STORM SURGES AND UNUSUAL SEA LEVELS ON ISRAEL'S MEDITERRANEAN COAST

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ABSTRACT

Storm surges occurring at Ashdod were investigated. It was found that the daily mean rise of the sea level due to storms may be considered as linearly related to the daily mean of wave heights or to wind velocities near the shore. The rise is about 6 cm per metre of increase in wave height, and about 7 cm for each 10 km/h increase in wind velocity. Most large storms raise the sea level by about 40-50 cm above the previously prevailing level, but in a few instances a short-term upsurge was found superimposed on the gradual daily rise of the storm surge. This additional rise of level is tentatively ascribed to a local storm effect, and might raise the sea level by a further 30-40 cm.

Unusually high and low sea levels were also investigated. The basic mean sea level is considered as affected by the daily inequality of the tides, the range of the spring tides, the seasonal and the annual fluctuations of the sea level, apart from storm effects. Evaluating these contributions it was found that if each factor would act at its maximum the hourly sea level might rise or drop by 1/4 m above or below the extremes (+ 100 cm, — 51 cm relative to the datum level) encountered in the 6 year period investigated.

INTRODUCTION

This investigation deals with storm surges and other conspicuous changes of the sea level on Israel's Mediterranean coast.

Storm surges have long been known to be associated with strong on-shore winds and large changes in air pressure (ROSSITER, 1963). Many theoretical analyses have been attempted, but WIEGEL (1964) concluded that it is very difficult to arrive at solutions applicable to natural conditions, because storms move, winds are not steady, the water depth is not constant and the coastline is not regular.

Because of the effect of storm surges on coastal installations, local studies were made, such as those of SCHALKWIJK (1947) for the Dutch coast, CONNER, KRAFT and HARRIS (1957) for the American Atlantic seaboard ROSSITER (1959) for the British east coast and TOMCZAK (1960) for the north-east German coast. The resulting empirical formulae usually correlate the observed surge heights linearly with meteorological variables.

This investigation is primarily an attempt to correlate local storm-occasioned rises of the sea level with suitable phenomena at the shore, which would serve as indicators of the storm's strength. However it also seemed appropriate to analyse the other factors which might cause unusual water levels, and to evaluate "aqua alta" conditions (GOLDMANN and TOMASIN, 1971) for our coast.

RESULTS

a) General hydrographic information

Changes of sea level were studied at Ashdod, a recently constructed port on a sandy stretch of the eastern Mediterranean coast. The straight coastline has a NNE alignment, and is approximately perpendicular to the major fetch directions :

Direction	W	W.WNW	WNW	NW	NNW
length of fetch (in km)	900	> 3 000	800	600	300

The sea is fairly shallow as shown by data taken from EMERY and BENTOR (1960) :

Distance from shore (in km)	2	4	8	17	23	28	54
Depth (in m)	24	35	41	100	200	400	1 000

b) The tides (*)

The sea level is recorded at Ashdod by an automatic mareograph and tables of hourly readings were published by the Coast Study Division of the Ports Authority (1965-1970).

(*) Following ROSSITER (1963), the use of the term tides is here restricted to phenomena attributed, directly or indirectly, to the gravitational influence of the sun and the moon.

Analysing the data it is found that the tide at Ashdod is semidiurnal and its various ranges (from peak to trough) occur as follows :

TABLE 1

The frequency distribution of tidal ranges, at Ashdod

Range (in cm)	0–9	10–19	20–29	30–39	40–49	> 50
Occurrence (in %)	7.5	23.6	28.8	32.3	7.5	0.3

Analysing the ranges of spring-tides for 6 years (1965-1970) it was found that the largest spring-tides recorded reached 52 cm (at the vernal equinox), the average range was calculated as 42.8 cm and the smallest range found was 35 cm. The range of spring-tides has a seasonal variation as shown in table 2 and in figure 1.

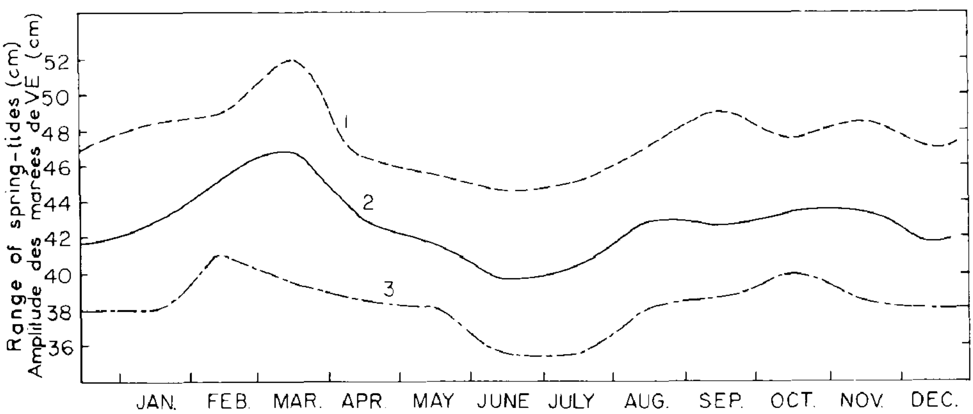

FIG. 1. — The seasonal fluctuation in the range of spring-tides at Ashdod.
Curve 1 : the mean of the two largest ranges.
Curve 2 : the mean monthly range.
Curve 3 : the mean of the two lowest ranges.

TABLE 2

The seasonal fluctuation in the range of spring-tides

Month	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
The mean monthly range (in cm)	42.7	45.2	46.9	43.0	41.6	39.6	40.4	42.8	42.6	43.3	43.4	41.7

c) The mean sea level

LISITZIN (1963) pointed out that the mean sea level is affected by tides and other periodic factors, by meteorological and hydrographic influences and, to a lesser degree, by eustatic factors.

At Ashdod the *daily* mean sea level changes by a few centimetres, mainly due to the diurnal inequality and asymmetry of the tidal rise and fall.

Apart from storm surges, the *monthly* mean sea level is chiefly affected by changes in atmospheric pressure and thermal expansion or contraction of the sea. At Ashdod the seasonal fluctuation of the mean sea level was found (STRIEM and ROSENAN, 1972) as follows:

TABLE 3

The seasonal fluctuation of the monthly sea level (relative to the annual mean sea level), in cm

Month	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
The relative monthly mean sea level	− 2.4	− 5.2	− 8.8	− 9.6	− 7.2	− 0.9	+ 7.9	+ 10.2	+ 6.8	+ 1.9	+ 3.5	+ 4.0

The *annual* mean sea levels (derived from the January-December monthly mean levels) fluctuate about their long-term average. For Ashdod the 13-year (1958-1970) average annual level was found to be + 8.0 cm, relative to the Israel Land Survey datum. The annual sea levels were below their average during 1958-1959, rose above it for 8 years (1960-1967) and recently (1968-1970) fell again below the average. The annual mean sea levels, and their deviation from the average are shown in table 4.

TABLE 4

The annual mean sea levels (cm)

YEAR	1958	59	60	61	62	63	64	65	66	67	68	69	70
annual mean	+ 6.5	+ 3.9	+ 13.2	+ 9.5	+ 9.0	+ 15.0	+ 9.7	+ 11.6	+ 10.7	+ 9.0	+ 2.8	+ 2.9	+ 0.8
deviation from average	− 1.5	− 4.1	+ 5.2	+ 1.5	+ 1.0	+ 7.0	+ 1.7	+ 3.6	+ 2.7	+ 1.0	− 5.2	− 5.1	− 7.2

d) Storm induced changes in the sea level

Unusual rises of the daily mean sea level were investigated for a 6-year period (1965-1970). Storm-occasioned rises were deemed to have occurred at Ashdod when the daily mean sea level rose by more than 20 cm during a few days and when this rise was accompanied by storm indicators, such as high winds or waves.

Figure 2 illustrates the behaviour of the hourly sea level during a period which included several days with storm conditions. The normal rise and fall due to the tides is seen to be superimposed on a slow rise, lasting

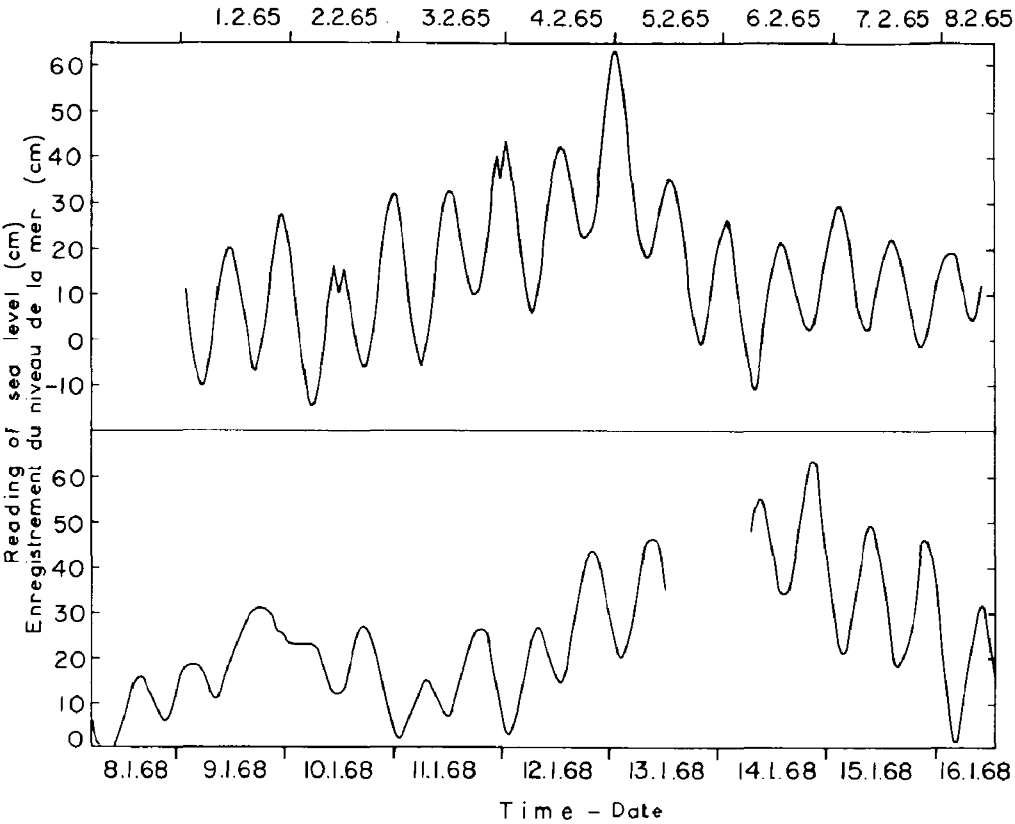

FIG. 2. — Illustrating hourly sea levels during storms.

for several days, which lifts the daily level by about 40 cm above its previous average.

By denoting the daily mean sea level two or three days before the peak of the rise as the zero level, the resultant (relative) rise was correlated with various variables, such as atmospheric pressure, wind velocities, wave heights and periods. To avoid error, storm surges occurring during spring tides were excluded.

Figure 3 shows examples of the correlation between the rises of the daily mean sea level and two indicators of storm strength : the daily average wave-height and the daily average wind velocity near the shore. The rise is seen to be approximately linear.

The data on storm occasioned rises of the sea level are summarized in figure 4. They lead in the first approximation to a linear correlation between the rise (R, in cm) of the daily mean sea level and the concurring daily mean wave height, (H, in metres), and also with the daily mean wind velocity (V, in km/hour). It is thus found that :

$$R = 6\ (H - 0.5) \qquad (1)$$

$$\text{and } R = 0.72\ (V - 5) \qquad (2)$$

The deviation is usually less than ± 6 cm for (1) and ± 8 cm for (2).

UZIEL (1968) in his preliminary investigation of storm surges at Ashdod also accepted a linear relationship.

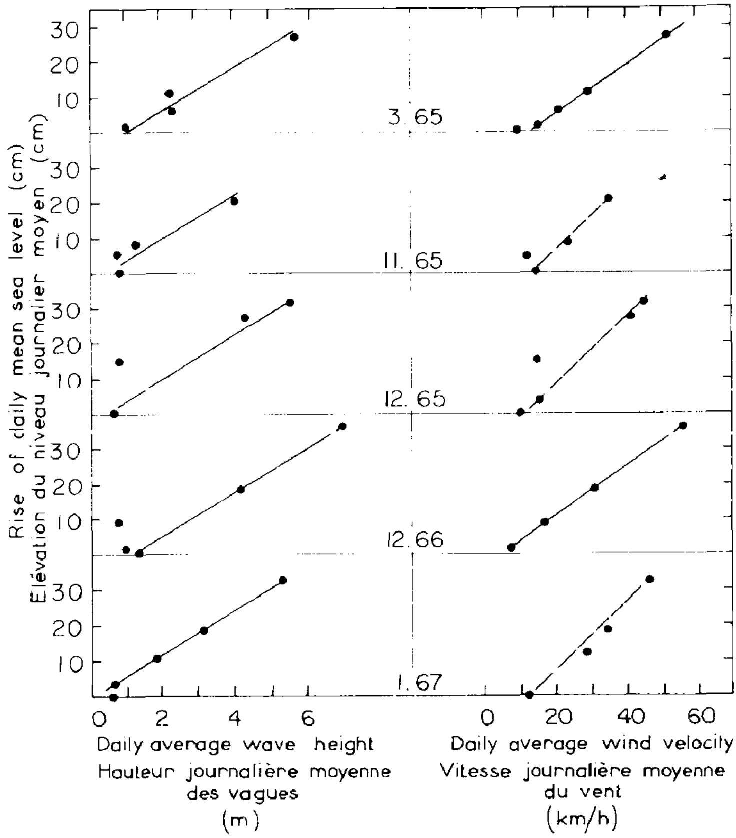

FIG. 3. Examples of individual storm surges.

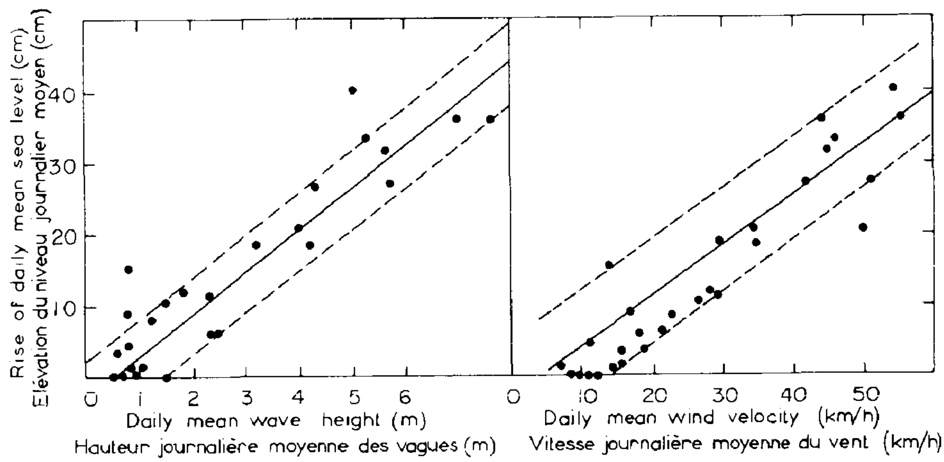

FIG. 4. — Storm surges at Ashdod vs. meteorological variables.

The data used so far concern a comparatively slow and steady rise of the sea level, lasting several days and associated with storm conditions in the eastern Mediterranean. At times, however, there occurs a major and rapid rise, which lasts for only a few hours. Such sudden rises at the shore differ conspicuously in rate from the storm surges described before and will here be denoted as "storm set-up".

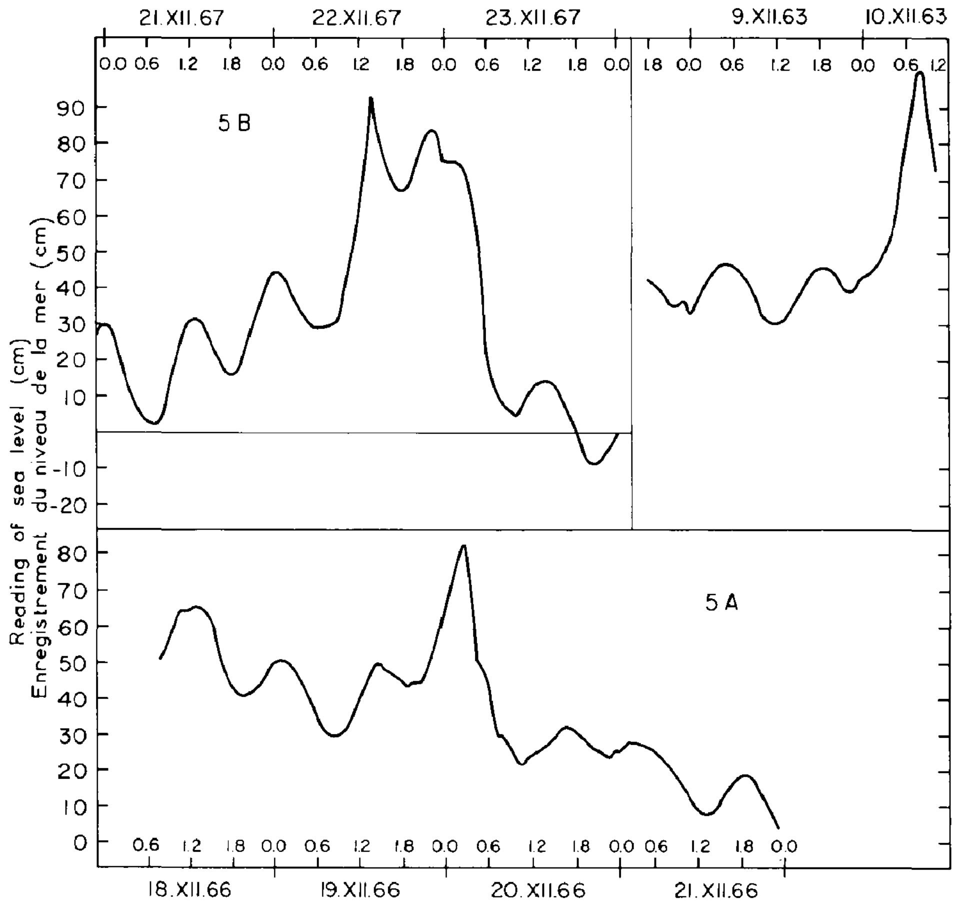

FIG. 5. — Examples of storm set-ups.

During the six years investigated only three cases of a storm set-up were found, and they are shown in figs. 5A and B. The latter is particularly instructive as both storm surge and storm set-up can be clearly discerned. The storm surge is seen in the steady rise of the sea level (from + 16 cm on 21 Dec. 1967 00 hrs) upon which is superimposed the normal tidal fluctuation (with an amplitude of about 11 cm). The hourly sea level rose steeply during the forenoon of 22 Dec. culminating at 14 hrs in a sharp peak. The wind velocity at the shore rose from 15 knots at 05 hrs to 30 knots (55 km/h) at 14 hours.

The peak at + 93 cm lies about 35 cm above the extrapolated position of the tidal peak on the storm surge (~ + 58 cm). This rise of the storm set-up agrees well with the rise expected from the formula $(R = 0.72\ (55 - 5) = 36\ \text{cm})$. After the spectacular upsurge, the mean sea level fell rapidly to — 18 cm at 16 hrs 24 Dec., about 34 cm below the original starting level, and returned to a steady level in the afternoon of 25 Dec.

The storm set-up herein described might be a local pile-up of water, perhaps conditioned by the harbour configuration or associated with seiches therein; however the concurrence with sharp increases of wind velocity points to the wind as the operative factor, and hence the suggested term "storm set-up".

DISCUSSION

The terms "storm surges" and "wind set-up" have both been used in the literature without clear differentiation. SAVILLE (1952) used the term "wind set-up" to describe the rise of the water level of a sea or lake due to storms, and TOMCZAK (1955) used the German equivalent "Windstau" to describe a storm flooding of the North Sea coast. ROSSITER (1963) attributed "storm surges" to large changes in air pressure and to strong wind fields operating over the sea. WIEGLER (1964) used "storm surges" to denote a more or less transient motion of a portion of a body of water. He considered part of the rise to be caused by low barometric pressure, but most of it to be due to coupled long waves and to wind set-up, which drag the surface water to the shore line. He noted that a surge may have a semi-periodic "tail" reflecting from the shore. NEUMAN and PIERSON (1966) defined storm surges as the changes of the sea level caused by the passage of a particular storm, and equated them to "Windstau", the piling-up of water against coasts due to wind action.

Most formulas for wind set-up are based on Ekman's basic equation for a stationary slope in an enclosed sea, in that the rise (Z, cm) is directly proportional to the square of the wind velocity (V, km/h) and the distance of the fetch (F, in km), and inversely proportional to the depth (D, in m), and becomes, in metric units,

$$Z = 1.84 \times 10^{-2} \frac{V^2 F \cos \theta}{D}$$

where θ is the angle of incidence between the fetch and the shore.

However, HARRIS (1963) summarized that although the best developed theory for wind stress over water implied that the stress should be proportional to the square of the wind speed, it was found that the empirical data support the assumption of a linear law as well as a quadratic law or any compromise between the two.

The quoted definitions and descriptions relate the rise of the sea level to a complexity of phenomena, whose common source might be termed "the power of the storm". The herein described correlation of the rise of the sea level with the height of the waves or the wind velocity at the shore is a correlation to secondary or derived indicators of the storm's strength. The linearity found here (equations 1 and 2) might be due to circuitous derivation, yet fig. 3 shows a strikingly linear correlation for the rise of the sea level during the development of the storm.

It may also be worth noting that a value derived from the Zuiderzee formula agrees with that derived by equation 2, when calculating the *maximal* rise of the sea level. Thus a severe storm in the eastern Mediterranean with an average wind velocity of 70 km/h and a fetch of 800 km (average depth 1500 m) should result in a 48 cm rise according to the Zuiderzee formula, and a 46 cm rise according to equation 2. This agreement may be considered fortuitous, and attributable to the approximations made for average wind velocity, effective fetch and average depth; however as these factors will be difficult to establish with any accuracy, the general correspondence may be of interest.

The rises of the sea level discussed so far were due to storms, a conspicuous factor affecting the sea level at the coast, albeit only one of several whose concurrence might cause unusually low or high sea levels.

Table 5 summarizes the factors lowering the daily sea level relative to a postulated basic still-water level.

TABLE 5

Factors lowering the sea level at Ashdod

Factor	Occurs at :	Approx. maximum of fall in sea level
(a) The extreme low of spring tides	vernal equinox	– 26 cm
(b) The low of the seasonal fluctuation	end of spring	– 10 cm
(c) A low of annual levels		– 6 cm
(d) A lowering due to the daily inequality of the tides		– 5 cm
	Total of effects not due to wind	– 47 cm
(e) A lowering due to : Eastern (offshore) winds		– 15 cm
or (Down-surge after onshore storms)		(or – 30 cm)
	Possible lowering due to concurrence of all factors	– 62 cm (or – 77 cm)

Bearing in mind that the mean annual sea level is about + 8 cm above the Israel Land Survey datum level, the concurrence of all factors lowering the sea level, each near its maximal effect, might produce short-lived sea levels of — 54 cm, or even — 69 cm. Such a concurrence of all lowering factors especially of maximal effects will be very rare. However, assuming a mere 15 % reduction of each factor would result in a sea level reading of — 45 cm (— 57 cm), and such readings have indeed been observed (See table 7).

The factors raising the level are similarly summarized in table 6.

TABLE 6

Factors raising the sea level at Ashdod

Factor	Occurring at	Approx. maximum rise of sea level
(a) The high of spring tides	vernal equinox	+ 26 cm
(b) The high of the seasonal fluctuation	mid-summer	+ 10 cm
(c) A high annual mean sea level		+ 7 cm
(d) A rise due to daily inequality of the tides		+ 5 cm
	Total of effects not due to wind	+ 48 cm
(e) Storm surges	winter	+ 40 cm
(f) Storm set-up	winter	+ 40 cm

The concurrence of all factors acting at their maximum, excepting (b) which occurs in the summer, would produce a rise of 118 cm above the basic level. Such concurrence must be deemed very rare, and would raise the hourly sea level to about + 126 cm relative to the Israel datum level. However, as table 7 shows, a level of + 100 cm has indeed occurred. With a general reduction of 15 % in all factors, and excluding the rare cases of storm set-up, the sea level would rise to + 74 cm, well within the range of observed levels.

CONCLUSIONS

Storm surges at Israel's Mediterranean coast were found to consist of gradual rises of the daily mean sea level, accompanying approaching storms. The rises could be linearly correlated with daily mean values of wave heights or wind velocities at the shore which were considered as indicators of the storm's power.

In a few cases a conspicuous rise in sea level accompanied by a sharp increase in wind velocity occurred within several hours. The term "storm set-up" was suggested for the phenomenon. The correlation formula previously used for *daily mean* values, would numerically also fit the rises and velocities during the pertinent time interval.

Possible extreme sea levels were evaluated by adding to or subtracting from a basic mean sea level the various non-storm contributions : the daily inequality and asymmetry of the tides, the high or low of spring tides, the seasonal and the annual fluctuations. It was found that if all factors, including storms, would act concurrently, each at its maximum, the hourly

TABLE 7
Extreme sea levels at Ashdod
(XII/1963 – XII/1970)

Year	month	day	hour (LST)	Sea level reading (cm)	Contributory factors (*)		
					tides	waves	winds
The six highest of the highest levels							
1963	XII	10	08	+ 100	[10]	W–7 ½ (10)	
1967	XII	22	14	+ 93	H [2]	W–5 ½ (9)	V–61 (on)
1966	XII	20	03	+ 83	H [9]	W–5 (10)	V–35 (on)
1965	II	5	00	+ 63	H [4]	W–7 (11)	V–55 (on)
1967	III	26	10	+ 63	H [1]	W–7 (11)	V–55 (on)
1968	I	14	21 22	+ 63	H 1	W–7 ½ (12)	V–46 (on)
The six lowest of the lowest levels							
1964	I	29	03-06	– 51	L 2	W–1 (4 ½)	
1966	III	24	05	– 46	L 1	W–1 (5)	V–5 (off)
1968	III	26	17-18	– 45	L 2	W–1 (4)	V–11 (off)
1968	II	12	03	– 42	L 3	W–½ (3)	after day off V–11 (off)
1970	X	16	05	– 41	L 0	W–1 (5)	V–3 (off)
1968	IV	12	03	– 40	L 1	W–½ (3)	V–2 (off)

(*) Legend for "Contributory factors'
Tides : High (H) and Low (L) of Spring-tides,
Number denotes days to approaching [or : preceding] spring-tide ;
Waves : W – wave height to nearest half metre :
(number) denotes period (in sec) ;
Winds : V – wind velocity (in km/h) ;
wind direction : (on) onshore, (off) offshore.

sea level would rise or drop by 1/4 m above or below the extremes observed, viz. + 100 cm, — 51 cm.

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