Numerical simulation of M2 tide in the Makassar Strait

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Abstract. Because of the ITF system, Makassar Strait (MS) has an important role in the Indian Ocean and Indonesia seas. Tides, current, heat, and freshwater from the Pacific Ocean transferred to that ocean through the MS. By using a two-dimensional numerical model, this paper aims to observe the M2 patterns and their effect on the current circulation. For model validity, we compared the M2 tides with the assimilation data obtained from Geospatial Indonesian Agency (BIG tides). The model of amplitude and phases of Makassar Strait show good results. Amplitude is high in the southern bay of Kalimantan and the northeast of MS. The low amplitude can be seen at the south of MS. The phases are denser in the south of MS than in the center and north of MS. The M2 current circulation always moves to the south of MS during M2 periods (t=T/4, t=T/2, t=3T/4, and t=T). The currents are strong around Sulawesi Island. The results show that M2 has a great contribute to MS circulation and the ITF.

1. Introduction

With a variety of parts and ocean basins, the Indonesian sea provides a rotating route for tropical Pacific water to flow into the Indian Ocean, which is referred to as Indonesian throughflow (ITF). The tendency of the ITF to pass through the western part is most widely available in the Indonesian sea, establishing the Makassar Strait as the main entry point for Pacific water [1]. However, the ITF component entered deeper, which was blocked by Dewakang Sill 680 m in the south of the Makassar Strait [2].

The Makassar Strait is a strait located in the islands of Borneo and Sulawesi in Indonesia [3]. This channel connects the Sulawesi Sea to the north and the Java Sea to the south. These waters are influenced by the monsoon, tides, and thermohaline circulation. During the western monsoon, the circulation of surface currents in the Makassar Strait goes south and turns east then continues to the Pacific Ocean and the Arafura Sea. Whereas in the eastern monsoon, the currents in the Makassar Strait go south which turn west towards the Java Sea and eastward towards the Pacific Ocean [4]. Due to monsoonal wind, this strait have variation of Chlorophyll-a and sea surface temperature (SST) [5] and they cause fishing ground location and fish species [6, 7].

The Makassar Strait shows significant tidal and intravenous variability, defined as non-tidal oscillations with specific periods of less than 100 days. Intraseasonalvariability was previously documented in the Indonesian region [8].

Two-dimensional tidal currents generally involve two components of velocity u and v that join together to move water particles around the elliptical path. For individual constituents (say M2
with M2 angular frequency), these components take the form of a cosine function of time \( t \) with different amplitudes \( u_{M2} \) and \( v_{M2} \) and phase \( \delta u \) and \( \delta v \) [9]. M2 waves are the primary tidal waves that dominate most of the ocean. M2 tides vary and are influenced by topography, depth, astronomy and meteorology [10]. Information about tidal components of M2 tides still needs to be studied due to topographic variations.

2. Materials and Methods
The domain of model is Makassar Strait between the islands of Kalimantan and Sulawesi, Indonesia. The strait also connects the Sulawesi Sea in the north with the Java Sea in the south. The Makassar Strait belongs to the deep sea category and is one of the Indonesian Archipelago Sea Grooves.

The domain of this paper covers the waters of Makassar Strait between \( 116^\circ -120^\circ \) E and \( -3^\circ -1^\circ \) N. Spatial resolutions are \( \Delta x = \Delta y = 3 \) minutes and \( \Delta t = 20 \) seconds following criteria (CFL). The condition of Makassar Strait is deep waters where the most profound depth is 3000 meters.

![Figure 1. Bathymetry of Makassar strait](image)

The models used are based on 2D numerical models as was applied in the Aceh Barat Daya waters and Sabang Bay [11, 12]. The solution of this model was derived by [13] and has been used by several authors with friction coefficient below \( r = 0.0025 \) (this coefficient is the same as used by [14 -17]) and lateral eddy viscosity \( A_h = 100 \). The constituents of tides (amplitude and phase of M2) are obtained from the BIG tide data that has been provided by Geospatial Information Agency (GIA). Based on the simulation results by [14], the value of open boundary is significant in determining the magnitude and direction of ocean currents in a two-dimensional model. This model also implemented in Aceh waters such as Sabang, West Aceh, and North Aceh waters [18, 19, 20].

BIG data tides the full domain is used as a comparison to our model. The hydrodynamic equation used in this study is as follows [13]:

\[
\frac{\partial u}{\partial t} + \text{Adv}_h(u) - f v = -g \frac{\partial \eta}{\partial x} \frac{x_{\text{top}}}{\rho_{\text{h}}} + \text{Diff}_h(u) \tag{1}
\]

\[
\frac{\partial v}{\partial t} + \text{Adv}_h(v) + f u = -g \frac{\partial \eta}{\partial y} \frac{x_{\text{top}}}{\rho_{\text{h}}} + \text{Diff}_h(v) \tag{2}
\]

\[
\frac{\partial \eta}{\partial t} + \frac{\partial (u \eta)}{\partial x} + \frac{\partial (v \eta)}{\partial y} = 0 \tag{3}
\]
The open boundary equation is shown in Equation 4:

\[ \eta = A_m \cos \left( \frac{2\pi}{T_{m2}} t - \phi_{m2} \right) \]  

(4)

while equations (5) and (6) are used to calculate the amplitude and phase from the results of the two-dimensional model simulation.

\[ A = \sqrt{\left(0.5 \left( \eta^{TM2/4} - \eta^{2TM2/4} \right)^2 + 0.5 \left( \eta^{TM2} - \eta^{TM2/2} \right)^2 \right)} \]  

(5)

\[ \phi = \tan \left( \frac{0.5 \left( \eta^{\phi m2/4} - \eta^{3\phi m2/4} \right)}{0.5 \left( \eta^{\phi m2} - \eta^{3\phi m2/2} \right)} \right) \]  

(6)

The depth-integrated vertically velocities are indicated by \( u(t, x, y) \) and \( v(t, x, y) \), respectively. Meanwhile, \( \text{Adv}_u \) and \( \text{Adv}_v \) are advection for \( u \) and \( v \) components. \( \eta \) is sea level elevation, \( \text{Diff}_u \) and \( \text{Diff}_v \) are diffusion of \( u \) and \( v \). Parameter \( f \) is Coriolis parameter \( f = 2 \), \( g \) is gravity, \( \tau_x^{\text{bot}} \) and \( \tau_y^{\text{bot}} \) are the bottom friction in the \( x \) and \( y \) fields. Angle in the amplitude and phase of \( M2 \) tides where \( M2 \) period is 12.42 hours. M2 tide model is simulated for 40 periods to obtain phase stability. For amplitude and phase analysis, data for the last period are stored and divided every quarter of the \( M2 \) period \( (T/4, T/2, 3/4T \text{ and } T \text{ whereby } T = 12.42 \text{ hours}) \).

3. Results and Discussion

Turbulent mixing significantly affects the Makassar Strait as a meeting area for different water masses, such as fresh Javanese seawater and Pacific saltwater [21]. The Makassar Strait has a current pattern that is dominated by a mass of water from the Pacific Ocean, but the water turns into drastically fresh water in the south of Makassar Strait [22, 23]. Figures 2 (a, b) and 3 (a, b) show the amplitude and phase in the Makassar Strait waters obtained from Big tides and model simulations, respectively.

Figure 2. BIG data (a) M2 amplitude and (b) M2 phase
Amplitude M2 from BIG data and simulation results are almost the same where amplitude increases from the southern open boundary to northern open boundary. Likewise, with the BIG tide phase, the phase is quite tight in the southern part of the Makassar Strait. This result shows that the numerical model used for the simulation is satisfactory enough, although there are slight differences in the phase in the northern open boundary section.

Amplitude did not look dense in the Makassar Strait or the south open boundary. The amplitude on the coast of Kalimantan is seen dense in deep water areas, while in the coastal waters of Sulawesi, amplitude lines are rarely formed. Sulawesi coast is included in the category of deep water. The amplitude distance is affected by the depth of the Makassar Strait.
coastal part of Kalimantan. But when viewed M2 phase looks different, it is also caused by sea level in areas at higher current speeds.

![Figure 6. M2 current at 0.75 T](image1)

In M2 elevation at $t = 0.25$, we have the elevation conditions based on the contours formed. The smallest elevation value is 0.3 m in the southern open boundary section, while the highest elevation value is 0.5 m, which is in both open boundary sections. In the middle part of the Makassar Strait, the elevation value is not significant from the highest and lowest elevation values of 0.45 m.

M2 elevation at $t = 0.5$ shows that the formation of contours that show elevation values in each part, but the elevation that occurs is very small and almost no elevation occurs. The lowest elevation value is 0, but for the highest elevation value. It can be seen that the elevation value is 0.05 m, which is only found in the northern open boundary section. M2 elevation that occurs at $t = 0.75$ shows the lowest elevation value is 3.5 m in the open boundary section in the south. The northern open boundary had elevation 0.6 m. The elevation at $t = 1$, it can be seen that in the southern part of the open boundary the elevation is smaller than the elevation in the north.

4. Conclusions

Currents in the Makassar Islands moves from north to south with higher current velocity in the Sulawesi sea level flow from the Pacific Ocean to the Makassar Strait then from the Makassar Strait to the Java Sea. M2 amplitude occurs tightly in the east coast of Borneo Island, and then shallow depth is rarely in the middle. The shallow area of the Makassar Strait, namely the East Coast of Kalimantan M2, the phase is tighter in parts of Kalimantan; the island is rare shallow.

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