Signatures of Tropical climate modes on the Red Sea and Gulf of Aden Sea Level

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Long–term sea level data (1958–2010) for the Red Sea (RS) and Gulf of Aden (GA) obtained from Simple Ocean Data Assimilation (SODA) were analyzed to examine its relation to the tropical climate modes. The continuous wavelet power spectrum analysis of sea level reflects the presence of significant power peak in semi-annual and annual band throughout the study region over the entire period. This variability is clearly associated with Nino3.4, which were accounted from the analysis of wavelet coherence. The results show an in-phase relation in semi-annual band while the sea level lags the Nino3.4 by 9-10 months in annual band in all regions, which in-turn is associated to the peak difference between mean SST and sea level. Whereas, there is no significant interaction is identified with SOI and IOD. However, the wavelet coherence of Nino3.4 and SOI showed 2-7 years band in all regions, which corresponds to the sequence of strong El Nino/La Nina events during 1968-1976 and 1997-2003.

[Key words: Red Sea, Gulf of Aden, Sea Level, Climate Modes, Wavelet Analysis]

Introduction

The Red Sea (RS) is a semi-enclosed, elongated marginal basin which extends from 12.5°N to 30°N with an average depth of about 490 m and is surrounded by arid and semi-arid land on both sides. It is connected to the Arabian Sea and Indian Ocean via Gulf of Aden (GA) through the Bab-al-Mandab Strait, (see Fig. 1). Water exchange through Bab-al-Mandab exhibits a distinct seasonal cycle. In winter, two layer system occurs, surface water as inflow to the RS and deep water as outflow. In summer, the GA intermediate water is observed as inflow and it balanced by both surface and deep water outflow.

The surface wind over the RS is constrained by the high mountains and plateaus on both sides. During summer (June-September) the entire RS experiences the north-northwest wind, while in winter (November-March) the south-southeast wind builds up in the southern part and converges with the north-northwest wind at around 19°N.

The wind over the GA follows the north Indian monsoon cycle; westerly during summer and northeasterly during winter.

The factors affecting the regional sea level are generally classified into three groups; geological and astronomical processes, large scale processes and regional scale processes. Regional scale includes inverse barometric effect (atmospheric pressure), steric effects (temperature and/or salinity) and local oceanic and atmospheric factors (wind, current, waves and fresh water input and etc.). In the RS, the sea level is mainly governed by wind pattern and combined effect of evaporation and water exchange via Bab-al-Mandab Strait. It rises in winter and falls in summer. However, it is characterized by annual and semi-annual cycles; the annual cycle is very clear in all the basins and is controlled by wind pattern and water exchange, while the semi-annual cycle is controlled by the evaporation.
In winter season, the advent of strong southwest-southeast wind into the RS induces the surface flow northward and sea level rises, with central bulge located in the wind convergence zone (19°N) \(^1\). While in summer, the sea level drops due to the northwest wind in the whole basin. In the southern RS, when the wind changes from southeast to northwest during early summer, the current changes direction with the same phase of wind, but there is a one month lag between them when it becomes southeast during early winter.

Papadopoulos et al. \(^19\) investigated the role of atmospheric circulation on the heat flux in the RS, and found that the highest heat loss is associated with strong, cold and dry continental air masses originally from the linkage between the Azores and Siberian high pressure regions, while the lowest heat loss occurs with weak, warm and moist air masses that come from the Arabian Sea and Indian Ocean. Recently, Abualnaja et al. \(^20\) examined the effect of different climate modes on the RS and found that El Niño–Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD) or Dipole Mode Index (DMI) have the significant role in the air–sea heat exchange. Similar observations have been identified on the wind-wave energy distribution in the RS \(^21\).

El Niño–Southern Oscillation (ENSO) is described as the most energetic climatic phenomenon over the earth that involves fluctuations in both SST and wind in the tropical Pacific Ocean. While the IOD is a coupled ocean-atmosphere phenomenon in the equatorial Indian Ocean, which is defined by the difference in SST between two poles, east and west parts of the Indian Ocean \(^22\). Both Phenomenon cause great ecological and social impacts worldwide.

This study is set to investigate the multi-scale interaction between the sea level in the RS and GA with the SST in the tropical Pacific and Indian Oceans. Only a few researches discuss the climate modes effect in this area and most of them used coral oxygen isotope records \(^23, 24, 25, 26\), while Raitos et al. \(^27\) discussed it using remotely sensed chlorophyll. The present study focuses on the sea level in this regions, where no previous study has linked its variability with tropical climate modes. The overall structure of the study is as follows, section 2 describes the dataset and methods used here. Section 3 and 4 discuss the results and discussion respectively. The conclusions are given in section 5.

**Materials and Methods**

The study of climate requires long and continuous data, which is missing for the RS and GA. Sea level data used in this study are from Simple Ocean Data Assimilation (SODA). It is re-analyzed monthly average data during 1958-2010, assimilated using General Circulation Model with 0.25°×0.4° resolution, but the data are remapped on the uniform horizontal grid 0.5°×0.5°\(^28\).

The time series of Nino 3.4 index defined as the SST anomaly from Extended Reconstructed Sea Surface Temperature Version 4 (ERSST.v4) in the east central tropical Pacific Ocean (5ºS- 5ºN, 170º-120ºW) while the Southern Oscillation Index (SOI) are downloaded from the NOAA-Earth System Research Laboratory-physical science division (http://www.esrl.noaa.gov/psd/data/climateindices/list/). Indian Ocean Dipole Index represent the gradient of SST anomaly between west (50 º E-70 º E and 10 º S-10 º N) and east (90 º E-110 º E and 10 º S-0 º N) equatorial Indian Ocean are obtained from the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) derived from HadISST dataset (http://www.jamstec.go.jp/frcgc/research/d1/iod/HTML/Dipole%20Mode%20Index.html). The monthly mean of the all climate modes data set during 1958-2010 are shown in Fig. 2.

Based on the wind pattern climatology, the area was divided into three regions, GA (42.75º-51.25º E), Southern RS (12.75º-20.25º) and Northern RS (20.25º-28.25º N). Wavelet analysis was used following Torrence and Compo \(^29\) and Grinsted et al. \(^30\) methods. The wavelet analysis becomes a very effective tool for analyzing the variations of power within a geophysical time series. It transforms any time series or frequency...
spectrum (one-dimensional) to time–frequency space (two-dimensional). In order to give a good feature extraction, the frequency was adjusted $= 6$. And to avoid the edging error resulting from the artifact edge of the time series, the edge was dropped by a factor $e^{-2}$.

Results

Time series of monthly mean sea level anomaly (SLA) in the GA was investigated with different faces of climate modes (Fig. 3). While a strong, pure El Nino event occurred during 1965-1966, a positive SLA (17 cm) was observed in GA.

![Figure 2: Time series of monthly mean Nino3.4 (upper panel), SOI (middle panel) and IOD (lower panel).](image)

This event starts in June 1965, while the maximum SLA was observed in May 1966. During May 1988, a strong La Nina occurs, a negative SLA was observed (-18 cm) in August 1989 in the GA. The same situation was found during La Nina in 2001, but the negative SLA reached -23 cm in August, where this event starts earlier in July 1998 and extended for 33 months till March 2001. However the pure negative IOD tend to decrease the sea level during 1958, 1989 and 1996 events, while the SLA decreased by -19, -22, and -20 cm during September of the following year, except in the case of 1996 where it appears in September of the same year. No significant results were observed during pure positive IOD events, but the years of combined El Nino and IOD (during 1972, 1982 and 1997) increased the SLA by 15, 14 and 16 cm during Feb. 1973, May 1983 and March 1998, respectively. The same effect occurs in the southern and northern RS, but with lesser range and variability (not shown).

Furthermore, the wavelet technique was applied in order to know the existing physical link between the climate indices and the sea level. Wavelet can uncover the periodicities of the time series and at what time these occur.

![Figure 3: Time series of monthly mean sea level and different ENSO and IOD events. The red circle is pure positive ENSO, magenta circle is combine positive ENSO and IOD events, and green circle is pure negative IOD while the brown circle is pure negative ENSO. The ENSO events was obtained from the following site http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml, while the IOD events from Hong et al. (2008).](image)

The continuous wavelet power spectrum of sea level shows significant power peak in annual band in all regions, Fig. 4, with appearance of semi-annual band in the northern RS only. Both bands have above 5% significant level and persisted throughout the period. The continuous wavelet of Nino3.4, SOI, and IOD are shown in Fig. 5. Nino3.4 exhibits a power peak in semi-annual band with a weak significant level. The annual band appears in Nino3.4 and IOD, 2-6 years band appears in Nino3.4, SOI and IOD with strong significant level. While SOI alone reflects 11-15 year band after 1975. However, it is hard at this stage to confirm which signal is dominant in the area, but the coherence wavelet analysis is very helpful in this manner.
Figure 4: Continuous wavelet of monthly mean Sea level for the GA (top), South RS (middle) and Northern RS (bottom). The thick black contour is 5% significant level against the red noise, while the COI (solid line) appears as lighter shaded region.

Figure 5: Continuous wavelet of monthly mean climate indices, Nino3.4 (top), SOI (middle) and IOD (bottom). The thick black contour is 5% significant level against the red noise, while the COI (solid line) appears as lighter shaded region.
The squared WTC of Nino3.4 and Sea level is shown in Fig. 6. The above 5% significant level indicates that Nino3.4 contribute to both annual and semi-annual band. The phase relation in the Semi-annual band is in-phase, while in the annual band the sea level lags Nino3.4 by 270°-300° corresponding to 9-10 months in all regions. However 2-7 year band appears in all regions; the phase relation shows that Nino3.4 leads the sea level by 90° in GA and by 120° in the northern RS corresponding to 3-4 months. Also 11-18 years band appears around 1980, with -90° to -120° phase relation in the southern RS and continues but inside the COI, implying that Nino3.4 leads the seal level by 3-4 months. The most interesting result is a shift in phase angle in 2-7 band from 1 month (-30°) around 1972 to 4 months (-120°) around 1997 in the northern RS. Furthermore, during 1990 to 2010 there is evidence of a shift in the period of high power and coherency from 2-7 years up to around 5-7 years band in the southern RS, which also appears in the northern RS with same phase angle.

Fig. 7 shows the wavelet coherence of SOI and sea level. It is very similar to Nino3.4 feature of power peak in 2-7 year band as it is atmospheric component of ENSO, but of course completely out of phase. Both Nino3.4 and SOI reflects 11-18 years band in the southern RS, the phase angle about -60° to -90° indicates that the SOI leads the sea level by 2-3 months. Furthermore, SOI reflects weak indication of annual and semi-annual band compared to Nino3.4, with unclear phase angle.

The wavelet coherence of IOD reflects weak signal to the RS sea level compared to Nino3.4 and SOI, Fig. 8. Its contribution appears in annual band around 1970, 1988 and 2006 in all the regions with fairly randomly distributed phase angle, except for the northern basin where only first two are appearing. In addition, it contributes in 2-7 years band during 1980-2000 in the southern RS, and it leads sea level by 90° corresponding to 3 months. Furthermore, the IOD becomes active during the weakening of Nino3.4 in the southern RS, the 3-5 years band took place in the southern RS after the shifting of 2-7 years band of Nino3.4 to 5-7 years band after 1990.

Discussion
An assessment was done on the effects of tropical climate indices on the long term sea level data. The SLA in the RS and the GA shows significant fluctuations with climate modes. The positive SLA coincides with positive face of both ENSO and IOD, while the negative SLA occurs during La Nina and negative IOD events. The opposite results observed along the east coast of India, the positive (negative) ENSO and IOD and also the combined events decreased (increased) the SLA. In addition, the variability of SLA depends on the timing and intensity of the events, the stronger positive events, the large negative SLA. This argue does not completely occur in the RS and GA, as an example, during 1997, the strongest ENSO event co-occurs with strongest IOD, but the observed positive SLA (16 cm) is less than the moderate ENSO event during 1965 by 1 cm. However, the period of maximum positive and negative SLA varies from event to event, but the majority of positive SLA occurs during February-May, while the negative SLA occurs during August and September.

The wavelet results show that the climate indices have a role in semi-annual, annual, interannual and decadal variations of sea level in the RS and GA. Annual and semi-annual variations which appear in continuous wavelet of sea level in Fig. 4 and wavelet coherence of sea level with Nino3.4 in Fig. 6 are well known in a previous study, and can be link to the combine effect of wind regime and both water exchange at Bab-al-Mandab and evaporation, respectively. Sultan et al. figured out that the annual cycle of sea level at Jeddah and Port-Sudan are 20 and 13 cm, respectively, with 44% variance, while the semi-annual cycle are 10 and 8 cm with 10% and 16% variance, respectively. However, Clarke and Liu and Sakova et al. observed the annual band in the eastern Indian Ocean and referred it to the alongshore monsoon wind, while the semi-annual cycle is linked to the semi-annual zonal equatorial wind and thermohaline process which is related to Wyrtki jet. The new results here are physically linked to the El Nino, which have not previously been described.

The phase angle of the annual band indicates that sea level is out of phase with Nino3.4 by about 270-300°. The peak of mean SST in Nino3.4 region occurs during April and May, while the sea level peak occurs during February and March, meaning that sea level lags the Nino3.4 SST by 9-10 months, which in-turn is associated to the peak difference between mean SST in the Pacific Ocean and sea level In the RS and GA. In the semi-annual band, the sea level and Nino3.4 are in-phase. Chambers et al. speculate that Indian Ocean warming lags the Pacific Ocean by 3-5 months, while the peak of the warming lag by about 7-9 months.
Figure 6: Wavelet coherence of monthly mean Nino3.4 and sea level for the GA (top), South (middle) and Northern RS (bottom). The thick black contour is 5% significant level against the red noise, while the COI (solid line) appear as lighter shaded region. Arrows indicate that right: in-phase, left: out of phase, down: Nino3.4 leading sea level by 90° and up: sea level leading Nino3.4 by 90°.

Figure 7: Wavelet coherence of monthly mean SOI and sea level for the GA (top), South RS (middle) and Northern RS (bottom). The thick black contour is 5% significant level against the red noise, while the COI (solid line) appear as lighter shaded region. Arrows indicate that right: in-phase, left: out of phase, down: SOI leading sea level by 90° and up: sea level leading SOI by 90°.
Nevertheless, annual and semi-annual bands are very weak in SOI, meaning that these properties are clearly associated with Nino3.4. This finding agrees with Torrence and Webster, where SOI does not reflect clear annual cycle.

The 2-7 years band is consistent with the previous studies, where different cyclicities (1.7, 2, 2.7, 3.8-3.9, 5.7, 7.6 and 8.5) were detected in the coral oxygen isotopes from the northern RS, but the most dominant one is 5.7 year. They argued that the interaction between the ENSO and NAO throughout the Pacific-North American Pattern (PNA) can bring the ENSO signal not only up to the RS alone but till the Middle East, especially in this dominant time scale. Furthermore, same results were observed in the sea level. Globally, Torrence and Webster found it as 2-8 year in 125 years of Nino3 and SOI data, Wang and Wang in the East Pacific SST and SLP, while Gu and Philander in the tropical zonal wind. This band reflects all the main events of ENSO, as example during 1968-1976 in the southern RS and 1997-2003 in the GA and the northern RS. During the first period, the SST in the tropical Pacific region shows a cycle of warm/cold/warm/cold episodes, but the famous are El Nino1972 and La Nina 1973. The same situation occurs during the second period, sequence of warm/cold/warm episode and the famous are El Nino1997 and La Nina 1999. These findings physically imply that the variability of SST in the tropical Pacific Ocean has a high coherence with sea level in the RS and GA even via oceanic and/or atmospheric teleconnections.

The shift of the phase angle (-30° to -120°) in 2-7 year band in the north from 1972 to 1997 may represent indication of the global shift of climate regime from the mid 1970 which is extensively documented in different locations including the RS. Increasing of IOD signal when the ENSO is weakening during 1980 to 2000 in the Southern RS is consistent with the findings of Nakamura et al. in Kenya. Nakamura et al. pointed out that the warming of the Indian Ocean enhanced the IOD to overshadow the ENSO-Indian Ocean Summer Monsoon interaction by increasing the frequency and intensity events from 1960’s. On the other hand, the above phase shift and the intensified events prove the non-stationary relation of those modes with sea level.

The interdecadal variability (11-18 year band) was previously detected in different studies. Jevrejeva et al. observed it as 12-20 year band in the ice condition of both Baltic and Barents Sea. Jevrejeva et al. conclude that it appears in the Arctic oscillation associated to SOI. The mechanism that cause this oscillation still remain under study, but the same phase relation between 11-18 and 2-7 years band in the southern RS may suggest same mechanism from the tropical eastern Pacific. The weakening of IOD in the RS is not a new finding; Abualnaja et al. investigate its effect in the heat flux, and conclude that El Nino is most influential tropical phenomenon especially during winter over the southern basin.

**Conclusion**

The time series of sea level anomaly in the RS and GA reflects different phases of Nino3.4 and IOD events. Positive phase of both Nino3.4 and combine events (+Nino3.4 and +IOD) contributes to rising the sea level in the RS and GA. Maximum positive SLA mainly occurs in the following year during February to May. Moreover the negative phase of Nino3.4 and IOD contribute to falling of the sea level. The negative SLA occurs in the following year during August and September.

However the wavelet analysis extracts different periodicities (semi-annual, annual, 2-7 and 11-18 years band) of sea level with Nino3.4, SOI and IOD. The Nino3.4 is in-phase with semi-annual band and leads the annual band by 9-10 months, corresponding to the peak difference of mean SST in the Nino3.4 region (April-May) and sea level in RS and GA (February-March). Moreover the contributions of SOI and IOD in both bands are weak compared to Nino3.4.

The 2-7 year band reveals that Nino3.4 and SOI lead sea level by 3 months in the GA, but 4 months was observed in the northern RS, while 11-18 year band of both modes lead it by 3-4 months in the southern RS only around 1980. In addition to that, the power peak of 2-7 year band was shifted to 5-7 year in the southern RS during 1990-2000, but it appears in the north by the same phase angle in the same period. IOD effect becomes well clear during this shift in the southern RS, where 3-5 year band is observed.

The SOI feature is similar to Nino3.4 as it considered the atmospheric part of ENSO, but completely out of phase, whilst the IOD contribution is weak in all band when we compare it with ENSO. Furthermore, all the above findings clearly reflect the non-stationary property of climate modes in the RS and GA which is documented in the previous studies.
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References


