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Tide and Sea Level Characteristics at Juaymah, West Coast of the Arabian Gulf

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Abstract. Based on hourly values of the sea level record for the year 2000 and 2005 at Juaymah, Arabian Gulf, the harmonic tidal analysis was performed. It showed a mixed type of tide (F ≈ 0.44) with semidiurnal dominance. On an annual basis, the astronomical tide comprised about 90% of the water level variations. Most of the residual variation (observed minus astronomical component) depends on the variation in atmospheric pressure, water density, and the wind stress. The atmospheric pressure seems to be important compared to density variation and the wind stress in both years. The atmospheric pressure is higher in winter and lower in summer with a consequence of lower residual sea level in winter and higher in summer.

Keywords: Arabian Gulf, harmonic tidal analysis, observed tide astronomical tide, meteorological tide, mean sea level.

Introduction

The Arabian Gulf extends about 1000 km in length and maximum width is approximately 370 km. The average depth is about 36 m and surface area is approximately 239×10^3 km^2 (Emery, 1956). It is located in an arid region and mostly dominated by the Shamal; a northwesterly wind which occurs almost year round (Perrone, 1979). The evaporation rate is nearly 2 m/yr (Privett, 1959; Hastenrath and Lamb, 1979; Meshal and Hassan, 1986; and Ahmad and Sultan, 1991). The net freshwater input by precipitation and river discharge is 0.15 m/yr (Johns *et al*., 2003). The major fresh water source in the Arabian Gulf is through the Shatt-Al-Arab, at the head of the Gulf and fed by the Euphrates, Tigris and Karun rivers. The flow from the Tigris and Euphrates through Shatt-Al-Arab varies considerably through the year and has recently been reduced significantly due to the ongoing river basin modification in upstream countries (Al-Yamani, 2008). Tides in the Arabian Gulf are complex exhibiting; semi-diurnal, diurnal, and mixed nature (Reynolds, 1993). According to Najafi (1997) the major semi-diurnal and diurnal tidal constituents in the Arabian Gulf are M_2, S_2, K_1, and O_1. The semi-diurnal tide has two amphidromic points that are located in the north-western and southern ends of the Gulf, while the diurnal tide has a single amphidromic point in the centre of the Gulf near Bahrain (Najafi, 1997 and Hunter, 1982). Najafi (1997) predicted tidal flows of 0.9 m/s near the Strait of Hormuz and at the head of the Gulf, and 0.3 – 0.6 m/s elsewhere in the Gulf.

The scope of this study is to apply the least square harmonic method to investigate tidal characteristics and sea level fluctuation at Juaymah (26^o 51.6′ N, 49^o 54.5′ E) west coast of the Arabian Gulf (Fig. 1).

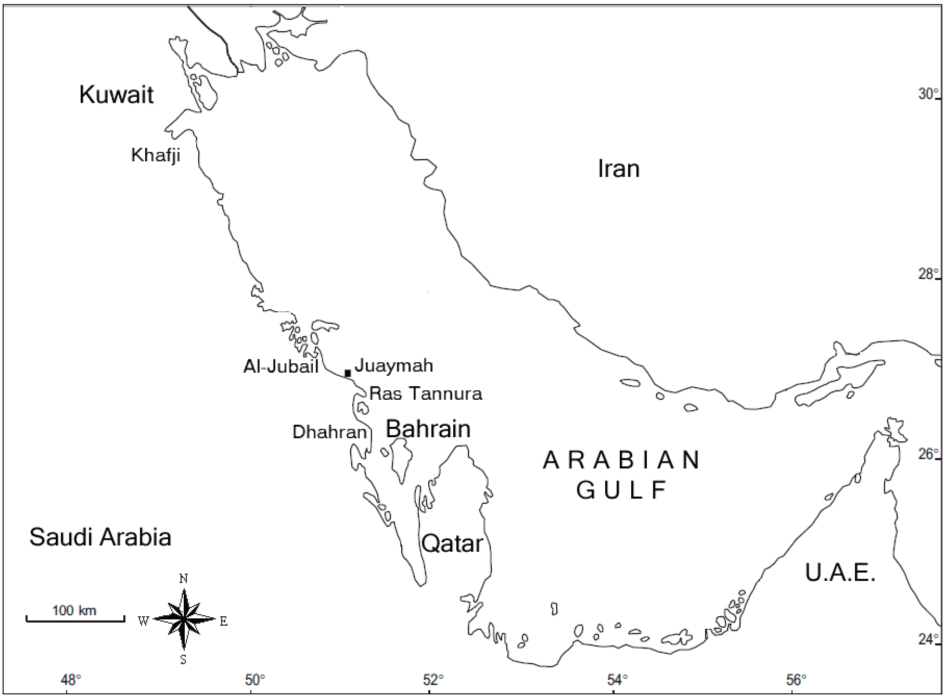

Fig. 1. Map of the Arabian Gulf showing the locations of Juaymah and Dhahran in the west coast; where the tide and meteorological data were obtained respectively for the year 2000 and 2005.

Data and Methods of Analysis

The purpose of the analysis is to find out the amplitude and phase for the five important tidal constituent; namely M_2, S_2, N_2, K_1, and O_1. Finding the tidal harmonic constants at a place allows one to predict astronomical tide at that place. Furthermore, the meteorological tide; a change in water level caused by local meteorological conditions can be found by subtracting the astronomical tide from the observed tide data. Once the meteorological tide determined, a straight forward correlation with meteorological and oceanographic data gives the main factors affecting the sea level fluctuation at that site.

Three types of data were obtained to carry out this study. The tide data are an hourly observed tide for the periods of Jan 1 – Dec 31, 2000 and Jan 1 – Dec 31, 2005. The data were obtained from Saudi Aramco Company. However, these two records are the only data available at the time of the study.

The meteorology data are obtained from PME (Presidency of Meteorology and Environment) Jeddah, Saudi Arabia. The meteorological data (for the year 2000 and 2005) are on a daily basis for Dhahran city; ~ 40 km south of Juaymah. Both meridional and zonal components of wind stress were computed using the wind speed and direction. The components of wind stress were adjusted for the North–West orientation of the coastline. The monthly means of the evaporation rates at the Arabian Gulf were calculated using the latent heat flux (Q_e) values presented in (Ahmad and Sultan, 1991).

Due to the importance of sea water density effect on the variations of sea level (Abdallah and Eid, 1989); the oceanographic data; monthly averages of salinity and temperature at standard depth were obtained from NODC–WOA05 (National Oceanographic Data Center – World Ocean Atlas 2005). The oceanographic data were obtained for the purpose of calculating water density. These data are a 1-degree gridded data and have been chosen for the closest grid to the station; *e.g.* 50.5^{o}E and 26.5^{o}N. The data are for the standard depth intervals up to 50 m deep.

This study employs the World Tides ver. 2009 by John Boon; a GUI-based program for tidal analysis and prediction using up to 35 tidal harmonic constituents under Matlab© package which can be downloaded from the following URL: http://www.mathworks.com/matlabcentral/fileexchange/24217-world-tides. The program is made for the analysis and prediction of tides using the least squares harmonic analysis. It allows the user to decompose a water level record into its tidal and non-tidal components by fitting between 5 and 35 tidal harmonic constituents. The constituents can then be saved to allow future prediction of tides. A brief mathematical background (abstracted from (Boon, 2004)) is presented below:

To predict tide at a place, we simply apply the following harmonic equation:

$$h(t) = h_0 + \sum_{j=1}^{m} f_j H_j \cos\left(\omega_j t + u_j - k_j^*\right) \tag{1}$$

where;

t is the time in serial hours, $h(t)$ is the predicted water level at t, h_0 is the mean water level, f_j is the lunar node factor for jth constituent, H_j is the mean amplitude for jth constituent over 18.6-year lunar node cycle, ω_j is the frequency of jth constituent, u_j is the nodal phase for jth constituent, k_j^* is the phase of jth constituent for the time origin in use (midnight beginning December 31, 1899), m is the number of consitutents. For purely solar constitunets, f_{j}=1 and u_{j}=0. Others are obtained by formula of (Doodson and Warburg, 1980 and Schureman, 1958). To compute the tidal constituent amplitude (H_{j}) and phase (K_{j}) the least squares harmonic analysis should be applied. However, the least squares criterion requires a solution for the harmonic constants that will produce the minimum possible sum of squared differences for a series of observations h_{t} of length n:

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

Therefore, equation (1) will be re-written as:

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

where;

$A_0 = h_0, R_j = \sqrt{A_j^2 + B_j^2} = f_j H_j,$ and $\phi_j = \tan^{-1}\left(\frac{B_j}{A_j}\right) = k_j^* - u_j.$ The unknown A_0, A_j, B_j in equation (2) are obtained by solving the general matrix equation for least squares approximations:

$$[C] = [SSX]^{-1}[SXY] \tag{4}$$

where; [C] is a $2m+1 \times 1$ vector of unknowns, [C] = [A_0 A_1 B_1 A_2 B_2 .. A_m B_m] with [SSX] = [X]'[X] and [SXY] = [X]'[Y] where;

[X] = [■(1& ⟦cos𝜔⟧↓1 𝑡↓1 ⟦sin𝜔⟧↓1 𝑡↓1 & … & ⟦cos𝜔⟧↓m 𝑡↓1 ⟦sin𝜔⟧↓m 𝑡↓1@1
& ⟦cos𝜔⟧↓1 𝑡↓2 ⟦sin𝜔⟧↓1 𝑡↓2 & … & ⟦cos𝜔⟧↓m 𝑡↓2 ⟦sin𝜔⟧↓m 𝑡↓2 @ …
& … … & … & … … @1& ⟦cos𝜔⟧↓1 𝑡↓n ⟦sin𝜔⟧↓1 𝑡↓n & … &

and [Y] = [h_1 h_2 h_3 .. h_n]' is a vector containing n observations. The prime symbol (') used in these equations indicates the *transpose* of a matrix or vector whereas the unit negative exponent indicates the *inverse* of the *2m+1* x *2m+1* square matrix, [SSX]. It is important to mention that, while there is a term representing the mean in equation (1), there is no term representing a linear trend; therefore, the tide hourly data were de-trended before starting the analysis.

The whole-year observed tide data were visually inspected at the beginning to look for outliers and errors. The monthly observed tide data then were inspected for computing the amplitudes and time for the HHW (Highest High Water) and LLW (Lowest Low Water) in each month. Afterward, the data were analyzed on a whole year basis (2000 and 2005) and on a monthly basis (January to December) in order to compute the following: (1) amplitudes and phases of tidal constituents, (2) HAT (highest astronomical tide), (3) LAT (lowest astronomical tide), (4) the weight of astronomical tide relative to observed water level, and (5) the daily periodogram of the meteorological tide. Once the meteorological tides were discriminated in each year, they were averaged to obtain daily and monthly averages for correlation with meteorological and oceanographic factors.

Results and Discussion

The observed tide for the year 2000 and 2005 are given in Fig. 2 & 3 respectively. The data for year 2000 have discontinuity in the last week of May which does not alter the computation anyway.

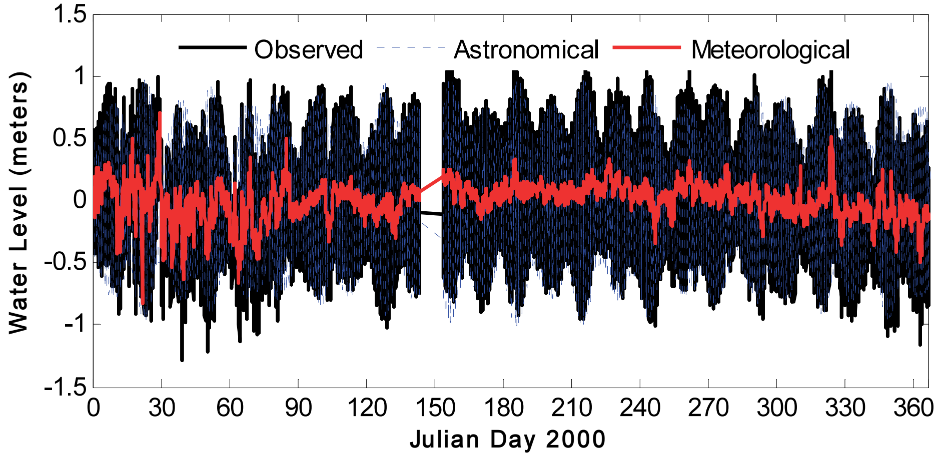

Fig. 2. Observed, astronomical, and meteorological tide hourly values for Juaymah station during the year 2000.

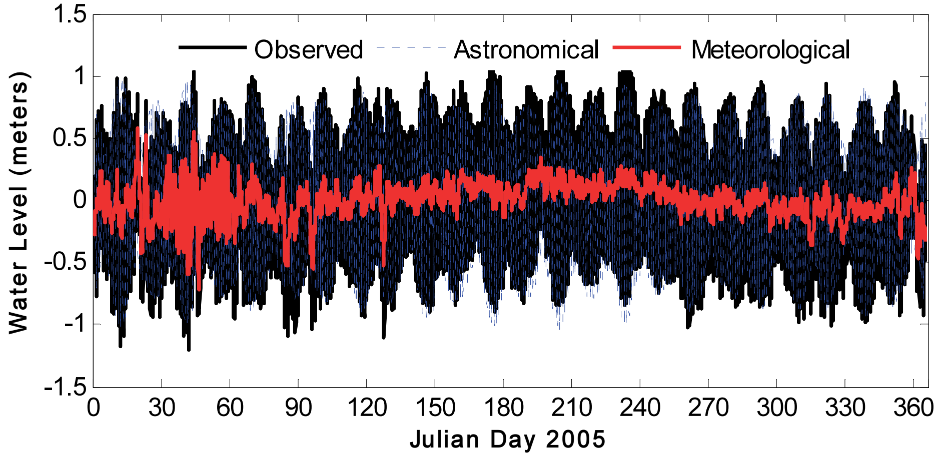

Fig. 3. Observed, astronomical, and meteorological tide hourly values for Juaymah station during the year 2005.

The Highest High Water (HHW) and Lowest Low Water (LLW) in each month for both years as well as the Highest Astronomical Tide (HAT) Lowest Astronomical Tide (LAT) are given in Table 1.

Table 1. The monthly HHW and LLW for the year 2000 and 2005 as well as the HAT and LAT values.

Month	2000				2005			
	HHW		LLW		HHW		LLW	
	W. L. (cm)	**Time** (Day.hour)	**W. L.** (cm)	**Time** (Day.hour)	**W. L.** (cm)	**Time** (Day.hour)	**W. L.** (cm)	**Time** (Day.hour)
Jan	498	21.17	301	24.13	496	10.17	280	12.12
Feb	493	23.19	269	08.13	502	13.20	279	11.12
Mar	496	09.06	285	04.01	499	10.17	291	26.11
Apr	492	22.07	320	12.04	500	26.06	298	06.09
May	490	08.08	298	08.01	506	26.07	292	07.22
Jun	515	05.07	313	17.23	513	24.07	315	25.00
Jul	516	03.06	308	31.23	519	23.06	321	21.23
Aug	510	03.07	307	31.01	517	21.06	323	20.23
Sep	512	17.19	304	02.13	502	20.18	306	17.22
Oct	507	15.18	311	19.14	505	19.18	324	08.13
Nov	523	18.22	311	27.11	505	17.18	310	19.12
Dec	499	11.17	293	27.12	508	17.18	313	04.12
	HAT Value: 1.011		**LAT Value: -1.010**		**HAT Value: 1.019**		**LAT Value: -1.041**	

Tidal harmonic constituents are shown in Table 2. The amplitudes and phases seem to be identical for both years. According to the ratio; $F = (M_2+S_2 \ / \ K_1+O_1)$, both years showed a mixed type of tide with semidiurnal imposed. F= 0.43 for 2000, and = 0.44 for 2005. These values as well as the HAT and LAT values are in agreement with those of annual Saudi Aramco tide tables (current version for the year 2009).

Table 2. Tidal harmonic constituents at Juaymah station for the year 2000 and 2005.

Tide Constituent	2000		2005	
	Amplitude	Phase	Amplitude	Phase
O1	0.129	227.36	0.133	225.18
K1	0.165	315.78	0.172	316.59
N2	0.106	315.44	0.107	316.14
M2	0.512	071.05	0.508	069.35
S2	0.182	185.43	0.184	182.22

In both years, the astronomical tides comprise almost 90% of the total water level variations; (89.70% and 89.93% for year 2000 and 2005 respectively). However, these values change when we consider the month-by-month tides (Table 3).

Table 3. Monthly astronomical and meteorological tides weight (%) of total water level variance

Month	2000		2005	
	Astromical tide (%)	Meteorological tide (%)	Astromical tide (%)	Meteorological tide (%)
Jan	81.87	18.13	87.90	12.10
Feb	88.35	11.65	92.08	07.92
Mar	81.54	18.46	91.23	08.77
Apr	95.91	04.09	92.71	07.29
May	96.28	03.72	94.41	05.59
Jun	96.51	03.49	97.16	02.84
Jul	98.25	01.75	96.91	03.09
Aug	97.60	02.40	98.26	01.74
Sep	95.47	04.53	96.63	03.37
Oct	96.02	03.98	97.06	02.94
Nov	91.02	08.98	94.82	05.18
Dec	92.62	07.38	92.26	07.74

From the above table, it is obvious that the month-to-month percentage weights of both the astronomical and meteorological tides are different annually and seasonally. Year 2000 shows slightly lower percentage of astronomical tides as compared with year 2005. Moreover, during winter season the meteorological tides have larger amplitudes in comparison with summer months. This is in concurrence with higher astronomical tides during summer (late May to Aug.) and in autumn transition period (Sept. and Oct.).

The periodogram of the meteorological tide for both years are shown in Fig. 4 & 5 respectively. In both figures diurnal and semi-diurnal cycles noticeably appear. However, the strength of these cycles differs due to the nature of altering daily weather from year to year. For instance, the meteorological tide shows stronger semi-diurnal cycle than the daily cycle in 2005.

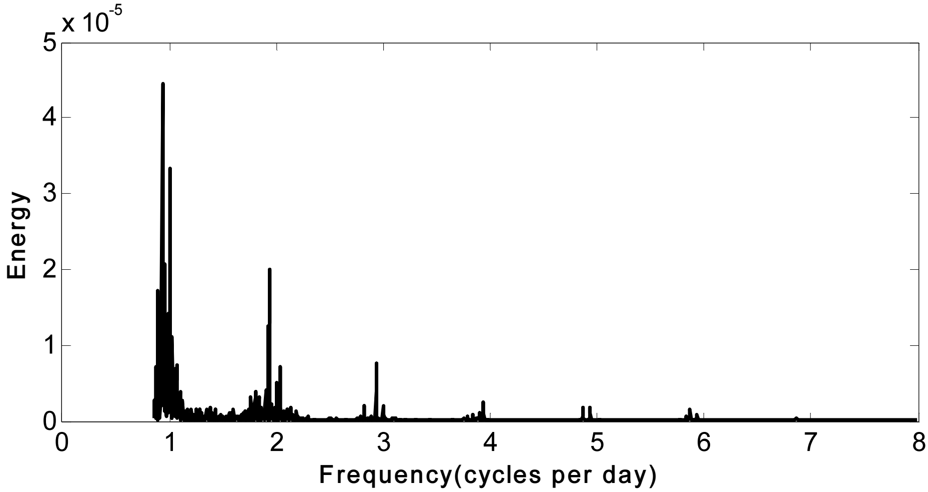

Fig. 4. The periodogram of the meteorological tide for the year 2000.

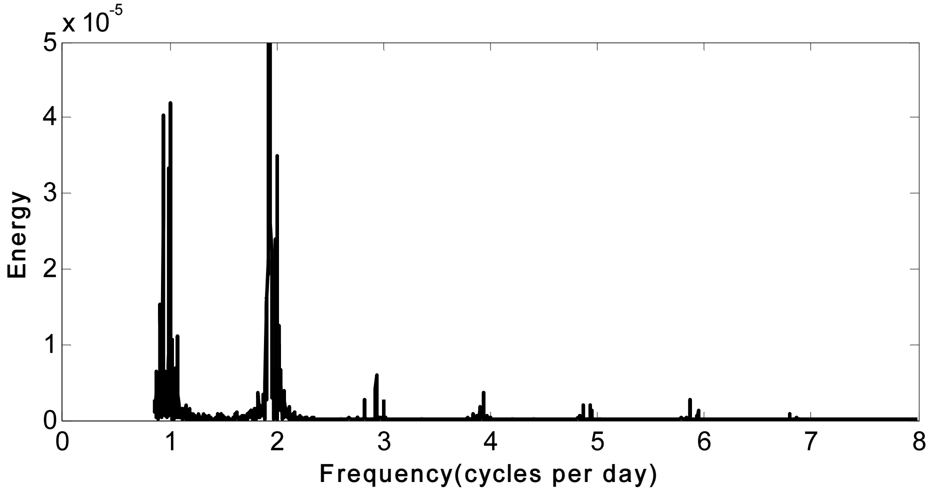

Fig. 5. The periodogram of the meteorological tide for the year 2005.

The monthly mean sea level in both years shows a high correlation with atmospheric pressure. The correlation values range between -0.738 to -0.831 with significant P value 0.001. Figures 6 & 7 represent the correlation between monthly mean sea level and atmospheric pressure in 2000 and 2005 respectively.

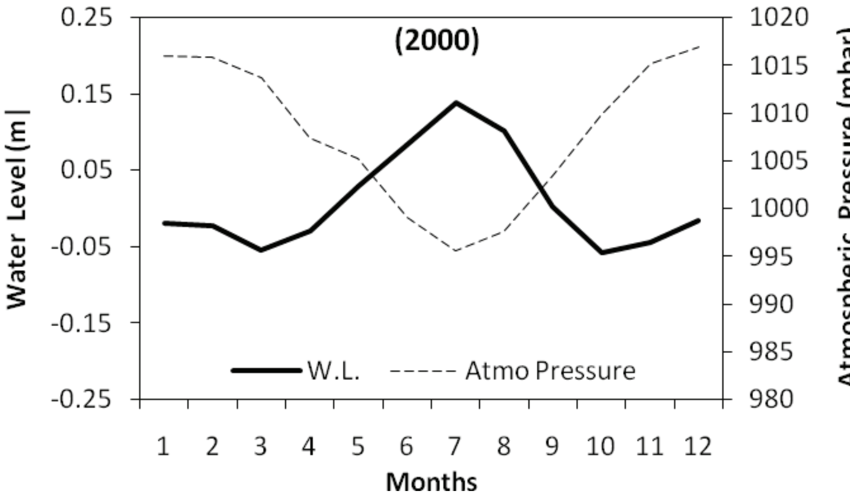

Fig. 6. Correlation of monthly meteorological tide with the atmospheric pressure in the year 2000.

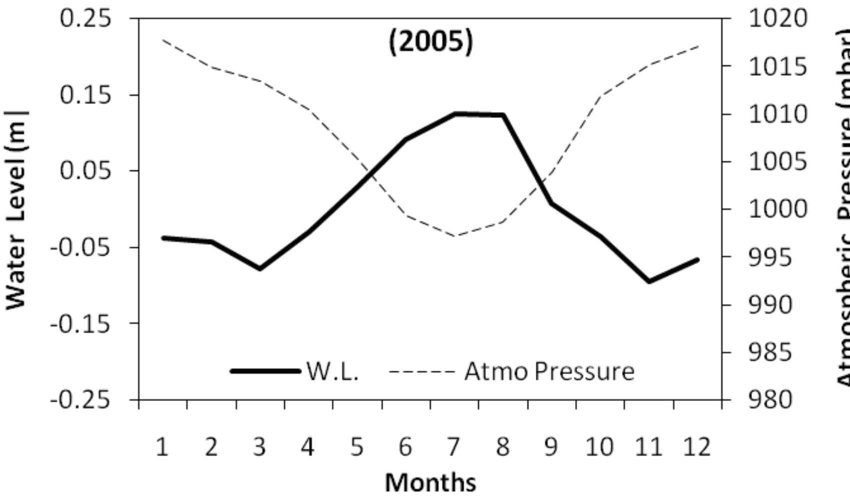

Fig. 7. Correlation of monthly meteorological tide with the atmospheric pressure in the year 2005.

Figures 6 and 7 show higher residual mean sea level in summer and lower mean sea level in winter for both years. This agrees with the findings of (Sharaf El-Din, 1988, El-Gindy, 1991, and Sultan *et al.* (1995)). The latter remarked that "the sea level responds to atmospheric pressure as a near perfect inverse barometer" which is depicted in the above two graphs.

On a daily basis, the atmospheric pressure is in a strong correlation with the meteorological tide in winter season (Dec through Mar) and the spring transition period (Apr and May). Figures 8 & 9 represent the correlation between daily mean sea level and atmospheric pressure in January 2000 and January 2005 respectively.

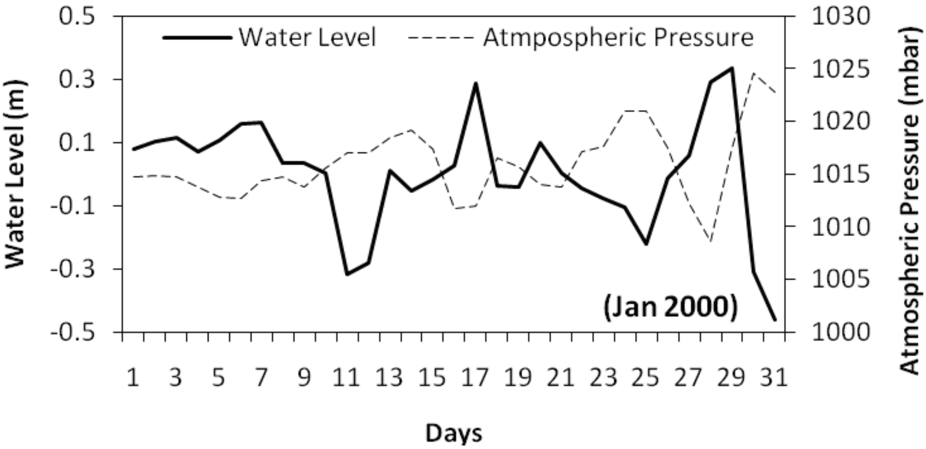

Fig. 8. Correlation of daily meteorological tide with the atmospheric pressure during January 2000.

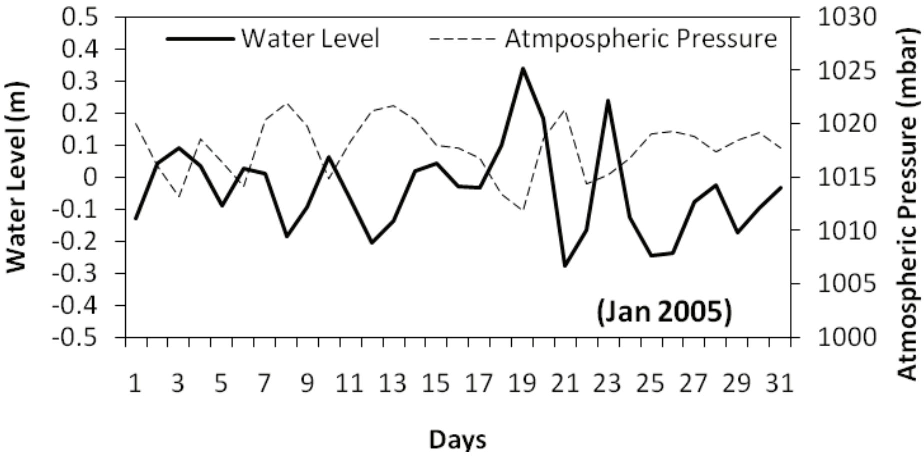

Fig. 9. Correlation of daily meteorological tide with the atmospheric pressure during January 2005.

The analysis of the monthly mean sea level shows that in summer season (June through Aug) the monthly mean sea level has a fair correlation with water density of the water column. Figures 10 and 11 illustrate this correlation for the year 2000 and the 2005 respectively. Correlation values are -0.570 with P value 0.005 and -0.562 with P value 0.005 for the year 2000 and 2005 respectively. This is almost in agreement with the results of Sultan *et al*. (1995). Due to non-availability of the daily values of salinity and temperature, the daily correlation of water density and meteorological tide could not be computed.

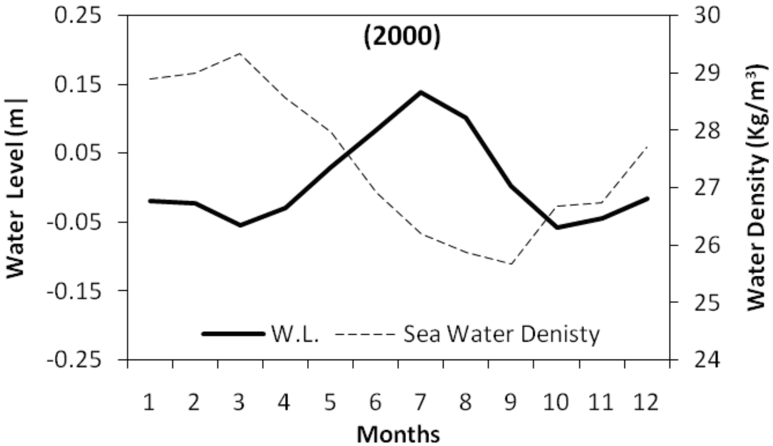

Fig. 10. Correlation of monthly meteorological tide with the water density in the year 2000.

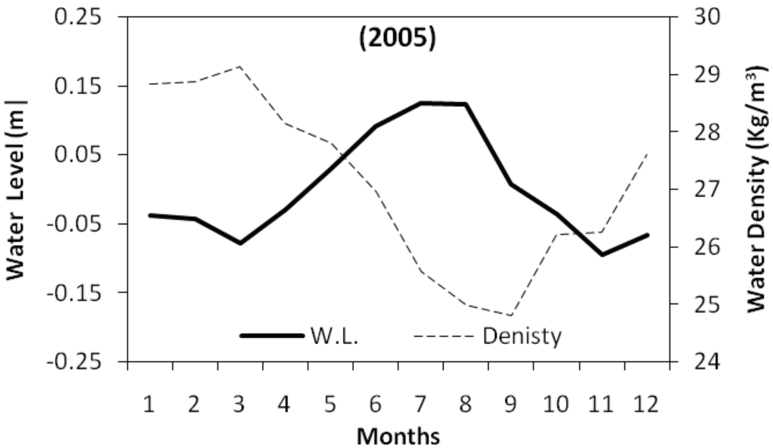

Fig. 11. Correlation of monthly meteorological tide with the water density in the year 2005.

The autumn transition period (mid Sep through mid Nov) however demonstrate another controlling factor. In both years a clear negative correlation with wind component appears. In the year 2000, the correlation between the zonal component of wind stress and the meteorological tide represent a value of -0.679 with P value of 0.001 during the month September (Fig. 12). On the other hand, the meridional component of wind stress shows also a correlation of about -0.574 with P value 0.001 for the month of October 2005 (Fig. 13). This may be due to the variation in daily wind pattern. The periodogram of the meteorological tide for the year 2000 and 2005 (Fig. 4 and 5) also show difference in energy concentration.

The evaporation rate during the year 2000 and 2005 did not show any significant correlation with the changes in mean sea level.

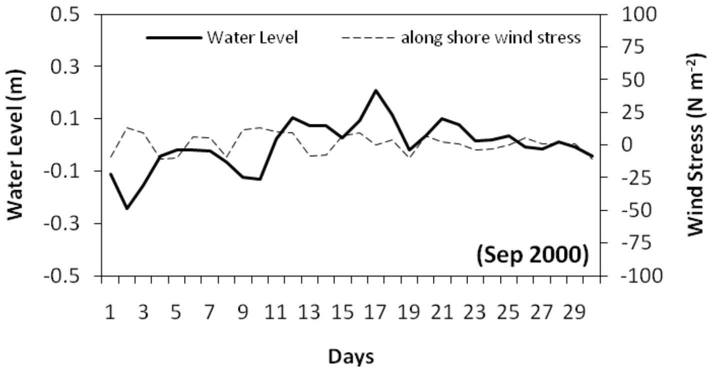

Fig. 12. Correlation of daily meteorological tide with the along-shore wind stress during September 2000.

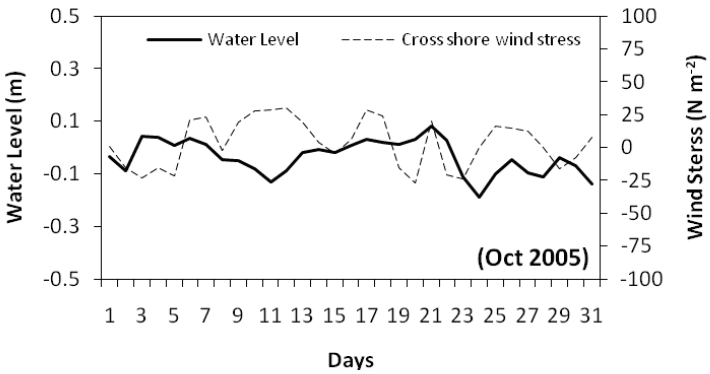

Fig. 13. Correlation of daily meteorological tide with the cross-shore wind stress during October 2005.

A multiple regression model using the least square method was carried out to construct the best fit equation between sea level and the meteorological factors. The predicted water level (P.W.L) for both years; 2000 and 2005, is given by the following equation:

$$\text{P.W.L.} = 3.66 - 0.3P_a + 0.01U_w + 0.005V_w + 0.2D$$

where;

P_a is the atmospheric pressure, U_w is the zonal wind, V_w is the meridional wind, and D is the water density. The regression model output for both years is given in Fig. 14 & 15 respectively.

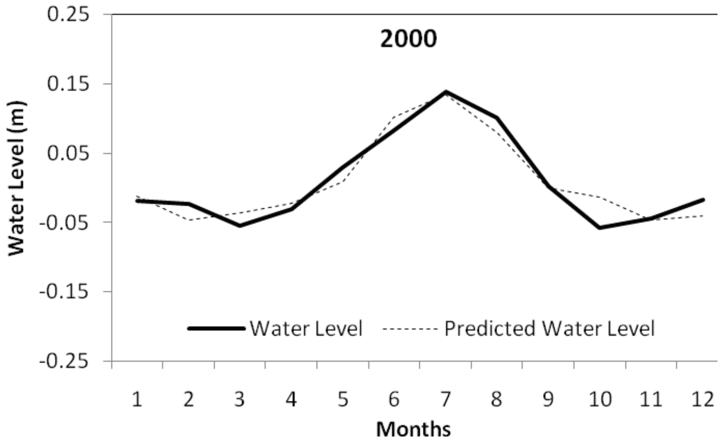

Fig. 14. The regression model output for the year 2000.

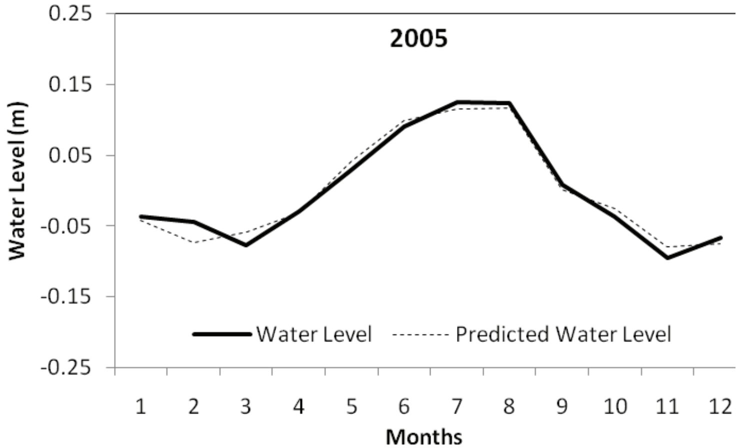

Fig. 15. The regression model output for the year 2005.

Conclusion

At Juaymah station, the observed tide data for the year 2000 and 2005 show a mixed type of tide with semidiurnal dominance. On an annual basis, the astronomical tide comprises of about 90% of the total water variation. On monthly basis, the astronomical tide proportion ranges from 81.54% during March to 98.25 in July for the year 2000 and from 87.90 in January to 98.26 during August in the year 2005. The meteorological tide shows a correlation with atmospheric pressure and the water column density for both years. On a daily basis, the winter data show a strong correlation with atmospheric pressure. Due to the non-availability of the daily values of temperature and salinity with depth the correlation between the density variation and the residual water level could not be obtained. During the autumn transition period, the correlation with wind components appears clearly.

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خصائص المد والجزر ومنسوب سطح البحر في الجعيمة، الساحل الغربي للخليج العربي

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المستخلص. تم إجراء التحليل الطيفي للقيم الساعية للتغير في مستوى سطح البحر لعامي ٢٠٠٠ و٢٠٠٥م في الجعيمة في الساحل الغربي للخليج العربي. أظهرت البيانات أن المد والجزر كان من النوع المختلط ($F \approx 0.44$) مع ظهور المركبة نصف اليومية بصورة أوضح. عند تحليل البيانات على المستوى السنوي، شكل المد والجزر الفلكي قرابة ٩٠٪ من تذبذبات منسوب سطح البحر. التذبذبات المتبقية (الفرق بين البيانات المقاسة والمد الفلكي) كانت بسبب تأثير الضغط الجوي، الكثافة، ومركبات إجهاد الرياح على التوالي. كان الضغط الجوي أكثر تأثيرًا من الكثافة وإجهاد الرياح في تغير منسوب سطح البحر في كلا العامين. كما كان لارتفاع الضغط الجوي في فصل الشتاء وانخفاضه في فصل الصيف الأثر العكسي المباشر في انخفاض منسوب سطح البحر في فصل الشتاء وارتفاعه في فصل الصيف.

كلمات مفتاحيّة: الخليج العربي، التحليل الطيفي للمد والجزر، المد والجزر المشاهد المد والجزر الفلكي، المد والجزر الجوي، متوسط منسوب سطح البحر.