Turbulent mixing process in the Lombok Strait

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Abstract. Turbulent mixing process in the Lombok Strait was evaluated from density inversions in CTD (Conductivity Temperature Depth) profiles obtained from the INSTANT (International Nusantara Stratification and Transport) recovery cruise, June 14-19th, 2005. The quality of the detected-overturn regions has been improved by applying wavelet denoising to CTD signals. The Thorpe analysis shows that many overturn regions less than 7 m were detected in throughout the water column of the Lombok Strait. Based on linear relationship between Thorpe Scale and Ozmidov Scale, the turbulent kinetic energy dissipation rate $\varepsilon$ was estimated about $10^{-12}$-$10^{-6}$ W kg$^{-1}$ and density of eddy diffusivity $K_{\rho}$ ($10^{-6}$-$10^{-2}$ m$^2$s$^{-1}$). A relatively high of $K_{\rho}$ $\Theta$ ($10^{-2}$ m$^2$s$^{-1}$) was found at the southern part of the strait, near the sill which obstruct the Indonesian Throughflow into the Indian Ocean. The dipped and rebounded isopycnal surfaces of $\sigma_\theta = 25.5$–26.5 near the sill and the presence of strong shear at the same depth of the interval solitary wave (150 to 250 m) indicate that strong turbulence in this layer was driven by shear instability associated with breaking internal waves.

Keywords: internal wave, Lombok Strait, turbulent mixing

1. Introduction

Internal Indonesian seas are semi-enclosed seas that has strong baroclinic tidal to form Indonesian Throughflow (ITF) water mass as a unique character, e.g. [1, 2, 3]. By using tidal model [3] found that the energy of baroclinic tides remains trapped inside Indonesia seas being a main source of mixing process. According to [4], Indonesian archipelago is one of the world’s largest internal tides generation sites and the dominant driving force for turbulence is the M$2$ of internal tide.

As the exit gateway from ITF western route, the Lombok Strait contributes significantly in transforming the ITF water mass. Strong turbulent mixing is expected to be high due to the active regions of internal tidal wave. The strong internal tidal wave generation in Lombok Strait is caused by the presence of stratified water column, rough bottom topography and strong tidal currents [5].

The internal tidal wave in the Lombok Strait has been detected using satellite images and model [5, 6, 7]. The strength of the internal tidal wave can be detected from sea surface as shown by using RADARSAT SAR imagery, for example in the southern part of Lombok Strait on 14 July and 7 August 1997 [6] and in period of 2014-2015 there were 14 internal solitary wave event were detected by Landsat 8 [7]. The internal solitary wave in the Lombok Strait propagate to the northern (arc-like internal wave type) and southern part (irregular internal wave type) of the sill and it will deflect when go further out of the strait [7].
A non-hydrostatic 2D model shows that the internal tidal wave is capable to generate vertical mixing of $6 \times 10^3 \text{m}^2\text{s}^{-1}$ [8]. Then it was confirmed by microstructure measurement that large energy dissipation ($\varepsilon > 10^{-6} \text{Wkg}^{-1}$) were observed in the Lombok Strait [9]. As a mixing hotspot, water mass transformation in the Lombok Strait occurred within very short distances, $\Theta$ (10 km). The mixing itself occurred in both vertical and horizontal that enhanced by submesoscale topography eddies [9].

The ITF flows about 20-25% of total ITF transport through the Lombok Strait and 50% of the total transport flow is at 100 m depth [10, 11]. ITF outflow in the exit passages have variability is over all time scales. However, through direct measurement, the annual ITF transport in this strait about $1.7 \pm 1.2$ Sv [11], and 2.6 Sv during 2004-2006 INSTANT program [12].

Besides ITF, the hydrodynamic of the Lombok Strait is influenced by many other factors. A major effect on surface current comes from the monsoon system and its association with El Nino/La Nina events. The maximum transport of ITF in Lombok Island was 4 Sv during the Southeast Monsoon [11].

The existence of internal tidal waves and Kelvin waves of the Indian Ocean also have influence in the Lombok Strait. When Indian Ocean Kelvin waves strike the west coast of Sumatra, they produce a reflected Rossby wave, and a coastal trapped Kelvin wave, which propagates north and south [13]. Kelvin waves were later reported to propagate along the southern coast of Sumatra, Java, Bali, Lombok and the Lesser Sunda Islands [14]. The instability of the water column at the bottom layer of the pycnocline becomes larger during the period of Kelvin wave signals [14].

The hydrodynamic and water mass distribution leading to mixing and strong turbulence in the Lombok Strait. Therefore, our aim in this study is to estimate the strength of turbulent mixing that can be strongly influenced by tide-topography interactions or other physical forcing.

2. Materials and methods

2.1. Datasets

This research used datasets derived from moored-ADCP (Acoustic Doppler Current Profiler) RDI LongRanger 75 kHz and 15 CTD (SBE Sea bird 911 plus) casts from INSTANT Program June 14-19th 2005. ADCP recording was taken from Lombok East Deployment 1 Mooring which placed in $8^\circ$ 24.144’ S and $115^\circ$ 53.881’ E at 1144 m depth. ADCP data was analysed around the time of CTD observation, of June 2005. CTD casts were designed in north-south direction as the axis of ITF. Map of study area and CTD and ADCP stations are presented in Figure 1.
2.2. Methods
Hydrodynamic and water masses background were analysed through the distribution of density, TS diagram of water masses, stability of water column using buoyancy frequency ($N^2$), shear instability ($S^2$) and Richardson number ($Ri$) as:

$$Ri = \frac{N^2}{S^2}$$  \hspace{1cm} (1)

where $Ri < 0.25$ indicating the role of shear instability in turbulence mixing.

2.2.1. Wavelet denoising
Before processed by Thorpe method, we applied wavelet denoising on CTD signals to eliminate noise. We followed wavelet-thresholding algorithm based on Mallat scheme [15]. In this study, we used mother wavelet Daubechies 9 with a certain level of decompositions to produce clean CTD signals. Then, the clean tested-CTD signals is used in Thorpe method to identify overturn regions.

2.2.2. Thorpe method
Thorpe analysis is an indirect method in studying turbulent mixing. Dillon [16] stated instability in density profile, i.e. density inversion, may indicate overturning eddies. Thorpe [17] calculates density of reference profile $\rho_m(z)$ by sorting the density observation profiles $\rho(z)$. There are two values obtained from this method: density fluctuation defined as $\rho'(z) = \rho(z) - \rho_m(z)$ and Thorpe displacement ($d_T$), i.e. the vertical individual fluid particle must move to get a stable density profile. The sum of rms of $d_T$ is defined as Thorpe Scale ($L_T$). All $L_T$ passed Galbraith and Kelly [18] test (GK’ test) with threshold 0.7 designated as real overturn regions.

2.2.3. Turbulent parameter
The strength of turbulent mixing in this study was examined through the turbulent kinetic energy dissipation rates $\varepsilon$ where

$$L_o = \left( \frac{\varepsilon}{N^2} \right)^{1/2}$$  \hspace{1cm} (2)

and density of eddy diffusivity $K_{\rho}$

$$K_{\rho} = \Gamma_T \frac{\varepsilon}{N^2}$$  \hspace{1cm} (3)

with mixing efficiency $\Gamma_T = 0.2$ [19] and $N$= buoyancy frequency. These parameters were estimated through relationship between Ozmidov Scale ($L_o$) and Thorpe scale ($L_T$), $L_o \approx 0.8L_T$ as proposed by Dillon [16].

3. Results and discussion

3.1. Dynamic of the Lombok Strait
Before describing the mixing processes in the Lombok Strait, first we inspected the hydrodynamics and distribution of water masses. The specific topography features of the study area show that the northern part of Lombok Strait is relatively deep (800–1000 m depth) while in the southern part is shallow with a sill of 330 m depth. This sill blocks the Indian Ocean water masses from entering the Lombok Strait. Thus, the internal Indonesian seas has more impact from the dynamics of the Lombok Strait than from the southern sea of Java except when Indian Ocean Kelvin wave arrives.

In the Lombok Strait, current flows stronger at the surface layer compared to the thermocline layer (Figure 2). From INDESO (Infrastructure Development for Space Oceanography) 3-D Model, surface salinity distribution in Figure 2a confirms that water from internal Indonesia seas exit strongly to Indian Ocean through the Lombok Strait. However, in the thermocline layer (Figure 2b), the current
flows slower and the sill at the southern of the strait blocks the entry of Indian water mass. It clearly seen from the contrast of salinity values in the northern sea of Bali and Lombok Strait, which are much lower than in the southern part of the islands.

Figure 2. Distribution of salinity and current from INDESO 3-D model at the surface (a) and thermocline layer (b) of Lombok Strait, June 14th 2016.

From moored-ADCP which placed in the northern part of the Lombok Strait, we found the mean southward surface current about 0.40 m s$^{-1}$ then weaker with increasing depth. At 150 m depth was 0.25 m s$^{-1}$, at 350 m depth was 0.16 m s$^{-1}$ and continues decreasing to 0.12 m s$^{-1}$ at 750 m depth. The vertical transport structure of ITF in the Lombok Strait is primarily surface intensified, although the flow has a weak subsurface maximum at 50-60 m [20].

The surface current direction was mostly to the south but can reverse in 180° as revealed at 50 m depth (Figure 3a). The reversal flow is associated with the arrival of Indian ocean Kelvin wave in this strait [1, 14, 21]. In the deeper layer (350 to 750 m depth), current direction does not show the tight consistency likes at the surface, spread out in all directions and was weaker (Figure 4a).

The magnitudes of tidal current, as indicated by green line in Figure 3 and 4 (b and c), were smaller than non-tidal current. The tidal current amplitude in the northern part of the Lombok Strait was found only 0.5 to 1 m s$^{-1}$ [11]. Unfortunately, the ADCP recording was stop while CTD casts were conducted because the mooring had been recovered. Therefore, the shear used in this study is derived from ADCP recording around the time of CTD observation.

3.2. The distribution of water masses in the Lombok Strait

Although the current was relatively strong in the Lombok Strait but the water column itself was strongly stratified (Figure 5a). From TS Diagram in Figure 5b, we still can find the core layer of NPSW and NPIW at 150 m and 300 m depth, respectively. But their values were attenuated compared to those in the Makassar Strait in which $K_{ρ}=10^{-3}$ to $10^{-2}$ m$^2$s$^{-1}$ in the depth of NPSW and NPIW, deducing the core layer values to 34.6 and 34.7 psu, respectively [22].

The core layer of Smax of Indian water mass ($σ_θ=27$) was found in the southern sea of Lombok but it does not enter the strait due to blocked by the sill. From distribution of salinity, this Indian water mass found at 400 m depth (Figure 5a).
Figure 3. Current stick plot (a), u and v component (b and c), overlaid with tidal current (green line) at 50 m depth. The northward direction is indicated by the direction of the upward current arrow (0°), with the direction of rotation clockwise (east-90°; south-180°; west-270°).

Figure 4. Current stick plot (a), u and v component (b and c), overlaid with tidal current (green line) at 750 m depth. The northward direction is indicated by the direction of the upward current arrow (0°), with the direction of rotation clockwise (east-90°; south-180°; west-270°).
Figure 5. Distribution of salinity (a) and TS diagram of water masses (b) in the Lombok Strait. The colour dots in TS diagram indicate the stations on the map (below).

3.2.1. Overturn regions in the Lombok Strait
In this study, we have removed the noise from the CTD signal thereby improving the quality of Thorpe displacement ($d_T$) resulted from the Thorpe method. Especially at the small gradient density, we must be careful when detecting the real overturn. However, we were able to detect even the small overturn regions because wavelet denoising kept the CTD signals without losing the small perturbation.

The $d_T$ profiles at several stations (St. 5, 7 and 10) are used to illustrate the caution in detecting overturn region in small density gradient or near to the bottom (Figure 6). Most of large $d_T$ in deeper layer or near to the bottom cannot be confirmed as real overturn as it is rejected by GK’ test. Conversely, the small $d_T$ passed the GK’ test. All overturn regions used to estimate the turbulent strength have passed the GK’ test.

Static stability in the Lombok Strait as revealed by the profile of $N^2$ (Figure 7a) indicates that small density gradient occurred at depths below 200 m. This means below 200 m, disturbances will easily grow to turbulence where $Ri$ number less than 0.25 [23].

By using the clean CTD signals, we were able to detect overturn regions in all depths (Figure 7b). Most of overturn regions are small (>0.5 m) and in small density gradient below 200 m depth, we found even more the overturn regions and the large overturn regions (5-7m) (Figure 7c). Thorpe [23] stated turbulence in the stratified ocean is patchy and occurred due to disturbances in vertical stability, including shear, wind friction and internal wave breaking [24, 25]. Thus, there are many possible mechanisms influencing turbulent mixing in the Lombok Strait considering the overturn regions were found throughout the water column.
3.2.2. The strength of turbulent mixing in the Lombok Strait

The strength of turbulent mixing in the Lombok Strait was estimated using turbulent kinetic energy dissipation rate $\varepsilon$ and vertical eddy diffusivity $K_\rho$. Limited by the resolution of the pressure, temperature and conductivity sensors on the CTD instrument, the lower limit of $\varepsilon$ that can be detected using the Thorpe method is only up to $\mathcal{O}(10^{-12})$ W kg$^{-1}$. Therefore, the order of magnitude found in Lombok Strait in June 2005 is in the range of $\mathcal{O}(10^{-12}-10^{-6})$ W kg$^{-1}$. The turbulent strength described by the vertical density value of the eddy diffusivity ranges from $\mathcal{O}(10^{-6}-10^{-2})$ m$^2$ s$^{-1}$. A relatively high
value of $\Theta\left(10^{-2}\right)\text{m}^2\text{s}^{-1}$ was found in the southern part of the strait near the sill (Figure 8). The values of $\varepsilon$ and $K_{p}$ similar as found by [26] and confirmed by microstructure measurement [9]. The density field in Figure 8 indicated that pycnocline layer lies on 100–300m depth. Inside this pycnocline, there are dipped and rebounded of isopycnal surfaces of $\sigma_{\theta}$ ~25.5–26.5 around the sill in the southern part of Lombok Strait that indicating the presence of internal tide. The expectation of strong turbulent mixing occurs in the Lombok Strait is also supported by appearance the $M_2$ non-linear internal tide with an amplitude of ~90m in ~30 km from the sill [25].

![Figure 8. Distribution of potential density with eddy diffusivity $K_{p}$ in the Lombok Strait.](image)

At the moment of CTD observation, the echogram EK500 showed the presence of internal solitary wave in the study area [5] (Figure 9a). And from ADCP, we found the strong shear occurred at the same depth of the internal solitary wave (Figure 9b). The stronger shear (indicated by red color) occurred about six days before the CTD observation time. However, the strong shear between 150-250m depth persists during the CTD observation (light orange box). Internal wave produces transient shear, locally reducing the $Ri$ number and occasionally leading to instability or wave breaking. Therefore, we speculate the strong turbulence layer is associated with the internal wave.

![Figure 9. (a) Internal wave observed on Lombok Strait in June 2005 [5] (b) the distribution of shear stress at the same depth of the internal wave around the CTD observation time.](image)

Source: Susanto et al (2005)
To ensure the mechanism forcing of the strong turbulence, we examine relationship between stability (presented by $N^2$) and instability ($S^2$) to overturn regions. Then we plot Thorpe scales on the $N^2$, shear, $Ri$ number as reveal in Figure 10. It is clearly seen that the overturn regions are below $Ri=0.25$, confirms that shear instability associated with internal wave breaking as the main forcing in turbulent mixing.

4. Conclusion
Small overturn regions mostly less than 0.5 m, has been found throughout the water column of the Lombok Strait. These eddy overturning layers can be driven by many factors, but at subsurface to 200 m depth, the turbulent mixing due to shear instability associated with local breaking of internal wave. Especially near the sill in the southern part of the Lombok Strait, a relatively high $K_\rho \phi (10^{-2} m^2s^{-1})$ has been found together with the dipped and rebounded isopycnal surfaces of $\sigma_\theta=25.5-26.5$. It clearly indicates the presence of internal tide.

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