Variation of seawater properties on tidal-scale in the entrance of Padangbai Lombok Strait Indonesia

Y Suteja1,3, A S Atmadipoera2*, M N Natih1, M Wattimena1, V Masoleh1, Y Pranoto1, D Adhyatma1, P Widiastuti1, S R Deswanti2, A Triwahyuni1, H Watari1, A W Hastuti1, A Mamun6, A Vladoiu7 and Chonnaniyah8

1Graduate Program in Marine Sciences, IPB University, Bogor Indonesia
2Department of Marine Sciences and Technology, IPB University, Bogor Indonesia.
3Department of Marine Science, Udayana University, Bali Indonesia
4Faculty of Sciences, Yamaguchi University Japan
5Institute for Marine Research and Observation, Bali Indonesia
6Institute for Marine Fisheries Research, Jakarta Indonesia
7LOCEAN, Sorbonne University Paris France
8Center for Remote Sensing and Ocean Science (CReSOS) Udayana University, Bali Indonesia

*email: atmadipoera_itk@apps.ipb.ac.id

Abstract. During Marine Science Summer Course 2017, a continuous 24-h conductivity-temperature-depth (CTD) “yoyo” measurement has been carried out at the entrance of Padangbai Lombok Strait to investigate seawater properties variations on semidiurnal tidal-scale which is dominant in the strait. The SBE CTD 19 plus is equipped with optional sensors such as pH, turbidity and chlorophyll-a derived-fluoro. During 24-h field observation, 15 CTD casts from sea surface to about 60 m depth have been acquired. It is shown that observed seawater properties fluctuate strongly four times a day, following semidiurnal-tide period with two flood-tide and two ebb-tide conditions. During flood-tide, water mass is derived from open strait with colder, saltier, denser and low dissolved oxygen characteristics. In contrast, during ebb-tide, local water mass is recirculated back from the inner bay to the open strait. It is interesting to note that fluctuation of chlorophyll-a indicates a diurnal signal. In addition, fluctuation of pH, turbidity and dissolved oxygen showed a weak semidiurnal signal.

1. Introduction

The Indonesia Throughflow (ITF) is a part of ocean thermohaline circulation. The ITF transfers water masses from the Pacific Ocean to the Indian Oceans mainly in the interior layer [1][2][3]. There are three channels of ITF i.e. primary, secondary and tertiary. The primary channel is conveying 13.3 ± 3.6 Sv (1 Sv/Sverdrup = 10^6 m^3 s^-1) [5] water masses via Sulawesi Sea to Makassar Strait that consists of the thermocline (North Pacific Subtropical Water/NPSW) and sub-thermocline (North Pacific Intermediate Water/NPIW) waters [4][6][7]. The secondary channel is conveying 2.5 Sv water masses via Maluku Sea to Seram sea in the deep layer and strongly characterized by South Pacific Subtropical Lower Thermocline Water (SPLTW) [4][7][8]. The last channel drawn 3.6 ± 0.8 Sv water masses in northwest monsoon and 0.8 Sv annually average via South China Sea to Karimata Strait in surface layer which dominated by fresher and warmer water masses [9,10]. All of the ITF water masses (around 15 Sv) flowing to the Indian Ocean through the Timor Passage that brings most dominant seawater (7.6 Sv), and the remain flushing through Lombok Strait (2.6 Sv) and Ombai Strait (4.9 Sv) [11][12]. The ITF...
also characterized by strong vertical mixing in some areas which is able to change the characteristics of the water masses [4][14][15]. One of the most energetic energy sources for this vertical mixing has come from the internal tide that already observes in some areas [16][17].

Lombok Strait is one of the outflow straits that transfer ITF water masses which comes from Makassar Strait [4][11]. The water masses of this strait also getting input from the Indian Ocean which drawn by the combination of equatorial Kelvin Waves and South Java Current (SJC) in the upper layer and South Java Under Current (SJUC) in the deep layer [11][18]. Besides that, Lombok Strait is also the route of M2 Tide wave propagation to the Indonesian Seas [19]. This strait located between Lombok Island on the eastern side and Nusa Penida Island (Bali) on the western side which characterized by narrow (+ 30 km long) and shallow (maximum 300 m) water. This narrow strait creates a strong tidal current (close to 1 m s⁻¹) mainly in the western part [11][19][20]. Interaction between energetic tide current and rough topography (Lombok Sill) generates the internal wave [21]. This internal wave propagated widely to the northward reach close to the Kangean Island and narrowly to the southward. This internal tide already proved through satellite imagery [16][22].

One part of the Lombok Strait is the Padangbai waters located on the eastern side of Bali Island. This area is well known as a port for public transportation that connected Bali and Lombok islands. The process in Lombok Strait is thought to affect the condition of water properties in the entrance of Padangbai. The objective of this paper was to investigate seawater properties on tidal-scale at the entrance of Padangbai Lombok Strait.

2. Methods

The CTD “yoyo” measurement in the entrance of Padangbai Lombok Strait was conducted in dry season on 24 – 25 July 2017 (Figure 1). 15 CTD casts were collected during two semidiurnal tidal period (24 hours) with variation of instrument depth (from 35 m to 60 m) during repeated casts due to strong tidal current (Tabel 1). At the beginning of the measurement, sampling interval was set to one hour, but due to rough sea state and strong winds, starting at the night sampling interval was changed to every 2-hour. To keep fixed position in the sampling point, the survey boat was attached to a navigation buoy. The CTD measurement was set for both upcast/downcast profiling and was processed using standard procedure following [15] using the SBE data processing 7.21a software. The CTD data were analysed and visualized using Ocean Data View (ODV) software. Tidal prediction data during field measurement were obtained from Balai Pusat Observasi Laut (BPOL) Bali that were available on http://bpol.litbang.kkp.go.id/imro-oifs/#show_select_tides_predictor.

![Figure 1. Map of sampling site at the entrance of Padangbai Lombok Strait.](image-url)
Table 1. Description of CTD “yoyo” measurement in Padangbai Lombok Strait.

| Station | Date       | Time (local time) | Instrument Depth (m) |
|---------|------------|-------------------|----------------------|
| 1       | 7/24/2017  | 12:08             | 56                   |
| 2       | 7/24/2017  | 13:10             | 56                   |
| 3       | 7/24/2017  | 14:14             | 51                   |
| 4       | 7/24/2017  | 15:10             | 55                   |
| 5       | 7/24/2017  | 16:07             | 55                   |
| 6       | 7/24/2017  | 17:06             | 55                   |
| 7       | 7/24/2017  | 18:58             | 55                   |
| 8       | 7/24/2017  | 21:10             | 44                   |
| 9       | 7/24/2017  | 22:51             | 57                   |
| 10      | 7/25/2017  | 00:32             | 56                   |
| 11      | 7/25/2017  | 03:23             | 35                   |
| 12      | 7/25/2017  | 05:22             | 56                   |
| 13      | 7/25/2017  | 07:02             | 59                   |
| 14      | 7/25/2017  | 09:04             | 58                   |
| 15      | 7/25/2017  | 10:58             | 57                   |

3. Results and discussion

3.1 Semidiurnal tide in Lombok Strait

Tidal prediction results which downloaded from BPOL website show that within 24 hours there were 2 peaks and 2 valleys formed, it indicates that the study site had a semidiurnal tidal type. The tidal graph also shows the daily inequality where the peak of the first tidal wave is higher than second tidal peak wave. The highest flood occurred at 01.00 while the lowest ebb occurs at 18.00 with each water level elevation were 0.61 and -0.74 m, the highest and the lowest tidal range were 1.35 and 0.69 m respectively (Figure 2a). This tidal range can be wider or narrower depending on the time of measurement whether it coincides with spring or neap tide. The clear signal of strong semidiurnal (M2) tide propagation which induces relative strong current (close to 1.4 ms\(^{-1}\)) was successfully simulated in Lombok strait and its model also has good agreement with observation data [19].

The schematic view also portray that the northward M2 tidal propagation from Indian Ocean enter the Makassar Strait, Flores and Java Seas through Lombok and Ombai Strait. The direct measurement of current speed in Lombok strait showed southward flow reach maximum velocity close to 3.00 ms\(^{-1}\) [33]. Recent study by International Nusantara Stratification and Transport (INSTANT) Program showed the deep southward current flow in Lombok strait was marked by westerly intensification [11]. The combination of narrow strait which induce strong current, and existence of underwater obstacle (shallow sill or ridge) will disturb the subsurface strong stratification layer and generate baroclinic tide (internal tide). All of this criteria are found in Lombok Strait and provoke intense baroclinic tide.

The internal wave in Lombok strait was clearly showed in south and north of Lombok Sill through Phased Array L-band Synthetic Aperture Radar (PALSAR) from Advanced Land Observing Satellite (ALOS) [22] and Synthetic Aperture Radar (SAR) from European Remote Sensing (ERS) Satellite [16]. The northward internal wave propagation were reaches Kangen Island, which is around 200 km away from the wave generation site [22]. The wavelengths packets of this internal tide were increase monotonically from the rear to the front [16][22]. The tide also has significant effect on water masses properties. The salinity (temperature) in Balikpapan Bay from in situ measurement was recorded higher
(lower) during flood and vice versa during ebb [36]. The turbidity (density) in Ile Rouge Bank also showed similar pattern which become lowers (higher) and found retreat shoreward during flood [37].

Figure 2. The tidal surface elevation (a), temperature (b), density (c), and salinity (d) during 24 hours CTD measurement in the entrance of Padangbai, Lombok Strait.

3.2 Semidiurnal fluctuation of temperature–salinity–density
The data measurement showed that temperature was warmer in the surface layer and then decreases with increasing depth because the surface layer gets more energy from solar radiation than the bottom layer. The highest and the lowest temperature were 29.1598 °C and 18.1703 °C respectively. The temperature also higher during daylight time until the beginning of the night and then decrease in night time because there were no heats coming from the sun. The salinity has contrast pattern compare to the temperature. Salinity minimum was found in surface layer because there was an input of low-salinity water that comes from precipitation, meanwhile the highest (34.9271 psu) in the bottom layer that less contact to the surface. The lowest salinity (33.4063 psu) was found in the early morning due to high intensity of precipitation at the time. The density (Sigma-t) was derived from temperature, salinity and depth data. Vertical distribution on density showed that the denser were lies below the less dense water. The highest (lowest) density was found in deep (surface) layer. The vertical density distribution pattern was similar to the temperature but in different values. Density is reciprocal of temperature, when temperature is low, density will increase, vice versa. Contrasting result was found in Balikpapan Bay, the water density was dominantly derived by high salinity gradient than temperature [36].

Overlapping tidal data to water masses properties (temperature, density, and salinity) from CTD measurement data showed in Figure 2. This clearly showed that there were strong differences between water masses during flood and ebb tides. During flood the water masses characterized by cooler, denser
and saltier, meanwhile during ebb the water masses were warmer, less dense and less salty. During flood the water masses come from the open ocean and move northward from Indian Ocean, but during ebb the water masses flowed from the inner bay that close to the mainland. Northward (southward) water mass movement during flood (ebb) in Lombok Strait has successfully described with the previous study [23]. Warm temperatures at low tide were caused by the water masses coming from shallow water (inner bay) and close to land so that maximum heating occurs in the water column, but vice versa at low tide. The warm shallow water has a significant effect to heat up Indonesia seawater [24]. Fresher salinity water also flowed during low tide. The runoff process from the mainland at low tide also has a contribution to make salinity become fresher. The precipitation during sampling also plays an important role in reducing salinity. Research in the Caribbean Sea also confirms that runoff and precipitation have a significant effect on dilute seawater salinity [25]. The highest salinity was found during the flood do to the high seawater input from the open ocean. The results of this study were similar to those found in Skagite Rivers Estuary at flood where intrusion from the open sea causes increasing salinity significantly [26]. Beside dilute seawater salinity, the river also drew pollutant to the sea [34][35].

3.3 Fluctuation of chlorophyll-a, turbidity and dissolved oxygen
The fluorescence data were collected to derived chlorophyll data. The Padangbai Water generally was limpid water which indicated by low turbidity level Figure 3. The turbidity did not fluctuate as other data. The highest concentration of turbidity and fluorescence was found in the bottom layer, close to the seafloor. Shear stresses in the bottom layer caused to increase in bottom turbidity [27]. The fluctuation of turbidity concentration showed there is no correlation with tide, it is contradicting with previous study that found the sediment resuspension was strongly induced by tide in the idealized estuary [28]. According to [29] that turbidity and fluorescence have positive correlation i.e., increased turbidity will increase fluorescence. From the Figure 3 also showed that the fluorescence was increase (decrease) during ebb (flood), this is presumably because the water masses from the inner bay carry more nutrients and increase fluorescence derived chlorophyll. A similar result also found in the eastern side of Lombok Strait which found an increase in chlorophyll concentration during low tide [30].

Oxygen concentration has a similar pattern with fluorescence because photosynthesis produces oxygen. Apart from chlorophyll, the oxygen concentration is influenced by respiration and decomposition of organic matter by bacteria [31]. Vertical distribution of oxygen showed the surface and bottom layer has the lowest concentration, meanwhile the middle layer has the highest concentration. The dissolved oxygen concentration was increase at noon and decrease at midnight. The lowest pH concentration was found in the surface layer was thought to originate from the presence of precipitation. Figure 3 also showed the pH increases with increasing depth. Brunt-Vaisala Frequency shows an irregular pattern because it is shallow water (mixed layer depth) and no stratification. The tropical seas have mixed layer depth depending on the season with range from 25 m till 80 m depth [32]. Overlapping tidal elevation with fluorescence, turbidity, and oxygen data are shown in Figure 3. During flood, the water masses characterized by low fluorescence and oxygen concentration, while compete during ebb the concentration of fluorescence and oxygen were increase. The pH, turbidity and Brunt-Vaisala Frequency have a pattern that did not affect by tides. The turbidity in Padangbai water was contradicting with previous study in Saint Lawrence estuary which found the turbidity retreat shoreward during flood tide [37]. The differences of river input from the mainland were the main reason of these phenomena.
Figure 3. The tidal surface elevation (a), fluorescence (b), turbidity (c), oxygen (d), pH (e) and Brunt Vaisala Frequency (f) during 24-hour CTD measurement in the entrance of Padangbai Lombok Strait.

4. Conclusion
This study has successfully revealed an evidence of strong variation of seawater properties on semidiurnal variation related to tidal dynamics. During flood-tide, water mass is derived from open strait with colder, saltier, denser and low dissolved oxygen. In contrast, during ebb-tide, recirculation
of local water mass from the inner bay. However, chlorophyll-a derived-fluorescence indicates diurnal fluctuation. The pH, turbidity and Brunt-Vaisala Frequency show a weak semidiurnal fluctuation.

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