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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: (abducps@gmail.com)

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Seasonal, Interannual and Long-term Sea-level Changes in the Arabian Gulf

Cheriyeri Poyil Abdulla ^{a,b*}

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ABSTRACT

The present chapter explores the seasonal, interannual, and long-term sea-level changes in the Arabian Gulf. Tides, winds, and density-driven currents are the primary drivers of circulation in the Arabian Gulf. The sea level is relatively high during fall and low during spring, with a maximum during November and a minimum during April. The sea-level variability in the Arabian Gulf is considerably different from or nearly opposite to the pattern of sea-level changes in the adjacent marginal basin (Red Sea). Using Principal Component Analysis, the analysis of low-passed sea-level has shown that the first mode of variability explains 87.9% of the long-term variability. Long-term linear sea-level trends in the Northern Arabian Gulf are 2.58 mm/year and 3.14 mm/year, respectively, with an overall average of 2.92 mm/year. The long-term linear trend in sea-level for the post-2000 period at the northern and southern regions are 4.06 mm/year and 4.44 mm/year, respectively, with a basin average trend of 4.29 mm/year. The numerical estimates for the RCP2.6, RCP4.5, and RCP8.5 scenarios reveal a predicted rise in sea level in the Arabian Gulf of 8.1 cm, 1.3 cm, and 6.8 cm by 2050, and 16.9 cm, 17.7 cm, and 39.1 cm by the end of the century, respectively.

Keywords: Arabian Gulf; long-term linear trend; Sea level; ENSO; IOD; NAO; Satellite altimetry.

1. INTRODUCTION

The Arabian Gulf is one of the busiest shipping routes in the world, geographically located between 23°N-31°N, 47°E-56°E with a length of ~1000 km from the "Hormuz strait" to the northern end, and an area of $\sim 2.39 \times 10^5$ km². The width varies from as narrow as 56 km at the strait to 338 km inside the Gulf (Fig. 1). The Arabian Gulf experiences intense evaporation due to the surrounding arid climate and the shallow nature. The circulation in the Arabian Gulf is mainly associated with tides, winds, and density-driven currents. The wind system and the density gradient mainly drive the region's residual circulation [1–12].

^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: abducps@gmail.com;

Sea-level is one of the primary climate indicators that directly impact a major portion of the world population, especially the coastal community where one-third of the population resides [13–16]. Tide gauge measurements and altimetry have shown that the sea-level has been rising during the last century and continuing at a faster rate. The projected sea-level for different scenarios from IPCC also agree with a future increase in the rate of sea-level rise.

Sea-level variability in the Arabian Gulf is mainly driven by the meteorological conditions in the region and the water exchange along the Strait of Hormuz [17,18]. In the Arabian Gulf, most of the studies are based on tide gauges for a few locations and different periods of relatively short time resulting in considerably different values for the rate of sea-level rise. Also, the information on interannual variability and the link to climatic modes and remote forces is unclear. The present work used nearly three decades of sea level data and discussed the mean, interannual, and long-term variability along with the associated dynamics. The data sets used include maps of sea level anomaly and sea surface temperature along with the re-analysis data of wind fields and secondary data of climate indices (for more details, please refer to [19]).

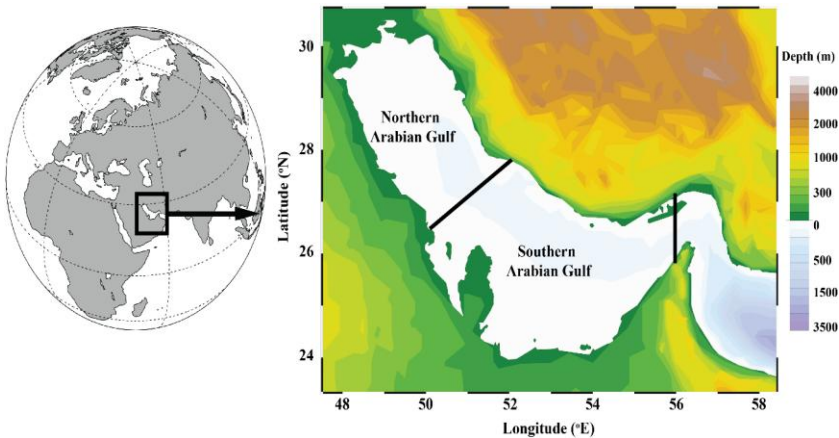


Fig. 1. The geographical location of the study area, Northern and southern regions of the Arabian Gulf are marked

2. RESULTS

2.1 Climatological Features in Mean Sea-level

The annual climatology of sea-level, prepared from monthly mean sea-level of nearly three decades from 1993 to 2020, is shown in Fig. 2. The Arabian Gulf's sea level is generally higher on the southern and western sides. The presence of mesoscale eddies is visible from multiple patches in the annual climatology. The figure shows the presence of a cyclonic eddy near the Strait of Hormuz along the

eastern coast, showing the possible propagation of cyclonic and anti-cyclonic eddies from the Arabian Sea to the Gulf along the coast as coastal high/low centers of sea-level.

The annual mean sea-level in the Arabian Gulf is relatively lower than that of adjacent marginal seas (the Mediterranean Sea and the Red Sea) and Gulfs (Gulf of Oman and Gulf of Aden). The climatologically averaged annual mean sea-level for the Arabian Gulf is 3.40 cm, while that for the Mediterranean Sea and the Red Sea are 3.68 cm and 4.02 cm and for the Gulf of Oman and Gulf of Aden are 3.49 cm and 4.08 cm.

Sea-level in the Arabian Gulf is higher during fall than the rest of the year (Fig. 2). A significant spatial and temporal variability is observed in the Arabian Gulf sea-level from season to season. During winter, the northern Gulf has a relatively lower sea-level while the rest of the region has a higher sea-level. This pattern continues in spring also, with the northern lower sea-level extended to a wider area towards the southwestern coast. During summer, the pattern is reversed with higher sea-level towards the northern and western sides. An extension of the lower sea-level from the Gulf of Oman to the Arabian Gulf through the Strait of Hormuz is also visible. During fall, the northern higher sea-level almost spread into the entire Gulf. The maximum and minimum sea-level are observed during the fall and spring seasons, respectively. The maximum sea-level in a seasonal cycle is observed during November and the minimum during April.

2.2 Interannual and Long-term Variability of Sea-level

The northern and southern sides follow a similar pattern of sea-level variability in the interannual time scale (Fig. 3). The years 1995, 2000, 2005, 2009, 2011, and 2016 were observed to have fall events, while 2007, 2010, 2015, and 2019, etc., experienced rise events in sea-level. The sea-level was observed to have a long-term increase from 1993 to the present. The northern and southern Gulf have a similar pattern of variability for most of the years with some non-linearity in a few years. The interannual variability for winter, spring, summer, and fall seasons is separately analyzed.

The interannual variability is minimum during spring, while the intensity is high during the winter and fall seasons. A relatively intense rise in sea-level is observed during the winter of the years 1995 and 1998 (figure not shown). The fall season of 1994 and 1997 also experienced a similar variability, where the 1-year difference between the events (i.e., 1994 fall and 1995 winter) is because the fall season of the year is compared with the winter of the next year. The analysis based on empirical orthogonal function (after removing the seasonal) shows that the first mode of variability explains almost 88% of the observed variability while the second mode explains a major part of the remaining (6%).

2.3 Long-term Trend in Annual and Seasonal Mean Sea-level

The long-term linear trends in sea-level are 2.58 mm/year for the Northern Arabian Gulf and 3.14 mm/year for the southern Gulf. The overall trend is 2.92

mm/year. The analysis of sea-level in the adjacent Arabian Sea has shown a faster rate of sea-level in the post-2000 period. The sea-level in the Arabian Gulf is separately examined from 2000 to the present to assess whether similar changes exist in the Arabian Gulf.

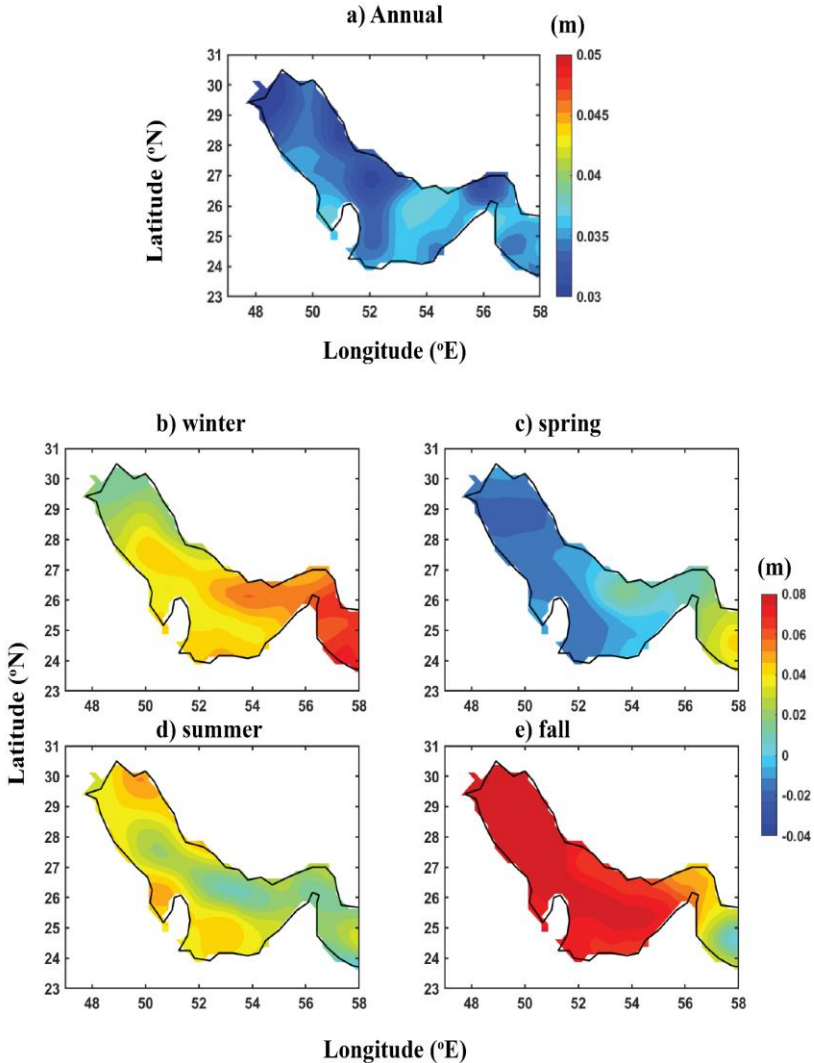


Fig. 2. The climatology of mean sea-level for a) annual, b) winter, c) spring, d) summer, and e) fall for the Arabian Gulf (sea-level given in meters)

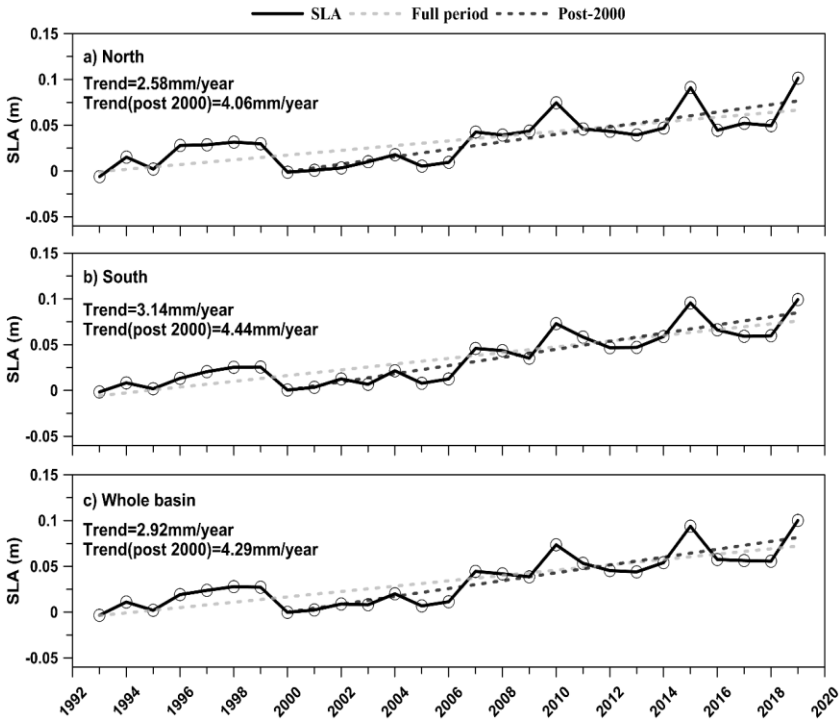


Fig. 3. Annual mean sea-level in the Arabian Gulf for the northern (a), southern (b), and whole (c) basin. The dashed grey and black lines represent linear trends for the full and post-2000 periods, respectively

The long-term linear trend for the post-2000 period in the Northern Arabian Gulf is 4.06 mm/year and for the southern Gulf is 4.44 mm/year with an average trend of 4.29 mm/year. The seasonally averaged sea-level time series shows a relatively higher rate of increase in sea-level during summer and fall seasons (higher than 3 mm/year) while winter and spring seasons have lower rates (less than 3 mm/year).

Similar to the annual mean sea-level time series, the seasonal sea-level variability also has consistent variability between the northern and southern Gulf. The linear trend for the entire period during winter, spring, summer, and fall seasons are respectively 2.32 mm/year, 2.63 mm/year, 3.26 mm/year, and 3.48 mm/year, while that during post-2000 are respectively 3.82 mm/year, 3.47 mm/year, 4.14 mm/year, and 5.93 mm/year. The fall season is characterized by the highest rate of increase in sea-level. The seasonal mean sea-level is also highest during the fall season. The Arabian Sea sea-level has an abrupt increase in the rate of sea-level rise during the post-2000 period. The results have shown that the Arabian Gulf's sea level also experienced a similar increase.

2.4 Projected Sea-level Changes in the Arabian Gulf

The expected sea-level projection under RCP2.6, RCP4.5, and RCP8.5 scenarios for the Arabian Gulf is shown in Fig. 4. The predicted sea-level for the Arabian Gulf for the year 2050 is 52.9 cm, 50.7 cm, and 54.9 cm and for the year 2100 is 61.7 cm, 67.1 cm, and 87.2 cm, respectively. According to this, the sea-level is expected to rise by 8.1 cm, 1.3 cm, and 6.8 cm by 2050 for scenarios RCP2.6, RCP4.5, and RCP8.5 and by 16.9 cm, 17.7 cm, and 39.1 cm, respectively by the end of the 21st century, respectively.

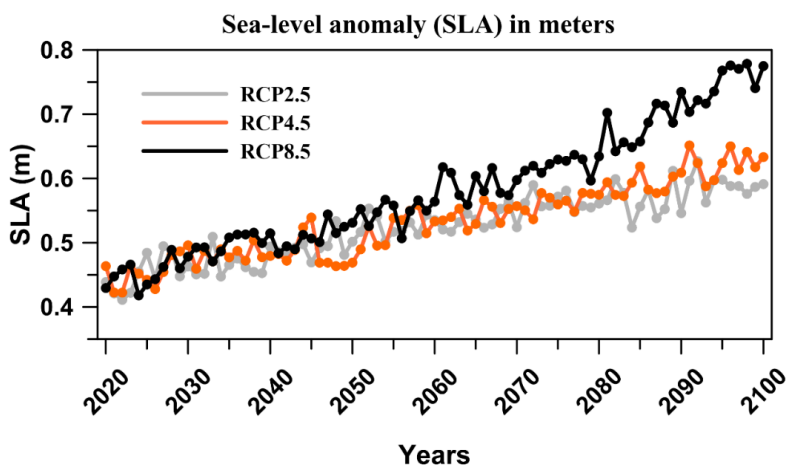


Fig. 4. The projected SLA for the Arabian Gulf

The sea-level variability in the adjacent marginal seas and major world ocean basins are analyzed and compared with the sea-level variability in the Arabian Gulf (Figs. 5 & 6). The annual mean sea-level time series is overlaid in the Figures for easy comparison. The eastern and western side sea-level trend is separately estimated when the longitudinal extension of the basin is relatively large. Results show that the sea-level is increasing in all the basins while the rate of increase differs between the basins.

The Arabian Sea is experiencing a long-term linear trend of 3.16 mm/year in sea level. The Red Sea experiences a slightly higher rate (3.88 mm/year). The Mediterranean Sea is experiencing a trend of 3.34 mm/year on the eastern side and 2.17 mm/year on the western side. For the post-2000 period, the sea-level is increasing faster for most of the region, with 4.57 mm/year for the Arabian sea, 6.40 mm/year for the Red Sea, and 4.07 mm/year for the Eastern Mediterranean Sea.

As already reported by previous researchers, the long-term linear trend in sea-level differs regionally [14,15,20–22]. The observed trend in sea-level is consistent with global warming and the associated increase in sea-level. It is also

important to note that interannual sea-level variability in the Arabian Gulf is different from the pattern of sea-level change in the selected basins. However, the observed trend in sea-level is in agreement with that of the Arabian sea indicating that the local forces can be the dominant drivers over the remote forces.

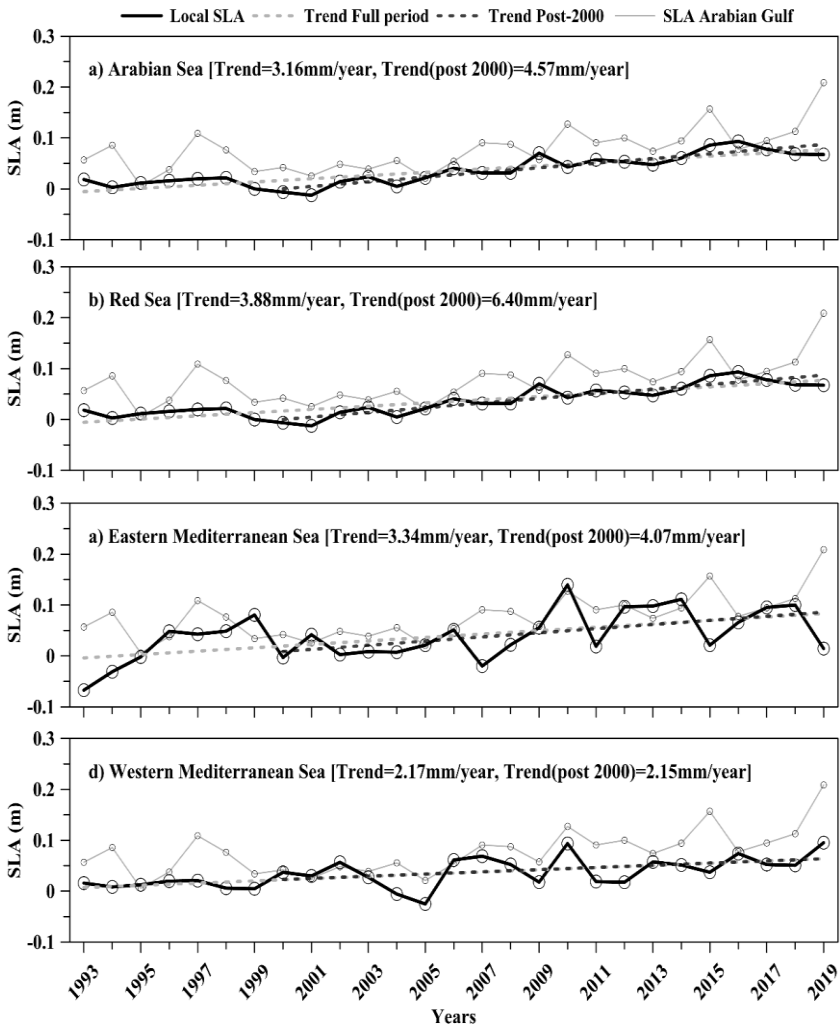


Fig. 5. The annual mean sea-level for a) the Arabian sea, b) the Red Sea, c) the Eastern Mediterranean Sea, and d) the Western Mediterranean Sea. The trends are shown in dashed lines for the post-2000 period (black) and for the entire period (grey)

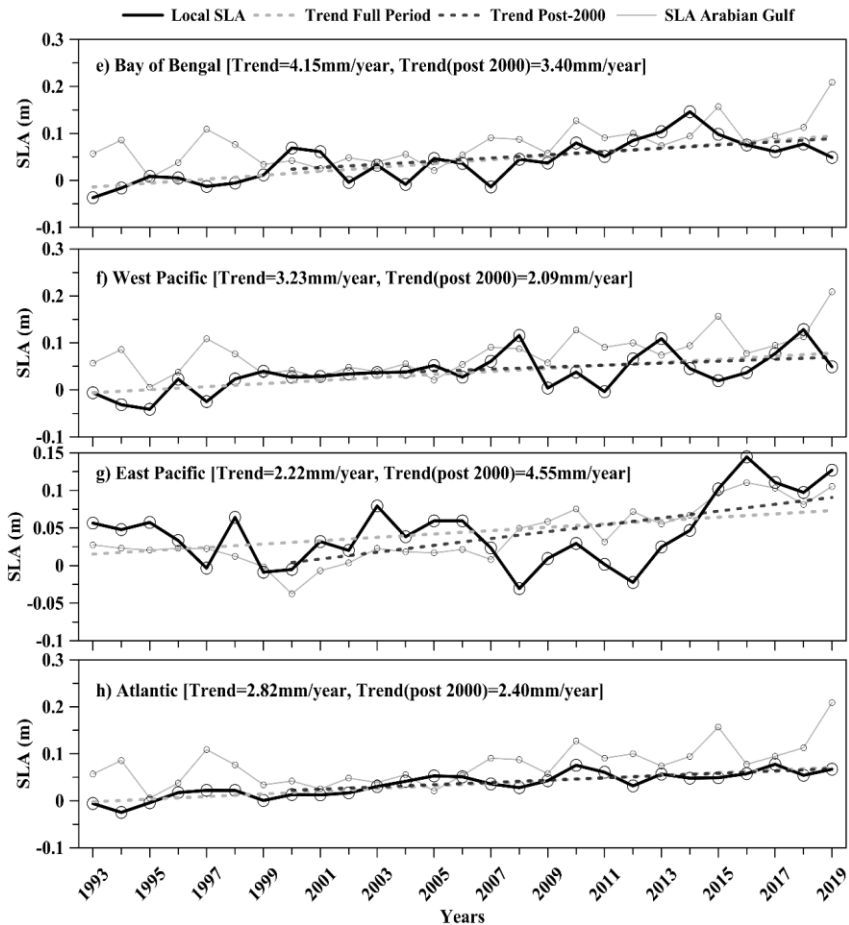


Fig. 6. Same as in Fig. 5, but for e) the Bay of Bengal, f) the West Pacific, g) the East Pacific, and h) the Atlantic

2.5 Impact of Global Warming: Results from Sea Surface Temperature

The change in sea surface temperature is examined to understand how the ongoing global warming impacts the sea-level variability of the Arabian Gulf. The wavelet analyses for monthly mean values of sea-level and SST match well where the seasonal signal dominates the variability (Figure not shown). The results for filtered sea-level and SST for seasonal and intra-seasonal signals (<12 months removed) show the presence of a multi-year variability of periodicity roughly between 32 and 64 months (Fig. 7a and 7b). The energy of the signal

varies over the years. The principal component analysis also has shown similar variability where the first mode of variability explains nearly 90% of the variance (Figs. 7c and 7d).

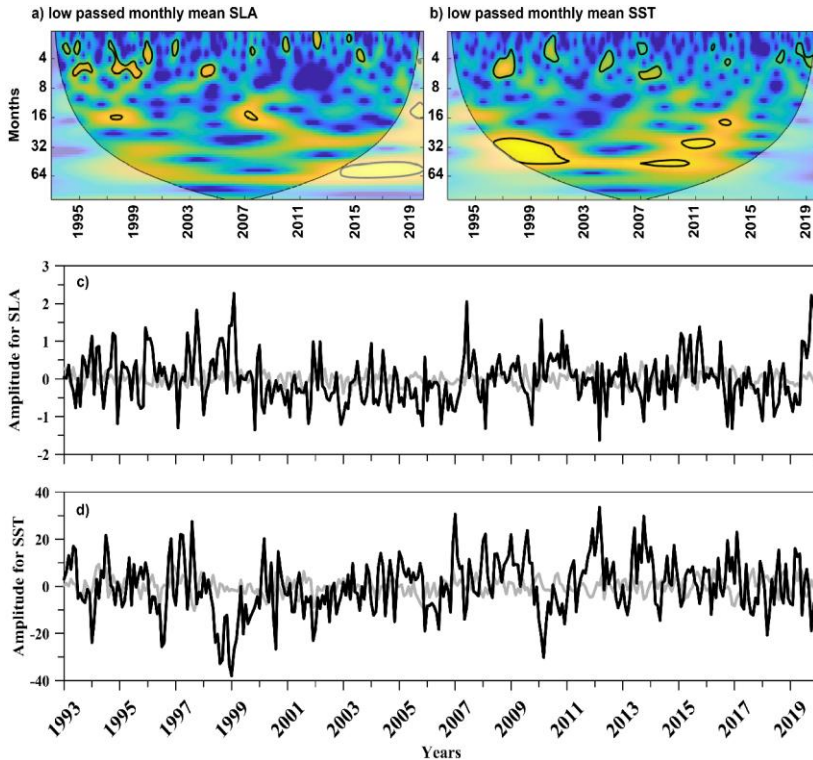


Fig. 7. The results of wavelet analysis for low passed monthly mean (a) sea-level and (b) SST. The dominant modes of variability from the principal component analysis for (c) sea-level and (d) SST after removing the seasonal cycle

The long-term variability of SST is shown in Fig. 8. Results show that both the northern and southern Gulf has experienced considerable warming over the years of the study period. The rate of increase in SST for the northern Gulf is slightly higher than the southern Gulf, with a linear trend of $0.027^{\circ}\text{C}/\text{year}$ and $0.010^{\circ}\text{C}/\text{year}$, respectively. Considering the post-2000 period alone, the rate of increase in the northern Gulf is slightly higher ($0.033^{\circ}\text{C}/\text{year}$) while that of the southern Gulf is slightly lower ($0.006^{\circ}\text{C}/\text{year}$). The correlation between sea-level and SST in the Northern Arabian Gulf is 0.54. At the same time, the southern side is relatively low (0.28). The average correlation is 0.42 with a p-value of 0.02.

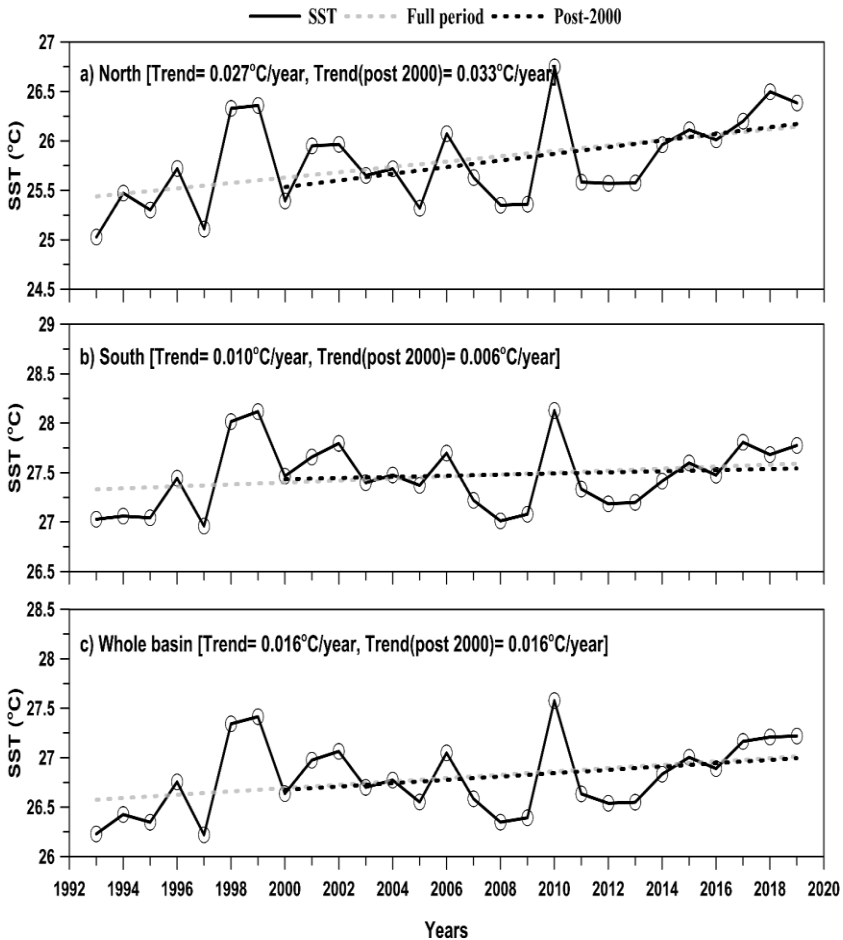


Fig. 8. The annual mean SST in the Arabian Gulf for the a) northern, b) southern, and c) whole Arabian Gulf. The linear trends are shown by dashed lines for the full period (grey) and post-2000 (black)

The expected value of SST from numerical simulations under RCP2.6, RCP4.5, and RCP8.5 scenarios for the Arabian Gulf is shown in Fig. 9. The predicted SST for the Arabian Gulf for the year 2050 is 26.00, 25.94, and 26.80, and for the year 2100 is 25.34, 26.93, and 28.58, respectively. According to these projections, the SST is expected to rise by 0.55, 0.11, and 2.03 by 2050 for scenarios RCP2.6, RCP4.5, and RCP8.5, and by -0.11, 1.11, and 3.82, respectively by the end of the 21st century.

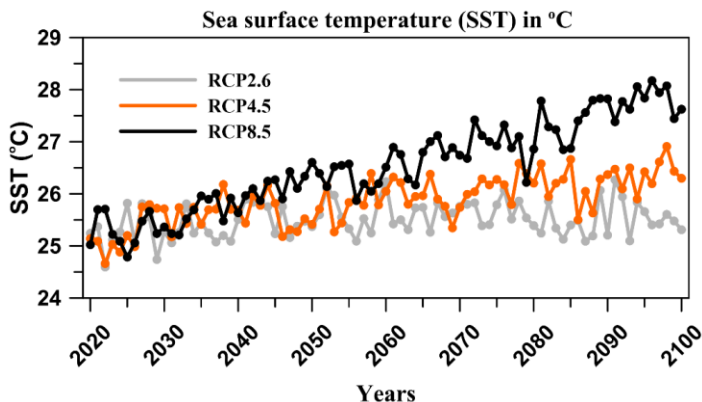


Fig. 9. The projected SST for the Arabian Gulf

3. DISCUSSION AND CONCLUSIONS

The sea-level climatology and long-term variability in the Arabian Gulf are investigated and compared with the adjacent marginal seas and other world ocean basins. The satellite altimetry data of nearly three decades, from 1993 to the present, is used to carry out these analyses. The main features of seasonal, interannual, and long-term changes are also described. The seasonal variability of sea-level in the Arabian Gulf is nearly opposite to that of the adjacent Red Sea basin. A detailed analysis revealed that the observed difference is mainly associated with the difference in wind patterns in the Red Sea and the Arabian Gulf. The mean seasonal cycle has shown a significant difference from the directly connected Arabian Sea, indicating that the local forces dominate the seasonal cycle more than the exchange between the Arabian Sea and the Arabian Gulf.

The observed trend in the Arabian Gulf sea-level is consistent with global warming and the associated increase in sea level. It is also important to note that the pattern of interannual sea-level variability in the Arabian Gulf is different from the pattern of sea-level change in the directly connected Arabian Sea and other selected basins.

The correlation coefficients between the sea-level and climate indices are relatively low, indicating that the possible impact on sea-level is limited. The sensitivity experiments using numerical simulations may provide further insight into this, which can be executed as a continuation of this work in the future [23]. Suppose the contemporary global warming (due to different factors including anthropogenic activities) caused by the increase in greenhouse gas concentration continues over the years. In that case, the projection of sea surface temperature and sea-level is expected to increase tremendously, leading to irrevocable harm to the human life and socio-economical system. Timely

actions to mitigate the concentration of greenhouse gases through sustainable development may help to lessen the impact to some extent.

COMPETING INTERESTS

Author has declared that no competing interests exist.

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Biography of author(s)



Cheriyei Poyil Abdulla

Department of Marine Physics, King Abdulaziz University, Jeddah 80200, Saudi Arabia and 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.

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