Numerical study of M2 tide on the Gulf of Thailand

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Abstract. According to the previous study, M2 from SCS amplified around the coastal region but almost low in the Gulf of Thailand (hereafter GoT). To detect the M2 at the shallow part of GoT, we used the 2D numerical model simulation. The model was driven by M2 amplitude and phase from a high-resolution spatial data provided by the Geospatial Indonesia Agency. M2 model was well verified with the recent studies and assimilation data. We showed the amphridomic point around southeastern of GoT around 103.5° E and 8.5-8.6° N. The amphridomic point has clockwise direction. We also showed a virtual amphridomic point at the east of GoT (100° E and 11.5-12° N). The M2 amplitude was highest in the Bangkok Bay. The study showed an important of the high-resolution model simulation on the GoT tides.

1. Introduction

The GoT is a shallow bay located between the continental shelf of Thailand and the South China Sea (an area of about 35,000 km²) [1]. GoT is bordered by Vietnam, Cambodia, Thailand and Malaysia [2]. The maximum depth of the GoT is 80 m, and the average is 45 m [3]. GoT is also connected with a large estuary such as the Chao Phraya river and the Mekong river. The water flow from the rivers makes GoT low salinity (3.05-3.25%) and also rich in sediment [4].

Tides in the GoT were dominated by diurnal tides originating from the Pacific and the South China Sea [5]. The dynamics of tides in the GoT had been studied in some recent researchs [6-8]. According to Yanagi & Takao [7], the tidal period of semidiurnal and diurnal constituents in the GoT was much shorter than the inertia period. Also, in the bay section, which was narrower than the length of the Rossby deformation, the Coriolis force was not affect the tidal phenomenon. Meanwhile, the study showed that M2 was quite small in the GoT and almost the same as the central part of the SCS [8]. M2 from the Pacific was transmitted from the Pacific Ocean to the GoT via the Luzon Strait and SCS. M2 experienced a very significant reduction after going through the Luzon Strait as a result of topographic friction.
In recent days, information about M2 tides still needs to be studied because the topographic variation of the GoT had a significant impact on M2 tides. According to Sindhu & Unnikrishnan [9], tides could be mapped better if the representation of the depth of the shallow waters was precisely known. This research aimed to study the dynamics of M2 in GoT with two-dimensional numerical simulations. Tides had a significant contribution to bay dynamics such as sedimentation, flood disasters, and other meteorological disasters. The results of the simulation was compared with previous research and analysis data.

2. Materials and Methods
The model domain (99.00 - 105.25 E and 8.5 - 13.75 N) was obtained from SRTM30. The model was discretized with spatial resolution $\Delta x = \Delta y = 5$ minutes and $\Delta t = 20$ seconds following the criteria of CFL (Courant-Freiderichs-Lewy), so that the size of 76 x 64 grids was obtained. The model used was based on 2D numerical models and successfully applied by several authors [10-16]. This model was derived by explicit and semi implicit difference methods [17]. Advection and diffusion completion used TVD (total variation diminishing) with a friction coefficient below $r = 0.0025$ and lateral eddy viscosity $A_h = 100$.

The hydrodynamic equation used in this study is as follows [17]:

$$\frac{\partial u}{\partial t} + \text{Adv}_h(u) - f v = -g \frac{\partial \eta}{\partial x} - \frac{\tau_{bot}}{\rho_0 h} + \text{Diff}_h(u)$$

$$\frac{\partial v}{\partial t} + \text{Adv}_h(v) + f u = -g \frac{\partial \eta}{\partial y} - \frac{\tau_{bot}}{\rho_0 h} + \text{Diff}_h(v)$$

$$\frac{\partial \eta}{\partial t} + \frac{\partial (uh)}{\partial x} + \frac{\partial (vh)}{\partial y} = 0$$

The set of the equation includes the equations of zonal (1) and meridional (2) momentum with the influence of advection ($\text{Adv}_h(u,v)$), gradient pressure force due to sea level, bottom friction, and diffusion ($\text{Diff}(u,v)$). Where $\eta$ is sea level, while $u$ and $v$ are components of west-east and south-north current velocities, respectively. The coriolis style is defined as $f=2\Omega \sin \phi$ ($\Omega = 7.29 \times 10^{-5}$ and $\phi = $...
The bottom friction stress is indicated by \( \tau_{x,bot} \) for the directions x and \( \tau_{y,bot} \) for the y direction. The M2 tide generator equation in open boundary is as follows:

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

(3)

Open boundaries were amplitude and the M2 phase of BIG tides (http://tides.big.go.id). BIG tides data were obtained from the analysis of on the spot measurements and models provided by the Indonesian Spatial Information Agency (BIG). In addition to the open boundaries, the data BIG tides were also used to verify the numerical model output.

The simulation produced sea level in every quarter of the M2 period (\( \eta T/4 \), \( \eta T/2 \), \( \eta 3T/4 \), and \( \eta T \)) then analyzed by equations (3) and (5) to get the chart of the amplitude (A) and phase (\( \phi \)) M2.

\[
A = \sqrt{0.5 \left( \eta_{TM2/4}^2 - \eta_{3TM2/4}^2 \right) + 0.5 \left( \eta_{TM2}^2 - \eta_{TM2/2}^2 \right)}
\]

(4)

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

(5)

3. Results and Discussions

The numerical simulation results and BIG data was shown in Figure 2. Simulations showed that in the middle of the bay, the amplitude of the model was quite similar to BIG tides (Fig. 2a and Fig. 2c). But in the Bangkok bay, the amplitude M2 model was quite large compared to BIG tides. It confirmed by recent research that stated the water level was higher and more variable at the top of the GoT than at the bottom of the bay [18]. Also, a strong bay coastline caused tidal M2 intensified in coastal areas.
Figure 2. M2 amplitude and phase obtained from the results of models (a, b) and BIG tides (c, d)

Our finding showed there were the virtual amphridomic and clockwise amphridomic in the west of GoT and the southeast of GoT, respectively. The amphridomics were indicated by the low of sea level and its direction based on cotidal or phase line. M2 amplitude that obtained from the model and BIG tides data were different around the Bangkok Bay. However, if we compared between our model and Zu et al. [8] results, we could find that M2 amplitude was high at the Bangkok Bay so that our model was good enough. The BIG tides and Zu et al. [8] also showed the clockwise amphridomic in the southeast of GoT.

Lines in Figure 2 (b, d) showed that the phase of the two data looks appropriate, pairs propagated mainly from the open boundary area towards the bay of Bangkok. The phase propagation was very stable, but there was an amphridomic in both of these results near the open boundary section.
Figure 3 showed the tidal current M2 in the period t = 0.25, 0.5, 0.75, and t = TM2. At t = 0.25, the current from Pattaya bay moved out of the coastline at a speed of about 0.2 m / s. Flow in parts was faster than other parts. On the other hand, the current from open boundary moved towards the Gulf and weakens around the 10 N latitude due to the high sea level in parts of Pattaya.

The current in Pattaya Bay turned at t = 0.50T M2, the current from the bay led to Pattaya Beach and towards Cambodia with a current velocity of about 0.2 m/s. The fastest current was also seen in the current to Pattaya Beach. At the current pattern t = 0.50 T M2, current from open boundary led to Cambodia. Here in the bay, it could be seen the calm stream in the middle

The current pattern looked towards the open boundary at the current pattern T = 0.75 T M2 at a speed of 0.2 m/s. On the other hand, there was also a flow pattern that leads to the Pattaya beach with a current velocity faster than the other currents.

The current on the Pattaya beach led to the bay at T = TM2, and the current was faster than the other currents. The average current was 0.2 m / s and became weak when it reached the middle of the bay. On the fringe of the Cambodian coast, there was a stream towards Phang Nga beach and the middle of the bay. In the middle of the bay, a quieter current was caused because on Pattaya beach had a low sea level.

4. Conclusions
We successfully simulated the tidal dynamics of GoT using a two-dimensional numerical model that modified from Kämpf [17]. We found the virtual amphridomic and clockwise amphridomic in the west of GoT and the southeast of GoT, respectively. The amphridomics were indicated by the low of sea level and its direction based on cotidal or phase line. M2 amplitude obtained from the model and BIG tides data were different around the Bangkok Bay. It was higher in our model than in BIG tides. However, if we compared between our model and Zu et al. results [8], we showed the same results whereby M2 amplitude was relatively high at the Bangkok Bay. It was caused by the shoaling due to narrowing of topography and shallow in depth. According to our model, BIG tides, and Zu et al. [8], we also found that the amplitude was low on the offshore or middle of GoT. Beside amplitude and phase, we also derived the M2 current from the model. M2 currents were strong in the Bay of Bangkok. The currents from the Bay of Bangkok and Pattaya Waters flew to the offshore during periods t = 0.25 T M2 and t = TM2 and reversed during t = 0.5 T M2 and t = 0.75 T M2. Based on the variation of amplitude and current at the Bay of Bangkok, we supposed that the higher resolution model was needed to resolve the M2 tides in GoT and adjacent seas.
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