Sea level changes along the Saudi coast of the Arabian Gulf

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Sea level records over a period of 15 years (1980-1994) along the Saudi coast of the Arabian Gulf have been analyzed. The sea level changes, being dominated by a seasonal signal, are spatially coherent over the study area. The short term changes are characterized by large irregular amplitudes during winter, while summer variations are relatively small and uniform. An inverted barometer response close to the isostatic hypothesis (-1 cm mb⁻¹) holds for both short term and seasonal variations. The study also reveals that over this particular period the sea level exhibits an increasing trend of 0.17 cm y⁻¹ which is in agreement with the worldwide accepted value.

Oceanographers are somewhat divided on the issue dealing with the rate of sea level increase due to global warming. Various estimates of global sea level increase are given by Barnett. Empirical Orthogonal Function (EOF) analysis of long term annual means by Barnett revealed that the global rate of sea level increase is about 15 ± 1.5 cm per century. This value is now accepted worldwide. Global warming affects the sea level directly by increasing the volume of the sea through expansion, and indirectly by melting land bound ice sheets thus increasing the mass of the world’s oceans. Such effects will be global in nature, although the variations need not be uniform over the globe. Interestingly the amplitude of sea level rise due to expansion is greater than that caused by ice melting. An isostatic land uplift which is a measure of a decrease in sea level may occur along coasts which have only recently been relieved of their ice burden.

Relative sea level changes occurs as a result of the integrated effect of a variety of geophysical processes that span a broad range of spatial and temporal scales. The spatial scales of sea level changes are separated into global (eustatic) and regional components. Eustatic change is due to large scale input of heat and mass through the ocean boundaries, while regional changes are caused by boundary momentum fluxes and internal redistribution of mass. Temporal variability is separated into decade scale climate-induced changes and short-term changes. The latter encompasses a diversity of factors such as surface gravity waves, tidal oscillations, wind forcing and current regimes. Contribution from oceanic and meteorological processes produce a convoluted signal in which large amplitude short-term fluctuations mask small amplitude climate-induced changes. Besides there are changes from geological motion of the continental blocks and quasi-geological time scale changes, such as melting and freezing of ice caps, which change the total volume of the ocean. Such effects sustain permanent displacement of the mean sea level from the geoid with difference that may exceed 1.0 m.

The Arabian Gulf is a shallow marginal semi-enclosed water body. It is situated in an arid zone where evaporation greatly exceeds precipitation and river runoff. Evaporation has been estimated by various authors which indicates a greater rate in December and a lesser rate in May or June. Privett estimated the annual rate of evaporation to be 144 cm y⁻¹. Recent estimates of evaporation amount to about 200 cm y⁻¹. The freshwater influx is mainly from the Shatt-Al-Arab river estuary with a minor contribution from Iranian rivers in the north. Estimates of the annual freshwater discharge vary over a wide range from 5 to 100 km³ y⁻¹. Taking the area of the Gulf to be 226 × 10⁶ km², these estimates range from 2 cm y⁻¹ to 44 cm y⁻¹. More recently the fresh water input was estimated to be 46 cm y⁻¹. These estimates indicate that about 25% of water lost by evaporation is compensated by fresh water input from surrounding rivers. Thus the majority of the water balance occurs through an exchange with the Gulf of Oman across the Strait of Hormuz like an
inverse estuary with a surface inflow and a subsurface outflow. During summer (May to October) the surface inflow accentuated by the south-west monsoon, is greater than the sum of outflow and evaporation, which results in high sea level over the entire Gulf and the reverse is the case in winter (November to April).

The sea level of the Arabian Gulf is influenced by a number of processes. These are the high rate of evaporation, prevailing wind regime, atmospheric pressure, water exchange through the Strait of Hormuz and other meteorological/oceanographic conditions. A comprehensive survey of the sea level of the northern part of the Gulf from the geological viewpoint is given by Al-Asfour14. Analyses of daily and monthly means of the sea level15,16 over a 6 year period showed that the changes are mainly dominated by a seasonal signal. Analysis of monthly means over an 11 year period showed that 80% of the variance is due to seasonal changes17.

In the present study a continuous record of monthly mean sea levels, over a period of 15 years (1980-1994), was obtained from Ras Tanura station. The daily means for one year was taken from nine stations. To clearly indicate the variations during winter and summer the period of the daily means was chosen to run from Nov. 1991 to Nov. 1992. The objectives of the present investigation is to examine sea level variations of different time scales in relation to the atmospheric and oceanographic forcing. The time series was also examined for the relative sea level (RSL) increase and compared with the worldwide increase rate. Owing to the characteristic of the measuring gauge ordinary high-frequency waves were excluded. Geological time scale variations were also excluded, since the records were not long enough.

Materials and Methods

Monthly means of sea level over a 15 years period (1980-94) were made available by the Saudi Arabian oil company (Aramco) at Ras Tanura oil terminal (Fig. 1). Atmospheric pressure and wind speed and direction during the same period were obtained from the Meteorological Environmental Protection Administration (MEPA) at Dhahran Airport (Fig. 1). Hourly measurements of sea level at nine selected stations from a total of twelve stations representing the offshore and onshore areas of the Gulf along the Saudi Arabian coast were taken during the period 1991/92. These stations represent locations where missing data are minimal with the longest gap being

![Map of the Arabian Gulf showing the tidal and meteorological stations.](image-url)
of less than three days. The daily means of sea level were extracted from the hourly observations by using a sophisticated, two step filtering operation using TOGA software. Daily means of atmospheric pressure and wind data were obtained simply by computing averages over 24 hours.

Results and Discussion
Seasonal changes
Empirical Orthogonal Function (EOF) analysis of the monthly means indicates that the first eigenmode accounts for about 97% of the total variance. This mode implies that sea level changes are coherent over the study area and that the area can be represented by a single station. Sea level changes at Ras Tanura are selected to represent the study area. The monthly means of sea level at this station, and atmospheric pressure and wind stress components at Dhahran Airport together with their spectra are shown in Figs. 2 and 3. The sea level is mainly characterized by a seasonal signal with high values in summer and low values in winter. The highs and lows of the sea level acquire different values in different years with a difference of 48 cm between the highest high and the lowest low. Changes other than the seasonal signal, although small, can also be seen Fig. 2A. The time series of the atmospheric pressure shows a seasonal signal only with a high pressure in winter and a low pressure in summer (Fig. 2B). The wind stress is decomposed into cross- and long-shore components.

Fig. 2—Time series of the monthly means of sea level (A), atmospheric pressure (B) and their respective spectra (C, D).
Such a decomposition is beneficial in assessing the relative importance of the two components influencing sea level changes. The negative values of the cross-shore wind stress implies an onshore direction while those of the long-shore wind stress indicates a northwesterly direction (Fig. 1). It is clear from, Fig. 3A, that the cross-shore stress is strong and dominated by annual changes with a prevailing onshore direction. In contrast the long-shore stress variability is relatively weaker and dominated by a semi-annual variation with a predominant northwesterly direction (Fig. 3B).

The results of spectral analysis (Figs. 2 and 3) confirm the fact that the annual signal is dominating the changes in the sea level, the atmospheric pressure and the cross-shore wind stress. There is also a weak indication of a semi-annual cycle in both sea level and atmospheric pressure but it is more discernible in the former. Additionally other low frequency changes with duration longer than a year are evident in the sea level but with a very small contribution. The cross-shore wind stress also shows variations at frequencies other than the annual, but their contribution seems to be less significant. The spectrum of long-shore wind stress shows that the semi-annual component dominates the changes with the second next significant component is the annual cycle. In fact the energy in this component of wind stress is distributed over a wide range of frequencies. This behavior of the long-shore stress appears to be a characteristic feature of the region. Similar situations have also been observed in the Red Sea\textsuperscript{19}. Changes at frequencies other than the seasonal signal appear to contribute more in the long-shore wind stress than in the cross-shore wind stress.

The seasonal signal is represented as the sum of an annual and semi-annual component\textsuperscript{20} as follows,

\[
T_i(m) = M + C_1 \cos \left( \frac{2 \pi m}{12} \right) + S_i \sin \left( \frac{2 \pi m}{12} \right) \quad \text{(1)}
\]

Fig. 3—Time series of the monthly means of the cross-shore (A), long-shore (B) wind stress components and their respective spectra (C, D).


\[ T_2(m) = M + C_2 \cos \left(\frac{2\pi m}{6}\right) + S_2 \sin \left(\frac{2\pi m}{6}\right) \quad \ldots \ (2) \]

where \( M \) is the mean, \( C_1 \), \( S_1 \), \( C_2 \) and \( S_2 \) are constants to be found by regression, \( m \) is the month. Amplitudes, phases and variances explained by the two components for the various parameters are given in Table 1.

About 75% of the variance in the sea level is related to the seasonal signal. In the atmospheric pressure almost all (97%) of the variance is due to the seasonal signal. In the cross-shore stress the annual component constitutes about 60% of the variance, while the contribution of the semi-annual cycle is nil. The two components explain about 26% of the variance in the long-shore stress with 6% in the annual and 20% in the semi-annual.

**Effect of atmospheric forcing**

Atmospheric pressure: Regression analysis between the sea level and atmospheric pressure results in an equation of the form

\[ SL = 1409 - 0.98 \text{AP} \quad \ldots \ (3) \]

The correlation coefficient is 0.79 and the percentage of explained variance is 62%. The regression coefficient, being -0.98, is very close to the theoretical value (-1 cm mb\(^{-1}\)). Therefore it can be concluded that the sea level responds almost perfectly to the atmospheric pressure as an inverse barometer. The above equation predicts about 25.4 cm of the changes in the sea level, which is almost the same amount as that required for the predicted sea level changes according to the hydrostatic hypothesis.

Wind stress: Regression analysis between the sea level and the two components of the wind stress explains about 7% of the variance and is mainly due to cross-shore component. The equation of regression is

\[ SL = 420 - 7.71 \text{WSC} + 3.97 \text{WSL} \quad \ldots \ (4) \]

where WSC and WSL are the cross- and long-shore wind stresses respectively. Regression between the adjusted sea level and both components of wind stress has increased the percentage of explained variance to about 12% with the cross-shore component being the dominant. The increase in the percentage of explained variance, although small, reflects the interaction between the wind field and atmospheric pressure. The above regression equation predicts about 10 cm of sea level changes.

The combined effects of the various forcing can be assessed with a multiple regression model\(^{10}\). With such a model the sea level is represented by the sum of long term mean, trend, seasonal, atmospheric pressure effect, wind stress contribution and residual as follows:

\[ SL = X_o + a_0 M + a_1 S_1 + a_2 S_2 + a_3 \text{AP} + a_4 \text{WSC} + a_5 \text{WSL} + \text{residual} \quad \ldots \ (5) \]

A multiple regression taking into account all the parameters above lead to the following equation:

\[ SL = 1805 + 0.00122 M + 6.3 \cos \left(\frac{2\pi m}{6} + 42.6\right) + 2.8 \cos \left(\frac{2\pi m}{6} + 17.6\right) - 1.37 \text{AP} + 0.10 \text{WSC} + 2.79 \text{WSL} + \text{residual} \quad \ldots \ (6) \]

and the percentage of variance explained is about 81%. The only main factor that has not been included in the above model is the steric changes.

The monthly departures of the sea level and atmospheric pressure from the long term mean are presented in Fig. 4. These are obtained by averaging all January, February etc. and then subtracting the overall mean from the monthly means. The monthly departures of steric sea levels\(^{17}\) calculated over a period of 7 years and the long term evaporation rate\(^{9}\) are also shown in Fig. 4. An inverse relationship between the sea level and the atmospheric pressure is very clear when high sea level is accompanied by low atmospheric pressure and vice versa. The steric effect looks much like that of sea level with the temperature being the controlling factor as steric level is high in summer and low in winter. The steric sea level was previously estimated\(^{17}\) to be about 6 cm. An inverse

### Table 1—Amplitude, phase lag and explained variance by the annual and semi-annual components of the various parameters

<table>
<thead>
<tr>
<th>Variable</th>
<th>Annual</th>
<th>Semi-annual</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Amplitude</td>
<td>Phase degree</td>
</tr>
<tr>
<td>Sea level</td>
<td>11.2 cm</td>
<td>38</td>
</tr>
<tr>
<td>Atmospheric pressure</td>
<td>10.2 mb</td>
<td>69</td>
</tr>
<tr>
<td>Cross-shore stress</td>
<td>0.37 Pa</td>
<td>45</td>
</tr>
<tr>
<td>Long-shore stress</td>
<td>0.09 Pa</td>
<td>55</td>
</tr>
</tbody>
</table>
relationship between the sea level changes and the evaporation rate does not seem to exist as high level is associated with high evaporation and vice versa.

Secular variation

Regression of the annual means on time results in an equation of the form

\[ SL = 420 + 0.17 Y \]

which indicates an increasing trend in the Arabian Gulf sea level of 17 cm / century. This agrees well with the global rise in sea level. Therefore the increase in the sea level in the Arabian Gulf over 15 years is estimated to be about 2.6 cm. Figure 5 shows the annual means of the sea level during the study period together with the regression line.

The predicted sea level changes form the regression models and the computed steric change amount to 44 cm which is in a fairly good agreement with the observed changes (48 cm).

The daily means

There are nine tidal stations where there is no missing data during the period from Nov. the 25th 1991 to 24th of Nov. 1992 covering the whole Saudi water. The reason of extending data through the above specified period is to include the winter and summer variations. Winter period is regarded to extend from Nov. to April inclusive when the sea level is characterized by large amplitude fluctuations. Summer period extends from May to October inclusive with fluctuations of smaller amplitudes. The basic statistics of the whole series, winter and summer periods for the various stations are given in Table 2. As the sea levels were measured with respect to different references at the various stations it is better for comparison purpose to use the coefficient of variation, CV. This is defined as: \( CV = 100 \times \frac{STD}{M} \), where M is the statistical mean of the time series obtained separately for the whole year, winter and summer and STD is standard deviation. This provides a normalized measures of the spread. Table 2 shows that the standard deviations, ranges and coefficients of variation differ significantly between winter and summer. The variations in winter are slightly more than double those in summer as indicated by large values of the standard deviation and the coefficient of variation. On the other hand sea level variations for the whole year are slightly less than those in winter.

Prior to the eigen analysis the individual time series have been normalized to have unit variance and zero mean. This is achieved by subtracting the mean from the individual values and dividing by the standard deviation of the time series. This step ensures that each station has equal weight. The results of the EOF analysis of the daily means are given in Table 3 and in Fig. 6. It is clear that the sea level changes in the study area are mainly dominated by the first eigen mode which captured about 95% of the variance. This
mode implies that almost all the changes in the sea level over the study area are in unison and that the components of the first most energetic eigen vector have the same sign. The remaining 5% of the total variance represents the out of phase fluctuations in the sea level, which could be locally induced. All the stations have about the same energy, therefore contributing equally to the pattern (Fig. 6). The summer period changes are almost half of those for the whole year while the winter period is characterized by larger values of the first eigen vector as compared with the whole year. A comparison between the first principle component and the original series of any of the nine stations revealed that almost all the changes have been reproduced (Fig. 7). The similarity between the two time series is expected as the first principle component accounts for 95% of the variance. Therefore the daily sea level changes can also be represented by a single station as for the monthly changes. The daily mean sea levels (Fig. 7) display a seasonal signal of high level in summer and low level in winter with a range of 84 cm. Superimposed on the main signal are fluctuations with duration ranging from two days to less than a month as they are all smoothed out in the monthly mean (Fig. 2). These changes are characterized by large amplitudes in winter and small in summer. When approximated by the sum of an annual and semi-annual component the seasonal signal amounts for 50% of the variance with 42% in annual cycle and 8% in the semi-annual cycle. The remaining 50% of the variance is due to the short lived fluctuations. Similar representation for the atmospheric pressure shows that the seasonal signal accounts for about 89% of the variance. This is about 10% less than the seasonal signal abstracted from the monthly mean atmospheric pressure and indicates that the short lived fluctuations contribute slightly to the total variance.

Regression analyses between the daily sea levels and atmospheric pressure leads to an equation of the form

\[ SL = 1334 - 0.906 \ AP \] (7)

The correlation coefficient is 0.458 and the percentage of explained variance is about 21%. Once again the regression coefficient, being -0.906, is close to the theoretical value (-1 cm mb⁻¹).

The regression equation (Eq. 7) predicts about 25.4 cm of the daily changes. That is 2.6 cm less than that expected according to the hydrostatic hypothesis as the daily atmospheric pressure range is 28 mb. It is interesting to note that the predicted sea level changes are the same for both monthly and daily means. This indicates that the hydrostatic hypothesis holds for

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### Table 2—Basic statistics of the daily sea levels for the nine selected tidal stations

<table>
<thead>
<tr>
<th>Station Name</th>
<th>Whole year</th>
<th>Winter</th>
<th>Summer</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>STD (cm)</td>
<td>Range (cm)</td>
<td>CV (%)</td>
</tr>
<tr>
<td>Ras Tanura (1)</td>
<td>14</td>
<td>84</td>
<td>3</td>
</tr>
<tr>
<td>Juyymah (2)</td>
<td>14</td>
<td>84</td>
<td>4</td>
</tr>
<tr>
<td>Abu Ali (3)</td>
<td>15</td>
<td>90</td>
<td>4</td>
</tr>
<tr>
<td>Tanjib (4)</td>
<td>17</td>
<td>100</td>
<td>6</td>
</tr>
<tr>
<td>Safaniya P (5)</td>
<td>16</td>
<td>97</td>
<td>4</td>
</tr>
<tr>
<td>Safaniya Pf (6)</td>
<td>18</td>
<td>103</td>
<td>6</td>
</tr>
<tr>
<td>Marjan (7)</td>
<td>14</td>
<td>95</td>
<td>4</td>
</tr>
<tr>
<td>Lawhah (8)</td>
<td>14</td>
<td>83</td>
<td>5</td>
</tr>
<tr>
<td>Arby (9)</td>
<td>14</td>
<td>90</td>
<td>5</td>
</tr>
</tbody>
</table>

STD: standard deviation. CV: coefficient of variation (STD/MEAN).

### Table 3—Eigenvalues for the different modes (\(\lambda_n\)) and the explained variance: \(\lambda/\Sigma\lambda_n\) (%)

<table>
<thead>
<tr>
<th>Period</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Whole year</td>
<td>8.8</td>
<td>0.2</td>
<td>0.1</td>
<td>0.05</td>
<td>0.04</td>
<td>0.03</td>
<td>0.02</td>
<td>0.01</td>
<td>0.008</td>
</tr>
<tr>
<td></td>
<td>%</td>
<td>95.4</td>
<td>2.2</td>
<td>0.7</td>
<td>0.6</td>
<td>0.4</td>
<td>0.3</td>
<td>0.2</td>
<td>0.16</td>
</tr>
<tr>
<td>Winter time</td>
<td>13.3</td>
<td>0.3</td>
<td>0.1</td>
<td>0.07</td>
<td>0.05</td>
<td>0.03</td>
<td>0.02</td>
<td>0.01</td>
<td>0.007</td>
</tr>
<tr>
<td></td>
<td>%</td>
<td>96</td>
<td>1.9</td>
<td>0.65</td>
<td>0.51</td>
<td>0.35</td>
<td>0.21</td>
<td>0.14</td>
<td>0.07</td>
</tr>
<tr>
<td>Summer time</td>
<td>4.4</td>
<td>0.2</td>
<td>0.07</td>
<td>0.03</td>
<td>0.02</td>
<td>0.01</td>
<td>0.008</td>
<td>0.006</td>
<td>0.004</td>
</tr>
<tr>
<td></td>
<td>%</td>
<td>93</td>
<td>3.1</td>
<td>1.4</td>
<td>0.72</td>
<td>0.41</td>
<td>0.29</td>
<td>0.18</td>
<td>0.12</td>
</tr>
</tbody>
</table>
both short- and long-term changes. The percentage of explained variance by regression of sea level on atmospheric pressure is much lower in the daily means than in the monthly means. This is not unexpected as the short term fluctuations are very irregular, highly energetic and do not follow a certain pattern. Additionally other factors such as wind and waves may contribute more to short term sea level changes. This may reduce the sea level response to atmospheric pressure in the daily means. Examination of the relationship between the deseasonalized daily means of sea levels and atmospheric pressure leads to the equation:

$$SL = -0.419 - 1.43 \times AP \quad \ldots \quad (8)$$

The negative coefficient indicates that an inverse relationship exists between sea level and atmospheric residuals. However the response of the sea level to atmospheric pressure is about 50% higher than expected according to the hydrostatic hypothesis.

A multiple regression model after removing the seasonal signal from the atmospheric pressure and wind stress components leads to the following equation:

$$SL = 422 - 0.002 D - 1.28 \times AP - 282273 \times WSL + 232612 \times WSC + 14.2 \cos(2\pi D/366 + 85) + 6.1 \cos(2\pi D/183 - 21) + \text{residual} \quad \ldots \quad (9)$$

where D is the day, AP is the atmospheric pressure, WSL is the component of long-shore wind stress, WSC is the component of cross-shore wind stress, and the last two terms represent the annual and semi-annual components of the seasonal signal. The above regression line accounts for about 60% of the total variance. The remaining 40% of the variance is due to the residuals. Residual variations of periods ≥ 10 days are believed to be induced by planetary atmospheric waves, while shorter periods are due to cyclonic and anticyclonic disturbances.

**Daily residuals**

The above discussion shows that a significant proportion of the variance (40%) of the sea level is contained in the daily residuals. Therefore it is worthwhile examining the interrelationship between the daily residuals. The daily residuals were obtained by filtering the significant cycle (seasonal). The advantage of this procedure is that the minor variations in the residuals can be subjected to more accurate analysis than when they are hidden by simultaneous seasonal cycle. Determination of the statistical process (model) that generates the data requires a prior identification of normality and stationarity. The assumptions of normality and stationarity are valid for any physical system and can be readily supported by a non-parametric approach such as the χ² test and the run test. The interrelationship between the residuals can be examined with the aid of the autocorrelation function, the correlogram (Fig. 8). The 95% confidence limits are approximately equal to 2/√N (Chatfield). The correlogram shows that the autocorrelation functions drop sharply up to 2 days lag for the whole year and winter period while decreases exponentially up to lag 5 for the summer period. This indicates that the daily residuals of sea level are not completely random but
exhibit some degree of persistence. Therefore a significant portion of the variance can be explained in terms of a statistical model. An autoregressive model of order 1 [AR(1)] was calibrated to fit the time series. An AR(1) model is defined as follows:

\[ R(t) = \varphi R(t-1) + \epsilon(t) \]  

(10)

Where \( \varphi \) is the model parameter and \( \epsilon(t) \) is an uncorrelated process with zero mean. The estimated values of the model parameter for winter and summer are 0.54 and 0.77 respectively. The percentages of variance accounted for by the AR(1) model are 29 and 58% respectively. This indicates that in the summer period the residuals are better represented by AR(1) model. This is expected as the summer fluctuations although small are more regular than the winter perturbations. The stationarity of the process can be assured by the value of model parameter. According to Box \& Jenkins\(^{24}\) a sufficient condition for the process to be stationary is that \(-1 < \varphi < 1\) which is readily justified in the AR(1) model for both periods.

The results showed that the sea level variations are mainly dominated by a seasonal signal with high level in summer and low level in winter. The seasonal signal is approximated by the sum of an annual and semiannual components. Low frequency changes are also evident but seemingly with a small contribution. The sea level responds to the atmospheric pressure almost perfectly according to the hydrostatic hypothesis. The percentage of variance explained by regression of monthly sea level on atmospheric pressure is 62%. Wind stress components only explain about 12% of the total variance. However, a multiple regression model between the sea level and the various parameters explains about 81% of the total variance. The trend, estimated to be 17 cm/century, is in good agreement with the global rise in the mean sea level.

The daily means display large amplitude short term fluctuations in winter and small more regular changes in summer. The daily means and daily residuals of the sea level respond to the atmospheric pressure according to the hydrostatic hypothesis. Analysis of the daily residuals shows that a significant proportion of the variance can be accounted for by a first order autoregressive model AR(1).

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