

Sea level changes in the central part of the Red Sea

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Daily means of sea level and atmospheric forcing over a period of three years (1991-1993) at Jeddah are examined by spectral and regression methods. The analysis reveals the presence of a large annual and a semi-annual component in the time series. Average amplitudes of the two signals in the sea level changes are 19 and 8 cm, respectively, and account for 58 % of the total variance. The two signals are induced by the combined effect of wind stress and evaporation rate. Wind stress plays a major role in inducing the annual cycle. Sea level is inversely related to the evaporation rate only during the transition periods. Isostatic response of sea level is limited, 4 % of the total variance, and is frequency dependent with observed period of 9 days. Analysis of daily residuals shows that about 78 % of the variance can be modeled by a first order auto-regressive model AR (1).

[**Key words** : Atmospheric pressure, evaporation, Jeddah, Red Sea, sea level, steric , wind stress]

The study of sea level changes is beneficial to navigation, coastal defense systems and construction. These beneficiaries require a detailed understanding of sea level behavior. Water exchange between adjacent seas through straits and the associated current patterns are intimately related to sea level changes. Similarly tidal and non-tidal changes in sea level play an important role in the water exchange between the coastal and open areas. Such an exchange has a marker effect on the extent and distribution of pollutants in the area.

Tides, due to their nature as standing waves, contribute unevenly to sea level changes along the Red Sea coast. The influence of the tides is greatest at the southern and northern ends of the sea, where tidal range is relatively large and decreases gradually towards the centre where an amphidromic region forms¹. From the meteorological view point in the region around 19° N a convergence zone forms, where NNW winds meet those from SSE in winter in the southern Red Sea. Incidentally the area of low tidal range coincides with this zone, although the position of the latter may vary from one year to another. In such an area, it is expected that non-tidal changes would contribute largely to sea level variability. Jeddah is situated approximately 225 km north of the low tide zone, where tides account for only 15 % of the yearly sea level variance².

Non-tidal changes in the sea level can be either of meteorological or oceanographic origin. The relative

importance of the various factors influencing sea level changes depends on time and locality. Effect of meteorological disturbances are greater in shallow areas³. Exchange of energy between the atmosphere and ocean occurs at all space and time scales. Resulting sea level changes range from sub-tidal to seasonal and long term.

Low frequency variations of the Red Sea levels are mainly controlled by the influence of high rate of evaporation, the reversal of the wind regime and the associated water exchange through Bab-el-Mandab Strait. Recently the evaporation rate has been estimated by a number of investigators⁴. More recent estimates⁵⁻⁷ are 2 m/yr. The wind regime reverses over the southern Red Sea between NNW in summer to SSE in winter. During winter, the surface inflow through Bab-el-Mandab Strait exceeds the sum of the subsurface outflow and evaporation, thus resulting in higher levels while the opposite occurs in summer. Seasonal changes of sea level at different places in the Red Sea have been already investigated^{1,2,8-10}.

It is of interest to analyze the way in which atmospheric factors (atmospheric pressure and wind) act on the sea and the contribution of these atmospheric manifestations make to the total sea level changes. This paper presents the results of a study of three years of sea level data at Jeddah together with appropriate meteorological data. The objective of the study is to describe sea level changes at different time

scales, ranging from two days to seasonal. It is also aimed at achieving a more detailed understanding of the influence of atmospheric forcing on the Red Sea level.

Materials and Methods

Hourly sea level values were extracted from records obtained by a pressure type recorder (OSK LP2) moored from 2 December 1990 to 30 November 1993 at a depth of 3 m at Jeddah (Fig. 1). The data return was greater than 95% with gaps filled by linear interpolation. The sea level station is situated at the entrance of the Obhur creek, a finger of the Red Sea extending inland. The creek serves as an ideal location for sea level gauge installation as it is protected from direct effects of wind and waves. The accuracy of the device is ± 0.5 cm. Timing error on the records was minimal (of the order of few minutes per 45-days chart length). Meteorological parameters were simultaneously obtained from Jeddah International Airport Station, about 2-3 km from the gauge site.

Daily mean sea levels were determined after elimination of the tidal effects. The latter was achieved by applying the Doodson χ_0 filter to the hourly data¹¹. Diurnal and semi-diurnal and shorter tidal constituents are rigorously suppressed by this filter which incorporates 38 hourly intervals centered at 12.00 noon. The daily mean of atmospheric pressures were obtained by averaging hourly values. Wind stress was

computed according to the quadratic law: $\tau = \rho_a C_D W^2$, where ρ_a 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^{12,13}. Hourly wind stresses were then resolved into orthogonal cross- and long-shore components. This was achieved by adding 25° , the approximate angle of the coast of Jeddah from the north to the wind direction. Daily means of the wind stress components were then obtained from hourly values. Monthly means of all the time series were obtained by averaging the daily mean values. Additionally published data given by Osman⁹ are carefully re-examined and those given by Abdallah & Eid¹⁵ are re-analyzed for further support.

Spectral and cross-spectral analyses were performed with the aid of a computer program using the method of Fast Fourier Transform (FFT). Regression analysis and fitting of auto-regressive model were performed using the statistical program package MINITAB.

Results and Discussion

Time series of the daily mean sea level shows a pronounced oscillation with a period of one year, having a minimum June, July and August in summer and maximum December, January and February in winter (Fig. 2A). This oscillation has always been associated with the prevailing wind regime that reverses over the southern Red Sea^{1,2,8-10}. In addition to the annual cycle there are numerous variations of shorter periods of relatively larger amplitudes in winter than in summer. Their period range from two days to less than a month as they are smoothed out when obtaining the monthly means (Fig. 2B). A possible cause of this variation is the effect of atmospheric pressure and wind. The plot of the monthly means (Fig. 2B) indicates the presence of a semi-annual component; in addition to the rise in winter and fall in summer, sea level peaks in April and decreases during February. Figure 3A displays the spectrum of the daily means of the sea level for the study period. It is clear that the annual cycle accounts for a major proportion of the total variance. In addition the existence of the semi-annual cycle is clearly discernible above the background.

Amplitude, phase and variance accounted for by both cycles are presented in Table 1. The variance captured by the semi-annual cycle tends to be larger in years when that of the annual cycle is small. The average variance explained by the annual and

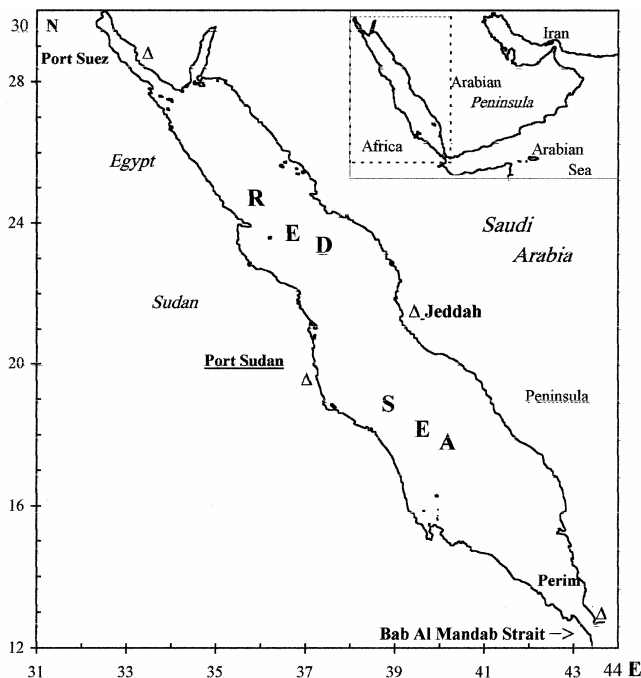


Fig. 1 — Map of the Red Sea showing the Station's Positions

semi-annual cycles are about 48% and 10% respectively. Their respective average amplitude are 19 and 8 cm. Therefore the two components explain 58% of the total variance and there remains a substantial proportion (42%) of the variance caused mostly by fluctuations of shorter period. The computed amplitude of the annual and semi-annual cycles according to the equilibrium theory¹⁴, being 0.7 and 5.7 mm respectively, are very small in comparison with those

observed and thus contribute insignificantly to seasonal sea level change.

The semi-annual component of the sea level has not been recognized in previous investigations. However, a careful scrutiny of the monthly means of sea level over a 7-year period (1962-1968) given by Osman¹⁰ reveals the presence of a semi-annual variation beside the annual cycle. Additionally examination of the data given by Abdallah & Eid¹⁵ exhibits the presence, although not the same size, of semi-annual variations at three stations along the Red Sea; Perim, Port Sudan and Port Suez. The results of the reanalysis of the data given by these authors are reported in Table 2. The semi-annual component was first documented by Sultan *et al.*¹⁶ from the analyses of six-year record of sea level at Port Sudan (1986-1991).

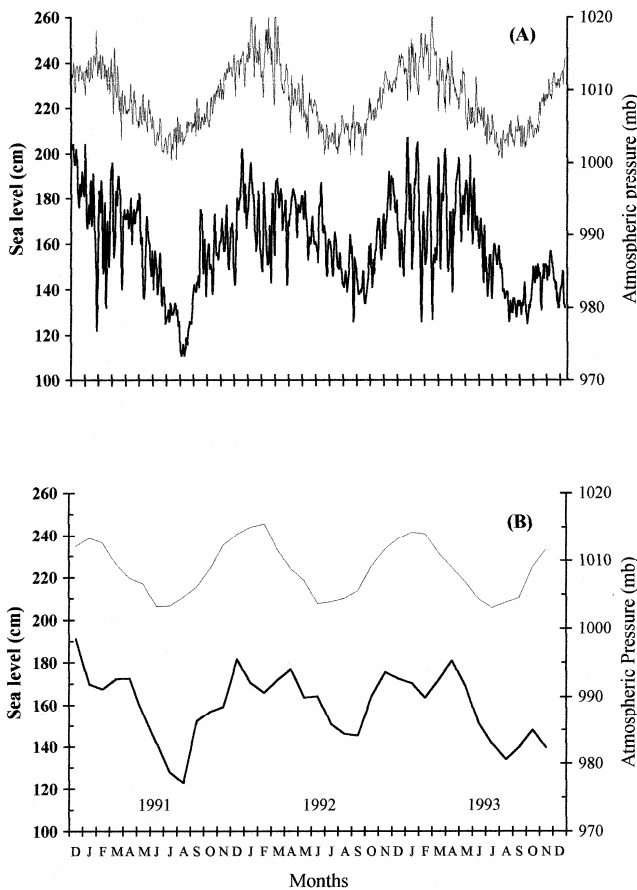


Fig. 2—The daily means (A) of sea level (SL) and monthly means (B) of atmospheric pressure (AP) for the period 1991-1993 at Jeddah.

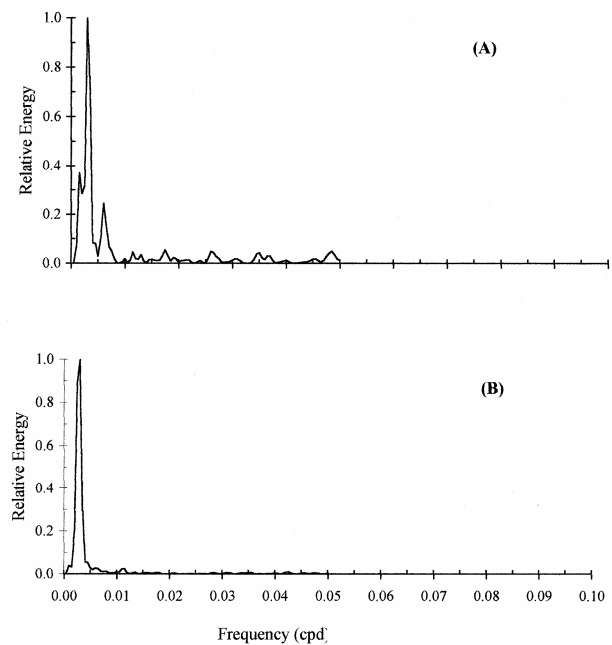


Fig. 3—The spectra of sea level (A) and atmospheric pressure (B) at Jeddah

Table 1—Amplitude, phase and variance accounted for by the annual (1) and semi-annual (2) cycle

Year	Annual cycle (1)			Semi-annual cycle (2)		
	Amplitude (cm)	Phase (degree)	Variance explained (%)	Amplitude (cm)	Phase (degree)	Variance explained (%)
1991	23	55	56	9	56	9
1992	13	65	37	9	27	18
1993	20	85	50	5	38	3
Average	19	—	48	8	—	10

Table 2— Variances explained by the annual and semi-annual components of the various parameters based on long term monthly means

Variable	Location	Annual (%)	Semi-annual (%)	Both (%)
Sea level	Port Suez*	84.0	12.4	96.0
	Jeddah	77.3	21.0	98.0
	Port Sudan*	82.1	16.6	98.0
	Perim*	81.2	15.7	96.0
Cross-shore stress	Jeddah	68.2	26.5	94.7
Long-shore stress		22.4	50.4	72.8
Evaporation	Central Red Sea	34.6	38.6	73.3

*Data from Abdallah & Eid¹⁵

Sea level and atmospheric pressure

Daily mean of atmospheric pressure also displays a basic oscillation with a period of one year over which are superimposed short-lived fluctuations (Fig. 2 A). The spectrum of the atmospheric pressure (Fig. 3) shows that the basic oscillation accounts for most of the variance, about 85 % of the total. The monthly changes show high sea level in winter concurs with that of atmospheric pressure and *vice versa* in summer (Fig. 2B). Thus the annual sea level cycle is not a result of inverted barometer response to atmospheric pressure. This is not a new finding, but merely a confirmation of an already known fact.

In order to see whether the geostrophic control imposes flow constriction through Bab-el-Mandab Strait the critical dimensionless parameter ε is considered¹⁷⁻²⁰. This parameter is given by $\varepsilon = \omega f A / g H$, where ω is the frequency, f is the Coriolis frequency, A is the area of the basin (for Red Sea $0.438 \times 10^6 \text{ km}^2$), g is the acceleration due to gravity and H is the mean depth of the Strait (for Bab-el-Mandab, 110 m). For a very small value of ε (low frequency) the flow through the strait is sufficient to permit an isostatic response of the basin to atmospheric pressure. If the parameter ε is not very small, there is insufficient time for the flow through the strait to equalize sea level changes in the basin. Indeed the values of the parameter ε (0.0007-0.12) are very small for the range of all the fluctuations observed in the Red Sea. Moreover Lascaratos & Gacic²¹ defined a time scale which is an estimate of the upper limit above which geostrophic control does not impose flow constriction. In which case, the flow is sufficient to permit an isostatic response of the basin. The time scale is expressed as

$T = A f / g H$. With the appropriate numerical values, T is estimated to be 10 hours. Therefore, the flow through the Strait of Bab-el-Mandab is not geostrophically controlled and the strait does not prevent the Red Sea from having a barometric response at the time scales of the observed fluctuations. In the Red Sea, however the effect of the wind dominates that of the atmospheric pressure. Reversal of the wind regime over the southern Red Sea appears to play a major role in inducing the annual cycle of the sea level. Having stated this fact does not exempt sea level variations at other time scales from having an inverted response to atmospheric pressure. In order to examine whether such a relationship exists at other time scales the seasonal signal was first eliminated from the time series of the sea level and atmospheric pressure. This was achieved by filtering the annual and semi-annual cycles. The annual cycle is eliminated by fitting a combination of a cosine and a sine function of angular frequency $2\pi/365$ (day) applying the least-square method. Similarly the semi-annual component is removed by a function of angular frequency $2\pi/82.5$ (day). These were then subtracted from the original data to produce daily residuals (Fig. 4). The residual variance of the sea level is 42 % of the original while that of the atmospheric pressure is 15 % of the original. Regression of the sea level residual (SLR) on those of atmospheric pressure (APR) results in an equation of the form:

$$\text{SLR} = -0.49 - 1.9 \text{ APR}$$

The variance accounted for by the regression of sea level on atmospheric pressure is about 10 % of the residual variance. This is equivalent to about 4 % of the total variance. The above equation with a negative

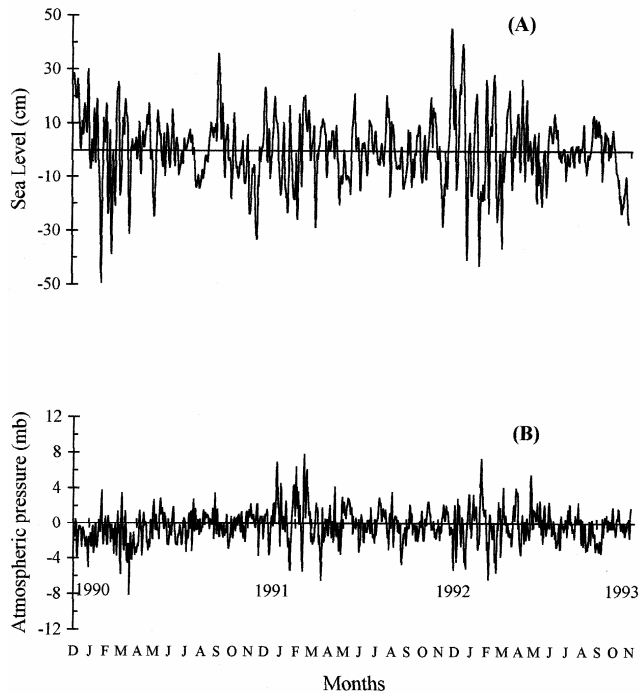


Fig. 4—The daily residuals of sea level (A) and atmospheric pressure (B) for the period 1991-1993 at Jeddah

coefficient implies that there is an inverted response of the sea level to atmospheric pressure, however, the response is far from the hydrostatic equilibrium ($-1 \text{ cm}/\text{mb}$). As the regression coefficient is $-1.9 \text{ cm}/\text{mb}$, the equation predicts sea level changes almost a factor of 2 higher than the isostatic response.

It is worth examining whether the isostatic response shown above is frequency dependent. This is accomplished by performing cross-spectral analysis between the residuals of the daily means of sea level and atmospheric pressure. Figure 5 shows the coherence squared phase and gain spectra. The dashed line represents the 95% confidence over which the coherence is significant. The most significant peak occurs at frequency of 0.11 cycles/day corresponding to a period of 9 days. At this time scale the sea level changes are almost 180° out of phase with those of atmospheric pressure. This means that the sea level has a greatest inverted response at this frequency. The second significant peak occurs at a time scale of 3 days. Once again the variations of the two variables are 180° out of phase.

Wind stress

Figure 6 shows the daily means of the cross- and long-shore components of the wind stress at Jeddah. A sign convention is adopted such that negative

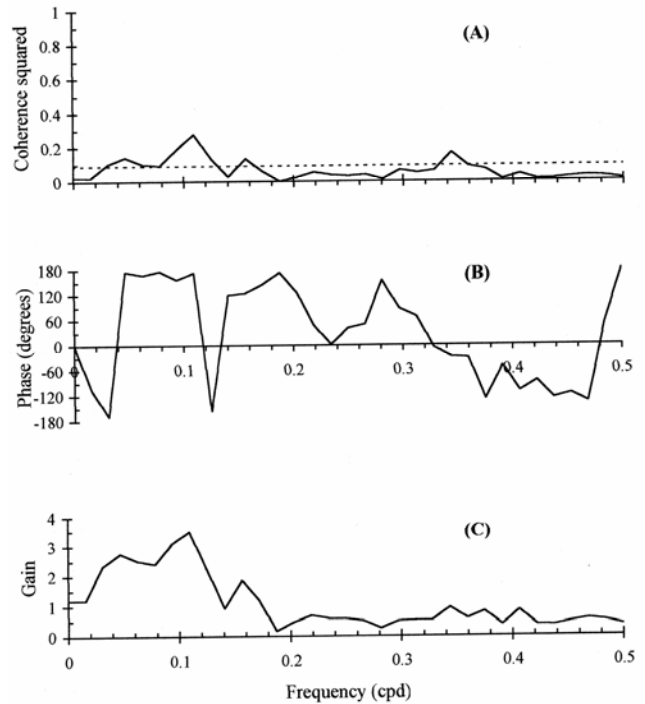


Fig. 5—The coherence squared (A), phase (B) and gain (C) between the residuals of sea level and atmospheric pressure

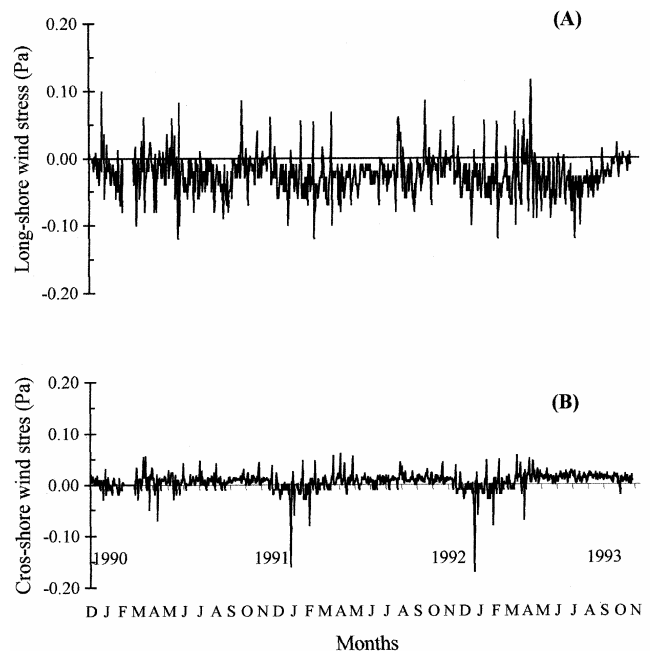


Fig. 6—The daily means of long- (A) and cross- (B) shore wind stresses for the period 1991-1993 at Jeddah

values of cross-shore and long-shore stresses are directed offshore and towards the south respectively. Accordingly the predominant direction of the cross-shore component is onshore while that of the long-shore is southward. This is expected as the prevailing

direction of the wind in the northern part of the Red Sea is from NNW all year round. The component of long-shore stress is stronger than the cross-shore. Figure 7 shows the spectra of the two components. The cross-shore stress is characterized by two cycles, an annual being dominant and a semi-annual. In contrast the semi-annual component is dominating the long-shore stress. There are also other variations at almost all frequencies in the long-shore stress but less significant.

Figure 8 presents the monthly means of sea level, wind stress components and evaporation rate. Apart from evaporation, the monthly means were obtained by averaging over the study period (1991-1993). On the other hand evaporation represents long term monthly averages⁶. The above parameters display annual and semi-annual cycles which contribute unequally to the total variance of the different variables (Table 2).

It is clear that the annual component constitutes a major proportion of the variance in the sea level at all stations and in the cross-shore stress at Jeddah. In contrast the semi-annual cycle accounts for 50% of the variance of the long-shore wind stress at Jeddah. The semi-annual component of the sea level increases slightly southwards along the African coast. It accounts for 12% at Port Suez and 16% at Perim. At Jeddah the semi-annual component accounts for the largest variance among all stations (21%) where the long-shore stress is dominated by a semi-annual com-

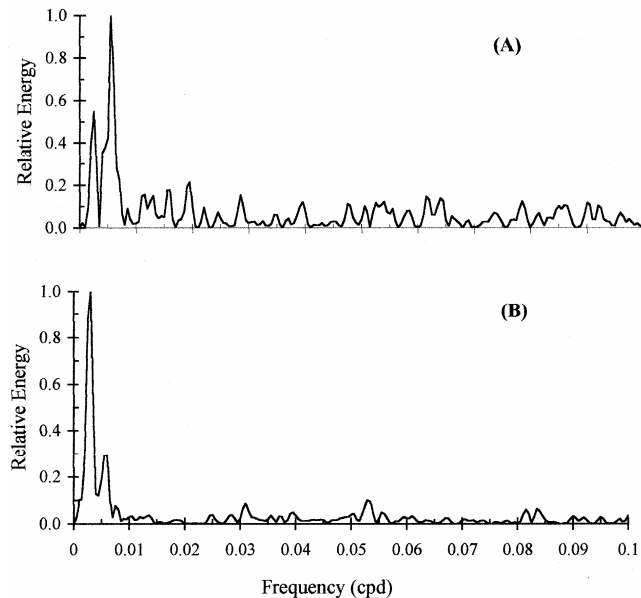


Fig. 7 — The spectra of long- (A) and cross-shore (B) wind stress at Jeddah

ponent. The presence of the annual component in the wind stress is expected due to seasonal changes of wind speed and direction in association with the southwest monsoon. However the mechanism of how the semi-annual component is induced is not yet clear. It is probably related to the reversal of the wind regime over the southern Red Sea. In order to confirm the presence of this cycle, analysis of the monthly wind speed over a 16 years period (1970-1985) at Jeddah was carried out. The spectrum of the monthly wind speed shows in addition to the dominant annual cycle, the presence of the semi-annual cycle (Fig. 9). The presence of this cycle appears to be a permanent feature of the wind field at Jeddah.

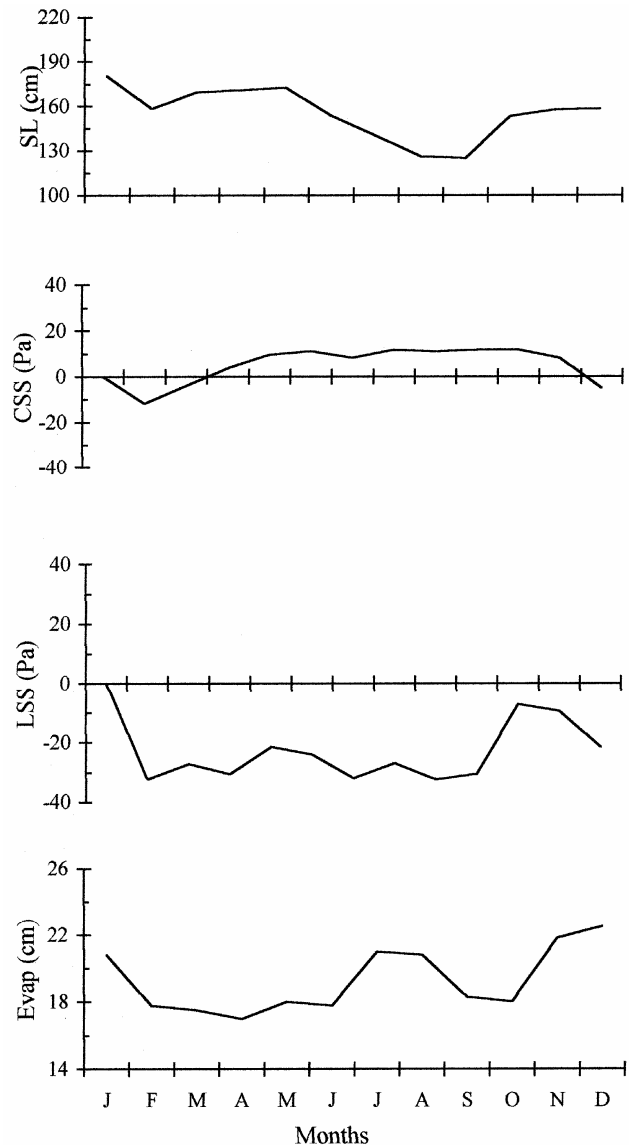


Fig. 8 — Monthly means of sea level (SL), cross- (CSS) & long- (LSS) shore wind stress and evaporation (Evap) at Jeddah

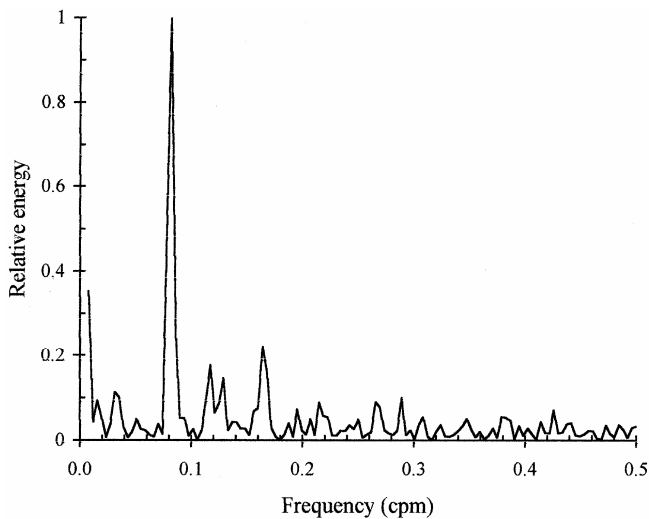


Fig. 9—The spectrum of the monthly wind speed over the period 1970-1985 at Jeddah

Regression analysis shows a strong correlation between monthly means of sea level and wind stress components. The correlation coefficient, being 0.695, is significant at the 95 % confidence level for 10 degrees of freedom. The percentage of variance R^2 accounted for by regression of sea level on wind stress is 48 %. Regression analysis based on the individual years shows a strong correlation for 1991 ($R^2=68$) and weak for year 1992 ($R^2=18$). The variance accounted for by the cross-shore stress is steady at 20 % , while that explained by long-shore stress varies from a minimum (3 %) in 1992 to a maximum (29 %) in 1991 and averages 16 % . The two components of wind stress are not totally independent of each other. The degree of their dependency varies from one year to another. They are moderately correlated in the years 1991 and 1993 and almost independent of each other in 1992.

Evaporation

Evaporation results in the lowering of the mean sea level. The rate of evaporation from the Red Sea has been estimated by a number of investigators. The most recent estimate⁶ amounts about 2 m/yr. The values of evaporation at the central Red Sea were taken from Ahmad & Sultan⁶ after been converted into cm/month. Monthly means, presented in Fig 8, are characterized by two maxima, one in summer (July) and one in winter (December) and two minima in April and October. Table 2 shows that the semi-annual component contributes only slightly (38 %) more than the annual component (34 %) to the total variance. The low sea level in summer could be

caused by the combined effects of evaporation and the long-shore component of the wind stress. The effect of the two processes are in phase. Strong wind stress and high evaporation tend to lower sea level in summer. However it is difficult to separate the percentage of sea level lowering caused by each. In contrast during winter, the two factors have opposing effect on the sea level. High rate of evaporation tends to lower sea level while weak long-shore stress may rise it. Wind reversal over the southern part appears to weaken the long-shore stress in the northern Red Sea. Clearly the wind effect dominates that of evaporation and results in high sea level. The lowest evaporation occurs in April when the sea level is highest. In October the evaporation is low while the sea level just starts to rise. April and October represent the transition periods when the winds reverse over the southern Red Sea. During these periods of the year the sea level seems to be inversely related to the evaporation rate. During the remaining part of the year this relationship is masked by the prevalent wind action. The presence of a semi-annual component in wind speed induces a semi-annual change in the evaporation rate. The combined effect of the semi-annual components of wind stress and evaporation appear to induce the semi-annual changes in sea level. Relative importance of the processes is difficult to assess at present. During April and October small values of long-shore stress are concurrent with those of evaporation rate.

Steric effect

Lack of continuous measurements of temperature and salinity with time and depth at Jeddah makes it difficult to assess the steric effect on the sea level changes. According to Patzert²² seasonal steric changes calculated relative to 200 m indicate that the effect of seasonal variation in steric sea level is to raise the level in summer and lower it in winter. More recently Abdallah & Eid¹⁵ presented a comprehensive analysis of the steric effect on sea level. Their results show that the annual range of steric departure from mean sea level relative to 300 m varies from 7 cm to 5 cm in the southern and central regions respectively. In the northern part of the Red Sea steric departures are insignificant. The fact that sea level is lower in summer implies that steric changes do not contribute to the seasonal signal of sea level.

Analysis of daily residual of sea level

It is shown in the previous sections that the two major cycles account for 58 % of the total variance in

the daily means of sea level. On the other hand about 4 % of the variance can be modeled by regression of sea level on atmospheric pressure. Consequently a large proportion of the variance (38 %) remains in the daily residuals. Therefore it is of interest to examine the relationship among the values of the residuals at different time lags. The advantage of this procedure is that the minor variations in the residuals can be subjected to a more accurate analysis than when they are hidden by a simultaneous seasonal cycle and trend. This can be achieved with the aid of the auto correlation function (ACF) defined as $\rho(k)$, where k is the time lag.

Prior to the identification of the appropriate statistical model, the time series of the daily residuals of sea level must be checked for normality and stability. These properties are often saliently assumed to exist for any physical system. These assumptions can be readily supported by a non-parametric approach such as the χ^2 test and the run test²³. In the present study the normality is fulfilled with the histogram of the daily residual (Fig. 10A). It is clear from the bell-shaped distribution that the data are normally distributed. On the other hand a sufficient condition for the process²⁴ to be stationary is that $-1 < \Phi < 1$, where Φ is the model parameter. Calculated auto correlation coefficients of the daily residuals differ significantly

from zero for lags up to 10 days (Fig. 10B). The correlogram shows that the auto correlation function decreases exponentially with an increasing lag time k . This implies that the daily residuals of sea level are not completely random but exhibit a persistence, so that a major portion of the variance can be explained as an auto regressive model. Applying the technique recommended by Essenwanger²⁵ an auto regressive model of order 1 [AR(1)] has been fitted to the time series. AR(1) is defined as:

$$R(t) = \Phi R(t-1) + \Sigma(t)$$

where Φ is the model parameter and $\Sigma(t)$ is uncorrelated process with zero mean. The ACF of AR(1) model is presented in Fig. 10B. The estimated value of the model parameter $\Phi = 0.89$ and the percentage of variance of $R(t)$ accounted for by AR(1) model is 78 %.

Conclusion

Analysis of sea level and atmospheric forcing over a period of 3 years (1991-1993) at Jeddah reveals the presence of an annual and semi-annual component in the sea level, evaporation, cross-shore and long-shore stress. The semi-annual signal appears to be a feature of sea level changes everywhere in the Red Sea with its greatest effect in the central and southern parts. The percentage of the variance in the daily sea levels accounted for by the two signals is about 58 %. Both wind stress and evaporation rate appear to contribute to the seasonal changes. Wind stress has a dominant effect over the evaporation in winter resulting in high sea level while in summer both processes act together to lower the sea level. However the relative contribution of these forces in lowering the sea level is not clear in summer. On the other hand evaporation plays an important role in inducing the semi-annual cycle. During the months of April and October when winds abate and then reverse over the southern Red Sea, the sea level is inversely related to evaporation. The weakening of the winds during these periods causes the sea level to inversely change with the evaporation rate. As the effect of wind ease during these periods the effect of evaporation becomes more apparent on the sea level. During the remaining part of the year this relationship is masked by the prevailing wind influence. Moreover the winds are characterized by a semi-annual cycle at Jeddah. Therefore it may be concluded that the semi-annual changes in the sea level are induced by the combined effect of evaporation and wind stress.

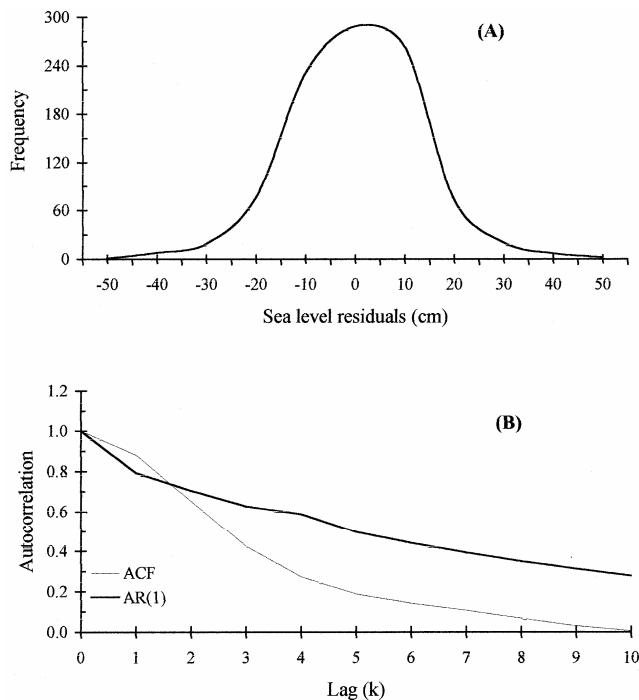


Fig. 10 — Frequency distribution of the daily residuals of sea level (A) and (B) the Auto-correlation functions ACF & AR(1)

The isostatic response (-1 cm/mb) of sea level does not hold on a seasonal basis. Regression analysis of the daily residuals shows that there is a limited inverse barometer response. However the response is far from the isostatic one with a regression coefficient of about -2 cm/mb. Cross-spectral analysis shows that the response is frequency dependent with a preferred frequency of 0.11 cycles/day (9 days).

Examination of the daily residuals of sea level shows that they are strongly inter-correlated. Therefore an auto regressive first order model AR(1) was calibrated to the daily residuals which accounts for 78% of the variance. This implies that about four fifth of the residual changes in the sea level propagate from the previous day.

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