Characteristics of Tidal Currents in the Lombok Strait Using 3D FVCOM Numerical Model

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Abstract. The Lombok Strait located between Bali Island and Lombok Island, Indonesia. Lombok Strait is a complex area because influenced by Indonesian Throughflow and influenced by Tidal Current. For this case want to research about tidal current circulation and simulated using a three-dimensional baroclinic hydrodynamic numerical modeling method by Finite Volume Coastal Ocean Model (FVCOM). The study was simulated during 1-year on 2004, February. The model just simulated by barotropic condition and only influenced by elevation tide in open boundary. The verification of ocean current (u and v components) from the model compare with observation data has a high coefficient of determination, i.e., 0.9, respectively. This verification result shows good agreement between model and observation data. For the result model, in the Lombok strait dominant influenced by M2 semidiurnal component from Indian Ocean and K1 diurnal component from Pacific Ocean. The current circulation in the near surface dominant movement pattern from southern to northern. On the other hand, for the vertical current in 100 – 600 meter is different with near surface. The current movement from northern to southern. In the sill area have upwelling phenomenon in the north side of the sill and downwelling in south of the sill.

1. Introduction
The water mass condition in the Lombok Strait is influenced by the water mass from the Pacific Ocean to the Indian Ocean. This is due to the difference in sea level between oceans. The Pacific Sea level is higher than the Indian Ocean, which is one of the drivers of Indonesian Throughflow (ITF). The condition of this sea-level difference varies seasonally [1, 2, 3].

Besides being influenced by the ITF, the waters of the Lombok Strait are waters with a complex coastline and are influenced by the tide phenomenon [4, 5]. A previous study conducted on the waters of the Lombok Strait conducted by Hatayama [6] still using a rough grid resolution of 1/12 x 1/12 degree.
Several studies have investigated the ITF and internal waves in the waters of the Lombok Strait, but rarely discuss the characteristics of tidal currents in the waters of the Lombok Strait. In this paper, we will discuss the characteristics of tidal currents in the waters of the Lombok Strait using numerical calculations. Furthermore, it will be analysed horizontally and vertically with 1-year time simulation.

2. Methods

2.1. Model Design
The location of the model simulation covers the Lombok Strait area, and detail can be seen in Figure 1. The specifications of parameters and notes related to the model can be seen in Table 1. The model is barotropic. This model does not consider other parameters like wind stress, atmospheric pressure, heat flux, and freshwater flux. It is reasonable to investigate the impacts of stratification to add baroclinic tides into our future model. Furthermore, the ITF, which is not resolved in this model, has not interacted with the tides and alters tidal dynamics in this region. In the future model, the ITF will be used to evaluate the effect of the throughflow on the tidal fields.

![Figure 1. Model area domain](image)

Table 1. Hydrodynamic model design

| Item            | Information                                                      |
|-----------------|------------------------------------------------------------------|
| Grid            | Unstructured triangular grid with a resolution of 500m - 6000m (distance between the two closest nodes) |
| Layer           | Parabolic layer with 30th sigma layer                             |
| Open boundary   | Tide elevation (S2, M2, N2, K2, K1, P1, O1 dan Q1) from Tide Model Driver (TMD). |
2.2 Hydrodynamic Model
This study using numerical modelling Finite Volume Coastal Ocean Model (FVCOM). FVCOM using two modes (external and internal), which are calculated separately with the hydrodynamic model equations consist of continuity and momentum equations (1 - 3), temperature (4), salinity (5), and density (6) [7] as follows:

\[
\frac{\partial \zeta}{\partial t} + \frac{\partial Du}{\partial x} + \frac{\partial Dv}{\partial y} + \frac{\partial \omega}{\partial \sigma} = 0
\]

\[
\frac{\partial uD}{\partial t} + \frac{\partial u^2 D}{\partial x} + \frac{\partial uvD}{\partial y} - f vD = -gD \frac{\partial \zeta}{\partial x} - gD \frac{\partial}{\partial \sigma} \left[ \frac{\partial}{\partial x} \left( D \int_{0}^{\sigma} \rho d\sigma' \right) + \sigma \rho \frac{\partial D}{\partial \sigma} \right] + \frac{1}{D} \frac{\partial}{\partial \sigma} \left( K_m \frac{\partial u}{\partial \sigma} \right) + D F_x
\]

\[
\frac{\partial vD}{\partial t} + \frac{\partial v^2 D}{\partial x} + \frac{\partial uvD}{\partial y} - f uD = -gD \frac{\partial \zeta}{\partial y} - gD \frac{\partial}{\partial \sigma} \left[ \frac{\partial}{\partial y} \left( D \int_{0}^{\sigma} \rho d\sigma' \right) + \sigma \rho \frac{\partial D}{\partial \sigma} \right] + \frac{1}{D} \frac{\partial}{\partial \sigma} \left( K_m \frac{\partial v}{\partial \sigma} \right) + D F_y
\]

\[
\frac{\partial TD}{\partial t} + \frac{\partial T uD}{\partial x} + \nu \frac{\partial TvD}{\partial y} + \frac{\partial T \omega}{\partial \sigma} = \frac{1}{D} \frac{\partial}{\partial \sigma} \left( \frac{K_h}{\partial \sigma} \right) + D \dot{H} + D F_T
\]

\[
\frac{\partial SD}{\partial t} + \frac{\partial SuD}{\partial x} + \nu \frac{\partial SvD}{\partial y} + \frac{\partial S \omega}{\partial \sigma} = \frac{1}{D} \frac{\partial}{\partial \sigma} \left( \frac{K_h}{\partial \sigma} \right) + D F_S
\]

\[
\rho = \rho(T,S)
\]

Where \(x, y,\) and \(\sigma\) are directions for east and west, north and south, and also vertical in the Cartesian coordinate system; \(u, v,\) and \(\omega\) are the components of the current velocity for the \(x, y,\) and \(\sigma\) directions; \(T\) is the temperature; \(S\) is salinity; \(\rho\) is the density while \(\rho_0\) is the reference density; \(f\) is the Coriolis force; \(g\) is gravity; \(K_m\) is the vertical eddy viscosity; and \(K_h\) is the thermal vertical eddy diffusion coefficient. \(F_x, F_y, F_T,\) and \(F_s\) represent friction in the \(x\) and \(y\) directions, thermal, and salinity diffusion; \(D\) is the total depth of the water column; is the absorption of radiation into the water column; \(\zeta\) is the height of the water surface elevation.

2.3. Model Verification
The \(u\) and \(v\) component of current model will be validated with observation data taken in 2004 (1-29 February) using the Acoustic Doppler Current Profiler (ADCP) from INSTANT (International Nusantara Stratification and Transport) program. Locations of observation points for verification of current, can be seen in Figure 2.

To verify between model result and observation data, correlation analysis and root mean square error (RMSE) were carried out, which were written in equations (7) and (8) as follows:

\[
r = \frac{\sum_{i=1}^{n} x_{insitu,i} - x_{model,i}}{\sqrt{\sum_{i=1}^{n} (x_{insitu,i} - x_{model,i})^2}}
\]

\[
RMSE = \sqrt{\frac{\sum_{i=1}^{n} (x_{insitu,i} - x_{model,i})^2}{n}}
\]

\[
\sum_{i=1}^{n} xy - \left( \sum_{i=1}^{n} x \right) \left( \sum_{i=1}^{n} y \right)
\]

\[
\sqrt{\left( \sum_{i=1}^{n} x^2 - \left( \sum_{i=1}^{n} x \right)^2 \right) \left( \sum_{i=1}^{n} y^2 - \left( \sum_{i=1}^{n} y \right)^2 \right)}
\]
where $r$ is the correlation coefficient, $n$ is the number of samples, $\sum x$ is the total number for the item variable $x$, and $\sum y$ is the total number for the item variable $y$. While in the RMSE equation, $X_{\text{instu}}$ is the value of the observations and $X_{\text{model}}$ is the value obtained from the model results, and $n$ is the amount of data.

![Figure 2. Observation data location of ADCP from INSTANT Data](image)

3. Result and Discussion

3.1 Verification of Hydrodynamic Model Result

The comparison of the current verification between the model results and observations for $u$ and $v$ components can be seen in Figure 3. The calculation of the correlation between the $u$ and the $v$ components shows a significant correlation value of 0.9, respectively. This value implies a good agreement current pattern between model and observation data. Meanwhile, the Root Mean Square Error (RMSE) calculation between the model and observations for $u$ and $v$ components i.e. 0.006 m/s and 0.025 m/s, respectively. The current conditions in the model can describe conditions in the field.

![Figure 3. Verification of $u$ (above) and $v$ (below) components between model (blue line) and observation (black line) data on February 1 to February 29, 2004 in Lombok Strait (Depth 100m)](image)
3.2 Tidal Components and Phase

Figures 4 and 5 show the simulation of co-range and co-phase in Lombok Strait. The model results show that the condition of the waters of the Lombok Strait is dominantly influenced by the condition of the M2 tidal component, namely the semi-diurnal condition. Meanwhile, diurnal conditions are influenced by the tidal component of K1. These results are in agreement with previous studies conducted by Ray [8] and Yang. The tidal component of M2 in the waters of the Lombok Strait itself is influenced by the Indian Ocean, while for K1, it is influenced by the waters of the Pacific Ocean.

![Figure 4. Co-range in Lombok Strait](image1)

![Figure 5. Co-phase components in Lombok Strait](image2)
3.3 Near Surface Current Circulation

Figures 6 show the simulation of the average current circulation in the near-surface layer in 15 days, 30 days, and one year in Lombok Strait. The current is dominant from the Indian Ocean to the north of Lombok Strait from the figure. On the other hand, the current in Badung Strait comes from the Indian Ocean through Lombok Strait and moves to the Indian Ocean again with the maximum current in Lombok Strait is 1.5 m/s (red color). The current circulation is almost the same on every average (15 days, 30 days, and 1-year) due to the strength of the M2 component factor from the Indian Ocean.

Figure 6. The Average current; A (15 Days), B (30 Days), C (1-year) from Spring Tide

Ray [8] also shows that the Indian Ocean has a big influence on the energy flux vector of the M2 tidal component, which travels through Indonesian seas to the Pacific Ocean. When travelling along the Arlindo exit route through tight straits such as the Lombok Strait, Timor Sea, Ombai Strait, and other small straits near Nusa Tenggara, this M2 component has more energy. The Pacific Ocean, which passes across Indonesian waters and into the Indian Ocean, influences the energy flux vector of the K1 component. The M2 component energy flux is more dominating, with a flux energy range of 250 kW/m, while the K1 component flux energy range is only around 150 kW/m.
3.4 Dynamic of Vertical Current Circulation

The cross-sectional study area was carried out in the Lombok Strait with analysis from a depth of 0 m – 600 m; more details can be seen in Figure 7-8. The characteristics of the waters on transect A-A’ show different current velocity conditions from 0 – 100 m the current come from south to the north, and 100 – 600 m the water mass come from north to the south. From 0 – 100 m, the water mass influence by the M2 component from the Indian Ocean; on the other hand, from 100 – 600 m, the water mass influence by the K1 component from the Pacific Ocean.

The water mass movement in-depth 100 – 600 m is very strong from northern to southern. This situation affects the occurrence of upwelling and downwelling in the sill area. As seen in Figure 8, there is a strong upwelling and downwelling phenomenon in the sill area. Strong upwelling occurs north of the sill, with a maximum current of 1.2 m/s. Meanwhile, downwelling occurs in the south of the sill, with a maximum speed of 2 m/s. The high downwelling current velocity in the southern area of the sill is due to intense friction between the descending water mass and the irregular sill surface. The condition of the vertical current is almost the same on average 15 days, 30 days, and one year.

In addition, previous studies conducted by Hendrawan and Asai [4] also found the same results, where strong upwelling and downwelling phenomena were found in the north and south sills. The presence of the M2 component influences the upwelling and downwelling phenomena in the area, then the high downwelling current velocity in the southern area due to the influence of short internal tidal waves. In addition, the movement of high upwelling currents in the northern part of the sill allows particles to rise rapidly. As for the southern sill area, strong downwelling allows the particles to descend more quickly. After one cycle of the M2 tidal period, particles on the northern side of the Lombok sill were swiftly flowing upward; some of these particles on the northern side of the sill only needed one cycle of the M2 tidal period to reach the upper layer [4].
Figure 8. The pattern of average current on the transect A-A’ (0 m - 600 m) from Spring Tide
4. Conclusion
The results show that the M2 component affects the waters in the Lombok Strait. The M2 component is dominated by tidal waves propagating from the Indian Ocean; In this case, it results in semidiurnal energy. Meanwhile, waves from the Pacific Ocean are the K1 component in the Lombok Strait; in this case, it results in diurnal energy.

The water mass in 0-100 m and 100 – 600 m have a different characteristic pattern. In 0 – 100 m, the water mass comes from southern; on the other hand, in 100-600 the water mass come from southern. That is conditions influence upwelling (north side of the sill) and downwelling (south side of the sill).

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