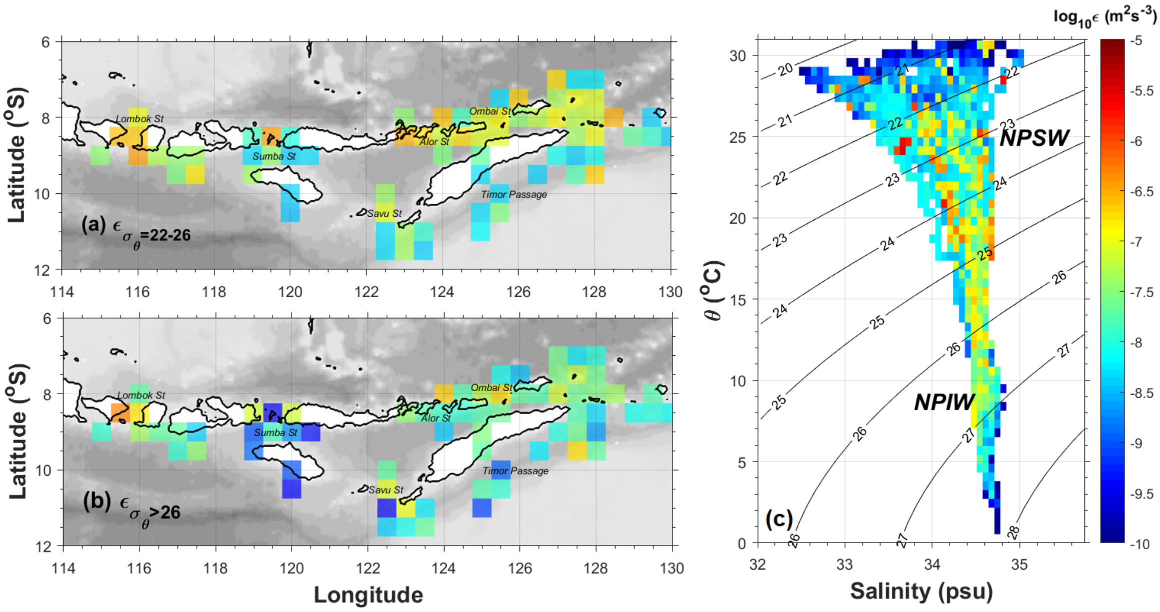


TKE Dissipation Rate (ε)

The Lesser Sunda waters is characterized by strong dissipation rate. Very strong dissipation rate of greater than 10^{-7} m^{2}s^{-1} is observed in the Lombok Strait, Sape Strait (north of Sumba Strait), Ombai Strait and Timor passage.

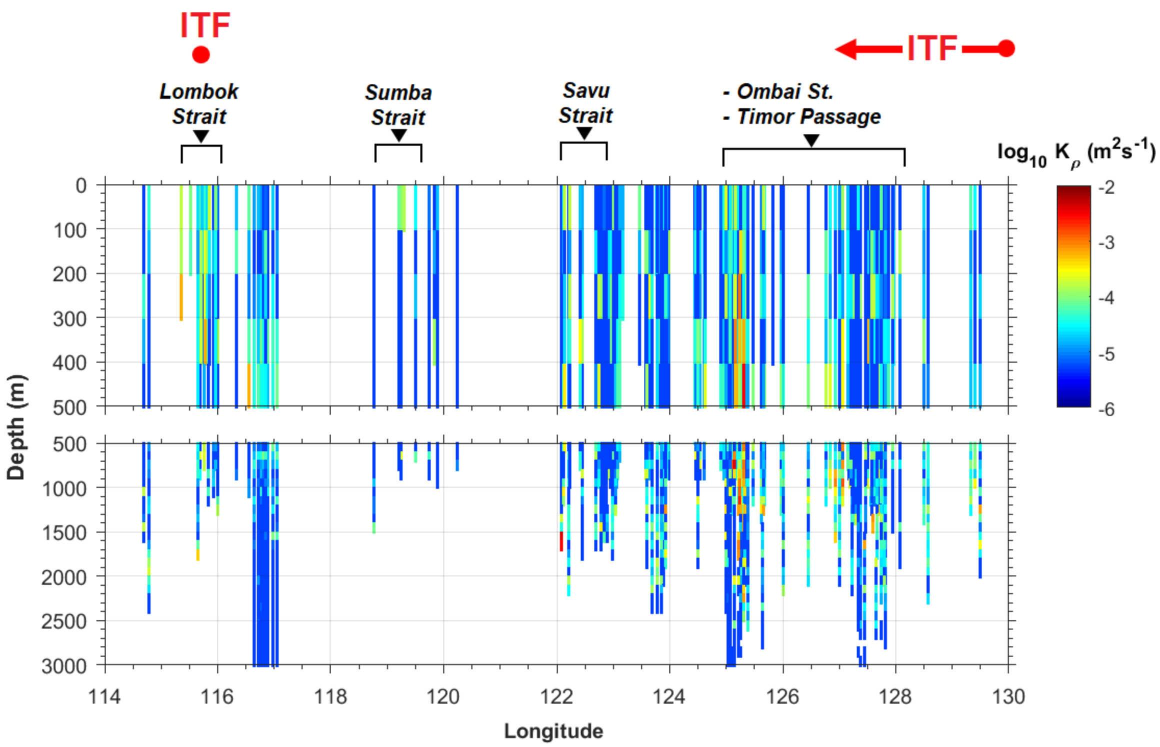


These strong TKE dissipation rates will potentially reduce the Pacific thermocline layer (North Pacific Subtropical Water, NPSW) signature.

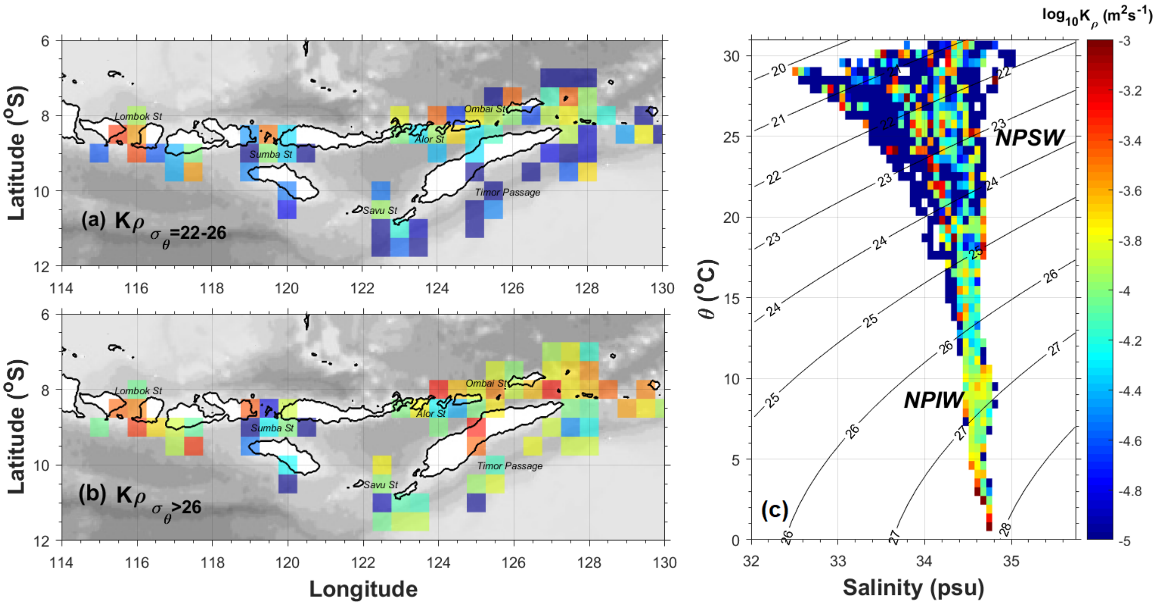


Vertical Eddy Diffusivity (K_ρ)

We found an increasing value of K_ρ with depth due to the decrease of stratification at depth. Large vertical diffusivities greater than 10^{-3} $m^{-2}s^{-1}$ are observed in Ombai Strait .



The mean values are above typical open ocean value of $1x10^{-5}$ m^2s^{-1}. The median of the distribution shifts toward higher values with increasing depth as a result of the decreasing stratification. The highest values were observed in the deeper layer [800-2000] m with a mean and a median of $1.6x10^{-3}$ m^2s^{-1} m^2s^{-3} and $2.7x10^{-4}$ m^2s^{-1}, respectively.



Comparison with Model

We compared our observation based TKE dissipation rate with Nagai and Hibiya (2015) 3D Hydrostatic MITGC model. In both model and observations, the same trends are observed where the dissipation rates are relatively high in this region.

The ratio between the gridded observed dissipation rates and the gridded model-based estimates remains below an order of ten.

CONCLUDING REMARKS

- A careful handling of CTD dataset by means of improved classical Thorpe method is a promising approach to map TKE dissipation rates amid the lacking of direct measurements in the Indonesian seas.
- The Lesser Sunda waters with their narrow passages and shallow straits was proved to be an effective mixing hotspot of the ITF before entering the Indian Ocean.
- The dissipation rate inferred from high-resolution 3D MITGCM forced by M2 tides is consistent with our observational estimates in the hot spots of strong turbulence, suggesting the baroclinic tidal energy dissipation is the main driving mechanisms working in this area.
- Direct measurements using microstructure profiler is needed in the future to validate this indirect Thorpe method.

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