Annual and semi-annual variations of sea level at Jeddah, central coastal station of the Red Sea

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A well-known fact of the Red Sea is that, its sea level is high in winter and low in summer. The atmospheric pressure changes are concurrent with those of the sea level, indicating non-isostatic response. Besides tidal changes account for about 15-20% of the variance in a year long record of the hourly sea level at Jeddah1. The seasonal sea level changes of the Red Sea are mainly controlled by the effect of the high rate of evaporation and the reversal of the wind regime2. These factors are not uncorrelated. The evaporation rate in the Red Sea has been reported earlier3-5. The wind regime reverses over the southern Red Sea from NNW in summer to SSE in winter. The exchange of water with the Gulf of Aden is driven by the effect of high evaporation and in a manner similar to that of a negative estuary with surface inflow and deep outflow. However the water exchange is complicated by the reversal of wind regime resulting in two- and three-layer systems in winter and summer respectively. In summer the inflow is sandwiched between the surface and deep outflows. During winter the surface inflow exceeds the sum of subsurface outflow and water lost by evaporation, while the opposite occurs in summer. This results in a high level in winter and a low level in summer over the entire Red Sea. The seasonal changes of the sea level at different parts of the Red Sea have been investigated previously1,2,5,6. The monthly means of sea level are used to investigate variations with timescales of months to years that have climatological implications5,7.

The present study is based on the monthly means of sea level and meteorological parameters over a three-year period. It is aimed at analyzing the seasonal changes of the sea level in relation to wind stress and evaporation rate and to determine their relative contribution to the sea level changes.

Material and Methods

The hourly sea level highs were extracted from records obtained by a pressure type recorder (OSK LP2) installed temporarily at the mouth of Obhur Creek, Jeddah during the period 1991-1993 (Fig. 1). The creek represents a finger extending inland from the Red Sea. It serves as an ideal location for sea level gauge installations as it is protected from the direct effects of wind and waves. The retrieval of the data is more than 95% of what was expected and the gaps were filled by mathematical interpolation. The accuracy of a single reading is estimated to be within 0.5 cm. Timing error on the records was minimal (of the order of few minutes per 45-day chart length). Meteorological parameters were simultaneously obtained from Jeddah International Airport Station (Fig. 1), about 2-3 km from the sea level gauge site.

The monthly means of sea level were obtained from the daily means. The determination of the daily means requires the elimination of the tidal effects. This is achieved by applying an appropriate filter to the hourly data. In the present study a Doodson X, filter has been used10. Diurnal, semi-diurnal and shorter tidal constituents are vigorously suppressed by the use of the above filter. This filter incorporates 38 hourly intervals centered at 1200 hrs. Long-period
tidal constituents are filtered out by taking the monthly means. The monthly means of atmospheric pressure were obtained by averaging the daily means. The latter were obtained by simple averaging of the hourly values. Hourly wind stress was computed according to the quadratic law: $\tau = \rho C_D W^2$, where $\rho$ is air density, $C_D$ is the drag coefficient and $W$ being wind speed. As the wind stress depends on the drag coefficient, the choice of the appropriate value is based on the observed range of the wind speed $^{1,2}$. The hourly wind stresses were then resolved into orthogonal cross- and long-shore components. This was achieved by adding $25^\circ$ to the wind direction, the approximate angle of the coast at Jeddah from the north. Finally the overall monthly means were obtained by averaging over the study period (1991-1993).

Results and Discussion

The monthly mean sea level, atmospheric pressure, long-shore stress and cross-shore stress averaged over a three-year period (1991-1993) are presented in Fig. 2A-C. The monthly evaporation rates for the central Red Sea extracted from Ahmad & Sultan $^3$ are also shown in Fig. 2D. These rates represent the long term monthly means (1970-1984). The negative values of long- and cross-shore stresses are directed to the south and offshore respectively. The component of the long-shore wind stress is stronger than that of the cross-shore stress and is directed to the south all year round. The cross-shore wind stress is directed offshore in winter and onshore in summer. In addition to the annual cycles Fig. 2 shows that all the variables considered display semi-annual variations. Therefore the seasonal signal can be approximated by the sum of annual and semi-annual components. Table 1 displays the variances explained by the two components for the various parameters. The annual variations dominate the changes in the sea level and cross-shore stress. In contrast the semi-annual variations dominate the changes in the long-shore stress. The semi-annual cycle of the evaporation rate is only slightly stronger than the annual one. Table 1 shows that almost all the seasonal signals of the sea level and cross-shore stress are induced by the annual and semi-annual cycles. On the other hand about 74% of the variance in the seasonal signals of the long-shore stress and evaporation rate are due to the annual and semi-annual cycles. The annual cycle of the sea level is
Table 1—Variances explained 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>Sea level</td>
<td>78</td>
<td>20</td>
</tr>
<tr>
<td>Cross-shore stress</td>
<td>68</td>
<td>27</td>
</tr>
<tr>
<td>Long-shore stress</td>
<td>23</td>
<td>51</td>
</tr>
<tr>
<td>Evaporation rate</td>
<td>35</td>
<td>39</td>
</tr>
</tbody>
</table>

indicated by a high level in winter and a low level in summer over which semi-annual cycle is superimposed. The semi-annual cycle is indicated by an alternate rise in April and December and an alternate fall in February and August. The presence of the semi-annual cycle is unprecedented. However a close inspection of the data given by Osman and Abdallah & Eid at Port Sudan and Port Suez indicates the existence of the semi-annual cycle all over the Red Sea. This cycle was first documented by Sultan et al. from the analysis of a 6 yr. record at Port Sudan. The two components account for 78% and 20% of the variance respectively. Their respective amplitudes were 17.3 and 8.7 cm. A well-known fact in sea level of the Red Sea is that the seasonal changes are not due to the inverse barometric effect. The annual variations of sea level and atmospheric pressure at Jeddah indicates high sea level is concurrent with high pressure and vice versa (Fig. 2A). On the other hand the amplitudes of the annual and semi-annual tides computed according to the formulae given by Listzin are 0.7 and 5.7 mm respectively. These are very small in comparison with the observed ones, therefore their contribution to the seasonal changes of the sea level is negligible. Additionally steric changes do not contribute to the seasonal changes of the sea level of the Red Sea. The steric effect would raise the sea level in summer and lower it in winter. As this fact is not observed in the Red Sea, this implies that the main factors causing the seasonal changes in the sea level are wind stress and evaporation rate. The relationships between sea level changes and these factors are examined by regression analysis as below:

Annual cycles

Figure 3 displays the annual cycles of the various parameters. Simple regression between the annual component of sea level (SL) and evaporation rate (EVAP) led to an equation,

\[ SL = -1.39 - 4.13 \times EVAP \]  \hspace{1cm} (1)

and the percentage of variance explained is about 12%. The above equation indicates that sea level is inversely related to the evaporation rate. Regression of sea level on the long- (LSWS) and cross-shore (CSWS) stresses explains about 3% and 85% of the variance respectively. The regression lines are

\[ SL = -1.08 - 536 \times LSWS \]  \hspace{1cm} (2)
\[ SL = 0.57 - 1849 \times CSWS \]  \hspace{1cm} (3)

From the above, it is clear that the cross-shore stress is the dominant factor influencing the annual cycle of the sea-level changes. Also notice that the annual cycle of the cross-shore stress is stronger than the semi-annual cycle (Table 1). Multiple regression of the sea level on evaporation rate, long-shore stress and cross-shore stress explain all the variance. The regression line is

\[ SL = -0.00329 - 1399 \times LSWS - 2039 \times CSWS + 0.245 \times EVAP \]  \hspace{1cm} (4)

The regression Eq. 4 shows different coefficients than those obtained by simply adding the individual Eqs. 1, 2 and 3. This is a result of the strong interrelationships between the various parameters. This is expected, since both evaporation rate and wind stress strongly depend on the wind speed. Figure 3A shows that the predicted annual component of sea level lies exactly on the observed one.

Semi-annual cycles

Figure 4 shows the semi-annual cycle for the various parameters. It is clear that the evaporation rate leads the sea level changes by about one month. Simple regressions led to the following equations

\[ SL = -0.56 - 3.79 \times EVAP \]  \hspace{1cm} (5)
\[ SL = 0.13 + 836 \times LSWS \]  \hspace{1cm} (6)
\[ SL = -0.21 + 622 \times CSWS \]  \hspace{1cm} (7)

where SL, EVAP, LSWS and CSWS stand for sea level, evaporation, long-shore stress and cross-shore stress. The percentage of variance explained by regression lines are 50%, 70% and 20% respectively. Once again an inverse relationship was obtained between sea level changes and evaporation rate (Eq. 5). It appears that the evaporation rate contributes more to the semi-annual sea level changes as compared with the annual changes. The long-shore stress appears as the dominant factor influencing the
semi-annual changes in the sea level. It is also noted that this cycle is stronger than the annual one in the long-shore stress (Table 1). Due to the strong interrelationship between the various variables multiple regression led to the following equation:

\[ SL = 0.792 + 1782 \times \text{LSWS} - 11899 \times \text{CSWS} + 1.27 \times \text{EVAP} \quad \text{... (8)} \]

The percentage of explained variance is 93%. The regression coefficients and the constant in Eq. (8) are different from those given in the individual Eqs. 5, 6 and 7. Evaporation rate is strongly correlated with cross-shore stress \( (R^2 = 76\%) \) and moderately correlated with long-shore stress \( (R^2 = 23\%) \). The predicted and the observed semi-annual changes in the sea level are very close to each other (Fig. 4A).

Analysis of the monthly means of sea level averaged over a three-year period (1991-1993) shows that the seasonal signal can be represented by the sum of an annual and semi-annual cycle. These cycles are induced by the combined effect of wind stress and evaporation rate. The cross-shore wind stress is the major factor influencing the annual cycle, while the long-shore stress dominates the semi-annual cycle in the sea level. Both components of the sea level are inversely related to the evaporation rate. Evaporation rate contributes more to the semi-annual cycle than to the annual one. It appears that the sea level is strongly related to the stronger component of wind stress.

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References