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Seasonal Fluctuations of Mean Sea Level at Gizan, Red Sea

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ABSTRACT

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Hourly sea levels recorded for the period (1992–1994) from a tide gauge at Gizan have been analyzed for low frequency oscillations. The major tidal constituents were identified and tides are described as semi-diurnal. Monthly mean sea level variations show higher levels in winter and lower in summer with a range of 40 cm. The local oceanographic and meteorological factors that control the sea level variability were investigated. Results indicate that the seasonal changes of sea level are highly correlated with steric effects, evaporation rates and long-shore wind stress component. A multiple regression model was proposed to explain the observed fluctuations in the mean sea level at Gizan.

ADDITIONAL INDEX WORDS: *Mean sea level, seasonal, Red Sea, Gizan.*

INTRODUCTION

Sea level data show the displacement of the sea surface relative to that of land. These data have recently received a considerable attention on the local and global scales due to the need for proper coastal zone management. Long term changes of mean sea level (secular changes) require several decades of recorded data while seasonal variations can be estimated from relatively shorter records. Sea level is continuously responding to the astronomical tides and meteorological and oceanographic forcings.

Observations of the mean sea level in the Red Sea are very scarce (MORCOS, 1970). VERCELLI (1931) studied the monthly and annual mean sea level at 3 stations; Suez, Port Sudan, and Perim and show a general decrease in summer and a mean rise in winter at all the stations. In addition, he observed that the atmospheric pressure in the Red Sea decreases to minimum during summer. LISITZIN (1965) estimated a steady decrease of 30 cm in mean sea level along the entire Red Sea from south to north. PATZERT (1972) studied the mean sea levels at 4 stations; Suez, Port Sudan, Perim and Aden and concluded that the mean sea level rises in winter and decreases sharply from May to late summer. With the advent of the monsoon (in September), sea level rises again reaching 33 and 35 cm at Port Suez and Port Sudan, and 24 cm at Perim and Aden above the annual mean. This was explained on the basis of the seasonal reversals in circulation. MORELY (1975) measured the daily sea level at Jeddah over the full year of 1973 and showed an annual mean sea level range of 80 cm. He reported S to SSW winds that blow for 3 days reaching a maximum strength of 48 knots during February. The associated surge increased sea level by about 60 cm, then the wind veered to the north during one day causing a drop in sea level by 60 cm. This quite sudden change in sea level demonstrates the strong effect of wind forcing on the coastal water level. OSMAN (1985) showed a seasonal variation in sea level at Port Sudan of 25.5 cm and 5.4 mm/year as the secular rate over the period (1962–1979). An amplitude of sea level change of 50 cm that was correlated with the long-shore wind stress was estimated at Jeddah by AHMAD and SULTAN (1993). SULTAN *et al.* (1995) show a smaller amplitude at Port Sudan (44 cm), that is correlated mainly with the cross-shore wind stress component. EDWARDS (1987) stated that the sea level range in the Red Sea varies from a maximum depression of 20–30 cm in August and September, to an elevation of 10–20 cm in December and January.

The present study is an attempt to investigate the seasonal changes of the mean sea level at Gizan. Sea level data with the associated meteorological and oceanographic information available for Gizan are utilized to estimate the major tidal constituents and to examine the physical parameters that control the seasonal changes of sea level. Gizan area has an increasing potential for future development, however, no intensive study was reported in literature regarding the sea level variabilities at Gizan.

DATA ANALYSIS AND RESULTS

Sea levels were recorded on half-hourly basis using a tide gauge fixed at Gizan (Figure 1) from October 1992 to the beginning of August 1994. Atmospheric pressure at sea level, precipitation and winds were simultaneously measured at Gizan weather station (Lat. 16° 53′ 49″ N, Long. 42° 35′ 05″ E). Both tidal and meteorological data were made available by

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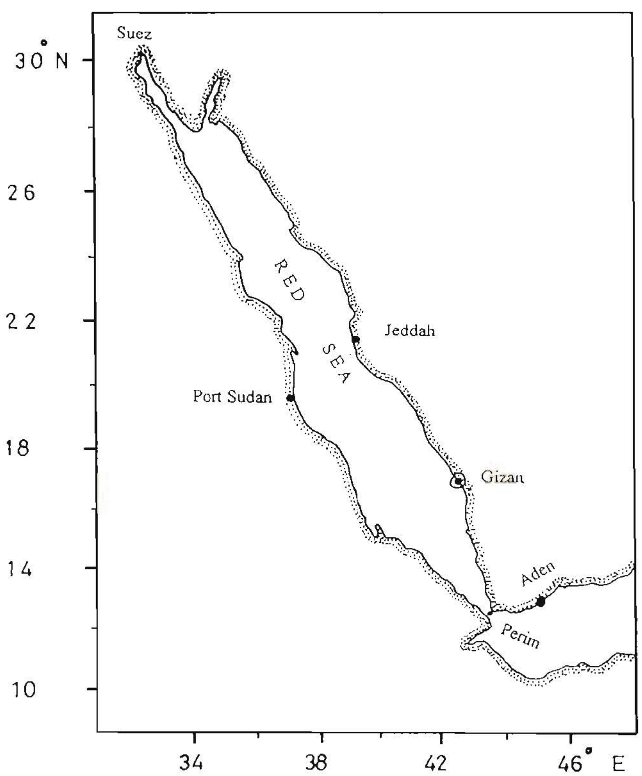

Figure 1. Location of the tide gauge at Gizan (16° 53′ 43.6″ N, 42° 32′ 8.3″ E) on Red Sea map.

Meteorology and Environmental Protection Administration (MEPA). The sea level data were provided in digital form with an accuracy of 0.1 cm. For each month, hourly sea level data were first plotted to check any spikes, timing errors or gaps. Gaps were due to telecommunication difficulties. The software program is intended to be used on complete years of data and its quality control procedures remedy the problem of gaps, rescue the missing data and ensure the scientific validity of it (CALDWELL, 1991). TOGA software was used to investigate the major tidal constituents, in addition to the daily and monthly mean sea levels.

Major Tidal Constituents

Harmonic analysis of the recorded data was performed and 64 tidal constituents were determined. Table 1 lists the 11 major constituents whose amplitudes exceed 4% of M_2 amplitude. Each constituent is described by its period, amplitude and phase lag. M_2 shows the largest amplitude (32.4 cm). The tide at Gizan was found to be dominated by the large amplitudes of the major semi-diurnal constituents M_2, S_2, and N_2 as shown in Table 1. Diurnal components, O_1 and K_1, show the smallest amplitudes among the listed constituents. Longer period constituents such as solar semi-annual S_{sa}, Lunar monthly M_m and Lunar fortnightly M_f present relatively higher amplitudes than the diurnal components. The ratio M_2/S_2 at Gizan is 3.12 compared with 2.2 as suggested by the tidal equilibrium theory at any given locality. The character of the tide is determined by the ratio $(K_1 + O_1)/(M_2 + S_2)$ according to VERCELLI (1925). The ratio was found to be much less than 0.25, which describes the tide at Gizan as strongly semidiurnal. The effect of purely astronomical tides is not significant on the seasonal oscillation of the mean sea level at the latitudes of the Red Sea and they do not exceed 1.2 cm, (PATTULLO *et al.*, 1955).

Table 1. *Major tidal constituents at Gizan; their period, amplitude and phase lag relative to local time (GMT + 3).*

Constituents	Period (hour)	Amplitude (cm)	Phase Lag (°)
S_{sa}	4,382.89	7.9	30
M_m	661.30	3.2	358
M_f	327.86	3.7	243
N_2	12.66	10.3	8
Nu_2	12.63	2.6	22
M_2	12.42	32.4	34
S_2	12.00	10.4	68
K_2	11.97	2.7	63
O_1	25.82	1.6	183
K_1	23.93	1.4	183
$2N_2$	12.90	1.9	310

Monthly Mean Sea Level

The non-tidal components were obtained by low pass filtering the hourly sea level data. Two step filters were used. First, the dominant diurnal and semidiurnal tidal components are removed. Secondly, an 119-point convolution filter centered on local noon time (local time = GMT + 3) is applied to remove the remaining high frequency energy and to prevent aliasing when the data are reduced to daily values. The 95, 50, and 5% amplitude points are 124, 60.2 and 40.2 hours. The Nyquist frequency of the daily data is at a period of 48 hours which has a response of about 5% amplitude, thus, aliasing is minimal (CALDWELL, 1991).

The resulting low pass filtered daily records were averaged to calculate the monthly sea level, then corrected off the annual mean sea level. TSIMPLIS and WOODWORTH (1994) stated that when focusing on seasonal cycles, year to year datum history is not necessary provided that the datums are constant within each individual year. Monthly mean sea level that contains no or minimal gaps was selected to complete one year of monthly data during the recording period. Linear interpolation was applied to obtain August mean sea level since only a few days were recorded during that month. The monthly means of sea level at Gizan are shown in Figure 2 in which pronounced seasonal fluctuations are observed. Higher sea levels are observed from December to May with a maximum of 13.5 cm while lower sea levels occur from June to November reaching a minimum of −27.1 cm in July. This seasonal pattern is in agreement with the earlier measurements for two southern stations on the Red Sea; Perim and Aden. A relative increase in sea level during April was also observed in the earlier studies along the Red Sea stations suggesting a weak semiannual oscillation. The seasonal change in sea level gives an annual range of 40 cm with minimum during summer and maximum during winter.

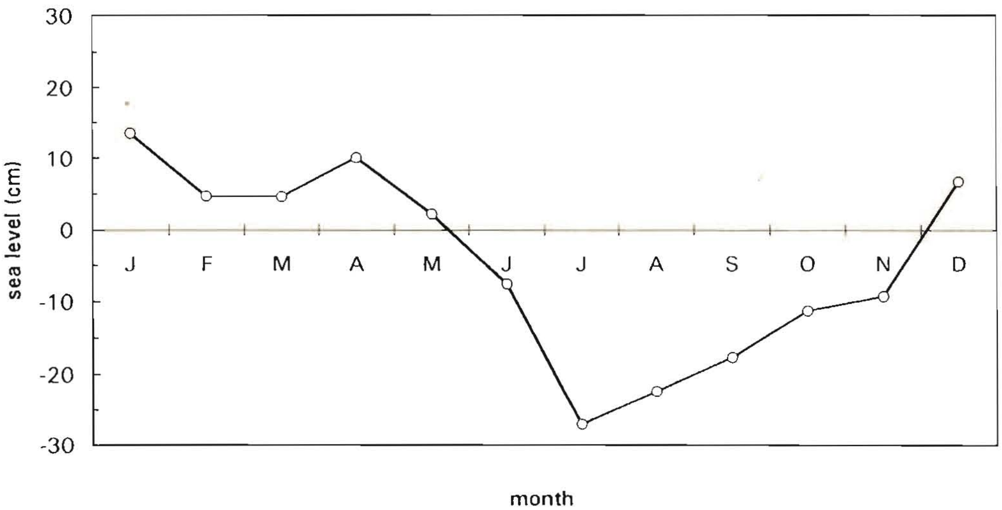

Figure 2. Monthly mean sea level changes at Gizan during 1992–1994.

FACTORS CONTROLLING THE MEAN SEA LEVEL VARIABILITY

Investigation of the observed variation of sea level requires examining the forcing parameters that affect the sea level such as: atmospheric pressure, evaporation, steric effect, current and wind regime. Simultaneous monthly mean sea level and values for each controlling factor are discussed separately to study their effects on the sea level fluctuations at Gizan.

Atmospheric Pressure

Monthly means of air pressure adjusted to the sea level at Gizan show an annual oscillation range of 11.6 mb during the recording period (1992–1994) and 10.7 mb based on climatological means (1985–1991). Unlike the Arabian Gulf, the air pressure over the Red Sea is minimum in summer and maximum in winter. According to the hydrostatic hypothesis, the sea surface reacts like an inverted barometer that lowers the sea level by 1 cm for each 1 mb increase in atmospheric pressure. The associated correction to the monthly mean sea level due to air pressure (1992–1994) in cm was computed and shown in Figure 3. It is clear from Figure 3 that the monthly observed sea levels at Gizan are departing from the isostatic response, which implies that the observed variations in mean sea level are not only a consequence of the atmospheric pressure changes. However in reality, the variations in atmospheric pressure are always associated with the changes in

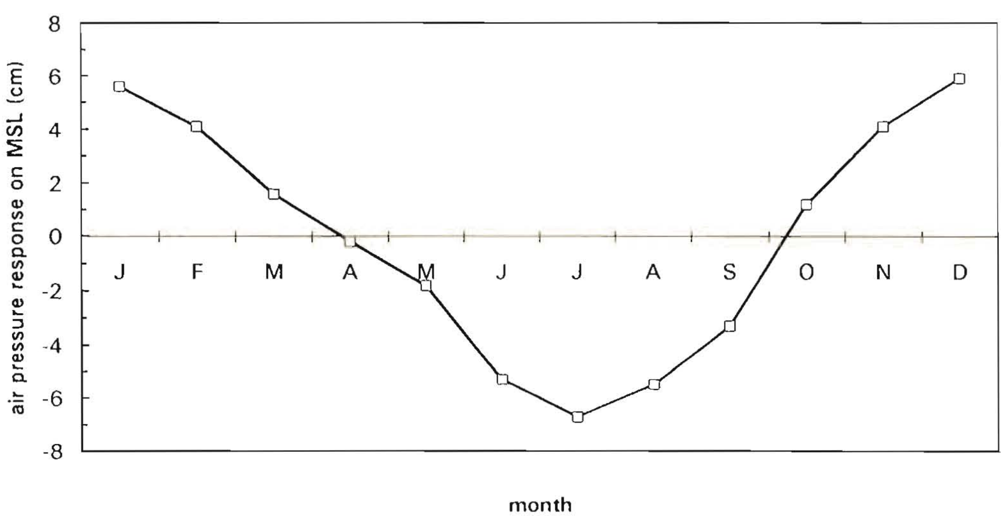

Figure 3. Monthly mean theoretical response of the sea surface due to the observed atmospheric pressure (1992–1994) relative to the mean sea level at Gizan.

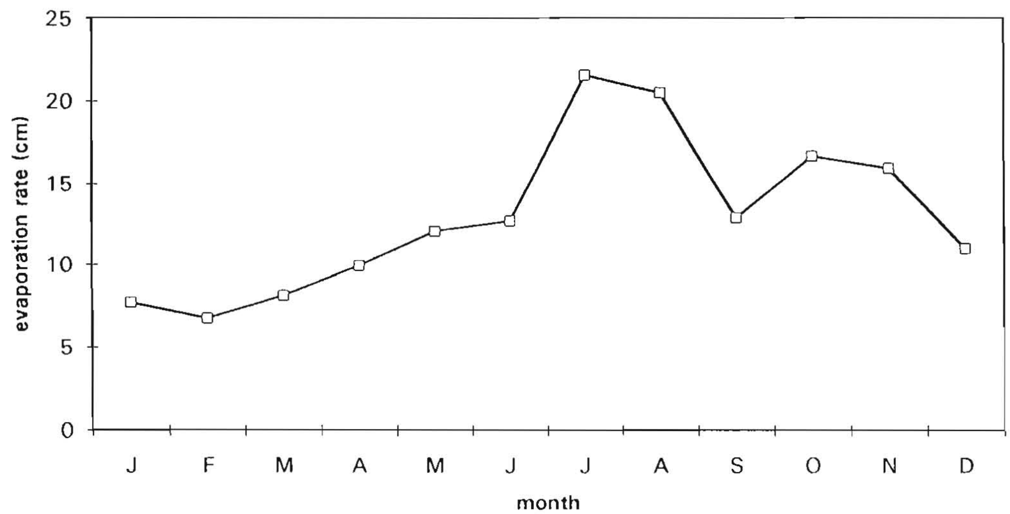

Figure 4. Monthly means of evaporation rate at Gizan (Abdelrahman and Ahmad, 1995).

the wind speed and direction (LISITZIN, 1974, p. 59) and thus have indirect influence on the sea level.

Evaporation

The evaporation rate in the Red Sea exceeds precipitation and run-off. The annual precipitation measured during the period of sea level recording was 1.3 cm at Gizan and less than 1 cm based on a longer data set (1985–1991). Moreover, there is no large river discharge into the area. The annual mean rate of evaporation at Gizan was estimated as 156 cm/year; 13 cm/month, (ABDELRAHMAN and AHMAD, 1995). Maximum evaporation rate occurs during summer and minimum in winter (Figure 4). Evaporation results in lowering the mean sea level. Monthly sea levels show maximum depression during summer associated with the higher rates of evaporation. Therefore, the sea level at Gizan is directly correlated with the loss of water by evaporation. The loss of water due to evaporation all over the entire Red Sea is compensated by the surface inflow coming from the Gulf of Aden.

Steric Sea level Effect

The steric sea level is high when water is warm and/or less saline thus less dense and becomes low when it is cold and/or more saline. Direct measurements of the hydrographic conditions are not readily available for Gizan. PATZERT (1972) computed the monthly geopotential anomalies in the upper 300 m at Aden and Perim stations and concluded that the seasonal variations in steric sea level at these southern sta-

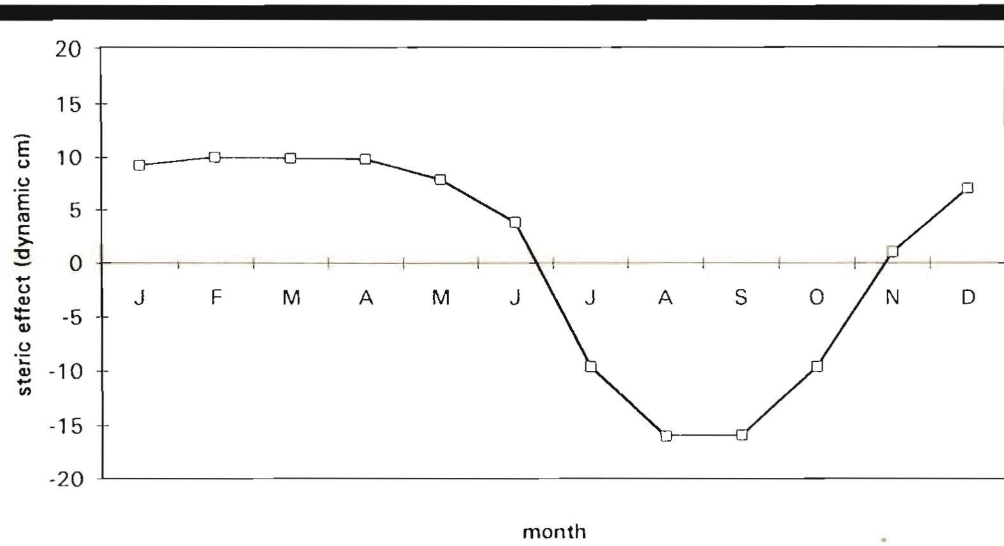

Figure 5. Monthly steric effect at Perim (after Patzert, 1972).

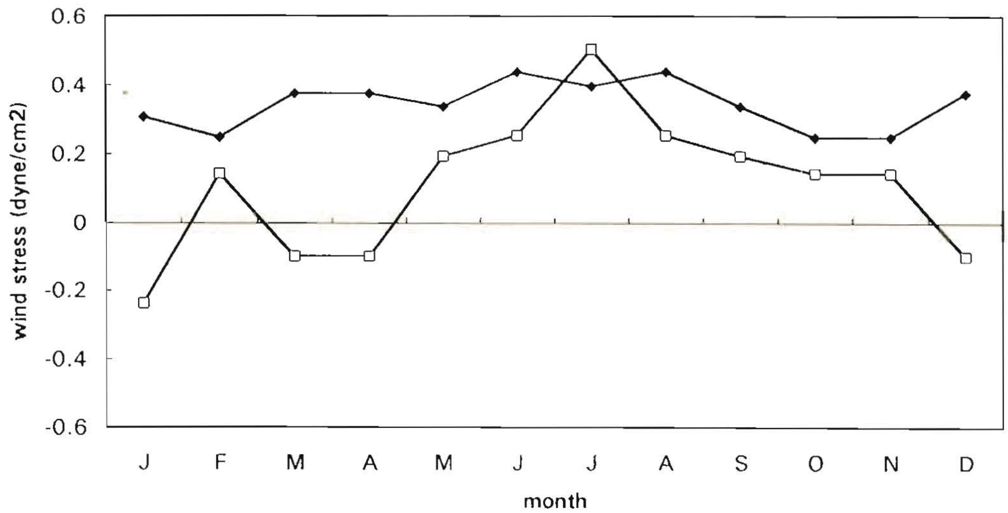

Figure 6. Monthly mean wind stress components at Gizan during 1992–1994: positive longshore (—□—) is directed southwards and northwards when negative, cross-shore (— ♦ —) is always directed shorewards.

tions have the same phase with the monthly mean sea level. Different phases were observed in the north. The prevailing conditions that control the steric effect at Perim in the southern part of the Red Sea are expected to be the same at Gizan, since Gizan is dominated by the same seasonal reversal in wind and water circulation. Steric effect at Perim, computed by PATZERT (1972), was reproduced and shown in Figure 5. During winter, surface inflow of less saline and warmer waters from Gulf of Aden are deflected by Coriolis force to follow the Saudi coast causing positive steric effect and high sea level at Gizan. During summer, outflow of colder and more saline waters cause negative steric effect and sea level is lowered. This allows to conclude that sea level changes at Gizan are correlated with the steric effect.

Wind Effect

The effect of the wind stress will raise or lower the sea level causing positive or negative surges. Analysis of the wind field at Gizan shows that the prevailing winds blow from a window between SSW to WNW. The most frequent winds are from W during summer and SW during winter. Wind speed is relatively high in summer and reaches maximum in July. The wind vector was decomposed into long-shore and cross-shore directions considering the orientation of the coastline. Wind stress components are calculated considering the quadratic law with a drag coefficient based on the wind speed range. The cross-shore component of wind stress shows steadiness in Figure 6 and is always directed shorewards; piling up the water onshore and causing an increase in sea level over the entire year. In any month, the cross-shore wind stress component is always larger in magnitude than the long-shore component except in July. The long-shore component of wind stress is directed southward in summer (positive values) and northward (negative values) in winter. The average value of the long-shore wind stress is higher during summer than winter. In winter, the wind driven surface currents are directed into the Red Sea by the influence of the SSE wind at the southern area of the Red Sea when sea level is observed high. In summer, sea level drops rapidly to minimum with the reversal of wind field. The long-shore component of wind stress is in agreement with the prevailing wind pattern that enhances the long-shore component in summer and reduces it in winter. Thus, the pattern of the monthly mean sea level is clearly a consequence of the reversal of the wind regime, in particular the longshore wind stress component.

DISCUSSION AND CONCLUSION

The above analyses indicate that the pattern of mean sea level has a pronounced seasonal variation and seems to be a consequence of the simultaneous wind regime, evaporation and steric effects and not with the atmospheric pressure alone. Stationarity of these changes from one year to another is assumed valid for the observed data set. If so, a statistical relation can be established between sea level and each of the forcing parameters. Linear regression analysis of monthly mean sea level on the above controlling factors was performed and the regression equations, correlation coefficients and the standard error of estimates are summarized in Table 2. Calculations were made with 95% confidence intervals. The steric effect, evaporation and the longshore wind stress component display the most highly correlated factors with the sea level variation giving correlation coefficients 0.90, −0.90 and −0.86 respectively associated with the lowest standard error of estimates 5.96, 6.24 and 7.05. It is worth mentioning that the magnitude of the wind speed and its squared value gave a lower correlation with the sea level changes (-0.48 and −0.52) confirming that the decomposition of wind vector magnifies the effective component of the wind vector.

Stepwise variable selection analysis was applied and a for-

Table 2. *Linear regression analysis of mean sea level (s_l) on: evaporation (cm/month), long-shore and cross-shore wind stress (dyne/cm²), steric effect (dynamic cm), wind speed (cm/sec) and squared wind speed (cm²/sec²).*

Parameter	Linear Regression Equation	Correlation Coefficient	Standard Error of Estimate (cm)
Evaporation	$S_l = 27.64 - 2.47E$	−0.90	6.24
Longshore wind stress	$S_l = 1.52 - 55.72W_l$	−0.86	7.05
Cross-shore wind stress	$S_l = 11.51 - 46.55W_x$	−0.24	13.58
Steric effect	$S_l = -5.18 + 1.15S_t$	0.90	5.96
Wind speed	$S_l = 45.81 - 0.14W$	−0.48	12.28
Squared wind speed	$S_l = 22.03 - 1.2E\text{-}4W^2$	−0.52	11.98

ward routine was fed by all the possible factors including wind speed, squared wind speed, air pressure, the associated response of air pressure, wind stress components, evaporation and steric effect. Analyses show that the steric effect, evaporation and long-shore wind stress component, that are highly correlated with the mean sea level changes, are significant independent factors. Steric effect (S_t) and the long-shore wind stress (W_l) were selected in the final step of the analysis as the smallest set of independent factors to be included in a fitted model. The suggested model for the monthly mean sea level (S_l) in cm is;

$$S_l = -1.6 - 31.3\, W_l + 0.8\, S_t \qquad (1)$$

The model explains 95% of the variations in the monthly mean sea level and gives 2.95 and 2.13 as standard and mean absolute errors.

Multiple regression on the monthly mean sea level and the main significant controlling factors; steric effect, long-shore wind stress component besides evaporation is attempted. Results give the following fitted model for the monthly mean sea level;

Table 3. *The coefficient estimates of the multiple regression model, their standard error and the 95% confidence intervals.*

Equation Parameter	Coefficient Estimate	Standard Error	Lower Limit	Upper Limit
Equation constant	4.91225	4.22104	−4.82421	14.6487
Long-shore wind stress (W_l)	−26.2083	6.08500	−40.2442	−12.1723
Evaporation (E) (cm/month)	0.53524	0.33856	−1.31617	0.24570
Steric effect (S_t) (dynamic cm)	0.63010	0.13353	0.32209	0.93811

$$S_l = 4.9 - 26.2\, W_l - 0.5\, E + 0.6\, S_t \qquad (2)$$

where W_l is in dyne/cm², E evaporation rate in cm/month and S_t in dynamic cm. It turned out that including the evaporation rate to the multiple regression model improves the explained variation of the mean sea level from 95 to 96%. The coefficient estimates with their standard error and the 95% confidence intervals are given in Table 3. The fitted model was compared with the observed monthly sea levels in Figure 7 and indicates good agreement with the sea level pattern at Gizan. Inclusion of the atmospheric pressure and cross-shore wind stress component to the multiple regression model reduces the explained variation and increases the standard error of estimate confirming that the model given by equation 2 gives the best fit

In conclusion, this investigation allowed the determination of tidal constituents at Gizan. A pronounced seasonal fluctuations of the monthly sea level were observed being lower in summer and higher in winter. Examining a number of possible causes, sea level fluctuations are explained mostly by the steric effect, evaporation and longshore wind stress component. These significant factors are mainly resulting in the seasonal wind and water exchange reversal circulation dominating the southern part of the Red Sea. A multiple regression model that explains 96% of the monthly sea level fluc-

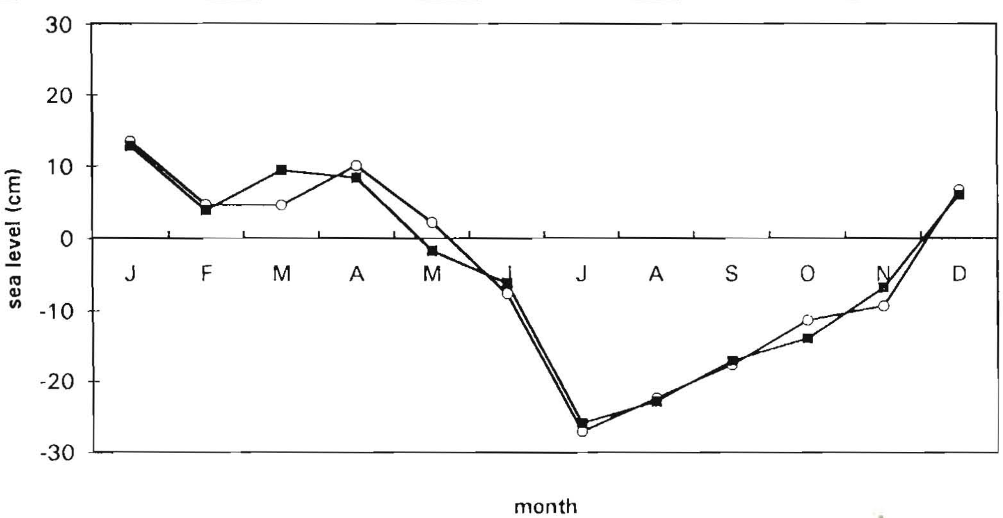

Figure 7. Monthly observed (—○—) and predicted (—■—) mean sea level based on the proposed multiple-regression model.

tuations was proposed that simulates properly the observed sea level pattern.

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