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Relationship Between Sea-level Variability and Meteorological Conditions in Abu-Qir Bay (Alexandria – Egypt)

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ABSTRACT

This study shed light on the main sea-level characteristics of Abu-Qir Bay, which is one of the sensitive Egyptian coastal zones prone to sea-level variations and the sea-level rise problem. The present analysis was performed by the T_TIDE package for hourly sea-level records from January 2008 to December 2010. A simultaneous meteorological data set was obtained from the automated weather station at Alexandria International Airport. This comprised records of air temperature, atmospheric pressure and wind regime. Although few studies were previously conducted to examine the sea-level variations in Abu Qir Bay, this is the first to correlate these variations with the three main affecting meteorological conditions. Results revealed that the Bay had a mean sea level (MSL) of 50.1cm, which is relative to the tide gauge zero-level and exhibited a semidiurnal tidal cycle. The Bay exhibited a MSL seasonal behavior, with the lowest mean in spring (38.6cm) and the highest in autumn (58.7cm). 19 astronomical constituents were significant out of 69 with solar annual and semi-annual components having the highest amplitudes of 7.2 and 4.6cm, respectively. The M_2 principal lunar tidal constituent had an amplitude of only 1.5cm. The water levels had a spring-to-neap range ratio of 5. Residuals had the upper hand on the observed variations in the sea level of Abu-Qir Bay. Storm surges with elevations greater than 65cm contributed up to 7% of the observed sea level in the bay. Correlation coefficients between the sea level and the affecting meteorological conditions during the study period were calculated on both hourly and mean monthly basis. This revealed that air temperature is the key meteorological player in the observed variations and that the sea level is affected by the zonal wind component rather than the meridional one.

INTRODUCTION

Low-elevated coastal zones (LECZs) are widespread in the Mediterranean Basin, and are extremely susceptible to environmental phenomena: sea-level rise (SLR), storm surges and extreme weather events, which can have a direct or indirect influence on the coastal community **(Galassi & Spada, 2014)**. The latest issue of the IPCC report (AR6) on the Mediterranean Sea region released in 2022 has assessed that the Mediterranean Sea exhibits robust accelerating SLR rates at different magnitudes in different locations, which will impact the life of one-third of the Mediterranean population, i.e. ~ 150 million people, currently living close to the sea borders **(Ali *et al*., 2022)**. Moreover, the AR6 report revealed that the Mediterranean Sea level rose by 1.4 mm/yr during the twentieth century and by 2.4±0.5 mm/yr from 1993 to 2012; it is expected to rise further in the future **(Ali *et al*., 2022)**. In the LECZ Mediterranean regions (37% of its coastline), especially in the delta regions such as the Nile, regulated retreat may be necessary to defeat coastal flood risks due to continuous SLR **(Wong *et al*., 2014)**. Nature-based solutions, such as beach and shore nourishment, dune restoration or ecosystem-based adaptation and restoration in LECZ are among the adaptation options to SLR in the Mediterranean **(Aspe *et al*., 2016; Danovaro *et al*., 2018; Ali *et al*., 2022)**.

The Egyptian Mediterranean coast is one of the Mediterranean LECZs subjected to various environmental stresses. About 30% of Egypt's population lives in the Nile Delta LECZ **(Black *et al*., 2011)**. According to the United Nation Development Program **(UNDP, 2014)**, the Nile Delta and Egypt's Mediterranean coast have both been identified as being particularly vulnerable to SLR brought on by climate change. **Dasgupta *et al*. (2009)** placed Egypt among the top ten (out of 84) most impacted countries in terms of the population potentially displaced by a 1m SLR. Further, **Syvitski *et al*. (2009)** asserted that, because of subsidence and human meddling, the Nile and Niger Deltas are the most endangered of all the African deltas. In the 2070s, according to the population susceptible to coastal flooding, Alexandria is anticipated to be placed the 11th out of 20 coastal cities worldwide **(El-Deberky & Hunicke, 2015)**. The city exhibited a general SLR rate of the order of 2.17mm/ year over 33 years from 1974 to 2006 **(Maiyza & El-Geziry, 2012; Hendy *et al*., 2021)**. It was comprehensively acknowledged that the tides on the Egyptian Mediterranean coast are semidiurnal and only a few centimetres in height, among the studies reporting these data are those of **Moursy (1989, 1992, 1993, 1994, 1998)**, **Hussein *et al*. (2010)**, **Saad *et al*. (2011)**, **El-Geziry and Radwan (2012)**, **Maiyza and El-Geziry (2012)**, **Radwan and El-Geziry (2013)**, **El-Geziry (2013; 2021)** and **El-Geziry and Said (2014, 2020)**.

In regions where tidal impacts are weak such as the status of the Egyptian Mediterranean coast, atmospheric forcing is critical for determining the local water level **(Afshar-Kaveh *et al*., 2020)**. Evaporation, cooling processes and the upwelling of denser subsurface waters decrease the sea level, whereas rain, saltwater heating and water piling up on the shoreline raise it. A phenomenon, known as the local inverse barometer (LIB), happens when the sea surface rises in reaction to a decrease in local air pressure and vice versa **(Pugh & Woodworth, 2014)**. Sea-level changes, according to **Goring (1995)**, are produced by more than merely atmospheric pressure, especially in coastal areas. When winds blow through shallow ocean areas, they cause wave set-up/set-down **(Afshar-Kaveh *et al*., 2020)**. Winds have different effects on the observed sea level depending on the morphometry and location of the area **(El-Geziry, 2013)**. Wind stress is more effective in coastal areas due to shallow waters, water pileup along the coast and resonant effects **(Bertin *et al*., 2012; Pineau-Guillou *et al*., 2020)**. Furthermore, when the waves dissipate, the radiation stress, which is the momentum flux carried by the waves, generates nearshore currents and wave setup (i.e. additional surge) **(Bertin *et al*., 2015; Choi *et al*., 2018)**.

Abu-Qir Bay (AQB) is a semi-circular aquatic basin 35km east of Alexandria, located at 31° 16'-31° 28' N and 30° 03'-30° 22' E (Fig. 1). The Bay’s depth gradually slopes towards its center, with a maximum depth of approximately 22m and a mean depth of less than 10m. Between Rosetta in the northeast to the Abu Qir headlands in the southwest, Abu Qir Bay's coastline spans for around 50 kilometres **(Abdallah *et al*., 2007)**. The bay has a total surface area of almost 360km^2 and a total water volume of approximately 4.3km^3 **(Said *et al*., 1995)**. The bay joins Lake Edku through Boughaz El-Meadeya. AQB, like many coastal regions close to large cities, is utilized for a variety of activities, e.g. commercial fishing, swimming, recreational boating, shipping and the disposal of sewage effluent **(Emam *et al*., 2013)**. Many important agricultural and industrial zones are located along the bay’s land border. From west to east, these include the Qaha Company for the food industry, Rakta Company for the paper industry, Raslan and El-Tarh agricultural zones, Abu-Qir Fertilizers Company, Abu-Qir Old and New Electricity Companies, Petroject Petroleum Company and Rasheed Petroleum Company. AQB is one of the susceptible coastal regions to the sea-level variations and the SLR problem. The research of sea-level variability in this significant bay; however, has only recently been the subject of a small number of studies. This comprises the work of **El-Geziry (2013)**, **El-Geziry and Said (2014)**, **Said *et al*. (2019)** and **El-Geziry and Said (2020)**. Their findings revealed that the bay exhibits a seasonal pattern of sea-level variability. They also declared that, the bay’s tidal cycle is of the semidiurnal type, and the amplitude of the M_2 principal lunar constituent is generally less than 2.0cm. **El-Geziry (2013)** deduced that, the tides in AQB are steric meteorological tides, i.e. the wind pattern has a greater influence than the astronomical impact. **Said *et al*. (2019)** calculated a SLR rate of 6.0mm/ yr in the bay over the period 1990-2010. In addition, they investigated the positive and negative surge behavior in the bay under study. Unfortunately, none of these studies has investigated the correlation between the observed variations in sea level and meteorological conditions over AQB. Thus, this work is the first attempt to spotlight this correlation, considering air temperature, atmospheric pressure and wind regime.

MATERIALS AND METHODS

The sea-level data were obtained on an hourly basis from an automatic Inter-Ocean Wave and Tide Gauge (WTG904 Version 3.009) installed and operated by Abu-Qir Harbour Authority (31°19.54’ N, 30°04.5’ E; Fig. 1). The data were referred to the zero level of the instrument. The data covered 3 years from 01-Jan-2008 to 03-Dec-2010, which means 25632 hours. However, gaps existed and the obtained data were only for 24792 hours (96.7 %). A simultaneous hourly meteorological data set was obtained from the automated weather station (62318) at Alexandria International Airport:
www.ncei.noaa.gov/access/search/data-search/global-hourly?stations=%5B62318099999%5D
This consisted of air temperature, atmospheric pressure and wind regime (speed and direction).

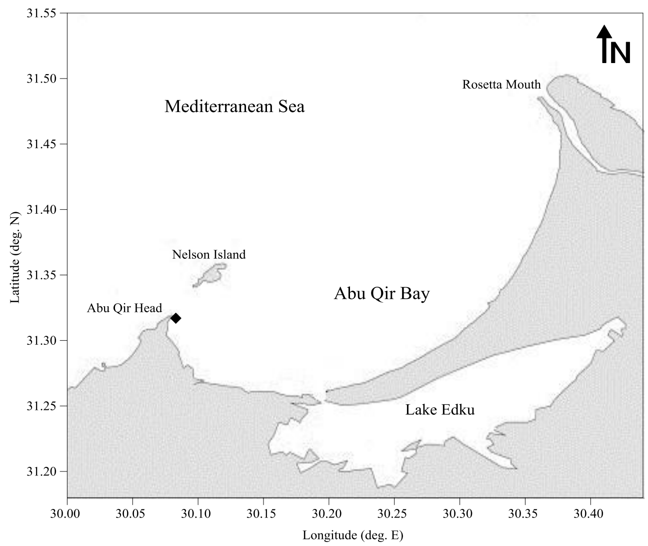


Fig. 1. General map of Abu Qir Bay and the deployment site of tide gauge (♦)

The present sea-level analysis was performed by applying the T_Tide software **(Pawlowicz *et al.*, 2002)**. This provided the astronomical tidal constituents and residual elevations in AQB during the period of interest. The main governing equation of the T_Tide package is given as:

$$\eta(t) = \sum_n A_n \cos\left(\frac{2\pi}{T_n} t + \phi_n\right) \quad (1)$$

Where, η(t) is the vertical movement of the sea surface as a function of time (cm); A_n = the amplitude of a harmonic component (cm); T_n is the period of a harmonic component (s) and ϕ_n is the phase of harmonic component.

A signal-to-noise power ratio (SNR), which is the square of the ratio of amplitude to amplitude error larger than 1 was used to identify the significant components, which are shown with a "*" in the output sheet **(Pawlowicz *et al.*, 2002)**. The ratio of the principle diurnal (O_1 and K_1) to the principle semidiurnal (M_2 and S_2) amplitudes, known as the Form Factor, was determined to specify the nature of tidal cycle in the studied bay. The featured water levels dominating AQB were calculated according to **Doodson (1957)**.

A zonal component (W_x) and a meridional one (W_y) were used to analyze the wind data as follows:

$$W_x = W \sin[(\emptyset+180) \times (3.14)/180] \quad (2)$$

$$W_y = W \cos[(\emptyset+180) \times (3.14)/180] \quad (3)$$

Where,

W_x and W_y are the zonal and meridional wind components, respectively (cm/s);

W is the total wind speed recorded at the meteorological station (cm/s), and

ϕ is the wind direction measured from the True North (°)

The direct correlations between the three meteorological parameters and the observed sea level in AQB were calculated using Microsoft Excel® 2010 and presented in this work.

RESULTS AND DISCUSSION

1. Sea-level Characteristics in Abu-Qir Bay

The result of the sea-level analysis, using the T_Tide package is shown in Fig. (2). The hourly sea-level records varied between 5.0 and 99.7cm above the zero level of the instrument (Fig. 2), i.e. 94.7cm in range, with a mean sea level (MSL) of 50.1cm. This was previously determined as 52.0cm over the two years of 2005 and 2006 **(El-Geziry, 2013)**, 50.1cm over the period of 2005-2010 **(El-Geziry and Said, 2014)** and 47.0cm over 21 years from 1990 to 2010 **(Said *et al*., 2019)**, with their data referred to the zero level of the tide gauges. The difference between the calculated means may be primarily attributed to the different spans over which the mean is calculated. The general statistics of the monthly sea level are shown in Table (1). Fig. (3) depicts the month-to-month variations in the calculated MSL in AQB. This reflects a seasonal behavior with the lowest value (38.6cm) attained in spring and highs exceeding 50.0cm in summer (54.0cm), autumn (58.7cm) and winter (56.1cm). This seasonality is mainly attributed to the atmospheric scheme impacting the eastern Mediterranean basin, with highs and lows **(Tsimplis *et al*., 2005)**. The strong NW wind dominating the region during this season can be blamed for the area's higher MSL in autumn and winter, which causes a severe damage to the coastal infrastructure and minor flooding of lowlands inside the territory of AQB **(Said *et al*., 2019)**. This seasonal pattern coincides with that of **Said *et al*. (2019)** who declared the lowest monthly MSL of 40.0cm in spring and the highest monthly MSL of 52.0cm in autumn for the AQB. Additionlly, **El-Geziry and Said (2020)** calculated the lowest monthly MSL of 41.0cm in April (spring) and the highest monthly MSL of 52.0cm in November (autumn). This seasonal pattern is also consistent with that previously figured at several places over the lengthy Egyptian Mediterranean coastline, e.g. Mersa Matruh, Alexandria Western Harbor, Alexandria Eastern Harbor, El-Burullus New Harbour and Port Said **(Moursy, 1998; Khedr *et al*., 2018; El-Geziry & Said, 2019; Said *et al*., 2019; El-Geziry & Said, 2020; El-Geziry, 2021; Ibrahim, 2021; El-Geziry & El-Wakeel, 2022)**.

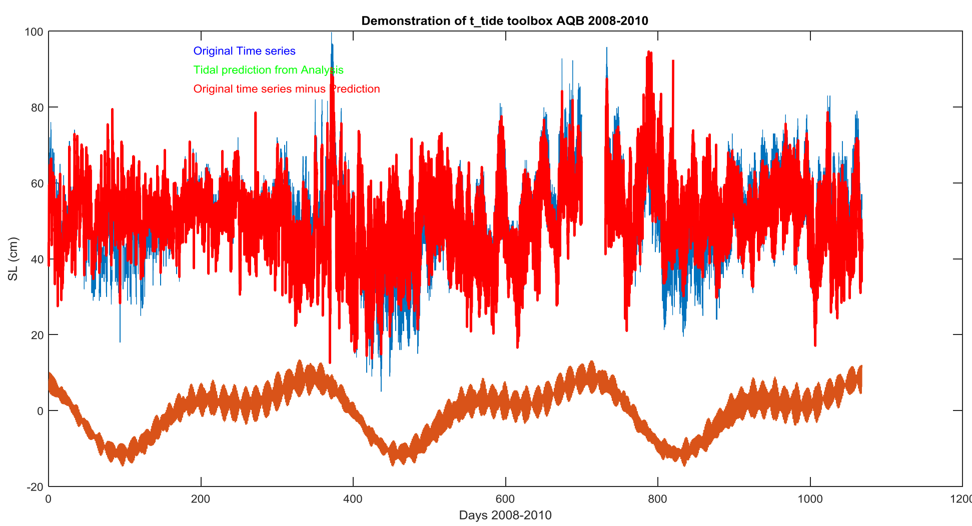


Fig. 2. Sea-level analysis in AQB (2008-2010) produced by the T_Tide package

Table 1. Statistical characteristics of monthly sea level in Abu-Qir Bay (2008-2010)

	Jan	Feb	March	April	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Min. (cm)	21.0	9.0	5.0	15.0	21.0	31.0	26.0	23.0	21.0	18.0	29.0	36.0
Max. (cm)	99.7	89.7	86.0	65.5	69.0	73.0	74.0	81.0	78.0	83.0	92.8	82.0
Range (cm)	78.7	80.7	81.0	50.5	48.0	42.0	48.0	58.0	57.0	65.0	63.8	46.0

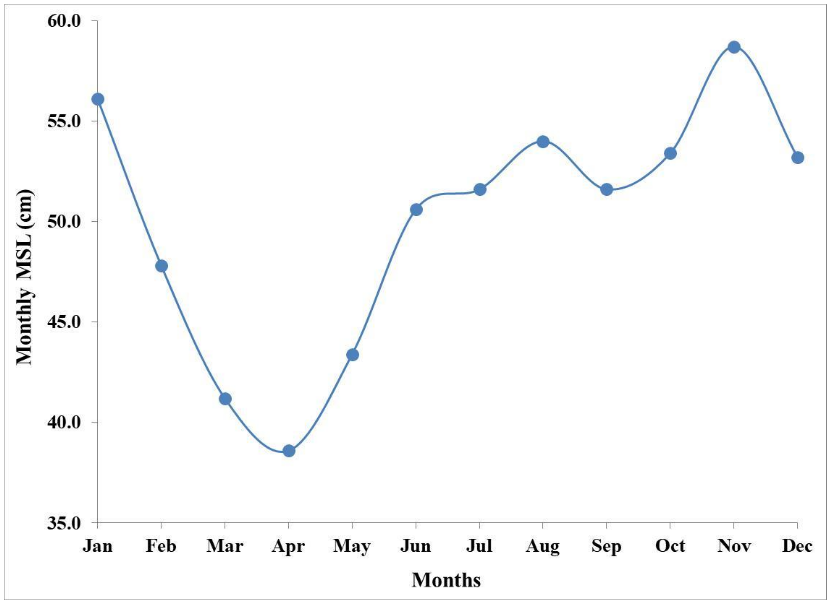


Fig. 3. Monthly MSL variations in AQB (2008-2010)

2. The Astronomical Tides

The sea-level analysis revealed that the hourly elevations of astronomical tides at AQB fluctuated between -14.80 and 13.40cm, with a tidal range of 28.2cm. This range was previously calculated over the period of 2005-2010 (30.0cm) **(El-Geziry and Said, 2014)**. The T_TIDE package produced 69 tidal constituents of which 19 were significant (Fig. 4). Table (2) shows a comparison between the present and previous amplitudes and phases of the four main diurnal and semidiurnal components in AQB. In this work, the Sa and SSa constituents were significant and had the greatest amplitudes of 7.2 and 4.6cm, respectively. This agrees with the findings of **Vigo *et al*. (2011)** who declared that, the annual cycles amplitudes in the Mediterranean Sea range between 4.0 and 11.0cm. According to the present results, the form factor is 0.25, which means that the tides in AQB are semidiurnal. This factor was previously calculated for AQB with 0.24 **(El-Geziry & Said, 2014)** and 0.21 **(Said *et al*., 2019)**. **El-Geziry (2013)**, on the other hand, reported a mixed mainly semidiurnal tidal cycle in AQB, with a form factor of 0.50. This difference can be attributed to the smaller principle semidiurnal amplitudes (Table 2) produced by the World Tides package used by **El-Geziry (2013)** in his research. The main tidal level characteristics in AQB are shown in Table (3). These practicable water levels should be considered when designing coastal infrastructure or coastal protection and in the planning of beachfront framework since flooding is a major concern in bays, semi closed basins, estuaries and ports at these undeniable levels **(Nimura, 2013; Hill, 2015; Said *et al*., 2019)**.

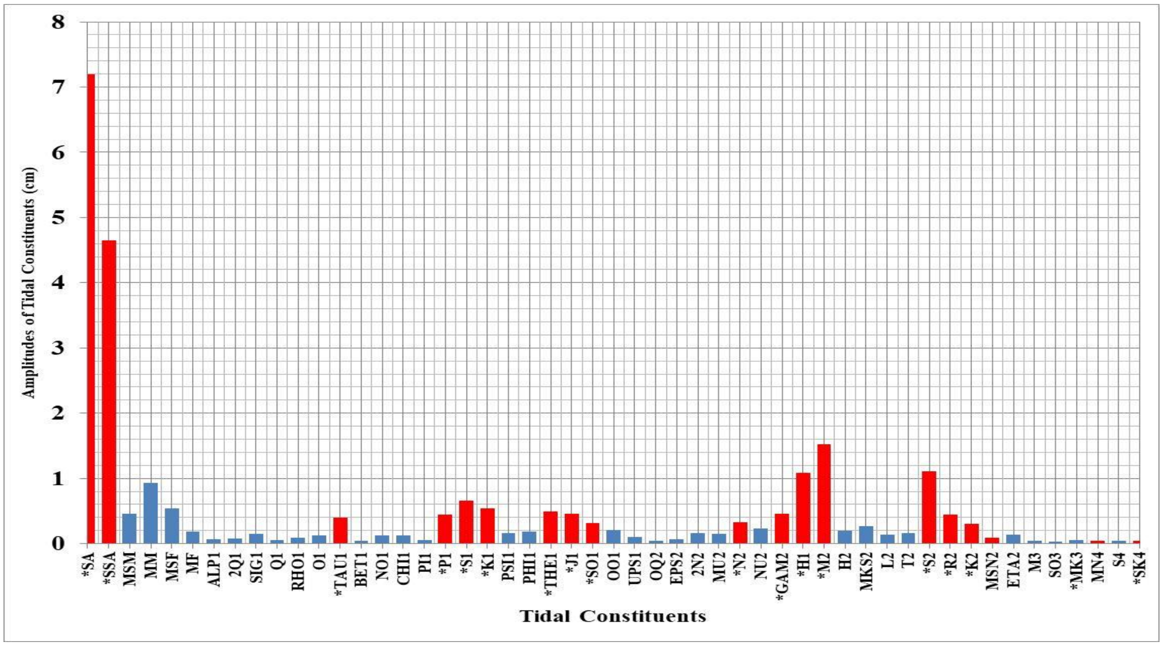


Fig. 4. Astronomical constituents and their amplitudes affecting AQB during the study period (Red bars denoting the significant constituents)

Table 2. Comparison between the results of this study and those previously carried out in AQB

	Present study		**El-Geziry (2013)**		**El-Geziry and Said (2014)**		**Said *et al*. (2019)**	
Data span	2008-2010		2005-2006		2005-2010		(1990-2010)	
	A (cm)	Φ (°)	A (cm)	Φ (°)	A (cm)	Φ (°)	A (cm)	Φ (°)
O1	0.1	274.1	0.3	179.8	0.3	210.7	0.2	238.5
K1	0.5	317.8	0.4	348.0	0.3	101.3	0.4	320.6
M2	1.5	328.6	0.8	247.9	1.8	173.1	1.6	251.5
S2	1.1	316.7	0.5	332.6	0.6	288.4	1.3	306.6

Table 3. Sea-level characteristics calculated in this study compared to previous research on AQB

	Present study	**Said *et al*. (2019)**	**El-Geziry and Said (2020)**
MSL (cm)	50.1	47	48
Highest high water level (cm)	53	51	53
Lowest low water level (cm)	47	44	43
Highest range of tides (cm)	6	7	10
Mean high water spring (cm)	53	50	51
Mean low water spring (cm)	48	45	45
Mean spring range (cm)	5	5	6
Mean high water neap (cm)	51	48	49
Mean low water neap (cm)	50	47	47
Mean neap range (cm)	1	1	2
Spring to neap ratio	5	5	3

3. The Residuals

In AQB, the residual elevations varied between 12.5 and 94.7cm over the period of interest, with a range of 82.2cm. This range was formerly determined to be 68.0cm **(El-Geziry, 2013; El-Geziry & Said, 2014)**. The residuals had a mean of 50.7cm over the period from 2008 to 2010. This is higher than the calculated MSL (50.1cm), which may confirm the upper hand of residuals (meteorological-induced elevations) in the sea-level fluctuations in AQB. This is consistent with the conclusions of **El-Geziry (2013)**. The frequency of the residual occurrence (Fig. 5) revealed that they varied between 4 hourly events (15cm) and 5490 hourly events (55cm). Storm surges affecting the bay under study were concentrated on residual levels above 65cm elevations, with 6.8% occurrence.

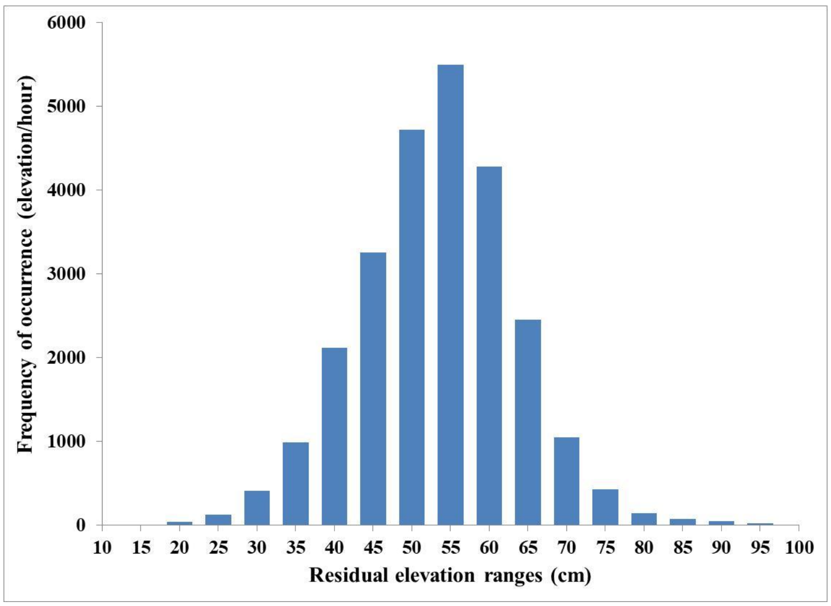
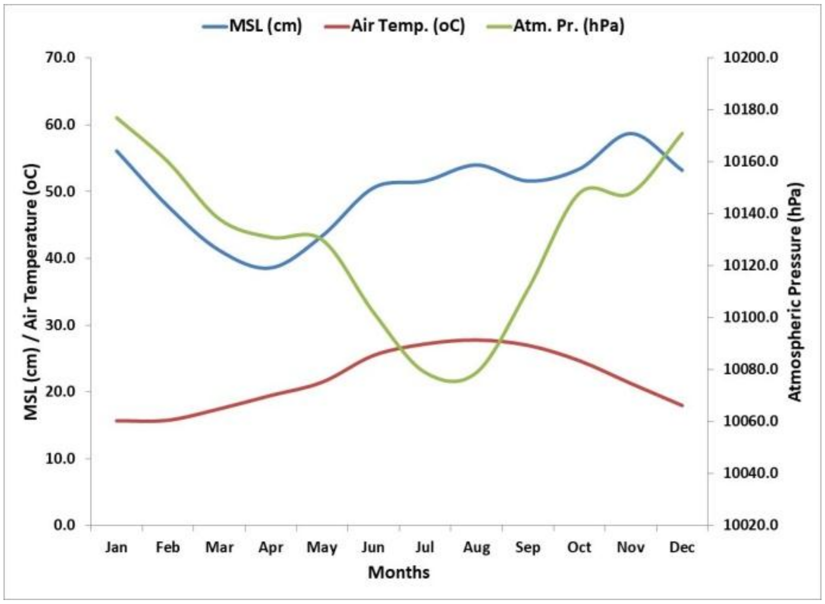


Fig. 5. Occurrence frequency of different residual levels at AQB (2008-2010)

3. Correlations of sea level to the meteorological conditions in Abu-Qir Bay

Fig. (6) depicts the monthly MSL versus the dominant meteorological elements. To graphically illustrate the relationships between the examined variables, The inverse relationships with air temperature and atmospheric pressure were clearly detected. Moreover, the dominancy of the W_y component with its inverse relationship to the monthly MSL could easily be observed, compared to the W_x component.



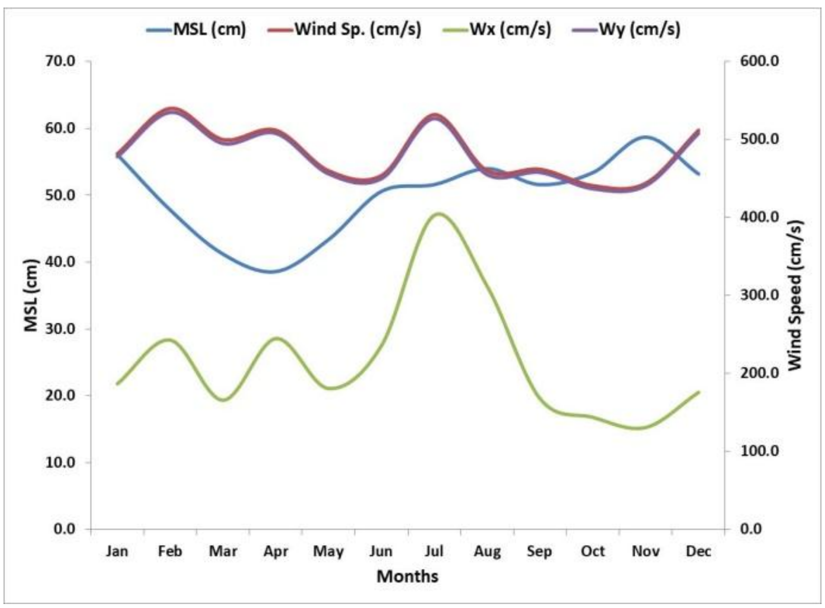


Fig. 6. The relationships between the monthly MSL, air temperature, atmospheric pressure (upper) and wind speed (lower) for AQB (2008-2010)

Table (4) displays the correlation coefficients between the hourly sea levels and atmospheric conditions in AQB during the period of interest. Although the coefficients are generally weak, they depict the normal relationships between sea level and meteorological parameters. The sea level in the bay under discussion is double-affected by the zonal wind (0.12) than the meridional one (0.06). This is consistent with the natural morphometry of the Bay (Fig. 1). The correlation to the total wind speed was previously calculated by **El-Geziry (2013)** to be 0.19, i.e. 3 times the present results. This may be attributed to the different spans in the two studies. However, the present study and that of **El-Geziry (2013)** declared that the correlation to the wind direction is 0.14. Additionally, these coefficients declare the higher impact the air temperature has on the observed sea-level variations in AQB than any other meteorological parameters.

Furthermore, the correlation coefficients between the monthly MSL and the monthly means of the different meteorological parameters affirm the above-mentioned relationships concluded on an hourly basis (Table 5). Air temperature is still the major meteorological player affecting the sea level (0.25), and atmospheric pressure is still correlated with a coefficient of -0.06 on a mean monthly basis. The coefficients changed to +0.02 for the wind direction and +0.07 for W_x, but it has been reversed to -0.36 for W_y.

Table 4. Correlation coefficients between hourly sea-level records and hourly recorded meteorological parameters in AQB durig the study period

	Air Temp. (°C)	WD (°)	WS (cm/s)	Atmos. Pres. (hPa)	W_x (cm/s)	W_y (cm/s)	SL (cm)
Air Temp. (°C)	1.00						
WD (°)	0.24	1.00					
WS (cm/s)	-0.03	0.13	1.00				
Atmos. Pres. (hPa)	-0.66	-0.23	0.02	1.00			
W_x (cm/s)	0.09	0.10	0.48	-0.10	1.00		
W_y (cm/s)	-0.03	0.13	1.00	0.03	0.48	1.00	
SL (cm)	0.27	0.14	0.06	-0.06	0.12	0.06	1.00

Table 5. Correlation coefficients between monthly MSL and monthly mean meteorological parameters in AQB over the study period

	Air Temp. (°C)	WD (°)	WS (cm/s)	Atmos. Pres. (hPa)	W_x (cm/s)	W_y (cm/s)	SL (cm)
Air Temp. (°C)	1.00						
WD (°)	0.78	1.00					
WS (cm/s)	-0.44	0.02	1.00				
Atmos. Pres. (hPa)	-0.85	-0.91	0.11	1.00			
W_x (cm/s)	0.40	0.72	0.50	-0.69	1.00		
W_y (cm/s)	-0.48	-0.02	1.00	0.16	0.47	1.00	
SL (cm)	0.25	0.02	0.07	-0.06	0.07	-0.36	1.00

CONCLUSION

To conclude, the recorded sea-level in AQB is of seasonal behavior, with a larger contribution in the observed variability of residuals than the astronomical tides. Storm surges with elevations greater than 65cm contributed up to 7% of the observed sea level in the bay under study. An immediate correlation between recorded sea-level and meteorological conditions was utilized to build our comprehension of sea-level variability in AQB. The sea-level fluctuations in the bay are more affected by air temperature than the atmospheric pressure or wind regime (whether zonal or meridional speeds).

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