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Sea level variability in the central Red Sea

Sea level
Wind stress
Spectral analysis
Red Sea

Niveau de la mer
Tension du vent
Analyse spectrale
Mer Rouge

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ABSTRACT

Analyses of the daily means of the sea level at Jeddah and Port Sudan for the year 1991 reveal that a large proportion (60%) of the energy is concentrated in the seasonal variations. The seasonal signal is approximated as the sum of an annual and semi-annual components. The amplitudes of the annual component are 20.3 and 12.7 cm respectively and constitute about 44% of the total variance. The amplitudes of the semi-annual cycle are 9.6 cm and 7.7 cm and explain about 10% and 16% of the variance respectively. At Jeddah cross-spectral analysis between the sea-level and the wind stress components shows that the annual cycle is mainly induced by the long-shore component. In contrast no correlation exists between the sea level and the cross-shore wind-stress at any frequency. At Port Sudan both components of wind stress contribute significantly to the annual cycle of the sea level. Variations of 3.5-day period are also related to the long-shore stress, while those of 2- and 6-day periods are associated with the cross-shore stress. The semi-annual cycle is strongly related to the evaporation rate. Cross-spectral analyses between the sea level changes show that low frequency variations are coherent across the sea, while high frequency fluctuations are due to local meteorological conditions. Tidal analysis shows that the tide at Jeddah is mixed mainly semi-diurnal with large diurnal inequalities, while at Port Sudan the tide is of diurnal type.

RÉSUMÉ

Variabilité du niveau de la mer au centre de la Mer Rouge.

Le niveau de la mer a été observé à Jeddah et à Port-Soudan pendant l'année 1991 ; les valeurs moyennes journalières indiquent que la plus grande partie (60 %) de l'énergie se trouve dans les variations saisonnières. Le signal saisonnier est la somme d'une composante annuelle et d'une composante semi-annuelle. Les amplitudes de la composante annuelle, respectivement de 20,3 et 12,7 cm, représentent environ 44 % de la variance totale. Les amplitudes du cycle semi-annuel, 9,6 cm et 7,7 cm, correspondent respectivement à 10 % et 16 % de la variance.

A Jeddah, l'analyse spectrale croisée entre les composantes du niveau de la mer et la tension du vent montre que le cycle annuel est principalement induit par la composante orientée le long de la côte. En revanche, il n'y a aucune corrélation entre le niveau de la mer et la tension du vent perpendiculaire à la côte, quelle que soit la fréquence.

A Port-Soudan les deux composantes de la tension du vent contribuent de manière significative au cycle annuel du niveau de la mer : des variations de 3,5 jours de période sont liées à la tension le long de la côte, tandis que des périodes de 2 et 6 jours sont associées à la tension perpendiculaire à la côte. Le cycle semi-annuel est fortement lié au taux d'évaporation. L'analyse spectrale des variations du niveau de la mer montre que les variations à basse fréquence sont cohérentes à travers la mer Rouge, tandis que les fluctuations à haute fréquence sont dues aux conditions météorologiques locales. L'analyse de la marée montre qu'à Jeddah, elle est semi-diurne avec de fortes inégalités diurnes tandis qu'à Port-Soudan elle est diurne.

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INTRODUCTION

The relative importance of tidal and non-tidal variations depends on the time of the year and the local bathymetry. Apart from tsunamis, non-tidal fluctuations in the sea level are of meteorological and oceanographic origin. Meteorological disturbances are greater in shallow areas (Pugh, 1987). Exchange of energy between the atmosphere and the ocean occurs at all space and time scales and the resulting changes range from the sub-tidal to longer and secular motions. Chao and Pietrafesa (1980), Marmorino (1983), Pugh and Thompson (1986) and Lascaratos and Gacic (1990) discuss the subtidal and low-frequency response of the sea to different types of forcing, whereas Thompson (1980), Palumb and Mazzarella (1982), Spillane *et al.* (1987) and Isoda *et al.* (1991) study the longer and secular variability. The response of the semi-enclosed seas to the weather forcing is far from uniform.

In the Red Sea the tidal range is small, being 0.9 m in the south near Bab-el-Mandab and 0.6 m in the north near the Gulf of Suez (Edwards, 1987). In the central part of the sea the tidal heights are even less and range between 30 and 20 cm over a spring-neap cycle.

The Red Sea levels are strongly influenced in the long term by the high rate of evaporation and the balance between the in- and out-flowing waters. In winter the inflow exceeds the combined effect of outflow and loss due to evaporation despite the fact that the evaporation rate on the average 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. Morcos (1970) has summarized previous work on the mean sea level which indicates a higher level in winter. Previous work is mainly related to the investigation of the seasonal changes in the Red Sea level which vary from a maximum depression of 20-30 cm in summer (August) to a rise of 10-20 cm in winter (January) (Osman, 1984 and 1985; Edwards, 1987), whereas the present paper investigates the response of the sea to the different components of the external forcing.

DATA COLLECTION AND PROCESSING

Hourly sea-level heights were abstracted from sea-level records obtained during 1991 (January to December) by a pressure-type recorder (OSK LPT. 2) temporarily installed at about 3 m below the surface in the coastal water of Jeddah (Fig. 1). The accuracy is estimated to be within 0.5 cm

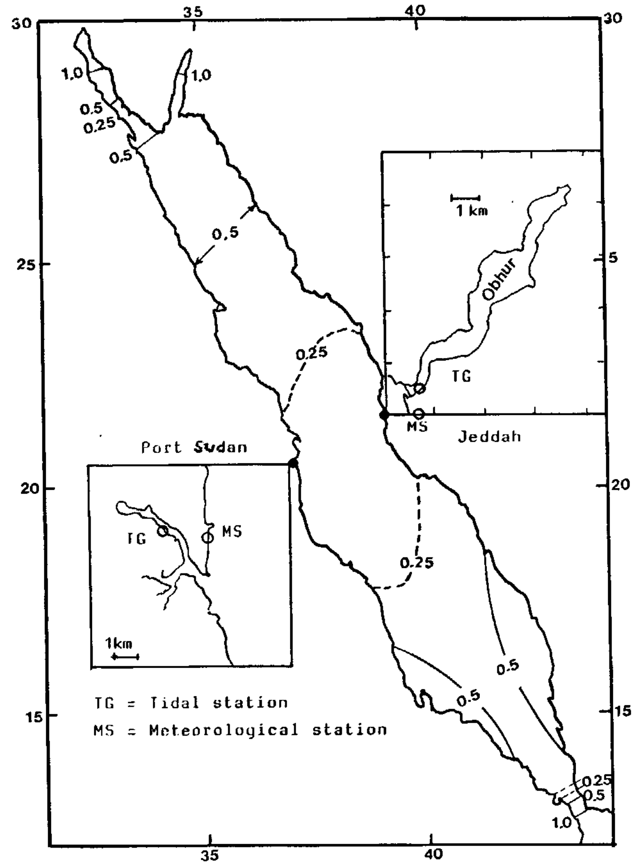

Figure 1

Map of the Red Sea showing station positions (tide co-range lines in m).

and the timing error is a few minutes per 45 days of chart length. Meteorological parameters were simultaneously obtained from Jeddah International Airport Station which is about 1 km from the coast. Therefore the recorded winds can easily be considered as representative of the wind field over the study area. At Port Sudan, hourly values of sea level and three-hourly values of atmospheric pressure, wind speed and direction for the same year were obtained from the Sudanese Survey and Meteorological Department.

Daily means of sea level were computed using Doodson's X_0 filter (Doodson and Warburg, 1941) centred at 12.00 noon. This filter rigorously eliminates diurnal, semi-diurnal and shorter tidal constituents to third decimal place. Daily means of atmospheric pressure were obtained by averaging the hourly and three-hourly values at Jeddah and Port Sudan respectively. 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 drag coefficient and W is 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 $10^{-3} C_D = 0.63 + 0.066 W_{10}$ $2.5 m.s^{-1} < W_{10} < 21 m.s^{-1}$ (Smith, 1980 ; Large and Pond, 1981). The hourly and the three-hourly wind stresses were then resolved into orthogonal cross- and long-shore components from which the daily means were obtained by simple averaging. Positive cross- and long-shore stresses are onshore and to the south respectively. Monthly means of the sea level were obtained by averaging the daily means.

Spectral analyses were performed with the aid of a computer program using the method of Fast Fourier Transform (FFT). Cross-spectral analyses were carried out by Fourier Transform of the cross-correlation function. Regression analyses were performed using the MINITAB package programs. Tidal analyses were carried out using TAPP a Tidal Analysis and Prediction Package to determine the principal components of the tide (Sherwin, 1987).

RESULTS AND DISCUSSION

Tides

Figure 2 shows the plots of the hourly raw sea levels and the tides at Jeddah. The spectrum of the tides averaged over 20 spectral estimates is shown in Figure 3. Three distinct peaks corresponding to third diurnal, semi-diurnal and diurnal components are clearly discernible in this figure. Although weak, the band of third diurnal tides stands out clearly above the background noise. The tides account for only 10% of the total variance of the sea level at Jeddah and tidal energy is mainly concentrated in the semi-diurnal band. However the larger non-tidal energy is confined at the low frequency band of the spectrum. Figure 3 clearly indicates the efficiency of the X_0 filter in isolating the tidal variations. The amplitudes and phases of the principle tidal constituents are given in Table I.

The combined non-linear effects due to the shallowness, bottom friction and the shape of the coastline appear to vary as the square or even a higher power of the tidal amplitudes (Pugh, 1987). This results in the presence of a number of higher harmonics, which constitute about 8% of the principle lunar semi-diurnal (M_2) at Jeddah. Theoretically the amplitude of the spring-neap modulation component MF is 17% of the lunar semi-diurnal (M_2). The present analysis shows that the amplitude of MF is about 22% of M_2 at Jeddah. In fact the non-linear shallow water effects induce a harmonic variation called MSF with a period of 14.77 days which is the same as the period of the spring-neap cycle. The extra 5% above the theoretical value could be due to the induced harmonic. However it is difficult to separate these two components. The amplitude of the lunar monthly component (MM) is 2.6 cm, which is four times greater than the theoretical value. The value of the form ratio $F = (K_1 + O_1)/(M_2 + S_2)$ is 0.58. Therefore the tide at Jeddah can be classified as a mixed type, mainly semi-diurnal with large inequalities in range and time between highs and lows.

The amplitudes of the tidal constituents at Port Sudan are also given in Table 1. The semi-diurnal components (M_2, S_2) are small here in comparison with those at Jeddah. This could be due to the proximity of Port Sudan to the amphidromic point where the amplitudes of the semi-diurnal components

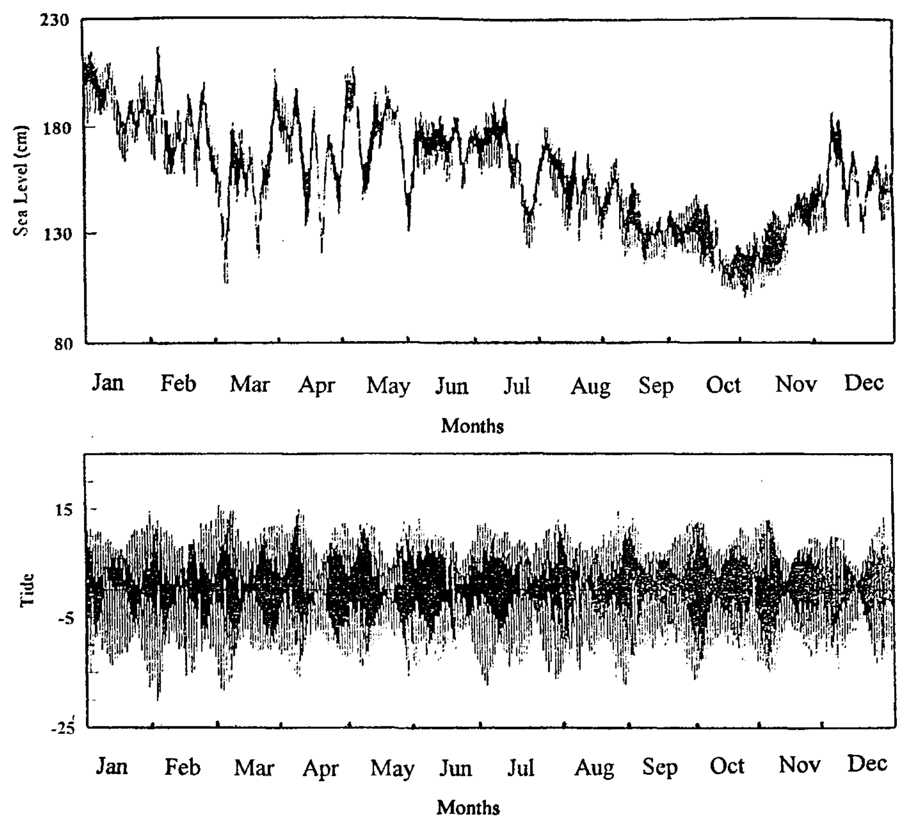

Figure 2

Plots of hourly sea levels and tides at Jeddah, 1991.

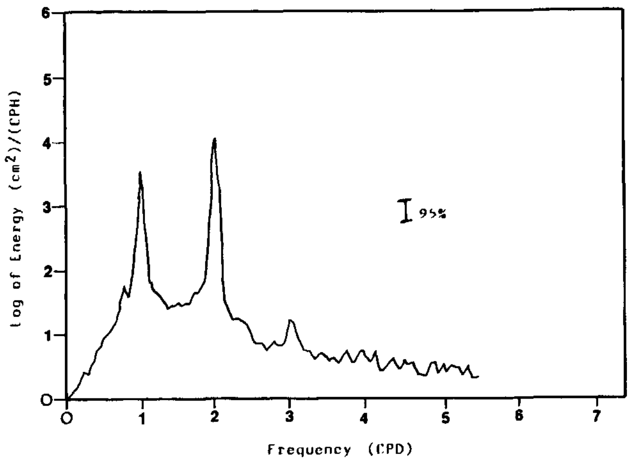

Figure 3

Spectrum of the observed tide at Jeddah.

Table 1

Amplitude and phase of the principal components of the tides at Jeddah and Port Sudan based on the data analysis for the year 1991.

Tidal Components	Amplitude (cm)		Phase in degrees relative to Greenwich Meridian	
	Jeddah	Port Sudan	Jeddah	Port Sudan
MM	2.6	8.7	7.0	355.8
MSF	1.6	6.1	122.5	124.4
Q1	0.4	0.3	145.4	105.7
O1	1.8	1.7	157.1	116.8
P1	1.3	1.1	139.3	144.0
K1	3.1	3.3	155.2	144.0
J1	0.2	0.4	145.2	104.0
2N2	0.7	0.1	349.8	351.8
MU2	0.2	0.2	353.9	22.0
N2	2.5	0.7	65.3	351.8
NU2	0.4	0.1	105.4	351.8
M2	6.8	1.0	97.4	91.8
L2	0.1	0.1	133.6	158.3
T2	0.2	0.0	114.8	219.2
S2	1.6	0.5	126.7	219.2
K2	0.9	0.1	126.9	219.2
2SM2	0.0	0.1	223.1	56.9
M3	0.2	0.1	310.3	197.1
MK3	0.1	0.1	345.5	245.1

are minimal. Once again the amplitudes of the fortnightly and monthly components are large . In fact they are much larger than the semi-diurnal ones. The form ratio (F) being 3.3 is indicative of diurnal type tide.

Seasonal and Mesoscale Changes

Daily means of the sea level at Jeddah and Port Sudan are shown in Figures 4 and 5. At both sites the highest sea levels have been observed in winter and the lowest in summer. Superimposed on the seasonal signal is a background of short-term fluctuations. The time scales of these fluctuations range from two days to less than a month, as they are all smoothed out in the monthly means. They are characterized by large amplitudes in winter and small in summer. Figure 6 displays the monthly means of the sea level at both stations and the evaporation rate. A careful scrutiny of this figure reveals the superposition of the smaller semi-annual cycle on the larger annual one in the sea-level changes. Both stations display a slight increase in the signal during April and a decrease in March. Recent study based on the analysis of a six-year record of the sea level at Port Sudan already revealed the presence of the semi-annual cycle (Sultan *et al.*, 1995). Therefore the seasonal variations can be approximated as the sum of an annual and semi-annual components (Thompson, 1980). The results of such representation show that the annual cycle accounts for about 44% of the total variance with amplitudes of 20.3 and 12.7 cm at Jeddah and Port Sudan respectively. These values are very large compared with the solar annual component which is 1% of M_2. The semi-annual components explain about 10% and 16% of the variance, with amplitudes of 9.6 and 7.7 cm respectively. These amplitudes are also much larger than the solar semi-annual component which is about 8% of M_2.

Spectra of the daily means of the sea level are shown in Figure 7. They display that the energy is mainly concentrated at the low frequency end of the spectrum and decreases gradually with increasing frequency. The higher energy at low frequency corresponds to long-period and seasonal changes. Superimposed on the general shape of the spectrum are a number of peaks that are of less significance. However the peak at about 0.04 cycles per day (about 24 days) which is just significant at 95% confidence limits seems to be a real one. This peak most probably corresponds to the short-term fluctuations observed in the daily means that have large amplitudes especially during winter (Figs. 4 and 5).

The cross-spectrum between the daily means of the sea levels at the two stations given in Figure 8 shows a significant correlation at the low-frequency band. The coherence squared between the seasonal cycles is 0.68. Variations of a 24-day period are also significantly correlated with coherence squared of 0.56. In contrast, there is no correlation between short-term fluctuations over the width of the Red Sea. Changes with period of 14 days and less seem to be site-specific and may be due to local effects.

Hydrostatic Response

The daily means of atmospheric pressure at both stations (Figs. 4 and 5) display a similar pattern with higher values in winter and lower in summer, on which are superimposed short-term fluctuations. The departure from isostatic response is obvious on the seasonal basis. This agrees with the previous findings. A casual look at Figures 4 and 5 suggests that the sea-level activity over a few days follows the hydrostatic hypothesis (-1 cm/mbar). However, neither cross-spectral analysis nor linear regression between the

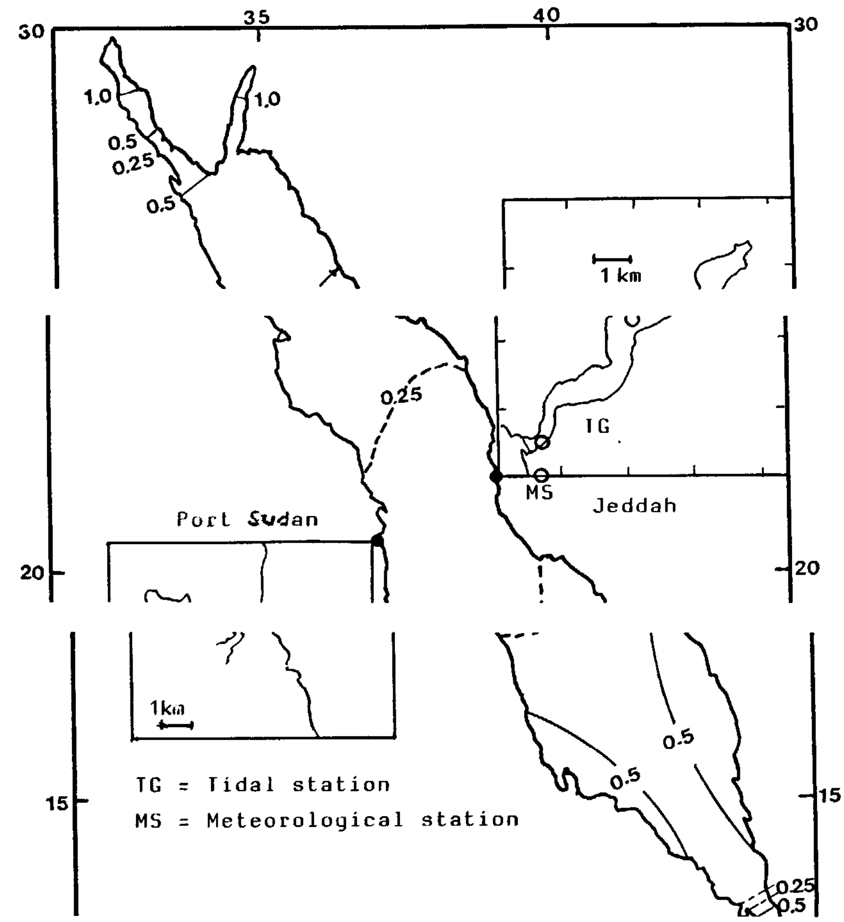

Figure 4

Daily means of sea level, atrmospheric pressure and long and cross-shore wind stresses at Jeddah, 1991.

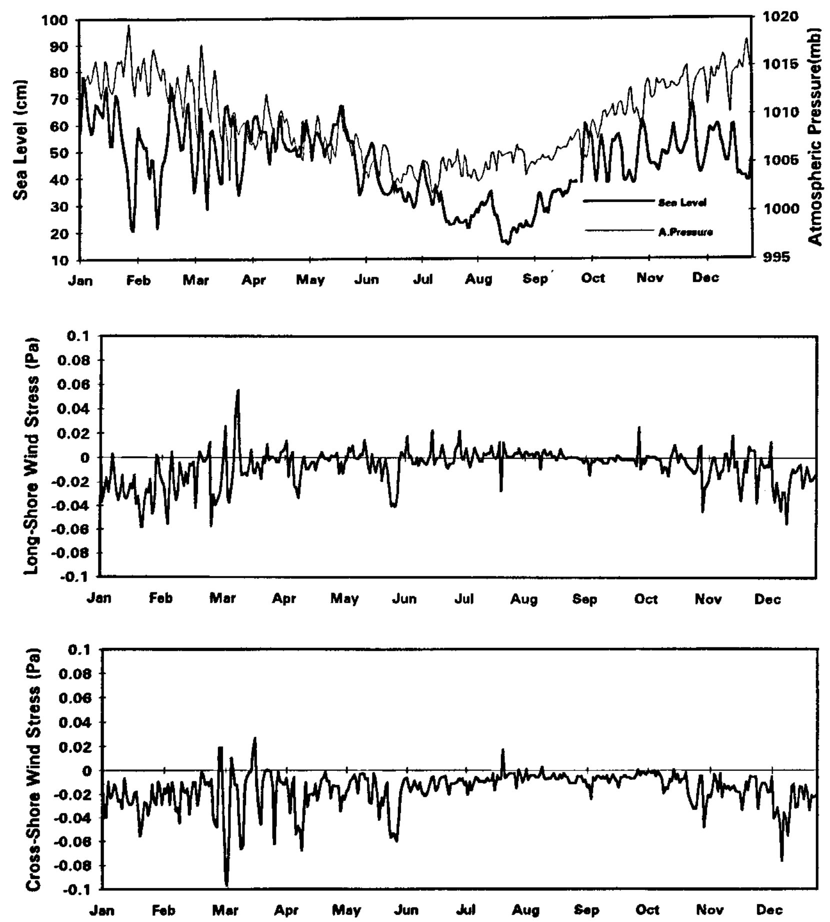

Figure 5

Daily means of sea level, atmospheric pressure and long and cross-shore wind stresses at Port Sudan, 1991.

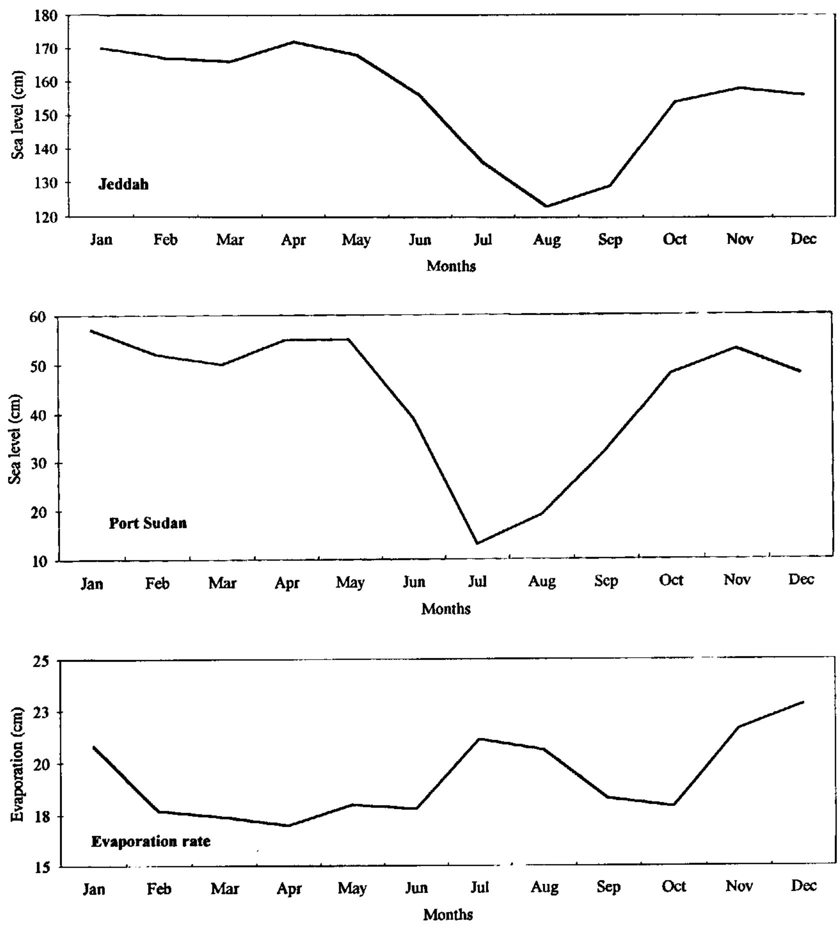

Figure 6

Monthly means of sea level at Jeddah and Port Sudan and evaporation rate in the central Red Sea.

sea level and atmospheric pressure justified the inverse barometer response. In order to see whether the geostrophic control imposes constriction to the water flow through the Strait the critical dimensionless parameter $\in$ is determined (Garrett and Toulany, 1982; Garrett, 1983; Toulany and Garrett, 1984). The key factor $\in$ is expressed in term of measured parameters as

$$\in = W f A / g H$$

where W is the frequency of the fluctuation, f is the Coriolis parameter, A is the area of the basin, g is the acceleration due to gravity and H is the mean depth of the strait. Whether or not the flow through the Strait is sufficient to permit an isostatic response of the basin to atmospheric pressure depends on the values of $\in$ (Garrett and Majaess, 1984). For very small values of $\in$ the flow is sufficient to allow an isostatic response. If the value is not very small, then there is insufficient time for the flow through the strait to equalize sea level changes in the basin. The surface area of the Red Sea and the average depth of the Strait of Bab-el-Mandab are 0.44 x 10^6 km^2 and 110 m respectively. Substituting these values in the above equation results in very small values of $\in$ (0.02 - 0.14) for the whole range of the observed fluctuations in the Red Sea. Additionally Lascartos and Gacic (1990) defined a time scale (T = Af/gH) as an estimate of the upper limit above which geostrophic control does not impose flow constriction. In that case, the flow is sufficient to permit an isostatic response of the basin. With the appropriate numerical values for the Red Sea, T is estimated to be ten 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 for the time scale of the observed variations. However the prevailing wind action results in a non isostatic response. On the other hand, regression analysis on the basis of individual months reveals that there is a limited hydrostatic response in the winter months but not during summer. The regression equation between the sea-level (SL) and atmospheric pressure (AP) for the month of January is SL = 6056 - 5.8*AP. The correlation coefficient is 0.53 and the percentage of the variance explained is found to be 28%. A plausible explanation for this behaviour of the sea level can be attributed to the dominance of the wind action and its reversal over the southern half of the Red Sea. It appears that the southeast Monsoon disrupts or even weakens the northwest winds. Consequently the wind effect on the sea level abates and therefore results in an inverse response to the atmospheric pressure. However such a conclusion requires further justification, perhaps from measurements at stations located in the southern half of the Red Sea. In addition, the response amplitude deviates significantly from the hydrostatic equilibrium (-1 cm/mbar). The above equation predicts the changes in the sea level within a factor of 6 of the hydrostatic response. It is also interesting to note that fluctuations with large amplitudes occur in winter and reduce to a minimum in summer.

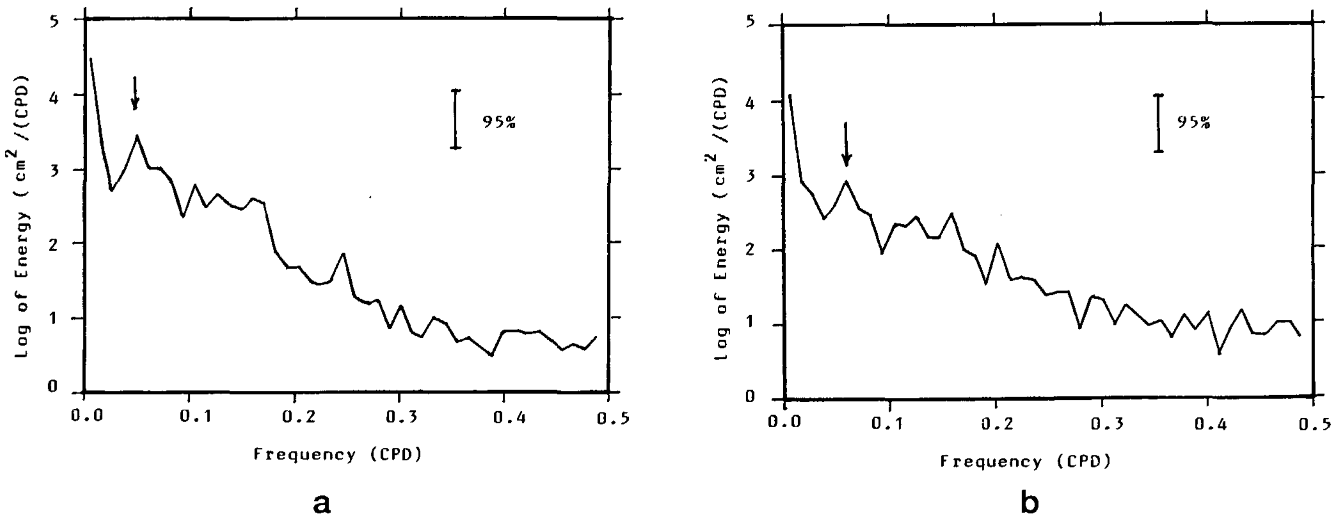

Figure 7

Spectra of the daily means of sea level (a) Jeddah (b) Port Sudan.

The seasonal signal is large and constitutes about 60% and 85% of the changes in the sea level and atmospheric pressure respectively. The presence of the seasonal signal could overshadow the relationship between the sea level and atmospheric pressure. Therefore it is worth examining the relationship between the residuals after filtering the seasonal signal. The regression line between the residuals of the sea level (SL) and atmospheric pressure (AP) is SL(Res) = 1.31-3.20*AP(Res). The correlation coefficient was 0.33 and the percentage of variance explained was 11%. It is clear that the sea-level response is again far from the hydrostatic one. At Port Sudan no correlation was found between residuals of the sea level and atmospheric pressure.

Although the above equations justify the theoretical relationship between the sea level and the atmospheric pressure in the sense that the coefficients have minus values, their predictions are far from the equilibrium hypothesis. In fact the sea level response to atmospheric pressure as an inverted barometer occurs only when the sea is fully adjusted to atmospheric pressure. However the exact inverted barometer response is seldom found in practice. One reason for this departure is the dynamic response of the shallow coastal waters to the movement of atmospheric pressure fields (Pugh, 1987). Another reason could be the correlation between atmospheric pressure and wind fields.

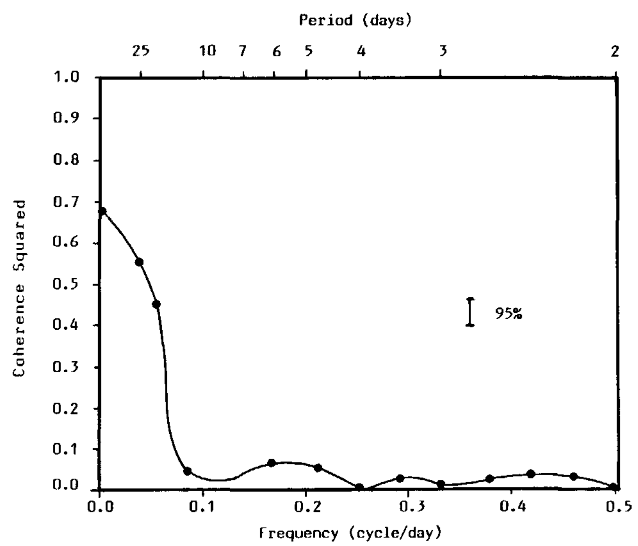

Figure 8

Spectrum of coherence squared between sea level changes at Jeddah and Port Sudan.

Wind stress

The long- and cross-shore components of wind stress at Jeddah and Port Sudan are shown in Figures 4 and 5 respectively. The negative values of the long-shore stress at two stations signify a northerly direction. The negative values of the cross-shore stress at Jeddah and Port Sudan are directed off-shore and on-shore respectively. At Jeddah the long-shore component of wind stress is significantly stronger than the cross-shore component, and is mainly directed to the south throughout the year. The cross-shore component is directed on-shore. At Port Sudan the cross-shore stress is mainly directed on-shore while the long-shore stress fluctuates between the northern and southern directions. In general the numerical values of the two components of wind stress are of the same order of magnitude.

Simple and multiple linear regression between daily means of the sea level including and excluding the seasonal signal and wind stress components did not show any significant correlation at both stations. However, cross-spectral analysis shows a strong correlation at specific time scales. The coherence squared between the sea level and wind stress components at Jeddah is shown in Figure 9. No significant correlation at any frequency exists between the sea level and cross-shore wind stress. On the other hand the low frequency variations are significantly correlated with the long-shore wind stress.

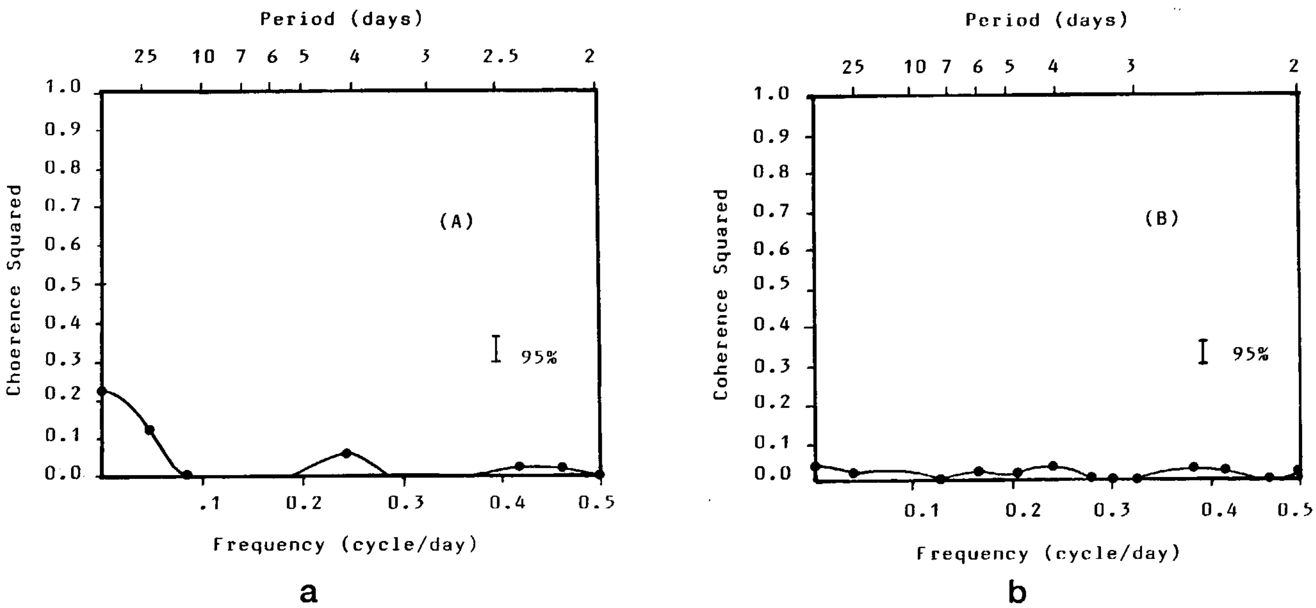

Figure 9

Coherence squared between (a) sea level and long-shore stress; (b) sea level and cross-shore stress at Jeddah.

The coherence squared between the sea level and wind stress components at Port Sudan is shown in Figure 10. Here the low frequency changes in the sea level are strongly correlated with both components of wind stress. Changes of about 3.5-day period are related to the long-shore stress while those of 2- and 6-day periods are associated with the cross-shore stress.

Evaporation

The rate of evaporation in the central Red Sea has been estimated recently to be about 2 m/year (Ahmad and Sultan, 1989). Figure 6 displays the monthly means of evaporation rate and the sea level at both stations. It is clear that low level in summer and high level in winter are both accompanied by high rate of evaporation. The evaporation rate has two maxima, during summer (July/August) and winter (December/January). Therefore it cannot be concluded that the high rate of evaporation in summer lowers the sea level as the high rate in winter is associated with high sea level. No doubt the evaporation rate influences the sea level changes. However its effect appears to be overshadowed by the winds during winter. The lowering of the sea level in summer is probably due to the combined effects of evaporation and wind. During the months of April and October the evaporation rate is low, while the sea level is high. These months correspond to the transition periods

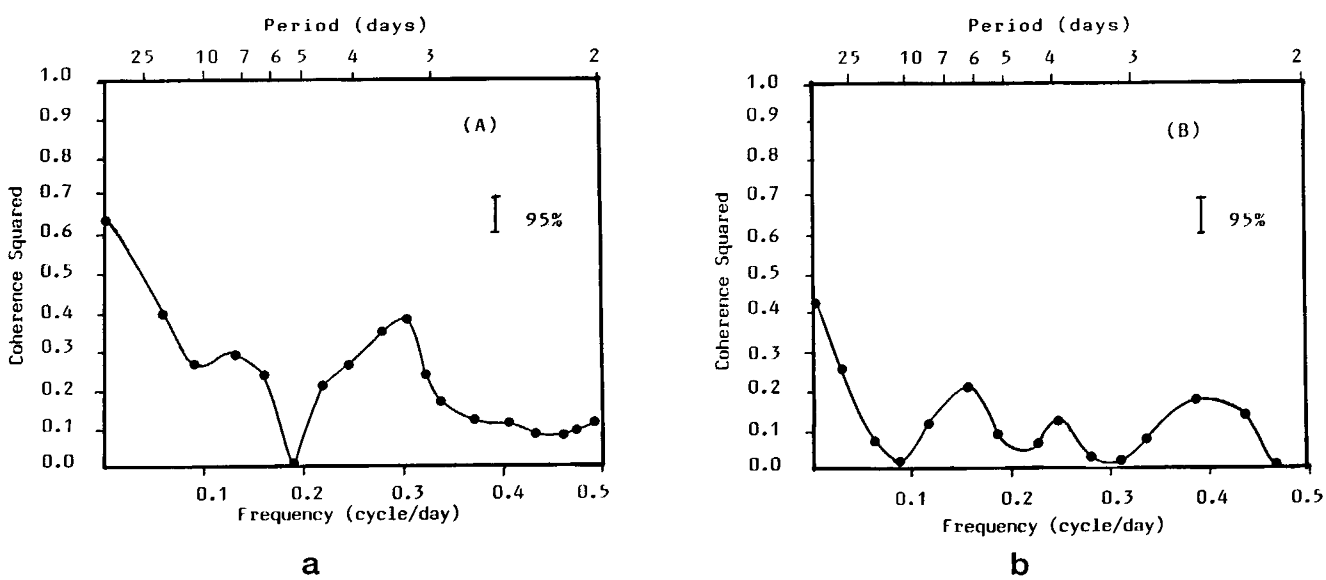

Figure 10

Coherence squared between (a) sea level and long-shore stress; (b) sea level and cross-shore stress at Port Sudan.

when the wind reverses over the southern Red Sea. It appears that during these times of the year the sea level is inversely related to the evaporation rate. During the remaining part of the year this relationship is completely masked by the effect of winds. Therefore it can be concluded that the semi-annual component in the sea level changes is induced by the effect of evaporation.

CONCLUSION

Spectral analysis of the daily means of the sea level at Jeddah and Port Sudan during 1991 revealed that a major part of the energy is concentrated at the low-frequency band. About 60% of the total variance is contained in the seasonal signal. The seasonal signal is approximated by the sum of an annual and semi-annual components. At Jeddah the annual cycle is strongly related to the long-shore stress, while at Port Sudan both components of wind stress contribute significantly to the annual variations. The amplitudes of the annual cycle are 20.3 and 12.7 cm respectively. A relationship seems to be established between low-frequency changes in the sea level and the stronger component of wind stress. The amplitudes of the semi-annual cycles are 9.6 and 7.7 cm respectively. This cycle seems to be strongly related to the evaporation rate, which has two maxima, one during summer and the other in winter. The wind effect masks the influence of evaporation on the sea level during most of the year except during the transition periods (April and October). During these periods the sea level varies inversely with evaporation. Low-frequency variations of the sea level are correlated at both stations, while high-frequency changes appear to be induced locally. On a seasonal basis the sea level response completely departs from the hydrostatic equilibrium. The analysis of daily residuals showed that there is a limited response of the sea level to the atmospheric pressure. Similarly linear regression gave an equation that justifies the relationship between sea level and atmospheric pressure in winter months but not during summer. However the response deviates significantly from the isostatic hypothesis.

Acknowledgments

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