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VARIATION OF SEA LEVEL AT PORT-SUDAN

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ABSTRACT

Continuous records over a 7-year period (1962-1968) from a tide gauge installed at Port-Sudan harbour were used to investigate monthly and annual sea level changes. The seasonal variations of sea level were examined in relation to the corresponding fluctuations of various hydrographic and meteorological factors. At Port-Sudan the monthly sea level is chiefly affected by changes in the wind field.

INTRODUCTION

The variation of sea level along the Red Sea coasts has not been studied in detail. This is attributed to the lack of systematic sea level records. The only published information is that for four coastal stations (Fig. 1), namely : Port-Suez, Port-Sudan, Perim and Aden (VERCELLI, 1931; PATTULLO *et al.*, 1955). However, both Port-Suez and Aden are located outside the northern and southern limits of the Red Sea (IHB, 1937); therefore, the only available data from the Red Sea proper are those published by VERCELLI (1931) for a 4-year period for Perim (1923-1926) and Port-Sudan (1925-1928).

By the end of 1961 the Survey Department of Sudan started to operate a tide gauge, which has been installed on the western side of Port-Sudan harbour (Fig. 2). This was the only tide gauge operating along the Sudanese coast (650 km) of the Red Sea.

The tidal records available for a 7-year period (1962-1968) are used to study monthly and annual sea level variations. The 7-years' average monthly sea levels, together with surface meteorological data from Port-Sudan coastal meteorological

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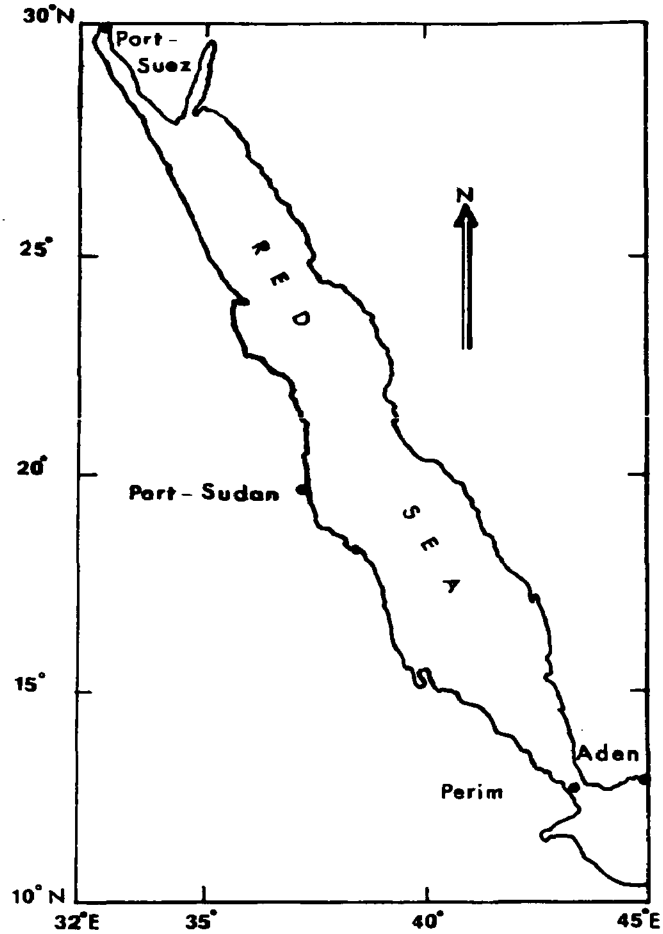

FIG. 1. — Tide gauge stations in the Red Sea.

station, and additional information from different sources, are considered in order to investigate the contribution of the various hydrographic and meteorological factors to seasonal level variations.

DATA SET

The continuous tidal records available for the 7-year period (1962-1968) were used to determine the daily mean sea level by arithmetical averaging of the hourly heights per day. This method eliminates, to a large extent, the regular astronomical tides and also reduces the transient variations (LISITZIN, 1974). From the daily means the monthly and annual means were both computed. The average monthly and annual sea levels for the whole period of observations (1962-1968) were calculated.

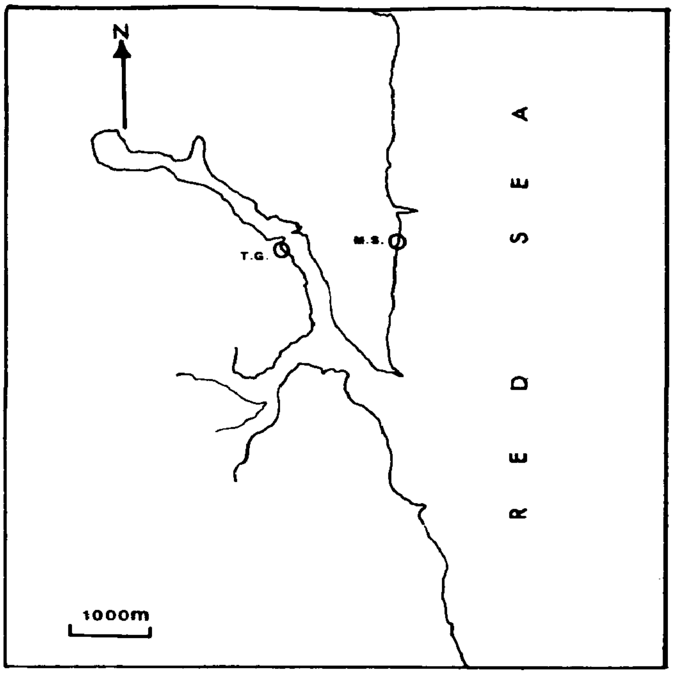

FIG. 2. — Location map of Port-Sudan tide gauge (T.G.) and coastal meteorological station (M.S.).

Average monthly amounts of precipitation, sea-level atmospheric pressure and wind velocity, which had been determined from unpublished surface meteorological data taken throughout the same period, were available from Port-Sudan coastal meteorological station (Fig. 2).

RESULTS AND ANALYSIS

a) Sea level variations

Monthly mean sea level heights throughout the period from 1962 to 1968 are represented in figure 3. This graph indicates that, quite independently of the small differences in phase and amplitude for the enumerated years, the seasonal variations are characterized by a fairly pronounced regularity. The general features reveal that the lowest monthly mean sea level heights occur mainly in August. However, the time of occurrence of the highest sea level heights is not as regular; it varies over a period covering four months (November to February).

The annual mean sea levels, as derived from the January-December monthly mean values for the 7 years investigated, are given in table 1. At Port-Sudan the 7-years' (1962-1968) average annual sea level is found to be 58.8 cm above the zero of the tide-gauge. From table 1, it is evident that the annual sea levels fluctuate about their average with a maximum deviation of merely ± 3.9 cm.

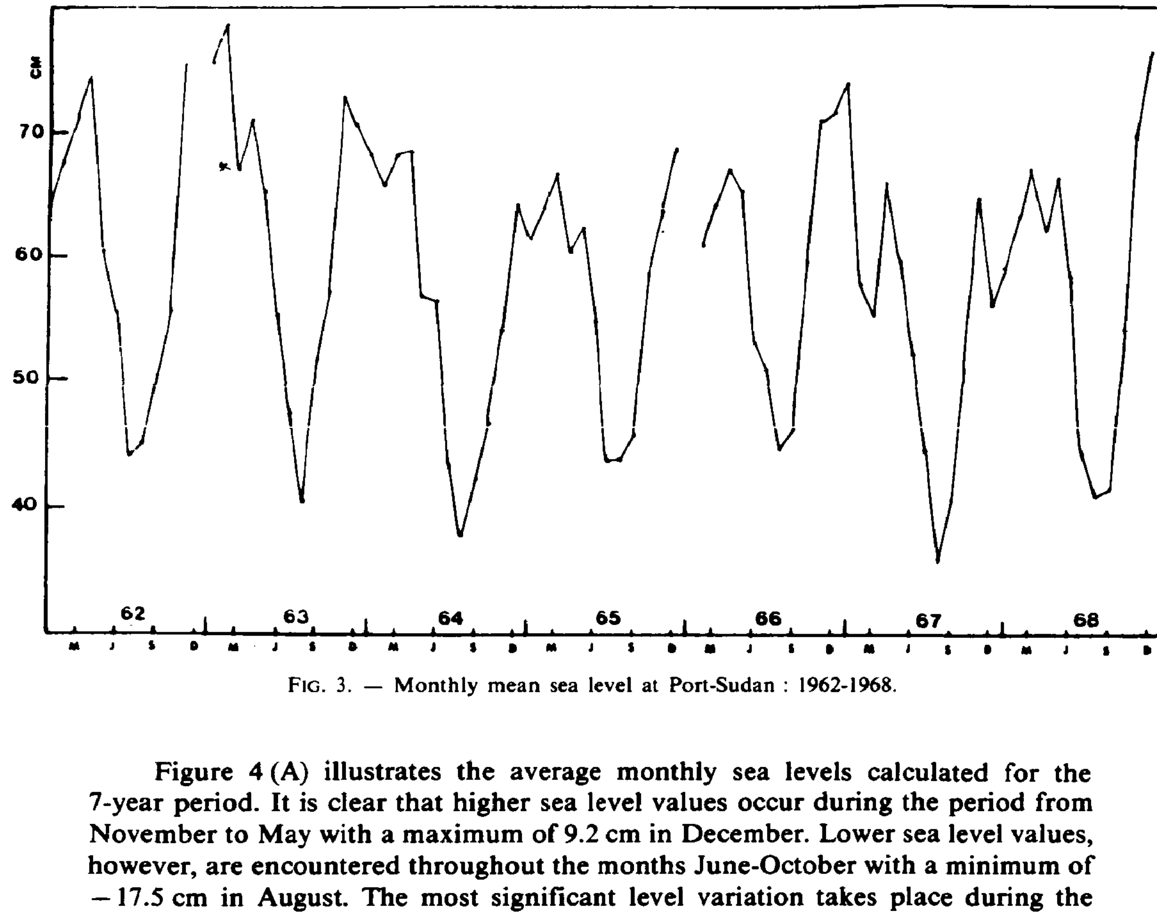

FIG. 3. — Monthly mean sea level at Port-Sudan : 1962-1968.

Figure 4 (A) illustrates the average monthly sea levels calculated for the 7-year period. It is clear that higher sea level values occur during the period from November to May with a maximum of 9.2 cm in December. Lower sea level values, however, are encountered throughout the months June-October with a minimum of − 17.5 cm in August. The most significant level variation takes place during the periods May-July and September-November, while for the rest of the year month-to-month variation in sea level is less pronounced.

Variability between the different sets of data available for Port-Sudan can be judged by comparing their respective average monthly and annual values. In figure 4, together with the graph (A) representing the 7-years' (1962-1968) average monthly sea level, is included the curve (B) illustrating the corresponding values calculated by VERCELLI (1931) for the 4-year period (1925-1928). Although both curves (Fig. 4 A and B) show approximately the same phase, however, there are differences in the magnitude of the average monthly sea levels. Generally, the numerical values of monthly sea levels (relative to the annual mean) obtained from

TABLE 1
The annual mean sea levels (cm)

YEAR	1962	1963	1964	1965	1966	1967	1968
Annual mean	60.3	62.7	56.0	57.8	59.6	54.9	58.8
Deviation from average	+1.5	+3.9	−2.8	−1.0	+0.8	−3.9	0

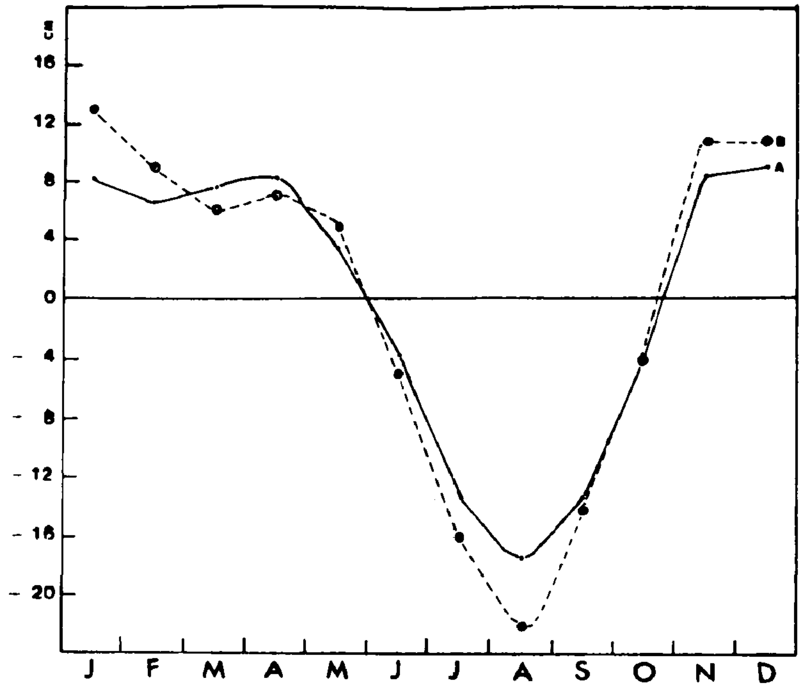

FIG. 4. — The seasonal fluctuation of monthly sea level (relative to the annual mean). Curve A : 1962-1968 average. Curve B : 1925-1928 average (after VERCELLI, 1931).

the recent information (1962-1968) are less, with the exception of those representing March and April, than the corresponding values given by VERCELLI (1931). Differences of more than 4.5 cm are encountered in January and August, i.e. the months of extreme values of sea level. This accounts for the difference in the annual amplitude between the two data sets. The 7-years' (1962-1968) average annual level, as previously stated, was found to be 58.8 cm above the zero of the Port-Sudan tide gauge. This value is 21.8 cm higher than the value listed by VERCELLI (1931).

Although it is difficult to comment on the reliability of the figures given by VERCELLI (1931) for Port-Sudan (MORCOS, 1970), the preceding comparison indicates that sea level oscillations, and consequently the conditions that control them, can vary from one set of data to another.

b) The effect of the hydrographic and meteorological factors

To understand why the above-mentioned variations occur, we must examine the parameters that control mean sea level. The seasonal oscillations of tide-free sea level depend upon the effects of : precipitation, runoff, evaporation, steric sea level, atmospheric pressure and winds.

Judging by records from coastal stations (ANONYMOUS, 1963) the longitudinal variation of the annual rainfall, which is mainly during the cold season of the year, reveals an increase from 20 mm at the northern part of the Red Sea to about

100 mm at its central zone. The annual rainfall attains a maximum value of 190 mm near Massawa and declines southward to reach 50 mm at the southern end of the Red Sea. From table 2 it is evident that the 7-years' average annual rainfall over Port-Sudan constitutes merely 98 mm, most of which (about 71 %) occurred in November and December. Since rainfall is extremely small, and no rivers discharge into the sea, the effects of these factors on level variations are negligible.

Evaporation from the Red Sea is exceedingly high as a result of the arid climate of the area. The recent estimates of the average annual evaporation from the Red Sea surface vary from 183 cm (PRIVETT, 1959) to 230 cm (YEGOROV, 1950). PRIVETT's (1959) calculations, which are believed to be an improvement over earlier ones (MORCOS, 1970) show that, for the whole Red Sea, evaporation is at a maximum in November, while the minimum is attained in May. The comparison between monthly sea level fluctuations at Port-Sudan and the seasonal variations in evaporation indicates that the latter cannot be the controlling factor.

Water density is one of the factors affecting the oscillations of sea level. Changes of the density within a water column, from which steric sea level can be determined, are dependent on thermal and haline variations within the column. PATZERT (1972) calculated the monthly mean geopotential anomaly relative to 200 m level (the depth at which all seasonal effects vanish) within a 1° area adjacent to Port-Sudan. Taking the monthly values of this anomaly to represent the seasonal steric changes, the results suggest that they are incongruous with the observed sea level fluctuations. Therefore, variations in steric sea level are not responsible for the high monthly sea levels that occur in winter and the low values taking place in summer.

The effect of atmospheric pressure on level variation at Port-Sudan can be demonstrated from the data given in table 2. It is evident that the sea level does not respond to the corresponding pressure changes as an inverted barometer. Accordingly, the observed variations in sea level are not a consequence of atmospheric pressure changes. Nevertheless, the variation in the pressure field affects the sea level not only hydrostatically, but also through the associated changes in the direction and speed of the winds. The latter is a conspicuous factor contributing to the fluctuations of sea level at the coasts.

In order to find out the effect of surface winds on level variations, the wind data from Port-Sudan coastal station were thoroughly examined. During the 7 years investigated it was quite clear that throughout the cold part of the year winds blow

TABLE 2
Average monthly sea level heights
and surface meteorological parameters at Port-Sudan
(1962-1968)

MONTH	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Sea level height (cm)	67.0	65.4	65.7	67.1	62.3	55.1	45.5	41.3	45.5	54.7	67.4	68.0
Precipitation (mm)	6	TR	TR	1	2	TR	8	3	TR	8	50	20
Atmospheric pressure (mb)	1013.6	1012.5	1010.7	1008.4	1007.0	1004.8	1003.4	1003.7	1006.0	1009.5	1011.5	1013.2
Wind speed (cm/s)	49.2	39.7	45.3	42.5	36.3	38.6	34.1	36.3	28.5	35.2	43.6	55.3

mainly (with a percentage frequency of more than 75 %) from directions between N and NE, with relatively high speeds. During the hot season, however, winds from all directions occur with reduced speeds and calm conditions are more frequent. Table 2 indicates that the average monthly wind speeds, calculated for the 7-year period, are highest from November to April with a maximum of 55.3 cm/s in December. From May to October the winds are weakened, attaining in September a minimum value of 28.5 cm/s which is about half the magnitude of wind speed encountered in December.

A closer examination of the data given in table 2 reveals that a certain relationship may be discerned between monthly sea level heights and wind speeds. The correlation coefficient is equal to 0.76, indicating the close connection between seasonal variations in sea level and month-to-month changes in wind regime over Port-Sudan.

DISCUSSION AND CONCLUSIONS

From the analysis of the various meteorological and hydrographic factors affecting sea level changes at Port-Sudan discussed so far, it could be concluded that the steady and relatively strong winds blowing from the N-NE quarter throughout the winter are mostly favourable for higher sea levels, while the light and variable winds taking place during summer are responsible for the observed lower sea level heights.

Sea level information obtainable from the previously mentioned four coastal tide-gauge stations was analyzed by PATZERT (1972) in his investigation of the general circulation system of the Red Sea. He concluded that sea level variations in the Gulf of Suez (Port-Suez) and the central Red Sea (Port-Sudan) are related to the complete reversal in wind direction over the southern part of the sea. The explanation presented by PATZERT (1972) will be recapitulated briefly below.

From October to May the strong SSE winds present in the south cause a large surface inflow and pile-up of surface water in the zone of converging winds (central part of the Red Sea). In the north, however, the surface transport is to the NNW against the wind. Consequently, monthly mean sea levels are highest at this time in the central and northern parts of the Red Sea. From June to September, the NNW winds blow over the entire length of the Red Sea and the surface flow is directed towards the Gulf of Aden, where there is a negative set up as a result of the SW monsoon. The observed summer drop in sea level at Port-Sudan and Port-Suez is, according to PATZERT (1972), a regional response to dropping sea level in the south and the resulting reversal in circulation between Port-Suez and Aden.

The preceding discussions indicate that the sea level at Port-Sudan may be influenced by the general circulation system of the Red Sea, in addition to the effect brought by the wind conditions characteristic for Port-Sudan. Nevertheless, it seems to PATZERT (1972) that the level variations at Port-Sudan are controlled more by the general circulation regime of the Red Sea rather than by any local effect.

It is relevant to note that the circulation scheme of the Red Sea outlined above was drawn on the basis of data representing only the mean atmospheric and hydrographic conditions along the central axis of the sea, regardless of the lateral variations. Actually, *not until the temporal and spatial* variability of water circulation in the different parts of the Red Sea and along its coasts is known in detail will it be possible to evaluate its contribution to sea level changes.

In our opinion, the question to be answered is not as to which of these factors, the local or the regional, is responsible for the level variations at Port-Sudan, but, rather, what combination of them causes the observed changes during the different months. Due to the lack of extensive data indispensable for this purpose, this question remains open for future investigations.

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