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Tide variation and signals during 2000-2004 in the northern Gulf of Aqaba, Red Sea

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ABSTRACT

Variations of tide and mean sea level (MSL) were studied during the period August 2000-March 2004 in the northern Gulf of Aqaba to detect the seasonal differences of tide records and tide components signals. The study revealed seasonal cycle of the MSL in the northern Gulf, which was lower during summer than in winter due to the relative strong wind and higher evaporation during summer. The MSL during the year of 2003 was the lowest comparing to the other years during the study period which might be related to wind driven force and mixed layer depth. The statistical comparison analysis of the MSL among winters, springs and summers of the years 2000-2004 exhibited significant difference values ($p < 0.0001$) among springs and summers, whereas no significant differences among winters ($p \sim 0.1$) were manifested. Power spectrum analysis of the MSL revealed six distinguished signals with different periods that four of these signals (12.36, 6.19, 4.12 and 1.01 h) were superimposed by seiches in both the Gulf of Aqaba for the first mode and the Red Sea for the second and third mode with the principle harmonic components. The signals of 23.87 and 8.44 h are basically a luni-solar diurnal partial tide (*K*1) and a lunar terdiurnal constituent (M3), respectively.

Keywords: Sea Level; Seiches; Semi-Enclosed Seas; Gulf of Aqaba; Red Sea

1. INTRODUCTION

The Gulf of Aqaba is a unique semi-enclosed water body located at the northern end of the Red Sea (**Figure 1**). The seasonal variation of the sea surface temperature in the Gulf is about 6˚C - 7˚C with mean value of about 23.9˚C. The upper 200 m of the water column has different water mass characteristics during summer and winter. During summer, the stratification exists, while mixing condition dominates during winter. Below 200 m the water is homogenous during summer and winter [1-3].

The Gulf of Aqaba is located within the very warm portion of Sahara bio-climatic zone. The climate is arid with high evaporation (200 - 365 cmy^{-1}) and negligible precipitation (~2.2 cmy^{-1}) and runoff [4,5]. The area is influenced by the airflows from the Indian monsoonal trough and the Mediterranean low-pressure system [6]. Winds during all seasons of the year are fairly similar in terms of magnitude (mean: 4 - 5.5 ms^{-1}) and direction (90% northerly winds). During summer, winds represent a diurnal cycle, while no signals appear during winter and spring seasons [7-9].

The water inflow and outflow of the Gulf of Aqaba are controlled by sea level and density differences between the Gulf and the Red Sea. On the other hand, the sea level changes of the Gulf are determined by the water balance of the Red Sea, which depends on a real decrease of water volume due to intensive evaporation from sea surface, the variation of a positive component of water exchange through Bab el Mandeb and Suez Canal and the water redistribution in the sea due to the wind [8,10].

The present work focuses on investigating the seasonal variation of mean sea level (MSL) in relation to Global MSL, seasonal differences of tide records, and tide components signals in the northern Gulf of Aqaba in order to present a scientific rationale for possible planning and directing to the decision makers for durable development.

2. MATERIALS AND METHODS

A pressure sensor was deployed on a base settled on the bottom of coastal water in front of the Marine Science Station (MSS) in the northern Gulf of Aqaba (**Figure 1**). The water pressure measurements (mean sea level data) over the sensor were sent directly and continuously to the tide gauge with interval of 10 minutes. In addition, mean sea level (MSL) at a suggested bench mark nearby the tide gauge (**Figure 2**), which is represented a known altitude in proportionality to Global MSL, were measured using physical scales on the ground and correlated with the concurrently recorded MSL at the MSS by the tide gauge in order to generate a long term records of the MSL in the northern Gulf of Aqaba reference to Global MSL during the period August 2000-March 2004 (**Figures 1** and **2**). The spectrum and statistical analysis of tide were performed using MATLAB 5.3 software.

3. RESULTS

3.1. Long Term Mean Sea Level (MSL) Records

Weekly average of the MSL records (cm) in the years 2000-2004 in the northern Gulf of Aqaba revealed obvious variations from year to year (**Figure 3**). A decrease trend of the MSL during the study period was detected which is following the linear fit curve:

$$\mathbf{MSL} = -\mathbf{0.053t} + \mathbf{64.55};\ \mathbf{R}^2 = \mathbf{0.53},$$

where MSL is the mean sea level, t is the Julian days after August 1st, 2000.

This implies that the decrease rate of the MSL was 19.18 $\text{cm}\cdot\text{yr}^{-1}$ among the years 2000-2004. The monthly mean and standard deviation of the MSL records in the northern Gulf are shown in **Table 1**. The highest MSL

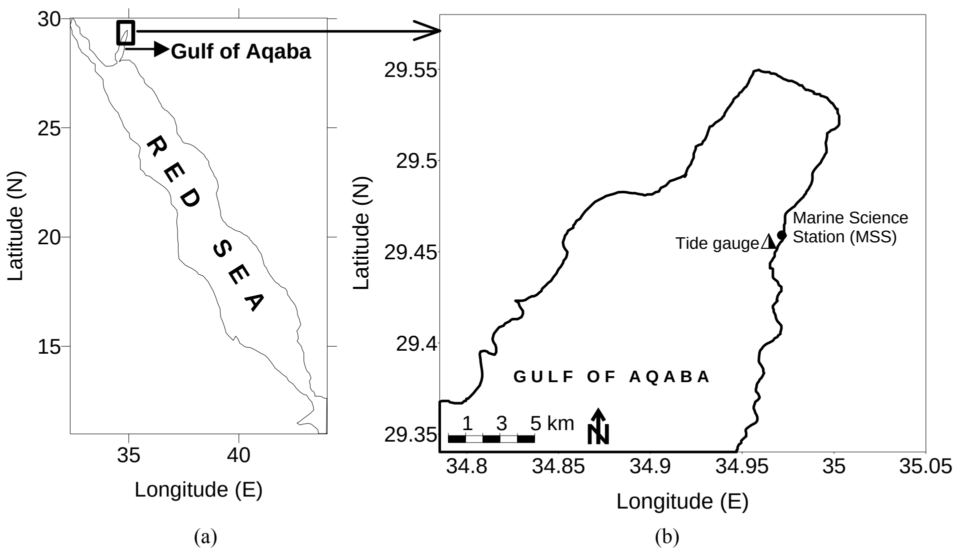

Figure 1. (a) Map of the Red Sea showing the location of Gulf of Aqaba and the study area. (b) Study area and tide gauge location in the northern Gulf of Aqaba.

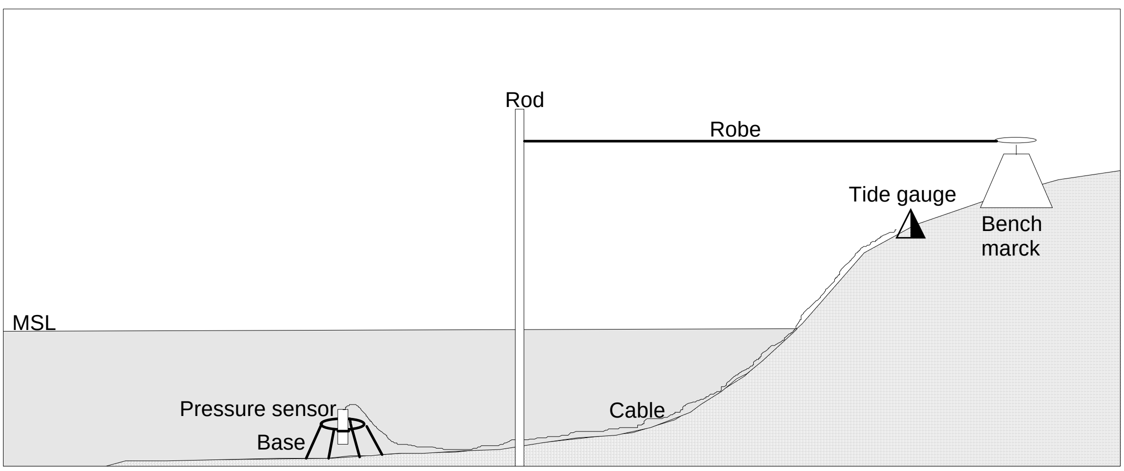

Figure 2. Schematic of the tide gauge measurement system in the northern Gulf of Aqaba.

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Table 1. Monthly statistical summary of the MSL (cm) records in the northern Gulf of Aqaba during the period August 2000-March 2004.

	Monthly average of MSL in the northern Gulf of Aqaba (cm)							
	Month	Mean	Min	Max	Range	Std dev	Std err	count
2000	Aug	40.1	−21.5	99.8	121.3	25.61	0.38	4464
	Sep	44.6	−12.3	108.7	121.0	25.44	0.39	4320
	Oct	50.2	−12.6	110.4	123.0	25.70	0.38	4464
	Nov	64.8	6.4	121.1	114.7	27.85	0.42	4320
	Dec	65.5	3.1	116.3	113.2	24.91	0.37	4464
2001	Jan	60.2	−15.9	127.5	143.4	27.43	0.46	3530
	Feb	59.0	−7.3	118.3	125.6	27.58	0.43	4032
	Mar	76.3	22.1	140.9	118.8	25.39	0.47	2970
	Apr	64.6	19.3	128.1	108.8	24.00	0.42	3330
	May	60.9	6.1	118.6	112.4	25.09	0.38	4464
	Jun	48.8	−2.0	95.9	97.9	23.96	0.36	4320
	Jul	49.6	1.7	106.2	104.6	23.78	0.36	4464
	Aug	36.4	−33.6	88.0	121.6	26.45	0.40	4456
	Sep	38.9	−24.1	105.7	129.8	27.31	0.42	4305
	Oct	52.4	−5.9	114.9	120.8	25.34	0.38	4448
	Nov	61.5	7.3	120.0	112.7	24.54	0.37	4311
	Dec	10.5	−58.7	120.2	179.0	38.69	0.58	4455
2002	Jan	24.6	−43.1	104.2	147.3	27.88	0.42	4464
	Feb	70.9	−14.4	125.7	140.1	26.27	0.41	4026
	Mar	72.9	−16.3	125.2	141.5	27.53	0.41	4464
	Apr	67.8	8.0	124.1	116.0	26.43	0.40	4315
	May	51.1	6.1	96.9	90.9	20.78	0.44	2238
	Jun	13.7	−38.9	57.0	95.9	25.99	0.61	1815
	Jul	19.2	−24.1	68.2	92.3	22.22	0.33	4461
	Aug	13.8	−34.1	73.3	107.4	23.74	0.36	4462
	Sep	10.3	−55.4	64.0	119.4	26.39	0.40	4320
	Oct							
	Nov	7.5	−32.7	61.4	94.1	21.34	0.49	1923
	Dec	0.6	−55.9	64.6	120.5	27.64	0.41	4464
2003	Jan	7.9	−52.5	64.3	116.7	23.56	0.38	3786
	Feb	−2.3	−74.1	62.4	136.5	26.46	0.42	4032
	Mar	−6.1	−72.5	55.2	127.7	26.26	0.43	3653
	Apr							
	May	6.8	−46.1	57.1	103.2	22.14	0.33	4464
	Jun	−10.8	−56.7	33.9	90.6	21.89	0.33	4316
	Jul	−15.1	−66.3	28.8	95.2	21.92	0.33	4458
	Aug	−14.8	−69.3	31.8	101.0	23.30	0.35	4464
	Sep	−22.6	−70.3	30.2	100.5	24.55	0.39	3909
	Oct	−3.7	−60.2	44.0	104.2	23.42	0.35	4450
	Nov	8.8	−40.7	67.2	108.0	24.43	0.37	4320
	Dec	10.7	−41.8	68.6	110.3	23.21	0.35	4464
2004	Jan	15.7	−47.1	70.4	117.5	23.57	0.35	4461
	Feb	18.6	−46.3	78.4	124.7	25.23	0.39	4176
	Mar	20.8	−39.1	69.6	108.8	24.84	0.37	4464

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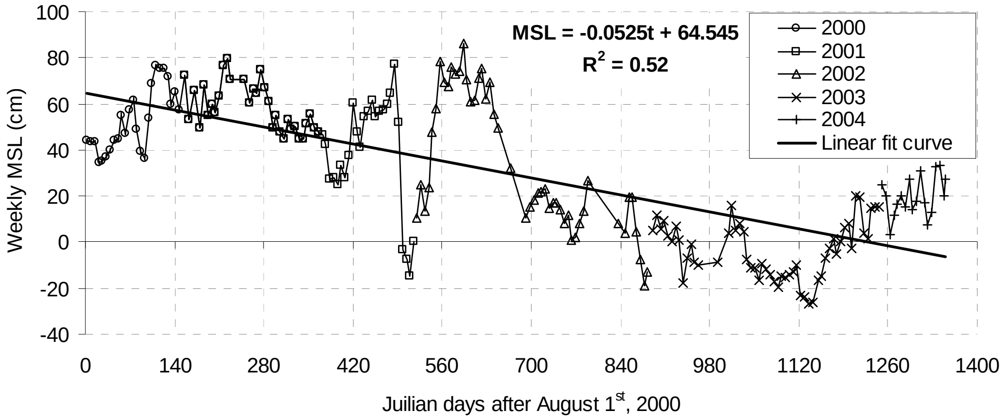

Figure 3. Weekly average of mean sea level (cm) records during the period of August 2000 to March 2004 in the northern Gulf of Aqaba.

was recorded during March 2000 (76.3 cm) and the lowest was −22.6 cm recorded during September 2003.

3.2. Seasonal Variation of Mean Sea Level (MSL)

During summer the MSL decreased significantly than during winter. Subsequently, this created a seasonal cycle of the MSL during the years 2000-2004 (**Figure 4**). One way ANOVA test were performed to examine the differences of MSL among winters, springs and summers of the years 2000-2004 (**Figure 5**, **Table 2**). No significant differences ($p \sim 0.1$) of MSL variation among winters, whereas significant differences ($p < 0.0001$) was patent among springs and summers during the study period (**Table 2**). The decrease of MSL during winter, spring and summer of the year 2003 was significant (mean values: 9.1, −10.1 and −10.0 cm, respectively) comparing with the other years, while during the year 2001 the MSL was significantly the highest during all seasons (mean values: 44.1, 66.7 and 47.8 cm, respectively; **Table 2**).

3.3. Tide Components Signals

Spectrum analysis of tide records in the northern Gulf of Aqaba was done in order to detect components of the tide signals. The analysis revealed six distinguished signals with different periods (**Figure 6**). The diurnal (T_1 = 23.87 h) and Semidiurnal signals (T_2 = 12.36 h) were dominated with distinctive amplitude comparing with the other signals. Based on the principle harmonic components (**Table 3**) [11], the semidiurnal tide signal is basically principle lunar partial tide (M_2) and the diurnal tide signal is luni-solar diurnal partial tide (K_1).

Moreover, the periodic signals T_3 (8.44 h), T_4 (6.10 h) and T_5 (4.12 h) represent shallow water compound and overtides of the principal solar and lunar constituents. The signal T_3 might comprise the lunar terdiurnal constituent (M3), T_4 might imply the lunar or/and solar quarter-diurnal harmonics (M4; S4; MS4), and T_5 might comprise the lunar and solar sixth diurnal harmonics (2MS6; 2SM6).

On the other hand, the signals (T_2, T_4, T_5 and T_6) might be generated or superimposed by unbroken standing waves or so-called *seiches*. The reason for these seiches is that progressive barotropic waves traveling along the basin are reflected at the far ends and then the two sets of waves traveling in opposite directions can interfere with each other resulting in a standing wave with the resonance period of the basin. Owing to the fast propagation, $C = \sqrt{gH}$, the effect of the inertial frequency can be ignored. Then the period of oscillation (T) of the seiches is given by:

$$T_n = \frac{2L}{nC} = \frac{2L}{n\sqrt{gH}}, \quad (1)$$

which is known as Merian's formula
where L is the length of the water body [m], C is the long wave speed [ms^{-1}], g is the earth gravity [ms^{-2}], H is the mean depth of the water body [m], and n is a positive integer [11-13], Equation (1) was derived for a long water body of uniform width and depth.

The fundamental periods of the seiches in both the Gulf of Aqaba and Red Sea have been calculated using Equation (1) based on the mean depth H, and the length L of the water body, L. Due to the complex bathymetry of both the Gulf of Aqaba and the Red Sea we can expect only approximated results.

For the Gulf of Aqaba we take $L = 180 \times 10^3$ m, $g = 9.81$ ms^{-2}, $H = 800$ m, and $n = 1$; and for the Red Sea we use $L = 1930 \times 10^3$ m, $g = 9.81$ ms^{-2}, $H = 750$ m, and $n = 1$. Then the fundamental periods of the first mode seiche are 1.13 h and 12.51 h for the Gulf of Aqaba and Red Sea, respectively. The seiche period in the Gulf of Aqaba agrees well with the observed value T_6 (1.01 h) and T_2 (12.36 h), respectively (**Figure 6**). Nevertheless, for the second and third mode seiche in the Red Sea (n = 2 and

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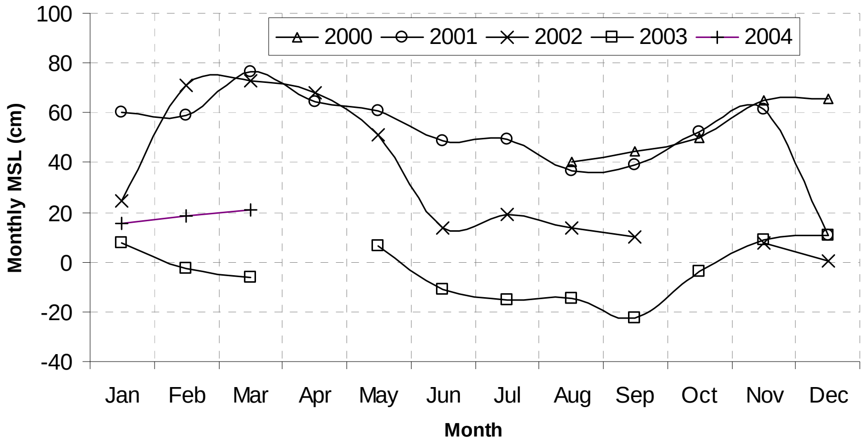

Figure 4. Monthly average of mean sea level (cm) records during the period of August 2000 to March 2004 in the northern Gulf of Aqaba.

Table 2. Statistical comparison analysis of mean seal level (cm) records during winters, springs and summers seasons of the years 2000-2004 in the northern Gulf of Aqaba.

Winter					
Source of variation	**SSq**	**DF**	**MSq**	**F**	**p**
Year	2328.2	2	1164.1	3.49	0.0987
Within cells	2000.7	6	333.5		
Total	4328.9	8			
Spring					
Source of variation	**SSq**	**DF**	**MSq**	**F**	**p**
Year	13243.5	3	4414.5	80.35	<0.0001
Within cells	384.6	7	54.9		
Total	13628.1	10			
Summer					
Source of variation	**SSq**	**DF**	**MSq**	**F**	**p**
Year	11699.1	3	3899.7	29.54	<0.0001
Within cells	2112.3	16	132.0		
Total	13811.4	19			

Winter by year	**n**	**Mean**	**SD**	**SE**	**95% CI of Mean**	
2001	3	44.1	29.08	16.79	−28.2	to 116.3
2002	3	10.9	12.36	7.14	−19.8	to 41.6
2003	3	9.1	1.41	0.81	5.6	to 12.6
Spring by year	**n**	**Mean**	**SD**	**SE**	**95% CI of Mean**	
2001	3	66.7	8.83	5.10	44.7	to 88.6
2002	3	70.5	2.55	1.47	64.2	to 76.9
2003	3	−10.1	10.33	5.96	−35.7	to 15.6
2004	2	19.7	1.56	1.10	5.7	to 33.7
Summer by year	**n**	**Mean**	**SD**	**SE**	**95% CI of Mean**	
2000	3	44.9	5.06	2.92	32.4	to 57.5
2001	6	47.8	9.02	3.68	38.4	to 57.3
2002	5	21.6	16.77	7.50	0.8	to 42.4
2003	6	−10.1	10.30	4.20	−20.9	to 0.8

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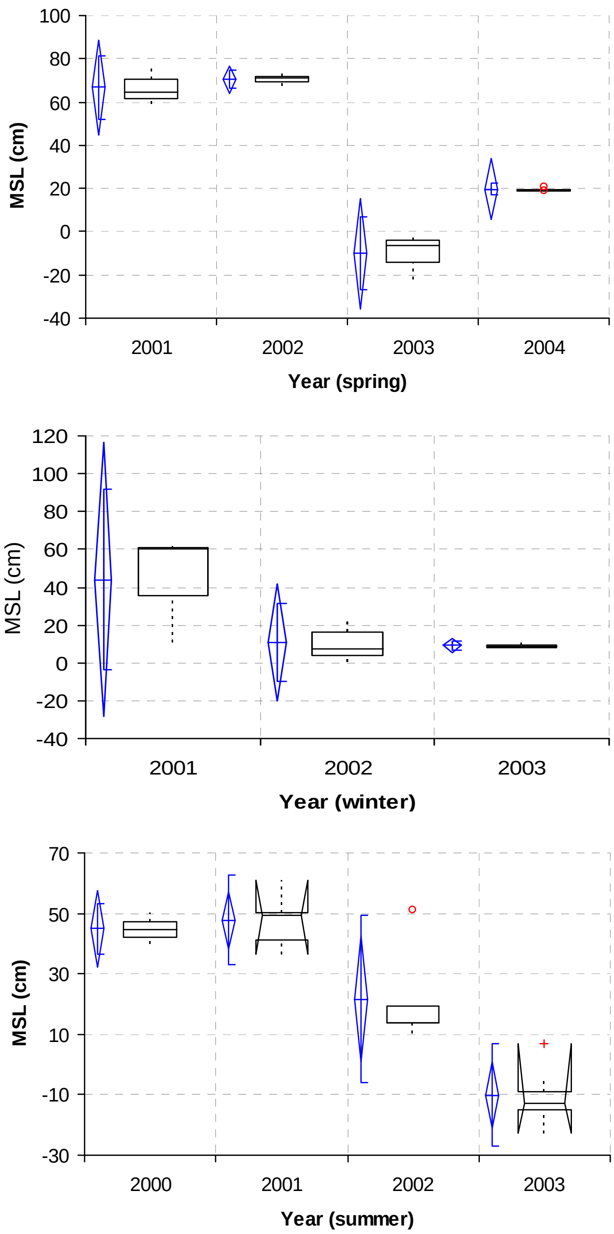

Figure 5. Box-Whisker plots of mean sea level (cm) during winters, springs and summers seasons of the years 2000-2004 in the northern Gulf of Aqaba.

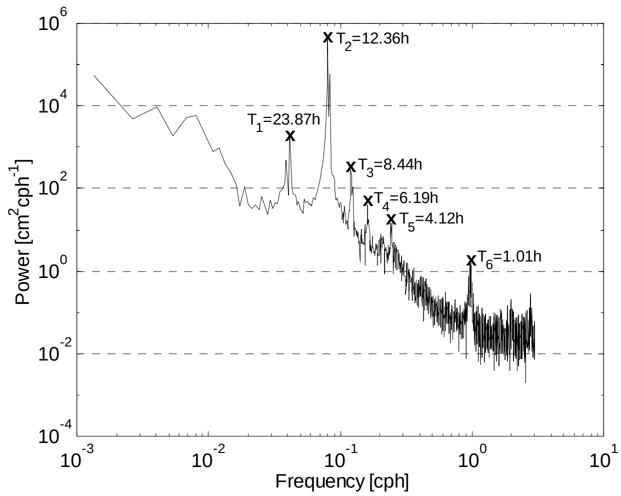

Figure 6. Power spectrum of mean sea level of the years 2000-2004 in the northern Gulf of Aqaba.

3), the fundamental periods using Equation (1) will be 6.25 h and 4.17 h, respectively, which they are close well to those detected periods T_4 (6.19 h) and T_5 (4.12 h), respectively (**Figure 6**). Therefore, the period signals of T_2, T_4, T_5 and T_6 are superimposed by seiches in both the Gulf of Aqaba and the Red Sea with the principle harmonic components.

4. DISCUSSIONS AND CONCLUSION

In general, various factors affect the volume or mass of the ocean, leading to changes in MSL, such as changes of atmospheric pressure (the inverse barometer effect), climate, ocean currents, local ocean temperature and shape of the ocean basins and land/sea distribution.

In the Gulf of Aqaba, the maximum range of seawater temperature in the upper 300 m of the water column was 6˚C - 7˚C among the years 1997-2003. The statistical analysis of temperature measurements in the Gulf of Aqaba showed no significant spatial and temporal difference between three sites in the upper 300 m depth during the study period [2,8], thus temperature variation is quit stable and has a low annual range in the northern Gulf of Aqaba, which can not affect significantly on the MSL variations.

Atmospheric pressure in the northern Gulf of Aqaba (**Figure 7**) for different periods during the years 2002 and 2003 revealed a stable and standard pressure variation in such arid and warm portion of Sahara bio-climatic zone. The average atmospheric pressure during summer was 1006 hPa, while during winter it was 1014 hPa. Therefore, atmospheric pressure in the northern Gulf of Aqaba plays no roles as a factor affecting the MSL.

Tidal currents and water levels in the northern Gulf of Aqaba show strongly the effects of remote forcing. Water levels reflect remote forcing, with annual variations in sea surface height in the Gulf driven by wind-induced setup in the main part of the Red Sea, although winds on the Gulf itself are also important [14]. [15] estimated that annual variability in the sea surface tilted between Aqaba and the strait of Tiran is approximately 7 to 8 cm depending mostly on annual variations in mixed layer depth in the Gulf, with the greatest depression of the free surface near Aqaba occurring in late summer when the mixed layer is the shallowest.

The source of sea level change is due to changes in the average density of the water column and sometimes es-

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Table 3. Principle harmonic components according to Defant (1961).

Name of partial tides	Symbol	cos sin	Argument	Speed per mean solar hour	Period in solar hours	Coefficient ratio M_2: 100
			Semi-diurnal components			
Principle lunar	M_2	cos	255.55	28.98410˚	12.42	100.0
Principle solar	S_2	cos	273.55	30.00000	12.00	46.6
Larger lunar elliptic	N_2	cos	245.65	28.43973	12.66	19.2
Luni-solar semi-diurnal	K_2	cos	275.55	30.08214	11.97	12.7
Larger solar elliptic	T_2	cos	272.55	29.95893	12.01	2.7
Smaller lunar elliptic	L_2	cos	265.45	29.52848	12.19	2.8
Lunarelliptic second order	$2N_2$	cos	235.75	27.89535	12.91	2.5
Larger lunar evectional	γ_2	cos	247.45	28.51258	12.63	3.6
Smaller lunar evectional	λ_2	cos	263.65	29.45563	12.22	0.7
Variational	μ_2	cos	237.55	27.96821	12.87	3.1
			Diurnal components			
Luni-solar diurnal	K_1	sin	165.55	15.04107˚	23.93	58.4
Principle lunar diurnal	O_1	sin	145.55	13.94304	25.82	41.5
Principle solar diurnal	P_1	sin	163.55	14.95893	24.07	19.4
Larger lunar elliptic	Q_1	sin	135.65	13.39866	26.87	7.9
Smaller lunar elliptic	M_1	sin	155.65	14.49205	24.84	3.3
Small lunar elliptic	J_1	sin	175.45	15.58544	23.10	3.3
			Long-period components			
Lunar fortnightly	*Mf*	cos	075.55	1.09803˚	327.86	17.2 8.6
Lunar monthly	*Mm*	cos	065.45	0.54437	661.30	9.1 4.6
Solar semi-annual	*Ssa*	cos	057.55	0.08214	2191.43	8.0 4.0

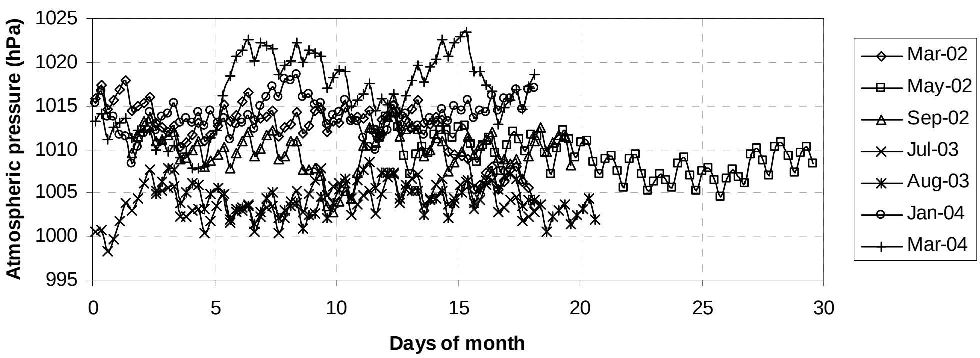

Figure 7. Atmospheric pressure (hPa) distribution during selected days in the years 2002-2004 in the northern Gulf of Aqaba.

timated by computing the steric height (e.g., [16]), or by estimating the baroclinc pressure field (as was done by [17]). Through these computations, the findings of annual changes in steric amount are only several cm in the Red Sea near the strait of Tiran [16,17].

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