Journal of Physics: Conference Series

PAPER • **OPEN ACCESS**

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To cite this article: Ning Wang *et al* 2023 *J. Phys.: Conf. Ser.* **2486** 012039

Analysis of Characteristics of Tide and Tidal Current in the east China Seas

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Abstract. The features of tide and tidal current in the east China seas were studied by the FES2014 tide data and tide gauge station data. It is found that FES2014 data is in well agreement with the observation. Among the four major tidal components (M2, S2, K1, and O1), M2 is the strongest tidal component with the maximum amplitude (tidal current) exceeds 100 cm (100 cm/s), followed by S2 tide with its maximum amplitude (tidal current) reaches 60 cm (50 cm/s). The results indicate the east China seas are dominated by semi-diurnal tides. There are four amphidromic points for semi-diurnal tides, and two amphidromic points for diurnal tides. Rotating tidal current dominates the areas far from the coast, and rectilinear current dominates the coastal sea area. The strong tidal currents are often distributed in some places with special topography such as bays and estuaries.

1. Introduction

The tide and tidal current in the ocean refer to the periodic vertical and horizontal movement of seawater under the action of tidal forces caused by celestial bodies such as the moon and sun. Tide and tidal current not only play an important role in ocean dynamics such as circulation and transport, but also are closely related to human life, such as fishing, port construction, navigation and military activities. The east China seas, which includes the Bohai Sea, the Yellow Sea and the East China Sea, are the marginal seas of the Pacific Ocean. Most of the east China seas are located on the continental shelf, and their tide and tidal current characteristics are greatly affected by topography. Ogura (1933) first gave the tidal chart in the east China seas based on observational data [1]. With the development of numerical models, many researchers began to use numerical models to simulate tide and tidal current and analyze their characteristics in the East China Sea. Based on a two-dimensional numerical model, Fang and Yang (1985) studied the characteristics of tide and tidal current and found a new current-amphidromic point for tidal current in the Bohai sea [2]. Guo and Yanagi (1998) simulated the tide and tidal current using a three-dimensional tidal current model, and analysed their three-dimensional structure in the east China sea and the Yellow sea [3]. Using a three-dimensional model with fine horizontal and vertical resolution, Bao et al. (2001) computed the tide and tidal current in the east China seas, and found the simulated results are in good agreement with the observed results for the principal tidal constituents [4]. Then, they made a detailed analysis of the characteristics of tide and tidal current in the east China seas. Zhang et al. (2006) conducted a series of numerical experiments with different bottom friction coefficient for the simulation of the M2 tidal constituent in the Bohai sea with a numerical adjoint model [5]. Zhu et al. (2012) simulated the tide and tidal current in the east China seas with the Finite Volume Coastal Ocean Model (FVCOM) [6]. Based on the simulated results, they found five semi-diurnal and three diurnal constituents independent anticlockwise rotary tidal systems appear in the east China seas. Recently, Chen and Cheng (2020, 2021) studied the tidal energy, dissipation, and tidal residual circulations in the eastern China seas using the regional ocean modeling system [7,8]. In addition to numerical model, the satellite altimeter data and observed data also used to analyze the characteristics of tide based on the method of harmonic analysis [9,10]. For example, Teague et al. (1998) revealed the tide and tidal current in the southern Yellow Sea based on three pressure gage and ADCP moored at depths ranging from 77 to 89 m [9]. Dong et al. (2002) extracted tide information in the east China seas from TOPEX/POSEIDO data [10]. Hu and Chen (2007) conducted a similar study [11]. Compared to the simulated results, the tides obtained from the satellite altimeter data are usually coarser but more accurate. In this paper, we will review the characteristics of tide and tidal current in the east China seas using a relatively new tidal dataset with very fine resolution.

2. Data

2.1. FES2014 Global Ocean Tidal Dataset

Provided by Aviso, FES2014 is the latest version of finite element solution tidal model, which is the improved version of FES2012. Compared with FES2012 or the earlier versions, FES2014 utilizes longer time series of altimeters and new altimeter standards, as well as improved modeling and data assimilation techniques, more accurate ocean depths and a finer shallow water grid. As a result, the performance of FES2014 is significantly improved in all ocean regions, especially in shallow waters and coastal seas. Compared to the other available global ocean tidal datasets, FES2014 clearly shows improved de-aliasing performances in most of the global ocean areas [12]. With the horizontal resolution of 1/16°×1/16°, FES2014 is one of the finest global tidal datasets. FES2014 provides 34 tidal components, which is the largest number of tidal components among the global tidal datasets. Available information including the amplitude and phase of 34 tidal components, and the amplitude and phase of tidal currents in meridional and zonal directions.

2.2. Tide Gauge Station Data

Tide gauge station data is hourly high frequency water level data recorded by five tide gauge stations located in the east China seas. As seen in figure 1, the name of the stations from south to north are station1 to station 5, respectively. Tide gauge station data is mainly used to verify the accuracy of FES2014 tidal data in the east China seas.

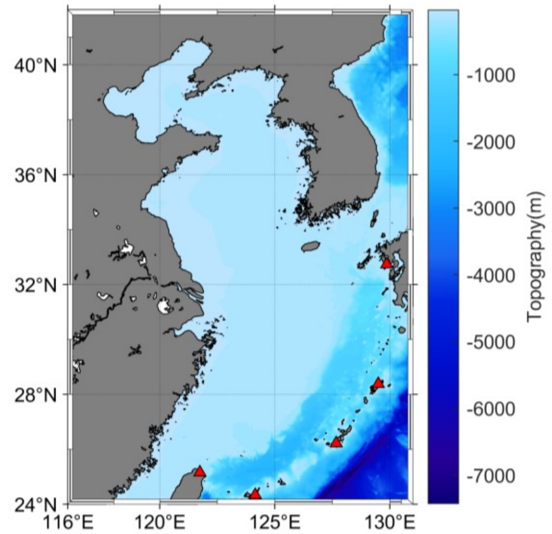

Figure 1. Topography of the east China seas and the location of tide gauge station. The five stations from south to north are named Station1 to Station5, respectively.

3. Results

3.1. Accuracy of FES2014

Firstly, the harmonic constants of 59 tidal components of five tide stations were obtained from one year of hourly water level data by harmonic analysis using the t_tide toolbox. After removing the insignificant tide components and sorting the other tide components by amplitude, it was found that all of the shallow water tides M4, M6 and MS4 of the five tidal stations were not significant. The first eight largest components were M2, S2, K1, O1, N2, K2, P1 and Q1 (the order of different tidal stations was different), and the sum of the amplitudes of the eight main components accounted for more than 80% of the amplitude. Therefore, the FES2014 tidal data are verified based on these eight main components. The comparison of amplitude and phase of the main eight components derived from the tide gauge station data (hereafter, "station amplitude" and "station phase" for simplicity) and FES2014 data (hereafter, "FES2014 amplitude" and "FES2014 phase") are shown in figure 2. As can be seen from the figure, the results obtained from FES2014 datasets and tide gauge station data are basically consistent. Table 1 shows that the mean root-mean-square error between station amplitude (phase) and FES2014 amplitude (phase) for the eight main components is only 1.08 cm (4.6°). The mean relative error between station amplitude (phase) and FES2014 amplitude (phase) for the eight main components is 1.7% (-2.1%). The above results indicate that the FES2014 tide data is in good agreement with the observed results. Among the five tide gauge stations, M2 is the strongest component (figure 2a), followed by S2 except for Station1. The result means that the east China seas is dominated by semi-diurnal tides. Additionally, the FES2014 data has been used to study the distribution of tidal character in the East China Sea [13]. The detail characteristics would be revealed by the FES2014 data in further analysis.

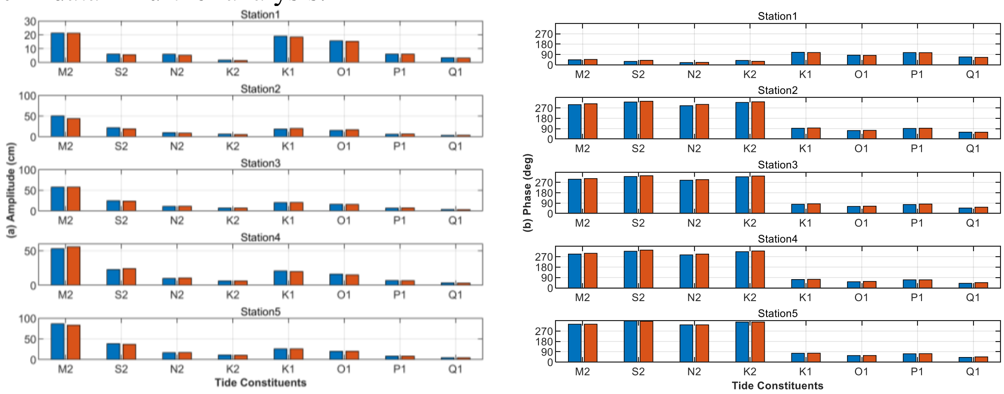

Figure 2. Amplitude (a) and Phase (b) obtained from FES2014 datasets (blue bar) and tide gauge station (red bar)

Table 1. Compared results of harmonic constants derived from between FES2014 data and tide gauge station data with amplitude in the left of symbol "/" and phase in the right of symbol "/". The first to third columns are root-mean-square error (RMSE, in cm and degree, respectively), mean bias (BIAS, in cm and degree, respectively), and mean relative error (MER, in %), respectively.

	RMSE	BIAS	MER
M2	3.4/5.5	1.5/-4.8	2.8/-1.8
S2	1.6/7.6	0.8/-6.1	3.8/-2.2
N2	0.7/6.4	0.1/-5.1	1.4/-2.1
K2	0.5/5.9	0.4/-2.3	6.4/-0.9
K1	0.8/2.4	-0.1/-1.3	-0.3/-1.4
O1	0.9/2.0	-0.1/-1.1	-0.5/-1.6
P1	0.4/2.3	-0.2/-1.4	-2.7/-1.7
Q1	0.2/5.0	0.1/-2.8	2.4/-5.1

3.2. Characteristics of the Tides

Figure 3 shows the co-tidal charts of 4 main component tides. It is obvious that the amplitude of M2 is larger than the other three components with the largest amplitude exceed 100 cm. The amplitude of the east coast of the Yellow Sea generally exceeds that of the west coast. The reason may be that the amphidromic points in the Yellow Sea are closer to the west coast. For the semi-diurnal tides, M2 and S2 tides show similar patterns despite the difference in amplitude. The semi-diurnal tidal waves in the east China seas are transmitted from the Pacific Ocean. Influenced by water depth, shoreline, topography and Coriolis force, four amphidromic points are formed. The corresponding tidal amphidromic systems rotate counterclockwise. The locations of the four amphidromic points are the eastern side of Chengshan Point, the outer side of Haizhou Bay, near Qinhuangdao, and close to the Yellow River Estuary. For diurnal tides, the characteristics of the two tidal components are basically the same except that the amplitude of K1 tide is slightly larger than that of O1 tide. The diurnal tidal waves in the east China seas are also transmitted from the Pacific Ocean, and forms two amphidromic points in the middle of the south Yellow Sea and Bohai Strait. The corresponding tidal amphidromic systems also rotate counterclockwise. The discriminative coefficient used to determine tidal type was calculated by

$$\mathrm{A} = \frac{H_{\mathrm{K1}} + H_{\mathrm{O1}}}{H_{\mathrm{M2}}} \tag{1}$$

where H stands for tidal amplitude, and the subscript stands for tidal name. According to the value of A, the tides can be divided into different types: 0-0.5 for regular semi-diurnal tide, 0.5-2 for irregular semi-diurnal tide, 2-4 for regular diurnal tide, and larger than 4 for regular diurnal tide. Fig. 4 shows the distribution of A. The areas west to 125°E are dominated by regular semi-diurnal tide except for the areas around the four amphidromic points of M2 where the amplitude of M2 is much little. The irregular semi-diurnal tide is more significant in the areas east to 125°E.

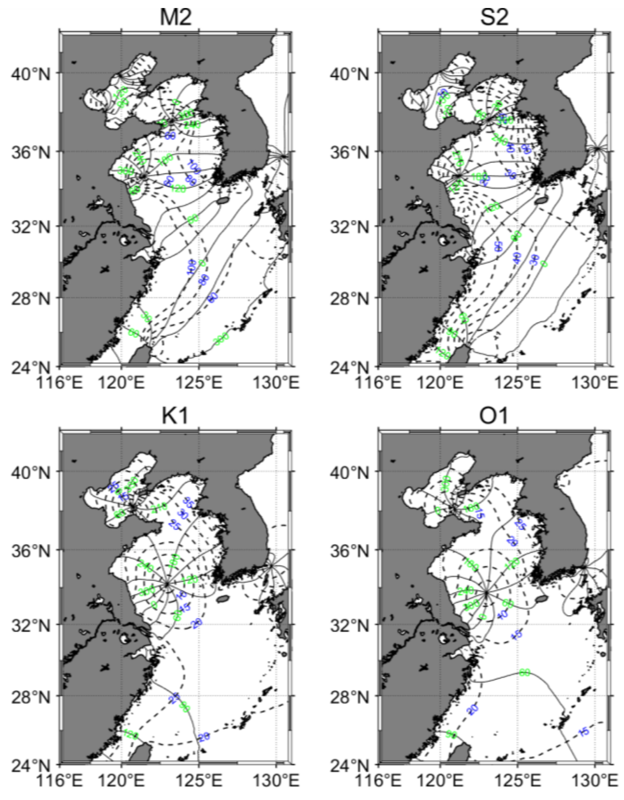

Figure 3. Co-amplitude lines (dashed, in cm) and co-phase lines (solid, in deg) of M2, S2, K1, and O1 tides in the east China seas.

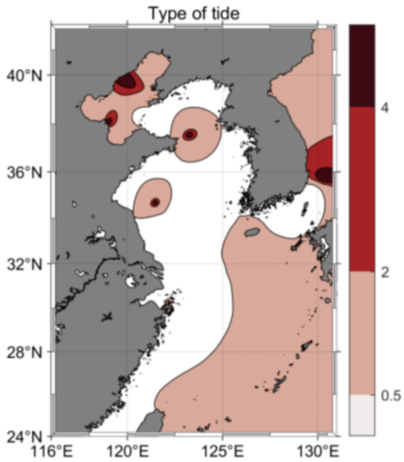

Figure 4. Distribution of discriminative coefficient of tidal type

3.3. Characteristics of the Tidal Currents

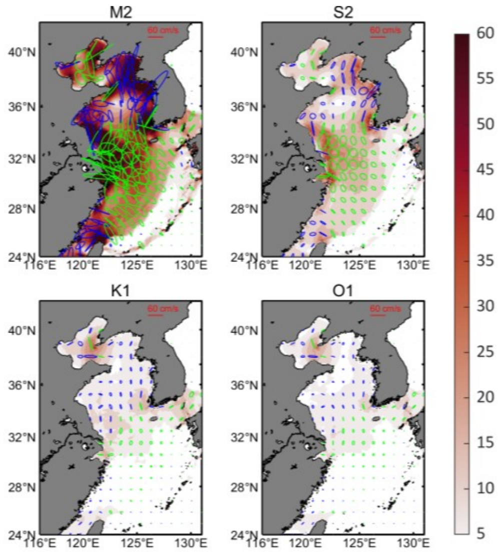

Figure 5. Maximum tidal current velocity (shaded, in cm/s) and tidal current ellipse (green for clockwise rotation and blue for counterclockwise rotation) for the main tidal components

The distribution characteristics of tidal currents are much more complex than those of tides due to the influence of topography, wind field, bottom friction, residual flow and nonlinear effects. Maximum tidal current velocity and tidal current ellipse for the main tidal components are given in figure 5. It can be seen that the M2 tidal current is the strongest with the maximum velocity exceeds 100 cm/s, followed by S2 tidal current, and the K1 and O1 tidal currents are very weak. Another significant character is that it is dominated by rotating current in the area far from the coast and rectilinear current in the coastal sea area. For the semi-diurnal tidal currents, the areas of the West Korea Bay, the Jianghua Bay, the southwest corner of the Korean Peninsula, the Lusi Outer Sea, the mouth of Hangzhou Bay, and the north of Taiwan Island show strong current. For the diurnal tidal current, strong current appears in the Bohai strait, the southwest corner of the Korean Peninsula, and the mouth of Hangzhou Bay with the maximum velocity about 30 cm/s.

The discriminative coefficient used to determine tidal current type was calculated by

$$\mathrm{B} = \frac{W_{\mathrm{K1}} + W_{\mathrm{O1}}}{W_{\mathrm{M2}}} \tag{2}$$

where W is the maximum velocity of tide, and the subscript stands for tidal name. According to the value of B, the tidal currents can be divided into different types: 0-0.5 for regular semi-diurnal tidal current, 0.5-2 for irregular semi-diurnal tidal current, 2-4 for regular diurnal tidal current, and larger than 4 for regular diurnal tidal current. Figure 6 shows the distribution of coefficient B. It can be seen that the east China seas are dominated by regular tidal current except for Bohai strait, the middle of the south Yellow Sea, and oceanic areas northwest of Taiwan island.

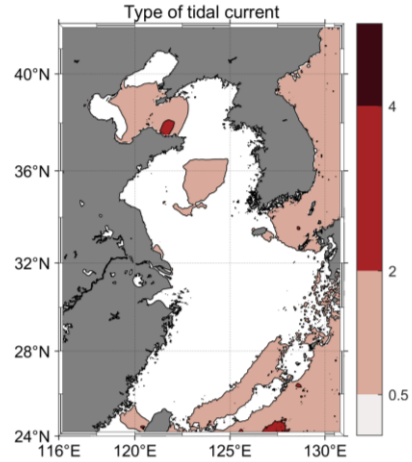

Figure 6. Distribution of discriminative coefficient of tidal current type

4. Summary and Conclusion

The FES2014 tide data and tide gauge station data were used to study the features of tide and tidal current in the east China seas. By comparing the harmonic constants derived from FES2014 dataset and tide gauge station data, it is found that FES2014 data has a good accuracy in the east China seas. Among the four major tidal components (M2, S2, K1, and O1), M2 is the strongest tidal component with the maximum amplitude and tidal current exceed 100 cm and 100 cm/s, respectively, followed by S2 tidal component with its maximum amplitude and tidal current reach 60 cm and 50 cm/s, respectively. There are four amphidromic points for semi-diurnal tides located in the eastern side of Chengshan Point, the outer side of Haizhou Bay, near Qinhuangdao, and close to the Yellow River Estuary, and two amphidromic points for diurnal tides in the middle of the south Yellow Sea and Bohai Strait. Results indicates that the east China seas are dominated by semi-diurnal tides. For the type of tide, regular semi-diurnal tide dominates the areas west to 125°E except for the areas around the four amphidromic points of M2 where the amplitude of M2 is much little, and irregular semi-diurnal tide dominates the oceanic areas east to 125°E. Rotating tidal current dominates the areas far from the coast, and rectilinear current dominates the coastal sea area. The strong tidal current is often distributed in some places with special topography such as the West Korea Bay, the Jianghua Bay, and the mouth of Hangzhou Bay.

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Acknowledgment
The FES2014 data used in this study is provided by AVISO(https://www.aviso.altimetry.fr/en/data/products/auxiliary-products/global-tide-fes/description-fes2014.html), and the tide gauge station data is provided by University of Hawaii Sea Level Center (https://uhslc.soest.hawaii.edu/). We appreciate the two institutes for their generosity.