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East-west Variability of Sea Level in the Red Sea

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ABSTRACT

The sea level changes and associated physical processes are not explored well compared to other parts of the world. In the present study, the sea level variability in the Red Sea is investigated with the help of more than two and half decades of remote sensing observations from satellite altimetry. Considering the east–west difference in sea level, the study revealed the presence of a persistent east–west pattern which is visible every year. This east–west (EW) difference is positive during winter when a higher sea level is observed on the eastern coast of the Red Sea and negative during summer when a relatively lower sea level is observed in the same region. May and October are transition months, with a variable pattern in the change in sea levels. The EW difference in the southern Red Sea is slightly larger than that in the northern part during summer, by an average of 0.2 cm. For both the northern and southern Red Seas, wavelet analysis reveals a large annual cycle as well as other signals of lesser amplitude. EOF1 correlates to 98 percent of overall variability, EOF2 to 1.3 percent, and EOF3 to 0.4 percent, according to Empirical Orthogonal Function (EOF) analysis. ENSO has a strong remote reaction to EW differences, whereas the Indian Ocean Dipole (IOD) and North Atlantic Oscillation (NAO) have minor responses. The occurrence of this EW differential phenomena is caused by three physical mechanisms: wind, buoyancy, and the polarity of eddies.

Keywords: Satellite altimetry; sea level anomaly; el-nino southern oscillation; Indian Ocean Dipole; north atlantic oscillation; red Sea.

1. INTRODUCTION

Sea level is one of the very important physical oceanographic variables with a significant impact on the physical and biological processes of the region. Being one of the crucial climate indicators, the sea level variability and long-term changes are studied on both global and regional scales [1–3] revealing various

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dynamics of upper layer ocean processes [4,5] that may lead to adverse impact on the marine environment [6,7]. Further, the sea level measurements since the 1880s reveal the presence of a gradual rise in global mean sea level where a major part of the rise happened in recent decades. Apart from this, the future predictions are showing the possibility of an accelerated rise in mean sea level associated with global warming and the melting of glaciers and ice sheets.

The Red Sea, located between the African and Asian continents (12-30°N & 32-44°N), is an important marginal sea known for unique oceanographic characteristics and complex distinctive marine ecosystems. It supports the high diversity of corals and holds precious repositories of marine biodiversity [8] with a length of about 2000 km, an average width of 280 km, and an average depth of about 500 m [9].

The sea level variability in the Red Sea is mainly influenced by the exchange between the Red Sea and the Gulf of Aden, which is primarily driven by the thermohaline effect and the seasonally reversing wind regime [10–14]. The region is characterized by a strong evaporation rate of about 2 m.yr^{-1} [15] with nearly zero precipitation and a seasonally reversing wind system [15,16]. The surface current flow is in the southward direction during summer and in the northward direction during winter [9,16]. The availability of satellite altimetry records for more than two and half decades has provided an unprecedented opportunity to better understand the spatial and temporal variability in sea level. In recent years, an increasing interest has been observed in altimetry-based sea level studies globally and regionally [2,3,17–20]. However, relatively less attention is paid to the Red Sea in comparison to other regions of the world.

The datasets used in the present study include sea level anomaly maps (SLA), wind fields, and climate indices corresponding to climate modes such as ENSO (El-Nino Southern Oscillation), IOD (Indian Ocean Dipole), and NAO (North Atlantic Oscillation) [for more details on the data sets, please refer [21]]. The season in the Red Sea is classified as follows: November to March is considered winter, during which the SSE wind prevails in the southern Red Sea and NNW winds prevail in the northern Red Sea; June to September is considered the summer, where the wind in the entire basin blows NNW and relatively stronger than in winter; the months April-May and October are, respectively, considered the spring and autumn seasons.

2. RESULTS

The spatial and temporal variability of the sea level in the Red Sea is analyzed based on satellite altimetry records for the period from 1993 to 2018. Apart from the previously documented findings [16,20], the analysis has shown an interesting pattern of the east–west difference in the sea level between the eastern and western sides of the Red Sea, which is seen in all years and has significant seasonal variability. The spatial and temporal variability of this east–

west difference (hereafter “EW difference”) is investigated to understand the short-term and long-term variability based on SLA derived from satellite altimetry records from 1993 to 2018 (26 years).

The Red Sea is geographically located in an inclined position with the imaginary axial line tilted by ~32 degrees in the anti-clockwise direction to the meridian. To consider this aspect in the analysis, we have considered the eastern and western regions using boxes in an inclined plane (32 degrees tilted toward the left) as shown in Figure 1a. The EW differences are estimated for the data points that fall into the boxes named B1 (northwestern), B2 (northeastern), B3 (southwestern), and B4 (southeastern) as shown in Figure 1a. The EW difference in sea level for the northern and southern Red Sea is shown in Figure 1b. The variability in both northern and southern Red Sea are in phase, however, a small difference is noticed in the amplitude of variability.

To quantify the contribution of different signals in sea level, an EOF analysis was carried out (figure not shown). The first three EOF modes together account for more than 99% of total variations of sea levels in the Red Sea. The first mode predominantly explains about 98% of the total variation and mainly represents the annual component while the second (1.3%) and third (0.4%) modes of variability are negligibly small. This is in agreement with previous studies [22,23], which have shown that the annual cycle is dominating the sea level variability of the Red Sea. The wavelet analysis on sea level after filtering the predominant annual signal (Figure 2) shows the presence of two dominant energy peaks for most of the data period with periodicities <12 months and 3-7 years, representing the intra-seasonal and ENSO signals respectively [20].

In brief, a significant seasonally reversing EW difference pattern is existing in the Red Sea. The average annual cycle of EW difference for the northern, southern, and whole basins of the Red Sea is shown in Figure 3. On average, the eastern side is higher than the western side from November to March and vice versa from June to September (Figure 3) indicating that the eastern side has a higher sea level for two times longer period (8 months) compared to that of western side (4 months).

The characteristics of eddies in the Red Sea are also analyzed, as the polarity of eddies (cyclonic or anticyclonic) can significantly influence the spatial sea level difference in narrow basins like Red Sea. The eddies were mostly concentrated in the central and northern Red Sea compared to the southern region. The number of cyclonic eddies was relatively larger than of anticyclonic eddies. Relative dominance of cyclonic eddies is observed in the western Red Sea during winter which more or less shifted to the eastern side during summer [18]. This can result in relatively lower sea level regions in the western Red Sea during winter and in the eastern Red Sea during summer.

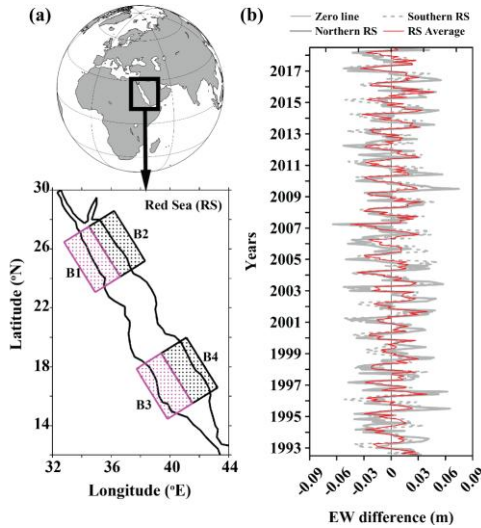


Fig. 1. The geographical location of the Red Sea and the bathymetry. The rectangular boxes indicate selected regions from the northern and southern Red Sea in an inclined plane (inclined to the left by 32 degrees from true north). The boxes are named B1 (northwestern), B2 (northeastern), B3 (southwestern), and B4 (southeastern). b) The time series of the EW sea level difference for the northern (B2-B1) and southern (B4-B3) basins

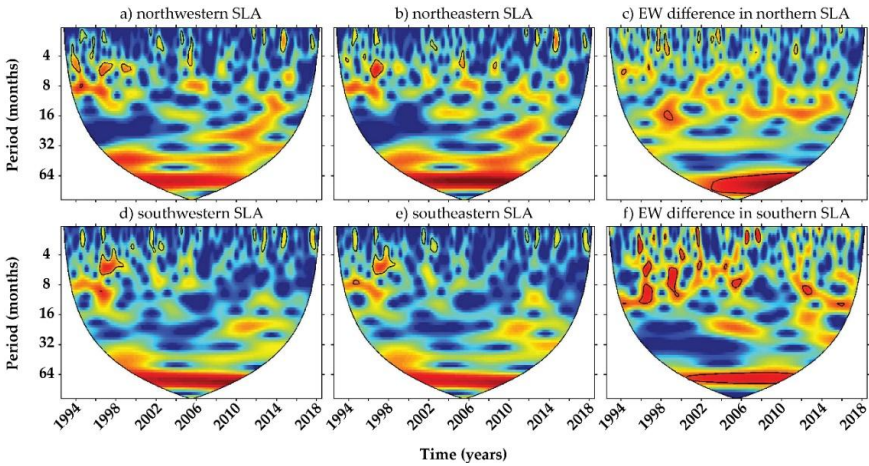


Fig. 2. The wavelet plots after filtering the annual signal for the selected boxes at a) northwestern, b) northeastern d) southwestern, and e) southeastern Red Sea along with the east-west difference at northern (c) and southern (f) Red Sea

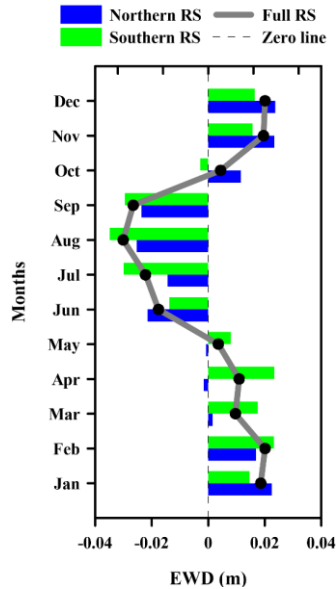


Fig. 3. The EW difference pattern for the northern, southern, and the whole Red Sea basin

The relation of the observed EW difference in sea level with climate events El Niño Southern Oscillation (Multivariate ENSO Index V2, MEI), Indian Ocean Dipole (Dipole Mode Index, DMI), and North Atlantic Oscillation (NAO index) are investigated to explore the possibility of the remote response of these events in the Red Sea. The EW difference in sea level is positively related to MEI throughout the year with maximum correlation during the spring and autumn seasons (with correlation coefficients of 0.44 and 0.51, respectively). The correlation values during winter and summer are also positive but are not statistically significant.

No significant relation is observed between the EW difference and DMI in the Red Sea. The previous study also reported similar results [24], that there is only a weak relation between sea level and DMI in the Red Sea. Similarly, the analysis also shows that the relation between NAO and EW difference is weak throughout the year indicating the absence of a significant influence of the EW difference on the sea level. These results are consistent with previous studies [20,24]. In brief, MEI (or ENSO) is observed to be the dominant remote forcing influencing the EW difference in sea level of the Red Sea.

3. DISCUSSION

The observed higher sea levels in the eastern Red Sea during winter and in the western Red Sea during summer are analyzed to understand the ongoing ocean

dynamics. During winter, the northward density gradient and the relatively strong SSE winds (>7m/s) in the southern Red Sea drive a mean northward current in the surface layer. During this period, a relatively weak NNW wind prevails in the northern Red Sea (<4m/s) which is in the opposite direction of the surface current flow [15,23]. However, the current continues its northward flow mainly overcoming the relatively weak opposite wind. The northward current results in an eastward pile-up of water associated with the Coriolis effect. Apart from this, a recent study [18] has shown that, during winter, the anticyclonic (cyclonic) eddies are predominant in the eastern (western) Red Sea. Since the Red Sea is a narrow basin, the eastward pile-up of water from the wind-buoyancy-driven current and the polarity of eddies together result in higher sea levels in the eastern Red Sea compared to the western side.

On the other hand, during summer, the NNW wind strengthens and prevails in the entire basin which reverses the surface current direction [15,23]. The southward flowing surface current may result in a Coriolis-induced pile-up of water towards the western side. Moreover, the dominance of eddies reverses during summer with anticyclonic eddies dominating on the western side while cyclonic eddies dominate on the eastern side [18]. The combined effect results in a relatively higher sea level in the western Red Sea during summer.

The EW difference during summer is comparatively higher than that of winter (0.3 cm). The main reason is the unidirectional and stronger wind during this period, which intensifies the surface current and associated westward pileup of water resulting in higher EW difference. The analysis shows that the wind, buoyancy, and the polarity of the predominant eddies are the main reasons for the observed EW difference pattern.

The spatial correlation of zonal winds in the Arabian Sea and MEI (Figure 4) illustrates that the ENSO is remotely influencing the EW difference in sea level of the Red Sea by regulating the flow of surface water into the Red Sea from the Arabia Sea. An enhanced easterly wind can intensify the surface inflow of the Arabian Sea water to the Red Sea [24].

During all the seasons, especially during spring and autumn, the zonal wind in the Arabian Sea displayed a negative relation with MEI indicating that, during the positive (negative) phase of ENSO, the easterly winds in the Arabian sea are intensified (abated or lessened), thereby strengthens (weakens) the surface inflow of the Arabian Sea water into the Red Sea and regulate the surface current and sea level in the Red Sea. A long-term analysis has also shown that sea level in the Red Sea is rising at a rate of 3.68 mm/year (p-value = 0.00) [25] in consistence with the global rate of rising sea level of 3.3 mm/year [26]. However, no significant trend is observed in the EW difference.

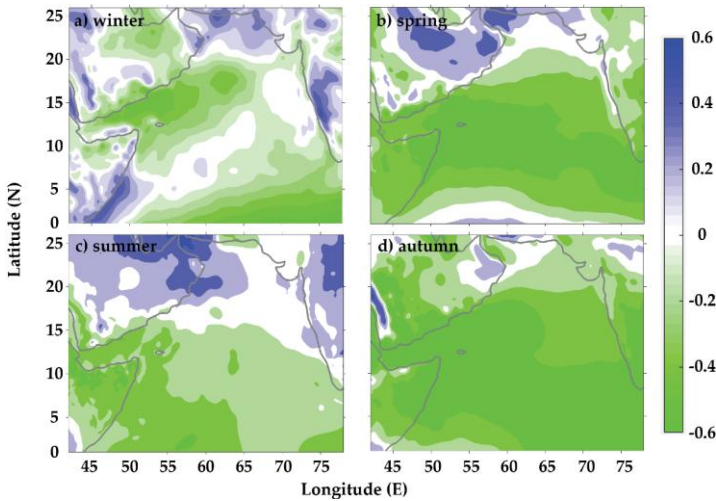


Fig. 4. The spatial correlation between zonal wind in the Arabian Sea and MEI for the period from 1993 to 2018 (the SLA data period)

4. CONCLUSIONS

The present study revealed a repetitive and seasonally reversing pattern of EW difference in the sea level between the eastern and western sides of the Red Sea. The positive value of the EW difference implies the sea level on the eastern side is higher than that of its western side. Climatology shows that sea level in the eastern Red Sea is higher than that of the western coast from November to April, and vice versa from June to September, while the months of May and October are transition months, with a mixed pattern of sea level difference. Moreover, the summer peak of sea level in the western region is slightly higher than that of the winter peak in the eastern region by 0.3 cm. Furthermore, the seasonal mean EW difference in spring and autumn seasons have a mixed pattern, while the winter and summer clearly show an eastward and westward slope in the sea level, with a higher sea level on the eastern side during winter and on the western side during summer. The EW difference for the northern and southern regions are in phase with small differences in the range of variability; the southern Red Sea has a slightly higher range compared to that of the northern region by 0.2 cm.

The wavelet analysis of sea level after filtering the annual signal shows the presence of two energy peaks for most of the data period, with a periodicity of <12 months and 3-7 years representing the intra-seasonal and ENSO signals, respectively. The observed EW difference in sea level is positively related to ENSO during spring and autumn, with positive correlation coefficients. For IOD and NAO, the relationship is weak in all the seasons. The analysis shows that wind, buoyancy, and the polarity of eddies are the primary physical causes of this

phenomenon. During winter, an eastward pile-up of water occurs due to the Coriolis effect and the dominance of anticyclonic eddies on the eastern side resulting in a higher sea level on the eastern Red Sea compared to the western side. During summer, the Coriolis-induced westward pile-up of water and the dominance of anticyclonic eddies on the western side results in relatively higher sea levels in the western Red Sea. Interestingly, the results have also shown that the MEI remotely influences the EW difference in the sea level of the Red Sea.

COMPETING INTERESTS

Author has declared that no competing interests exist.

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