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Research Article

Validity Assessment of the Global Tidal Models in the Coastal Area of the Persian Gulf and the Sea of Oman, using the Results Obtained from the Coastal Tide Gauges and the IOS Software

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Abstract

The aim of this research is the assessment of the validity of the NAO.99b, FES99, TPXO7.1, TPXO6.2, and FES2004 global tidal models in the water area of the Persian Gulf and the sea of Oman to select one of them as an optimum model for the region. Model can help to find out the tidal specifications of the region as well as to determine the mean sea level and eventually design a local tidal model. For evaluation of models, the results of the tidal analysis of the models compared with those extracted by the tide gauge stations in the ports of Jask, Chabahar, Rajaee, Kangan, Bushehr, EmamHassan, all situated on the northern coast of the Persian Gulf and the sea of Oman. In this research the tidal analysis based on tide gauges is conducted by utilizing the results of IOS software. By using the statistical methods, the RMS of the amplitudes and those of the vector of the wave functions, and the correlation coefficients of the amplitudes and the phases of the four tidal principal components resulted from models compared with the amplitude and the phases obtained from tide gauges. This investigation revealed that among the five global tidal models the results of the FES2004 model had the best fitness with the results of the tide gauges in this region. So that this model proved to have the least RSS for the RMS of the amplitudes (8.795 cm) and the least RSS for the RMS of the difference vector (9.378 cm), and the largest correlation coefficient for the amplitude (0.9427).

Keywords: Tide; Global Ocean Tidal Modes; Tidal Components; Mean Sea Level; Tide Gauge; Satellite Altimetry; Harmonic Analysis

Introduction

Regular changes in water height and the earth crust caused by the sun and the moon attractions called tide. Determination of the tidal forces and its correction is inevitable for the geodetic and the geodynamic accurate observations (Azmude-Ardalan and Farahani 2006). In recent years various global tidal models, are calculated and presented, using the satellite altimetry data and the data obtained by the tide gauges. Furthermore, the researcher designed several global tidal models from combining the altimetry results and the results from tide gauges, which have vast application in many scientific branches as geophysics, geodesy, oceanography, and so on. Considering these numerous models, the quantitative evaluation, the accuracy, gradation, and the selection of the best model among the existing ones is one of the update research subjects in this field. As tens of tidal models designed for the various parts of the oceans [1], the models for evaluation are so selected, that not only commensurate to the region and its geographic coordinates, but also to be applicable for this shallow water region. In section 2 we describe the application of the IOS Software for tidal analysis and prediction of the tide. Section 3 dealt with the introducing the global models, used for evaluation in the Persian Gulf and the Sea of Oman. In section four, we present the statistical methods to assess the models. Section 5 contains the gradation of the models and the selection of the optimum model. Finally, section 6 provides the conclusion.

Using the Foreman Software (IOS) for analyzing and prediction of the tide

In 1995, Foreman and his colleagues by using the results of the work of Goudin prepared a Fortran program for analyzing the tidal Phenomena and the tidal currents. They made use of the Fourier series and the least square method for analyzing the tide [2]. The aim of the application of this method is to minimize the following equation:

$$T = \sum_{i=1}^{N}\left[y_i - a_0/2 - \sum_{j=1}^{N} a_j \cos 2\pi f_j t_i - b_j \sin 2\pi f_j t_i \right]^2 \qquad 1$$

Where T is the non tidal waves, y is the results of the tide gauges, and j is the wave number. It is to mention that Foreman and his colleagues have modified the method after a large number of assessments (http://www.pac.dfo-mpo.gc.ca/). For running the IOS program, we use the following input data: 1) the results of the coastal tide gauges, 2) the coordinates of the studied tide gauge stations (latitude and longitude), and 3) date and time (century, year, month, day, and the hour) of the tidal observation. The output data are then the amplitudes and phases of the tidal components. In current research, we used the results of six-tide gauge stations, all situated in the northern part of the coastal area of the Persian Gulf and the Sea of Oman, namely the Jask, Chabahar, Shahid-Rajaee, kangan, Bushehr, and Emam-Hassan ports with hourly tidal records for the period of one year (2005). The data put kindly at our disposal by the National Cartographic Centre (NCC) of Iran. Using these data as input to the software, the amplitude and the phase of nine tidal components of the studied stations will be determined. Table 1 shows these results for the station Jask as a sample.

Number	Component	Period (hour)	Amplitude (cm)	Phase (deg)
1	S_2	12	26.93	290.74
2	M_2	12.4206	66.09	257.61
3	N_2	12.6583	15.83	247al.55
4	K_1	23.9345	39.84	32.84
5		24.0659	12.16	31.43
6		25.8193	19.79	30.64
7	Mf	327.859	0.5	321.67
8	Mm	661.3093	0.24	110.7
9		11.967	7.63	285.02

Table 1: Yearly tidal analysis of nine principal tidal components in Jask, for the year 2005, using IOS software.

The evaluated global oceanic tidal models in the area of the Persian Gulf and the Sea of Oman

The studied models are as follows:

- **TPXO6.2 model:** This model is one of the global ocean tidal models from the series of TPXO with the mean resolution power of 0.25× 0.25, which presented by Egbert and Erofeeva in the university of Oregon [3]. The aim to design this model was the extraction of the tidal components and determination of the tidal specifications such as velocities, amplitudes, and the phases of the tidal waves. To design this model one used the Topex/Poseidon data for the period of six years and the calculations performed on basis of the Laplace tidal equation and the least square method. This model may use for prediction of the tides in the region as well, which in turn can be useful for preparing the co-amplitude and the co-Phase maps of the region. The model may apply likewise for calculation of the tidal loading. The TPXO6.2 is an ASCII file, which has three output files contained the heights, and the velocity of the tidal components and their networks.
- **TPXO7.1 model:** With continuation of the Topex/Poseidon mission, and the possibility to collect more data and to modify the bathymetric methods, more than twenty ocean tidal models designed since 1994. The last hydrodynamic model of these series designed by Egbert and his coworkers at Oregon State University for the local and regional areas. To run the models TPXO6.2 and TPXO7.1, we have to use special software called "The Tide Model Driver (TMD). The TMD package contains scripted function for use in batch-mode Matlab processing. The input data are the geographical latitudes and longitudes of the studied area as well as the selected tidal components. The output data will be the amplitudes and the phases of the tidal components.
- **FES99 model:** Description and quantitative determination of the ocean tide has been ever an interesting subject for geophysicists and oceanographers all over the worlds. During the years 2002 to 2005, a French group under the supervision of Le–provost develops the series of FES models. They have used the finite element method for solution of the hydrodynamic equations. They also made use of harmonic analysis for tidal modeling. The series of FES models are FES2004, FES99, and FES95.2 [4]. The FES99 is in fact the modification of the FES95.2 model, by using 700 tide gauge data and 687 observing cycles of the Topex/Poseidon and ERS-2. The resolution power of this model is 0.25 degrees and can used for calculation the height and current velocity of M2, N2, O1, K2, S2, Q1, 2n2, and K1 tidal components.

- **FES2004 model:** Considering the weakness of the FES99 model in coastal areas, the FES2004 model developed in 2004 based on the hydrodynamic equations and assimilation to the tide gauge results of 671 stations. The model designed on a new network with resolution power of 0.125 deg. The access to FES models is possible through the Archiving, Validation and Interpretation of Satellite Oceanographic Data (AVISO) (http://www.aviso.oceanobs.com). Table 2 shows the results of tidal analyses for nine tidal components at Jask port, using the FES2004 model.
- **NAO.99b model:** Japanese researchers developed the NAO.99b global tidal model, by using five years data of the Topex/Poseidon altimetry satellite, and assimilating the data obtained from 219 tide gauge stations into hydrodynamic models. In 2000 Matsomoto and Takanazwa modified this model. The new model can determine the amplitudes and the phases of sixteen tidal components. Afterwards considering the local conditions of the Japan Sea and its near area, the NAO.99L tidal model designed, which can determine the amplitudes and the phases of seven long period components, namely Sa, Ssa, MSf, Mf, Mtm, MSm, and Mm [5].

Number	Components	Periods (hour)	Amplitudes (cm)	Phases (deg.)
1	S_2	12	27.044	186.17
2	M_2	12.4206	69.368	156.75
3	N_2	12.6583	17.142	140.35
4	K_1	23.9345	40.378	340.142
5		24.0659	13.32	339.938
6		25.8193	20.554	340.616
7	Mf	327.859	0.622	17.862
8	Mm	661.3093	0.302	8.438
9		11.967	7.22	187.17

Table 2: Tidal analysis for Jask, using the FES2004 tidal model.

Statistical methods used in this research for assessment the conformity of the results obtained from models and those from coastal tide gauges

As mentioned before for validity assessment of five used global tidal models (FES99, TPXO6.2, NAO99.b, TPXO7.1, and FES2004) in the area of the Persian Gulf and the Sea of Oman, different statistical methods applied and their results compared with those of six coastal tide stations, using the IOS software. These tide stations are located as mentioned along the north coast of these water basins.

Determination of the absolute values of amplitude differences of the principal components M2, S2, K1, and O1 resulted from the models and the tide gauges

Evaluation of the absolute values of the amplitude differences of four principal components resulted from the models and the tide gauges reveals that the maximum absolute values of the amplitude differences of five studied models and the tide gauges belongs to the semi-diurnal lunar component M2 in Shahid-Rajaee port. While the FES2004 model shows the least maximum value differences among the five applied models. The results also revealed that the least absolute value differences of the principal components for all models pertained to Jask, Chabahar, and Kangan, which are located near the open sea, where the satellite altimetry data are less accurate compared to the stations in the deep sea. The absolute values of amplitude differences resulted from the models and the tide gauges related to the tidal component M2 (lunar semi-diurnal) are presented in chart 1.

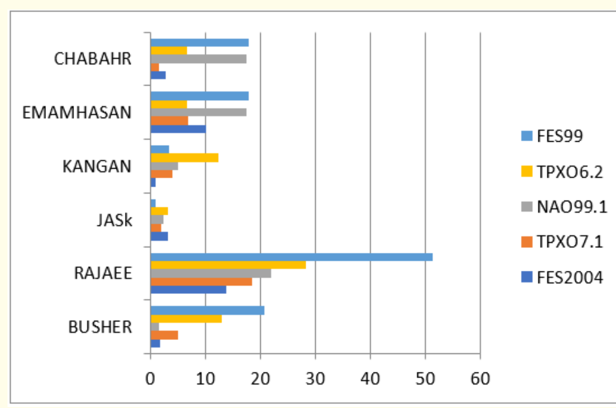

Chart 1: Comparing the absolute values of amplitude differences for M2 components resulted from the global models and those obtained from IOS software for six tide gauge stations (in cm).

Determination the root mean squares (RMS) of the Principal tidal components resulted from five global tidal models

For comparison the amplitudes of four tidal principal components M2, S2, O1, and K2 resulted from the models and these amplitudes obtained from tide gauges, we calculate their RMS through the equation (2).

$$\mathrm{RMS} = \frac{\mathrm{norm}(d)}{\sqrt{N}} \quad (2)$$

Where d is the amplitude difference between the models and tide gauge stations, and N is the number of stations used in this research. If the resulted amplitude of each model designated by (A_{oi}) and the related amplitude obtained for each station assumed to be (A_{oi}), then the RMS of the amplitudes can be calculated as follows:

$$\mathrm{RMS} = \left[\frac{1}{N}\sum_{i=1}^{N}\left(A_{mi} - A_{oi}\right)^2\right]^{\frac{1}{2}} \qquad (3)$$

The results are shown in chart 2.

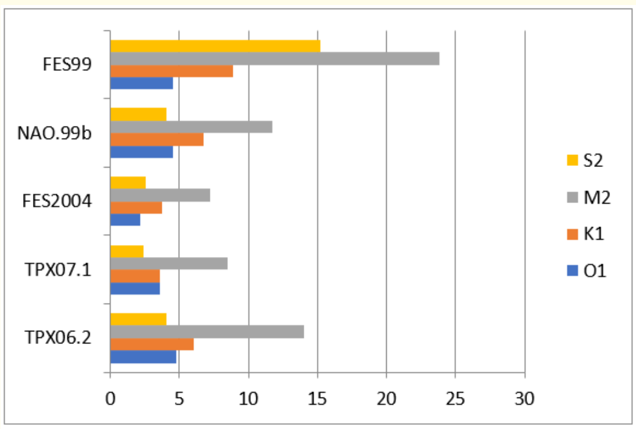

Chart 2: The comparison of the RMS of the amplitudes of the tidal Principal components obtained by the models and those extracted from the IOS software for six tide gauge stations.

The Root Sum Squares (RSS) for the RMS of the amplitudes of the tidal principal components

By using the RMS of the amplitudes, it is possible to compare the RMS of the models only for each single component. To evaluate the conformity of the results of the model with those of the tide gauges for all components, we use the RSS of the RMS of the amplitudes using the equation (4).

$$\mathrm{RSS} = \left(\sum_{j=1}^{m}\mathrm{RMS}^2\right)^{\frac{1}{2}} \qquad (4)$$

Table 3 shows the RSS for the RMS of the amplitudes resulted from the FES2004 model as a sample and chart 3 shows the RSS for the RMS of the amplitudes resulted from the NAO.99b, FES99, TPXO7.1, TPXO6.2, and FES2004 global tidal models

FES2004	K_1	O1	M2	S2	RSS (cm)
RMS of Amplitudes (cm)	3.7336	2.1682	7.2329	2.5291	8.795

Table 3: The RSS for the RMS of the amplitudes of the tidal Principal components obtained by the FES2004 as a sample and those extracted from the IOS software.

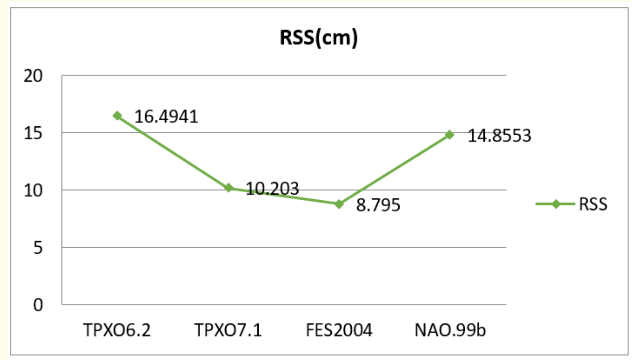

Chart 3: The RSS for the RMS of the amplitudes of the FES2004 as a sample, calculated by the IOS software.

Evaluation of the differential vector and the RMS of the differential vector of the tidal wave function for four tidal principal components resulted from the models in comparison to the amplitudes obtained by the Foreman software (IOS)

By using the data obtained from the tide gauges and the results of five global ocean tidal models, it is possible to determine the wave function resulted from the observations and that obtained by the models, through the following equations:

$$X_o(t) = \frac{a_0}{2} + \sum_{o=1}^{\infty}\left(a_o \sin\phi_o + b_o \cos\phi_o\right) \qquad (5)$$

$$X_m(t) = \frac{a_0}{2} + \sum_{m=1}^{\infty}\left(a_m \sin\phi_m + b_m \cos\phi_m\right) \qquad (6)$$

If we denote the amplitude of the tidal component multiplied by cosine of phase by u and the amplitude of the tidal component multiplied by the sine of phase by v, then we can write:

$$u = A\cos\phi$$
$$v = A\sin\phi \qquad (7)$$

If n is the number of considered stations, then we can determine the differential vector d of the two functions resulted from the tide gauge stations and the models, for each tidal component from the equation (8) [6]:

$$\mathbf{d} = \sqrt{\left(u_i - u_i^o\right)^2 + \left(v_i - v_i^o\right)^2} \quad (8)$$

Where u_i and u_i are the wave functions of the model and u_i and v_i are the wave functions of the tide gauge observations, which obtained by using of the IOS software.

In current research by using the equation (8), the differential vectors of the wave functions of the principal components of five global tidal models in comparison with the wave functions obtained from six tide gauge stations were determined.

As a sample, the results of the FES2004 model and the tide gauges are shown in chart 4.

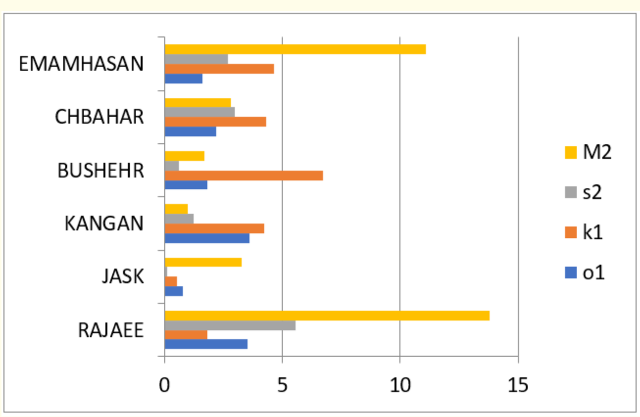

Chart 4: Comparison of the differential vector of the wave function resulted from FES2004 model and those obtained from six tide gauges (in cm).

Using the differential vectors of the wave functions, the RMS of the differential vectors of the wave functions of the principal components resulted from the models in comparison with same values obtained from the IOS software will be determined through the equation (9). Results are shown in table 4.

Model	O1	K1	M2	S2
TPXO6.2	5.034	15.7121	14.4073	5.034
TPXO7.1	2.9552	6.6076	9.164	2.727
FES2004	2.4687	4.2188	7.4797	2.8474
NAO.99b	4.743	7.1338	12.2616	4.0263
FES99	11.497	10.3026	24.1071	15.2929

Table 4: The comparison of the RMS of the differential vectors for the model functions amplitudes of the tidal Principal components obtained by the models and those extracted from the IOS software for six tide gauge stations.

$$\text{RMS} = \left\{ \frac{1}{2} \sum_{i=1}^{n} \left[\left(u_i - u_i^o\right)^2 + (v_i - v_i^o)^2 \right] \right\}^{1/2} \quad (9)$$

Statistical methods to determine the correlation coefficients for comparison of the amplitude resulted from the models and those extracted from tide gauges

If the amplitude of any principal component resulted from the studied models and from the tide gauge station marked as X and Y respectively, and N will be the number of the tide gauge stations, then it may be possible to determine the correlation coefficients between these two values from the equation (10).

$$r = \frac{\sum xy - \frac{\sum x \sum y}{n}}{\sqrt{\left(\sum x^2 - \frac{(\sum x)^2}{n}\right) \cdot \left(\sum y^2 - \frac{(\sum y)^2}{n}\right)}} \quad (10)$$

The results are shown in table 5.

Gradation of the models and selection of the optimum model

Comparison the RSS values for the RMS of the principal component amplitudes resulted from the global ocean tidal models with the same results obtained from the tide gauge stations and also the comparison of the RSS for the RMS of the differential vectors of their wave functions showed that in both comparisons the gradation of the models are similar. Besides the calculation of the mean correlation coefficients of the component amplitudes of the models in comparison to that of the tide gauge stations reveals that the same gradation of the models valid for the whole studied area. Therefore, we may gradate the studied models, based on conformity of their results with those of the tide gauges, as in the table 5 [7-12].

Model	RSS for the RMS of the components	RSS for the RMS of the differential vector of the wave function	Correlation coefficients of the component amplitudes	classification
FES2004	8.5843	9.378	0.9427	First
TPXO7.1	24.5391	11.992	0.8901	Second
NAO99.b	25.4283	15.538	0.8533	Third
TPXO6.2	26.8903	22.6177	0.8282	Fourth
FES99	30.9538	6836.89	0.2940	Fifth

Table 5: The results of the RSS calculation for the RMS of the principal component amplitudes of the models, the values of the differential vectors for the model functions as well as the correlation coefficients between the principal amplitudes of the models and tide gauges.

Conclusions and Remarks

We used five global tidal models in this research and compared their calculated tidal component amplitudes with the results obtained from six tide gauge stations along the northern coast of the Persian Gulf and the Sea of Oman. The total conclusions are as follows:

1. Comparison of the amplitudes of the tidal components resulted from the models with those obtained from tide-gauges showed that the greatest tidal amplitude is due to the semidiurnal component (M2), which its maximum value of about 100 cm observed in Shahid-Rajaee port. The minimum value of this amplitude of about36 cm is observed in Bushehr Port.
2. The Largest Values in the studied area are due to M2, S1, K1, and O1 components.
3. The absolute value of the amplitude differences between the models and the tide gauges, and also the comparison of the magnitude of the differential vectors of their wave functions showed that the least absolute values of the amplitude differences and the differential vectors observed in Jask, Chabahar, and Kangan, in the ports near the Open Sea. The fact that may be concluded due to different accuracies of the satellite altimetry data in deep water and near the coast.
4. Comparison of the results of the models with those of the tide gauges showed that the Shahid-Rajaee port exhibits the largest absolute value of the differential amplitudes of the principal components and the largest magnitude of the differential vectors of the wave functions.
5. Calculation of the magnitude of the differential vectors of the wave functions for the tide gauges, as well as the calculation of the absolute values of the amplitude differences between the models and the tide gauges verified that the FES2004 model has the the least maximum differences in amplitude as well as in differential vector in Shahid-Rajaee port.
6. Statistical results such as the least values of RMS and RSS for the RMS of the amplitudes and the same for the differential vector of the wave functions and also the largest correlation coefficients revealed that the results of the FES2004 model has the best conformity with the results obtained by the tide gauges. Therefore, we may conclude that this model may be the best suitable tidal model for the Persian Gulf and the Oman Sea area. Using this model and also considering the reasons, which may be responsible for differences between the results of different models and the tide gauges, such as the geometry of the coastal lines and also the scattering and perturbation of the tidal waves in the boundary between the strait of Hormoz and the Sea of Oman, It may be possible to design an accurate local model for this region.

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