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Tidal and Non- Tidal Sea Level off Port Said, Nile Delta, Egypt

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Abstract. In the current study, the observed sea level off Port Said is analyzed over one year (February/1999 to January 2000). The analyses use least square harmonic analyses to separate tidal part from the observed sea level. The direct correlation between sea level off Port Said and the sea surface temperature, mean sea level pressure together with 10m-wind speed components are used to understand the dynamic of sea level variability. The present study indicates that, the observed sea level off Port Said is significantly affected by the tidal part than the non-tidal part particularly during May and September months. Observed sea level off Port Said is significantly affected by mean sea level pressure and sea surface temperature. However, zonal and meridional wind speed has only a small effect on the sea level variations.

Keywords: tide, Port Said, mean sea level, sea surface temperature.

Introduction

The Nile Delta coast (Fig. 1) extends a distance of about 240 km along the Southeastern part of the Mediterranean Sea from Abu-Quir (31° 20'N, 30° 3'E) to Port Said (31° 15'N, 32° 30'E). It is considered as one of the most interesting natural laboratories not only because of its coastal processes and evolution of erosion and accretion, but also because of its economic and environmental importance related to human activity of agriculture, fish production, new industries and many maritime ports at Rosetta, Port Said and Damietta. Also, it has historical areas at Rosetta and Abu-Quir and beautiful beaches for tourists and Summer Sea resorts at Ras El-Bar and Gamasa. Recently dramatic discovery of the natural gas in the Nile Delta increases its economic importance.

Sea level variation studies attracted the interest of many oceanographers particularly in shallow areas. Lisitzin and Pattullo (1961) showed that, the steric effect is the dominant factor affecting the seasonal sea level variation in low and subtropical latitudes, however atmospheric pressure is the more important factor in higher latitudes areas. Mobarek and Anis (1974) analysesd sea level off Port Said from 1926 to 1973 and they calculated the highest high water level (HHWL) and the lowest low water level (LLWL) to be 60 cm and -20 cm respectively. They also expected that the maximum water level occur under the joint occurrence of storm and spring tides. Tetra Tech (1984) showed that, the tide along the Nile Delta coast is a semi diurnal in nature with mean and extreme ranges of tide of 17 and 118 cm respectively. Sharaf El Din *et al.* (1989) analyzed sea level off Port Said over 49 years from 1924 to 1976 and they found that the mean sea level is about 49.6 cm above the survey development zero level. They found also that the monthly mean sea level changes exhibit a seasonal range with low (higher) value during winter (summer) season. El Fishawi, (1993) showed that sea level off Port Said describes a significant positive trend of 1.3 mm yr-1 during the period 1926-1987. The Mediterranean sea level shows a significant trend since the last two decades due to thermal expansion (Cazenav *et al.*, 2001). Tsimplis and Rixen (2002) describe that the Mediterranean sea level variability is significantly affected by the steric effect.

Sea level along the Nile Delta coast as a part of the Mediterranean Sea is expected to have a significant positive sea level trend during the 21st century (Cazenav *et al.*, 2001 and IPCC, 2007). This may have a harmful effect especially for low land coastal areas as Nile Delta coast. In order to understand the dynamics of sea level along Nile Delta coast, hourly values of recorded sea level off Port Said over one year period has been used in the current study. This recorded hourly sea level is subjected to harmonic tidal analysis to investigate tidal characteristics and sea level variability off Port Said.

The paper aims to: (1) Study temporal sea level variability off Port Said, (2) apply the least square harmonic method to describe the tidal characteristics, and (3) evaluate sea level off Port Said variability due to sea surface temperature (SST), mean sea level pressure (SLP) and 10-m zonal wind speed (U) and 10-m meridional wind speed (V). The paper will give information on sea level spatial variability off Port Said. These results are expected to be useful to describe the dynamic of sea level variability in the study area.

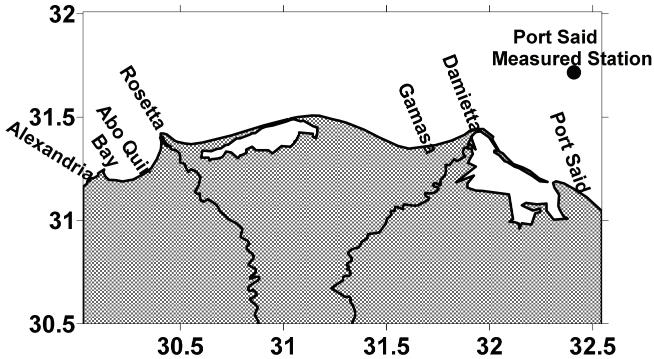

Fig. 1. Nile Delta coast showing the tide gauge station off Port Said.

Data and Methods of Analysis

This paper analyzes hourly sea level values off Port Said over one year period in terms of temporal and harmonic analysis. Sea surface temperature, mean sea level pressure, and 10m-wind data have been used to study their effects on sea level.

A-Data Used

Time series of sea level, SST, 10m-wind and SLP off Port Said coast (31° 43`N and 32° 24.5`E) at 45 m water depth for a period of 1 years extending from February-1999 to January-2000 were taken at an interval of 1 hour. These data were obtained from Fugro Global Environmental & Ocean Sciences (Fugro GEOS) using an Aanderaa Automatic Meteorological Station.

B- Methodology

Observed hourly sea level off Port Said is subjected to:

I. Descriptive statistical analyses to get the hourly, daily, monthly and seasonal sea level characteristics.

II. Least square harmonic analyses to separate its tidal and non-tidal components using World tide Matlab toolbox (Boon, 2004 & Boon, 2004) *via* http://www.mathworks.com/matlabcentral/fileexchange/24217-world-tides. The world tide toolbox calculates up to 35 tidal harmonic constituents and the equations are described in appendix A1. These constituents are used to predict previous, current and future tidal sea level. In the current study, only the important five tidal constituents (M2 (1.932 cycles/day, or cpd)), S2 (2 cpd), N2 (1.896 cpd), K1 (1.003 cpd), and O1 (0.930 cpd)) are used to describe Port Said tidal constituents. M2 is the principal lunar semidiurnal constituent and represents the rotation of the Earth with respect to the Moon. S2 is the principal solar semi diurnal constituent and represents the rotation of the Earth with respect to the Sun. N2 is the larger lunar elliptic semi diurnal constituent. K1 is lunisolar diurnal constituent. O1 is lunar diurnal constituent. K1 with O1 constituents expresses the effect of the Moon's declination. Moreover to analyze the sensitivity of the world tide Matlab toolbox, a sensitive run were performed by using all the 35 tidal constituents. Generally, t-test is used to determine whether the difference between the two runs is significant or insignificant.

III. Direct correlation with SST, SLP, U and V to describe the meteorological effect on sea level off Port Said.

Results

1- *Temporal Variation off Port Said Sea Level.*

Hourly sea level off Port Said described a range of 77 cm fluctuated from 38 cm to -39 cm with an average value of 0±12 cm as shown in Fig. 3. There is a significant monthly average sea level variation off Port Said ranged from 7.4 cm during July to -7.1 cm during December (Fig. 2a).

Moreover, there is a significant lunar sea level cycle (=29.53 day) off Port Said during the study year ranged from 3.4 cm during the day twelve of lunar cycle to -3.7 cm during the day five of lunar cycle (Fig. 2b).

There is a significant hourly sea level variation off Port Said during the day reaches its maximum values 6 cm at 0009 and 2100 while reaches its minimum values -6 cm at 0003 and 1500 as seen in Fig. 2c. This indicates that the sea level off Port Said has a semidiurnal tidal cycle.

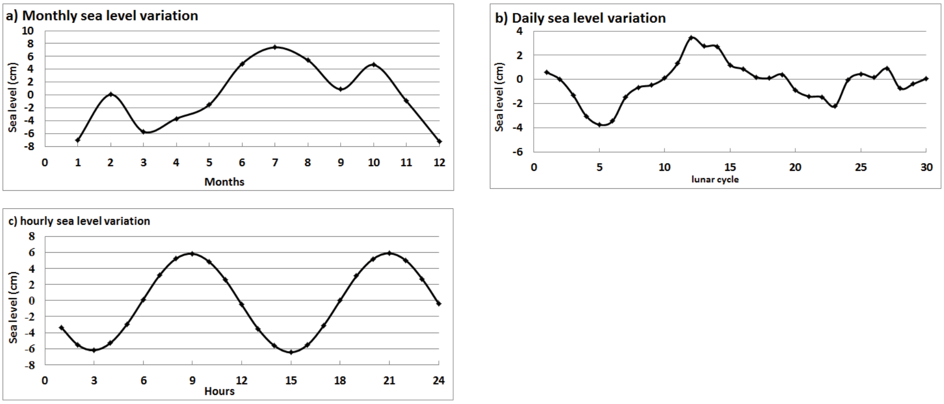

Fig. 2. Monthly and hourly variation of sea level off Port Said from February/99 to January/2000.

In addition to that, monthly statistics of observed sea level (Table. 1) showed that the highest high water level (HHWL) and the lowest low water level (LLWL) are changed from month to month, partly indicate that the observed sea level off Port Said has a significant annual cycle. The HHWL ranged from 39 cm during 23th November/1999 at 2000 to 19 cm during 29th and 30th May/1999 at 0700. While, LLWL ranged from -38 cm during 22nd December/1999 at 2000 to -14 cm during 28th July/1999 at 1400. The monthly range of the observed sea level ranged from 64 cm during June to 56 cm during December.

Table 1. The monthly observed sea level characteristics off Port Said from February/99 to January/2000.

Month	Highest high water level (HHWL)		Lowest low water level (LLWL)		Sea level range (cm)
	Water Level (cm)	Time Day-Month-Year Hours	Water Level (cm)	Time Day-Month-Year Hours	
February/1999	33	13-02-1999 18	-31	20-02-1999 04	**64**
March/1999	25	19-03-1999 21	-37	04-03-1999 15	**62**
April/1999	21	18-04-1999 09	-29	15-04-1999 13 15-04-1999 14 16-04-1999 01 16-04-1999 02 16-04-1999 14	**50**

Month	Highest high water level (HHWL)		Lowest low water level (LLWL)		Sea level range (cm)
	Water Level (cm)	Time Day-Month-Year Hours	Water Level (cm)	Time Day-Month-Year Hours	
May/1999	19	29-05-1999 07 30-05-1999 07	-26	14-05-1999 13 15-05-1999 14	**45**
June/1999	27	14-06-1999 08 29-06-1999 08	-16	01-06-1999 15	**43**
July/1999	36	14-07-1999 08 14-07-1999 09	-14	28-07-1999 14	**50**
August/1999	28	11-08-1999 07 11-08-1999 08 12-08-1999 08	-15	28-08-1999 15 29-08-1999 15	**43**
September/1999	30	25-09-1999 07 25-09-1999 08	-21	09-09-1999 14	**51**
October/1999	37	25-10-1999 20	-16	13-10-1999 03	**53**
November/1999	39	23-11-1999 20	-28	07-11-1999 01	**67**
December/1999	30	22-12-1999 20	-38	22-12-1999 20	**68**
January /2000	25	05-01-2000 19	-31	23-01-2000 03	**56**

2- *Tidal Characteristics off Port Said Sea Level.*

Least square harmonic analyses method is used to separate tidal (astronomical) part from observed sea level based only the important five tidal constituents (M2, S2, N2, K1, and O1) and the result is shown in Fig. 3. Astronomical annual tide ranged from the highest Astronomical Tide (HAT) values of 21.5 cm to the lowest Astronomical Tide (LAT) values of -21.2 cm. Moreover, tidal range showed a monthly behavior ranged from 36.9 cm during September to 42 cm during December (Fig. 3).

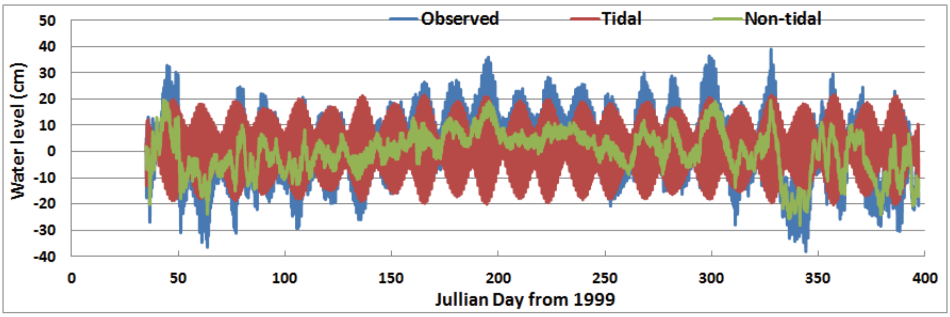

Fig. 3. Hourly observed, tidal, and non-tidal sea level off Port Said from February/99 to January/2000. (The run is based only on the important five tidal constituents).

From the least square harmonic analyses method, the most significant tidal harmonic constituents (amplitude and phase) are calculated as seen in Table 2. From this table, the tidal form ratio (F = (K1+O1) / (M2+S2)) indicate that sea level off Port Said described a fully semidiurnal tidal regime; F= 0.23.

Table 2. Tidal harmonic constituents off Port Said from February/99 to January/2000.

Tide Constituent	**Amplitude (cm)**		**Phase**	
	For the run used only the important five tidal constituents	For the run used All 35 tidal constituents	For the run used only the important five tidal constituents	For the run used All 35 tidal constituents
O1 (lunar diurnal)	1.6	1.6	192.28	192.77
K1 (lunisolar diurnal)	2.2	2.2	255.89	256.16
N2 (larger lunar elliptic semi diurnal)	1.8	1.8	89.13	87.97
M2 (the principal lunar semidiurnal)	10.4	10.4	169.77	169.87
S2 (principal solar semi diurnal)	6.2	6.2	237.2	337.35

In addition to that, separation of tidal part from observations described that there is a significant monthly variation of tidal weight (%) incomparable to non-tidal (Observation –tidal) weight. The monthly tidal weight is calculated as

$$\left(100\frac{|\text{tidal monthly average}|}{|\text{tidal monthly average}|+|\text{non-tidal monthly average}|}\right),$$

however the monthly non-tidal weight is calculated as

$$\left(100\frac{|\text{non-tidal monthly average}|}{|\text{tidal monthly average}|+|\text{non-tidal monthly average}|}\right)$$

to indicate the weather part has a significant effect on the observed sea level off Port Said. Generally tidal components describe 54% of the sea level observation off Port Said during the study period most pronounced during the respective May, September, April and June months (Table. 3). This may indicate the importance of tidal part and non-tidal part on the observed sea level.

Table 3. Annual/ Monthly tidal and non-tidal weight (%) of total water level observation.

Month	Tidal (%)		Non-Tidal (%)	
	For the run used only the important five tidal constituents	For the run used All 35 tidal constituents	For the run used only the important five tidal constituents	For the run used All 35 tidal constituents
February/1999	47	47	53	53
March/1999	52	53	48	47
April/1999	64	65	36	35
May/1999	71	73	29	27
June/1999	58	58	42	42
July/1999	50	49	50	51
August/1999	57	58	43	42
September/1999	67	69	33	31
October/1999	53	54	47	46
November/1999	57	58	43	42
December/1999	41	41	59	59
January /2000	46	46	54	54
Annual	54	55	46	45

T-test is used to examine the significant difference between two sensitivities run of the World tide Matlab toolbox. T-test indicates insignificantly change between two sensitivities runs (Table 2 and 3). Moreover, there is an insignificant change in HAT and LAT values among the two sensitivities runs. This may suggest that the tidal sea level off Port Said may be calculated only by using the constituents M2, S2, N2, K1, and O1.

Generally, the harmonic analysis for the sea level off Port Said (Fig. 4) shows that the most significant sea level cycles off Port Said are respective semi diurnal, annual and lunar cycles.

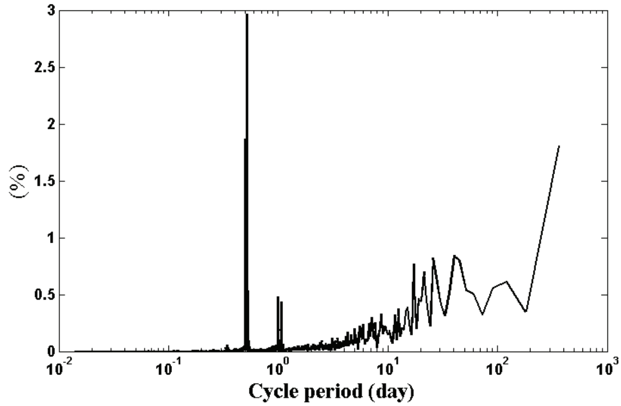

Fig. 4. The preiodogram off Port Said from February/99 to January/2000.

3- ***The Effect of Sea Surface Temperature, Mean Sea Level Pressure, and Wind on Observed Sea Level off Port Said.***

Figure 5 shows direct comparison between observed hourly sea level off Port Said with sea surface temperature (SST), mean sea level pressure (SLP), zonal wind (U) and meridional wind (V) to evaluate their effects on the observed sea level. There is a low significant correlation between hourly observed sea level off Port Said and the respective SLP (correlation coefficient ‘R’ = -0.35, number of observation ‘N’= 8000, level of Significance (P) <0.01), SST (R=0.31, N=8000, P <0.01) and U (R=0.16, N=8000, P=0.1). However, there is insignificant correlation between V and observed sea level. This is may indicate the importance of SLP and SST on the observed sea level off Port Said.

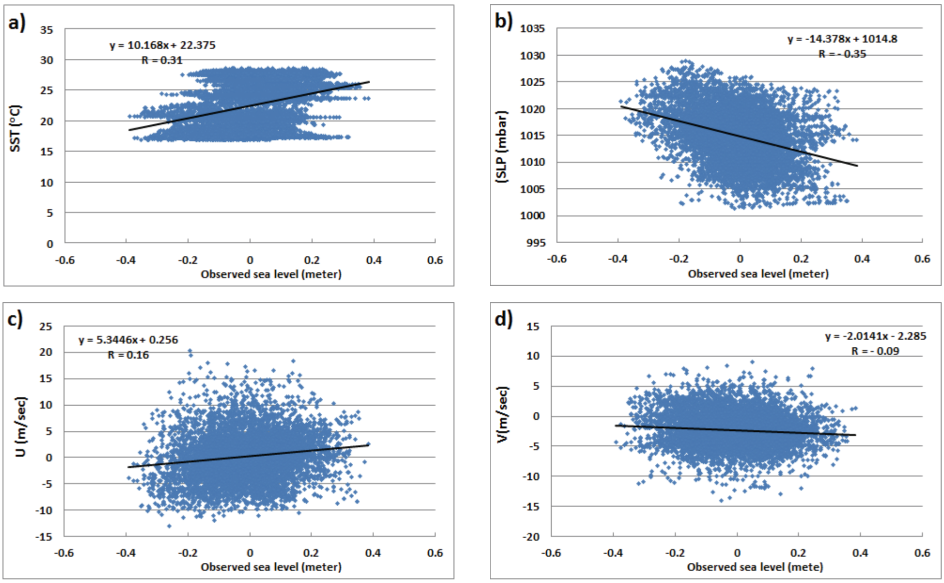

Fig. 5. The effect of hourly sea surface temperature (SST), mean sea level pressure (SLP), zonal wind (U) and meridional wind (V) on observed sea level off Port Said.

Monthly direct correlation between observed sea level off Port Said and the other studied parameters (Fig. 6) indicate that the sea level off Port Said is in significant monthly correlation with only SLP (R = -0.79, N= 12, P <0.01), SST (R=0.75, N=12, P <0.01) and V (R=-0.57, N=12, P=0.06).

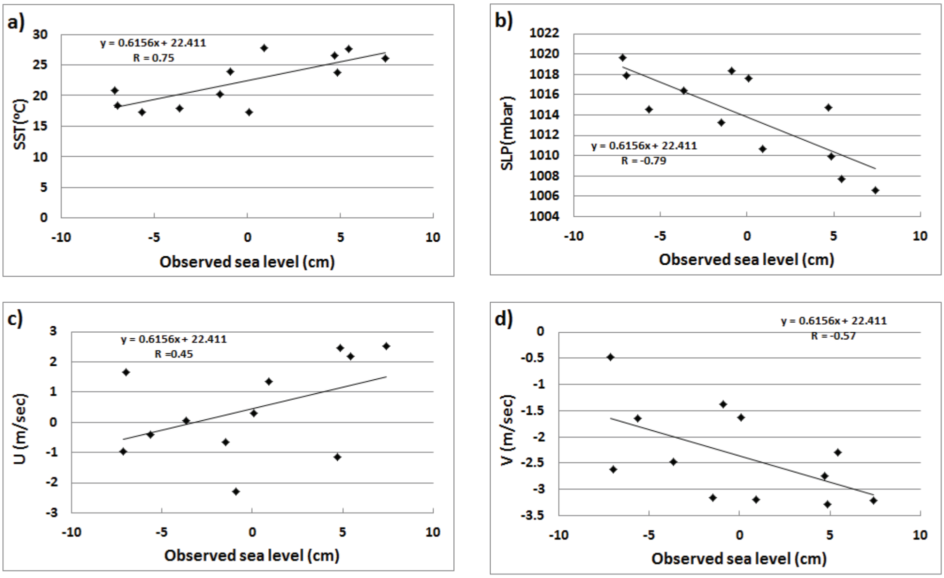

Fig. 6. The effect of monthly sea surface temperature (SST), mean sea level pressure (SLP), zonal wind (U) and meridional wind (V) on observed sea level off Port Said.

Discussion

The current study analyses sea level off Port Said at 45 m water depth over one year started from February 1999 to January 2000. This analysis is based on 1) temporal variation for the observed sea level, 2) separate tidal part from observed sea level using least square harmonic analyses, and 3) examine the effects of sea surface temperature, mean sea level pressure, 10m-zonal wind and 10m-meridional wind speed on the observed sea level.

Observed sea level off Port Said showed a significant hourly, daily and monthly variation. Hourly variation describes two cycles per day. While the daily variation showed highest sea level during full moon and new Moon days (spring tide; the Sun, the Moon, and the Earth are aligned) and showed lowest sea level during neap tide (Sun and Moon are at right angles to the Earth). During full Moon days, sea level off Port Said showed higher values than new moon days. The monthly variation range of sea level reached its maximum (minimum) values during summer (winter) season. This agrees with the previous findings of Sharaf El Din *et al*. (1989). The range between the highest water level and the lowest water level is 77 cm, which agrees with Mobarek and Anis (1974).

Tidal sea level is separated from observed sea level using least square harmonic analyses method. The present study suggests that using of the tidal constituents M2, S2, N2, K1, and O1 are sufficient to calculate tidal sea level off Port Said. Sea level off Port Said showed a fully semidiurnal tide of 42 cm annual tidal range and present about 54% of annual observed sea level, while 46% of observed sea level is presented by non-tidal sea level. This may suggest that the tidal predication is not sufficient to forecast sea level off Port Said (non-tidal part have to be considered).

Direct comparison between observed sea level and the other meteorological and oceanic components are used to increase our understanding of sea level variability. Mean sea level pressure, and sea surface temperature significantly affect the observed sea level off Port Said.

Finally, the research indicate that, the maximum water level off Port Said occurs under the triple occurrence of full moon days, lowest mean sea level pressure and height sea surface temperature (Fig. 7). The study area is characterized by the annual average values of sea level pressure (sea surface temperature) of 1013.9±5.1 mbar (22.3± 3.9°C) fluctuated from 1028.4 to 1000.5 mbar (16.8 to 28.6°C).

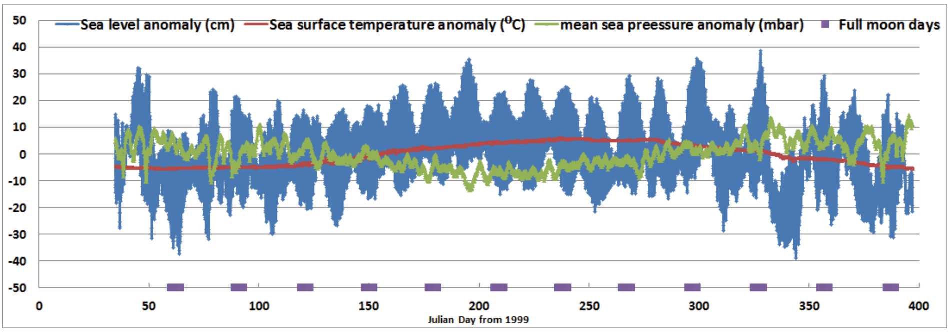

Fig. 7. Hourly time series anomalies of observed sea level, sea surface temperature and mean sea level pressure off Port Said. (Full moon days also display over the Julian Day x-axis).

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Appendix A1. WORLD TIDES

WORLD TIDES Matlab toolbox is an ideal package for tidal predictions from sea level observations ranging from several weeks to several months. This toolbox analyzes recorded sea level using Least Square Harmonic Analysis method to separate tidal predictable components. Thus, a tidal height prediction can be performed.

To calculate the predicted water level h (t), the equation for the harmonic model was used, assuming that the tidal motion is represented by the sum of a series of simple harmonic terms (tidal constituents):

$$h(t) = h_0 + \sum_{j=1}^{m} f_j H_j \cos(\omega_j t + u_j - k^*_j) \quad (1)$$

Where;

t is the time in serial hours, h_0 is the mean water level, f_j is the lunar node factor for j^{th} constituent, H_j is the mean amplitude for j^{th} constituent over 18.6-year lunar node cycle, ω_j (u_j) is the frequency (nodal phase) of j^{th} constituent, k^*_j is the phase of j^{th} constituent for the time origin in use (midnight beginning December 31, 1899), m is the number of constituents (for more details see *e.g.* Doodson and Warburg, 1944 reprinted 1980).

Least Square Harmonic Analysis method is used to compute H_j and k^*_j by assuming a solution for the harmonic constants that will produce the minimum possible sum of squared differences for a series of observations ht of length n:

$$\sum_{t=1}^{n} [h_t - h(t)]_2 = \text{minimum} \quad (2)$$

From 1 and 2

$$h(t) = A_0 + \sum_{j=1}^{m} A_j \cos \omega_j t + \sum_{j=1}^{m} B_j \sin \omega_j t \quad (3)$$

Where;

$$A_o = h_o,\ Rj = \sqrt{A_j^2 + B_j^2 = f_j H_j}\ ,\ \text{and}\ \ \phi_j = \tan^{-1}\left(\frac{B_j}{A_j}\right) = k^*_j - u_j$$

A_o, A_j and B_j are obtained by solving the least squares approximations general matrix:

$$[C] = [SSX]^{-1}\,[SXY] \qquad (4)$$

Where; $[C] = [A_0\ A_1\ B_1\ A_2\ B_2\ \ldots\ A_m\ B_m]'$, $[SSX] = [X]'[X]$ and $[SXY] = [X]'[Y]$ where;

The symbol (') indicate matrix or vector transpose,

$$[X] = \begin{bmatrix} 1 & \cos\omega_1 t_1 & \sin\omega_1 t_1 & \ldots & \cos\omega_m t_1 & \sin\omega_m t_1 \\ 1 & \cos\omega_1 t_2 & \sin\omega_1 t_2 & \ldots & \cos\omega_m t_2 & \sin\omega_m t_2 \\ 1 & \cos\omega_1 t_3 & \sin\omega_1 t_3 & \ldots & \cos\omega_m t_3 & \sin\omega_m t_3 \\ \ldots & \ldots & \ldots & \ldots & \ldots & \ldots \\ 1 & \cos\omega_1 t_n & \sin\omega_1 t_n & \ldots & \cos\omega_m t_n & \sin\omega_m t_n \end{bmatrix}$$

And

$$[Y] = [h_1 \quad h_2 \quad h_3 \quad \ldots \quad h_n]'$$

تأثير المكونات المدية و غير المدية على مستوى سطح البحر أمام بورسعيد، دلتا النيل– جمهورية مصر العربية

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المستخلص. في الدراسة الحالية نجد أن قياسات مستوى سطح البحر أمام بورسعيد قد تم تحليلها لمدة عام واحد في الفترة من فبراير ١٩٩٩ و حتى يناير ٢٠٠٠م. تم استخدام التحليل التوافقي لأقل مربع لفصل المد والجزر عن قياسات مستوى سطح البحر الفعلية. العلاقة المباشرة لبيانات مستوى سطح البحر ودرجة حرارة سطح البحر ومتوسط قيمة الضغط عند سطح البحر جنبًا إلى جنب مع نظام الرياح استخدمت لفهم ديناميكية تغير مستوى سطح البحر. الدراسة الحالية أشارت إلى أن المد والجزر يؤثر بشكل كبير في مستوى سطح البحر أكثر من تأثير الأحوال الجوية خاصة في فصل الصيف. من بيانات مستوى سطح البحر أمام بورسعيد نجد أنه يتأثر بشكل كبير بدرجة حرارة سطح البحر ومتوسط قيمة الضغط عند سطح البحر. الرياح المحلية ليس لها سوى تأثير بسيط على تغيرات مستوى سطح البحر.

كلمات مفتاحية: المد والجزر، بورسعيد، الضغط الجوي عند مستوى سطح البحر، درجة حرارة سطح البحر.