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ORIGINAL RESEARCH ARTICLE

Tide and mean sea level trend in the west coast of the Arabian Gulf from tide gauges and multi-missions satellite altimeter

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Summary Hourly data of the relative sea level from seven stations on the west coast of the Arabian Gulf, for the period 1979—2008 have been analyzed. The harmonic constituents of tide show pure diurnal tide at Murjan Island, semidiurnal type at Mina Salman and mixed type with semidiurnal dominance at the remaining five stations. Based on Multi-Missions Satellite Altimetry data, the mean sea level trend estimate was about 2.8 ± 0.4 mm/year for global ocean and about 3.6 ± 0.4 mm/year for the Arabian Gulf. Among the seven tide gauge stations, the highest sea level trend is found at Mina Salman (3.4 ± 0.98 mm/year) that agrees with the local estimate from the Multi-Missions Satellite Altimetry data. The minimum trend is found at Jubail (1.6 ± 0.71 mm/year) and Ras Tanura (0.7 ± 0.31 mm/year). At Arrabiyah Island station, the sea level trend is about 2.4 ± 0.66 mm/year, which is obtained after removing the interruptions from a relatively longer duration (15 years) data. This is in agreement with other stations and the estimates from the altimetry. The tidal analysis and trend estimation for Jubail station (29 years) have been conducted for the first time. At Murjan Island, the decadal cycle is evident from the long sea level data, giving the current estimate of trend more reliability as compared with previous studies.

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1. Introduction

The Arabian Gulf (AG), a semi-enclosed marginal sea covers a total area of about 239×10^3 km^2 with an average depth of about 36 m (Emery, 1956). Coastal areas in the northwest and the west are shallow. The average length of the AG is 990 km (Fig. 1). The main water exchange between the AG and the Indian Ocean is through the Strait of Hormuz. The wind (Shamal) blowing from north and northwest in the AG, that blow through winter and summer, is characterized by strong wind speeds during winter due to high atmospheric pressure disturbances and by a relatively lower intensity during summer (Perrone, 1979). The wind speed at the coast reaches as high as 15 m s^{-1} (Reynolds, 1993). The annual evaporation over the AG is about 2 m/year (Ahmad and Sultan, 1991; Hastenrath and Lamb, 1979; Meshal and Hassan, 1986; Privett, 1959; Xue and Eltahir, 2015), while fresh water input by precipitation is ~0.15 m/year (Johns et al., 2003). The main source of freshwater (mostly in the northern end of the AG) was the Shatt Al Arab river and its convergence with the Euphrates, Tigris and Karun rivers. However, the discharge of rivers is very small compared to evaporation.

Tides in the AG are complex, and the major tide is varying in nature from being semidiurnal, diurnal, and mixed type (Reynolds, 1993). Semidiurnal tides have two amphidromical points in the north-west and south, while the diurnal tide has one amphidromical point in the center of the AG, near the Kingdom of Bahrain. It also shows that the primary constituents are M2, S2, K1, and O1 (Najafi, 1997). The tidal propagation in the AG basin is counterclockwise from the Iranian coast north to the Saudi Arabia coast south.

The sea level variations in the west and northwest coasts of the AG have been the focus of the researchers (e.g. Al-Subhi, 2010; Alothman et al., 2014; Khalilabadi and Dariush, 2013; Reynolds, 1993; Sharaf El Din, 1988; Sultan et al., 2000). Sultan et al. (2000) calculated the meteorological effects causing (up to 75%) the seasonal signals of mean sea level in the AG, out of which the atmospheric pressure is contributed by 62% and wind stress by 12%.

Since 1992, high-quality satellite altimeters (TOPEX/Poseidon, ERS-2, GFO, Jason-1, Envisat, Jason-2 and Jason-3) lead to accurate estimates of the sea-level rise in global measurements. Gornitz (1995) estimated the rate of sea-level changes from long-term records, which show 1—2 mm/year increase globally, while altimetry data (short-term) show the increase around 3 mm/year (Antonov et al., 2005; Bindoff et al., 2007). Church et al. (2008) found that the sea level records from both tide gauge data and satellite altimeter data show sea level rising by more than 3 mm/year. Sultan et al. (2000) found that the sea level trend at Ras Tanura during 1980 and 1994 is 1.70 mm/year. Alothman and Ayhan (2010) analyzed the sea levels in 13 stations in the northwestern coast of the AG and found a relative rise of about 1.96 mm/year by correcting the vertical land motion.

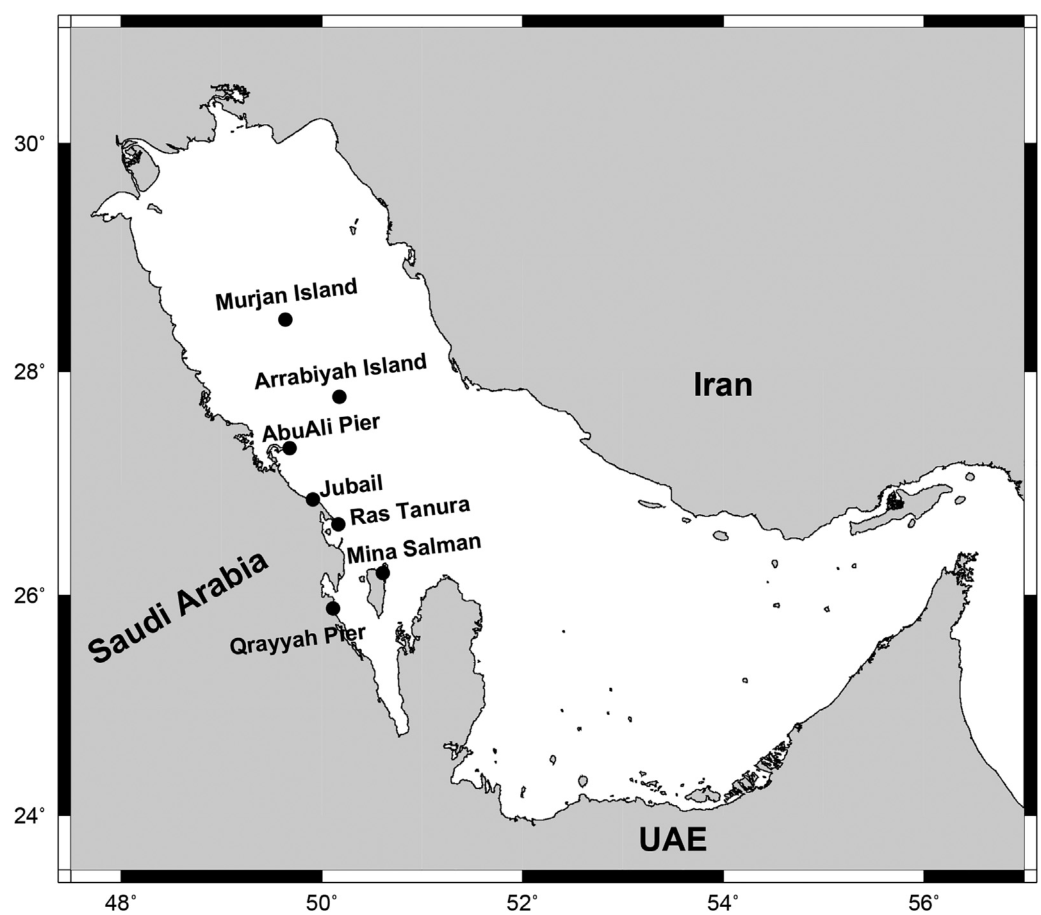

Figure 1 A map of the study area shows the name and location of the stations.

The subsequent study (Alothman et al., 2014) in the northwestern part of the AG found a trend of 2.20 mm/year when the vertical land motion trend was 1.50 mm/year.

Several studies describe the tidal constituents, with the four major tidal constituents (M2, S2, O1, and K1) that computes the amplitudes and phase (Kämpf and Sadrinasab, 2006; Lardner et al., 1982; Le-Provost, 1984; Najafi, 1997; Sultan et al., 1995; Thompson et al., 1994). John (1992) studied the tidal components from the current data and found that it changes from mixed with a dominant semidiurnal component at the northwestern region to mixed with a dominant diurnal component in the southwestern region. He also identified that the tides from the coast of Abu Ali Pier to Ras Tanura are semidiurnal type. Poul (2016) found similar results using tide gauge data for one year. Al-Mahdi et al. (2007) found that the tide in the eastern side of the AG is mixed with dominant semidiurnal component and the tidal range is over 2.50 m. Khalilabadi (2016) analyzed one-year tide gauge data at four locations along the south coast of Iran and concluded that the semidiurnal constituent was dominant in this region. Akbari et al. (2016) analyzed 8 tidal harmonic constituents (S2, M2, N2, K2, K1, P1, O1 and Q1) at 3 stations in the AG and found that the tide is generally mixed with a semidiurnal component, except near the amphidromic points. Sharaf El Din (1988) studied major harmonic constituents at 8 stations, including 6 ARAMCO tide gauges during 1980—1987 and found that the tide has diurnal and semidiurnal patterns with a dominant semidiurnal component. Al-Subhi (2010) carried out a tidal analysis for Juaymah during 2000 and 2005, and found that the tide is mixed with a dominant semidiurnal component. Table 1 summarizes the findings of all the above studies.

AG is an important area being an extension of the Indian Ocean across the Strait of Hormuz, with great economic importance (industry, commerce, and oil) and marine life.

The aim of this study is to investigate both tidal characteristics and sea level trend from seven stations on the west coast of the AG.

This is for the first time, a study incorporates records from seven tide gauge stations covering the west coast of the AG from 1979 to 2008 for analyzing tidal characteristics and linear trend together. Along with this, it is also utilizing all satellite altimetric data available from (1993—2018) for analysis of mean sea level trend.

2. Data and methods

The data used in this study include tide gauge data obtained from the Saudi Aramco Company for six stations along Saudi Arabian coast of the AG and Permanent Service for Mean Sea Level (PSMSL) data for the Kingdom of Bahrain region. The station names, coordinates and the data duration are listed in Table 2.

The satellite altimetry data (available from 1993 to 2018) were obtained from (NOAA) National Oceanic and Atmospheric Administration (https://www.star.nesdis.noaa.gov/sod/lsa/SeaLevelRise/LSA_SLR_timeseries.php).

The shortest recorded period in this study is 9 years for the Abu Ali Pier station and for the longest period recorded at Mina Salman — Ras Tanura and Jubail for 29 years.

Analysis of tide gauge data was conducted by employing World Tide MATLAB Software (WTWC) (Boon, 2004), which applies a selective least squares harmonic analysis to discriminate tidal component and prediction of tides and tidal currents, using up to 35 tidal components. It can analyze the sea level data and retain the residual sea level which is caused by forces other than the tide, which is mainly due to the meteorological forces.

By mathematical application to analysis the predict tidal, we obtain the equation

$$h(t) = h_0 + \sum_{j=1}^{m} f_j H_j \cos(\omega_j t + u_j - \kappa_j^*), \quad (1)$$

where t is the time in serial hours, $h(t)$ is a predicted water level at t, h_0 is the mean water level, f_j is a lunar node factor for the jth constituent, H_j is the mean amplitude for the jth constituent over 18.6-year lunar node cycle, ω_j is the frequency of the jth constituent, u_j is the nodal phase for the jth constituent, κ_j* is the phase of the jth constituent for the period origin is utilized (midnight beginning December 31, 1899) and m is a number of constituents.

For purely solar constituents, $f_j = 1$ and $u_j = 0$.

The amplitude (H_j) and phase (κ_j*) of the tidal constituent analysis by using the least squares method.

To identify the tidal type in each station, the form factor F (Defant, 1961) was estimated.

$$F = (K1 + O1/M2 + S2). \quad (2)$$

For $F < 0.25$ the tide is semidiurnal; for F between 0.25 and 1.5, the tide is mixed, mainly semidiurnal; for F between 1.5 and 3.0 the tide is mixed, mainly diurnal; and finally, for $F > 3.0$, the tide is diurnal.

Tide gauge (long-term) data were analyzed to acquire the monthly mean sea level elevations. As shown in Table 2, the period of the data varies from station to station; some stations have gaps of days or months. At Mina Salman, station

Table 1 The previous studies of the tidal constituents in the Arabian Gulf.

Study	Number of stations	Type of tide	Period of data
John (1992)	4	Diurnal and semidiurnal	1986—1987
Poul (2016)	31	Diurnal and semidiurnal	375 days
Al-Mahdi et al. (2007)	3	Semidiurnal	1993—1994
Khalilabadi (2016)	4 (3 inside the AG)	Semidiurnal	2009
Akbari et al. (2016)	9 (3 inside the AG)	Diurnal and semidiurnal	200 days
Sharaf El Din (1988)	6	Diurnal and semidiurnal	1980—1987
Al-Subhi (2010)	2	Semidiurnal	2000—2005

Table 2 The location of tide gauge stations in the western coast of the Arabian Gulf.

No.	Station	Longitude	Latitude	Period
1	Murjan Island	49.63°	28.45°	1986—2008
2	Arrabiyah Island	50.17°	27.77°	1985—2000
3	Abu Ali Pier	49.68°	27.31°	2000—2008
4	Jubail	49.91°	26.86°	1980—2008
5	Ras Tanura	50.16°	26.64°	1980—2008
6	Qurayyah Pier	50.11°	25.88°	1980—2000
7	Mina Salman	50.61°	26.20°	1979—2007

the data extend from 1979 to 2007 with seven-year gaps in 1981 and 1998—2003. The statistical mean of the residual sea level has been calculated to remove the seasonal effect. The monthly averaged residual sea level has been used to estimate the linear trend. Before fitting any linear model, the time series has been statistically tested for the significance of trend using the method of Mann—Kendall, which tests whether to reject the null hypothesis (H0, no trend) or accept the alternative hypothesis (Ha, if trend is present). Then the Least-Squares Line LSL method is used to fit the trend, which usually approximate the general patterns of the time series over its period (Crum, 1925; Hoshmand, 1997).

Fitting of linear trend through the Method of LSL is accomplished as follows:

The linear equation in general is

$$y = a + bx(i), \tag{3}$$

where a and b, can be expressed as follows:

$$a = \frac{y}{c}, \tag{4}$$

where c is the length of data,

$$x_m = \sum_{i=1}^{N} x_i - \tilde{x}. \tag{5}$$

The sum of square coefficient of the element x

$$X^2 = \sum_{i=1}^{N} x_{m(i)}^2. \tag{6}$$

Write the sum of y

$$y = \sum_{i=1}^{N} y_i. \tag{7}$$

We may rewrite these equations as

$$b = \frac{XY}{X^2}. \tag{8}$$

In order to estimate the value of the linear trend, Eqs. (4) and (8) are substituted in Eq. (3).

The standard error is calculated by dividing the standard deviation from the mean as

$$se = \frac{\sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(x_i - x_m)^2}}{\sqrt{N}}. \tag{9}$$

We used XLSTAT software (http://www.xlstat.com/en/) for calculating the probability value (P-value), and hypothesis testing. The Mann—Kendall test was applied to assess the significance of mean sea level trend, as follows

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} sgn(X_j - X_k), \tag{10}$$

where the data collected over time = $X1, X2, X3, \ldots, Xn$. $(X_j - X_k)$ is the difference between current values and all

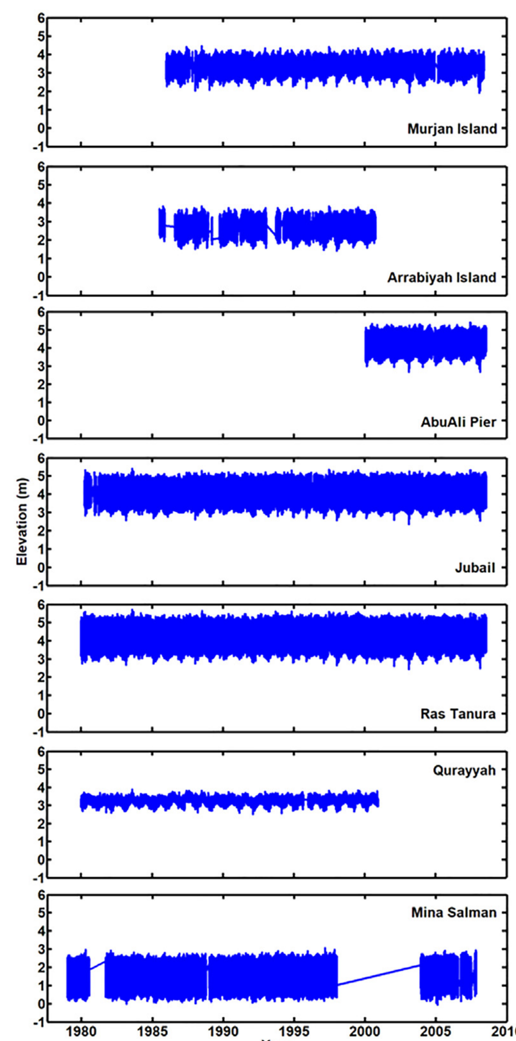

Figure 2 Time series of the tide gauge readings for seven stations.

Table 3 The highest astronomical tide (HAT) and lowest astronomical tide (LAT) elevation values for each station.

Station	HAT [m]	LAT [m]	Data recording time [day]
Murjan Island	0.56	−0.44	8187
Arrabiyah Island	0.92	−0.67	5556
Abu Ali Pier	0.88	−0.40	3110
Jubail	1.00	−1.01	10,074
Ras Tanura	1.13	−1.13	10,440
Qurayyah Pier	0.15	−0.19	7649
Mina Salman	1.02	−1.10	10,535

previous values, where $j > k$, that takes on the values of 1, 0, or −1.

Finally, the merged mean sea level from all the altimeters was analyzed to find the linear trend. The data filtered to approximately 10-days' time interval of $1° \times 1°$ grids with seasonal signals removed. The monthly mean sea level was calculated for both global data (66°S to 66°N) and for the AG region.

3. Results and discussion

Time series of the observed tide gauge data from all the stations are shown in Fig. 2. Over the study period, the tidal range (between HAT and LAT) is inconsistent from station to station. The highest range of about 2.00 m has been observed at Ras Tanura, Jubail and Mina Salman stations. The tidal range at Murjan Island is mostly about 1.00 m, while that at Arrabiyah Island is 1.60 m and at Abu Ali Pier is 1.27 m. The lowest tidal range is at Qurayyah Pier, which is about 0.34 m. Few stations, for instance, Abu Ali Pier, have discontinuities in data due to an error in recording or missing data from the source (Aramco). Mina Salman has discontinuity in the time series during 1998 and 2003.

Using the World Tides Package, the tidal and non-tidal components have been acquired for each time series. The Highest Astronomical Tide (HAT) and Lowest Astronomical Tide (LAT) in each station are shown in Table 3.

To estimate the tidal harmonic constituents, we selected uninterrupted one-year data for each station. However, the data for Arrabiyah in 1992 have a discontinuity of seven days in early February, which does not have an effect on the estimation of the tidal constituent.

4. The astronomical tides

The results of the harmonic analysis are listed in Table 4. The tidal type at each station is estimated by calculating the *F* ratio (see Eq. (2)). The major constituents M2 and K1 are determined as the most important semidiurnal and diurnal constituents. The results of the tidal harmonic constituents are plotted in Figs. 3—10.

Table 4 The amplitudes of the major tidal harmonic constituents in the west coast of Arabian Gulf; the constituents used for estimation of the form factor are bolded.

Stations	Amplitude of tide constituent								*F*-ratio	Type of tide
	Q1	O1	P1	K1	N2	M2	S2	K2		
Murjan Island	0.04	**0.21**	0.09	**0.32**	0.01	**0.05**	**0.03**	0.01	6.62	Diurnal
Arrabiyah Island	0.02	**0.14**	0.05	**0.19**	0.07	**0.34**	**0.13**	0.04	0.70	Mixed mainly semidiurnal
Abu Ali Pier	0.02	**0.13**	0.05	**0.16**	0.08	**0.41**	**0.14**	0.04	0.52	Mixed mainly semidiurnal
Jubail	0.02	**0.13**	0.05	**0.16**	0.10	**0.51**	**0.18**	0.06	0.42	Mixed mainly semidiurnal
Ras Tanura	0.02	**0.11**	0.04	**0.14**	0.12	**0.60**	**0.21**	0.07	0.30	Mixed mainly semidiurnal
Qurayyah Pier	0.002	**0.01**	0.01	**0.02**	0.01	**0.08**	**0.02**	0.01	0.30	Mixed mainly semidiurnal
Mina Salman	0.01	**0.07**	0.02	**0.11**	0.15	**0.68**	**0.22**	0.08	0.20	Semidiurnal

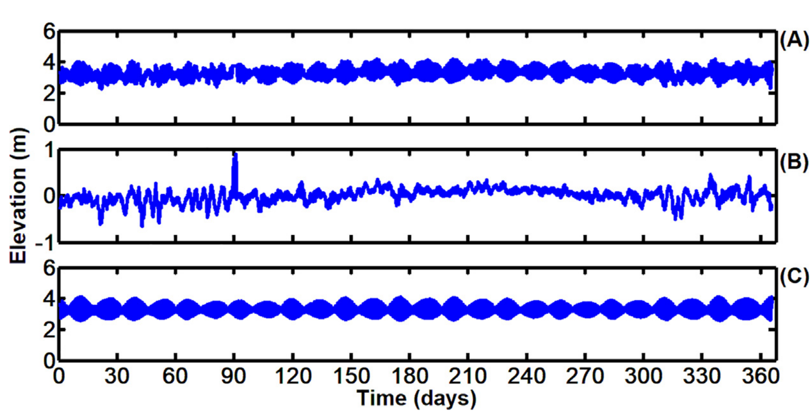

Figure 3 One-year time series of hourly tide gauge data (A), residual sea level (B) and the astronomical tide prediction at Murjan Island (C).

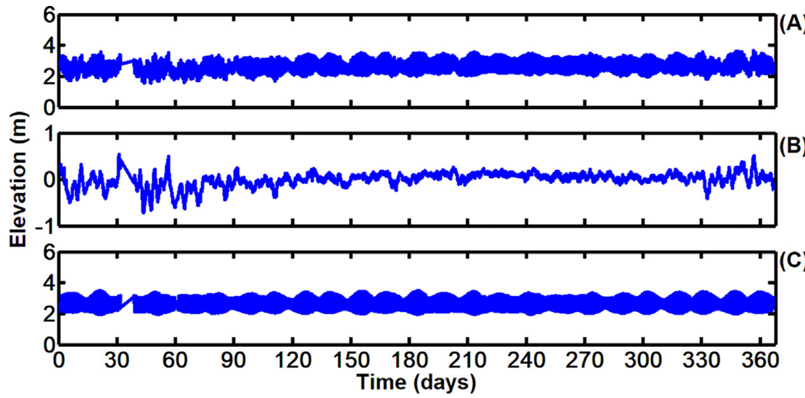

Figure 4 One-year time series of hourly tide gauge data (A), residual sea level (B) and the astronomical tide prediction at Arrabiyah Island station.

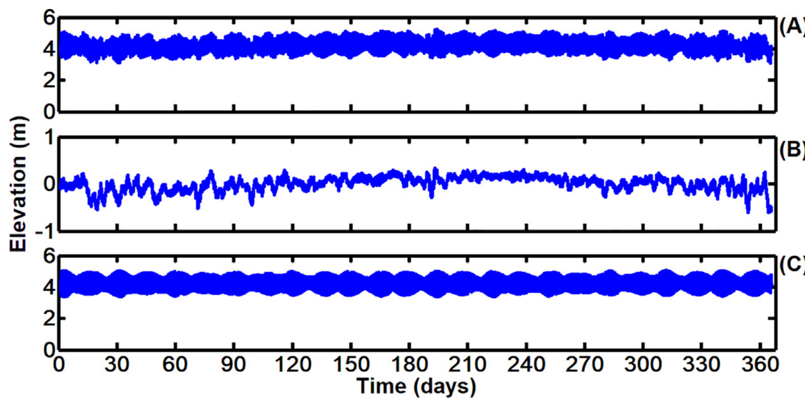

Figure 5 One-year time series of hourly tide gauge data (A), residual sea level (B) and the astronomical tide prediction at Abu Ali Pier station.

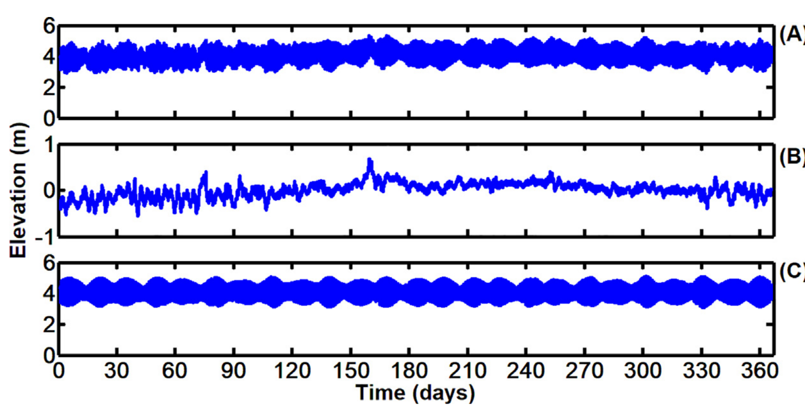

Figure 6 One-year time series of hourly tide gauge data (A), residual sea level (B) and the astronomical tide prediction at Jubail station.

Fig. 3 shows the time series of one-year raw tide gauge data, the residual sea level and the predicted astronomical tide at Murjan Island. The astronomical tide is dominant in the sea level variability with a range of ~1.00 m. Out of the eight major tidal constituents S2, M2, N2, K2, K1, P1, O1 and Q1, the amplitudes of diurnal constituents K1 and O1 show clear dominance (Fig. 10). It is also evident in the F-ratio ($F \approx 6.62$). At Arrabiyah, the tidal range is 1.60 m (Fig. 4) and the tide is mixed semidiurnal with clear dominance of semidiurnal component M2 (Fig. 10), where the F-ratio is ≈0.7. The tidal range at Abu Ali Pier is 1.27 m (Fig. 5). Here, the tide is mixed semidiurnal and the semidiurnal component M2 shows the highest amplitudes compared to the other tidal components (Fig. 10) with an F-ratio of ≈0.52. Previous studies also reported mixed semidiurnal tide in this station (John, 1992) and near the station (Najafi, 1997; Pous et al., 2012).

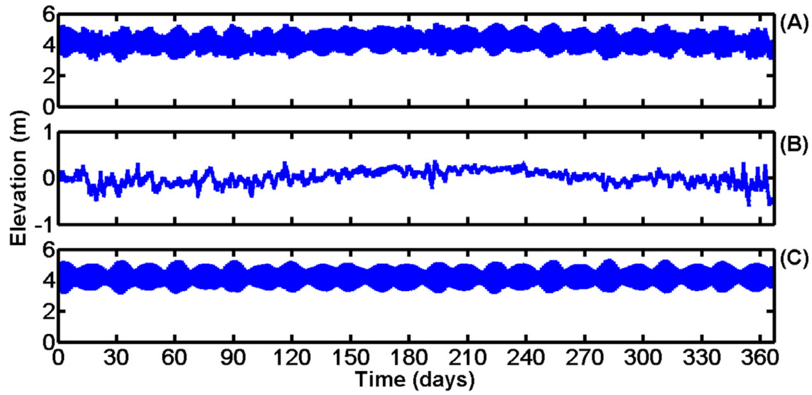

Figure 7 One-year time series of hourly tide gauge data (A), residual sea level (B) and the astronomical tide prediction at Ras Tanura station.

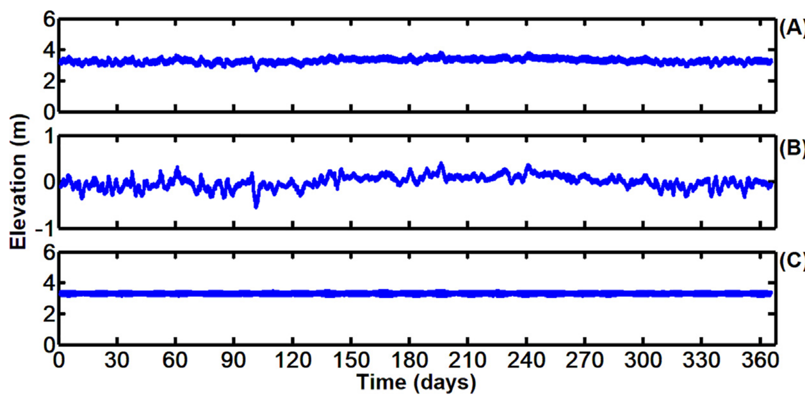

Figure 8 One-year time series of hourly tide gauge data (A), residual sea level (B) and the astronomical tide prediction at Qurayyah Pier station.

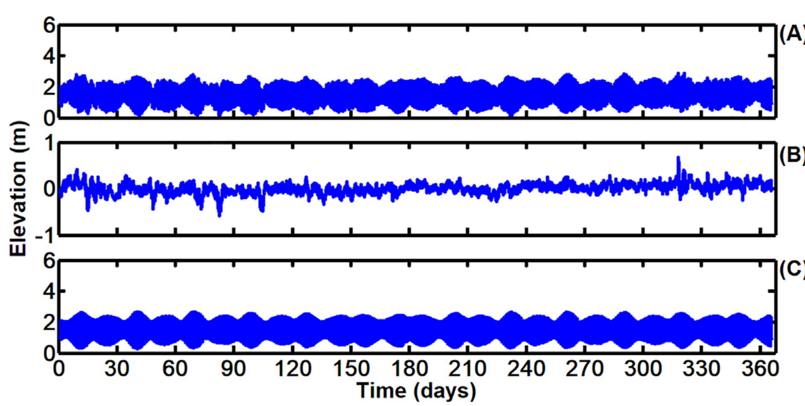

Figure 9 One-year time series of hourly tide gauge data (A), residual sea level (B) and the astronomical tide prediction at Mina Salman station.

The tidal range at Jubail is one among the highest in the AG, which is about 2.00 m (Fig. 6). The tide is mixed semidiurnal with the clear dominance of semidiurnal component M2, where the F-ratio is ≈0.42. This is consistent with other studies conducted in stations close to Jubail (Al-Subhi, 2010; John, 1992; Najafi, 1997; Pous et al., 2012). The maximum tidal range reported in this study is at Ras Tanura station, which is about 2.26 m (Fig. 7). Here, the semidiurnal constituents are dominant, with the clear dominance of M2 over the other major tidal components (Fig. 10). Hence, this is also of mixed semidiurnal (dominant) and the F ratio is ≈0.3. Several studies have been conducted to study the tide in this region, due to the economic importance of the area (John, 1992; Pous et al., 2012; Sultan et al., 1995).

The lowest tidal range is observed at Qurayyah Pier, which is around 0.34 m (Fig. 8). The tidal analysis shows that the highest amplitude among the 8 major tidal components was M_2 (Fig. 10). This station shows the same value of the F-ratio as that of Ras Tanura with mixed mainly semidiurnal, even though the two stations represent the two extreme ranges among all stations. Najafi (1997) results showed mixed semidiurnal tides at this station. The seventh station is Mina Salman with tidal range among the highest in the AG with 2.12 m (Fig. 9). The semidiurnal constituents M2 and S2 are dominant with highest amplitudes among the 8 major tidal components (Fig. 10). This station is the only station with semidiurnal tide with $F \approx 0.2$ which shows a similar tidal type to that reported by Sharaf El Din (1988) and El-Sabh and Murty (1988).

In general, the tide at Murjan Island is dominated by diurnal components, since this station is close to the semidiurnal amphidromic points in the northern AG. Similarly, the Mina Salman station is near to the diurnal amphidromic points, and hence the tide is dominated by semidiurnal constituents. The remaining five stations show the mixed tidal type. There are no previous studies available on tide analysis at Murjan Island, Arrabiyah Island and Jubail stations. Thus the results obtained in this study will significantly contribute to the scientific knowledge of the region.

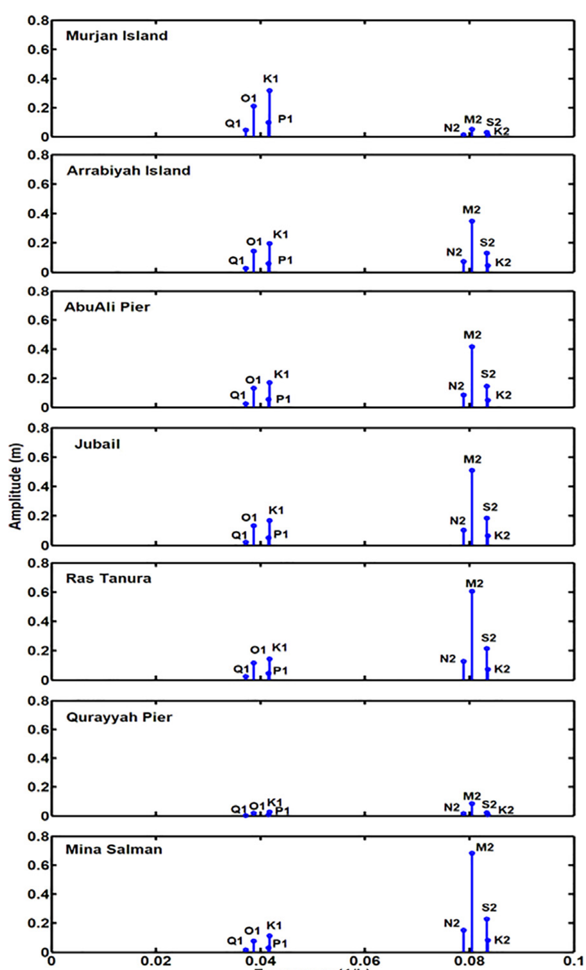

Figure 10 Tidal amplitudes of the major 8 constituents for all the stations.

5. Trend analysis

The monthly averaged residual sea level was used to estimate the linear trend. The sea levels from all the tide stations and those estimated from satellites show significant positive trends with P-value < 0.05, except at Mina Salman and Arrabiyah Island. The inconsistencies in these two stations are due to large data gaps in the time series. Mina Salman has discontinuity in data string from the available source about six years as shown in Fig. 2 (panel 7). However, the trend analysis for the uninterrupted period (1982—1997) show

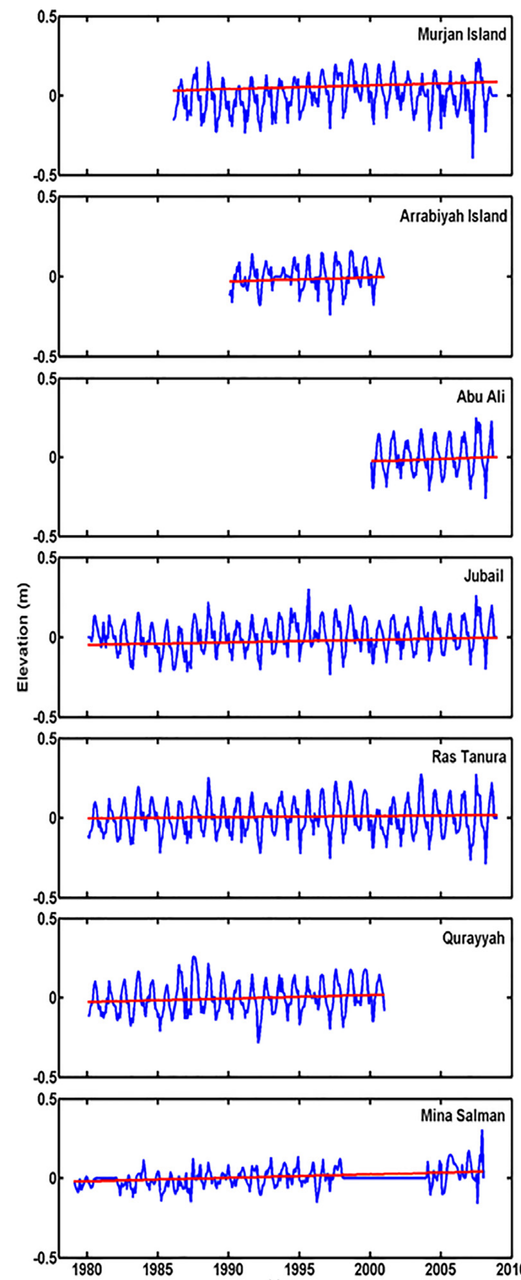

Figure 11 Estimated linear trend for TG stations.

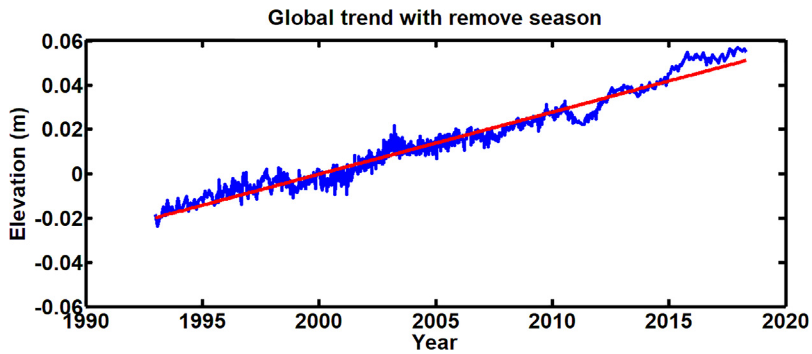

Figure 12 Global oceans mean sea level trend 2.8 mm/year, from multi-mission satellite altimetry.

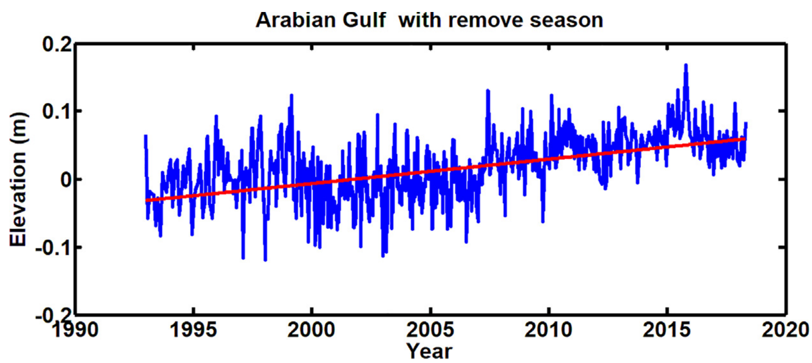

Figure 13 Arabian Gulf mean sea level trend 3.6 mm/year, from multi-mission satellite altimetry.

Table 5 Estimated mean sea level trend rates for the northwestern Arabian Gulf area as compared with the previous estimates.

Stations	The present study			Hosseinibalam et al. (2007)		Alothman and Ayhan (2010)		Alothman et al. (2014)	
	Estimated trend [mm/year]	*P*-value	Period	Estimated trend [mm/year]	Period	Estimated trend [mm/year]	Period	Estimated trend [mm/year]	Period
Murjan Island	2.4 ± 0.94	0.0001	1986—2008	9.75 ± 0.15	1990—2000	9.37 ± 2.02	1986—2001	7.05 ± 1.17	1986—2001
Arrabiyah Island	2.4 ± 0.66	0.032	1990—2000			−4.15 ± 3.52	1985—1998	−0.33 ± 0.18	1985—1998
Abu Ali Pier	3.1 ± 0.70	0.000	2000—2008	4.5 ± 0.04	1990—2000	1.74 ± 1.14	1980—2001	1.18 ± 0.63	1980—2001
Jubail	1.6 ± 0.71	0.002	1980—2008						
Ras Tanura	0.7 ± 0.31	0.015	1980—2008	0.84 ± 0.03	1990—2000	1.85 ± 1.05	1980—2001	0.74 ± 1.11	1980—2001
Qurayyah Pier	2.2 ± 0.84	0.001	1980—2000			3.29 ± 1.35	1980—1998	2 ± 0.99	1980—1998
Mina Salman	3.4 ± 0.98	0.0001	1979—2007			3.22 ± 0.58	1979—2007	2.97 ± 0.51	1979—2007

significant trend with *P*-value = 0.0001. Similarly at Arrabiyah Island, after removing the periods with severe gaps, the trend analysis (during 1990—2000) shows significant positive trend. Fig. 11 shows the monthly sea level with fitted trend at all the stations. The highest trend is seen at Mina Salman and Abu Ali Pier stations (3.4 ± 0.98 and 3.1 ± 0.7 mm/year, respectively). The lowest trend is found in Jubail (1.6 ± 0.71 mm/year) and Ras Tanura (0.7 ± 0.31 mm/year), while the trend at the remaining stations are as follows: at Murjan Island 2.4 ± 0.94 mm/year, Qurayyah Pier 2.2 ± 0.84 mm/year and at Arrabiyah Island 2.4 ± 0.66 mm/year. The monthly average of the Multi-Missions Satellite Altimetry data from 1993 to 2018 has been used to estimate the linear trend for global oceans and the AG. The estimated trends are 2.8 ± 0.4 mm/year (Fig. 12) and about 3.6 ± 0.4 mm/year (Fig. 13) respectively. They are significant with *P*-value = 0.0001. Table 5 lists all the trends estimated in this study as well as in the previous studies for an inter-comparison of values, however, the data duration may vary among the studies.

Even though, the estimated trend at Murjan Island station is in a good agreement with that of other stations in the AG, it is much less than the previous estimates (Alothman and Ayhan, 2010; Alothman et al., 2014; Hosseinibalam et al., 2007). The main reason for the inconsistency is the shorter duration in the previous studies (11—15 years). There are clear decadal signals in our estimates with 23 years of data (Fig. 11). We re-estimated the trends in same periods of the previous studies and the results show similar high values, which confirms the influence of decadal cycle in the analysis (figure not shown). At Abu Ali Pier, the estimated trend is 3.1 mm/year, which is lower than the estimate by Hosseinibalam et al. (2007) and higher than the estimated by Alothman and Ayhan (2010) and Alothman et al. (2014) (Table 5). At Qurayyah Pier, the estimated trend is similar to that of Alothman et al. (2014), while that at Ras Tanura agrees with the estimates of both Hosseinibalam et al. (2007) and Alothman et al. (2014). At Mina Salman, the estimated trend agrees with that estimated by Alothman and Ayhan (2010) and Alothman et al. (2014). At Arrabiyah Island, the estimated trend show contradictory results compared to previous studies; they found a decreasing trend (Alothman and Ayhan, 2010; Alothman et al., 2014). Alothman et al. (2014) related that decrease to human activities in that area and the existence of oil platforms near the station. We find that the data gaps in our records significantly affect the estimated trends. A rough estimate by incorporating the previous trends at the time of data gaps leads to a decreasing trend in this region. In the present study that period is excluded and only the data of minimal discontinuity is used (1990—2000) in the trend estimation. The mean trend value for all the stations is $\approx$2.3 mm/year in the AG.

6. Conclusion

In this paper, seven tide gauge stations on the west coast of the AG have been analyzed. The observed tide data show a pure diurnal tide at Murjan Island, semidiurnal at Mina Salman and a mixed type of tide with semidiurnal dominance at Arrabiyah Island, Abu Ali Pier, Jubail, Ras Tanura and Qurayyah Pier station. The highest tidal range is recorded at Ras Tanura with 2.26 m and the minimum tidal range is seen at southern coastal station (Qurayyah Pier) with 0.34 m (Table 3).

The linear trend has been estimated using monthly mean residual sea level for all stations. The highest trend values is at Mina Salman about 3.4 ± 0.98 mm/year and Abu Ali Pier about 3.1 ± 0.7 mm/year. At Arrabiyah Island and Murjan Island station the trend is about 2.4 ± 0.66 mm/year and 2.4 ± 0.94 mm/year, respectively. The trend estimate for Qurayyah Pier station is almost similar, with an estimate of 2.2 ± 0.84 mm/year. Lower trends have been estimated at Jubail and Ras Tanura stations with about 1.6 ± 0.71 mm/year and 0.7 ± 0.31 mm/year respectively. The average linear trend for all seven stations is about 2.3 mm/year.

The trend for global oceans based on satellite data for the period from 1993 to 2018 was estimated as 2.8 + 0.4 mm/year, while trend in the AG is about 3. 6 ± 0.4 mm/year.

The present study shows the tidal analysis and trend estimates for Jubail station from 29 years (1980—2008) for the first time. Similarly, at Arrabiyah Island the present study shows positive trend, which agrees with all other stations, while all previous studies show negative trend at the same station. The main reason for the negative trends in the previous studies was due to inclusion of high variability data (the period from 1985 to 1989) having lots of gaps. At Murjan Island, the longer duration data (23 years) produced good trend estimates, which agrees with that of the other stations. The previous studies show very high trend at this station, which is mainly due to shorter data record they analyzed.

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