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Evaluation of the global tidal model FES2014 with Tide Gauge data in the Coastal regions of the Persian Gulf

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ABSTRACT

Due to the importance of tidal phenomenon in coastal and port areas, it is necessary to study this issue extensively. For this reason, different global and regional models have been introduced. Among these models, the FES2014 model was considered for study due to its efficiency. One of the unique advantages of this model is the extraction of 34 harmonic components. For comparison, several study stations of the Persian Gulf including open coast areas, Khuran region (Qeshm channel) and northern areas of Khure-mousa were studied. The reason for choosing these areas was the importance and special conditions of these areas. The goal is to evaluate the FES2014 global tidal model in the Persian Gulf, especially in certain areas. It was tried to evaluate the accuracy of this model in these areas by comparing it with the results of tide gauge data. For this purpose, water level time series were predicted by tidal components of the FES2014 model. Finally, the model was compared with the results obtained from the analysis of observations using the IOS harmonic method. To evaluate the model, scatter plots and Q-Q plots of observations and predictions, statistical indices such as RV and RMSE have been used. The investigations conducted on the Pilot, Emam and Mahshahr stations showed that the further it was moved from the pilot station to the interior of Khure-mousa and Emam station, the conformity of the observations and predictions of the FES2014 model becomes less. As far as the Mahshahr station is concerned, due to the lack of model components, it is not possible to extract. In comparing of RV results, Asaluye and Chabahar stations had the highest number with 0.96 and Emam had the lowest value with 0.51. In the comparison of the RMSE results of Rajaei and Basaeedu stations, the values of 0.09 meters and 0.11 meters were closer to zero, of course, it should be kept in mind that 4 factors, the observation period, the quality of the observed data, the location of the stations, and the accuracy of the model have an effect on these results. The components of the FES2014 model were compared with the components of the TMD model and harmonics resulting from the analysis by the IOS method from the observations of tide gauges. The harmonic components in the stations of the open coast areas are more consistent than the model of other areas. Finally, this model does not have the necessary validity and accuracy in certain areas such as Khuran and Khure-mousa compared to the open coast areas. As a result, direct observations of tides in specific geographical areas are always necessary in global and regional models. One of the weaknesses of the global and regional models that use data assimilation to improve the model is the lack of sufficient information and observations of coastal stations in these areas.

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1. Introduction

In the last two decades, with the progress of measurement tools, many studies have been conducted on global and regional models of tides. It is important to predict the tides through these models. Ports and access channels are important economic areas, therefore, the prediction of tide in certain port areas is of particular importance for marine transportation. As a result, this prediction is very important for dredging, navigation, fishing, shipping, boating and other engineering needs.

Consequently, it is very important to have enough information for the instant sea level height. Furthermore, it is possible to model water level changes by mathematical methods and then calculate and extract tidal components. One of the famous models in this field is the FES2014 tide model, which is a combined and barotropic model (Hicks, 2006).

In this research, case studies have been carried out in certain areas of the Persian Gulf, such as Khuran (Qeshm channel) and Khure-mousa (including the ports of Mahshahr, Emam and Pilot) and areas of the open coast and coast.

On the other hand, these areas are of great importance in terms of shipping and navigation. The tidal range (the difference between the highest tide and the lowest tide) in these areas is higher than the rest of the open coast areas and may reach 4-6 meters (Sohrabi Athar et al., 2019).

Therefore, based on the calculations and evaluation of this tidal model in different areas of the Persian Gulf, especially the mentioned specific areas, is it possible to obtain sufficient accuracy in these areas for tidal analysis?

2. FES2014 Model

Many studies have been conducted in the field of analysis and forecasting of tides. On the other hand, due to the lack of direct access to tidal fluctuations information in all areas and the lack of full coverage of tidal stations, obtaining this information from tidal models is of particular importance.
During the conducted studies, these models are divided into three categories in terms of resolution and method of information collection, prediction and hydrodynamic calculations: experimental models, hydrodynamic models and combinational models (Hart-Davis et al., 2021).

The FES2014 model is one of the combinational models obtained based on the finite element solution (FES). The latest version of this model was developed in 2016-2014. FES2014 is an improved version of FES2012 model (Martin et al., 2009).

This model uses the time series of the longest altimeter standards (long-term altimetry data such as Topex/ Poseidon, Jason-1, Jason-2, TPN-J1N, and ERS-1, ERS-2, ENVISAT), the best data assimilation modeling methods and the most accurate ocean measurements in most shallow areas.

Special efforts have been made to investigate the main issue of nonlinear tidal currents and to determine accurate tidal currents. This model is based on solving tidal hydrodynamic equations of the Toulouse Unstructured Grid Ocean (TUGO) model (Martin et al., 2009).

This model has a global geographic coverage and also 34 tidal components are distributed on 1/16° grids (amplitude and phase) for each tidal component product: 2N2, EPS2, J1, K1, K2, L2, La2, M2, M3, M4, M6, M8, Mf, MKS2, Mm, MN4, MS4, MSf, MSqm, Mtm, Mu2, N2, N4, Nu2, O1, P1, Q1, R2, S1, S2, S4, Sa, Ssa, T2 (Garcia-Soto et al., 2021).

In the FES2014 model, about 2.9 million nodes are used, which is 50% more than FES2012, and in this version, the physics of the model has been improved, so that it becomes twice as accurate (Martin et al., 2009). The selection of altimetry observations for the data integration process depends on the mission, range, depth and resolution (Savcenko & Bosch, 2012; Schwartz, 2006).

3. Theory of issue

In order to evaluate the FES2014 global tidal model in the Persian Gulf, especially Khuran and Khure-mousa regions, in this research, tidal observations from coastal stations were analyzed using the IOS (Institute of Ocean Science) method in Mike 21 software (DHI). The amplitudes and phases of FES2014 model were extracted by programming and computing with MATLAB software and predicted by Mike 21 software. Finally, several statistical indicators were used to compare and evaluate the observations and predictions from the model components.

3.1. Tide analysis

In Mike 21 software, tide analysis is done by Fourier series expansion and least square method. This analysis can decompose the complex signal curves into simple cosine and sine harmonic signal curves (Doodson & Warburg, 1941). The quantities representing these curves are the amplitude and phases of the signals extracted from the analysis. These harmonic components are constant for any sea area and are almost unchangeable with respect to time change (Tajfirooz et al., 2018).

The IOS analysis method is based on the harmonic Fourier method and solving time domain equations. In general, the basic assumption for the application of the IOS method is that the changes in tidal height at each specific tidal station can be expressed with a limited number of harmonic terms, as follows (Schureman, 1994):

$$h(t) = c_0 + \sum_{j=1}^{m} \left(f_j(t) A_j \cos\left(2\pi \left(\sigma_j t + V_j(t) + U_j(t) \right) - g_j \right) \right) \quad (1)$$

Here, $h(t)$ is the instantaneous water height, c_0 is the mean level of the tide, g_j is the phase, A_j is the amplitude, σ_j is the frequency, $f_j(t)$ is the nodal modulation amplitude coefficient, $U_j(t)$ is the nodal phase correction and $V_j(t)$ are astronomical arguments that $j = 1{:}M$ are the main components of the tidal wave and the number of main components of the wave is M. Also, in this equation, the phase and amplitude of the j th component, g_j and A_j, respectively, are unknowns, and the rest of the parameters are observations and known values.

If $\emptyset_j$ is considered as the following relationship:

$$\emptyset_j = g_j - \left(V_j(t) + U_j(t)\right) \quad (2)$$

The goal is to obtain the amplitudes A_j, and the phases $\emptyset_j$ from the following function (Foreman, 1977):

$$h(t_i) = c_0 + \sum_{j=1}^{M} \left(A_j \cos(2\pi\,(\sigma_j\, t_i - \emptyset_j))\right) \quad (3)$$

Here, $i = 1{:}N$ and i is the number of the time epoch.

So that the amplitudes and phases of tides are best estimated from the series of observations of tide heights $h(t_i)$ in the above relationship. Assuming $N > 2M + 1$ and N is the total number of equations, a suitable method can be adopted to solve the above equations and estimate the parameters A_j and $\emptyset_j$. The best method to achieve such a solution is to choose the least-squares method (Foreman, 1977).

3.2. Tide prediction

In order to tide prediction, it is possible to use the superposition of harmonic components, the opposite of analysis. In the following, to validate the predicted values from the results of harmonic components, they are compared with the values of the original observations. These differences are called residuals, which are used to reveal large errors or estimate sudden changes in sea level caused by storms or any other natural phenomenon.

The components of the FES2014 model were downloaded from the aviso site (*FES2014 Data*), in NETCDF format. Then, the harmonic components of the desired stations were extracted through MATLAB software. As a result, whole the components were obtained in the network of 1/16 degree.

To find the amplitude and phase in a particular station, there are many interpolation methods. The weighted average method was used to find these components in these stations (Ranji et al., 2016).

In this research, the IOS method was used for forecasting based on the time of tidal observations. Since according to the results of Tajfirouz et al.'s research (Fok, 2012), this method is more suitable for long-term periods. It also extracts more components.

4. Experimental investigations

4.1 Observations and study information

In order to experimental investigations, the information of tide gauges in 14 stations selected for this research was obtained as observations. The study stations include 3 sections: 3 stations in open coast areas (Chabahar, Asaluyeh and Bushehr), 7 stations in Khuran region (between Qeshm and Bandar Abbas) and 4 stations in Khure-mousa region (VTS2, Pilot, Emam and Mahshahr). All data are without gap and have different sampling rates. The observation time interval at Bushehr, Chabahar and Asaluyeh stations is one hour and ten minutes at other stations (see Figure 1)

Regarding obtaining the amplitude and phase of observation components, as well as the analysis of tidal data, the standard IOS method was performed with Mike 21 software (see Table 1). In this case study, tidal components were extracted a total of at least 68 for one-year analysis and 30 for monthly analysis. The components of the FES2014 model were downloaded and the harmonic components of the desired stations were extracted using MATLAB software, water level predictions were made by Mike software.

Figure 1. position of case studies (Google Earth site)

Table 1: Frequency of eight main harmonic constituents (Foreman, 1977)

Constituents	Frequency	Constituents	Frequency
M2	0.0805114007	**K1**	0.0417807462
S2	0.0833333333	**O1**	0.0387306544
N2	0.0789992488	**P1**	0.0415525871
K2	0.0835614924	**Q1**	0.0372185026

4.2 Study in open coast areas

The studies were carried out on 3 stations of Chabahar, Asaluyeh and Bushehr in open coast areas and the following results were obtained.

As can be seen in Figure (2), in the open coast areas, the observation data and prediction of the FES2014 model are very consistent with each other, and their average differences are insignificant.

Therefore, the prediction in these areas has been done in an acceptable manner. Also, by looking at the scatter plots, it can be seen that the observation and prediction data of the FES2014 model are strongly related and dependent. They are almost on the trend line (see Figure 3). This high correlation with a positive slope is also seen in Figure (4), Q-Q plots (quantile-quantile plots) of open coast areas are linear, this indicates that there is no outlier data in the time series. In these three stations, the graph is close to the bisector line, but of course, the concentration in the bisector is a sign of the compatibility of the predicted results of the FES2014 model with the observations.

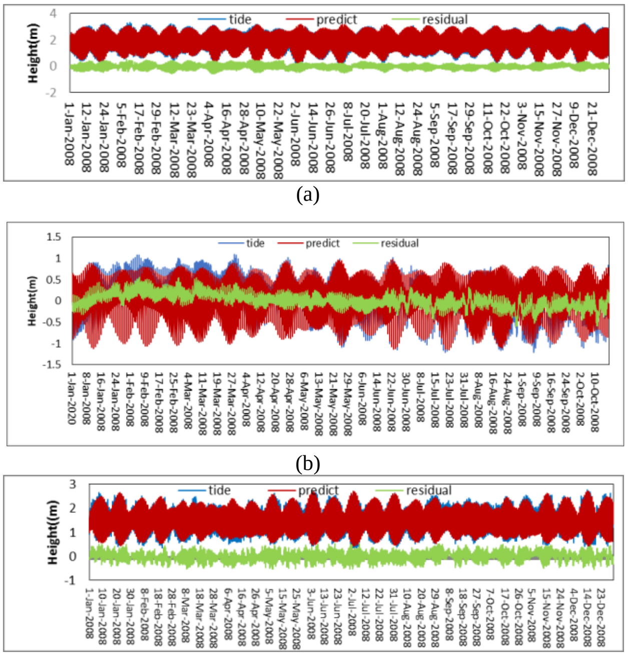


Figure 2. The tidal heights plots consist of tide observations from IOS method analysis, tide prediction from the FES2014 model and their differences (residuals) in 3 stations: (a) Chabahar, (b) Asaluyeh, (c) Bushehr

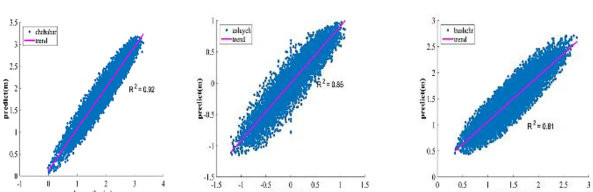


Figure 3. Scatter plots of observations and FES2014 model predictions from the stations (a) Chabahar, (b) Asaluyeh, (c) Bushehr

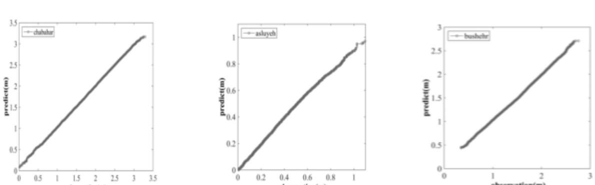


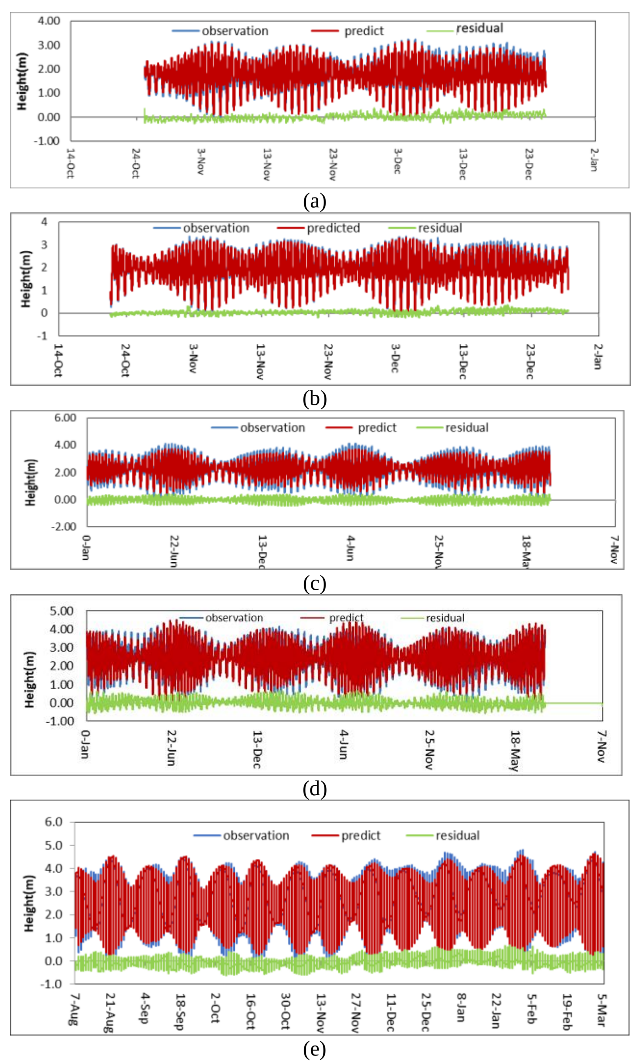
Figure 4. Q-Q plots of observations and FES2014 model predictions from the stations (a) Chabahar, (b) Asaluyeh, (c) Bushehr

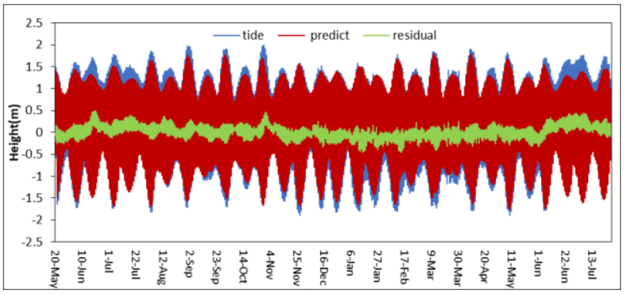
4.3 Study in Khuran region

The investigations were conducted on 7 stations in the Khuran region (between Qeshm and Bandar-Abbas) and the following results were obtained (Figure 5).

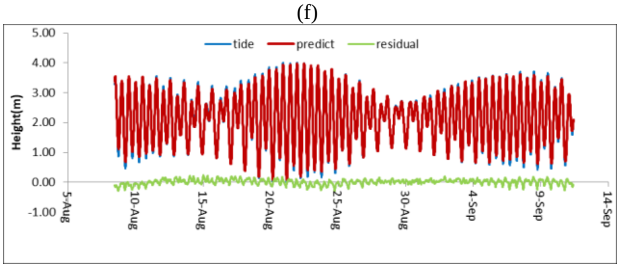
The tidal heights plots consist of tide observations from IOS method analysis, tide prediction from the FES2014 model and their differences (residuals) have been shown in Figure (6) for 7 stations separately. In addition, scatter plots of observations and FES2014 model predictions have been indicated from the stations in Figure (7).

Figure 5. position of stations in Khuran region (Google Earth site)





(f)



(g)

Figure 6. The tidal heights plots consist of tide observations from IOS method analysis, tide prediction from FES2014 model and their differences (residuals) in 7 stations: (a) Basaeedu, (b) Bahman, (c) Dragahan, (d) Khamir, (e) Pohl, (f) Qeshm, (g) Rajaei

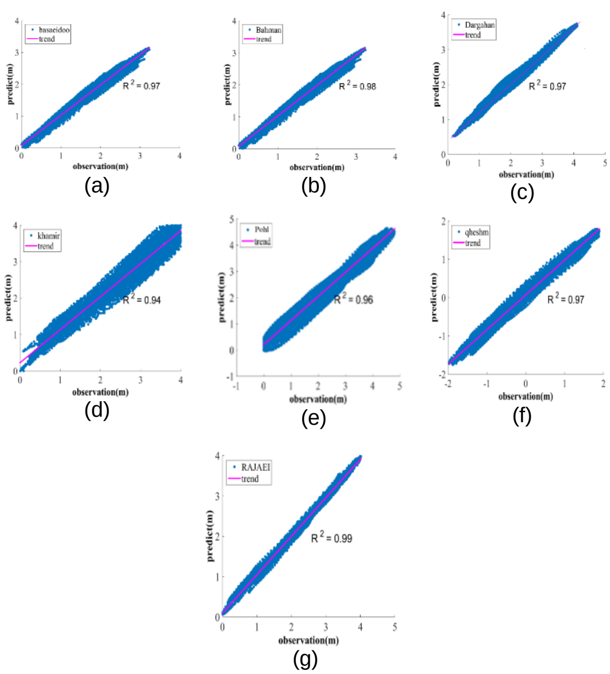
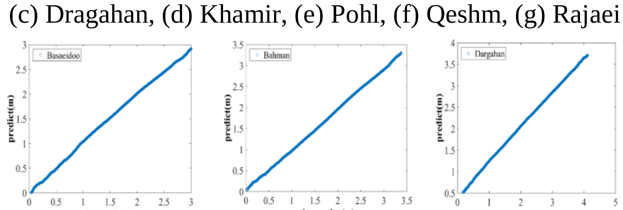


Figure 7. Scatter plots of observations and FES2014 model predictions from the stations: (a) Basaeedu, (b) Bahman, (c) Dragahan, (d) Khamir, (e) Pohl, (f) Qeshm, (g) Rajaei



(a) (b) (c)

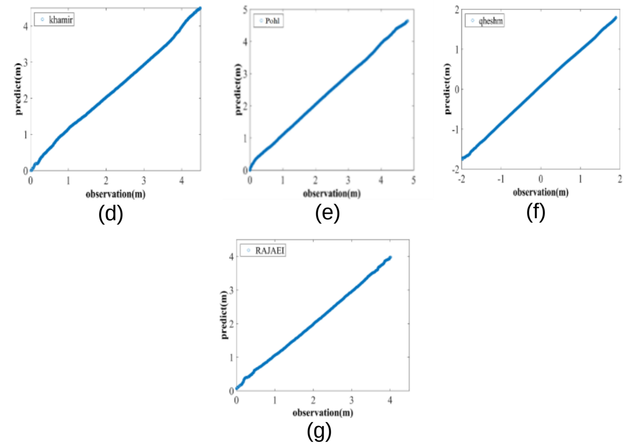


Figure 8. Q-Q plots of observations and FES2014 model predictions from the stations: (a) Basaeedu, (b) Bahman, (c) Dragahan, (d) Khamir, (e) Pohl, (f) Qeshm, (g) Rajaei

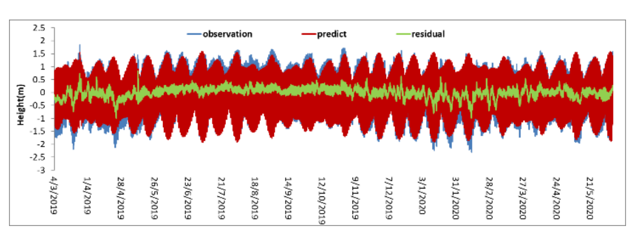
This correlation with a positive slope is also seen in Figure 8, Q-Q plots of Khuran region are linear, this indicates that there are some outlier data in the time series.

The results in some of these 7 stations such as Qeshm, Khamir, Dargahan and Pohl show that there is a more difference between the observation data and predictions of the FES2014 model. As well, compared to the open coast areas, favorable results have not been achieved in this region.

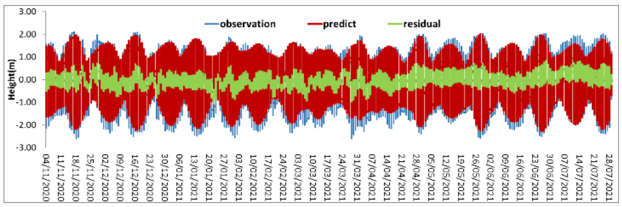
4.4 Study in Khure-mousa region

The investigations were carried out on 4 stations in the Khure-mousa region (consist of Pilot, VTS2, Emam and Mahshahr) and the following results were obtained (see Figure 9).

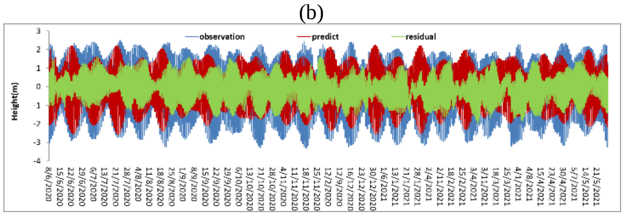
Figure 9. Position of stations in Khure-mousa region (Google Earth site)



(a)



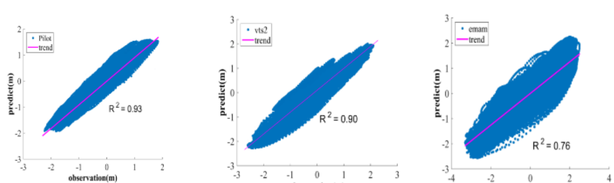
(b)



(c)

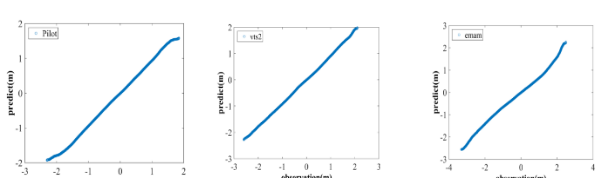
Figure 10. The tidal heights plots consist of tide observations from IOS method analysis, tide prediction from the FES2014 model and their differences (residuals) in 7 stations: (a) Pilot, (b) VTS2, (c) Emam

The tidal heights plots consist of tide observations from IOS method analysis, tide prediction fromthe FES2014 model and their differences (residuals) have been shown in Figure (10) for 3 stations separately.
In addition, scatter plots of observations and FES2014 model predictions have been indicated from the stations in Figure (11).



(a) (b) (c)

Figure 11. Scatter plots of observations and FES2014 model predictions from the stations: (a) Pilot, (b) VTS2, (c) Emam



(a) (b) (c)

Figure 12. Q-Q plots of observations and FES2014 model predictions from the stations: (a) Pilot, (b) VTS2, (c) Emam

This correlation with a positive slope is also seen in Figure 12, Q-Q plots of Khure-mousa region are linear, this indicates that there are many outlier data in the time series.
As can be seen in Figure (11), in the northern areas of Khure-mousa, the observation data and FES2014 model are less compatible than in the open coast areas. Furthermore, in this region, the further it was moved from the pilot station to the interior of Khure-mousa and Emam stations, the adaptation is less as far as there is no information for the FES2014 model on the Mahshahr station, and in this station, due to the lack of FES2014 components, no prediction was made.

4.5 Accuracy assessment

In order to evaluate the accuracy of FES2014 prediction model, two parameters route mean square (RMSE) and reduction in variance (RV) have been used.
As it can be shown in Table 2, the RMSE values are high and the RV values are low in Emam, VTS2, Khamir, Pohl and Pilot stations, respectively. Consequently, the model does not have good precision.

Table 2. Accuracy of observation vs model at different stations

Stations	RMSE (Meter)	RV
Mahshahr	Out	Out
Emam	0.64	0.51
VTS2	0.26	0.82
Khamir	0.23	0.88
Pohl	0.20	0.87
Pilot	0.20	0.88
Dargahan	0.19	0.85
Qeshm	0.12	0.84
Bahman	0.12	0.92
Basaeedu	0.11	0.92
Bushehr	0.19	0.92
Chabahar	0.17	0.96
Asaluyeh	0.17	0.96
Rajaei	0.09	0.92

It should be noted that the Mahshahr station is outside the accuracy range and has very low accuracy. Nevertheless, if RMSE=0, it indicates the agreement of observations and predictions. Therefore, the closer the RMSE is to zero, the higher the accuracy. Correspondingly, if RV = 1, it indicates the agreement of observations and predictions, so the closer RV is to one, the more accurate our calculations will be.

4.6 Comparison of FES2014 model results with IOS method and TMD model

There are many different tidal models, both local and global, the components extracted from the analysis of observations using the IOS method were obtained to compare with the components of the studied models. However, a comparison between FES2014 and TMD (Tidal Model Driver) model components has been done by analyzing observations using IOS method in order to validate the results (Padman & Erofeeva, 2005). The amplitude and phase of the components in TMD and FES2014 models were extracted from the MATLAB program and the IOS method by Mike 21 software. In the table 3, the amplitudes of the FES2014 model, TMD model and IOS method have been presented from the analysis of tide in the studied stations (Karizbala & Reza, 2019; Puntel de Oliveira & Junqueira, 2017).

To compare the values of 5 main harmonic components, 6 stations with a period of one year or more were selected. The Emam and Pilot stations were selected from Khure-mousa region, Qeshm station from Khuran region, Chabahar, and Bushehr stations from open coast areas.

Considering the Figure 13, it can be seen that all 5 main harmonic components in Emam and Pilot stations located in Khure-mousa region and Qeshm located in the Khuran region have more differences than the three stations located in open coast areas. In addition, the results of the harmonic components in the FES2014 model are more consistent with the IOS components obtained from the observations.

Table 3: Comparison of the amplitude of eight main harmonic constituents

Station	Amplitude	M2	S2	N2	K2	K1	O1	P1	Q1
Emam	TMD	0.557	0.166	0.069	0.021	0.360	0.202	0.086	0.030
	IOS	1.476	0.532	0.311	0.165	0.536	0.303	0.149	0.053
	FES2014	0.984	0.338	0.338	0.110	0.530	0.316	0.146	0.057
Vts2	TMD	0.471	0.142	0.067	0.018	0.354	0.197	0.083	0.029
	IOS	1.034	0.362	0.224	0.123	0.508	0.302	0.140	0.058
	FES2014	0.933	0.323	0.195	0.106	0.522	0.311	0.144	0.056
Pilot	TMD	0.524	0.157	0.080	0.019	0.371	0.208	0.087	0.029
	IOS	0.787	0.280	0.167	0.096	0.487	0.304	0.137	0.057
	FES2014	0.757	0.259	0.164	0.086	0.489	0.292	0.137	0.054
Rajaei	TMD	0.788	0.281	0.187	0.084	0.280	0.205	0.098	0.045
	IOS	1.092	0.530	0.278	0.120	0.293	0.240	0.110	0.052
	FES2014	1.049	0.398	0.247	0.113	0.346	0.234	0.113	0.049
Bahman	TMD	0.845	0.312	0.200	0.092	0.301	0.206	0.104	0.045
	IOS	0.830	0.260	0.140	*	0.390	0.210	*	0.040
	FES2014	0.878	0.332	0.217	0.097	0.323	0.221	0.106	0.047
Gheshm	TMD	0.844	0.311	0.200	0.092	0.301	0.206	0.104	0.045
	IOS	0.933	0.355	0.225	0.104	0.337	0.226	0.108	0.049
	FES2014	0.850	0.322	0.211	0.094	0.319	0.220	0.105	0.047
Dargahan	TMD	0.718	0.249	0.169	0.075	0.263	0.203	0.093	0.044
	IOS	0.850	0.322	0.211	0.094	0.319	0.220	0.105	0.047
	FES2014	1.077	0.244	0.244	0.113	0.334	0.232	0.108	0.048
Pohl	TMD	0.212	0.096	0.276	0.045	0.080	0.268	0.175	0.776
	IOS	0.236	0.119	0.352	0.047	0.134	0.495	0.284	1.222
	FES2014	0.254	0.108	0.343	0.048	0.119	0.488	0.229	1.155
Basaeedu	TMD	0.218	0.101	0.296	0.045	0.076	0.262	0.164	0.754
	IOS	0.210	*	0.390	0.030	*	0.270	0.160	0.830
	FES2014	0.226	0.096	0.317	0.044	0.084	0.323	0.173	0.810
Khamir	TMD	0.216	0.098	0.287	0.046	0.083	0.280	0.180	0.807
	IOS	0.240	*	0.270	0.050	*	0.600	0.270	1.250
	FES2014	0.247	0.247	0.338	0.048	0.120	0.473	0.235	1.147
Chabahar	TMD	0.677	0.261	0.164	0.075	0.394	0.202	0.117	0.043
	IOS	0.662	0.254	0.160	0.069	0.400	0.205	0.123	0.040
	FES2014	0.658	0.252	0.160	0.067	0.391	0.203	0.118	0.044
Bushehr	TMD	0.377	0.133	0.084	0.024	0.331	0.213	0.078	0.034
	IOS	0.386	0.148	0.086	0.044	0.344	0.222	0.098	0.045
	FES2014	0.382	0.151	0.086	0.049	0.337	0.221	0.097	0.040

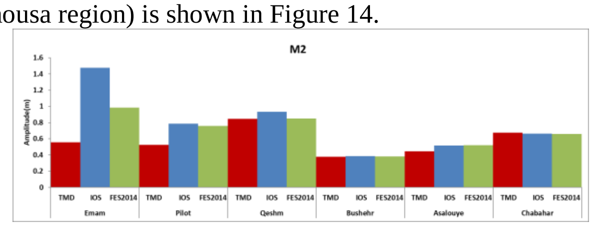
Asaluyeh	TMD	0.444	0.167	0.107	0.038	0.195	0.094	0.056	0.034
	IOS	0.515	0.177	0.121	0.058	0.232	0.121	0.073	0.045
	FES2014	0.519	0.177	0.125	0.057	0.250	0.138	0.075	0.040

Anyway, in order to evaluate the results of the amplitudes from the analysis of TMD and FES2014 models and Observations, the coefficient of determination or R-square (R^2) criterion has been used by drawing scatter plots. Considering Table 4, it can be concluded that the amplitudes of components in the scatter plots of the FES2014 model and the components of the IOS method obtained from the analysis of observations in the Khuran and Khure-mousa regions are less consistent than in the open coast region.

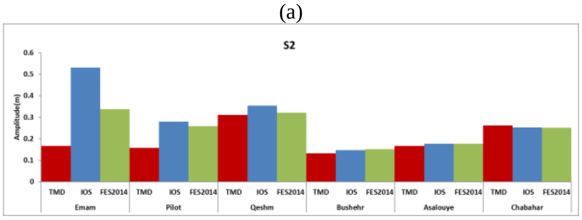
Table 4. The percentage of conformity of the calculation of amplitudes in different methods in the studied areas

regions	TMD and IOS models conformity mean	TMD and FES2014 models conformity mean	IOS and FES2014 models conformity mean
Open coasts	%99	%99	%99
Khuran	%98	%98.9	%98.9
Khure-mousa	%96	%98.6	%97

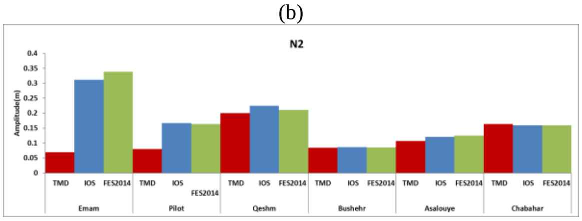
As an example, the scatter plot of Emam station (Khure-mousa region) is shown in Figure 14.



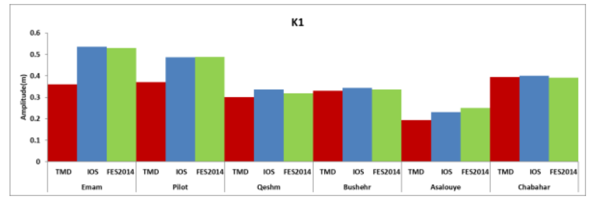
(a)



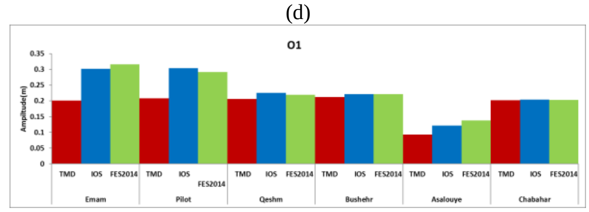
(b)



(c)

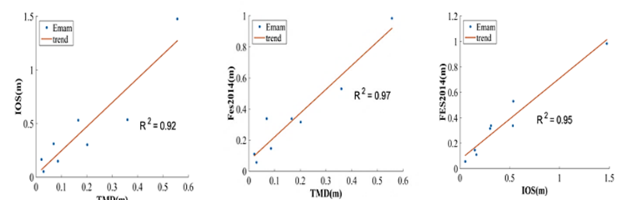


(d)



(e)

Figure 13. Comparison of the range of main harmonic components consist of (a) M2, (b) S2, (c) N2, (d) K1, (e) O1, in FES2014 and TMD and IOS models in 5 selected stations



(a) (b) (c)

Figure 14. The amplitudes of components in the scatter plots of TMD and FES2014 models and the components of the IOS method at Emam station (Khure-mousa region).

5. Conclusions and remarks

The following results were obtained from this research with experimental investigations:

In open coast areas (Bushehr, Asaluyeh and Chabahar stations), the data of tidal heights obtained from the analysis of observations using the IOS method and the prediction obtained from the FES2014 model are highly correlated. In addition, they are roughly on the trend line and have a high positive correlation.

The main point obtained from the results of this research is that the FES2014 model cannot be used in the Khure-mousa region (especially the Pilot, Emam and Mahshahr) and also inside the Khuran channel. In addition, the discrepancy between the results of the analysis of tidal observations obtained from the IOS method and the predicted results from the FES2014 model is large in these regions. In some places, these differences reach more than one meter. There was no tidal component of FES2014 model for Mahshahr station at all and FES2014 model has ignored this area.

As a general conclusion, it can be stated that the FES2014 model alone cannot have enough information for the specific areas targeted in this research, and to complete this model, a combination of this model and direct observations should be completed.

In examining the shortcomings of the FES2014 model, it was concluded that networking is difficult in certain areas with complex and narrow geography, such as Khuran channel or the northern areas of Khure-mousa.

In some very complex coastlines, with narrow channels, it leads to a loss of detail and accuracy. By using the FES2014 model in complex coastal areas (such as estuaries, narrow channels and straits), the accuracy of the tidal maps (atlas) is weakened.

The harmonic components in the stations of the open coast areas are more consistent than the model of other areas. Finally, this model does not have the necessary validity and accuracy in certain areas such as Khuran and Khure-mousa compared to the open coast areas. As a result, direct observations of tides in specific geographical areas are always necessary in global and regional models. One of the weaknesses of the global and regional models that use data assimilation to improve the model is the lack of sufficient information and observations of coastal stations in these areas. However, the use of new altimetry data can help to improve tidal models to some extent.

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