Title

Dynamics of Sea-level Changes in the Red Sea

Author

Cheriyeri Poyil Abdulla

Affiliations

- Department of Marine Physics, King Abdulaziz University, Jeddah-80200, Saudi Arabia
- Department of Physical Oceanography, Cochin University of Science and Technology, Kochi-682016, India

Corresponding Author Email: *(acp1@cusat.ac.in)*

Publication Information

Published as a Book Chapter
Book: *Current Advances in Geography, Environment and Earth Sciences Vol. 5*
DOI: https://doi.org/10.9734/bpi/cagees/v5/3216B

EarthArXiv Statement

Conflict of Interest: None.

Data Availability: All data and analyses supporting this work are contained within the published chapter. No additional datasets are associated with this submission.

Print ISBN: 978-93-5547-583-1, eBook ISBN: 978-93-5547-587-9

Dynamics of Sea-level Changes in the Red Sea

Cheriyeri Poyil Abdulla [a,b*]

DOI: 10.9734/bpi/cagees/v5/3216B

ABSTRACT

Under the recent global climatic changes, the information on sea-level changes is very important for the proper understanding of upper-ocean processes. The information on sea-level changes in the Red Sea is significantly lacking, especially the information on interannual variability, long-term trends, and associated dynamics. The present study attempted to fill this gap by analyzing the satellite altimetry sea-level data for nearly three decades (1993–2020) and is used to understand the variability and associated dynamics in the Red Sea sea-level. The sea level is generally higher during winter with maximum in December–January and lower during summer with minimum in August, following a steady pattern from south to north. The variability in global climate modes, such as El-Nino Southern Oscillation events, East Atlantic-West Russian oscillation, and the Indian Ocean Dipole, is closely correlated with interannual variations in sea level. The El-Nino Southern Oscillation has a greater impact on sea level than other climatic patterns. From 1993 until the present, the Red Sea's sea level rose at a rate of 3.88 mm/year, which was consistent with the global rate of 3.3 ± 0.5 mm/year. From 2000 until the present, the Red Sea experienced a considerably quicker rate of sea-level rise (6.40 mm/year).

Keywords: Red Sea; satellite altimetry; sea level anomaly; long-term linear trend; ENSO; IOD; NAO.

1. INTRODUCTION

Detailed information on the sea-level changes is vital for understanding the physical and biological processes in the upper layer of the ocean, especially in a climate-changing world with increased warming and sea-level rise for decision-making regarding navigation, coastal construction, and defense systems [1–8]. The sea-level is rising globally, mainly driven by thermal expansion and freshwater input from the melting of landlocked ice [4]. Further, the climatic modes like ENSO, IOD, NAO, etc., have a remarkable signature on sea-level [8,9].

---

[a] *Department of Marine Physics, King Abdulaziz University, Jeddah, 80200, Saudi Arabia.*

[b] *Department of Physical Oceanography, Cochin University of Science and Technology, Kochi, 682016, India.*

**Corresponding author: E-mail: acp1@cusat.ac.in;*

The Red Sea, characterized by unique features, known as one of the world's hottest and most saline regions, is located between Africa and Asia. The basin has no freshwater input from rivers and features significantly high evaporation of 2 m/year [10] and a limited amount of precipitation. The southern Red Sea is experiencing a seasonally reversing wind pattern. At the same time, the northern Red Sea is experiencing approximately unidirectional wind throughout the year, despite the intensity differing seasonally. SSE winds prevail in the southern Red Sea during summer, which reverses during winter to the NNW. The wind pattern in the northern Red Sea is predominantly from the NNW, with seasonally varying wind speeds. The surface current is mainly driven wind system and the buoyancy gradient. The surface current flows from the Red Sea to the Gulf of Aden during summer, which reverses during winter [11–13].

A significant effort has been made to understand the short- to long-term variability of sea-level in the regional as well as global ocean [1,6,7,14,15]. Tide gauge records have shown that the rate of sea-level rise at the beginning of the 20th century was (on average) 1.7 mm/year for the period 1901–2010 [16]. Previous studies based on remote sensing datasets show that the rate of sea-level rise is increasing over the years as seen from previous studies. The rates are as follows: 3.2 ± 0.4 mm/year for the period 1993–2009 [16], 3.19 ± 0.63 mm/year for the period 1993–2015 [17], and 3.3 ± 0.5 mm/year for 1993–2017 period [18].

Information on the Red Sea sea-level is relatively poor [19-26], especially the details on interannual variability, long-term trends, and associated dynamics [22-29]. The available studies are mostly restricted to analyses that rely on a relatively short period of data [19–21] from tide gauge stations. Other studies based on satellite datasets have focused mainly on the seasonal wind-induced sea-level variability [22], the improvement of sea-level estimates near the coastal region [23], the impact of climate modes in sea-level [24,25], and the seasonal oscillation of sea-level [26]. The present study aims to investigate the variability of sea-level in the Red Sea at different time scales, and compare the long-term variability with other ocean basins. The data sets used for the present work include remote sensing data sets of sea-level maps, sea surface temperature, and climate indices. The time-series analyses, including EOF (Empirical Orthogonal Function), wavelet, and correlation, are used to derive the superimposed signals at sea-level. The Red Sea is subdivided into northern (13 °N–18 °N), central (18 °N–23 °N), and southern (23 °N–28 °N) regions. For further details on the datasets and methods, please refer to [9].

2. RESULTS

2.1 Annual Mean Climatology of Sea-Level

The mean sea-level variability in the Red Sea was analyzed with nearly three decades of satellite altimetry data of sea surface height from January 1993 to March 2021. The delayed mode reprocessed data ranged from January 1993 to March 2020, while the near real-time data was available from April 2019 to March

2021. The analysis for both datasets was conducted separately, and the results were consistent. However, considering the long period of data availability, the results based on the delayed mode are discussed in the present study. The annual climatology has a general trend of higher sea-level on the eastern side compared to the western side (Fig. 1). The observed isolated patches indicate the presence of frequent mesoscale eddies in the region.

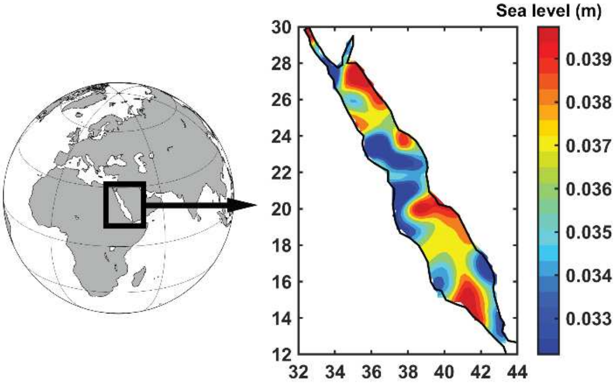

Fig. 1. The climatological annual mean sea-level for the Red Sea is estimated during the 1993–2020 period

2.2 Seasonal Variability of Sea-Level

The climatology of sea-level anomalies for winter, spring, summer, and fall are shown in Fig. 2. A significant spatial and temporal variability was observed in the Red Sea sea-level. The seasonal climatology was notably different from each other, indicating the relatively large spatial and temporal variability. During winter, the south, central-west, and north-west regions showed lower sea-levels while the central-east and north-east regions experienced higher sea-levels. During spring, the southeast and the central-east regions had higher sea-levels, while the south-west and the northern half showed lower sea-levels. During summer, the central and the northern region had lower sea-levels, while the south-west and the north-west region had higher sea-levels. During fall, the south, central-west, and north-west showed lower sea-levels, while the eastern side of central and northern regions experienced higher sea-levels [30].

The climatological mean seasonal cycle followed a similar pattern from north to south of the Red Sea. The Red Sea sea level is generally high during winter and low during summer, as shown in Fig. 3, with the highest values during December–January and the lowest values during August. These findings are consistent with previous studies [21,22]. The amplitude seasonal variability was found to be approximately 40 cm. Previous studies showed that wind was the dominant factor [22], controlling the seasonal variability in sea-level followed by evaporation [21].

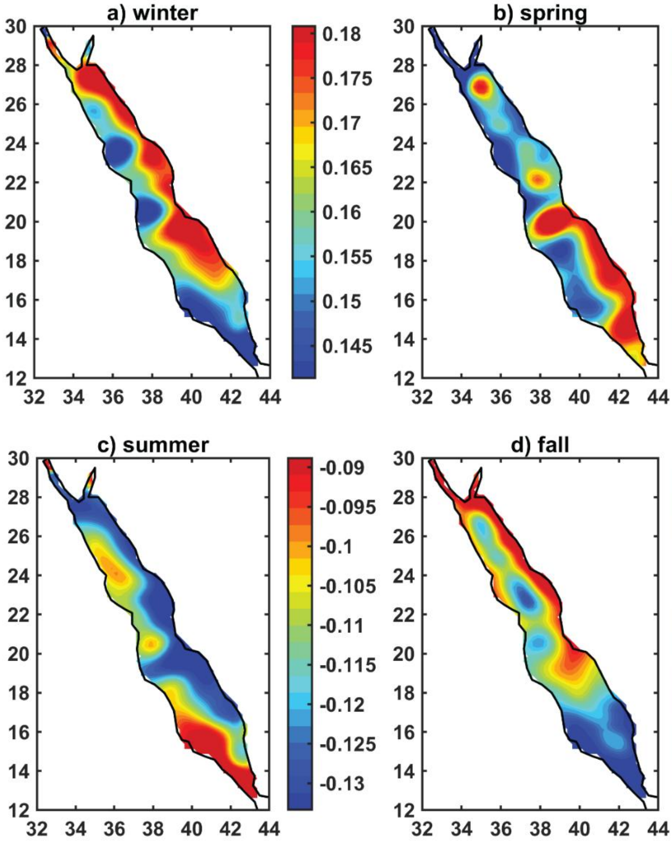

Fig. 2. The climatological seasonal mean sea-level (in meters) for the Red Sea, estimated for the 1993–2020 period during (a) winter, (b) spring, (c) summer, and (d) fall. Please note that different scales are used

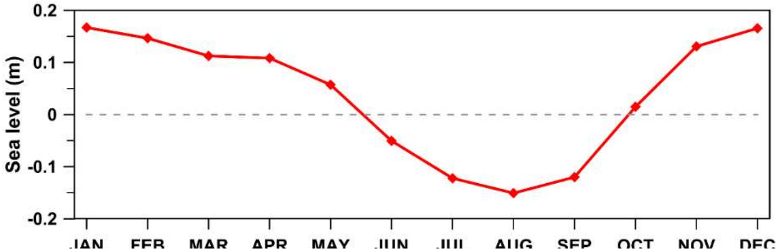

Fig. 3. The climatological mean seasonal cycle of sea-level for the Red Sea estimated for the 1993–2020 period

2.3 Interannual Variability of Sea-Level and long-term linear trend

The inter-annual variability of sea-level in the northern, central, and southern Red Sea was herein analyzed. The annual mean sea-level showed a falling sea-level until the year 2000, in which a rising trend with some nonlinearity ensued (Fig. 4). Multiple up-and-down fluctuations were seen in the inter-annual signal, with prominent rise events occurring during 2002, 2008, 2010, 2016, and 2019. Notable fall events occurred in 2000, 2007, 2011, and 2018.

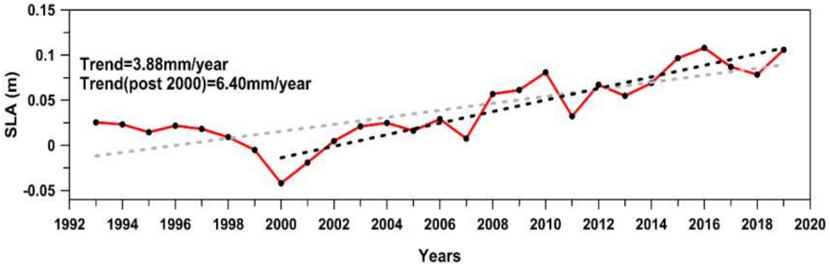

Fig. 4. The annual mean sea-level in the Red Sea for the entire Red Sea. The linear trends are shown by dashed lines for the full period (grey) and post-2000 (black)

The trend analysis in sea-level shows an abrupt rise in sea-level in the post-2000 period. The linear trend in sea-level for the period before and after the year 2000 was estimated separately, and the values are given in Fig. 4. The sea-level showed a falling trend until 2000, wherein rising no longer occurred. The significance test showed that the rising trend in the post-2000 period was statistically significant, while the falling trend before 2000 was insignificant.

The overall trend in sea-level for the north, central, and southern Red Sea was 4.23 mm/year, 3.82 mm/year, and 3.69 mm/year, respectively. However, the trend observed in the post-2000 period was significantly higher, with values of 6.83 mm/year, 6.59 mm/year, and 5.87 mm/year, respectively, for the north, central, and the southern Red Sea. The average trend in sea-level for the whole Red Sea was 3.88 mm/year for the entire period and 6.40 mm/year for the post-2000 period.

2.4 Comparison with the Arabian Sea, Bay of Bengal, Pacific, and Atlantic Ocean Basins

A rough comparison of sea-level was made between the Red Sea and the other ocean basins, i.e., the Arabian sea (18°N, 65°E), Bay of Bengal (18°N, 90°E), East-Pacific (18°N, 150°E), West-Pacific (18°N, 225°E), and Atlantic (18°N, 325°E) oceans (Table 1). For uniformity, sea-level from the same latitude belt for a two-by-two-degree box was selected in every region. Since the width of the pacific is relatively large, the eastern and western Pacific was separately considered.

Table 1. The long-term trend in annual mean sea-level for the Arabian sea, Bay of Bengal, East-Pacific, West-Pacific, Atlantic, and the Red Sea

Basin	**Sea-Level Trend (mm/Year)**	
	Full Period	**Post-2000**
Arabian Sea	3.16	4.57
Bay of Bengal	4.15	3.40
East-Pacific	2.22	4.55
West-Pacific	3.23	2.09
Atlantic	2.82	2.40
Red Sea	3.88	6.40

The observed trend in sea-level in the Arabian sea, Bay of Bengal, East-Pacific, West-Pacific, and Atlantic oceans were 3.16, 4.15, 3.23, 2.22, and 2.82 mm/year, respectively, for the full data period and 4.57, 3.40, 2.09, 4.55, and 2.40 mm/year, respectively, for the post-2000 period. The observed long-term increase in sea-level was consistent for all basins. However, a considerable regional difference was observed in the linear trend of the sea-level. The regional sea-level could considerably deviate from the global mean [31,32]. Among the basins compared, the sea-level variability in the Red Sea and the Arabian Sea matched well, indicating that the influence of global warming and remote forces were similar. Comparing the rising sea level rate, the Red Sea was observed to have a higher linear trend for the post-2000 period (6.40 mm/year), followed by the Arabian Sea.

2.5 Impact of Global Warming

The result from the wavelet analysis for the monthly mean SLA and SST in the Red Sea are shown in Fig. 5. Apart from the dominant seasonal variability, a multi-year (3–7-year period) variability was visible in both SLA and SST. The authors decomposed dominant modes of variability in sea-level after detrending and removing the seasonal signal to understand the long-term variability. The dominant signal obtained from the principal component analysis for sea-level is shown in Fig. 6a. The resultant PC values showed that the existence of a multi-year oscillation in the sea-level explained 89.1% of the variability. The percentages of variance for the second, third, and fourth modes were negligible (6.2%, 2.7%, and 1.9%, respectively). The PC values of SST also showed a similar multi-year variability in the SST (Fig. 6b). The observed multi-year variability is by the influence of the remote force from climate modes such as ENSO on the Red Sea sea-level and SST.

The annual mean values of SST (Fig. 7) showed that significant warming occurred in the Red Sea in recent decades. The overall trend in SST for the northern, central, and southern Red Sea was 0.0271, 0.0114, and 0.0109 °C/year, respectively, which is consistent with previous estimates [33]. The SST trend reached its maximum in the northern Red Sea, which was similar to the

SLA trend where the maximum trend was observed in the northern Red Sea. The correlation between the annual mean sea-level and SST was 0.43 (*p*-value = 0.02).

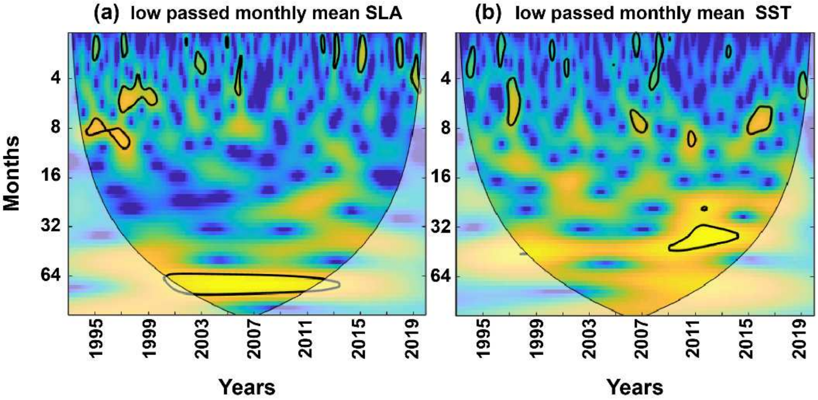

Fig. 5. The wavelet analysis for low passed monthly mean sea-level

The projected SLA and SST variability for the next 100 years was analyzed, and the expected values for the years 2050 and 2100 were tabulated (Table 2). The expected increase in SST during the post-2000 period under the RCP2.6, RCP4.5, and RCP8.5 scenarios were 0.068 °C, 1.158 °C, and 2.601 °C, respectively. Under the same scenarios, the expected sea-level rise was 15.2 cm, 17.0 cm, and 34.5 cm, respectively.

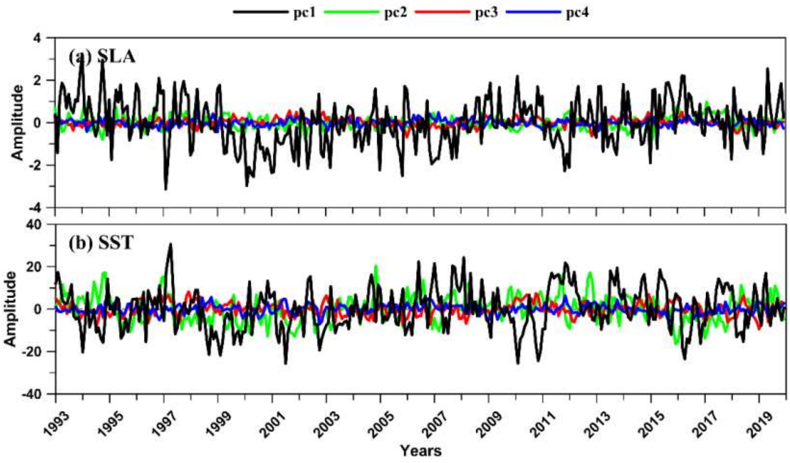

Fig. 6. The first four modes of variability from the principal component analysis for the filtered (a) sea-level and (b) SST

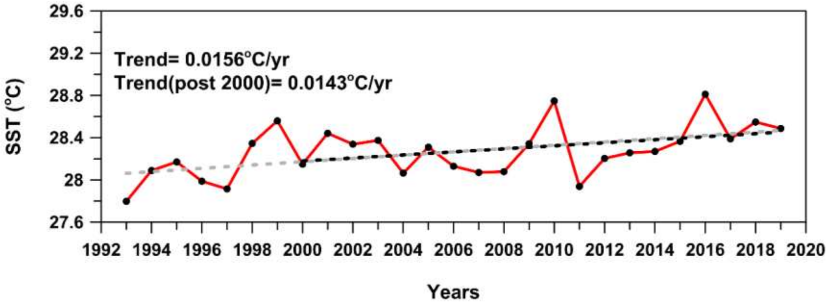

Fig. 7. The annual mean SST in the Red Sea for the (a) northern, (b) central, and (c) southern regions of the Red Sea, as well as the (d) entire the Red Sea. The linear trends are shown by dashed lines for the full period (green) and the post-2000 period (red)

Table 2. The projected values of SST and SLA for the years 2020, 2050, and 2100

Years	SST (°C)			SLA (m)		
	RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5
2020	25.243	25.141	25.023	0.439	0.464	0.429
2050	25.371	25.413	26.605	0.502	0.469	0.531
2100	25.311	26.298	27.624	0.591	0.633	0.775

4. DISCUSSION AND CONCLUSIONS

This paper discusses the variability of sea-level in the Red Sea based on available remote sensing datasets taken across three decades. We used this data to understand the dynamics of sea-level variability in the Red Sea. A significant spatial and temporal variability was observed in the sea-level.

The maximum seasonal sea-level was observed during winter and the minimum during summer. The pattern of higher sea-levels during winter and lower levels during summer was consistent throughout the Red Sea. In the annual and seasonal climatology of sea-level, multiple patches were visible, indicating the presence of frequent eddies in the Red Sea. The annual mean sea-level was observed to have multiple fall-and-rise events during the selected period. The analysis shows that the observed interannual fluctuations in sea-level are in close agreement with the fluctuations in the atmospheric changes in the Pacific Ocean (Table 5).

During 1998–1999 and 1999–2000, well-defined La-Nina events occurred. A significant fall was noticed in the Red Sea sea level during this period. This was due to the intensification of the low-pressure system in the western Pacific during La-Nina, causing the strengthening of westerlies in the equatorial Indian Ocean. This led to a negative anomaly in sea-level in the western equatorial Indian

Ocean and southwestern Arabian sea [34–37], which in turn resulted in negative sea-level in the adjacent Red Sea basin. During the 2014–2015 period, a weak El-Nino event occurred followed by a strong El-Nino event (2015–2016) and a weak La-Nina event (2016–2017). The Red Sea sea-level experienced a significant positive anomaly during the 2014–2015 and 2015–2016 periods, followed by a negative anomaly in 2016–2017. The observed variability in sea-level was due to the anomalous high pressure in the western Pacific during the El-Nino event, which intensified the easterlies in the equatorial Indian Ocean, leading to a positive anomaly in sea-level in the western equatorial Indian Ocean and southwestern Arabian sea [33–37]. This resulted in an associated positive anomaly of sea-level in the adjacent Red Sea basin.

Table 3. El-Nino and La-Nina events are listed based on their intensity

El-Nino			**La-Nina**		
Weak	**Moderate**	**Strong/Very-Strong**	**Weak**	**Moderate**	**Strong/Very-Strong**
2004–2005	1994–1995	1997–1998	2000–2001	1995–1996	1998–1999
2006–2007	2002–2003	2015–2016	2005–2006	2011–2012	1999–2000
2014–2015	2009–2010		2008–2009	2020–2021	2007–2008
2018–2019			2016–2017		2010–2011
			2017–2018		

A long-term positive trend of 3.88 mm/year was observed in the Red Sea sea-level, which was consistent with the global rate of sea-level rise of 3.19 ± 0.63 mm/year for the period 1993–2015 [17] and 3.3 ± 0.5 mm/year for the period 1993–2017 [18]. The results showed that there was an acceleration in the rate of rising over the years. Interestingly, the variability of sea-level in the Arabian Sea matched well with the Red Sea, indicating that the influence of global warming and the related remote forces were similar. Strikingly, the post-2000 period rate of sea-level rise in the Red Sea was observed to be much higher (6.40 mm/year) than in other basins.

Previous studies reported that the sea-level variability in the north Indian ocean was driven by steric contributions [38–40]. But, in the case of Red Sea, as it is an enclosed basin with no freshwater input through rivers and melting ice sheets, the SLA long-term increase could be mainly caused by increased warming. Due to the unavailability of sufficient salinity data for the steric computation, the SST data from AVHRR was analyzed and the results are shown here.

A noticeably faster rate of sea-level rise was observed in the Red Sea during the post-2000 period with a rate of 6.40 mm/year. This was higher than the global rate of 3.3 ± 0.5 mm/year. However, no significant difference was noticed in the rate of increase in SST during the post-2000 period, which indicates that a consistent increase was associated with global warming. The analysis of the Arabian Sea SLA and SST showed a similar pattern with an increase in the rate of sea-level rise (4.57 mm/year) and a nearly uniform rate of increase in SST. Both the Red Sea and Arabian Sea basins have experienced a significant fall in sea-level between 1998–2000, which is considered to be associated with consecutive La-Nina events.

The observed amplification in SLA trend during the post-2000 period could be due to the combined effect of two factors: (1) the recovery of sea-level from the abrupt fall in SLA associated with consecutive La-Nina events in 1998–1999 and 1999–2000; and (2) the rate of increase in global warming. If the greenhouse gas concentration continues resulting in active global warming in the upcoming years—as shown in different projection scenarios of SST and sea-level—irreversible harm to human life will be resulted, including the collapse of global socioeconomic systems. Further, the recent numerical models with better accuracy can be used to estimate contribution from different parameters to local sea-level [41], which can be conducted as future work.

COMPETING INTERESTS

Author has declared that no competing interests exist.

REFERENCES

1. Cazenave A, Gouzenes Y, Birol F, Leger F, Passaro M, Calafat F, Shaw A, Nino F, Legeais J, Oelsmann J, Restano, M, Benveniste J. Sea level along the world’s coastlines can be measured by a network of virtual altimetry stations. Commun Earth Environ 2022;3:117. https://doi.org/10.1038/s43247-022-00448-z
2. Cazenave A, Hamlington B, Horwath M, Barletta VR, Benveniste J, Chambers D, Döll P, Hogg AE, Legeais JF, Merrifield M, et al. Observational requirements for long-term monitoring of the global mean sea level and its components over the altimetry era. Front. Mar. Sci. 2019;6:14.
3. Chen X, Zhang X, Church JA, Watson CS, King MA, Monselesan D, Legresy B, Harig C. The increasing rate of global mean sea level rise during 1993–2014. Nat. Clim. Chang. 2017;7:492–495.
4. Church JA, Gregory JM, Huybrechts P, Kuhn M, Lambeck K, Nhuan MT, Qin D, Woodworth PL. Changes in Sea Level. In Climate Change 2001: The Scientific Basis. Contribution of Working Group 1 to the Third Assessment Report of the Intergovernmental Panel on Climate Change; Houghton, J.T., Ding, Y., Griggs, D.J., Noguer, M., van der Linden, P., Dai, X., Maskell, K., Johnson, C.I., Eds.; Cambridge University Press: Cambridge, UK, 2002;639–694.
5. Nerem RS, Beckley BD, Fasullo JT, Hamlington BD, Masters D, Mitchum GT. Climate-Change–Driven Accelerated Sea level Rise Detected in the Altimeter Era. Proc. Natl. Acad. Sci. USA. 2018;115:2022–2025.

6. Nidheesh AG, Lengaigne M, Vialard J, Unnikrishnan AS, Dayan H. Decadal and long-term sea level variability in the tropical Indo-Pacific Ocean. Clim. Dyn. 2013;41:381–402.
7. Legeais J-F, Ablain M, Zawadzki L, Zuo, H.; Johannessen, J.A.; Scharffenberg, M.G.; Fenoglio-Marc L, Fernandes MJ, Andersen, O.B.; Rudenko, S.; et al. An improved and homogeneous altimeter sea level record from the ESA Climate Change Initiative. Earth Syst. Sci. Data. 2018; 10:281–301.
8. Arpe, K Bengtsson L, Golitsyn, G.S.; Mokhov, I.I.; Semenov, V.A.; Sporyshev, P.V. Connection between Caspian Sea level variability and ENSO. Geophys. Res. Lett. 2000, 27, 2693–2696.
9. Abdulla CP, Al-Subhi AM. Is the Red Sea Sea-Level Rising at a Faster Rate than the Global Average? An Analysis Based on Satellite Altimetry Data. Remote Sens. 2021;13:3489. https://doi.org/10.3390/rs13173489.
10. Albarakati AM, Ahmad F. Variation of the surface buoyancy flux in the Red Sea. Indian J. Mar. Sci. 2013;42:717–721.
11. Morcos SA. Physical and chemical oceanography of the Red Sea. Ocean. Mar. Biol. Annu. Rev. 1970;8:73–202.
12. Patzert WC. Wind-induced reversal in Red Sea circulation. Deep. Sea Res. Oceanogr. Abstr. 1974;21:109–121.
13. Bethoux JP. Red Sea geochemical budgets and exchanges with the Indian Ocean. Mar. Chem. 1988;24:83–92.
14. Taqi AM, Al-Subhi AM, Alsaafani MA, Abdulla CP. Estimation of geostrophic current in the Red Sea based on sea level anomalies derived from extended satellite altimetry data. Ocean Sci. 2019;15:477–488.
15. Woodworth PL, Melet A, Marcos M, Ray RD, Wöppelmann G, Sasaki YN, Cirano M, Hibbert A, Huthnance, J.M.; Monserrat, S.; et al. Forcing factors affecting sea level changes at the coast. Surv. Geophys. 2019;40, 1351–1397.
16. Church JA, White N.J. Sea level Rise from the Late 19th to the Early 21st Century. Surv. Geophys. 2011;32:585–602.
17. Cazenave A, Chambers D, Champollion N, Dieng H, Llovel W, Forsberg R, Schuckmann K, Wada Y. Evaluation of the Global Mean Sea Level Budget between 1993 and 2014. Surv. Geophys. 2017;38:309–327.
18. Cazenave A, Meyssignac B, Ablain M, Balmaseda M, Bamber J, Barletta V, Beckley B, Benveniste J, Berthier E, Blazquez, A. Global Sea level Budget 1993-Present. Earth Syst. Sci. Data 2018;10:1551–1590.
19. Sultan SAR, Ahmad F, El-Hassan A. Seasonal variations of the sea level in the central part of the Red Sea. Estuar. Coast. Shelf Sci. 1995;40:1–8.
20. Sultan SAR, Ahmad F, Nassar, D. Relative contribution of external sources of mean sea level variations at Port Sudan, Red Sea. Estuar. Coast. Shelf Sci. 1996;42:19–30.
21. Sultan SAR, Elghribi NM. Sea Level Changes in the Central Part of the Red Sea; CSIR: New Delhi, India; 2003.
22. Sofianos SS, Johns, W.E. Wind induced sea level variability in the Red Sea. Geophys. Res. Lett. 2001;28:3175–3178.

23. Taqi AM, Al-Subhi AM, Alsaafani MA, Abdulla CP. Improving sea level anomaly precision from satellite altimetry using parameter correction in the Red Sea. Remote Sens. 2020;12:764.
24. Alawad KA, Al-Subhi AM, Alsaafani MA, Alraddadi T. Signatures of tropical climate modes on the Red Sea and gulf of aden sea level. Indian J. Geo.-Mar. Sci. 2017;46:2088–2096.
25. Alawad KA, Al-Subhi AM, Alsaafani MA, Alraddadi TM, Ionita M, Lohmann G. Large-scale mode impacts on the sea level over the Red Sea and gulf of aden. Remote Sens. 2019;11:2224.
26. Abdulla CP, Al-Subhi AM. Sea Level Variability in the Red Sea: A Persistent East–West Pattern. Remote Sens. 2020;12:2090. https://doi.org/10.3390/rs12132090.
27. Bailey G, Cawthra HC. The significance of sea-level change and ancient submerged landscapes in human dispersal and development: A geoarchaeological perspective. Oceanologia; 2021 (in press).
28. Sergiou S, Geraga M, Rohling EJ, Rodríguez-Sanz L, Hadjisolomou E, Paraschos F, Sakellariou D, Bailey G. Influences of sea level changes and the South Asian Monsoon on southern Red Sea oceanography over the last 30 ka. Quaternary Research. 2022;1-9.
29. Shaltout M. Recent sea surface temperature trends and future scenarios for the Red Sea. Oceanologia. 2019;61(4):484-504.
30. Johny A, Ramesh KV. Equatorial Indian Ocean Response during Extreme Indian Summer Monsoon Years Using Reliable CMIP5 Models. Ocean Sci. J. 2020;55:17–31.
31. Church JA, Monselesan D, Gregory JM, Marzeion, B. Evaluating the Ability of Process Based Models to Project Sea level Change. Environ. Res. Lett. 2013;8:014051.
32. Church JA, Clark PU, Cazenave A, Gregory JM, Jevrejeva S, Levermann A,, Merrifield MA, Milne, G.A.; Nerem, R.S.; Nunn, P.D. Sea Level Change; PM Cambridge University Press; 2013.
33. Chaidez V, Dreano D, Agusti S, Duarte CM, Hoteit I. Decadal Trends in Red Sea Maximum Surface Temperature. Sci. Rep. 2017;7:1–8.
34. Alexander MA, Bladé I, Newman M, Lanzante JR, Lau N-C, Scott JD. The atmospheric bridge: The influence of ENSO teleconnections on air–sea interaction over the global oceans. J. Clim. 2002;15:2205–2231.
35. Klein SA, Soden BJ, Lau N-C. Remote sea surface temperature variations during ENSO: Evidence for a tropical atmospheric bridge. J. Clim. 1999;12:917–932.
36. Saji NH, Yamagata T. Structure of SST and surface wind variability during Indian Ocean dipole mode events: COADS observations. J. Clim. 2003;16:2735–2751.
37. Saji NH, Xie SP, Yamagata T. Tropical Indian Ocean variability in the IPCC twentieth-century climate simulations. J. Clim. 2006;19:4397–4417.
38. Palanisamy H, Cazenave A, Meyssignac B, Soudarin L, Wöppelmann G, Becker M. Regional Sea Level Variability, Total Relative Sea Level Rise and Its Impacts on Islands and Coastal Zones of Indian Ocean over the Last Sixty Years. Glob. Planet. Chang. 2014;116:54–67.

39. Parekh A, Gnanaseelan C, Deepa JS, Karmakar A, Chowdary JS. Sea level variability and trends in the North Indian Ocean. In Observed Climate Variability and Change over the Indian Region; Springer: Berlin/Heidelberg, Germany, 2017;181–192.
40. Salim M, Nayak RK, Swain D, Dadhwal VK. Sea Surface Height Variability in the Tropical Indian Ocean: Steric Contribution. J. Indian Soc. Remote. Sens. 2012;40:679–688.
41. Raj N, Gharineiat Z, Ahmed AAM, Stepanyants Y. Assessment and Prediction of Sea Level Trend in the South Pacific Region. Remote Sensing, 2022;14(4):986.

Biography of author(s)

Cheriyeri Poyil Abdulla
Department of Marine Physics, King Abdulaziz University, Jeddah, 80200, Saudi Arabia.
Department of Physical Oceanography, Cochin University of Science and Technology, Kochi, 682016, India.

He is working as a Post Doctoral Fellow at Cochin University of Science and Technology-Kochi, India. He is an Oceanographer. He has completed his Master's in Oceanography from Cochin University of Science and Technology-Kochi, India, and Ph.D. from King Abdulaziz University, Jeddah, Saudi Arabia. He has been awarded the *Dr. DS Kothari Postdoctoral Fellowship – DSKPDF* in 2021 and the *Nansen Scientific Society Fellowship* in 2013. He has nearly 10 years of research experience from various institutes including the *National Institute of Oceanography-Goa, India; Indian Institute of Technology-Delhi, India; Cochin University of Science and Technology-Kochi, India; and King Abdulaziz university-Jeddah, Saudi Arabia*. During this period, he worked with scientists and experts from different countries on diverse topics including mixed layer depth and related physical processes, surface and subsurface mixing by eddies, surface and subsurface ocean currents, sea-level variability, and extreme wind speeds. He has been awarded a US-international patent for the work on “systems and methods for mixed layer depths” (US Patent App. 15/796046). He has ten peer-reviewed international publications to his credit.

DISCLAIMER
This chapter is an extended version of the article published by the same author(s) in the following journal.
Remote Sens, 13, 3489, 2021.