# Chapter 5
# The Application of Remote Sensing on the Studies of Mean Sea Level Rise in the Arabian Gulf

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**Abstract**  Mean sea level (MSL) trend at the Arabian Gulf has been estimated based on hourly tide gauge (TG) data of seven stations at the west of the gulf (1979–2008) and multi-missions satellite altimetry monthly mean (1993–2018). Analysis exposes that MSL is rising due to global warming. Altimetry data reveals a global rising trend by about $2.8 \pm 0.4$ mm/year while for the Arabian Gulf, trend estimation shows higher rate by about $3.6 \pm 0.4$ mm/year. This value almost in agreement with previous trend estimations for the gulf by many researchers and trend values in adjacent seas such as the Red Sea and Gulf of Aden. Based on TG hourly values, sea level trend is also showing a rising trend at all stations with variable rates. For example, at Mina Salman the trend value is about $3.4 \pm 0.98$ mm/year which agrees with the above estimate from the altimetry data followed by values from Arrabiyah Island station; $2.4 \pm 0.66$ mm/year. However, not all stations reflect the same MSL trend rising rates; for example, Ras Tanura recorded the lowest value of trend followed by Jubail station by about $0.7 \pm 0.31$ mm/year and $1.6 \pm 0.71$ mm/year respectively.

**Keywords**  Remote sensing · Mean sea level rise · Arabian gulf

## 5.1   Introduction

Marine studies gained countless benefits from remote sensing in the past four decades. To illustrate, these benefits include but not limited; coastal applications programs such as tracking sediment and erosion prevention. Furthermore, another advantage is to ocean applications where ocean dynamics can be tracked and modelled. This includes ocean circulation, climate studies, and tide and sea level fluctuations. Moreover, additional influence lies on the hazard assessments such as

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oil pollution. Of course, the natural marine resources have earned well assets from remote sensing such as coral reef health monitoring programs. One of the strong points to oceanographers is the advent of satellite altimetry with the Skylab in the mid-1970s. Satellite altimetry has accomplished revolutionary bounce in the advancement of ocean studies and those related to the climate. Climate changes, as a result of global warming, has raised the sea level in a dramatic rhythm affecting millions of lives in the global coastal areas. Sea level rise has become a concerning issue to almost all countries due to the increasing threat to their coastal areas and hence development. Satellite altimetry precisely measures the topography of the global sea surface in a short revisit time.

It is well known that oceans are the dynamic of the earth's climate. The most significant roles are played by the Pacific Ocean since it represents more than one-third of the surface of our globe and nearly half the area of its oceans. However, the ocean and seas get affected by climate change in two ways; direct and indirect. The direct effect is by the increasing of the water volume by melting of snow and ice and consequently, the sea level rises. When the ocean got more heat, its water column expands and hence, the sea level rises; this is an indirect effect of climate change and for oceanographers it is known as Steric Sea Level. For this reason, the projection of sea level rise is becoming the most concern for many countries and agencies. Before the era of satellites sea level data was collected merely from tide gauges distributed around almost all coasts. Lately these data were plugged in into hydrodynamic statistical models to figure out the future sea level rise projections. However, these models have so many shortage and limitations due to the absence of data in some parts of the globe. After the satellite altimetry data gained its wide coverage and reliability starting early 90s with TOPEX/Poseidon (T/P) revolutionary mission both climate and sea level rise studies got a lot of strength and scientific significant.

Satellite altimeter is an active microwave sensor measures the time took a radar pulse to hit the sea surface and reflects back to the receiving altimeter antenna in order to estimate SSH (Fig. 5.1). Thus, the SSH equals to the satellite orbit (O) which represents its height above the earth's ellipsoid after subtracting the satellite corrected range (R) which represents its height, above the sea surface:

$$\text{SSH} = \text{O} \; - \; \text{R}_{\text{corrected}}$$

Like many other satellites remote sensing, altimeters face difficulties and challenges. To illustrate, the troposphere and ionosphere distort microwave signals and attenuate their quality and hence required some technical corrections. The other difficulties arise due to complicated conditions of coastal areas, including their bottom topography, water dynamics and land proximity (Taqi et al., 2020). These costal difficulties prevent the extracting of SLA information directly from the microwave waveform within the first 50 km of the coasts (Taqi et al., 2017). For the above reasons, satellite altimetry data must go through many corrections for the atmospheric attenuations and land proximities. However, the land proximities for semi-enclosed seas and gulfs remains one of the big challenges that always prevent the full

## Satellite Altimeter
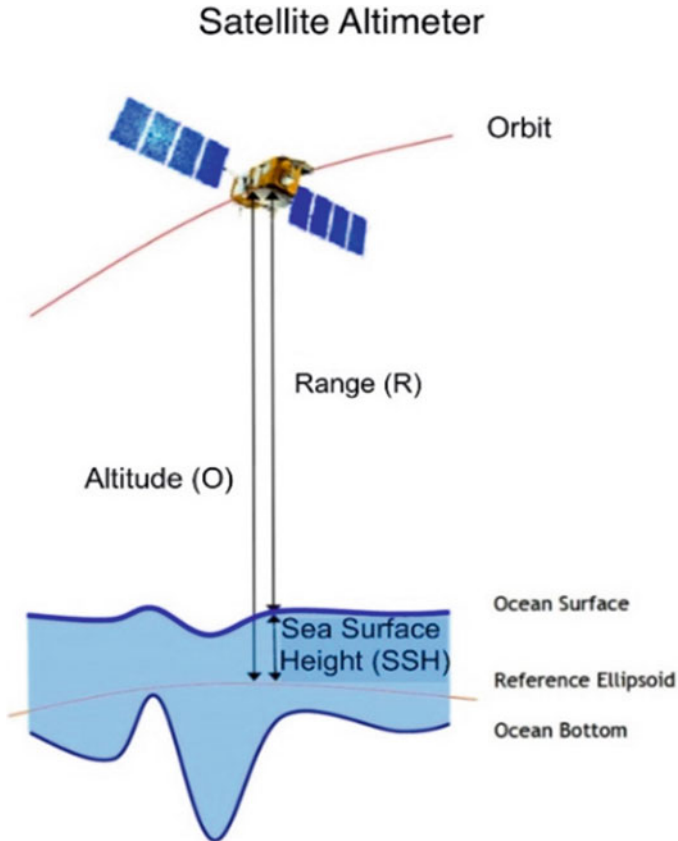


**Fig. 5.1** Satellite altimetry estimates Sea Surface Height (SSH) by measuring travelling time of radar pulse to sea surface and back to antenna. Modified version of the image from the Archiving, Validation, and Interpretation of Satellite Oceanographic Data (AVISO) at: http://www.aviso.altimetry.fr

use of altimeter data in these areas until recently when these issues have been fully resolved. (Taqi et al., 2020) have successfully improved SLA precision using a technique called the improved "Fourier series model (FSM01)" method in the Red Sea which in turn can be applied in any coastal areas around the world.

The Arabian Gulf (AG), is a semi-enclosed marginal sea covered a total area of about $239 \times 103$ 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. 5.2). 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 ms$^{-1}$ (Reynolds, 1993). The annual evaporation over the
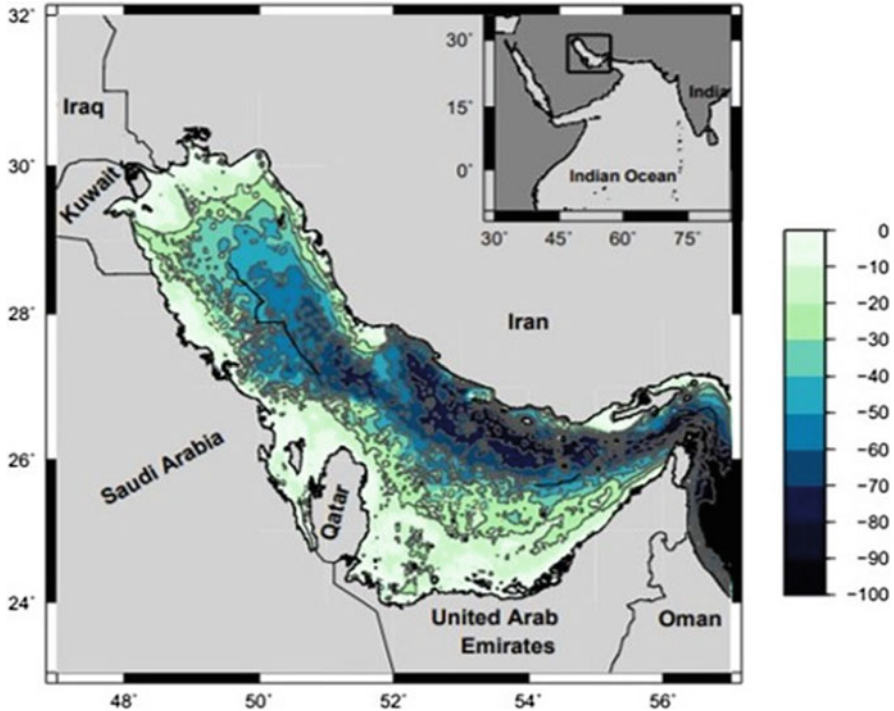
**Fig. 5.2** A map of the study area shows the name and location of the stations

AG is about 2 m/year (Ahmad & Sultan, 1991; Hastenrath & Lamb, 1979; Meshal & Hassan, 1986; Privett, 1959; Xue & Eltahir, 2015), while fresh water input by precipitation is ∼0.15 m /year (Johns et al., 2003). The main source of fresh water was occurred mostly in the northern end of the AG, through the Shatt Al Arab river by convergences the Euphrates, Tigris and Karun rivers in it. 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 semi-diurnal, diurnal, and mixed type (Reynolds, 1993). Semi diurnal 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 has been the focus of the researchers (Al-Subhi, 2010; Alothman et al., 2014; El Din, 1990; Khalilabadi & Mansouri, 2013; Reynolds, 1993; 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 an increasing trend of the global sea level non-satellite records to be 1–2 mm/year. Meanwhile, satellite altimetry data shows an increase around 3 mm/year (Antonov et al., 2005; Bindoff et al., 2007). However, (Church et al., 2008) found that the sea level trend from both TG and satellite altimetry data show sea level is rising by more than 3 mm/year. In the Arabian Gulf (AG), Sultan et al. (2000) found that the sea level trend at Ras Tanura during 1980 and 1994 is rising by 1.70 mm/year. Moreover, (Alothman & Ayhan, 2010) analysed sea level data in 13 stations in the north-western coast of the AG and found a relative rise of about 1.96 mm/year by correcting the vertical land motion. Later study conducted by (Alothman et al., 2014) in the same part of the AG found a trend of 2.20 mm/year and after correcting this value for vertical land motion the trend became 1.50 mm/year.

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

The aim of this study is to investigate sea level trend from seven stations on the west coast of the AG from 1979 to 2008. These data serve as a ground truth and validation for all satellite altimetric sea level data available from (1993–2018). It is important to mention that most of the results presented in this chapter have been published in (Siddig et al., 2019) and re-presented here with the permission of the publisher.

## 5.2   Data and Methods

The National Oceanic and Atmospheric Administration (NOAA) was the main source of the satellite altimetry data which extracted for the period between 1993 and 2018 from official website https://www.star.nesdis.noaa.gov/socd/lsa/SeaLevelRise/LSA_SLR_timeseries.php. The TG data of six selected stations along the Arabian Gulf, Saudi Arabian coast was obtained from Saudi Aramco Company. While the Permanent Service for Mean Sea Level (PSMSL) https://www.psmsl.org/data/obtaining/map.html was used for the data of the Mina Salman, Kingdom of Bahrain. Details of these stations, including the data duration, names and coordinate is listed in (Table 5.1). The study was done within the longest recorded period of 29 years conducted for Mina Salman, Jubail and Ras Tanura stations and the shortest recorded period in this study is 9 years for the Abu Ali Pier station.

In order to extract residual sea level, which is caused by forces other than tide mainly the meteorological forces, from the observed TG records, the World Tide MATLAB Software (WTWC) (Boon, 2004), has been used. The software applies a selective, least squares harmonic analysis to identify the tidal constituents and predict tides and tidal currents using a total of 35 tidal constituents.

**Table 5.1** The location of TG 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 |

**Table 5.2** The highest astronomical tide (HAT) and lowest astronomical tide (LAT) values for each station along with the period length of data recorded

| 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 |
| Min Salman | 1.02 | −1.10 | 10,535 |

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

$$h(t) = h_0 + \sum_{j=1}^{m} f_j \, H_J \, cos \left( \omega_j t + u_j - k_j^* \right) \tag{5.1}$$

where, t = time in serial hours;

h(t) = predicted water level at t;
h0 = mean water level;
fj = lunar node factor for jth constituent;
Hj = mean amplitude for jth constituent over 18.6-year lunar node cycle;
ωj = frequency of jth constituent;
uj = nodal phase for jth constituent;
κj* = phase of jth constituent for the period origin is utilized (midnight beginning December 31, 1899) and m = number of constituents.

For purely solar constituents, fj = 1 and uj = 0.

The monthly mean sea level elevations were determined by analysing the long-term TG data as illustrated in (Table 5.2). The length of the recorded data varies from station to station with some short gaps in a few stations while at Min Salman, the station has seven-year gaps in 1981 and 1998–2003.

In order to estimate the linear trend from the residual sea level data, first the seasonal effect has to be eliminated through calculation of the monthly averaged

residual sea level. Statistical testing is carried out on the time series for the trend significance prior to fitting the linear model using Mann-Kendall method, which tests whether to reject the null hypothesis (H0, no trend) or the alternative hypothesis (Ha, if trend is present), is to be accepted.

The trend is fitted using the Least-Square Line (LSL) method that is often used in the approximation of the general pattern of time series over the selected period (Crum, 1925; Hoshmand, 1997).

The linear equation in general

$$y = a + bx(i) \tag{5.2}$$

Where the a and b, can be expressed as follows:

$$a = \frac{y}{c} \qquad \text{where } c = \text{length of data} \tag{5.3}$$

$$x_m = \sum_{i=1}^{N} x_i - \widetilde{x} \tag{5.4}$$

The sum of square coefficient of the element x

$$X^2 = \sum_{i=1}^{N} x_{m(i)}^2 \tag{5.5}$$

Write the sum of y

$$y = \sum_{i=1}^{N} y_i \tag{5.6}$$

We may rewrite these equations as

$$b = \frac{XY}{X^2} \tag{5.7}$$

In order to estimate the value of the linear trend, Eq. (5.3) and (5.7) are substituted in Eq. (5.2).

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

$$se = \frac{\sqrt{\frac{1}{N-1} \sum_{i=1}^{N} (x_i - x_m)^2}}{\sqrt{N}} \tag{5.8}$$

The XLSTAT software (http://www.xlstat.com/en/) is used 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.

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} sgn\left(X_j - X_k\right) \tag{5.9}$$

Where, the data collected over time = X1, X2, X3......Xn.

$(X_j - X_k)$ is the difference between current values and all previous values, where j > k, that takes on the values 1, 0, or − 1.

For the satellite altimetry data, the sea level linear trend was determined from the merged sea level from all altimeter data. The data filtered to approximately 10-days' time interval of 1° x 1° grids with seasonal signals removed. The final stage involved determination of the monthly mean sea level for Arabian Gulf area as well as that of the global coverage which lies on the latitudes 66°S to 66°N.

## 5.3   Results and Discussion

As shown in Table 5.2, the HAT and LAT indicate that there are high variations of the tidal range between the stations over the study period. To illustrate, the highest range is noted in the station Min Salman, Ras Tanura and Jubail at 2.00 m and the lowest range is Qurayyah pier at about 0.34 m. the recorded TG time series of all stations are plotted in (Fig. 5.3). From the figure it is clear that Jubail and Ras Tanura station has the longest continuous recorded data while the lowest record is in Abu Ali pier.

### 5.3.1   The Linear Trend Analysis

The linear trends for AG and global oceans have been estimated from the entire satellite altimetry monthly mean time series as shown in (Figs. 5.4 and 5.5). The linear trend for AG and global oceans is 3.6 ± 0.4 mm/year and 2.8 ± 0.4 mm/year respectively with the significant values of P = 0.0001. The TG monthly mean sea level show significant positive trends with P value <0.05, for all stations except at Mina Salman and Arrabiyah Island. The inconsistencies in these two stations are due to large data gaps in the time series.

Figure 5.6 show the monthly mean sea level with fitted trend at all the TG station. Mina Salman, however, has a discontinuity in the record for about 6 years. The trend analysis for the uninterrupted period (1982–1997) shows a 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
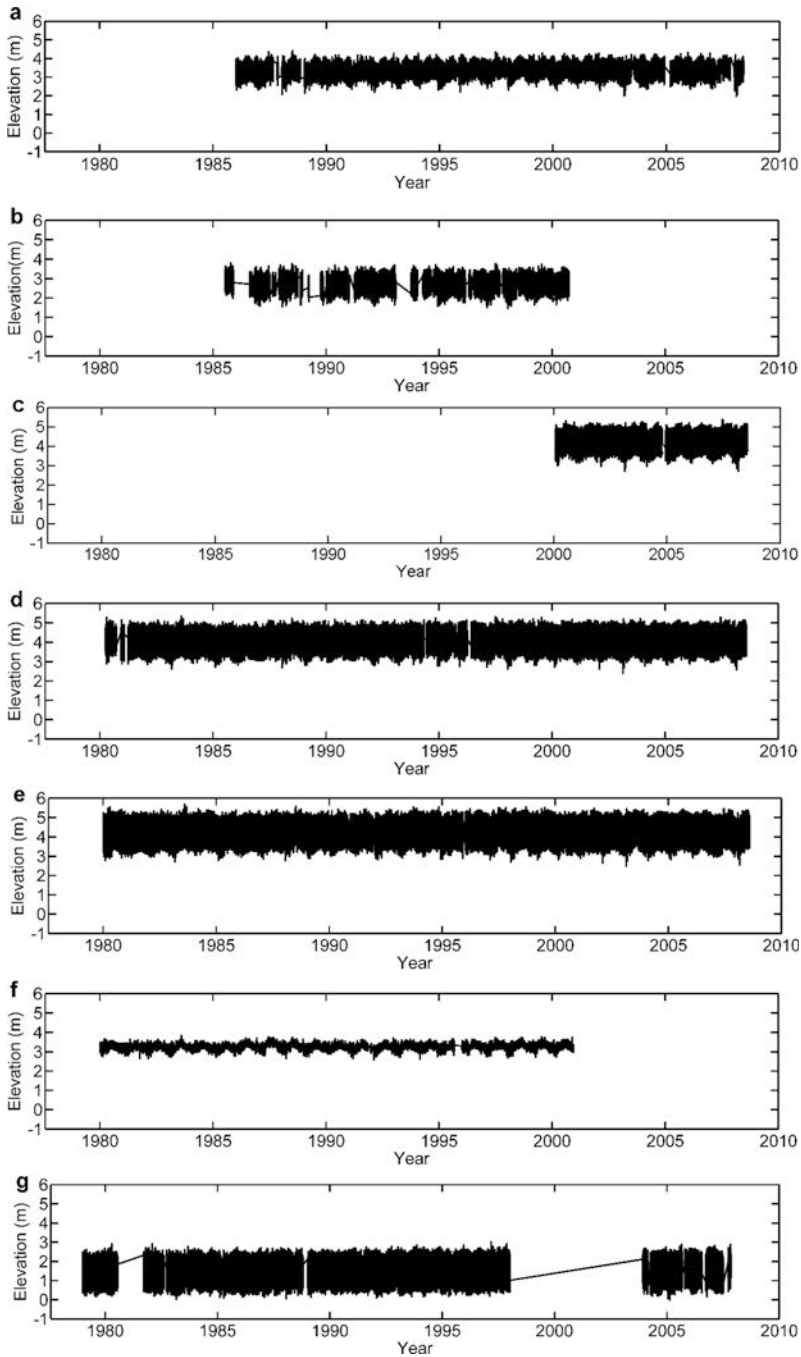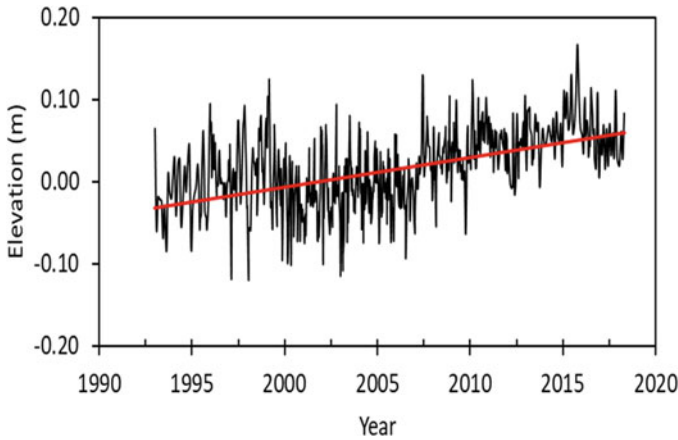
**Fig. 5.3** Time series of the records for seven stations. (**a**) Murjan Island, (**b**) Arrabiyah Island, (**c**) Abu Ali, (**d**) Jubail, (**e**) Ras Tanura, (**f**) Qurayyah, (**g**) Mina Salman.
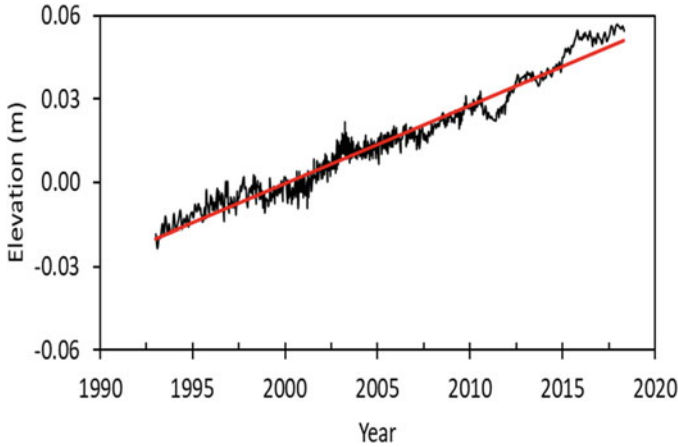
**Fig. 5.4** Global oceans mean sea level trend 2.8 mm/year, from multi-mission satellite altimetry
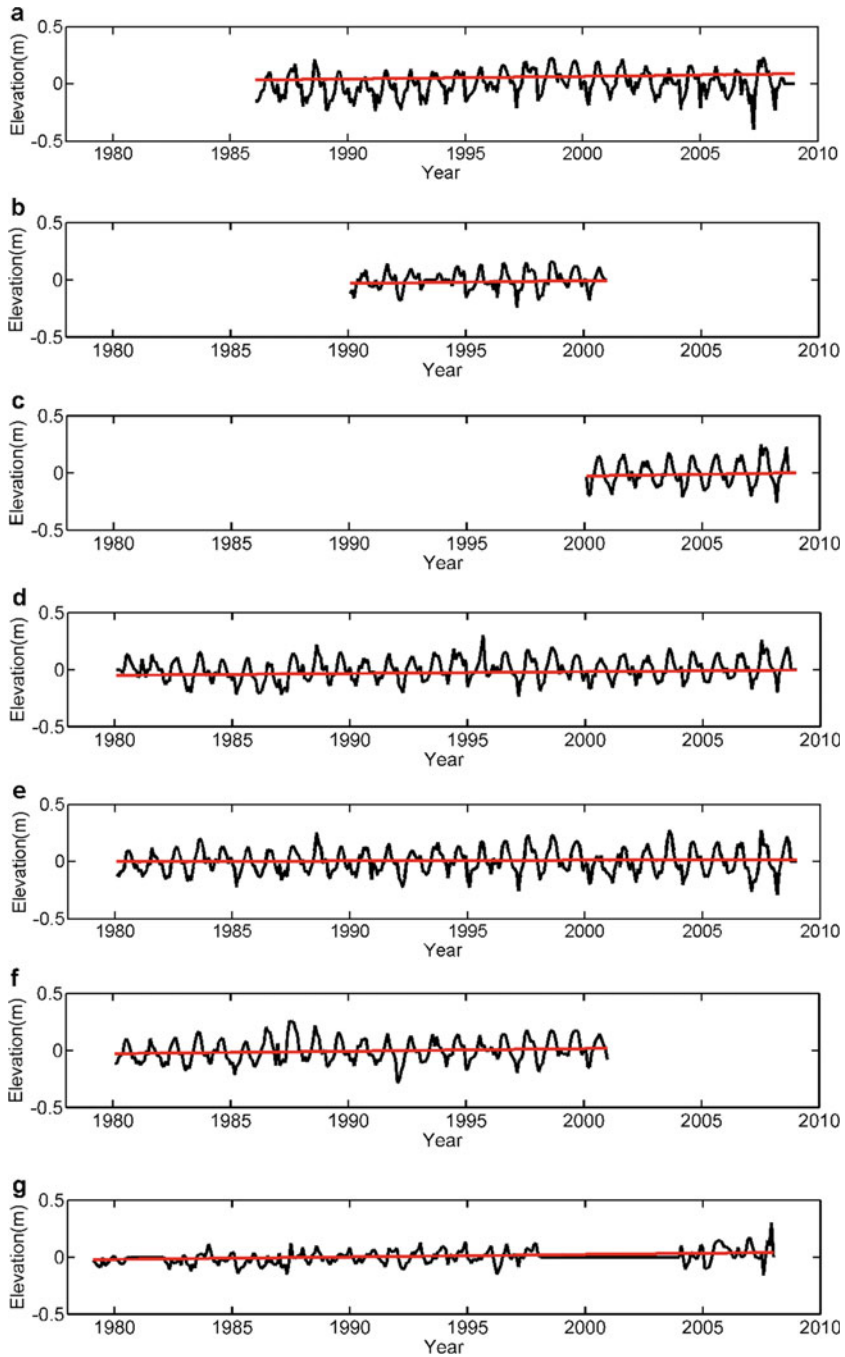


**Fig. 5.5** Arabian Gulf mean sea level trend 3.6 mm/year, from multi-mission satellite altimetry

trend. The highest trend of the monthly sea level can be noted at the stations Abu Ali Pier and Mina Salman with the values being 3.4 ± 0.98 mm/year and 3.1 ± 0.7 mm/year respectively. While at Ras Tanura and Jubail stations the trend values is 0.7 ± 0.31 mm/year and 1.6 ± 0.71 mm/year which considered the lowest trends among all station. The other stations recorded their trends as illustrated:

- Qurayyah Pier station =2.2 ± 0.82 *mm/yrar*
- Arrabiyah Island= 2.4 ± 0.66 *mm/year*
- Murjan Island station= 2.4 ± 0.94 *mm/year*

Table 5.3 list all the estimated trends in this study as well as in the previous studies for an inter-comparison of values, however, the data duration may vary among the

**Fig. 5.6** Estimated linear trend for TG stations. (**a**) Murjan Island, (**b**) Arrabiyah Island, (**c**) Abu Ali, (**d**) Jubail, (**e**) Ras Tanura, (**f**) Qurayyah, (**g**) Mina Salman

**Table 5.3** Estimated mean sea level trend rates for north-western Arabian Gulf area as compared with the previous estimates

| Stations | This study | | | Hosseinibalam et al., 2007 | | Alothman & Ayhan, 2010 | | Alothman et al., 2014 | |
|---|---|---|---|---|---|---|---|---|---|
| | Estimate trend mm/year | P-value | Period | Estimate trend mm/year | Period | Estimate trend mm/year | Period | Estimate 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 |
| Min Salman | 3.4 ± 0.98 | 0.0001 | 1979–2007 | | | 3.22 ± 0.58 | 1979–2007 | 2.97 ± 0.51 | 1979–2007 |

studies. In the present study, the estimated trend at Murjan Island station is in the same range with that of the rest of stations in AG, even though it is much less than the previous estimates of (Alothman et al., 2014; Alothman & Ayhan, 2010; Hosseinibalam et al., 2007). There are clear decadal signals in our estimates with 23 years of data (Fig. 5.6). This may explain the reason for the inconsistency in the trend estimation between the present study and previous studies, where the short data duration in the previous studies (11–15 years) may overestimate the trend values within the decadal signal. For confirmation, the trends were re-estimated in same periods of the previous studies and the results show similarly high values (Figure not shown). At Abu Ali Pier, the estimated trend is 3.1 mm/year, which in between the available estimates of the previous studies (Alothman et al., 2014; Alothman & Ayhan, 2010; Hosseinibalam et al., 2007) (Table 5.3). At Qurayyah Pier, Ras Tanura and Mina Salman, the estimated trends agrees with that of Alothman et al. (2014) for all stations and with Hosseinibalam et al. (2007) for Ras Tanura and with Alothman and Ayhan (2010) for Mina Salman. At Arrabiyah Island, the analysis shows increasing trend, which is in contradictory with previous estimate, where they reported a decreasing trend (Alothman et al., 2014; Alothman & Ayhan, 2010). Alothman et al. (2014) related that decrease to human activities in that area and the existence of oil platforms near the station. It is clear from our findings that the gaps in data records significantly affect the estimated trends. A rough estimate of trends by incorporating data with gaps of the same period of that of previous studies, leads to a decreasing trend in this region. In present study, period contains gap is excluded and only the data of minimal discontinuity is used (1990 to 2000) in the trend estimation. The mean trend value for all the stations is $\approx$ 2.3 mm/year in the AG.

## 5.4 Conclusion

In this study, seven TG stations on the west coast of the AG have been analyzed. 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 5.2). Based on satellite data for the period from 1993 to 2018, the trend was estimated for global oceans and for AG region with about 2.8 + 0.4 mm/year, and about 3.6 $\pm$ 0.4 mm/year respectively. The trend of the AG is higher than that of the global ocean, which is expected in semi-enclosed seas and regional gulfs. The monthly mean residual sea level is used for the estimation of the linear trend at all stations. Mina Salman station show the highest trend value with about 3.4 $\pm$ 0.98 mm/year, while at Abu Ali Pier the estimated trend is about 3.1 $\pm$ 0.7 mm/year. The estimated trend at Arrabiyah Island, Murjan Island and Qurayyah Pier stations show similar values with about 2.4 $\pm$ 0.66 mm/year, 2.4 $\pm$ 0.94 mm/year, and 2.2 $\pm$ 0.84 mm/year respectively. Lower trends have been estimated at Jubail and Ras Tanura stations with about 1.6 $\pm$ 0.71 mm/year and 0.7 $\pm$ 0.31 mm/year respectively. The average linear trend for all seven stations is about 2.3 mm/year. The present study shows the 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 shorter data record they analysed. The increasing trends in the AG indicate that the gulf is responding positively to the global warming phenomenon. However, this response will have its impact on several environmental issues such as coral reef which already experience high vulnerability of bleaching. On the other hand, coastal communities will be affected with sea level rising problem due to global warming.

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