Defence Science Journal, Vol. 75, No. 6, November 2025, pp. 698-703, DOI : 10.14429/dsj.21347

Influence of Climatic Events on Sea Level Variability over the Bay of Bengal: Insights from EOF Representation

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ABSTRACT

Climate modes can contribute significantly to sea level variability over shorter time scales. The present study examines annual and inter annual Sea Level Anomalies (SLA) in the Bay of Bengal, emphasizing the influences of El Niño /La Niña and the Indian Ocean Dipole (IOD). An Empirical Orthogonal Function (EOF) analysis is employed to discern the spatiotemporal variability within SLA measurements obtained from the satellite altimeter data. The Oceanic Nino Index (ONI) and Dipole Mode Index (DMI) were used to identify the climatic events and to investigate their influence on the SLA variations over the Bay. Results show distinct seasonal SLA patterns in both Western and Eastern Bay, transitioning from positive to negative anomalies and vice versa within a year. The leading mode of EOF explains 25.5 % variance and indicates a contrasting SLA pattern in the Bay. Significant variations in the sea level are observed during the co-occurrences of Positive Indian Ocean Dipole (PIOD) and El Niño, as well as Negative Indian Ocean Dipole (NIOD) and La Niña. Specifically, the co-occurred El Niño and PIOD (La Niña and NIOD) or pure strong PIOD (pure strong NIOD) is associated with increased (decreased) SLA in the western Bay and decreased SLA in the eastern Bay. However, a detailed analysis of individual events reveals that strong IOD events exert a greater influence on the SLA of the Bay of Bengal.

Keywords: Bay of Bengal; Sea level; El Niño; La Niña; Indian ocean dipole; EOF

1. INTRODUCTION

The global mean sea level rose at a pace of 1.5 mm yr^{-1} during the 20th century and the beginning of 21st century[1], and this rate is expected to increase in the future[2] which results in a lot of stress on coastal populations[3]. According to Church[4], the 20th century experienced an average sea level rise of 1.5 ± 0.5 mm yr^{-1}, and from the satellite data, the observed global sea level rise was 3.2 ± 0.4 mm yr^{-1} between 1993 and 2009[5-6]. Local variations may differ significantly from the global average of sea level rise[7]. Due to the significant economic and sociological effects on the region's large resident population, research on sea level variability in the Indian Ocean is particularly crucial. Low-lying coastal areas face devastating outcomes from rising sea levels[8]. Furthermore, as sea levels rise, storm waves from tropical cyclones in the North Indian Ocean cause more severe damage to the Bay of Bengal coastal areas, particularly in Bangladesh and India[9]. Monitoring changes in coastal sea level is therefore essential to comprehend how climatic variability can impact the world's densely inhabited coastal regions.

The IOD-ENSO climate modes are considered to have a significant impact on the Indian Ocean sea level variability[10-11] and the interannual variability in sea level is attributed to these events[12]. The impact of these climatic events over the Bay of Bengal was previously studied by Sreenivas[13], *et al.* considering the composites of each events.

In this paper, we focus on the contribution of El Niño/ La Niña and IOD events to regional sea levels in the Bay of Bengal. To assess the impact of these events, we rely on Empirical Orthogonal Function (EOF)-based analysis on sea level anomaly derived from altimeter data and we compare the temporal evolution of EOF patterns of sea level anomaly over the study region under these climatic events which are not yet discussed in any previous literatures.

2. METHODOLOGY

2.1 Study Region

The study area is the Bay of Bengal, located in the north-eastern part of the Indian Ocean, which stretches between longitudes 79°E – 99°E and latitudes 8°N–22°N (Fig. 1). It is considered to be the largest bay in the world and shares a coastline with India, Myanmar, Bangladesh, and Sri Lanka. The dynamics of the Bay are influenced by the seasonal reversal of the coastal current system[14] and the propagation of coastal kelvin waves[15].

Consequently, for more detailed study, the region is subdivided into Western Bay of Bengal (WBB) and Eastern Bay of Bengal (EBB) at the longitude 90 °E.

Received : 02 February 2025, Revised : 15 May 2025
Accepted : 12 October 2025, Online published : 06 November 2025

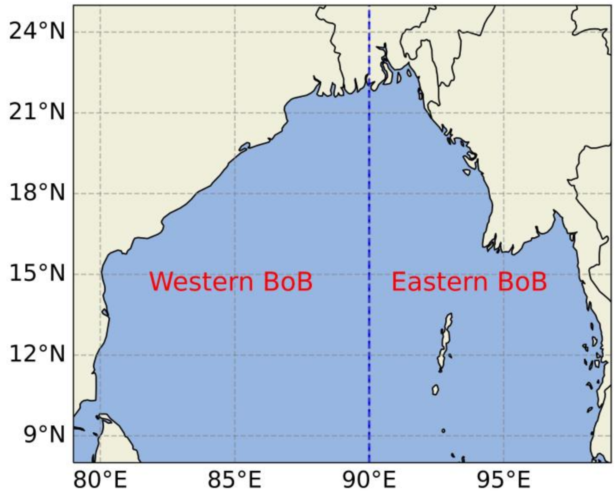


Figure 1. Study region: The Bay of Bengal.

2.2 Datasets

Monthly gridded 0.25° x 0.25° sea level anomaly (SLA) data covering the period 1993-2021 was obtained from the Copernicus Marine Environment Monitoring Service (CMEMS). Detailed information about the dataset is available at: https://doi.org/10.48670/moi-00148.

Using the Oceanic Nino Index (ONI) and the Dipole Mode Index (DMI) for the years 1993–2021, the ENSO and IOD years are taken into consideration to determine the climatic influence over sea level variation. ONI is obtained from the Physical Sciences Laboratory of NOAA https://psl.noaa.gov/gcos_wgsp/Timeseries/ and DMI from the Jet Propulsion Laboratory of NASA https://sealevel.jpl.nasa.gov/overlay-iod/.

2.3 Methods

The Annual cycle of SLA was obtained by calculating the climatological monthly mean. The SLA data from 1993-2021 was de-seasoned and detrended for assessing the interannual variations so that the resulting data is free from seasonal signals and short-term trends. Pearson's correlation coefficient 'R' is used to explain the relationship between the datasets used for comparison and the significance of the correlation is tested using students-*t* distribution[16].

2.3.1 Empirical Orthogonal Function (EOF) Analysis

The EOF method identifies the variability in spatial patterns and their temporal evolution, quantifying the significance of each pattern[17]. The method reduces the dataset into several spatial and temporal modes that characterize the dominant variability within the data[18]. An EOF was applied over the de-seasoned and detrended monthly SLA dataset to capture the interannual variability due to the climatic influence in its leading mode.

The Singular Value Decomposition (SVD) method is used in the calculation of the EOF[19] and the analysis employs a set of orthogonal functions (EOFs) to represent a time series[20] and given as:

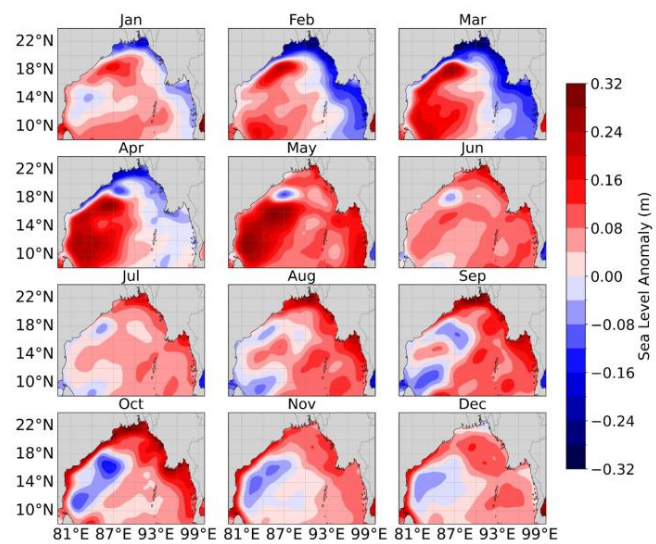
$$T(x,t) = \sum_{n=1}^{N} a_n(t).F_n(x) \quad (1)$$

where, $T(x,t)$ is the original dataset as a function of time and space, $F_n(x)$ reveals the spatial structure, and $a_n(t)$ indicates the temporal variation in the amplitude of each EOF.

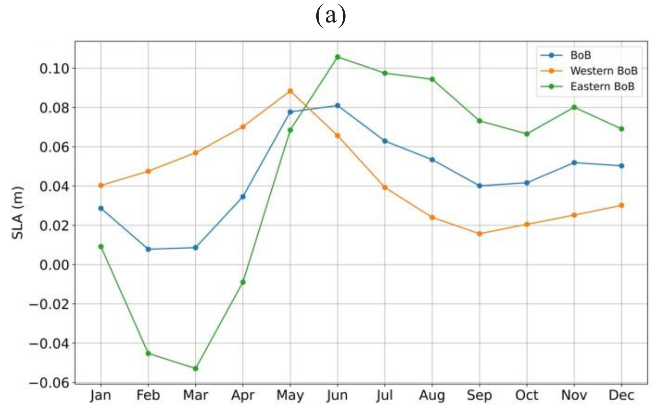
3. RESULTS AND DISCUSSION

3.1 Annual Cycle of Sea Level Anomaly

The Bay of Bengal exhibits distinct seasonal variations in sea level (Fig. 2), with coastal regions experiencing both positive and negative anomalies throughout the year. A negative SLA predominates over the northern to eastern Bay of Bengal from January to April, transitioning to positive anomalies for the remainder of the year. In contrast, the WBB displays a pattern of positive SLA beginning in February, which intensifies to reach a peak value of approximately 0.32 m during the pre-monsoon period (March to May). Throughout the Bay of Bengal, SLA remains predominantly positive from May to July (Fig. 2(a)) and accounts for the higher values (~0.07 m) within the entire annual cycle (Fig. 2(b)). Starting in August, a negative anomaly begins to develop in the south-western part of the Bay, intensifying by October (~0.1 m).



(a)



(b)

Figure 2. Annual cycle of SLA, (a) Spatial map; and (b) time series for entire Bay and sub regions.

During the summer monsoon (June to August), strong positive SLA exceeding 0.25 m is observed along the coastal stretch, from the northern to the EBB, intensifying by the end of the monsoon and persisting throughout the autumn season (September to October). A significant change is observed in the Eastern Bay time series, where sea levels drop to approximately 0.05 m. during the spring season and peak at positive values exceeding 0.1 m during the subsequent summer monsoon. In contrast, the average regional SLA in the WBB remains positive, reaching a peak in May. Coastal Kelvin waves and wind stress curl are considered the primary contributors to seasonal sea level changes. A positive correlation between SLA and wind stress curl has been observed in the Bay of Bengal during autumn[21]. Consequently, negative wind stress curl over the northern to north-eastern Bay and positive wind stress curl over the south-western Bay contribute to positive and negative SLA, respectively, during the autumn season. Additionally, coastally trapped Kelvin waves and the Rossby waves generated by them are responsible for SLA variations in the northern to EBB and the WBB during the pre-monsoon period[22-23].

3.2 Sea Level Trend over the Bay

Figure 3 presents the time series of monthly mean SLA averaged over the Bay of Bengal and its sub-regions, along with the linear trends for the observed period. The data indicate

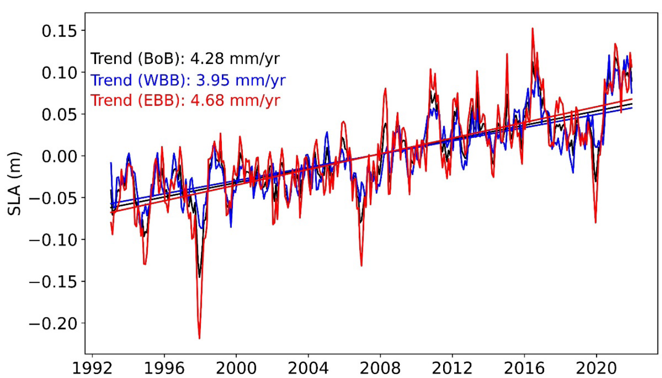


Figure 3. Time series of monthly mean sea level anomalies (SLA) from satellite altimeter data for 1993–2021 over Bay of Bengal (black), Western Bay of Bengal (blue), Eastern Bay of Bengal (red). Linear trends for the respective regions are also shown.

an increasing trend of sea level in the Bay of Bengal, with a rate of 4.28 mm yr^{-1}, surpassing the global mean sea level rise.

Both the EBB and WBB exhibit an increasing trend in sea level rise. The EBB experiences the most rapid rise at a rate of 4.68 mm yr^{-1}, compared to 3.95 mm yr^{-1} in the western Bay. Notable drops in sea level are observed in the years 1994, 1997, 2006, and 2019. The time series data for the entire Bay and its sub-regions during these particular years indicate that the overall declines in sea level are primarily due to negative SLA in the EBB. These sudden variations are likely influenced by climatic signals, as these specific years coincide with strong positive Indian Ocean Dipole events (Table 1).

3.3 Influence of Climate Modes in the Interannual Variability of SLA Explained Using EOF

The de-seasoned and detrended SLA data were used

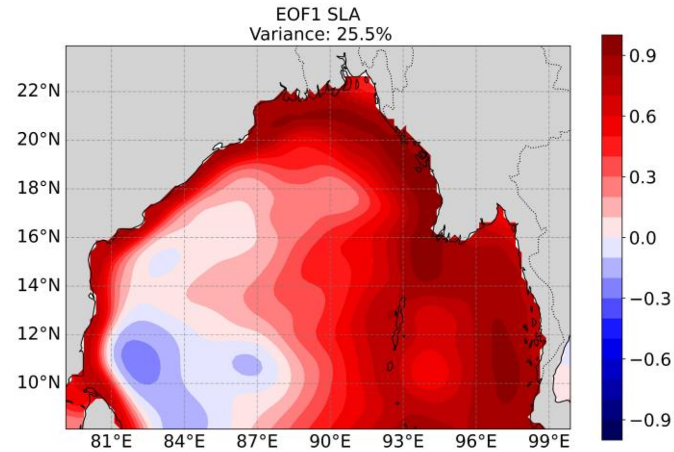


Figure 4. Leading mode of EOF for SLA.

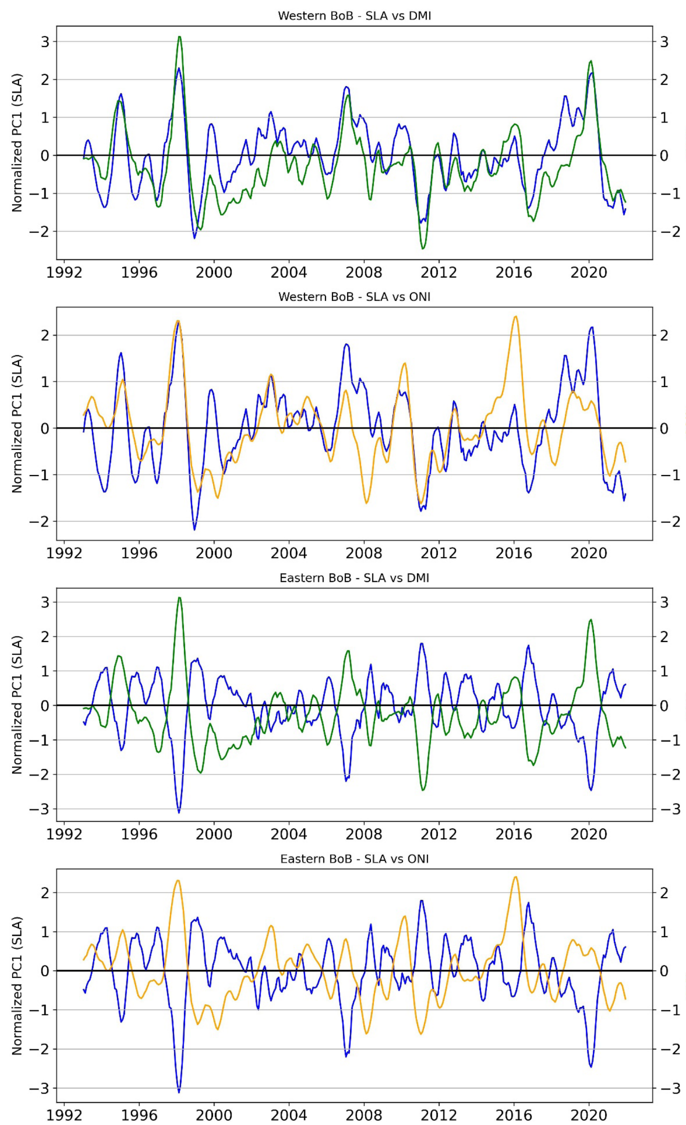


Figure 5. Comparison of PC1 of SLA with DMI and ONI (smoothed by 5-month running mean).

for Empirical Orthogonal Function (EOF) analysis to eliminate seasonal signals and noise, thereby enhancing the representation of dominant inter annual signals. The EOF analysis of SLA derived from satellite altimetry provides both spatial representation and temporal amplitude of SLA variations. The leading mode of EOF and its corresponding principal component were considered, with the first EOF mode (EOF1) explaining 25.5 % of the total variance (Fig. 4). The inter annual spatial signal captured by the leading mode of the EOF exhibits a contrasting pattern between the south-western Bay of Bengal and the EBB. The entire coastal stretch and the EBB display similar variability with positive SLA, whereas the south-western part of the Bay, excluding the coastal boundaries, shows opposite variability with slightly negative SLA. Modes 2 and 3 of the EOF are not considered due to their low percentage of explained variance.

The leading Principal component, PC1 of the detrended and de-seasoned SLA captures the inter annual sea level signal and indicates the strength and phase of the EOF1 pattern over time. IOD and ENSO climatic modes are considered to be responsible for the major inter annual variation of SLA over the Indian ocean[24]. The leading mode EOF of SLA has the main contribution from the oceanic Rossby and Kelvin waves which are in turn triggered by these climatic events[11,25]. The PC1 identifies the region of maximum variability within the study area, which is influenced by climatic events, and allows for a detailed examination of these changes.

Figure 5 compares the PC1 of SLA with the DMI and the ONI for the WBB and EBB. The PC1 shows a stronger correlation with the DMI than with the ONI, although both correlations are statistically significant at the 99 % confidence level (Table 2). It is noteworthy that the observed patterns between the PC1 and climatic indices exhibit contrasting differences between the WBB and EBB. The graph demonstrates that PC1 effectively captures the dominant inter annual signals triggered by these climatic events, particularly those related to the IOD, as evidenced by the stronger correlation (Table 2) and well-matched patterns.

Table 1. Classification of IOD and ENSO years based on datasets from PSL, NOAA (ONI) and JPL, NASA (DMI)

Events	Years
PIOD	1994, 1997, 2006, 2019 (all strong events)
El Niño	1994-95 1997-98 (strong) 2002-03 2006-07 2009-10 (strong) 2015-16 (strong)
NIOD	1998, 2010, 2016 (all strong events)
La Niña	1998-99, 2007-08, 2010-11 (all strong events)

Considering the years of El Niño /La Niña and IOD events from Table 1, it could be inferred that strong variations in SLA were observed during strong IOD years but not evident in pure El Niño/La Niña years. Indeed, significant sea level variations are observed during periods when IOD events coincide with El Niño or La Niña occurrences. The most substantial declines in sea level were observed during years such as 1994, 1997, and 2006, when a strong positive IOD coincided with an El Niño event. However, it is evident that a strong IOD event alone can contribute significantly to the largest changes in sea level, whereas a strong El Niño event by itself does not have as pronounced an impact. For instance, in 2016, which was a strong El Niño year, there was less variability in sea level compared to 2019, which experienced a strong positive IOD event and exhibited considerable sea level changes.

Table 2. Correlation coefficient between the PC1 of SLA for the sub-regions with DMI and ONI

Region	PC1 SLA & DMI	PC1 SLA & ONI
WBB	0.73	0.52
EBB	-0.85	-0.56

Another noteworthy aspect is the phase discrepancy between the patterns of PC1 and the DMI for the WBB and EBB. In the WBB, both time series are in phase and exhibit good pattern alignment, whereas, in the EBB, the patterns are opposite, with positive IOD years marking a fall in sea level. Two primary mechanisms considered to be influencing sea level variability in the Bay are direct wind forcing and the propagation of Kelvin waves, which subsequently radiate westward propagating Rossby waves[26]. During El Niño and PIOD events, equatorial easterly anomalies induce anti cyclonic Ekman pumping, leading to elevated SLA in the south-west Bay relative to normal conditions[27]. Conversely, in the EBB, upwelling Kelvin waves generate Rossby waves, resulting in widespread negative SLA[13]. Therefore, the inter annual spatial distribution of SLA during these climatic events across the Bay of Bengal can be interpreted. The findings from Fig. 5 underscore the significance of strong IOD years compared to El Niño /La Niña years. Even the strong El Niño event of 2016 did not induce significant changes in SLA. Thus, it can be concluded that strong IOD events exert a greater influence on inter annual sea level variations over the Bay.

The EOF and its corresponding PC were employed to statistically represent sea level variations. The latitude-averaged hovmöller diagram of inter annual sea level anomalies for the study period (Fig. 6) reinforces the earlier findings. During PIOD years, a negative sea level anomaly is evident over eastern longitudes, gradually diminishing towards the western longitudes of the Bay. Conversely, strong NIOD years show a positive SLA pattern over the EBB. Unlike the EOF analysis, the averaged SLA over the entire WBB is considered for the hovmöller diagram. This averaging approach results in slight differences compared to the EOF results specifically for the Western Bay since the region of maximum variability within the WBB is only considered in the EOF. Nevertheless, it effectively portrays the inter annual SLA variations associated with climate events throughout the study period.

4. CONCLUSIONS

The annual sea level in the western and eastern Bay experiences both positive and negative anomalies in a year which results from the effect of wind forcing and propagation of coastal kelvin waves. The total sea level over the Bay marks a steady rise with a trend of 4.28 mm yr^{-1}, which exceeds the global average. Notably, the eastern Bay experiences a faster rate of sea level rise compared to the

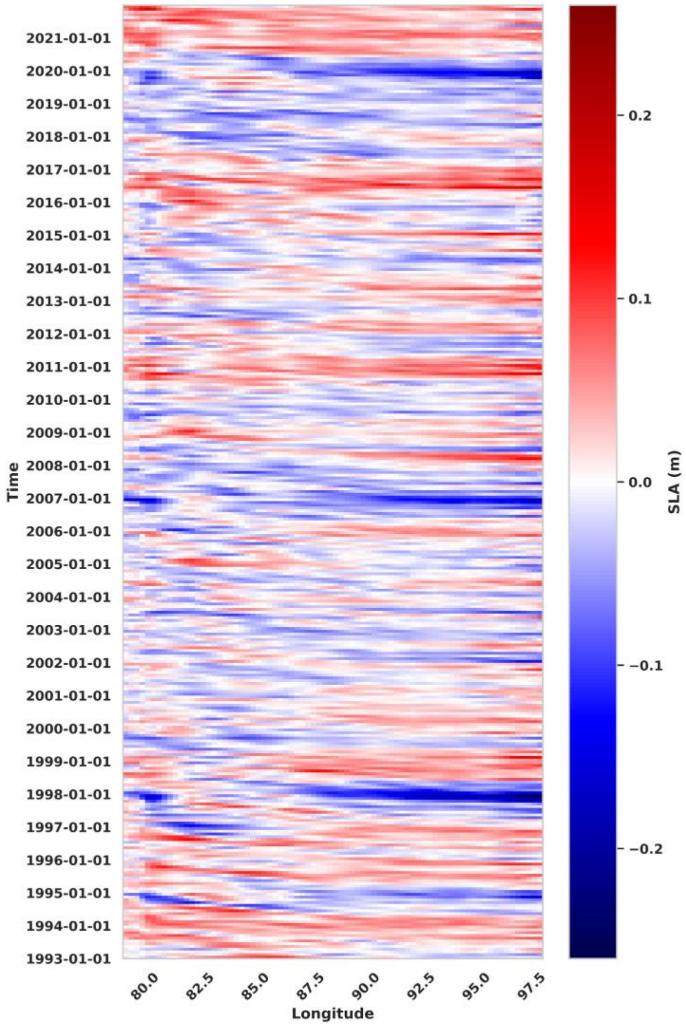


Figure 6. Latitude averaged hovmöller diagram of interannual SLA over the Bay of Bengal.

western Bay. This underscores the need for quantifying sea level changes in coastal areas for vulnerability assessments.

In the western Bay, particularly the south-western region, combined El Niño -PIOD events or isolated PIOD events lead to increased sea level. Conversely, in the eastern Bay, such events result in decreased sea level anomalies, attributed to the propagation of upwelling Kelvin waves along the coast and negative wind stress curl over the southwest Bay. The opposite pattern occurs during the La Niña-NIOD or pure NIOD years. The pure El Niño /La Niña events are not observed to have any profound impact on sea levels, but the influence is observed to be stronger during pure IOD years.

REFERENCES

1. Frederikse T, Landerer F, Caron L, Adhikari S, Parkes D, Humphrey VW, et al. The causes of sea-level rise since 1900. Nature. 2020;584(7821):393–7.
2. Hermans THJ, Gregory JM, Palmer MD, Ringer MA, Katsman CA, Slangen ABA. Projecting global mean sea-level change using CMIP6 models. Geophys Res Lett. 2021;48(5):e2020GL092064.
3. Nicholls RJ. Planning for the impacts of sea level rise. Oceanography. 2011;24(2):144–57.
4. Church JA, Gregory JM, Huybrechts P, Kuhn M, Lambeck K, Nhuan MT, et al. Changes in sea level. In: , in: JT Houghton, Y Ding, DJ Griggs, M Noguer, PJ Van der Linden, X Dai, K Maskell, and CA Johnson (eds): Climate Change 2001: The Scientific Basis: Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel. 2001. p. 639–94.
5. Nerem RS, Chambers DP, Choe C, Mitchum GT. Estimating mean sea level change from the TOPEX and Jason altimeter missions. Mar Geod. 2010;33(S1):435–46.
6. Church JA, White NJ. Sea-level rise from the late 19th to the early 21st century. Surv Geophys. 2011;32:585–602.
7. Stammer D, Cazenave A, Ponte RM, Tamisiea ME. Causes for contemporary regional sea level changes. Ann Rev Mar Sci. 2013;5:21–46.
8. Cazenave A, Cozannet G Le. Sea level rise and its coastal impacts. Earth’s Futur. 2014;2(2):15–34.
9. Karim MF, Mimura N. Impacts of climate change and sea-level rise on cyclonic storm surge floods in Bangladesh. Glob Environ Chang. 2008;18(3):490–500.
10. Saji NH, Goswami BN, Vinayachandran PN, Yamagata T. A dipole mode in the tropical Indian ocean. Nature. 1999;401(6751):360–3.
11. Deepa JS, Gnanaseelan C, Kakatkar R, Parekh A, Chowdary JS. The interannual sea level variability in the Indian Ocean as simulated by an ocean general circulation model. Int J Climatol. 2018;38(3):1132–44.
12. Miyama T, McCreary JP, Sengupta D, Senan R. Dynamics of biweekly oscillations in the equatorial Indian Ocean. J Phys Oceanogr. 2006;36(5):827–46.
13. Sreenivas P, Gnanaseelan C, Prasad KVSR. Influence of El Niño and Indian Ocean Dipole on sea level variability in the Bay of Bengal. Glob Planet Change [Internet]. 2012;80–81:215–25. Available from: http://dx.doi.org/10.1016/j.gloplacha.2011.11.001
14. Shenoi SSC, Saji PK, Almeida AM. Near-surface circulation and kinetic energy in the tropical Indian Ocean derived from Lagrangian drifters. J Mar Res. 1999;57(6):885–907.
15. Rao RR, Girish Kumar MS, Ravichandran M, Rao AR, Gopalakrishna V V., Thadathil P. Interannual variability of Kelvin wave propagation in the wave guides of the equatorial Indian Ocean, the coastal Bay of Bengal and the southeastern Arabian Sea during 1993-2006. Deep Res Part I Oceanogr Res Pap [Internet]. 2010;57(1):1–13. Available from: http://dx.doi.org/10.1016/j.dsr.2009.10.008
16. Obilor EI, Amadi EC. Test for significance of Pearson’s correlation coefficient. Int J Innov Math Stat Energy Policies. 2018;6(1):11–23.
17. Halldor B, Venegas SA. A manual for EOF and SVD analyses of climate data. McGill Univ CCGCR Rep. 1997;52.
18. Thomson RE, Emery WJ. Data analysis methods in physical oceanography. Newnes; 2014.
19. Chen X bao, Liu X tao, Li S nian, Annie C. A comparative

study on three EOF analysis techniques using decades of Arctic sea-ice concentration data. J Cent South Univ. 2015;22(7):2681–90.

20. Iskandar I. Variability of satellite-observed sea surface height in the tropical Indian Ocean: Comparison of EOF and SOM analysis. Makara J Sci. 2009;13(2):25.
21. Akhter S, Qiao F, Wu K, Yin X, Chowdhury KMA, Chowdhury NUMK. Seasonal and long-term sea-level variations and their forcing factors in the northern Bay of Bengal: A statistical analysis of temperature, salinity, wind stress curl, and regional climate index data. Dyn Atmos Ocean [Internet]. 2021;95:101239. Available from: https://www.sciencedirect.com/science/article/pii/S0377026521000361
22. Nienhaus MJ, Subrahmanyam B, Murty VSN. Altimetric observations and model simulations of coastal Kelvin waves in the Bay of Bengal. Mar Geod. 2012;35(sup1):190–216.
23. Schott FA, Xie S, McCreary Jr JP. Indian Ocean circulation and climate variability. Rev Geophys. 2009;47(1).
24. Barskar H, Senapati B, Kaundal M, Amere AB, Dash MK. Evolution of Tripole Pattern of Sea-Level Anomalies in the Indian Ocean During Concurrent ENSO-IOD Episodes. J Indian Soc Remote Sens. 2023;51(2):383–94.
25. Carton JA, Chepurin G, Cao X. A simple ocean data assimilation analysis of the global upper ocean 1950–95. Part II: Results. J Phys Oceanogr. 2000;30(2):311–26.
26. Aparna SG, Mccreary JP, Shankar D, Vinayachandran PN. Signatures of Indian Ocean Dipole and El Niño – Southern Oscillation events in sea level variations in the Bay of Bengal. 2012;117(March):1–13.
27. Rao SA, Behera SK, Masumoto Y, Yamagata T. Interannual subsurface variability in the tropical Indian Ocean with a special emphasis on the Indian Ocean dipole. Deep Sea Res Part II Top Stud Oceanogr. 2002;49(7–8):1549–72.

ACKNOWLEDGEMENT

The authors are grateful to the Nansen Environmental Remote Sensing Center for the support and encouragement given for carrying out this study. The first author expresses his gratitude to the Nansen Scientific Society, Bergen, for funding his PhD and the Faculty of Ocean Science and Technology, Kerala University of Fisheries and Ocean Studies for the academic support to undertake this study.

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His current contribution in this paper is in critically restructuring the framework of the study, validation, data curation, formatting, supervision, review and editing.

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His current contribution in this paper is conceptualisation, resource management and supervision.

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Contribution to the current study: Conceived the presented idea, provided the guidance and funding for the execution of the work.