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Variation of Surge Heights at Alexandria Port (Egypt)

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ABSTRACT. Hourly recorded data during 1990 of sea level, atmospheric pressure and winds in Alexandria Port were used to estimate the surge heights and the contribution of atmospheric pressure and winds on their variations are studied. In addition, a multiple regression equation is fitted for estimation of the surge height at Alexandria by knowing the atmospheric pressure and winds.

The negative surge heights appeared during January, February, March and May; while the positive ones were observed during the rest of the year.

The positive surge at Alexandria occurred with northwesterly winds and with lower atmospheric pressure. The negative surge was associated with northerly/northeasterly winds and with higher atmospheric pressure.

Introduction

Apart from the astronomical tide, sea level varies due to factors related to the climate. Along the Mediterranean Egyptian coast, the main factors affecting the sea level variation are the atmospheric pressure, wind and steric effects (Sharaf El Din, 1975).

Moursy (1976) calculated the storm surge heights at Alexandria during stormy days, with wind speeds more than 20 knots, of winter season over the period 1965-1969 by subtracting the astronomical tide from the observed sea level.

Hamed (1983) determined the number of stormy days at Alexandria over a 20 years period and concluded that the maximum number of the stormy days were during winter and early spring, with a much lower number in autumn while the summer season was free of storms. An empirical equation relating the surge height to wind speed and atmospheric pressure, was found in the form:

$$R = 3.04\ W - 0.05\ W^2 + 0.31\ P - 328.51 \text{ (Hamed, 1983)}$$

where: R is the residual height (cm), W is the wind speed (Knots) and P is the atmospheric pressure (mb).

Hamed and El-Gindy (1988) classified the storm surge at Alexandria, according to their height and the associated synoptic pattern during winter.

Moursy (1989) studied the surge height in details in Alexandria harbor during the period 1974-1983. The meteorological conditions and its relation to storm surges are also discussed.

Eid (1989) studied by different ways the effect of atmospheric pressure and water density on the fluctuations of monthly mean sea level off Alexandria coast. The sea level height generally decreased with increasing atmospheric pressure. Also, the density changes off Alexandria coast have a significant effect on the sea level variations. He concluded that, the monthly mean sea level corresponds in sign and magnitude with the isostatic departure except during winter.

Later, El-Gindy *et al.* (1992) formulated short-term forecasting equations of the storm surge height at the Western Harbor of Alexandria, using multiple regression analysis.

In this study, the effect of both atmospheric pressure and wind on the variability of the residual sea level at Alexandria will be discussed in detail.

Data and Method of Analysis

The tide gauge at Alexandria is located inside the innermost basin of the western harbor (Fig. 1). The instrument is an old huge machine of the floating type sea-tidal gauges with one day recording sheets erected in a double well with an accuracy of 0.1 cm. The hourly recorded sea level data for the year 1990 is used in this work.

The meteorological data (atmospheric pressure and winds) are taken from Ras-El-Tin meteorological station throughout the period of investigation.

The wind data is analyzed into two components, one parallel to the coast (Wx) and other one normal to the coast (Wy).

The residual sea level (surge height) is estimated by subtracting the predicted tidal height from the observed height of sea level. The prediction of tidal elevation at any time is calculated by applying the following equation (Murray, 1962):

$$T(t) = z_o + \sum_{i-1}^{n} F_i H_i \cos\left[(v+u)_i - g_i + \sigma_i t\right]$$

where:
$T(t)$ = The required predicted tidal elevation at time t,
z_o = The mean sea level,
i = The considered tidal components,
F_i = Nodal correction factor for the amplitude,
H_i = The amplitude of the i*th* tidal components (cm),
$(v+u)_i$ = Nodal argument of the i*th* tidal components (degrees),
g_i = Phase of the i*th* tidal components (degrees),

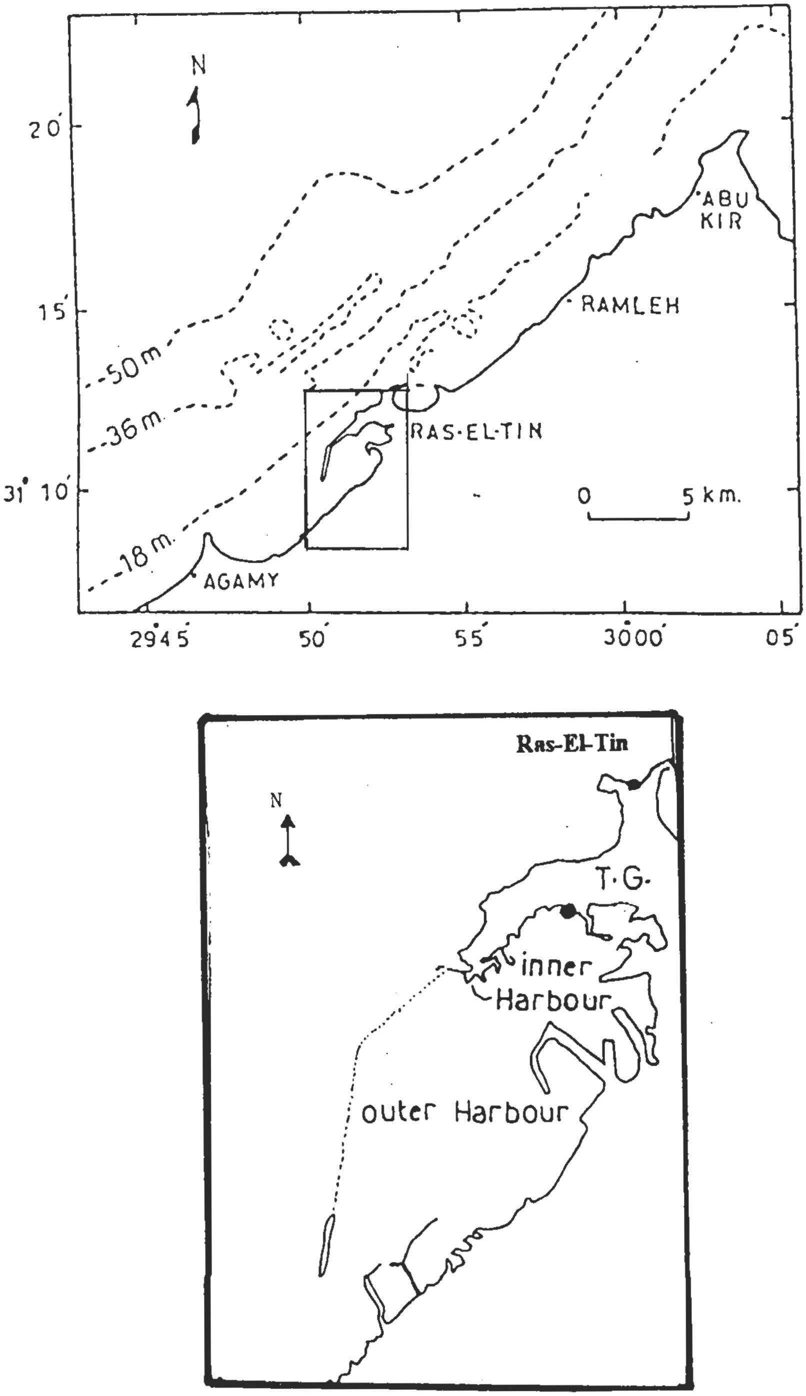

FIG. 1. *Upper :* Alexandria coast and its bathymetry,
Lower : Location of tide gauge inside Alexandria Harbour.

σ_i = Angular velocity of the *ith* tidal components, and
t = Time from the starting hour to the required predicted one.

The harmonic constituents at Alexandria Port are well studied by Rady (1979) by analyzing different lengths of sea level data throughout the period 1958-1976. Table (1) shows the selected constituents which applied in the above equation.

TABLE 1. The harmonic constituents used in the present study (after Rady, 1979).

Symbol	Amplitude (cm)	Local Phase (degrees)
1. Long-period Terms :		
SA	4.48	186.62
SSA	2.97	208.60
MM	0.96	181.93
MSF	1.36	173.24
MF	1.62	13.71
2. Diurnal Terms :		
O1	1.27	278.71
K1	1.65	315.63
P1	0.69	321.62
Q1	0.17	234.68
J1	0.14	284.93
S1	0.52	67.48
3. Semi-diurnal Terms :		
M2	7.02	314.73
S2	4.05	327.17
K2	1.38	317.09
N2	1.27	323.82
2N2	0.17	331.74
MU2	0.30	332.25
NU2	0.29	333.61
L2	0.24	313.47
T2	0.66	248.54
R2	0.52	90.24
MKS2	0.27	248.54
4. Ter-diurnal Term :		
M3	0.17	99.38
5. Shallow-water Terms :		
a – Quarter diurnal :		
MS4	0.05	51.93
S4	0.05	119.65
b – Sixth diurnal :		
M6	0.01	83.63

The influence of both atmospheric pressure and winds on the residual sea level is studied by constructing the frequency distribution of both parameters with positive and negative surge height.

A multiple regression analysis is used to relate the residual sea level (surge) to atmospheric pressure and wind components. The computational procedure is based on the equation:

$$surge = b_o + \sum_{i-1}^{m} b_i X_i$$

where : b_0 = constant values, b_i = coefficient of x_i variable, and m = number of the variables in the equation.

Results and Discussion

a. Statistical description of surge heights

The hourly values of the residual sea level (surge) are studied for each month by calculating the statistical descriptive values (mean, standard deviation, range, maximum and minimum). These statistical values are shown in Table (2). It is seen that, the monthly mean values of the surge height oscillated between a minimum of −17.5 cm in January and a maximum of 8.2 cm in September. The standard deviation of surge heights about the monthly mean changed between 6 cm during October and 12.9 cm during December. The minimum hourly value of surge (−41.25 cm) is observed during January, while the maximum (34.0 cm) is found during March. The range of surge heights during the different months varied between 33.1 cm (during October) and 61.8 cm (during May).

TABLE 2. Monthly statistical description of surge heights at Alexandria Port during 1990.

Month	Mean (cm)	Standard Deviation	Range (cm)	Minimum (cm)	Maximum (cm)
Jan.	−17.51	10.35	49.00	−41.25	7.75
Feb.	2.17	10.22	47.85	−19.36	28.49
Mar.	−10.02	9.16	60.78	−26.79	33.99
Apr.	0.45	8.65	48.50	−24.95	23.55
May	- 8.12	10.94	61.77	−37.98	23.79
Jun.	1.61	8.23	45.44	−18.33	27.11
Jul.	5.29	7.96	42.28	−23.30	18.98
Aug.	6.53	7.28	42.61	−14.05	28.56
Sep.	8.24	7.03	41.56	- 9.78	31.78
Oct.	2.49	5.97	33.11	−14.59	18.52
Nov.	2.96	10.04	53.17	−25.83	27.34
Dec.	6.13	12.88	54.04	−22.75	31.29

b. Frequency distribution of surge heights

The frequency distribution of both positive and negative surge heights during the different months is shown in Fig. (2). It is seen that, negative surges prevail during January, February, March and May, while positive ones prevail during the rest of the year. The maximum frequency occurrence of the negative surge was found during January (about 8%), while the minimum occurred during September (1%). The maximum frequency of positive surge (7%) was found during September, while the minimum ones (0.6%) is observed during January.

Figure (3) shows the frequency distribution of positive and negative surge heights with different wind directions. It is clear that, the positive surge prevails at Alexandria with winds blowing from the direction between 270° and 10°, while the negative ones occur with wind directions between 20° and 120°. It means that, the northerly and northeasterly winds gives a positive surge at Alexandria Port.

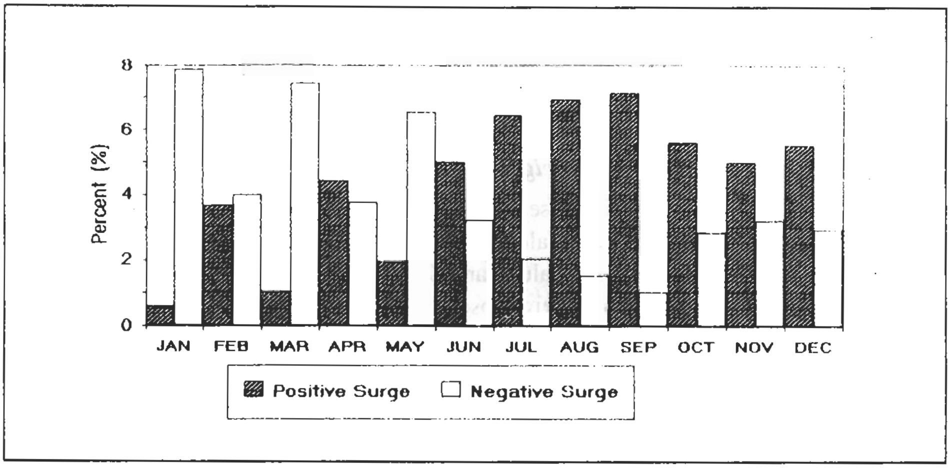

FIG. 2. Monthly frequency distribution of positive and negative surge during 1990.

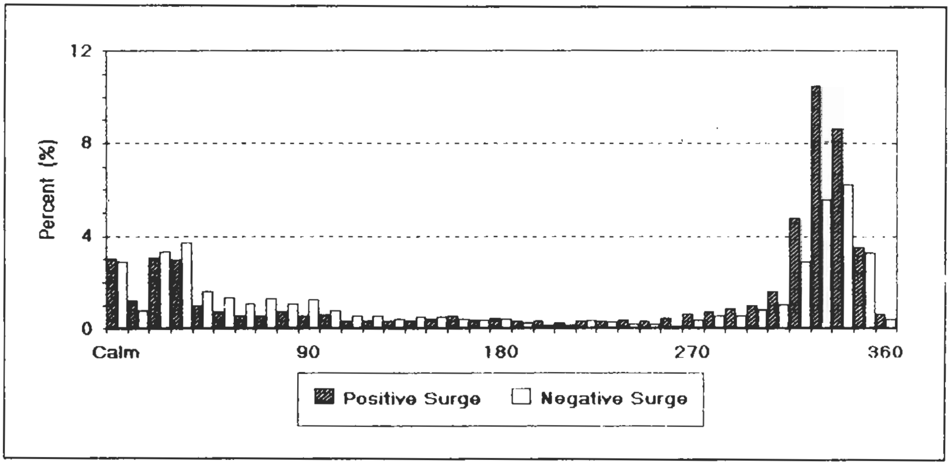

FIG. 3. Frequency distribution of positive and negative surge at different wind directions during 1990.

Note that, the higher frequencies of the surge height at the directions 320-350° are a reflection of the prevailing wind direction at Alexandria, which is northwest (330-340°).

The histogram of the frequency distribution of positive and negative surge heights with different wind directions for wind speeds > 10 knots is shown in Fig. (4). The general pattern of this distribution does not differ much from that when all wind data are used (Fig. 3). The positive surge occurs with wind directions between 240 and 330° with maximum frequency at direction 330°. The negative surge is observed with wind directions between 340 and 80° with maximum frequency at 340°.

In addition to the above analysis, the values of surge heights are sorted so as only those values higher than 20 cm at different wind directions are taken and represented in

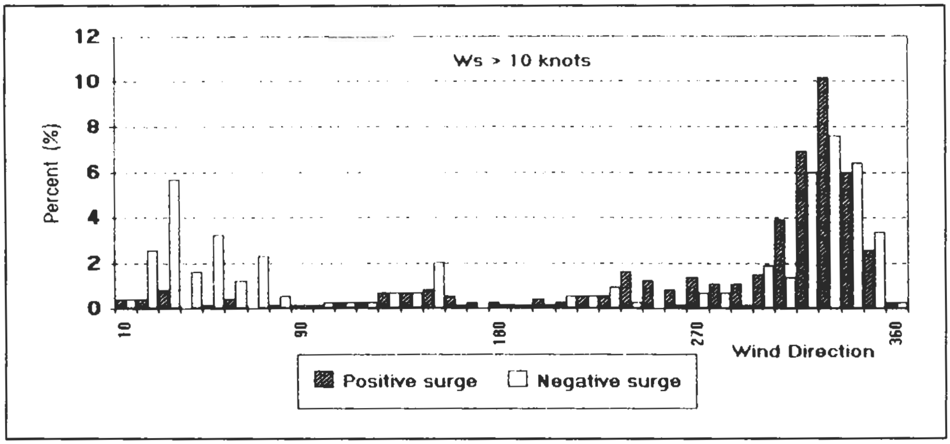

FIG. 4. Frequency distribution of positive and negative surge at different wind directions for wind speed > 10 knots during 1990.

histogram as shown in Fig. (5). The higher frequencies of the positive surge height is observed at wind directions between 270 and 330° with maximum frequency at 320-330°. The higher frequencies of the negative surge occurred at wind directions between 340 and 110° with maximum frequencies at 340-350° and 20-30°.

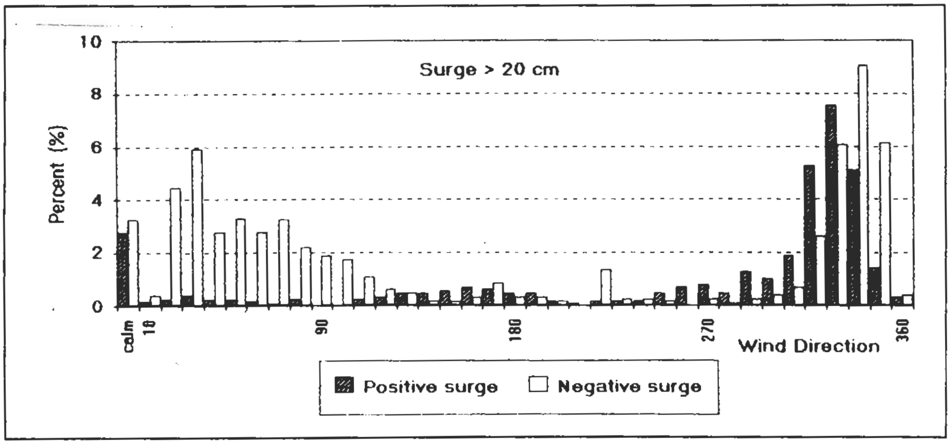

FIG. 5. Frequency distribution of positive and negative surge higher than 20 cm at different wind directions during 1990.

In general, from Figs. (3-5), the surge height is positive at wind direction between 270-330°, and is negative at wind directions 340-350° and 20-100°.

Moreover, the histograms of the frequency distribution of the positive and negative surge heights at different wind direction is represented at lower (< 1011 mb) and higher (> 1020 mb) atmospheric pressures (Fig. 6). The surge is always positive at lower atmospheric pressure with maximum frequency at 330°, and is always negative at higher atmospheric pressure with maximum frequency at 340° and 20°.

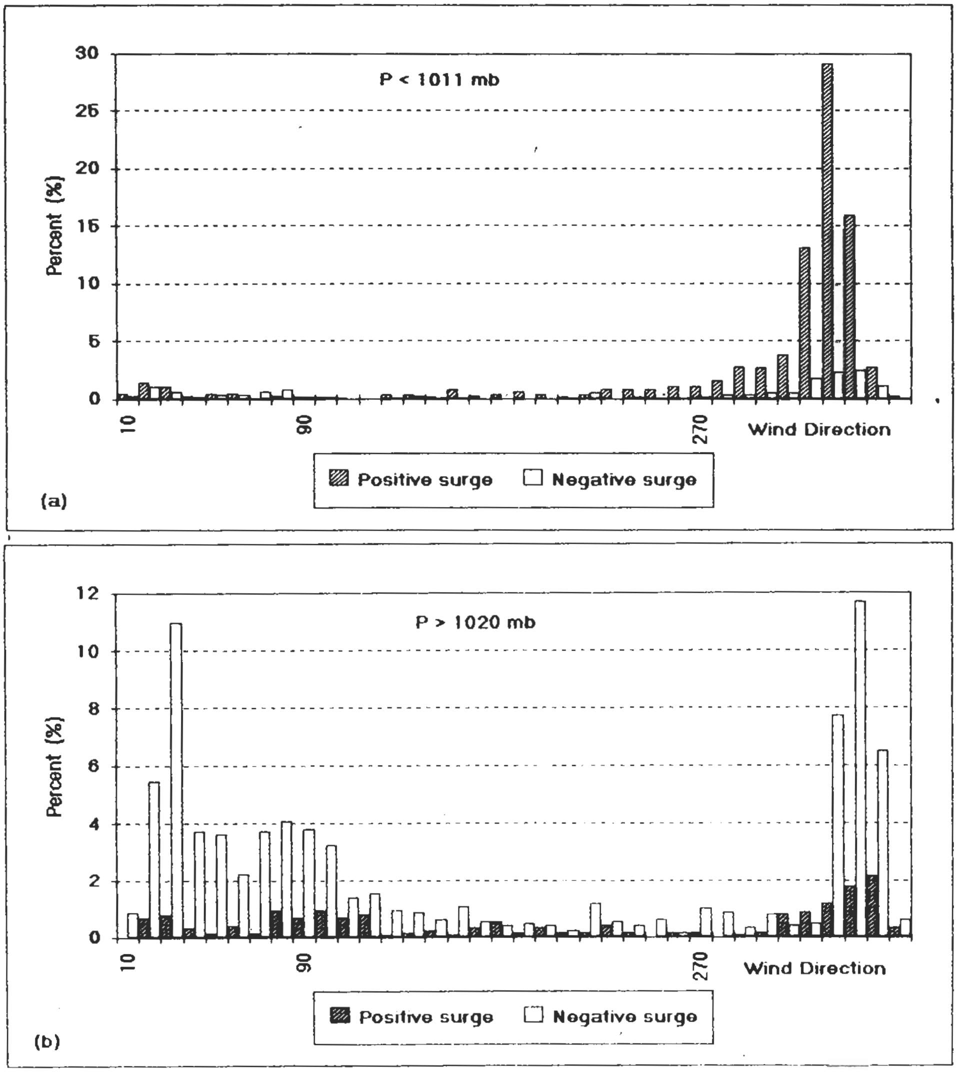

FIG. 6. Frequency distribution of positive and negative surge at different wind directions during 1990.
a) at pressure < 1011 mb; b) at pressure > 1020 mb.

The percent of occurrence of positive and negative surge are calculated at atmospheric pressure more and less than 1015 mb (the annual mean during 1990) and at positive and negative wind components (Wx and Wy). The result of these calculations are listed in Table (3).

From this table, it is clear that atmospheric pressure lower than its annual mean value leads to an increase in the surge height, *i.e.* a positive surge appears, and vice versa with higher atmospheric pressure. Also, the positive surge is dominant with positive wind component parallel to the coast (Wx) and directed toward northeast.

TABLE 3. Percent of occurrence (%) of both positive and negative surge heights at different atmospheric pressure and wind components.

Surge	Atmospheric Pressure		Wx		Wy	
	> 1015	< 1015	+ ve	– ve	+ ve	– ve
Positive	38.1	69.3	58.9	52.1	41.5	57.2
Negative	61.9	30.7	41.1	47.9	58.5	42.8

When the wind component normal to the coast (Wy) moves away from the coast (positive Wy), it leads to a negative surge (decreasing the surge height) and the reverse is true when the wind component is directed towards the coast (negative Wy).

c) Hourly changes of storm surges

i. Wind speeds > 10 knots

There are many short periods (not exceeding 3-4 days) which had a continuous record of wind speed more than 10 knots. To study the hourly changes of storm surges and their relation with other parameters, two different periods are selected, one with positive surge and other with negative one. Figures (7 & 8) show the hourly changes of surge, atmospheric pressure and wind components (Wx and Wy) for the two selected periods 28 February- 1March and 17-18 March respectively.

Figure (7) shows that during the period 28 February- 1 March, the surge height increases with time from a minimum of –1 cm to a maximum amount of about 34 cm and then decreases to about –5 cm. The atmospheric pressure was relatively low (between 1006.2 and 1017.8 mb) and lead to an increase in the surge. This depicts the existence of an inverse relation between atmospheric pressure and surge height with a correlation coefficient of –0.5918. The wind components during this period were positive for Wx and negative for Wy. This demonstrates the presence of direct and inverse relationships between the surge heights and Wx and Wy respectively.

From Fig. (8) (17-18 March), it is clear that, the surge height is negative (between –12 and –25 cm) and the atmospheric pressure during this period is relatively high (between 1019.8 and 1024.2 mb). It means that, the surge height decreases with increasing the atmospheric pressure. The wind components during this period are negative for Wx (*i.e.* southwestward away from the tide gauge) and oscillating around zero for Wy. In other words, the wind blowing from northeast direction parallel to the coast. This wind leads to decrease the surge height.

ii. Surge heights > 20 cm

Figures (9 & 10) show the hourly changes of surge, atmospheric pressure and wind components during two selected periods when the surge height is relatively high (more than 20 cm). These two periods are chosen to present positive and negative surge heights.

During the first period (16-20 January), Fig. 9, the surge height is negative and the atmospheric pressure is high (between 1021-1023 mb), *i.e.* an inverted relation is present. Also, it is seen that, when the wind component (Wy) directed toward the coast and the component (Wx) directed toward southwest, *i.e.* northeasterly wind, it yields a negative surge.

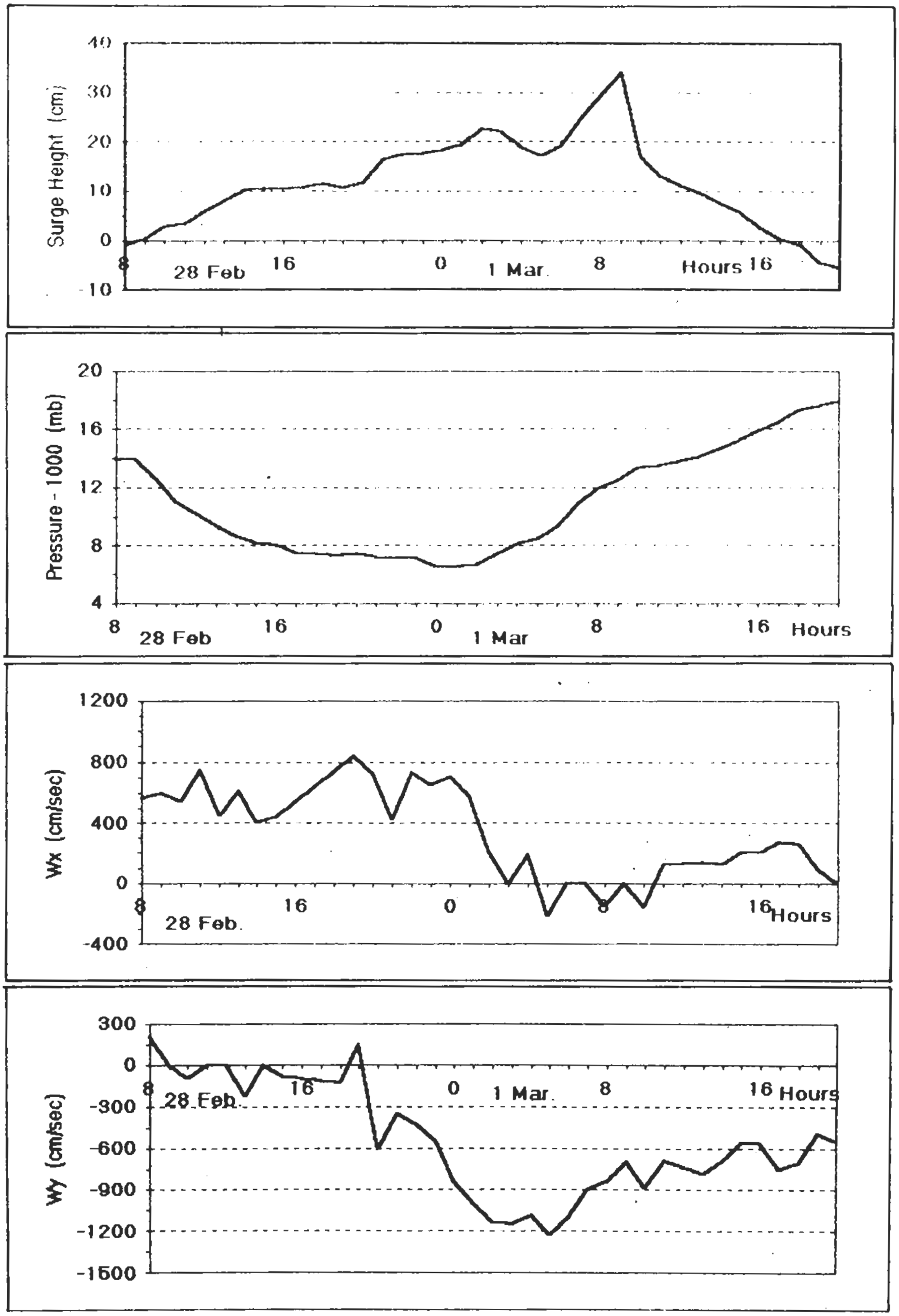

FIG. 7. Hourly variations of surge, atmospheric pressure and wind components during the period 28 February- 1 March 1990.

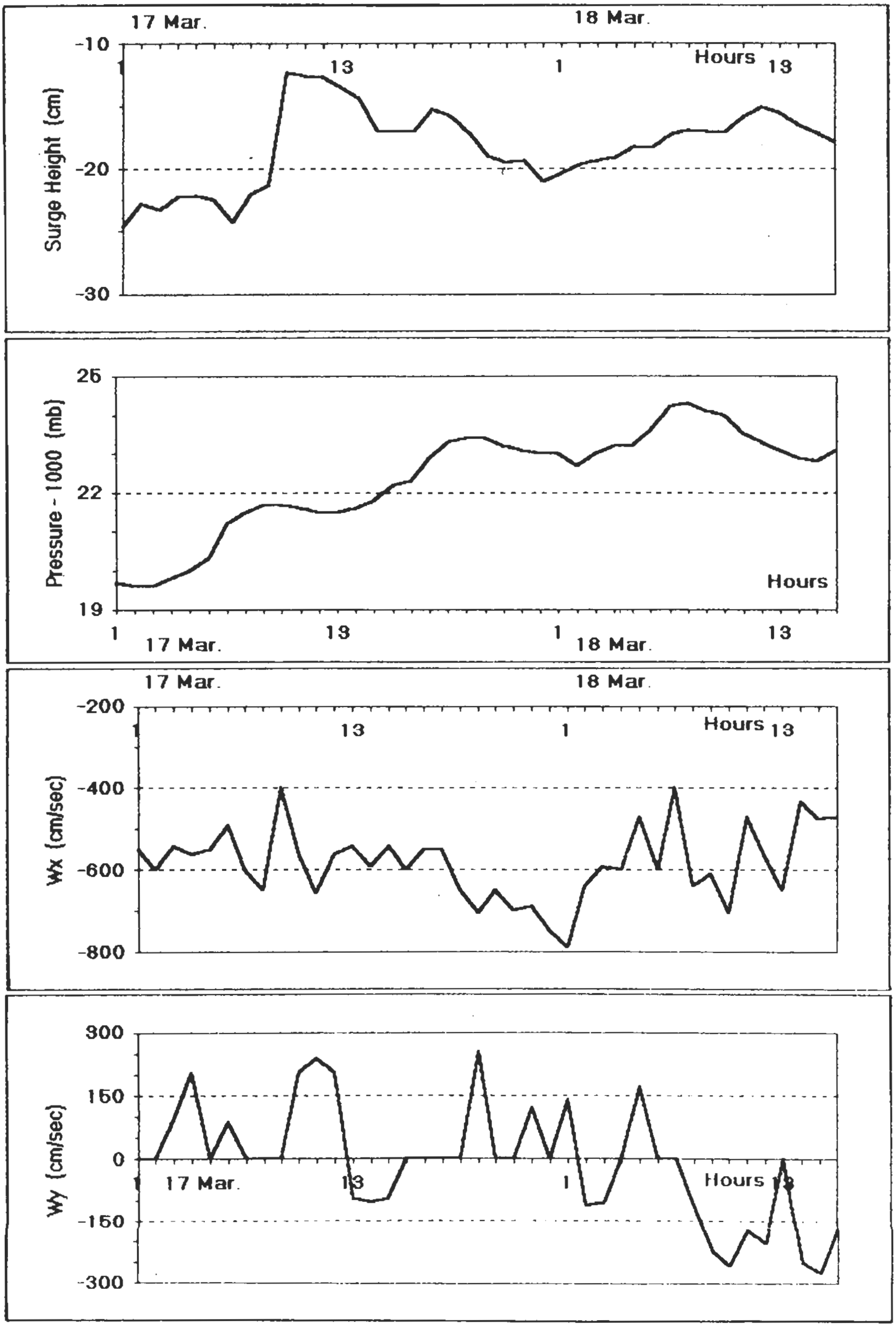

FIG. 8. Hourly variations of surge, atmospheric pressure and wind components during the period 17-18 March 1990.

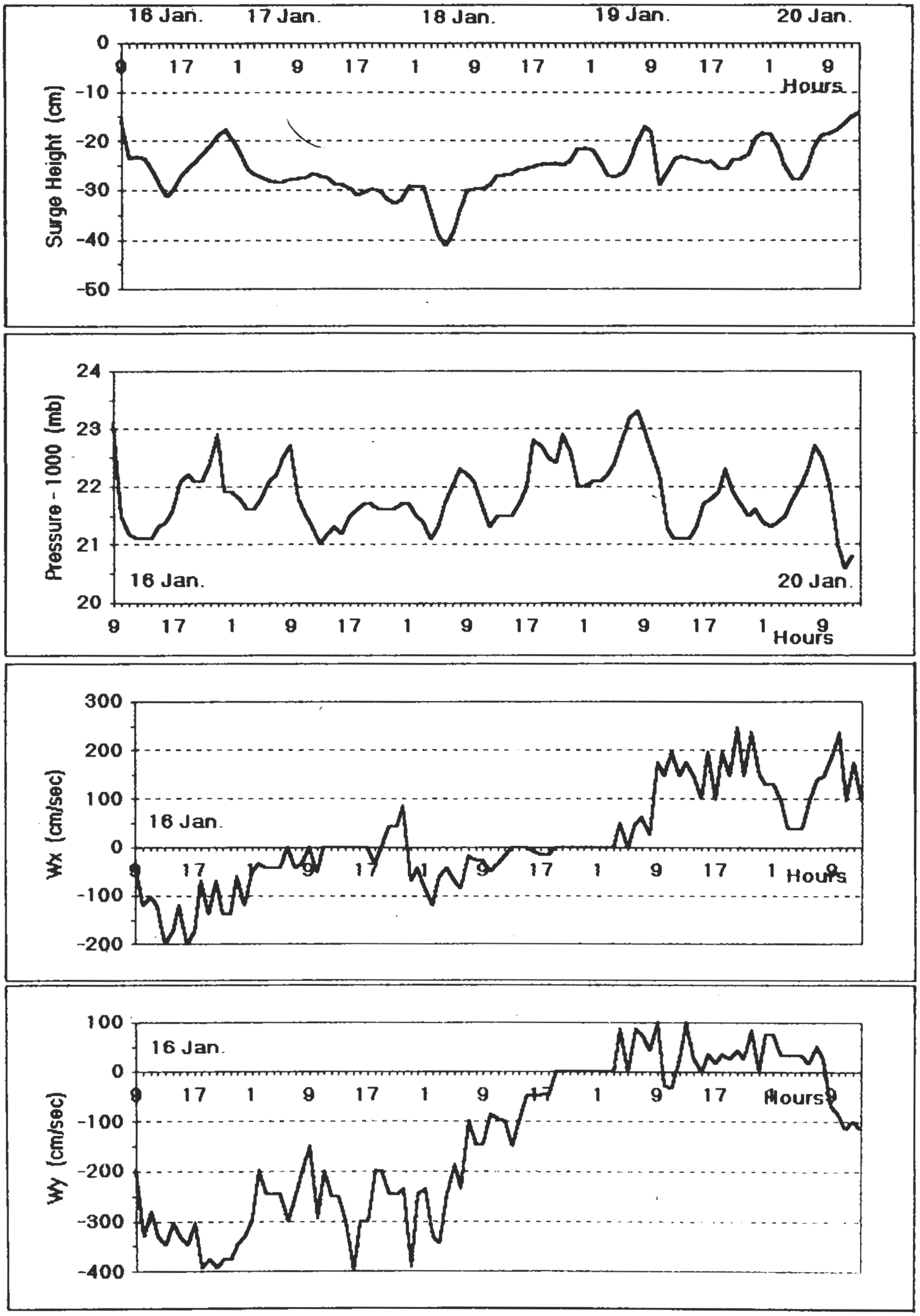

FIG. 9. Hourly variations of surge, atmospheric pressure and wind components during the period 16-20 January 1990.

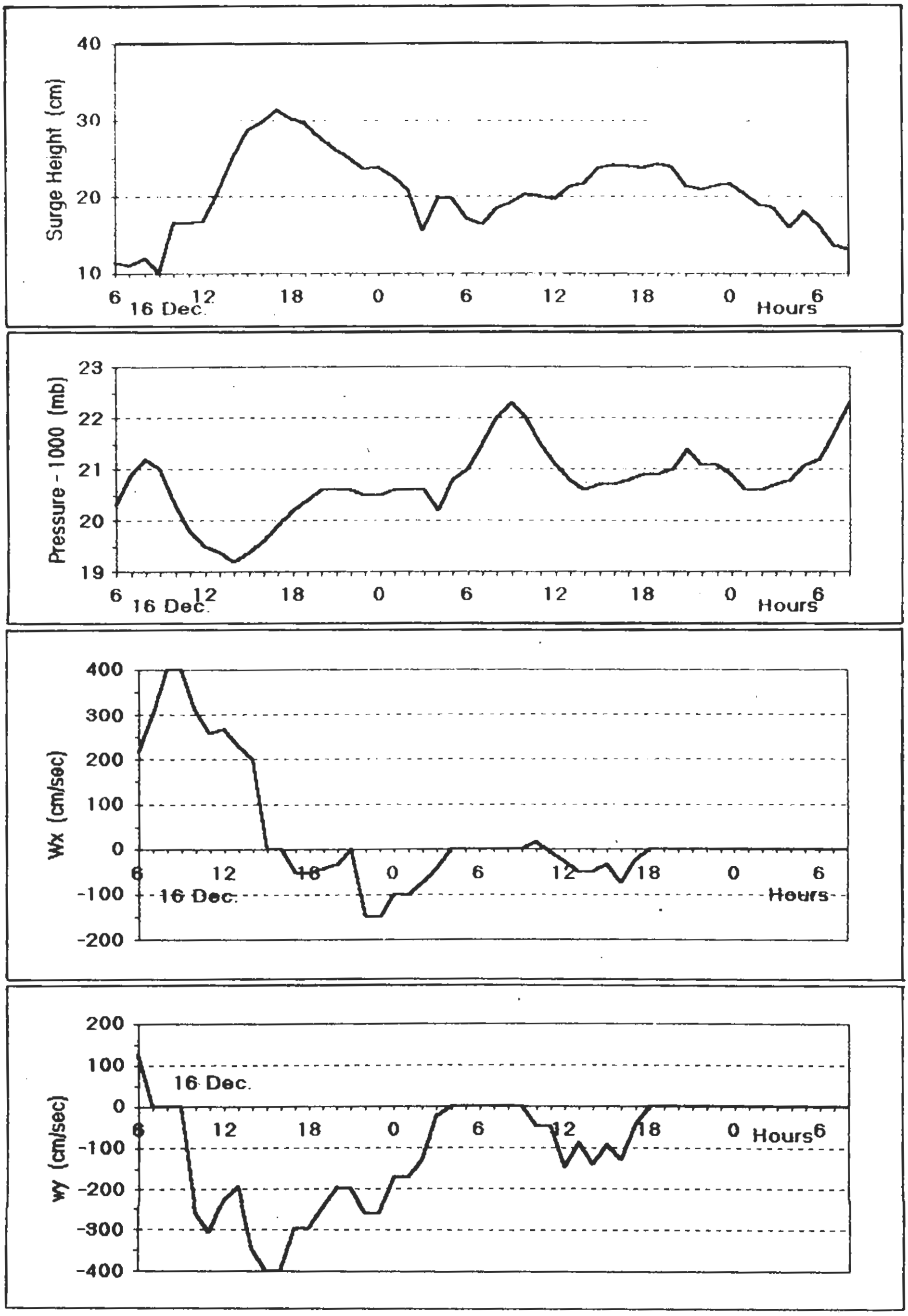

FIG. 10. Hourly variations of surge, atmospheric pressure and wind components during the period 16-18 December 1990.

Figure (10) shows the corresponding curves during the period 16-18 December. During this period the atmospheric pressure did not mainly affected surge height. The wind direction during this period changed between 270° and 350°, *i.e.* when (Wx) is positive and (Wy) is negative, they yield a positive surge.

d) Regression analysis

From the hourly values of the residual sea level, atmospheric pressure and wind components during 1990, a multiple regression equation is fitted for predicting the residual sea level (surge) at Alexandria port. In this equation the variables included are atmospheric pressure (P in mb) and wind components parallel to and normal to the coast (Wx and Wy respectively in cm/sec). This equation takes the form:

$$\text{surge} = 1107.56 - 1.09\,P + 0.009\,W_x - 0.0026\,W_y$$

This equation gives the residual sea level or surge height in cm.

The multiple correlation and standard error of above equation are 0.4743 and 10.5 cm respectively.

The above equation is compared with that equation derived by Hamed (1983). Figure (11) shows the estimated and predicted surge during a selected period (1-5 March 1990). It is seen that, a slight difference between the calculated surge and predicted ones. There is a big difference between the estimated surge and the predicted one deduced by using Hamed (1983) equation.

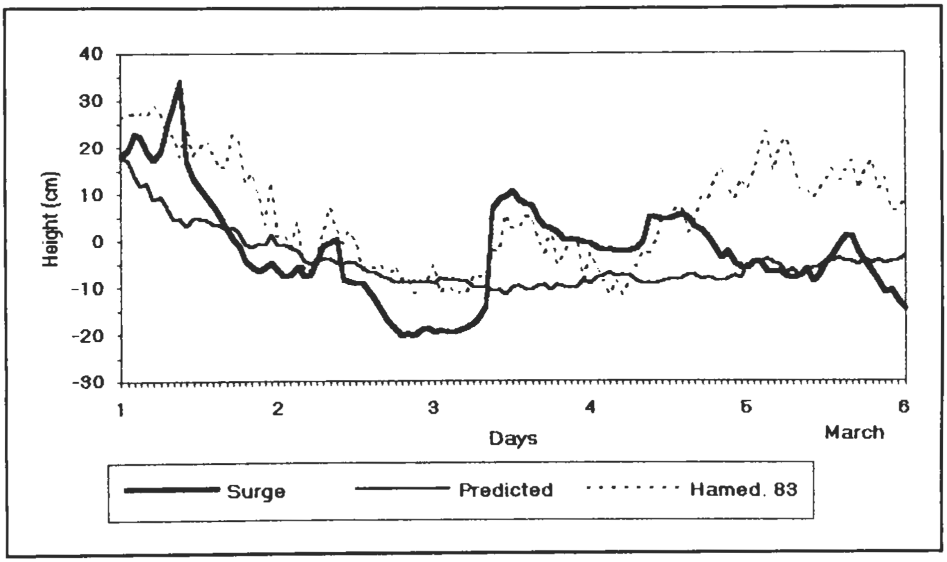

FIG. 11. The estimated and predicted surge during the period 1-5 March 1990.

Conclusion

Using the hourly recorded data of sea level at Alexandria Port during 1990, the surge heights are calculated by subtracting the predicted tidal height from the observed height of sea level. The contribution of both atmospheric pressure and winds on the surge heights is studied statistically by constructing the frequency distribution of each parameter with the positive and negative surge heights. Moreover, a multiple regression analysis is used to estimate the surge height as a function of atmospheric pressure and wind components. The results showed the following conclusions:

The hourly values of surge height oscillated between –41 cm (during January) and 34 cm (during March), while the monthly mean values varied between –17.5 cm (during January) and 8.2 cm (during September).

The mean surge height is negative during January, February, March and May, while it is positive during the rest of the year.

The positive surge prevailed at Alexandria with winds blowing from a direction between 270° and 330°, while negative ones occurred with wind directions 340-350° and 20-100°.

The surge height is positive at atmospheric pressure lower than its annual mean with maximum frequency at wind direction of 330°. It is negative at atmospheric pressure higher than its annual mean with maximum frequency at wind directions of 340° and 20°.

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تغير مستوى سطح البحر الناشئ من تأثير الرياح والضغط الجوي في ميناء الأسكندرية (مصر)

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المستخلص . باستخدام البيانات الساعية المسجلة لمستوى سطح البحر وكذلك بيانات الضغط الجوي والرياح في ميناء الأسكندرية عام ١٩٩٠م ، تم حساب ارتفاع مستوى سطح البحر الناشئ من تأثير الرياح والضغط الجوي فقط وذلك بعد حذف المد والجزر من قراءات مستوى سطح البحر . أظهرت الدراسة أن القراءات الساعية لمستوى سطح البحر الناشئ من تأثير الرياح والضغط الجوي تتذبذب بين -٤١ سم (في شهر يناير) و ٣٤ سم (في شهر مارس) - بينما تتغير المتوسطات الشهرية مابين -١٧,٥ سم (في شهر يناير) و ٨,٢ سم (في شهر سبتمبر) .

أيضًا أوضحت الدراسة أن ارتفاع مستوى سطح البحر الناشئ من تأثير الرياح والضغط الجوي كان سالبًا خلال الأشهر يناير ، فبراير ، مارس ، مايو - بينما كان هذا الارتفاع موجبًا خلال بقية العام . وقد لوحظ أن الارتفاعات الموجبة تسود في ميناء الأسكندرية عندما تهب الرياح باتجاهات مابين ٢٧٠ و ٣٣٠ درجة ، وأيضًا عندما يكون الضغط الجوي منخفضًا (أقل من المتوسط السنوي) . بينما تسود الارتفاعات السالبة لمستوى سطح البحر مع الرياح القادمة باتجاهات مابين ٢٠ و ١٠٠ درجة ، وأيضًا عندما يكون الضغط الجوي مرتفعًا (أعلى من المتوسط السنوي) .

أيضًا تم دراسة التوزيع التكراري لمستوى سطح البحر الناشئ من تأثير الرياح والضغط الجوي ، وقد أظهرت الدراسة أن أكبر تكرار للارتفاعات الموجبة كان مع الرياح ذات الاتجاه ٣٣٠ درجة ، بينما كان أكبر تكرار للارتفاعات السالبة مع الرياح الواقعية مابين ٣٤٠ و ٢٠ درجة .

أيضًا تم استخدام أنسب التحليلات الرياضية لوضع معادلة عامة لحساب ارتفاع مستوى سطح البحر الناشئ من تأثير الرياح والضغط الجوي بمعلومية الضغط الجوي ومركبتي الرياح الموازية للساحل والعمودية عليه .