

## Deep water masses exchange induced by internal tidal waves in Ombai Strait

A S Atmadipoera<sup>1\*</sup>, Y Suteja<sup>2</sup>

<sup>1</sup>Dept. of Marine Sciences and Technology, Faculty of Fisheries and Marine Sciences, Bogor Agricultural University, Bogor Indonesia.

<sup>2</sup>Dept. of Marine Science, Faculty of Marine and Fisheries, Udayana University, Bali Indonesia  
\*e-mail: agus.itk@gmail.com

**Abstract.** Yoyo CTD/LADCP measurement for a 24-h tidal period and along trackshipboard ADCP, has been carried out in the northern entrance of Ombai Sill during the INDOMIX Cruise in July 2010 to investigate current structure and associated near-bottom water mass exchange induced by internal tidal waves. The results show that a strong meridional current fluctuation is observed on quasi-semidiurnal period with much stronger southward flow, related to the existence of southward Ombai Indonesian Throughflow (Ombai ITF). The vertical extent of the current deepens to the sill depth (1600m). Under 500 m depth to the sill, the southward ebb flow brings cooler and less salty water Flores water to southern Ombai Strait in Savu Sea. In contrast, the northward flood flow supplies Flores/Banda Sea with much warmer and saltier water. Thus, on tidal period there exists deep water masses exchange induced by internal tidal waves. Strong baroclinic instabilities appear when induced northward tidal flow against Ombai ITF, resulting highest vertical diffusivity.

### 1. Introduction

The Indonesia Throughflow (ITF) is a main branch of the global thermohaline circulation, connecting between the Pacific and the Indian Oceans [1,2]. The ITF flow in interior Indonesian seas is mainly via western pathway, which conveys about 11.6 Sv (1 Sv =  $10^6$  m<sup>3</sup>/s) of water masses that consist of thermocline and sub-thermocline water masses from North Pacific Subtropical Water (NPSW) and North Pacific Intermediate Water (NPIW). The smaller contribution through eastern route which consists of South Pacific Subtropical Lower Thermocline Water (SPSLTW) and only drawn 2.5 Sv water masses [1,3,4,5,6,7]. Most of the western and eastern routes passes to Indian Ocean through the Timor Passage (7.6 Sv) and the rest exits through Ombai Strait (4.9 Sv) and Lombok Strait (2.6 Sv) [8,9].

Besides getting input from the Pacific Ocean, the ITF also gets water input from Indian Ocean. Previous research observed that there is an upper layer of North Indian Intermediate Water in northern Sawu Sea and Ombai Strait, as well as Indian Ocean Deep Water (IDW) in Timor Passage [7]. Ombai Straits is located closed to Timor Passage and its water masses are considered to be influenced from the Indian Ocean through the straits in the western part of Sawu Sea. INSTANT data in Ombai Strait indicated that there are flows into interior Indonesian seas through Ombai Strait drawn by the South Java Current (SJC) and South Java Under Current (SJUC), and also arrival of equatorial Kelvin waves from the equatorial Indian Ocean penetrate through the Savu Sea [10,9,11]. In addition to the coastally trapped Kelvin waves, water mass transport also strongly affected by internal waves generated by rough topography and sills [12].

Ombai Strait is one of the main ITF outflow straits to the Indian Ocean which constrains to deep sill of about 3250 m depth [13,9]. From numerical simulation showed that interaction between sill and



strong barotropic tidal current can generate internal waves [14]. Ombai Strait is one of the spot areas in Indonesia seas, which displays a high internal tidal energy, transferring from barotropic tides to baroclinic tides [15,16] and has strongest internal tidal current velocity (up to  $0.5 \text{ ms}^{-1}$ ), although it is only generated by M2 tidal component [17]. Internal tide is one of the main forcing for generating turbulent mixing in the ocean [18], including in the deep ocean [19].

Indirect method of turbulent mixing measurements using CTD showed that Ombai Strait revealed a higher turbulent mixing than other regions in Indonesia such as Banda Sea and showed highest vertical diffusivity of turbulent mixing in the deep layer but lowest in thermocline layer [20]. Vertical diffusivity estimates in Ombai Strait vary between  $1.2\text{--}9.7 \times 10^{-4} \text{ m}^2\text{s}^{-1}$  with its maximum of  $2.3 \times 10^{-1} \text{ m}^2\text{s}^{-1}$  [21,22]. The high value of tubulent mixing was thought by strong internal tidal energy and its interaction with deep sill in Ombai Strait [20].

Intense internal wave activity as seen from high energy transfer from barotropic tides to baroclinic tides, as well as high vertical diffusivity of turbulent mixing may influence strongly stratification and exchange of different water masses in Ombai Strait. The objectives of this study attempt to investigate vertical current structure during a tidal cycle (24-hour) and its associated deep water mass exchange and internal tidal waves in Ombai Strait, acquired from the conductivity-temperature-depth (CTD) and lowered acoustics Doppler current profiler (LADCP), and hull-mounted shipboard (SADCP) measurement during the INDOMIX cruise in July 2010.

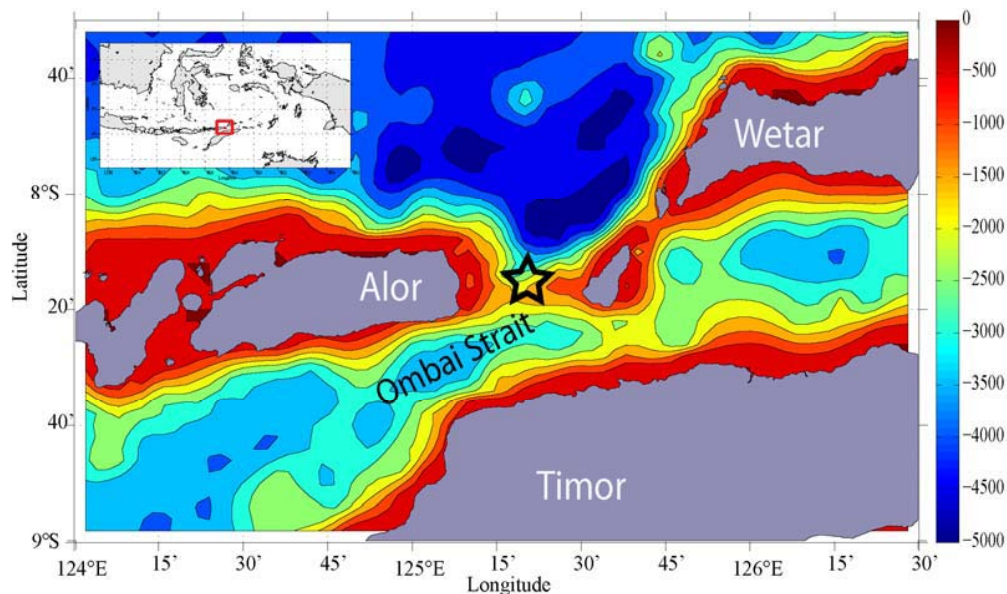
## 2. Methods

The Hydrographic data measurement in Ombai Strait has been carried out during the *Indonesian Mixing* (INDOMIX) 2010 cruise. During two weeks cruise, the INDOMIX voyage was started in Sorong, then to western equatorial Pacific Ocean, to Halmahera Sea, to Seram Sea, to Banda Sea, to Ombai Strait, to northern Sawu Sea, to Lombok Strait and finished at Tanjung Perak port in Surabaya. The CTD/LADCP "yoyo" measurement in Ombai Strait has been conducted in northern entrance of Ombai Strait (between Alor and Ataura, figure 1), collecting 9 CTD/LADCP casts for 24 hours (one tidal cycle) measurement on July 15-16, 2010. Measurement was conducted in the sill slope in the northern entrance of Ombai Strait with its width of about 17.5 km. Instrument depths during repeated CTD/LADCP measurement varied from 409 m to 1549 m depth. The CTD data processed by standard processing procedure using *the SBE data processing software* and CTD profile data were derived from downcasting data only. CTD data from INSTANT program on June 2005 in South Ombai Sill were used as a comparison to CTD profiles from INDOMIX data. The ocean current profiles measured by 2 Lowered Acoustics Doppler Current Profiler (LADCP) RDI 300kHz that installed in CTD frame, one is looking-upward and the other looking downward, where absolute current is obtained from bottom track of LADCP looking downward. The bin size for each water column is 8 m. The LADCP data processing follows the guidelines of [23], [24] and [25]. Ocean currents also measured using hull-mounted shipboard ADCP, known as the shipboard ADCP (SADCP). The SADCP data processing and analysis follows the guidelines from [26].

Data processing, analysis and visualization were done by using MATLAB and spreadsheet software. The Thorpe displacement ( $d$ ) is calculated from seawater density profile that has been re-ordered under stable stratification, i.e., conditions in which higher density water mass is below low density water mass. For example, if we have  $n$  samples at depth  $z_a$  with density  $\rho_n$  and to obtain static stability conditions samples at depth  $z_a$  are moved to depth  $z_b$  then the value of  $d$  is calculated [20] by using equation of :

$$d = z_a - z_b$$

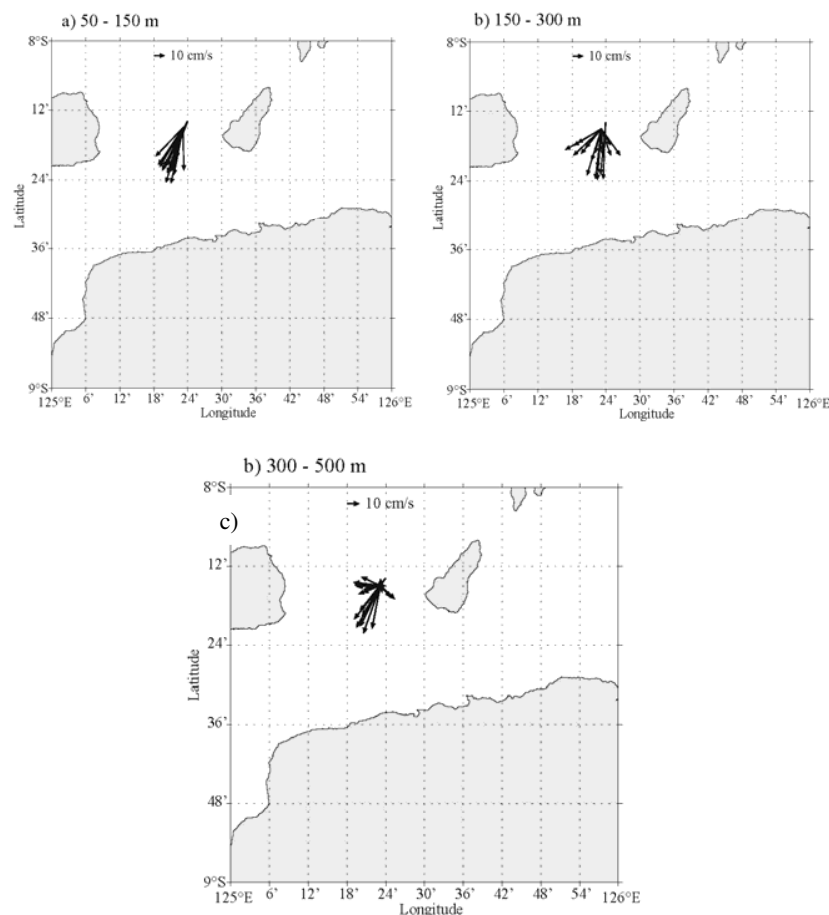
A positive  $d$  value indicates when a high density water mass is above a low density water mass, so to make static stability low density water mass must be moved up. In contrary, when the value of  $d$  is negative indicates high density mass must be moved down replacing the low density water mass to achieve static stability conditions.



**Figure 1.** Map of study area in Ombai Strait. The CTD/LADCP measurement during the INDOMIX cruise has been conducted in the sill slope of the northern entrance between Alor and Wetar. Star denotes for 24-hour repeated "yoyo" CTD/LADCP measurement on 15-16 July 2010. Bathymetry interval is 500.

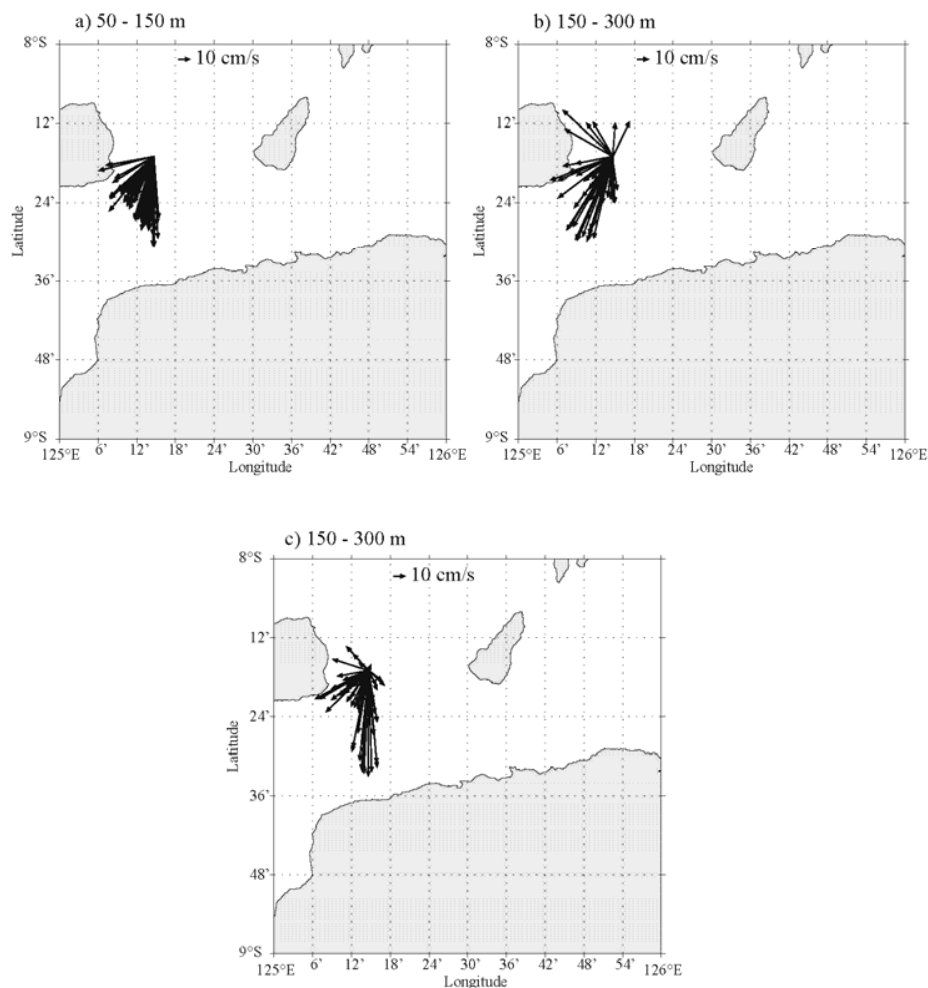
### 3. Results and discussion

Averaged current vectors at different depths in Ombai Strait during first SADC measurement is presented in Figure 2. From stick plot in East Ombai it is found that dominant current flow is southward and southwestward. However, there are variations in magnitude and direction at different averaged depths. Current direction average between 50-150 m depth is dominant southward with a slight zonal deflection. At 150-300 m depth, current direction spreads eastward and westward, but the southward flow are still dominant (figure 2b). Current velocity at 300 - 500 m depth flows dominantly southward, but the eastward and westward currents are getting stronger. This result also has good agreement with previous measurements using ADCP during November 1995 - November 1996 that show net flows current to Savu Sea in southern Ombai [9], but in December 1995 was found that above 160 m depth there is a current move towards the east [8].



**Figure 2.** Current vector plots from first SADC measurement in Ombai Strait; (a) averaged current vector between 50-150 m depth, (b) between 150-300 m depth, (c) between 300-500 m depth.

Averaged current vector at different depths in Ombai West (figure 3) show that the flow pattern of current at three different depths in Ombai west is similar to those observed in Ombai east, where the dominant flows are southward. However, the magnitude of current velocities are much stronger and the current directions are much variable in Ombai west. At 50-150 m depth the direction of current is southward (figure 3a), but some current vectors flow westward. In Ombai east, at the same depth, there is no current flowing westward (figure 2a). In lower layer (150-300 m depth), the northward velocity current is stronger than that in 50-150 m depth, but the current leading south remains dominant. The currents direction and velocity average between 150-300 m depth in western Ombai stronger and more northward than eastern Ombai. Northward current flow decreases between 300-500 m depth and the southward current increases. The current velocity in western Ombai is larger (zonal or meridional current) than the eastern Ombai at the same depth. The increased in vertical flow is supposed due to the maximum ITF transport in thermocline layer compared to surface layer [13,27]. From current measurements using SADC at two locations near the eastern and western sides of Ombai Strait (figures 2 and 3), it is clear that the dominant currents flowing southward and southwestward represent the ITF in Ombai Strait, where the current are stronger and intensive in the thermocline layer. Although current measurements are made only snapshots, but time measurement (in July 2010) has been part of the Southeast Monsoon period when seasonal variation of ITF maximum. From this current measurement, one interesting novel is revealed a western intensification (strengthening) flow in the northern entrance of Ombai Strait that is apparently the main pathway of ITF originating from the Flores Sea.



**Figure 3.** Current vector plots from second SADC measurement in Ombai Strait; (a) averaged current vector between 50-150 m depth, (b) 150-300 m depth, (c) 300-500 m depth.

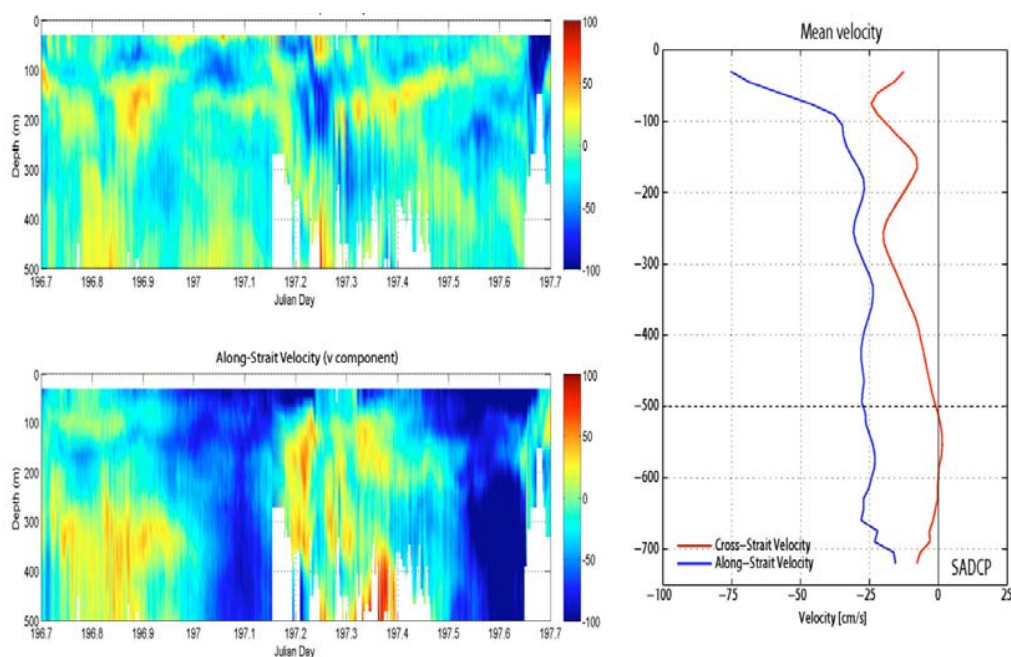
The depth-time plot of the zonal and meridional current components from 24-hour SADC measurements shows clearly temporal (tidal scale) and vertical (different depth) variations of the flow (Figure 4). The meridional current component (north-south component) is much stronger than zonal (east-west component) component, associated to configuration of the strait in north-south direction. The flow direction of meridional current component indicates alternating flow northward during certain period (yellow-red color) and southward during the opposite period (green-blue color). During 24-hour current measurement, it is found twice current reversal, which is strongly related to arrival of barotropic semi-diurnal tidal waves in Ombai Strait. Semi-diurnal tides propagate from the Indian Ocean entering through the Savu Sea and into the Ombai strait [28].

Distribution of meridional current component shows that magnitude of southward velocity is much stronger than the northward flow (Figure 4, bottom left panel), indicating an additional velocity quasi-constant derived from the ITF component that flows southward. It is also seen that, the southward flows are more consistent and much stronger between 0-500 m depths. The averaging of 24-hour current to eliminate tidal signal, indicating that the magnitude flow of meridional velocity is much stronger than the cross-strait velocity (Figure 4, right panel). The maximum velocity (about 75 cm/s) of meridional current is found near 25 m depth, then the velocity decreases to 35 cm/s near 100 m depth. Magnitude of meridional current velocity between 100 m and 650 m depth is relatively



persistent and quasi-constant (approximately 25 cm/s). From meridional velocity profile, it is found that Ombai ITF is relatively stable from sub-surface to about 650 m depth, which is good agreement with [8] and [9], where the vertical extent of Ombai ITF reach 800 m depth. A similar pattern of stronger along-strait flows is also found on Timor passage [29,30,31].

The zonal current component (cross-strait velocity) indicates that the currents moving westward are more dominant than those moving eastward (figure 4, upper panel). In contrast to the meridional component, the average of zonal component flow profile is much weaker and fluctuates with the maximum speed of 25 cm/s near 75 m and 250 m depth. The average flow to the west has a maximum speed of 25 cm/s near 75 m depth. The meridional current component is much more dominant than the zonal current flow with the highest speed near 25 m depth. The average meridional current also shows that the dominant current is moving southward.



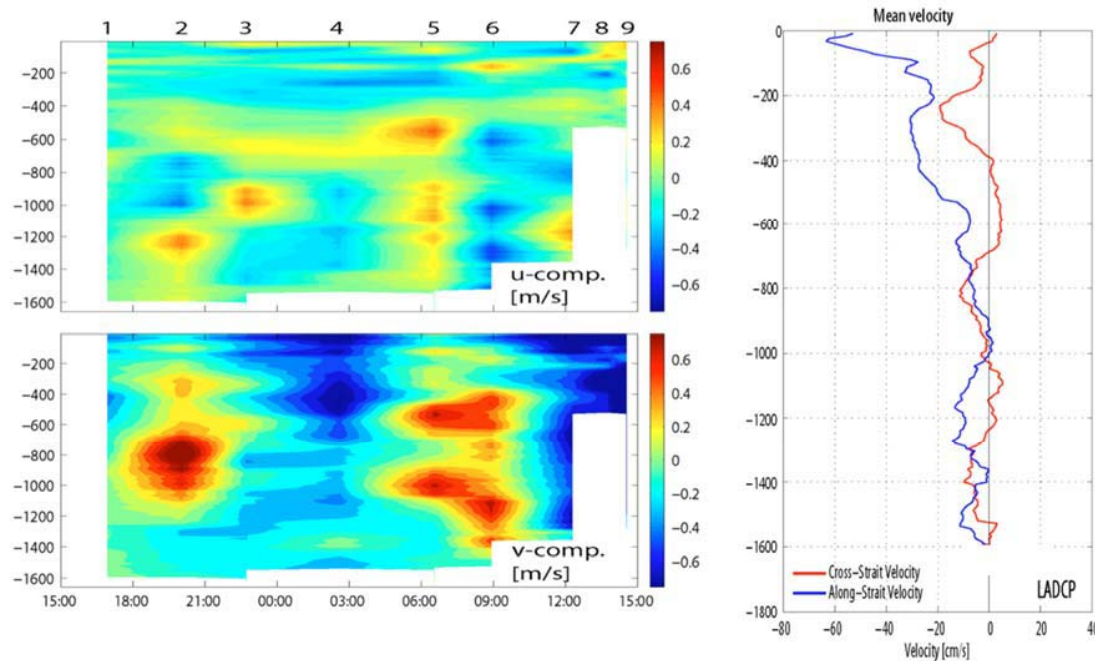
**Figure 4.** Zonal and meridional current components (left panel) and mean zonal (cross-strait) and meridional (along-strait) current profiles (right panel) from SADCP measurement on July 15-16, 2010 in northern entrance of Ombai Strait.

The zonal and meridional current components from LADCP measurement at varying depths according to the CTD casting (500 m to 1600 m) show a consistent pattern with SADCP measurement (figure 5). It is revealed two reversals northward and southward flows within approximately 24 hours. The meridional current component is much stronger than the zonal component (Figure 5, left). However, the depth-time plot of zonal and meridional current components with LADCP is much more detailed with the presence of strong meridional current cores northward (red) and southward (blue).

The zonal component is weaker than the meridional component (figure 5). In zonal currents it is seen that the variation of east-west direction has no significant, compared to north-south variation of meridional current. It is also show that there is a very strong flow in meridional component that changes two times in quasi-semidiurnal periods, where the current flowing northward at a particular time (18:00-21:00 and 06:00-11: 00) and southward at other times (00:00-04:00 and 11:00-15:00). The northward current dominant occurs at depth between 400 m - 1200 m, and between 400- 1400 m depth.

The mean zonal and meridional profile, averaged for 24 hours to eliminate the tidal current signal, show that the meridonal current is much stronger than the zonal current. The maximum speed of zonal current is 20 cm/s near 250 m depth, while the meridional current reveals a magnitude velocity more

than 60 cm/s near the surface layer. The southward flows are related to the existence of southward Ombai ITF as one of the main outflow straits to the Indian Ocean [8,7,9]. The mean meridional profile also shows that the current is weakening with increasing depth (Figure 5, right), even currents moving to the north near bottom (more than 1600 m).



**Figure 5.** Zonal and meridional current components (left panel) and mean flow profiles (right panel) from lowered ADCP measurement in Ombai Strait

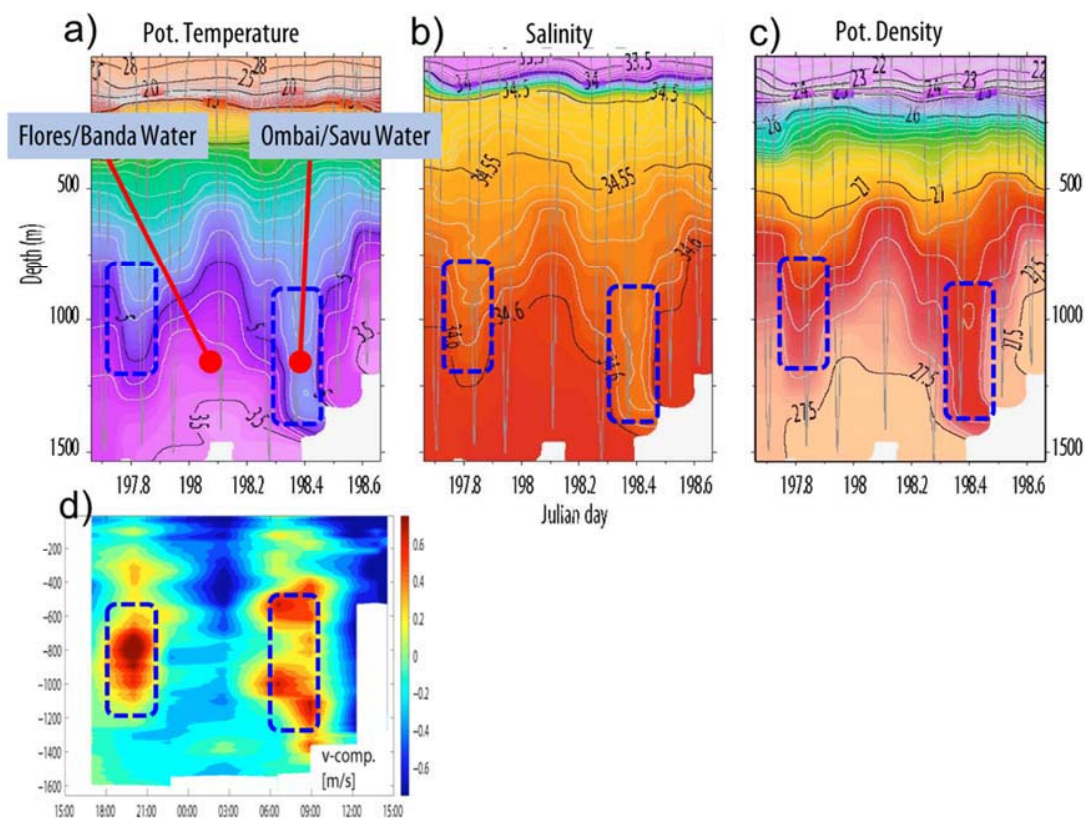
Stratification of water masses, expressed by its depth-time plot of potential temperature, salinity and potential density anomaly (figure 6, upper panel) revealed a quasi-semidiurnal oscillation of water masses within 600-1500 m depth water column. It is seen that the internal waves in the Ombai Strait prevails semidiurnal, because it has two peaks and two valleys during measurement (24 hours). This result also has good agreement with [32] that Indonesian waters are generally dominated by internal tides M2 (semidiurnal tidal component). More detail also we can see that the first internal wave height is lower than the second internal wave. The first internal wave has about 550 m height with the first internal wave crest at about 700 m depth and the wave trough is around 1250 m depth. The second internal wave has around 1000 m height with a wave crest at 500 m depth and a wave trough at about 1500 m depth.

Corresponding different water masses appear during one-tidal-cycle (24-hour) in Ombai Strait, one relatively warmer, less salty, and less dense water mass occur two times, for example around 197.8 and 198.4 Julian-day, and the other relatively colder, saltier and denser water mass appear alternately around 198.1 and 198.6 Julian-day (figure 6, a-b-c). The changes of water masses stratification, as indicated by abrupt changes of their isotherm, isohaline and isopycnal (Figure 6, a-b-c), indicate that the internal tidal waves control predominantly on structures of water masses and stratification. The internal wave activity in a water column affect greatly on the vertical profile (temperature, salinity, and density) of waters masses [33].

The presence of relatively warmer, less salty and less dense water mass around 197.8 and 198.4 Julian-day (figure 6, a-b-c) is associated with northward flow. Modeling tidal current showed that semi-diurnal tidal component propagates from the Indian Ocean, into Sawu Sea, then pass into Ombai Strait entering Flores Sea and Banda Sea [28,32]. Hence, the northward flow around 197.8 and 198.4 Julian-day corresponds to flood tide (high tide), which brings distinct water mass from Sawu Sea into

Flores/Banda Sea. On the other hand, the southward flow around 198.1 and 198.6 Julian-day (figure 6c) is related to ebb tide (low tide), plus quasi-constant of southward Ombai ITF that draws water mass from Flores/Banda Sea into Sawu Sea.

The internal wave pattern in deep layer (near bottom) affects the exchange of water masses in its layer. The southward ebb flow brings cooler and much salty water mass, which is derived from deep Banda/Flores Water [1,34,13]. In contrast, the northward flood in Ombai Strait brings less salty and much warmer water from Savu Sea, which may influence Flores or Banda water mass. Further research is needed to determine the origin of this water mass. Previous study showed that North Indian Intermediate Water (NIIW) at depth between 600-800 m depth is dominant in Sawu Sea, and at deeper layer upper Indian Deep Water (IDW) also occupies in the region [35,8,13,7].



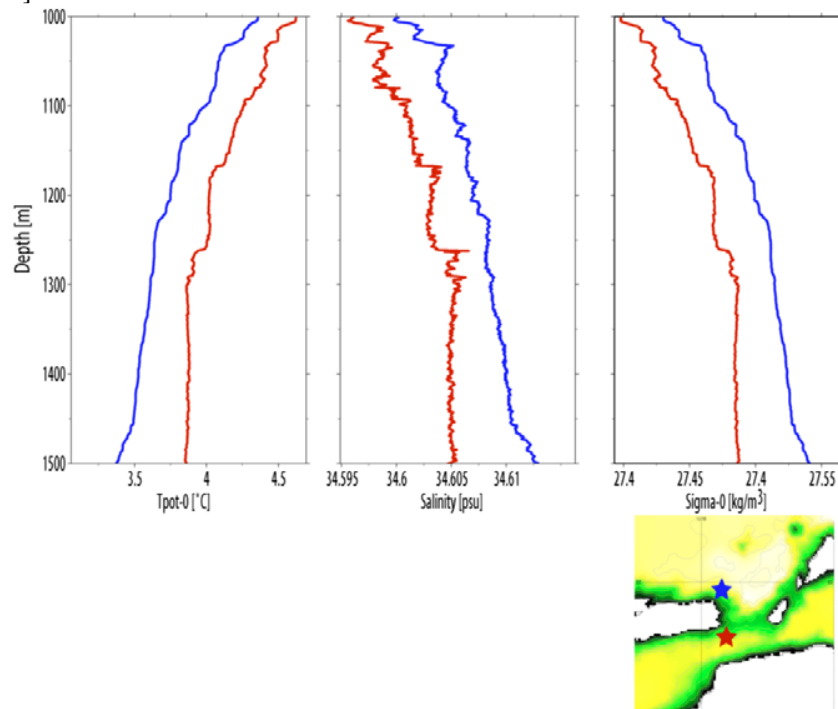
**Figure 6.** Fluctuation of seawater properties (potential temperature, salinity and potential density anomaly (a-c), and meridional current component (d) on quasi-semidiurnal time-scale in Ombai Strait.

Profiles of potential temperature, salinity and potential density anomaly ( $\sigma_t$ ) from INSTANT CTD measurements in the north Ombai side (Flores/Banda Sea) and south of Ombai (Savu Sea) between 1000-1500 m depth are separate (Figure 7). The Flores/Banda water masses in north side of Ombai is characterized by much cooler, saltier, and denser water, while Savu water mass in south side of Ombai is characterized by warmer, less salty and less dense water. Intense and strong internal tidal activities in deeper layer in Ombai Strait are strongly suspected to cause a mixing of water masses at semidiurnal tidal-scale.

Water masses in deeper layer before passing through Ombai Strait has a characterized by much cooler, saltier and denser water, but after passing through the Ombai Strait the characteristics of the water mass changes to be warmer, less salty and less dense water. This indicated that the vertical mixing is strong enough in Ombai straits to change the characteristics of the water mass. The intens



vertical mixing in Ombai Strait is strongly suspected due to the deep sill at the bottom of the waters interacting with the internal waves [16,20]. Baroclinic tides in Ombai Strait are generated by Ombai sill, generating strong internal tides waves [32], as confirmed by field measurement [21,20] and by the model [32,36].

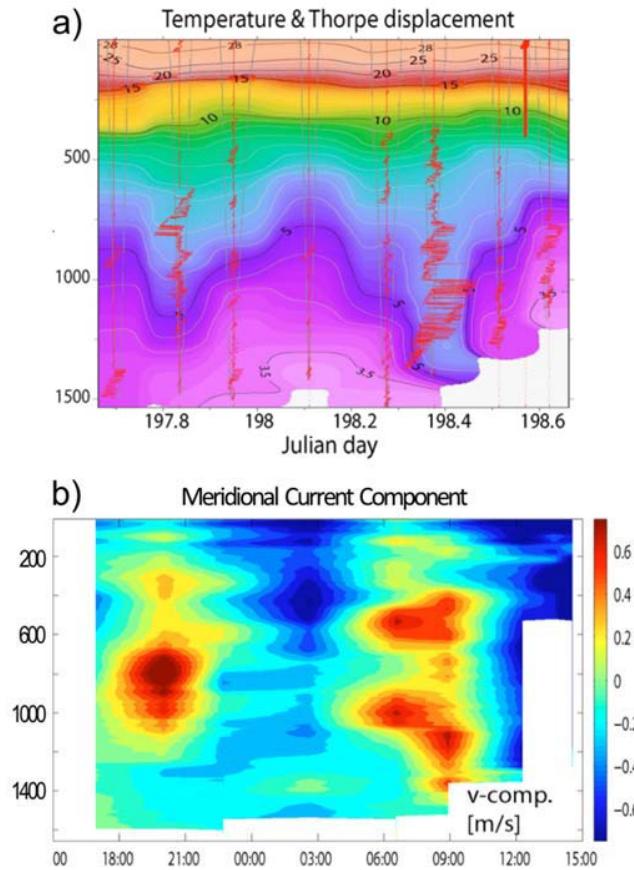


**Figure 7.** Comparison of potential temperature and salinity profiles in Ombai/SavuSea side and Flores/Banda Sea side at deeper layer between 1000 m and 1500 m depth. Colder, saltier and denser water mass is found in Flores/Banda Sea, compared to warmer, less salty and less dense water in Savu Sea. Data source: the CTD archive data from INSTANT measurement in June 2005 [7].

Depth-time plot of potential temperature, overlayed with Thorpe displacement ( $d$ ) profiles during a tidal cycle (Figure 8a) reveals that Thorpe displacement appears to be maximum at deeper layer between 600 m and 1500 m depth, in contrast, its minimum is found in the upper thermocline layer (0-500 m depth). The high static stability at the thermocline layer causes the low Thorpe displacement [37]. During the northward flood tide (yellow-red color in figure 8b), the Thorpe displacement increases in deeper layer, and conversely during the southward ebb tide. A strong Thorpe displacement occurs twice in 24-hour measurement, when reversal meridional current flows northward (yellow-red color, figure 8b). This is assumed because the northward propagation of the tidal current against the dominant southward flow of the Ombai ITF, so it can cause baroclinic instability of water column during this tidal period. High Thorpe displacement corresponding to the northward tidal current (for example around 20:00 and 09:00 local time), characterized by much warmer water mass. On the other hand, when the southward meridional current (for example around 03:00 and 13:00), Thorpe displacement are relatively low and is dominated by much cooler water mass. So it can be assumed that there is an exchange and mixing of water masses in the deep layer in Ombai between Flores/Banda water mass and Savu sea water mass.

Deep homogeneous layer in Ombai Strait revealed much larger Thorpe displacement that varies between 20 m and 107 m, compared to those observed in the mixed surface and thermocline layers [20]. The high value of Thorpe displacement at deeper layer may be due to the interaction between currents and rough topography [38]. The Ombai Strait is a region with a high current velocity (up to 0.5 m/s) [9]. The high Thorpe displacement in the Ombai Strait indicates that there is a strong mixing

of the water mass on deeper homogenous layer, so that, it is very reasonable that internal tidal waves influence strongly the characteristics of water mass when passing through Ombai Strait.



**Figure 8.** (a) Depth-time plot of potential temperature, overlaid with 9 Thorpe displacement profiles during a tidal cycle (24-hour); (b) Structure of meridional current component obtained from LADCP on July 15-16 2010.

#### 4. Conclusion

Vertical structure of zonal and meridional current components during a tidal cycle (24-hour) measurement in Ombai Strait has been described in its associated with possible deep water masses exchange induced by internal tidal waves. Since the north-south orientation of Ombai Strait, it is revealed that meridional (north-south) current component is predominant. It is found two reversals of meridional flow during a tidal cycle, expressed by northward flood current (high tide) and southward ebb current (low tide), associated with a propagation of semidiurnal tidal waves originated from the Indian Ocean. During the low tide, a quasi-persistent southward Ombai ITF modulates southward ebb current, resulting in asymmetric pattern of flood/ebb currents. Ombai ITF is characterized by a strong persistent southward flow that extends vertically to about 800 m depth. The northward flow (flood current) brings water mass from Savu Sea into Flores/Banda Sea, characterized by warmer, less salty and less dense water. On the other hand, the southward flow is associated with the arrival of cooler, much salty and much dense water from Flores/Banda Sea. A drastic increase of the Thorpe displacement is found during the northward flood current, when the flood current against the southward persistent Ombai ITF. This suggests that an intense of deep water mass mixing and exchange between Flores/Banda water and Savu Sea water may take place on semidiurnal tidal scale in Ombai Strait.

Further hydrographic and microstructure measurement is needed to quantify turbulent mixing in both sides of Ombai Strait.

### 5. Acknowledgment

The authors say many thanks to ministry of Ristekdikti who has funded this research. The authors also express great gratitude to Ariane Koch-Larrouy (INDOMIX PI), all INDOMIX cruise team and Marion Dufresne crew for their cooperation.

### References

- [1] Wyrski K 1961 *Physical Oceanography of the Southeast Asian Waters* Naga Report Volume 2 (California: University of California) p 225
- [2] Gordon A L 1986 Inter-ocean exchange of thermocline water *J. Geophys. Res.* **91** 5037-5046
- [3] Ffield A and Gordon A L 1992 Vertical mixing in the Indonesian thermocline *J. Phys. Oceanogr.* **22** 184-195
- [4] Gordon A L 2005 Oceanography of the Indonesian Seas and their Throughflow *Oceanography* **18** 14-27
- [5] Gordon A L, Susanto R D, Ffield R D, Huber B A, Pranowo W and Wirasantosa S 2008 Makassar Strait Throughflow, 2004 to 2006 *Geophys. Res. Lett.* **35** 1-5
- [6] van Aken H M, Brodjonegoro I S and Jaya I 2009 The deep-water motion through the Lifamatola Passage and its contribution to the Indonesian Throughflow *Deep-Sea Res.* **56** 1203-1216
- [7] Atmadipoera A, Molcard R, Madec G, Wijffels S, Sprintall J, Koch-Larrouy A, Jaya I and Supangat A 2009 Characteristics and variability of the Indonesian throughflow water at the outflow straits *Deep-Sea Res. I.* **56** 1942-1954
- [8] Molcard R, Fieux M and Syamsudin F 2001 The throughflow within Ombai Strait *Deep-Sea Res. Pt. I* **48** 1237-1253
- [9] Sprintall J, Wijffels S E, Molcard R and Jaya I 2009 Direct estimation of the Indonesian Throughflow entering the Indian Ocean: 2004-2009 *J. Geophys. Res.* **114** 1-19
- [10] Hautala S L, Sprintall J, Potemra J, Ilahude A G, Chong J C, Pandoe W and Bray N 2001 Velocity structure and transport of the Indonesian Throughflow in the major straits restricting flow into the Indian Ocean *J. Geophys. Res.* **106**(19) 527-546.
- [11] Sprintall J, Wijffels S E, Molcard R and Jaya I 2010 Direct evidence of the South Java current system in Ombai Strait *Dyn. Atmos. Oceans* **50**(2) 140-156
- [12] Shea E R and Broenkow W W 1981 The role of internal tides in the nutrient enrichment of Monterey Bay, California *Estuar. Coast. Shelf. S.* **15** 57-66
- [13] Gordon A L, Susanto R D and Vranes K 2003 Cool Indonesian Throughflow as a consequence of restricted surface layer flow *Nature* **425** 824-828
- [14] Nakamura T, Awaji T, Hatayama T, Akitomo K, Takizawa T, Kono T and Fukasawa M 2000: The generation of large-amplitude unsteady lee waves by subinertial K1 tidal flow: A possible vertical mixing mechanism in the Kuril Straits *J. Phys. Oceanogr.* **30** 1601-1621
- [15] Carrere L and Lyard F 2003 Modeling the barotropic response of the global ocean to atmospheric wind and pressure forcing - comparisons with observations *Geophys. Res. Lett.* **30**(6) 1275
- [16] Koch-Larrouy A, Madec G, Bouruet-Aubertot P and Gerkema T 2007 On the transformation of Pacific Water into Indonesian Throughflow water by internal tidal mixing *Geophys. Res. Lett.* **34** 1-6
- [17] Robertson R and Ffield A 2005 M2 baroclinic tides in the Indonesian Seas *J. Oceanogr.* **18** 62-73
- [18] Garrett C 2003 Internal tides and ocean mixing *Science* **301**(5641) 1858-1859
- [19] Laurent L S and Garrett C 2002 The role of internal tides in mixing the deep ocean *J. Phys. Oceanogr.* **32** 2882-2899
- [20] Suteja Y, Atmadipoera A S and Purba M 2015 Turbulent mixing in Ombai Strait (in Bahasa) *Jurnal Ilmu dan Teknologi Kelautan Tropis* **7**(1) 71-82

- [21] Koch-Larrouy A, Atmadipoera A, van Beek P, Madec G, Aucan J, Lyard F, Grelet J and Souhaut M 2015 Estimates of tidal mixing in the Indonesian Archipelago from multidisciplinary INDOMIX in-situ data. *Deep-Sea Res. Pt. I.* **106** 136-153
- [22] Bouruet-Aubertot P, Cuypers Y, Ferron B, Dausse D, Ménage O, Atmadipoera A and Jaya I 2018 Contrasted turbulence intensities in the Indonesian Throughflow: a challenge for parameterizing energy dissipation rate *Ocean Dynamics* (in press).
- [23] Thurnherr A M 2008 How to process LADCP data with the LDEO software (last updated for version IX.5)
- [24] Visbeck M 2002 Deep velocity profiling using lowered acoustic Doppler Current Profilers: bottom track and inverse solutions *J. of Atmos. and Oceanic Tech.* **19** 794-807
- [25] Thurnherr A M 2014 How to process LADCP data with the LDEO software (Versions IX.7 – IX.10)
- [26] Firing E and Hummon J M 2010 Shipboard ADCP measurements. The GO-SHIP repeat hydrography manual: a collection of expert reports and guidelines. IOCCP report 14, *ICPO publication series* **134**
- [27] Song Q and Gordon A L 2004 Significance of the vertical profile of the Indonesian Throughflow transport to the Indian Ocean *Geophys. Res. Lett.* **31** 1-4
- [28] Hatayama T, Awaji T and Akitomo A 1996 Tidal currents in the Indonesian seas and their effect on transport and mixing *J. Geophys. Res.* **101**(12) 353-373.
- [29] Cresswell G, Frische A, Peterson J and Quadfasel D 1993 Circulation in the Timor Sea *J. Geophys. Res.* **98**(C8) 14379-14389
- [30] Molcard R, Fieux M, Swallow J C, Ilahude A G, and Banjarnahor J 1994 Low frequency variability of the currents in Indonesian Channels *Deep-Sea Res.* **41** 1643-1661
- [31] Molcard R, Fieux M and Ilahude A G 1996 The Indo-Pacific throughflow in the Timor Passage *J. Geophys. Res.* **101**(C5) 12411-12420
- [32] Robertson R and Field A 2005 M2 Baroclinic tides in the Indoensian Seas. *J. Oceanogr.* **18** 62-73
- [33] Shanmugam G 2014 Review of research in internal-wave and internal-tide deposits of China:: Discussion. *J. Palaeogeogr.* **3**(4) 332-350
- [34] Van Bennekom A J 1988 Deep-water transit times in the eastern Indonesian basins, calculated from dissolved silica in deep and interstitial water *Neth. J. Sea Res.* **22** 341-354
- [35] Fieux M, Molcard R and Ilahude A G 1996 Geostrophic transport of the Pacific-Indian Oceans throughflow *J. Geophys. Res.* **101**(C5) 12421-12432
- [36] Nugroho D, Koch-Larrouy A, Gaspar P, Lyard F, Reffray G and Tranchant B 2017 Modelling explicit tides in the Indonesias seas: an important process for surface water properties *Mar. Poll. Bull.* doi: 10.1016/j.marpolbul.2017.06.033.
- [37] Thorpe S A 2007 *An introduction to ocean turbulence* (Cambridge: Cambridge University Press) p 235
- [38] Polzin K L, Toole J M, Ledwell J R and Schmitt R W 1997 Spatial variability of turbulent mixing in the Abyssal Ocean *Science* **276** 93-96