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Factors Controlling Seasonal Variability of Sea Level in the Western Gulf of Aden

Abdullah M. Al-Subhi

Department of Marine Physics, Faculty of Marine Sciences, King Abdulaziz University, B.O. Box 80207 Jeddah 21589, Saudi Arabia

amalsubhi@kau.edu.sa

Abstract. Daily means sea level has been computed from hourly observations at Aden and Djibouti for the period of 2011–2014 to study seasonal variability in sea level in the western Gulf of Aden. This variability is investigated against the following controlling factors: sea level pressure, wind, and steric sea level. Variability in sea level at Aden and Djibouti shows strong seasonality with higher sea level in winter and lower sea level in summer with a range up to about 35 cm. The high-frequency variability in sea level agrees with variability in pressure, especially during winter following normal inverse barometric relation. Cross-shore wind affects sea level variability in Djibouti more than that in Aden, while along-shore wind plays a significant role in sea level variability at Aden. Daily steric sea level for both stations play a significant role in seasonal sea level anomaly (SLA) variability. Both stations shows that strong signals are the annual and semiannual, while small frequencies are negligible in comparison. For Aden and Djibouti stations, steric sea level is the dominant factor with a determination coefficient (DC) of 0.73, and 0.71, respectively. Along-shore wind has the second higher contribution for Aden with (DC) of about 0.3. The cross-shore wind component has the second highest contribution on Djibouti SLA with a DC of about 0.3, while for Aden, this factor has no effect on SLA. Sea level pressure (SLP) contribution is clearly seen in short-period variability for both stations.

Keywords: Gulf of Aden, Mean Sea Level, Steric Sea Level, Wavelet, Atmospheric forcing.

1. Introduction

The Gulf of Aden is a strategic water body that connects the Red Sea with the Indian Ocean, and it is distinguished by the complexity and variability of its climate and oceanography. As part of the northwestern Indian Ocean, it falls under the control of the monsoon reversal wind regime, which contributes to the formation of various water circulation patterns such as water exchange with the Red Sea and the Arabian Sea, eddy formation, and coastal upwelling. In the winter NE monsoon, winds push the gulf's surface water westward along the axis of the gulf and continue to flow NNW into the Red Sea through the strait of Bab-el-Mandab. During the summer SW monsoon, winds are relatively stronger and reach 20–40 km/h (Sultan and Ahmed, 1997). The surface water of the gulf is pushed eastward under the effect of the SW wind along the Arabian coast and deflected SE; this type of steering causes some eddies to form along the center of the gulf (Alsaafani *et al*., 2007). Other eddies propagate to the gulf from the Arabian Sea (Alsaafani *et al*., 2007; Fratantoni, *et al*., 2006). Due to these eddies, some weak and scattered upwellings occur in a few spots along the Somali coast. Along the Arabian coast, strong upwelling occurs due to the Ekman transport, which pushes surface water offshore and is replaced with subsurface waters; in this season, upwelled waters come from much greater depth (Currie *et al*., 1973). The Gulf of Aden experiences strong evaporation; Ahmad and Sultan (1989) investigated the evaporation of the southern part of the Red Sea, including Bab-el-Mandab, and found that evaporation is higher in summer and lower in winter. Their annual average of evaporative heat flux in this region was 152 Wm^{-2}. The western Gulf of Aden has a mixed type of tide with similar tidal amplitudes and phases at both stations (Madah, 2020).

Sea level variability is affected by many factors, which operate at different temporal and spatial scales (Bergant, *et al*., 2005). The main variability in sea level in seasonal and interannual variability is related to meteorological and oceanographic forces (Woodworth *et al*., 1999; Tsimplis and Woodworth, 1994). The contribution of the gravitational forces of annual and semiannual frequencies present in the tide-generating potential can be neglected in comparison with meteorological and oceanographic forcing (Bergant, *et al*., 2005; Woodworth *et al*., 1999; Fukumori, *et al*., 1998; Pugh, 1987; Shankar, 2000). Oceanographic factors include circulation, changes in temperature, and salinity and eddies, while atmospheric factors include changes in average air pressure and wind fields. The impact of wind and atmospheric pressure on sea level was extensively globally studied in many areas (Tsimplis and Vlahakis, 1994; Garcia-Lafunte, *et al*., 2004). The most obvious contribution of oceanic factors is the thermosteric effect associated with heat fluxes at the surface layer of the ocean (Cheney *et al*., 1994; Tsimplis and Woodworth, 1994). Low-frequency variations in air pressure and wind fields associated with the seasonal pattern of atmospheric circulation contribute to the variability of sea level through the in-verted barometer response and wind setup, particularly in coastal areas. They also contribute to sea level variability by inducing fluctuations in the mean ocean circulation at both the regional and global scales (Wunsch, 1991).

Studies of sea level changes in the Gulf of Aden are scarce. Most recent studies related to sea level in the Gulf of Aden investigate the sea level rise in the gulf and its relation to global warming (Unnikrishnan and Shankar 2007; Woodworth *et al*. 2009) and climate modes (Alawad *et al*., 2019), or to study the impact of sea level rise on coastal areas (Dasgupta *et al*., 2009; Alsaafani, *et al*. 2015). The study by Patzert (1972) showed that sea level is higher in winter and low-er in summer, with a range up to 33 cm due to the steric effect and along-shore wind stress based on 1879–1893 and 1937–1946 sea level data at the Port of Aden. The study conducted by Cromwell and Smeed (1998) for sea level fluctuations based on altimetric data from TOPEX/Poseidon from 11 November 1993 to 16 January 1997 shows that the dominant cycle is annual with an amplitude of 13 cm and a secondary semiannual cycle with an amplitude of 4–8 cm. They believe that the annual cycle is due to wind forcing, while the semiannual cycle is due to evaporation. The nearest region to the Gulf of Aden is the southern part of the Red Sea, where fluctuations of MSL at Gizan (Jazan) are investigated by (Abdelrahman, 1997). The author reported that MSL was high in winter and low in summer with a range up to 40 cm, and its seasonal changes are affected by steric effects, evaporation rates, and along-shore wind.

However, since no previous studies investigated seasonal variability at Djibouti station, this study used four-year sea level data along with sea level pressure (SLP), wind stress, and the monthly climatology of steric sea level to investigate the annual and short-er-period variability in SLA, and its relation to the controlling parameters at both Aden and Djibouti.

2. Materials and Methods

Time series of sea level from two tide gauge stations; Aden and Djibouti, located in the western Gulf of Aden were used to investigate seasonal variations of sea level in the western part of the gulf associated with atmospheric forcing and steric sea level. (See Fig. 1 for locations). The daily and monthly mean sea levels were computed from hourly observations that spanned the period of 2011–2014. Tide-gauge data are collected by the Permanent Service for Mean Sea Level (PSMSL) (Holgate *et al.*, 2013), and retrieved from http://www.psmsl.org/data/obtaining/.

Hourly sea level data usually have a spectrum that covers all frequencies. Since our interest is in seasonal variability, we followed (Goden, 1972; Alsaafani, *et al.*, 2017) to smooth hourly data to eliminate the tidal effect by applying a filter of type $\frac{\propto_{24}^{2} \propto_{25}}{24^{2}25}$, which entails a loss of 70 h of smoothed observations. A sequence of means is first computed for 25 observations; then, a series of means for 24 of these means is repeated twice, and the mean of this last series gives the smoothed values. Daily and monthly sea level values are estimated from the smoothed one.

Sea level pressure (SLP) and wind stress components covering four years from 2011 to 2014 were provided by European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis (ERA) (Uppala *et al.*, 2005; Dee *et al.*, 2011).

The monthly steric sea level has been estimated for Djibouti (43.15 E and 11.61 N) and Aden (44.97 E and 12.79 N) using WOA18 climatology (Abdullah *et al.*, 2019) for the water column from surface till 700 m based on formula of (Gill, 1982), the daily climatology has been interpolated from the monthly climatology. Since the steric sea level has no noticed interannual variability, therefore the daily climatology of steric sea level is repeated for the four years to get similar time series length as the sea level for the wavelet analysis.

For wavelet analysis the data should be continuous, for that the gaps in Djibouti SLA data are filled and interpolated. As Aden and Djibouti stations show similar variability with (CC of 96% and DC of 92%), Aden SLA is used in interpolation. In this the interpolated value is set as an average value of the previous time step of Djibouti SLA and SLA of Aden from the same time step multiplied with its DC. The interpolated time series match will with AVISO (figure not shown) for the nearest grid to Djibouti station.

The seasonal relationships of sea level elevations to winds, SLP, and steric sea level were examined in both time and frequency domains; multiple linear regression techniques were used to quantify the relations between sea level and different forcing.

2.1. *Wavelet Analysis Approach*

The wavelet analysis transforms any time series to time-frequency space (two-dimensional). Torrence & Compo, (1998) defines the Morlet wavelet as

$$\omega_o(\eta) = \pi^{-1/4} e^{i\omega_\circ \eta} e^{-\eta^2/2} \qquad (1)$$

where η and ω_0 are the dimensionless time and frequency, respectively. Frequency $\omega_0 = 6$ represents a good balance between time and frequency localization. The continuous wavelet transform (CWT) of the time series X_n, as define by Torrence & Compo, (1998), is

$$W_n(s) = \sum_{n'=0}^{N-1} X_{n'} \Psi^* \left[\frac{(n' - n)\delta t}{s}\right] \qquad (2)$$

where, n = one…, N with a uniform time interval, while Ψ^* is the complex conjugate of Ψ. The cone of influence (COI) was used to avoid edging error; therefore, it is defined as the region of which the edge effects become important by distorting the feature either in the beginning or end of the wavelet power spectrum. Thus, the edge dropped by a factor of e^{-2}, where it is negligible here (Grinsted *et al.*, 2004; Torrence & Compo, 1998). The red noise is assessed using the first order autoregression model (AR1), while the Monte Carlo method was used to generate the 5% statistical significance level. To measure the intensity of the covariance of two time series X and Y, we followed the approach of

Torrence & Webster, (1999); the cross-wavelet spectrum was used and is defined as

$$W_{XY}(s,t) = W_X(s,t)W_Y^*(s,t) \quad (3)$$

where (*) indicates the complex conjugate.

From the cross-wavelet spectrum, wavelet transform coherence (WTC) can be determined. WTC is a useful method for discovering the coherence and phase lag between two time series as a function of both time and frequency using the following approach (Grinsted *et al.*, 2004; Torrence & Webster, 1999)

$$R_n^2(s) = \frac{\left|S\left(s^{-1}W_n^{XY}(s)\right)\right|^2}{S(s^{-1}|W_n^X(s)|^2)\cdot S(s^{-1}|W_n^Y(s)|^2)} \quad (4)$$

Where S is the smoothing operator.

3. Results and Discussions

Figure 2 shows the time series of daily mean sea level at Aden and Djibouti as well as the time series of sea level pressure, and along- and cross-shore wind stress components. For clarity in comparing the data, a value of 100 kPa (1000 mb) was subtracted from the sea level pressure time series. Wind stresses were calculated using the formula $(\tau_x\ \tau_y) = \rho C_d|V|(u,v)$, where ρ is the air density (1.25 kg m^{-3}), C_d is the drag coefficient, and |V|, u, and v are the magnitude, and along- and cross-shore components of wind speed (ms^{-1}), respectively.

Sea level variability at Aden and Djibouti reveals a similar pattern with strong seasonality of higher sea level in winter and lower sea level in summer (Fig. 2a). Superimposed on the seasonal signal is a high-frequency variability of time scale ranging from few days to 30 days, as they were smoothed out in the monthly average. The range in sea level variability is up to about 35 cm at both locations, which is similar to that of (Patzert, 1972). The pat-tern of variability is similar for the four years. Sea level data in Djibouti had more gaps during 2012.

Since Aden and Djibouti are located at the western part of the Gulf of Aden, the atmospheric forcing conditions are similar over the two locations, especially atmospheric pressure, which is high during winter and low during summer at the two stations. High-frequency variability is the same at both stations, with some variability during summer (Fig. 2b). The comparison between variability in daily sea level (Fig. 2a) and daily atmospheric pressure (Fig. 2b) shows high sea level during winter with high pressure and vice versa for summer; thus, the annual cycle of sea level is not the result of an inverted barometric response to atmospheric pressure.

The along-shore wind component also shows strong seasonality at both locations, with stronger positive stress during the southwestern monsoon (June–August) and weaker negative stress during winter, with higher values at Aden compared with those of Djibouti (Fig. 2c). This variability is in the same phase with sea level, with a low sea level lag with about one month with the along-shore wind. Like daily sea level and atmospheric pressure, high-frequency variability of the time scale of the along-shore wind ranges from few days to 30 days is superimposed on the seasonal signal.

The cross-shore component of wind stress is weak at Aden station compared with the along-shore component, with higher values during the southwestern monsoon at Djibouti station (Fig. 2d).

For a clear idea regarding the seasonal variability in sea level and its relation to the controlling forcing, the daily averaged time series for the no-gap year (2014) is selected for all the parameters at Aden and Djibouti. Figure 3 shows the time series of those parameters in addition to daily steric sea level interpolated from monthly climatology. For both stations, sea level variability shows a clear annual cycle with high sea level during winter and low during summer. High-frequency variability in sea level agreed with variability in pressure, especially during winter, where low sea level coincides with high atmospheric pressure, indicating a normal inverse barometric relation (Fig. 3a, b). The phase difference in low-frequency variability (more than 30 days) show that SLA precedes SLP with 3-4 months; these findings agree with those for the Mediterranean Sea (Le Traon and Gauzelin, 1997), where it is attributed to friction at the strait of Gibraltar. The seasonal cycle of cross-shore wind shows more variability, with a clear cycle for Djibouti, compared with Aden, while it is the oppo-site for the along-shore component (Fig. 3c, d). The along-shore wind is out of phase with SLA at Aden, with negative wind stress during low sea level (summer), and positive stress during winter. This indicates that along-shore wind plays a significant role in sea level variability at Aden. Fig. 3e shows the daily steric sea level for both stations, with a clear high-level annual cycle during winter, and a low-level during summer, which is in phase with sea level variability in both stations, which indicates that steric sea level plays a major role in seasonal SLA variability. The low steric level at summer can be associated with coastal upwelling at both stations.

Since Fig. 2 and 3 (a and b) do not show a clear high frequency relation between SLA and SLP signals; a high-pass filter has been applied for the SLA and SLP time series to make them more pronounced; Fig. 4a and b shows the comparison for the high frequency variability of SLA and SLP for Aden and Djibouti, respectively. The figure shows that the SLA has a prompt inverse parametric response to the SLP all over the year.

To clearly identify signals in all time series, spectral analysis has been conducted as shown in Fig. 5. Regarding the spectral SLA for both stations, Aden and Djibouti shows the most obvious annual and semiannual signals, while the small frequencies were negligible in comparison. For SLP, the annual signal is the most dominant for both stations, while the semiannual in Aden had more of a presence than that in Djibouti. The seasonal (quarter-annual) and semiannual signals are comparable. The along-shore wind signals are clear and strong in Aden and appears to be annual, semiannual, and seasonal. In Djibouti, the along-shore wind shows only the annual signal. The cross-shore wind shows the opposite situation for Aden and Djibouti, where all signals in Aden are weak. Steric spectral signals are almost identical for the SLA in both stations.

To clearly identify signals in all time series, spectral analysis has been conducted as shown in Fig. 5. Regarding the spectral SLA for both stations, Aden and Djibouti shows the most obvious annual and semiannual signals, while the small frequencies were negligible in comparison. For SLP, the annual signal is the most dominant for both stations, while the semiannual in Aden had more of a presence than that in Djibouti. The seasonal (quarter-annual) and semiannual signals are comparable. The along-shore wind signals are clear and strong in Aden and appears to be annual, semiannual, and seasonal. In Djibouti, the along-shore wind shows only the annual signal. The cross-shore wind shows the opposite situation for Aden and Djibouti, where all signals in Aden are weak. Steric spectral signals are almost identical for the SLA in both stations.

3.1. Correlation and Determination Coefficient

As seen from Fig. 6, the sea level is in the same phase with steric sea level and along-shore wind component for Djibouti station, while for Aden station, it is in the same phase with cross-shore wind and steric level. To understand the contribution of each of those factors on seasonal sea level variability, the correlation coefficient (CC) and determination coefficient (DC) were estimated and are summarized in Table 1. For both stations, steric level is the dominant factor with a CC (DC) of 0.86 and 0.84 (0.73, 0.71) for Aden and Djibouti, respectively. This result agrees with that of (Patzert, 1972) for Aden station. The along-shore wind had the second higher contribution for Aden, and the third highest for

Djibouti, with DCs of about 0.3 and 0.21, respectively. The cross-shore wind component had the second highest contribution on Djibouti SLA with DC about 0.3, while for Aden, this factor had no effect on SLA. SLP similarly contributed for both stations.

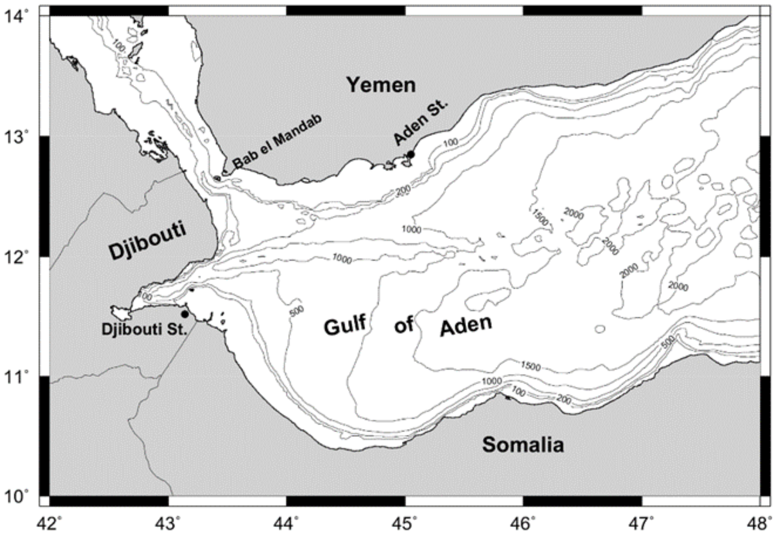

Fig. 1. Study area and tide-gauge stations.

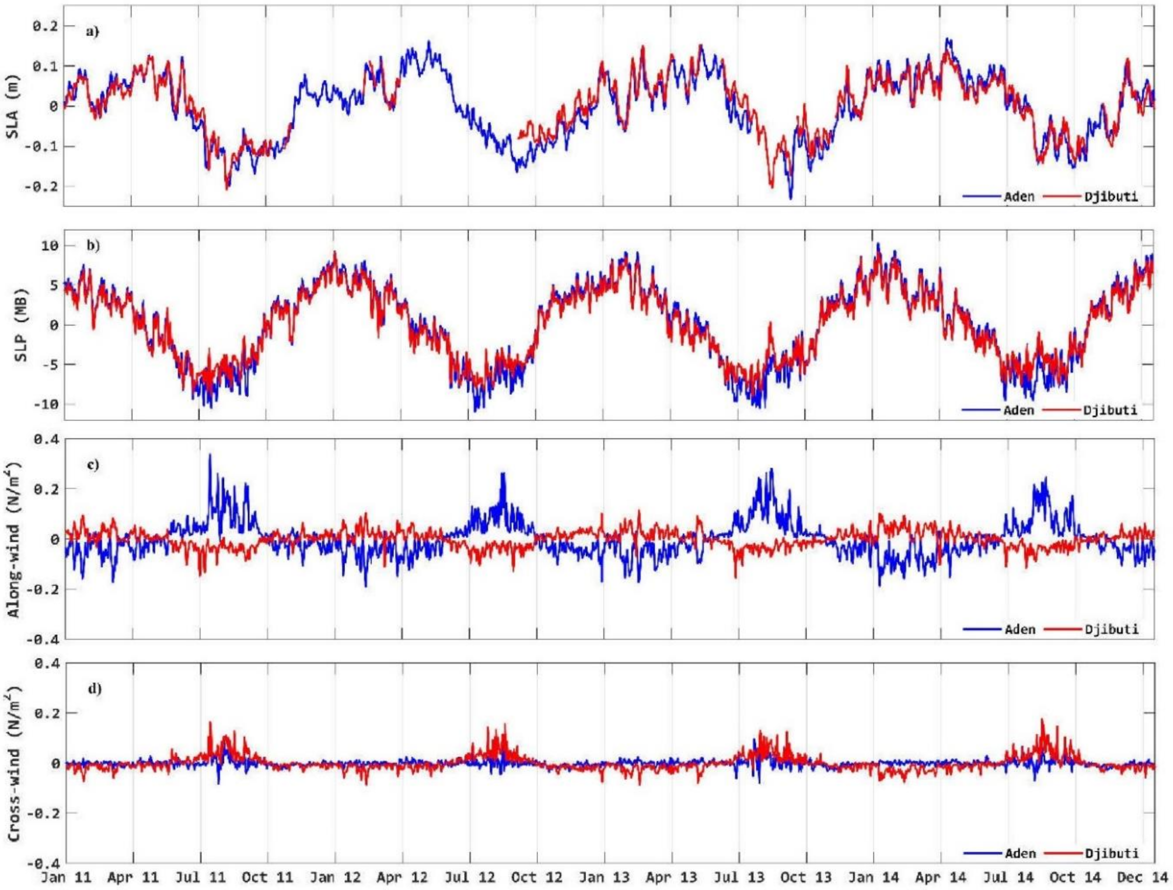

Fig. 2. Time series of daily mean SLA (a) at Aden and Djibouti, SLP (b), and along- and cross-shore wind stress components (c, d). For Aden (Djibouti) station, the cross-shore wind is positive (negative) inshore and negative (positive) offshore while the along-shore wind is positive eastward (northward) and negative westward (southward).

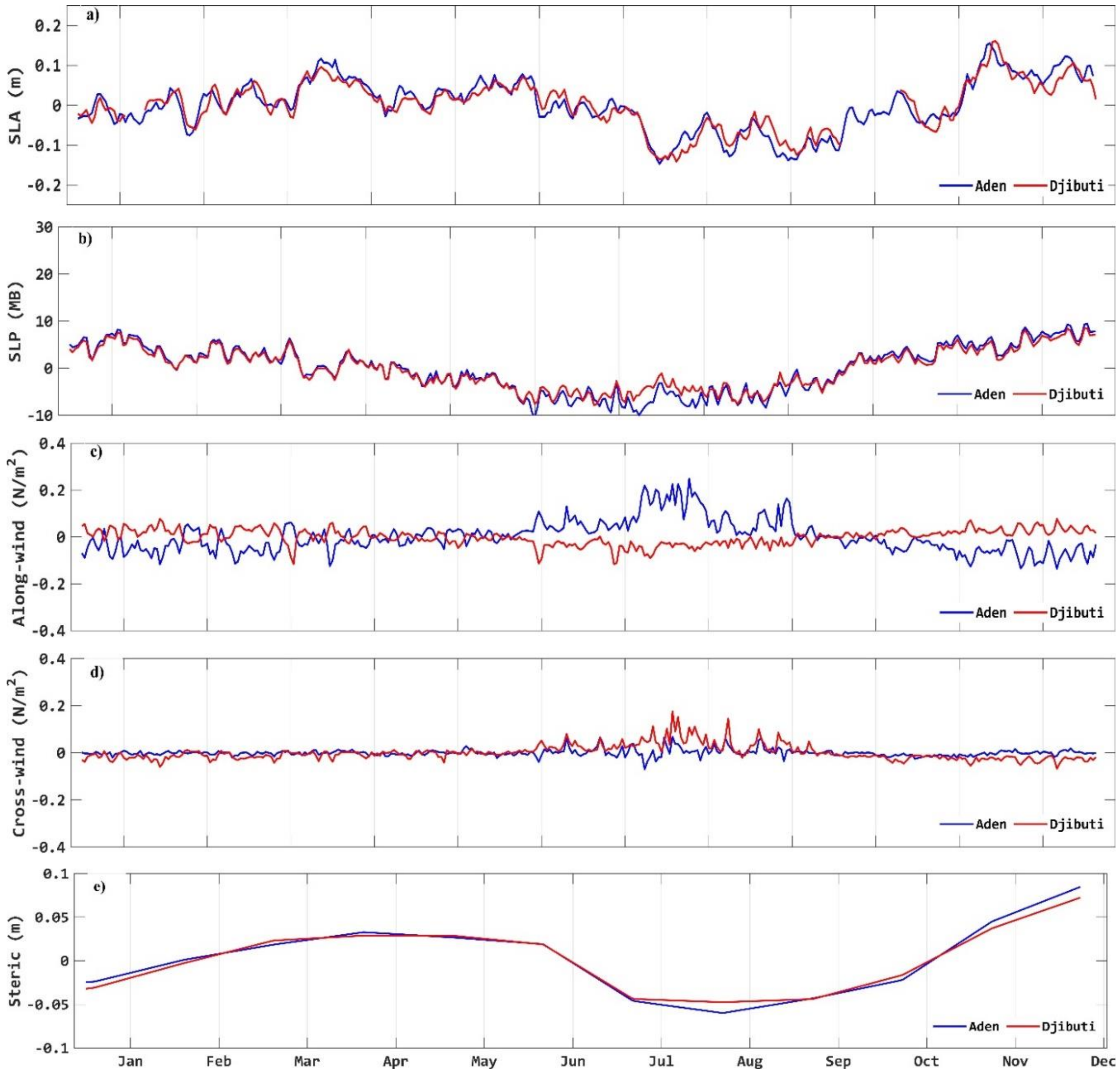

Fig. 3. Time series of daily average of 2014 SLA (a), SLP (b), along-shore (c), cross-shore (d), and steric sea level (e).

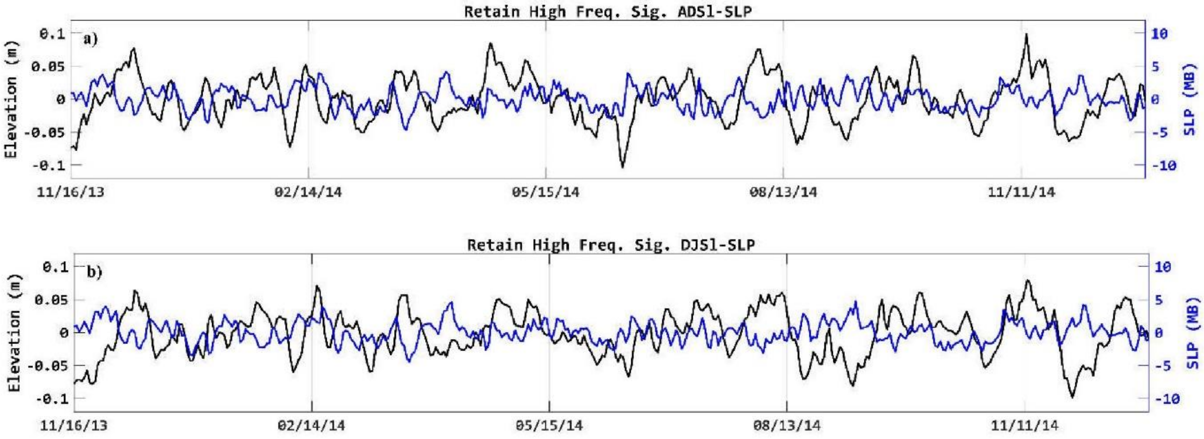

Fig. 4. The SLA and SLP high frequency variability at Aden (a) and Djibouti (b) after applying the high-pass filter.

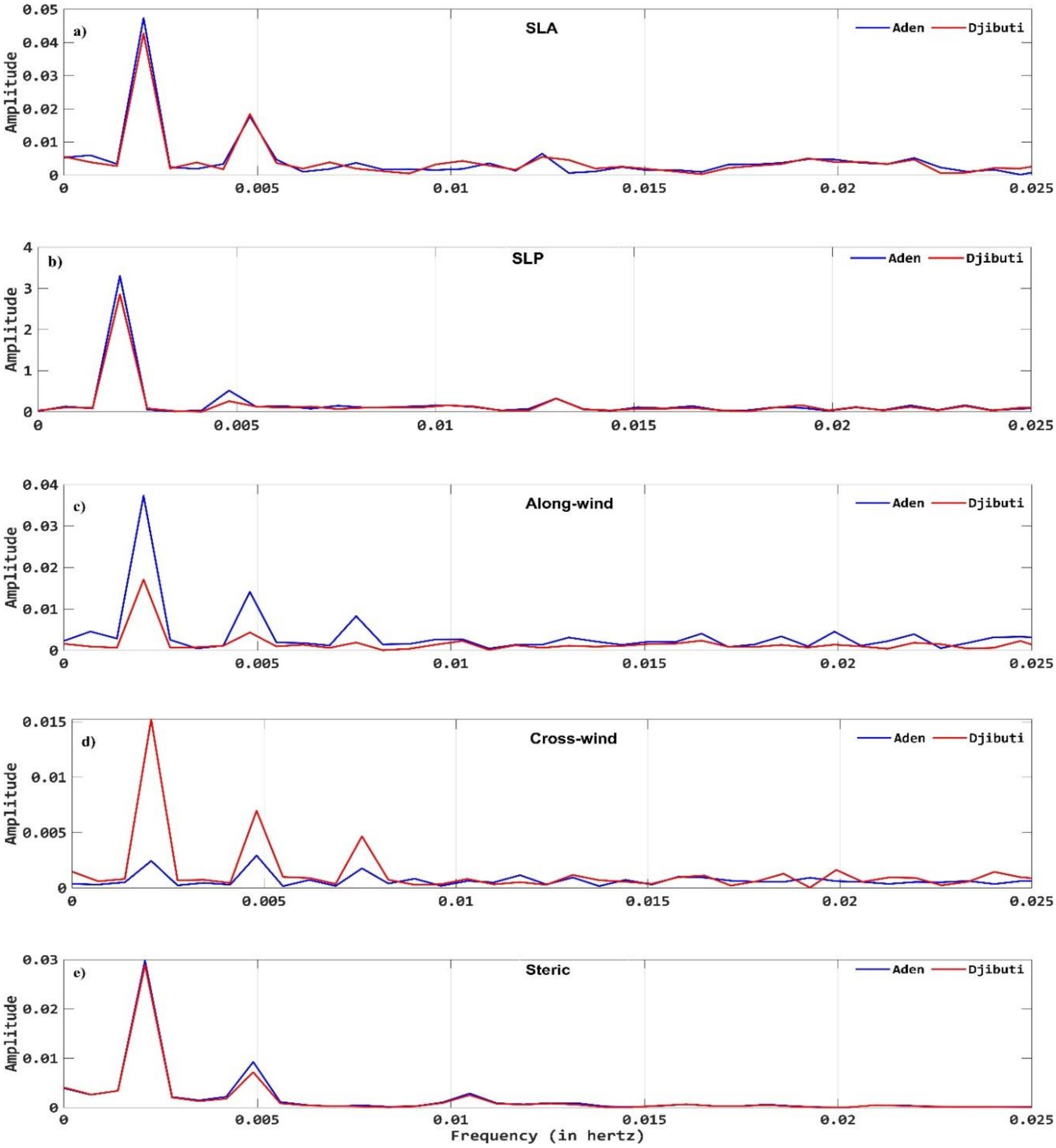

Fig. 5. Power spectrum of SLA, SLP, along-shore, cross-shore, and steric SL.

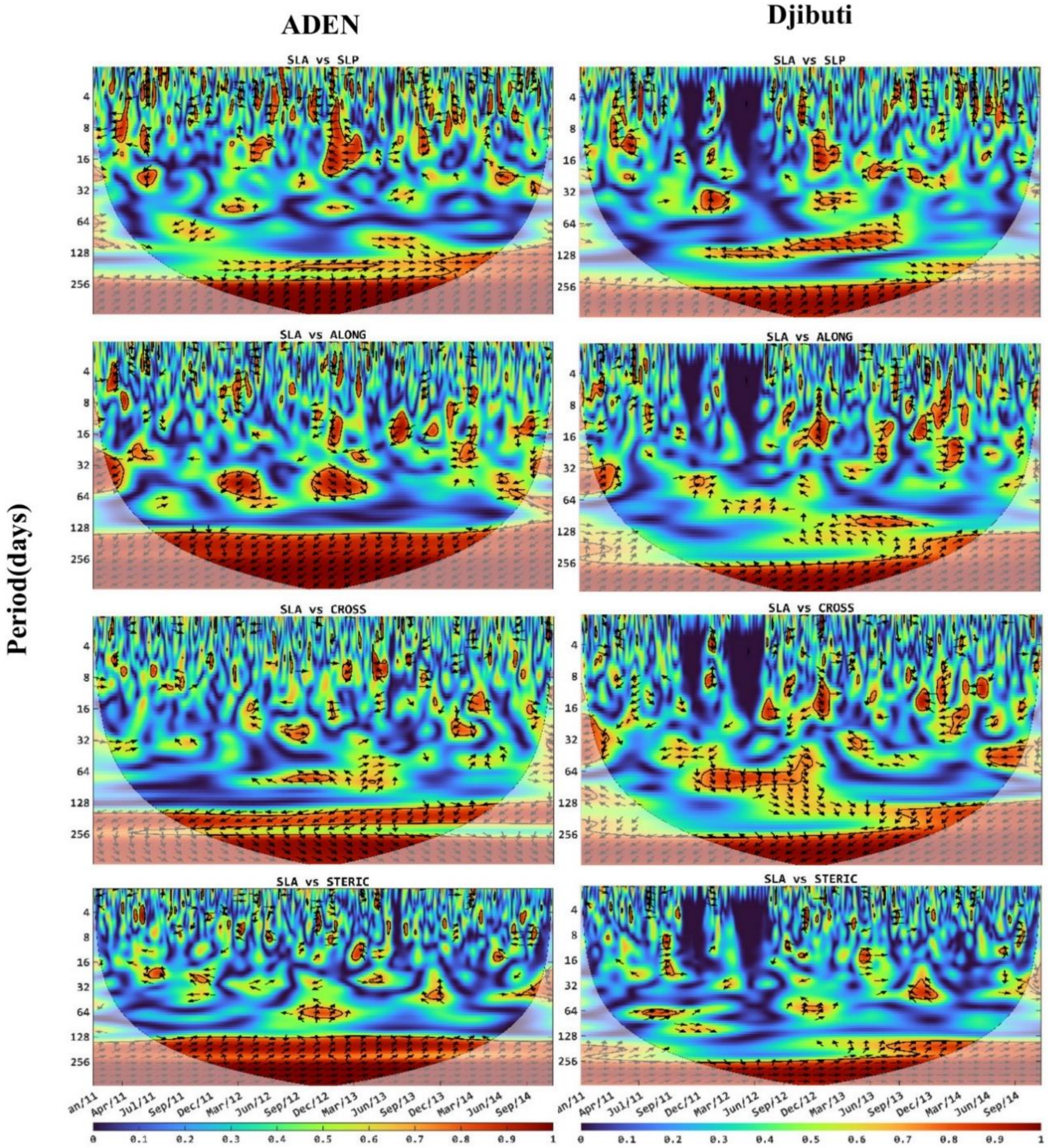

Fig. 6. Wavelet transform coherence (WTC) between SLA time series at (left) Aden and (right) Djibouti with SLP, steric SL, cross-shore wind, and along-shore wind for the same period. The relative phase relationship is shown as arrows (with in-phase pointing right, anti-phase pointing left, and SLA leading by 90◦ pointing straight down). The direction of arrows in the period of 6 month and above (seasonal period) indicates inphase relations among SLA and SLP, steric SL, and cross-shore wind, while it is off-phase with along-shore wind.

Table 1. Correlation and determination coefficients for SLA at Aden and Djibouti, and other controlling parameters.

Variables	Aden Station		Djibouti Station	
	CC (%)	DC (%)	CC (%)	DC (%)
SLP	0.42	0.175	0.37	0.14
Along-shore wind	−0.55	0.30	0.46	0.21
Cross-shore wind	−0.014	0.0002	−0.55	0.30
Strict	0.86	0.73	0.84	0.71

4. Conclusions

Variability in sea level at western Gulf of Aden shows strong seasonality of higher sea level in winter and lower in summer with a range up to about 35 cm which agrees with (Patzert, 1972). The comparison between the variability in daily sea level and daily atmospheric pressure indicates agreement in high sea level during winter with high pressure, and vice versa for summer; thus, the annual cycle of sea level is not a result of an inverted barometric response to atmospheric pressure. However, after applying high-pass filter for the high frequency variability of SLA and SLP for both stations; their SLA show a prompt inverse parametric response to the SLP all over the year. Moreover, the phase difference in low-frequency variability (more than 30 days) show that SLA precedes SLP with 3-4 months, which agrees with those of the Mediterranean Sea (Le Traon and Gauzelin, 1997). Seasonal cycle of the cross-shore wind reveals more variability with SLA in Djibouti compared with that for Aden, while it is the opposite for the along-shore component. The along-shore wind is out of phase with SLA at Aden, with negative wind stress during low sea level (summer) and positive stress during winter. This indicate that along-shore wind plays a significant role in sea level variability at Aden. Daily steric sea level for both stations exhibit an annual cycle with a high level during winter and low during summer, which is in phase with sea level variability in both stations.

Spectral analysis for SLA shows that the most obvious signals are the annual and semiannual, while the small frequencies (less than two months) are negligible in comparison. For SLP, the annual signal is the most dominant for both stations, while the semi-annual in Aden has more of a presence than that in Djibouti.

The seasonal and semiannual signals are comparable, though. Along-shore wind signals are strong in Aden and shows to be annual, semiannual, and seasonal. In Djibouti, only the annual signal could be observed. Cross-shore wind reveals the opposite situation for Aden and Djibouti, where all signals in Aden are weak. Steric spectral signals are almost identical for the SLA in both stations. The wavelet transform coherence (WTC) between SLA and SLP in both stations for short periods is in antiphase, which is the normal inverse barometric relation. For Aden station, the SLA is leading for periods from one season and longer, while the Djibouti SLA shows an antiphase for one season, and SLA is leading for the rest. This indicates that the SLP is not the major contributor to SLA fluctuation in the periods of one season and longer. Aden SLA shows the importance of along-shore wind for all periods with anti-phase relation in general; this effect is normal since Aden station is located along the northern coast of the gulf. The cross-shore wind effect is weak; however, it shows variable relation for the short period, and antiphase for one season, and SLA is almost inphase with short time lagging. Wind components play the opposite role at Djibouti station, where cross-shore wind is the most dominant component, which shows an anti-phase for one season and longer. For both stations, steric sea level shows an inphase with SLA, indicating that it plays a major role in sea level variability for seasonal and annual periods.

To summarize, the SLA shows strong seasonal variability with high values during winter and the opposite in summer. The major contributor for this variability is steric SL with CCs (DCs) of 0.86 and 0.84 (0.73 and 0.71) for Aden and Djibouti, respectively. The second contributor at Aden is along-shore wind with DCs of about 0.3 and 0.21, respectively, while it is cross-shore wind for Djibouti with a DC of about 0.3. The SLP similarly contributes for both stations, and only plays a major role in short SLA variability.

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العوامل التي تتحكم في التقلبات الموسمية لمنسوب سطح البحر في غرب خليج عدن

عبدالله محمد الصبحي

قسم الفيزياء البحرية، كلية علوم البحار، جامعة الملك عبد العزيز، ص. ب ٨٠٢٠٧ – جدة ٢١٥٨٩، المملكة العربية السعودية

amalsubhi@kau.edu.sa

المستخلص. تم حساب المتوسطات اليومية لمنسوب سطح البحر من البيانات الساعية في محطتي عدن وجيبوتي، خلال الفترة ٢٠١١–٢٠١٤م، وذلك لدراسة التغيرات الموسمية في منسوب سطح البحر (SLA) في غرب خليج عدن. تم التحقيق في هذه التغيرات مقابل عوامل التحكم التالية: الضغط الجوي عند سطح البحر، والرياح، ومنسوب البحر الستيريكي (الحراري). يظهر في (SLA) في عدن وجيبوتي تغيرات موسمية قوية مع ارتفاع في الشتاء وانخفاض في الصيف بنطاق يصل إلى حوالي ٣٥ سم. ويتوافق التغير عالي التردد في منسوب سطح البحر مع التغير في الضغط الجوي، خاصة خلال فصل الشتاء بعلاقة بارومترية عكسية طبيعية. تؤثر الرياح العابرة للساحل على تقلب منسوب سطح البحر في جيبوتي أكثر من تأثيرها في عدن، بينما تلعب الرياح الموازية للساحل دورًا مهمًا في تقلب منسوب سطح البحر في عدن. ويلعب منسوب سطح البحر الستيريكي لكلتا المحطتين دورًا مهمًا في التقلب الموسمي لـ (SLA). وتظهر كلتا المحطتين أن أقوى التذبذبات في (SLA) هي السنوية ثم نصف السنوية، في حين أن الترددات الصغيرة لا تكاد تذكر بالمقارنة. وبالنسبة لمحطتي عدن وجيبوتي، فإن منسوب سطح البحر الستيريكي هو العامل المهيمن بمعامل تحديد (DC) يبلغ ٠٫٧٣ و٠٫٧١ على التوالي. وتعتبر الرياح الموازية للساحل ثاني أعلى مساهمة في عدن بحوالي ٠٫٣. في حين تمثل الرياح الموازية للساحل ثاني أعلى مساهمة في جيبوتي بمعامل تحديد يبلغ حوالي ٠٫٣، بينما في عدن، لا يؤثر هذا العامل على (SLA). وتظهر مساهمة الضغط الجوي بوضوح في التذبذبات القصيرة لكلتا المحطتين.

الكلمات المفتاحية: خليج عدن، متوسط منسوب سطح البحر، منسوب سطح البحر الحراري، نظرية المويجات، العوامل الجوية.