SEASONAL FLUCTUATIONS OF MONTHLY MEAN SEA LEVEL ON THE COAST OF THE EASTERN MEDITERRANEAN

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ABSTRACT

Ten-year averages for monthly mean sea levels have been calculated for Ashdod and Haïfa. Their graph shows a major minimum in April, a major maximum in July/August, a minor minimum in October and a minor maximum in December, the range between extremes being 21 cm.

The main causes for these fluctuations are to be found in barometric pressure variations in the Eastern Mediterranean, in thermal expansion of the sea, and in storm surges. The curve resulting from a quantitative evaluation of these effects is similar in rhythm and magnitude to the graph of the observed values.

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The variations in sea level are readily observed and are attributable primarily to tides, although there are some fluctuations of the mean sea level not due to the effects of the tide.

PATULLO, MUNK *et al.* (1955) pointed out that seasonal oscillations in sea level are a world-wide phenomenon. They considered the steric component (this can be defined as the part of the oscillations which is derived from variations in the specific volume) of the oscillations agrees well with the recorded departures from the annual mean, while atmospheric pressure effects and long-period astronomic tides only accounted for a small part of the recorded fluctuations.

DIETRICH (1963) noted that the mean sea level had little in common with the astronomical tide, and that the prime causes of seasonal fluctuations of sea level are seasonal variations in atmospheric pressure, stratification of the ocean's water density, predominant winds, and discharges from the continents.

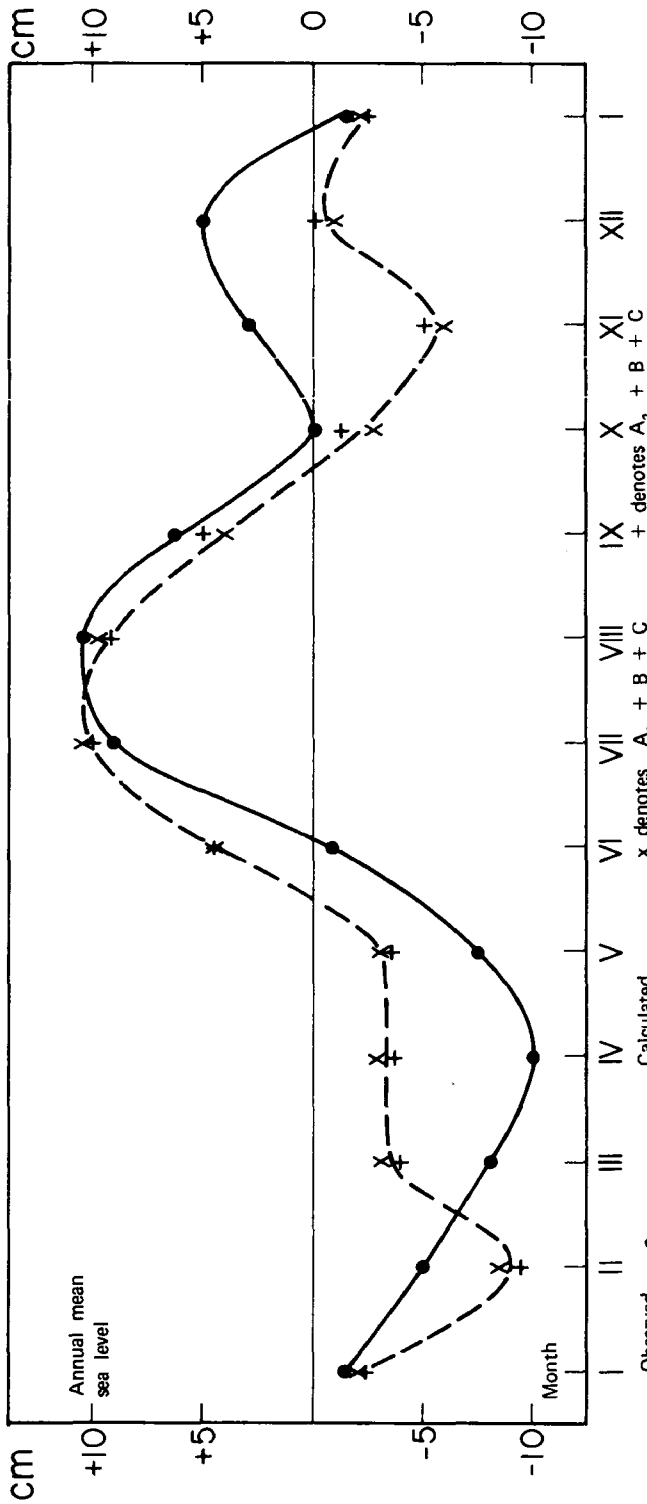

Fig. 1. — The seasonal fluctuations of the Mediterranean Sea Level at Ashdod.

LISITZIN (1964) quoted also the Coriolis force exerted on the currents and the seasonal oscillations in the transport of water masses as two additional effects contributing to variations in mean sea level.

CREPON (1965) analysed sea levels in the western Mediterranean and in the Straits of Gibraltar and calculated that there exists a close inverse correspondence between the variations in mean sea level and the atmospheric pressure.

For Israel's Mediterranean coast, the average monthly mean sea levels were calculated for Ashdod and for Haïfa, using tidal data compiled by the Coastal Study Division of the Ports' Authority.

The fluctuations of mean sea level are shown in figure 1 and in table 1. It is seen that the curves have two maxima and two minima : the major minimum occurs in April and is followed by the major maximum in July/August. The minor minimum occurs in October and is followed by the minor maximum in December. The maximum range between extremes is about 21 cm for the average monthly mean sea level, and about 26 cm for the average of the lowest monthly sea levels.

Since a similar fluctuation is found at Port Said when using the data of MORCOS (1960), the mean between the monthly sea levels at Ashdod and Port Said is deemed to reflect the general fluctuation of mean sea level along the coast of this south-eastern corner of the Mediterranean Sea.

Three major effects are considered to produce these seasonal fluctuations in sea level in this part of the Mediterranean : these are variations in barometric pressure, thermal expansion of the sea, and the piling of waters onshore as a result of storm surges that occur mainly in winter.

We have attempted to make a quantitative evaluation of the contribution of each of these three effects to the monthly variations in sea level.

1. *The barometric pressure difference* if acting alone on communicating seas might be expected to produce a difference of 1 cm per millibar in the sea level. Such an equivalence has been confirmed for the western Mediterranean by the results obtained by CREPON (1965).

On the basis of ten-year averages (World Weather Records) (1951 - 1960), mean monthly barometric pressures have been calculated for Haifa and Port Said — representing conditions on the Eastern Mediterranean coast — and for the Central Mediterranean by averaging barometric pressures at Rome, Taranto, Cagliari and Malta. The differences in barometric pressures between the Central and the Eastern Mediterranean are shown in table 2.

During winter the barometric pressure in the Central Mediterranean is lower than it is in the Eastern basin, and this would be compatible with a lower sea level in the Eastern Mediterranean. During summer the barometric pressure in the Central Mediterranean is higher than that of the Eastern basin, and this would be in line with a higher sea level in the Eastern Mediterranean.

In this paper we have tentatively assumed the variation in mean sea level in the Eastern Mediterranean to be due to this difference of barometric pressure between the Central and the Eastern Mediterranean. It is also

TABLE 1

Mean sea levels (MSL)

	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Annual Mean
Monthly MSL (in cm)													
Ashdod(1960-1969)	+ 7.9	+ 4.3	+ 1.2	− 0.8	+ 1.8	+ 8.5	+ 18.5	+ 19.9	+ 15.7	+ 9.3	+ 12.4	+ 14.5	+ 9.4
Haifa (1965-1969)	+ 10.0	+ 0.6	− 4.4	− 1.1	+ 1.5	+ 9.0	+ 16.8	+ 17.1	+ 17.1	+ 8.8	+ 12.0	+ 14.8	+ 8.5
Monthly MSL related to annual MSL													
Ashdod	− 1.5	− 5.1	− 8.2	− 10.2	− 7.6	− 0.9	+ 9.1	+ 10.5	+ 6.3	− 0.1	+ 3.0	+ 5.1	
Port Said	− 3.3	− 5.3	− 9.4	− 9.0	− 6.7	− 1.0	+ 6.9	+ 10.0	+ 7.4	+ 3.9	+ 4.0	+ 3.0	
Monthly MSL for the Eastern Mediterranean related to annual MSL	− 2.4	− 5.2	− 8.8	− 9.6	− 7.2	− 0.9	+ 7.9	+ 10.2	+ 6.8	+ 1.9	+ 3.5	+ 4.0	

TABLE 2

Mean barometric pressures

	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Annual Mean
Monthly barometric pressure at MSL, Eastern Med. coast (Mean for Haifa + Port Said values in mb above 1000 mb)	17.4	17.0	14.9	13.7	12.8	10.5	7.4	7.7	11.6	14.9	16.3	17.5	13.5
Seasonal variation in pressure in East. Med. related to the annual mean	+ 3.9	+ 3.5	+ 1.4	+ 0.2	− 0.7	− 3.0	− 6.1	− 5.8	− 1.9	+ 1.4	+ 2.8	+ 4.0	
Central Mediterranean (average for Rome, Taranto, Cagliari, Malta)	14.4	13.9	14.0	13.9	14.3	14.9	14.2	14.1	15.6	16.1	15.4	15.7	14.7
Difference of pressure : Central minus Eastern Med.	− 3.0	− 3.1	− 0.9	+ 0.2	+ 1.5	+ 4.4	+ 6.8	+ 6.4	+ 4.0	+ 1.2	− 0.9	− 1.8	+ 1.2

TABLE 3

Sea temperatures (in degrees Celsius)

	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Annual Mean
Monthly mean sea temperatures at Ashdod (1960-1969)	16.6	15.7	16.7	19.1	21.8	25.3	27.9	28.6	27.3	25.0	22.1	18.7	22.1
Difference : monthly minus annual mean	− 5.5	− 6.4	− 5.4	− 3.0	− 0.3	+ 3.2	+ 5.8	+ 6.5	+ 5.2	+ 2.9	0	− 3.4	

TABLE 4

Wave heights (in metres)

	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Annual Mean
Monthly means of significant wave heights at Ashdod (1960-1969)	3.4	2.3	2.7	2.1	1.4	1.7	1.8	1.6	1.5	1.3	1.5	3.2	
Excess of monthly means over lowest wave heights (October)	2.1	1.0	1.4	0.8	0.1	0.4	0.5	0.3	0.2	0	0.2	1.9	

TABLE 5

Variations in sea level due to barometric pressure, sea temperature, and storm surges

	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
A. Barometric pressure difference (Increase 1 mb → Decrease 1 cm)												
A_1. Seasonal variation in the Eastern Mediterranean	− 3.9	− 3.5	− 1.4	− 0.2	+ 0.7	+ 3.0	+ 6.1	+ 5.8	+ 1.9	− 1.4	− 2.8	− 4.0
A_2. Pressure difference between Eastern and Central Mediterranean	− 3.0	− 3.1	− 0.9	+ 0.2	+ 1.5	+ 4.4	+ 6.8	+ 6.4	+ 4.0	+ 1.2	− 0.9	− 1.8
B. Sea temperature difference : monthly minus annual mean (Increase 1°C → Decrease 1 cm)	− 5.5	− 6.4	− 5.4	− 3.0	− 0.3	+ 3.2	+ 5.8	+ 6.5	+ 5.2	+ 2.9	0	− 3.4
C. Storm surges 1 m excess wave heights (corresponding to a rise in sea level of + 5.5 cm)	+ 11.5	+ 5.5	+ 7.7	+ 4.5	+ 0.6	+ 2.2	+ 2.5	+ 1.6	+ 1.1	0	+ 1.1	+ 10.5
D. The calculated resultant effect $A_1 + B + C$	+ 2.1	− 4.4	+ 0.9	+ 1.2	+ 1.0	+ 8.4	+ 14.6	+ 13.9	+ 8.2	+ 1.5	− 1.7	+ 3.0
The relative monthly effect (related to the average annual effect of + 4.1 cm)	− 2.0	− 8.5	− 3.2	− 2.9	− 3.1	+ 4.3	+ 10.5	+ 9.8	+ 4.1	− 2.6	− 5.8	− 0.9
Alternative composition of effects $A_2 + B + C$	+ 3.0	− 4.0	+ 1.4	+ 1.6	+ 1.8	+ 9.8	+ 15.3	+ 14.5	+ 10.3	+ 4.1	+ 0.4	+ 5.2
The relative monthly effect (related to the annual average effect + 5.3 cm)	− 2.3	− 9.3	− 3.9	− 3.7	− 3.5	+ 4.5	+ 10.0	+ 9.2	+ 5.0	− 1.2	− 4.9	− 0.1

pointed out that the excess of monthly barometric pressure in the Eastern Mediterranean over its annual mean (table 2) follows closely the differences in barometric pressure between the Central and the Eastern Mediterranean. Thus either of these differences could be used to calculate the variation in mean sea level for the Eastern Mediterranean throughout the year.

2. *The thermal expansion of the sea* was calculated by adopting a 1 cm variation in sea level per 1° Celsius.

This assumption is based on an average variation in density of about 2.35×10^{-4} gr/cm^3 per 1° Celsius.

The measurements of sea temperature carried out by OREN (1966) and by STEYART (1966) enable us to generalize by saying that in the Eastern Mediterranean at a depth of about 85 m the variation in temperature becomes slow, and is negligible in relation to surface temperatures. The total volumetric increase can be linearly approximated by $1/2 \times 85 \times$ T $\times$ thermal expansion coefficient 2.35×10^{-4}, thus resulting in approximately 1 cm per 1° Celsius.

The ten-year averages of monthly sea temperatures were calculated for coastal waters at Ashdod, using data supplied by the Coast Study Division for the years 1960-1969. The resulting variations in sea temperatures are indicated in table 3.

3. *Storm surges,* or wind " set-up ", raise the sea level on a coast, and although the period of each storm's piling up of water is limited in duration intermittent variations in the daily mean sea level lead to a cumulative rise in the monthly sea level.

In spite of the considerable research already done, WIEGEL (1964) concluded that it is as yet very difficult to arrive at quantitative solutions for storm surges under natural coastal conditions (i.e. the orientation of the coast with respect to wind direction, the water depth, etc.). Storm surges at Ashdod have been studied, and a correlation with storm wave heights has been found (STRIEM, to be published), indicating that during large storms the sea level rises by about 5.5 cm with each increase of 1 m in wave height (above a threshold value of about 1.25 m).

Accordingly, the monthly averages for significant wave heights were calculated from wave data for the period 1965 - 1969 published by the Coast Study Division, and by applying the above mentioned relation it was possible to evaluate the expected monthly rise in sea level due to storm surges.

The calculated variations in monthly sea levels are indicated in table 5 and in the figure.

A comparison of the calculated with the observed monthly mean sea levels indicates that there is a fair measure of agreement as regards rhythm and magnitude.

It is realised that some of the calculations have been based on assumptions and values which are merely approximations, especially those concerning storm surges. However, the basic agreement between the calculated and the observed curves seems to justify our primary purpose which was to evaluate quantitatively the main factors contributing to the seasonal fluctuation in mean sea level in the Eastern Mediterranean.

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REFERENCES

[1] Coast Study Division, Ports' Authority, Israel : " Oceanographical Observations "; 1958 - 1965, 1965, 1966, 1967, 1968, 1969.

[2] CREPON, M. (1965) : L'influence de la pression atmosphérique sur le niveau moyen de la Méditerranée Occidentale et sur le flux à travers le détroit de Gibraltar. *Cahiers Océanogr.*, **XII** (1), pp. 15-32.

[3] LISITZIN, E. (1964) : La pression atmosphérique comme cause primaire des processus dynamiques dans les océans. *Cahiers Océanogr.*, **XVI** (1), pp. 17-22.

[4] OREN, O. H. (1966) : Résultats des observations hydrographiques de la croisière " Chypre 02 " en Méditerranée Orientale, *Cahiers Océanogr.*, **XVIII**, Suppl. 1.

[5] PATULLO, J., MUNK, W., REVELLE, R., STRONG, E. (1955) : The seasonal oscillation in sea level, *J. Marine Research*, **14** (1), pp. 88-149.

[6] STEYART, M. (1966) : Résultats des observations hydrologiques effectuées à bord du navire belge *Eupen*, Mai-Juin 1961. *Cahiers Océanogr.*, **XVIII**, Suppl. 1.

[7] WIEGEL, R. L. (1964) : Oceanographical Engineering, Prentice-Hall, N. Y., 523 p.