Numerical Simulation of the Shallow Water Tides in Bohai Sea

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Abstract. The Princeton Ocean Model (POM), a three-dimensional primitive equation ocean model, is used to reproduce the tidal mechanism in the Bohai Sea. Firstly, the model results are validated by examining the harmonic constants of four major tides at 11 tide gauges, and then the shallow water tides are further focused on. According to the model results, it is found that both M4 and MS4 tides propagate in the similar way, which is characterized by five tidal amphidromic systems in Bohai Sea, and four of them rotate anticlockwise while another one rotates clockwise. It is also found that the M6 tide shows seven amphidromic points in Bohai Sea, among which four rotate an ticlockwise and three rotate clockwise. The model results also show that the amplitudes of three shallow water tides are relatively large in shallow coastal waters, which is closely related to generation mechanism of the shallow water tides. 

Keywords: Shallow water tide; Bohai Sea; POM; Numerical simulation.

1. Introduction
Bohai Sea is a semi-enclosed shallow sea in China, and its mean water depth is about 18 m (see Figure.1). The water and material exchange is mainly driven by the tidal dynamics [1]. Considering the water depth, the shallow water tides may play a considerable role. However, the astronomical tides were the key research points, and the reports on the shallow water tides were rare. Meanwhile, the limited research reports were mainly issued several decades ago. Since human society enters the 21 century, China is developing in a rapid way. The usage and management of the sea area is also experiencing the drastic change, which means that the coastline and the topography have changed comparable to the previous situation and the tidal propagation and its dynamics may be influenced accordingly. Therefore, a primitive equation ocean circulation model is used to simulate the tides in Bohai Sea, and the shallow water tide characteristics are investigated in this paper.

2. Model Descriptions
The Princeton Ocean Model used in this study was originally developed by Blumberg and Mellor in Princeton University, so it is generally called POM [2]. It is a 3-D primitive equation ocean circulation mode providing the open code, so it can be modified by the user or researcher for the actual application. Although the detailed introduction of the model was given by Blumberg [2], some basic characters need to be summarized here. The sigma coordinate system is used in the model, which takes the free sea surface and bottom topography as the first and last layer in the vertical, respectively. So the variation of the sea surface elevation and the smooth representation of irregular bottom topography can be simulated. The vertical mixing and horizontal diffusion are reproduced by the 2.5 order Mellor-Yamada turbulence closure scheme [3] and Smagorinski scheme, respectively, which are generally used.
in other ocean models. The internal mode and external mode are separated for treating the slow internal gravity wave and the fast external gravity wave independently, thus the computation efficiency can be enhanced effectively. An one-order upwind scheme with anti-dissipation treatment is used to reproduce the advection. This scheme is monotonic and positive-definite, a feature essential for the salinity or biological tracers, since it does not permit negative values [4].

\[
\eta_t = \sum_{i=1}^{8} f_i H_i \cos(\omega_i \cdot t + (\nu + u)_i - g_i)
\]

where \(f_i\) is the nodal factor; \(\nu_i\) is the Greenwich initial phase, \(u_i\) is nodal correction; \(w_i\) is tidal frequency; \(H_i\) is the amplitude; \(g_i\) is the phase lag; the subscript indicates the tidal constituent, namely \(M_2, S_2, N_2, K_2, K_1, O_1, P_1\) and \(Q_1\).

3. Validation of Simulations

The model was run for 35 days from a cold initiation, and the model results of the last 30 days were used for analysis, since the first 5 days were left to reach the model stability. Figure 2 shows the simulated co-amplitude and co-phase lag of \(M_2\) and \(K_1\) tides. By comparisons, it is found that the model results agree with observations reasonably. Two amphidromic points for the \(M_2\) tide are obvious: one is close to Qinhuangdao and the other is adjacent to the mouth of the old Yellow River. Moreover, it is found that the former is further away from Qinhuangdao compared to Fang’s report [5], which may be due to the variation of the coastal line and the topography in the local sea region.

Table 1 gives the comparisons of the computed and observed harmonic constants of 4 major tides at 11 tidal gauges. The differences are positive at some stations and negative at the other sites, implying that the model results do not include the systemic errors. The square mean errors of 4 tides are further computed, in which the amplitude and phase lag of \(M_2\) are 11.82cm and 10.43° respectively; the
amplitude and phase lag of S\textsubscript{2} are 5.23 cm and 12.74° respectively; the amplitude and phase lag of K\textsubscript{1} are 6.40 cm and 9.63° respectively; the amplitude and phase lag of O\textsubscript{1} are 4.27 cm and 9.64° respectively. Therefore, the model results are reasonable and validated. As for the slight deviations at some stations, two potential reasons may be responsible for: (1) the new topography data has been used in this study, which may be incompatible with the primitive observations; (2) the tidal gauges are near the coastal line, the orthogonal grids adapted in the model may generate the interpolation errors. In addition, one amphidromic point of M\textsubscript{2} tide is close to the site 8, so the deviations at this station are especially obvious. Based on the comprehensive comparison and analysis, the simulation can reproduce the tidal system in Bohai Sea rather well, which is essential for the further investigating the shallow water tides by using the model results.

Figure 2. Simulated co-amplitude (cm) and co-phase lag (degree) of (a) M\textsubscript{2} and (b) K\textsubscript{1} constituent in Bohai Sea. Dashed and solid lines indicate amplitude and phase, respectively.

Table 1. Comparisons of computed and observed harmonic constants.

| Tidal gauge | Latitude (°N) | Longitude (°E) | ∆H(cm) | ∆g(°) | ∆H(cm) | ∆g(°) | ∆H(cm) | ∆g(°) | ∆H(cm) | ∆g(°) | Mean Square Error |
|-------------|---------------|---------------|--------|-------|--------|-------|--------|-------|--------|-------|------------------|
| 1           | 38.97         | 121.30        | -8.77  | -6.22 | -1.48  | -7.00 | -2.75  | -5.21 | -2.32  | 4.47  |                  |
| 2           | 39.27         | 121.60        | -10.05 | -12.51| -3.33  | -14.99| -8.11  | -18.15| -4.05  | -2.00 |                  |
| 3           | 39.40         | 121.28        | -8.44  | -11.09| -1.60  | -15.18| -5.62  | -7.02 | -4.65  | -2.16 |                  |
| 3           | 39.47         | 121.25        | -7.96  | -8.65 | -1.24  | -16.37| -4.15  | -7.41 | -2.14  | -0.20 |                  |
| 4           | 39.65         | 121.47        | -9.13  | -2.39 | -3.45  | -13.33| -4.84  | -5.01 | -3.09  | -1.61 |                  |
| 5           | 40.65         | 122.13        | -5.48  | -1.45 | -1.82  | 3.21  | -3.50  | -4.67 | -2.59  | -5.96 |                  |
| 6           | 40.72         | 121.00        | -10.44 | -4.93 | -6.70  | 4.32  | -0.93  | -8.37 | -1.80  | -2.68 |                  |
| 7           | 39.90         | 119.62        | -10.37 | -9.40 | 6.67   | 9.77  | -0.13  | 6.07  | 0.63   | 7.07  |                  |
| 8           | 38.62         | 117.58        | -22.57 | -22.47| 12.88  | -2.09 | 16.25  | 2.71  | 9.32   | -0.85 |                  |
| 9           | 37.98         | 120.68        | -10.88 | 12.23 | -3.06  | -4.63 | 5.18   | -4.95 | 4.45   | 29.52 |                  |
| 10          | 37.58         | 121.40        | -16.07 | -5.34 | -2.00  | -26.17| 1.17   | -20.70| 5.08   | -5.04 |                  |
| 11          | 38.97         | 121.30        | 11.82  | 10.43 | 5.23   | 12.74 | 6.40   | 9.63  | 4.27   | 9.64  |                  |
| Mean Square Error | -8.77  | -6.22  | -1.48  | -7.00  | -2.75  | -5.21  | -2.32  |      |       |       |                  |
4. Analysis of the Major Shallow Water Tides

4.1. M4 and M6 Tides
Both M2 and M6 tides arise from M2 tide, and they are the overtides of M2, since their frequencies are the integer multiples of M2. Figure 3 shows the simulated co-amplitude and phase lag of M4 and M6 tides. From Figure 3(a), it can be found that there are five amphidromic points for M4 tide in Bohai Sea, distributing in the north of Liaodong Bay, the water channel of Laotieshan, the west of Laizhou and Bohai bays, and the central basin, respectively. The present results are some different from the previous reports [5], in which only four amphidromic points were apparent and the amphidromic point in the west of Laizhou Bay became retrograde. From Figure 3(a), it is also found that four amphidromic points rotate counter-clockwise and the one in the central basin rotates clockwise. The simulated M4 tidal propagation pattern is consistent with the previous studies. The tidal counter-clockwise propagation is due to the Coriolis Effect in the Northern Hemisphere, and the clockwise propagation may be influenced by the topography in the central basin.

The different methods may lead to the result distinctions between this study and previous studies [5,6]. Fang, et al. used a two dimensional model to simulate the tides in Bohai Sea, in which the friction in the water column was not considered. However, the nonlinear interaction due to the friction in the water column is a key factor to generate the shallow water tides, so it should be stressed but not neglected. In addition, the variation in the topography and the coastal line in past decades may also be responsible to the deviations of different studies.

Comparable to the astronomic tide, the shallow water tide has the small amplitude by and large. Figure 3 shows that the nearer the shore, the shallower the water and the larger the shallow water amplitude. Close to the end of three bays, the amplitude of M4 tide can evolve to 25cm, and this value is considerable to the astronomic tide.

Compared with the situation of M4 tide, the M6 tidal propagation is more complicated. Figure 3(b) shows that seven amphidromic points for M6 tide can be found in Bohai Sea. The distribution patterns are as follows: one in Bohai Bay, one in Laizhou Bay, two in Liaodong Bay, and three in the central basin, among which four rotate counter-clockwise and three rotate clockwise. It should be noted that the amphidromic point in the end of Bohai Bay becomes retrograde. The simulated M6 tidal propagation is consistent to that given by He et al. using the T/P data [6], though the simulated amplitude is larger relative to He’s results.

**Figure 3.** Simulated co-amplitude (cm) and co-phase lag (degree) of (a) M4 and (b) M6 constituents in Bohai Sea. Dashed and solid lines indicate amplitude and phase, respectively.

4.2. MS4 Tide
MS4 constituent is the compound tide of M2 and S2 tides. Figure 4(a) shows the simulated MS4 tidal propagation in Bohai Sea. It can be seen that there are five amphidromic points in total, distributing in
the channel of Laotieshan, in the central basin, and in three bays respectively. Its propagation pattern is similar to that of \( M_4 \) tide, with one clockwise amphidromic point and four counter-clockwise amphidromic points.

The shallow water tide derives from the astronomic tide, so the astronomic tide is called the source tide, and the shallow water tide is called the overtide or compound tide. In general, the amplitude and phase lag between the astronomic tide and the shallow water tide adhere to some quantitative relations. The following formula given by Fang is used to estimate the \( MS_4 \) tide.

\[
\begin{align*}
H_{MS_4} & = H_{S_2} \\
H_{M_4} & = H_{M_2} \\
g_{MS_4} - g_{M_4} & = g_{S_2} - g_{M_2}
\end{align*}
\]

Where, \( H \) and \( g \) are the amplitude and phase lag, respectively; the subscript indicates different tides.

Figure 4(b) shows the estimated \( MS_4 \) tidal propagation in Bohai Sea. By comparisons, it can be found that there are seven amphidromic points in this situation. The positions of the surplus amphidromic points are consistent with that of \( S_2 \) tide. Based on equation (2), if the amplitude \( S_2 \) is zero, then \( MS_4 \) has an amphidromic point. Therefore, the surplus two amphidromic points arise from the computation errors, and do not exist genuinely.

Compared to \( M_4 \), it is also found that the strength of \( MS_4 \) is relatively weak, and the closer to coast, the larger the amplitude, and the largest value can reach 20cm.

5. Conclusions

Admittedly, the shallow water tide shows the weak strength comparable to the astronomic tide on the whole. However, Bohai is a shallow sea with the mean depth of 18 m, so the shallow water tides play an important role in the water mixing and transporting, especially in the coastal waters.

This study mainly focuses on three major shallow water tides based on the validated model results. It is found that there are 5 amphidromic points for the \( M_4 \) and \( MS_4 \) tides, respectively; and 7amphidromic points for the \( M_6 \) tide. The position of the amphidromic points is not much different for \( M4 \) and \( MS4 \) tides. Moreover, the estimated of \( MS_4 \) tide feature is also consistent with the model results, though some slight deviations exist between this study and the previous reports. Considering the new topography and the high grid resolution used in this model study, the results are meaningful to help us to recognize the tidal mechanism in Bohai Sea.
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