

TIDAL AND SEA LEVEL CHANGES AT JEDDAH, RED SEA

F. Ahmad and S.A.R. Sultan

Faculty of Marine Science, King Abdulaziz University, Jeddah-21441, Saudi Arabia

ABSTRACT: Tidal and sea level changes during 1991 at a coastal stations (Jeddah) in the central part of the Red Sea are investigated. Analysis shows higher sea levels in winter and lower in summer. The amplitude of change at Jeddah is above 50 cm. Analysis of wind stress at Jeddah indicates an insignificant contribution of the cross-shore component, while a major part of the changes in the sea level can be accounted for by the long-shore component.

KEY WORDS: Coastal waters - sea level - wind stress - Red Sea.

INTRODUCTION

Sea level changes are a result of tidal and nontidal forcing. The tidal components are regular and periodic and can be predicted accurately with the aid of an harmonic analysis programme. Nontidal variations in the sea level are mainly of meteorological and oceanographic origins. These changes have various time scales ranging from the subtidal to longer periods (Thompson, 1980; Chao and Pietrafesa, 1980; Palumbo and Mazzarella, 1982; Marmorino, 1983; Pugh and Thompson, 1986; Spillane *et al.*, 1987; Lascaratos and Gacic, 1990; Isoda *et al.*, 1991). Eustatic and isostatic changes are due to variations in the water volume and land level respectively. These changes occur over a geological time scale and are insignificant in short records, unless recent events, earthquakes, warrant their considerations. None have occurred in recent relevant history for this study.

In enclosed and semi-enclosed seas the tides are complex and may not be directly influenced by the tides in the oceans with which they communicate. The tides in the Red Sea are probably a combination of an independent oscillation of the waters within the basin and a forced, co-oscillation induced by the tides of the Gulf of Aden. The independent oscillatory tides are of small amplitude and of the semi-diurnal type. For example, high water occurs at one end of the Red Sea when it is low at the other with a time difference between successive high waters or low waters at any location of approximately 12 hours. The mean spring tides are 0.9 m in the south and 0.6 m near the mouth of the Gulf of Suez (Edwards, 1987). In between, the range decreases towards the central part of the sea where at about 20°N there is a nodal point of zero range. Between 19°N and 21°N the semi-diurnal tide is not appreciable. In addition, there is a subsidiary oscillation of very small amplitude with a diurnal period. In most places this is masked by the larger semi-diurnal oscillation.

In the long term the Red Sea sea levels are strongly influenced by the rate of evaporation and the balance between in an out-flowing waters. In winter the inflow exceeds the combined effect of outflow and loss by evaporation in spite of the fact that evaporation is higher in winter (Ahmad and Sultan, 1989). Consequently the mean sea level rises over the entire Red Sea. In summer, the reverse occurs and the mean sea level is lower. Based on very few measurements of levels in the Red Sea, Edwards (1987) showed that the range varies from a maximum depression of 20-30 cm in August and September, to an elevation of 10-20 cm in December and January.

Morcos (1970) summarized previous work on the mean sea level which indicates an even higher level in winter.

The present paper deals mainly with tidal and sea level analysis at a coastal station, Jeddah, Red Sea.

MATERIALS AND METHODS

The hourly sea levels were abstracted from sea level records obtained by a pressure-type recorder (OSK LPT.2) temporarily installed in the coastal water of Jeddah (Fig.1). The accuracy of a single reading is estimated to be within 0.5 cm. Timing error on the records were minimal (only a few minutes per 45-day chart length). Atmospheric pressure, wind speed and direction were simultaneously obtained from the Jeddah meteorological station.

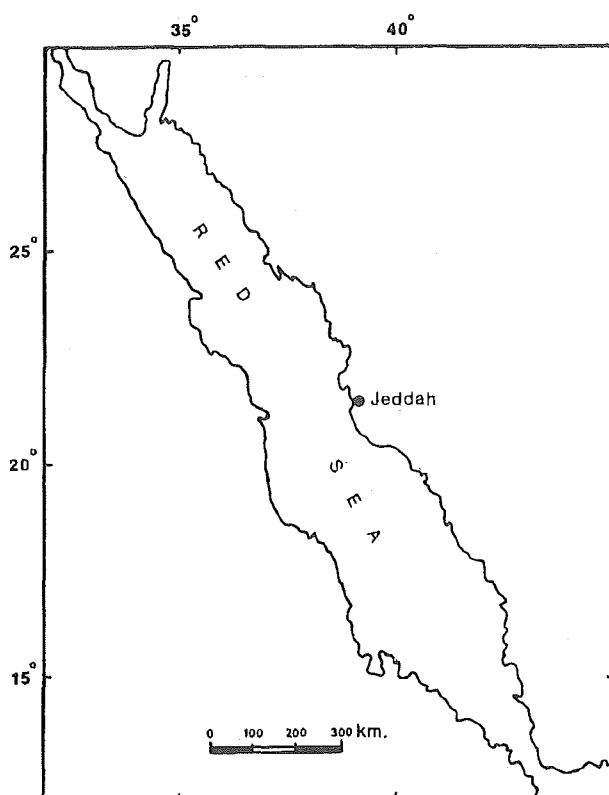


Fig. 1. Map of the Red Sea showing the station position.

The daily means of sea level were computed using 38 hourly intervals and centered at 12.00 noon (Doodson and Warburg, 1973). This allows elimination of diurnal, semi-diurnal and shorter tidal constituents. Resolution of the daily mean is of the order of 0.1 cm. Monthly means were obtained from the daily means. The monthly means of atmospheric pressure were obtained from the daily means which again were calculated by averaging the hourly values. The wind stress is computed using the quadratic law $\zeta = \rho_a C_D W^2$; where ρ_a , air density; C_D , drag coefficient; and W , wind

speed. The choice of the C_D is justified by the observed range of wind speed. The wind stress is then resolved into cross-shore and long-shore components. The estimation of the evaporation rate (cm/month) is based on the recent heat balance study of the Red Sea (Ahmad and Sultan, 1989).

RESULTS AND DISCUSSION

Figure 2 shows plots of the raw data for January and August representing winter and summer. The original data were analysed for tidal constituents at U.C.E.S. Anglesey using harmonic analysis and prediction programmes TAPP. Table I gives the periods, amplitudes and phases of the semi-diurnal (M_2 and S_2), diurnal (K_1 and O_1), and the long-term (MSF and MM) constituents.

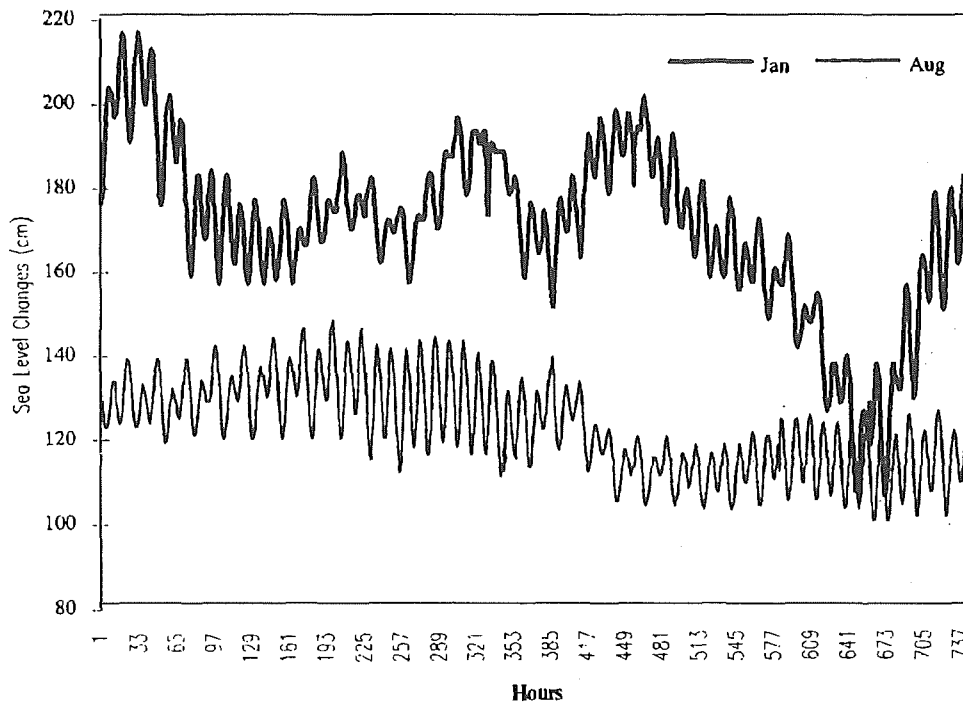


Fig.2. The observed sea level changes for January and August, 1991 at Jeddah.

The ratio of the diurnal to the semi-diurnal constituents $(K_1+O_1) / (M_2+S_2)$ is 0.6 which is indicative of a mixed type, mainly semi-diurnal with diurnal inequality (Vercelli, 1925). According to equilibrium theory, the ratio of the amplitudes of M_2 and S_2 is equal to 2.2. We obtain 4, with a difference between the observed and theoretical value greatly exceeding uncertainty limits. The disparity between the theoretical and actual tides could be due to shallow-water effects. It is worth noting that the amplitudes of the fortnightly (MSF) and the monthly (MM) components are relatively large. Figure 3 shows plots of the predicted tide for January and August.

Table. I. Amplitude, phase and period of main tidal constituents.

Constituents	Period (hour)	Height (cm)	Phase degree
M ₂	12.42	7.2	113.0
S ₂	12.00	1.8	143.0
K ₁	23.94	3.5	172.0
O ₁	25.82	1.7	164.0
MSF	354.40	3.3	129.0
MM	661.30	3.7	348.0

Spring and neap tides are very clear with mean ranges of nearly 30 and 20 cm, respectively. Superimposed on the diurnal and semi-diurnal constituents are the longer- period components. The tidal fluctuations constitute only a small portion (15-20%) of the total variance in the sea level changes. As the tides are small in the region, tidal contribution to sea level variability is expected to be minimal.

The monthly means of the sea level at Jeddah are presented in Fig. 4. It shows a high level in winter and a low level in summer. A slight rise in the signal during April is clearly discernable. Figure 4 also shows that the amplitude of changes in the sea level at Jeddah is about 50 cm.

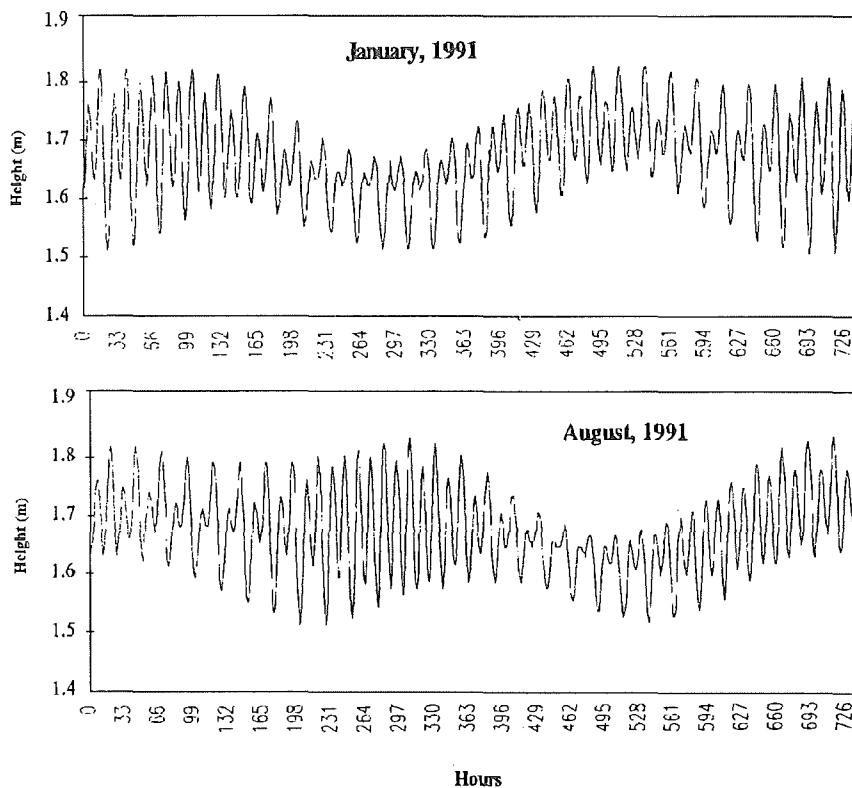


Fig.3. The predicted tides for January and August, 1991 at Jeddah.

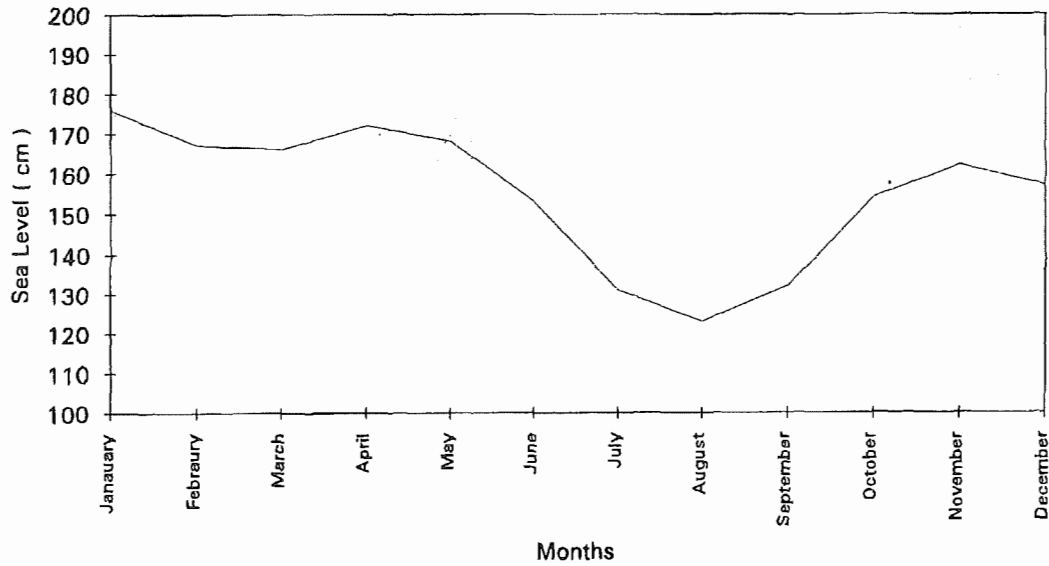


Fig.4. The seasonal sea level changes at Jeddah during 1991.

Monthly means of atmospheric pressure at Jeddah are shown in Fig. 5. Departures from the isostatic response of the sea level are very clear. This is in full agreement with previous works, which show that the Red Sea levels do not follow, on a monthly basis, the hydrostatic hypothesis (-1 cm/mb).

The lack of continuous measurements of temperature in the water column makes it difficult to assess the steric effect on the sea level changes. Based on computations of monthly geopotential anomalies relative to 200 db. Patzert (1972) indicates that the seasonal variation in steric sea level raises the level in summer and lowers it in winter, which is not borne out by the present data.

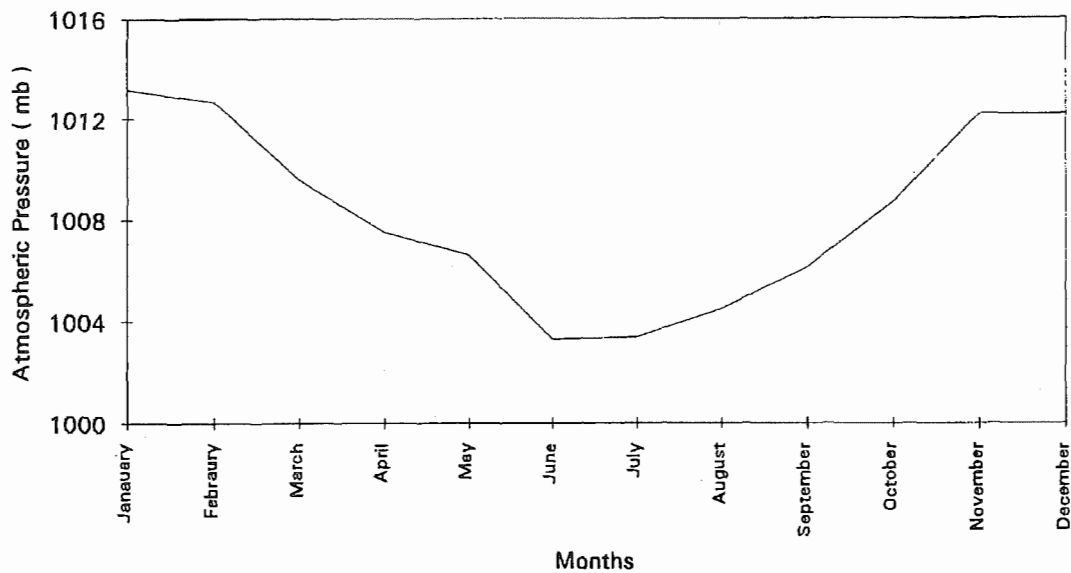


Fig.5. The seasonal changes of atmospheric pressure at Jeddah.

Figure 6 displays the monthly evaporation rate (cm) in the Red Sea. Evaporation on the average is higher in winter (118.2 cm, October to March) and lower in summer (112.8 cm, April to September) with an annual mean of 231 cm. Evaporation results in the lowering of the mean sea level. Consequently sea level should be slightly lower in winter than in summer. The fact that this is not observed implies sea level changes in the Red Sea are not directly correlated with evaporation.

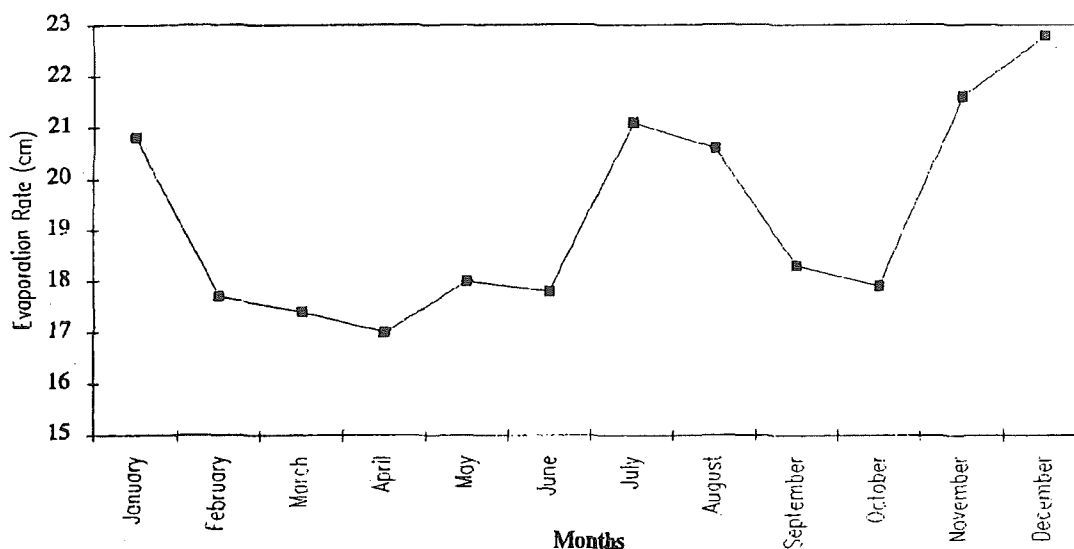


Fig.6. The monthly evaporation rate in the Red Sea.

Figure 7 shows cross-shore and long-shore components of wind stress at Jeddah. The negative values of cross-shore wind stress are directed offshore forcing the nearshore water away from the coast, resulting in low sea levels. However, this is not the case in this particular study in which the sea level is higher in winter than in summer, although the on-shore wind stress is almost steady. Linear regression of the sea level with the cross-shore stress results in an insignificant correlation. Therefore, it can be concluded that the cross-shore component of wind stress contributes insignificantly to the variation in the sea level.

The negative values of long-shore wind stress are directed towards the south. As the long-shore stress is almost four times higher than the cross-shore stress, it is expected that this component of wind stress plays a major role in the seasonal changes of the sea level. The average value of long-shore stress for the summer period (April to September) is almost twice that of the winter period (October to March). Thus the seasonal changes in sea level can be attributed mainly to the influence of the long-shore component of wind stress. Large values of wind stress in summer result in lower sea levels while smaller values in winter result in higher sea levels. The variation of the long-shore wind stress is in agreement with the prevailing wind regime over the Red Sea. In summer the entire Red Sea is under the influence of a N.N.W. wind.

In winter the southern half is influenced by the N.E. Monsoon and the wind is from S.S.E. Such a regime will enhance the long-shore component of wind stress in summer and reduce it in winter, thus accounting for the seasonal changes in the Red Sea sea levels. Linear regression of the sea level with the long-shore stress led to an equation of the form $SL=180-1183 \zeta_y$, where ζ_y is the wind stress. The correlation coefficient between the sea level changes and the long-shore stress is -0.65 . This value is significant at the 95% confidence level for the 11 degrees of freedom. The observed values of the long-shore stress induces changes in the sea level of about 39 cm. This constitutes almost 80% of the total changes. In the absence of long-shore stress the sea level could stand at 180 cm, which is 23 cm higher than the mean value (157 cm).

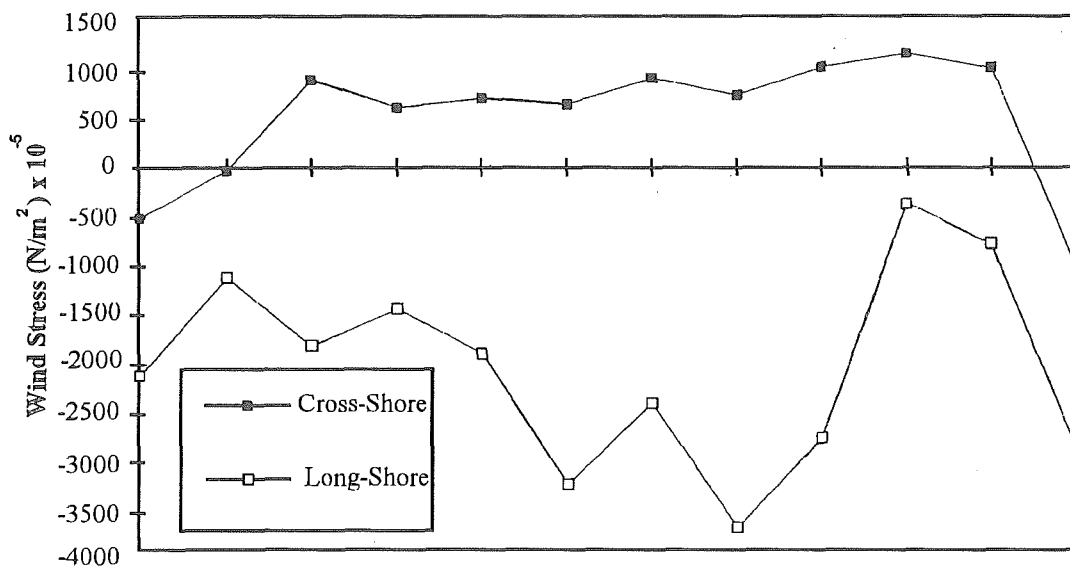


Fig.7. The monthly cross-shore and long-shore components of wind stress at Jeddah.

This is probably due to our neglecting the evaporation and other effects. The monthly average of the evaporation rate is 19 cm which is comparable to the difference between the intercept of the above equation and the mean sea level. Therefore, it can be concluded that the long-shore wind stress plays a major role in the sea level changes. However, a better understanding of the sea level variability can be achieved by fitting a multiple regression model using longer records which takes into account more factors.

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