Temporal and spatial analysis of dissolved oxygen, sea surface temperature and sea surface salinity in northern Indian Ocean: Implication for environmental trends and variability

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ABSTRACT

The Indian Ocean, a vital part of the world's climate system, influences both local and global environmental trends. Dissolved Oxygen (DO), Sea Surface Temperature (SST) and Sea Surface Salinity (SSS) in the northern Indian Ocean, are three crucial oceanographic parameters that provide a comprehensive temporal and spatial analysis. The main goal is to examine environmental trends and variability in this region, shedding light on the potential impacts of anthropogenic activities and climate change.Using data from the Copernicus Marine Environment Monitoring Service, with resolution of 0.25°, spanning from 1998 to 2020, we aim to understand the physical and biogeochemical dynamics of the Arabian Sea and the Bay of Bengal. The analysis reveals significant temporal and regional patterns in DO, SST, and SSS across the Indian Ocean basin, including clear seasonal variations, temporal long-term trends, and notable annual cycles.Variations in DO concentrations underscore the vulnerability of marine life to hypoxic or anoxic conditions, which could negatively affect biodiversity. Our results and statistical analyses emphasize the critical importance of ongoing monitoring and research in the northern Indian Ocean to understand the environmental changes occurring in this region. This study provides valuable insight into the intricate interplay of environmental trends and variability through a detailed examination of the temporal and spatial dynamics of DO, SST and SSS in the Northern Indian Ocean. It highlights the urgent needs for proactive measures to mitigate the impacts of climate change and human activities on this essential marine environment.

INTRODUCTION

Over the past few decades, global warming has significantly impacted weather, climate, human society and the economy (IPCC, 2018). Understanding the dynamics of critical oceanic parameters in these regions is essential for grasping their complex interactions and ecological processes. SSS, SST and DO are fundamental parameters that greatly influence the physical and biological properties of these oceanic areas (Smith et al., 2020). Detailed long-term studies of dissolved oxygen concentrations in the ocean, reveal a steady decline over the 50 years (Bushinsky and Emerson, 2018; Schmidtko et al., 2019). Decreasing DO levels are particularly evident in coastal oceans, leading to the proliferation and expansion of 'dead zones'. The oxygen cycle is associated with changes in ecosystem dynamics, nutrient availability and ocean circulation by global climate models (Emerson and Bushinsky, 2014).The loss of DO can have far-reaching consequences, affecting pelagic and benthic fisheries, tourism, ocean nutrient cycling, and the oceanic production of N_2O, a potent greenhouse gas.

The ocean obtains DO primarily through air-sea gas exchange and photosynthesis. DO is a critical parameter for marine organisms, as it reflects the availability of oxygen in seawater and is essential for their respiration and metabolic processes. The Arabian Sea and the Bay of Bengal, exhibit significant temporal and spatial variations in dissolved oxygen due to several factors. Subsurface dissolved oxygen is advected via water mass distribution pathways and mixed into adjacent water masses. Other contributing factors include surface solubility (affected by warming), decreased ventilation (due to increased stratification), and enhanced deep ocean respiration (driven by higher surface primary production and increased particle flux), all of which can result in de-oxygenation(Diaz and Rosenberg, 2008; Keeling et al., 2010; Peña et al., 2010). Physical, chemical and biological variables also play a crucial role in the dynamics of DO (Menzel and Spaeth, 1962). These include ocean currents, temperature, salinity, nutrient availability and biological productivity. Large-scale variability in seasonal average atmospheric inputs is reflected in the temporal and spatial variability of sea surface temperature, sea surface salinity and dissolved oxygen. Lower sea-surface oxygen concentrations, reduced mid-water ventilation due to ocean warming, and local eutrophication episodes, contribute to the expansion of marine dead zones (Stramma et al.,2008; Diaz and Rosenberg,2008).

Sea Surface Temperature (SST) refers to the temperature of the ocean's uppermost layer, while Sea Surface Salinity (SSS) denotes the concentration of dissolved salts in the same layer. Both SST and SSS are fundamental oceanographic indices critical for understanding the physical and chemical properties of the ocean and their influence climate and ecosystems (Schmidt et al., 2019). SST variability is a multidimensional phenomenon driven by various natural and anthropogenic factors. SST oscillations are influenced by solar radiation, air-sea heat exchanges, monsoonal circulation patterns, oceanic forcing mechanisms and human activities (Smith et al., 2020). These intricate interactions of mechanisms, underscore the need for comprehensive research into the complex dynamics of SST and its implications for climate and ecosystems. SSS concentration is regulated by multiple factors, including river freshwater discharge, precipitation, evaporation, climate variability, and oceanic currents (Rao and Sivakumar, 2003). The annual SST fluctuation in the Arabian Sea(AS) and the

Bay of Bengal (BoB), is bi-modal (Colborn et al., 1975), with surface warming occurring in April-May and October, and surface cooling observed during the SW monsoon and winter months. However, the Arabian Sea experiences faster cooling during the SW monsoon. Previous studies highlight the significance of Arabian Sea. SST is significant due to its potential influence on the inter-annual variability of the Indian summer monsoon (Li et al., 2001; Vinayachandran,2004; Wilson-Diaz et al., 2009).

During the south-west monsoon, winds are stronger over the Arabian Sea than over the Bay of Bengal due to the presence of the Findlater Jet (Shenoi et al., 2002). These stronger winds enhance evaporation, upwelling, and the spread of coastal cold waters along the shores of Arabia and Somalia, resulting in a broad distribution of cooler SST water into the central Arabian Sea. SST also influence monsoon onset (Vinayachandran2004) and biological productivity (Murtugudde et al., 2007) in the Arabian Sea. In both the Arabian Sea and Bay of Bengal, surface heat fluxes predominantly drive monthly SST variation, except the upwelling zone along the western boundary of the Arabian Sea(Chowdary et al., 2014;Du et al., 2019). SST fluctuation is further influenced by salinity effects and subsurface processes such as barrier layers, vertical entrainment, in solar radiation penetration depth, and zonal advection (Thangaprakashet al., 2016). Monsoon driven variability in rainfall significantly impacts near-surface salinity variations, especially in the Bay of Bengal which exhibits a pronounced annual cycle of sea surface salinity (Akhil et al., 2014). Freshwater influx at the bay's northern end forms a shallow, stratified mixed layer with low salinity which is advected southwards along India's east coast being diminished by vertical mixing (Akhil et al., 2014). This variability in freshwater input also contributes to the seasonal cycle of barrier layer thickness in the Bay of Bengal (Jana et al., 2015). Sea surface salinity has been widely used to describe oceanic phenomena such as ocean circulation, sea-level changes, instability waves, and Rossby waves. Changes in seawater density, caused by colder and saltier water, can lead to sinking to greater depth sustaining global ocean circulation.The Indian monsoon drives strong mixing and high productivity in the Arabian Sea, while in the Bay of Bengal, heavy rainfall and stratification limit mixing, but enhance atmospheric convection (Shenoi et al., 2002).

Understanding the interaction of DO, SSTand SSS in these regions, is crucial for a comprehensive description of their marine environments. These parameters play an essential role in shaping the physical, chemical, and biological aspects of ecosystem dynamics, hypoxia and anoxia, climate change and ocean-atmosphere interactions.These parameters are interconnected, influencing one another and driving the physical and biogeochemical processes that define marine ecosystems and climate dynamics. This study synthesizes relevant literature and research findings to provide a comprehensive understanding of the variability and interdependencies of SSS, SST and DO in the Arabian Sea and Bay of Bengal. It highlights their ecological implications and contributes to a holistic assessment of these vital oceanic regions. DO dynamics are particularly significant in the Arabian Sea and Bay of Bengal. A multidisciplinary approach involving field measurements, remote sensing and modeling techniques, has been employed to uncover the driving mechanisms and ecological impacts of DO variability. Similarly, SST or SSS are critical drivers of weather patterns, ocean currents, and marine ecosystems in these regions. Research on SST and SSS variations leverages satellite observations, in-situ measurements, and numerical models to unravel there complex patterns and underlying mechanisms, and temporal and spatial dynamics. By exploring the interdependencies of these parameters and their implications for the marine environment, this study provides valuable insights into the ecological and climatic processes shaping the Arabian Sea and Bay of Bengal.

STUDY AREA

The study area in the Arabian Sea and the Bay of Bengal (Figure 1), provides a unique opportunity to investigate the inter-connectedness of physical and bio-geochemical processes and their impact on marine ecosystems. Through this study, we aim to enhance the broader understanding of complex oceanic dynamics, and ecological responses and the factors influencing the health and sustainability of marine environments. To facilitate a better understanding of variability, the study area is divided into specific regions, northern Arabian Sea , western Arabian Sea, eastern Arabian Sea, central Arabian Sea, northern Bay of Bengal, western Bay of Bengal, eastern Bay of Bengal and central Bay of Bengal.

DATA AND METHODOLOGY

Data

Copernicus Marine Environment Monitoring Service (http://marine.copernicus.eu/), utilizing a horizontal resolution of 0.25º, provided the data for this study. The analysis employed the Global ocean analysisv3.6 NEMO (Nucleus for European Modeling of the Ocean), integrated with the PISCES (Pelagic Interaction Scheme for Carbon and Ecosystem Studies) biogeochemical model, using atmospheric forcing from European Centre for Medium-Range Weather Forecasts (ECMWF). Data spanning from 1998 to 2020 was used to understand the physical and biogeochemistry of the Arabian Sea and Bay of Bengal.

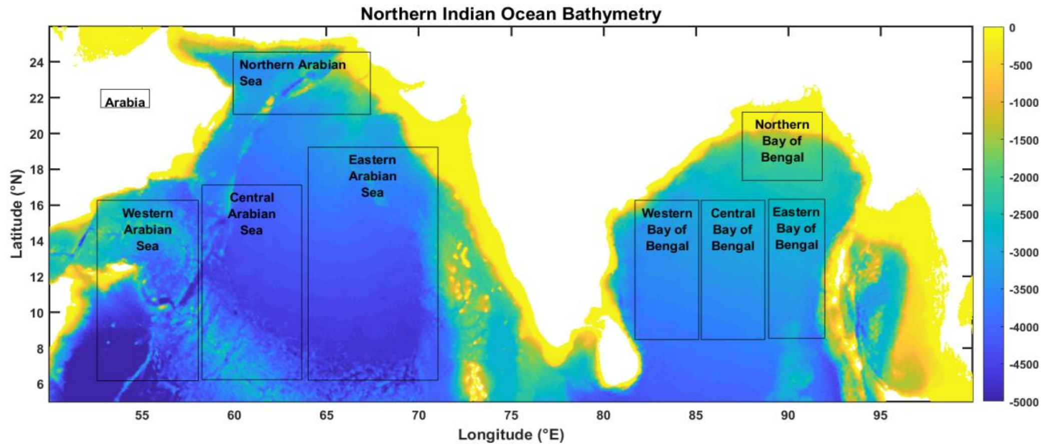

Figure 1. Different studied regions of theNorthern Indian ocean

Methodology

In the present study, line graphs were used to illustrate the time series distribution of vital biogeochemical variables over the study period in the Arabian Sea and Bay of Bengal. This visual representation enables the observation of temporal patterns and trends, providing valuable insights into the variability of these variables. To explore the relationships between these variables, Pearson's correlation test was conducted and statistical analysis assessed the strength and direction of the relationships among the biogeochemical variables. By quantifying the magnitude of these correlations, the study deepened our understanding of how the variables influence each other within the study area. Additionally, multiple linear regression models were developed separately for the Arabian Sea and Bay of Bengal, with DO concentration as the dependent variable. The analysis considered other biogeochemical variables as independent predictor to identify significant drivers of DO concentration. This approach revealed the critical factors influencing DO levels in the region and provided insights into the relative importance of different variables in shaping its distribution. Ultimately, this research enhanced our understanding of the factor affecting DO concentration in the Arabian Sea and Bay of Bengal. By identifying significant predictors and quantifying their impacts, it contributes to the broader understanding of biogeochemical processes and the dynamics of these vital oceanic regions.

Descriptive Statistics

Descriptive statistics were employed to summarize the biogeochemical data.

Mean (μ)

The arithmetic average of the dataset, calculated as:

$$\mu = \frac{\sum x_i}{n}$$

where $x_i$represents individual data points, and n is the total number of observations.

Standard Deviation (σ)

A measure of data dispersion around the mean, computed as:

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \mu)^2}{n}}$$

Pearson Correlation Coefficient (r)

This correlation coefficient between two variables (X and Y) is given as:

$$r = \frac{\Sigma_{i=1}^{n}(x\overline{-x})(y_i - \bar{y})}{\sqrt{\Sigma_{i=1}^{n}(x_i - \bar{x})^z \sum_{i=1}^{n}(y - \bar{y})^2}}$$

where, x_i and$y_i$represent the individual data points for variables X and Y, while $\bar{x}$ and$\bar{y}$ are their respective means.

Regression Analysis

To identify significant predictors of dissolved oxygen (DO) concentration, multiple linear regression models were developed for both the Arabian Sea and Bay of Bengal. The dependent variable in these models was DO concentration**,** while independent variables included theother biogeochemical parameters. The following model summary statistics were used to evaluate model performance:

Model Summary Statistics

$$R^2 = \frac{\text{Explained variance}}{\text{Total variance}}$$

Adjusted R^2, corrects R^2 for the number of predictors in the model which can be given as,

$$\text{Adjusted } R^2 = 1 - \frac{(1 - R^2)(n-1)}{n-k-1}$$

Where$n$is the number of observations, k is the number of predictors, R is the correlation between observed and predicted values of the dependent variable.

Standard error of the estimate (SE) measures the accuracy of predictions and can be written as a

$$SE = \sqrt{\frac{\sum_{i=1}^{n}(Y_i - \hat{Y})^2}{n-k-1}}$$

where Y_i is the observed value, and $\hat{Y}$ is the predicted value.

Change Statistics

R^2 Change: The increment in R^2 due to additional predictors.

F Change: The F-statistic for the change in R^2, and can be calculated as,

$$\text{F change} = \frac{(R^2\text{new} - R^2\text{old})/m}{(1 - R^2\text{new})/(n-k-1)}$$

where m is the number of new predictors added.

RESULTS

Seasonal variability of dissolved oxygen, sea surface temperature and sea surface salinity

During the pre-monsoon season (Figure 2) in the northern Arabian Sea, DO levels range from 200-210mmol/m^3, SST 24.5-25ºC and SSS, 37-37.5PSU.These comparatively high values indicate that northern Arabian Sea waters have adequate oxygen levels, which are crucial for marine organisms that are reliant on dissolved oxygen for respiration. This temperature range is conducive to normal ocean circulation and weather patterns, and supports many marine species. The salinity levels suggest moderately saline waters, which influence ocean currents, density and the distribution of marine species. It also suggest, moderately saline waters, which influence ocean currents, density, and the distribution of marine species, as some are adapted to specific salinity conditions. In the western Arabian Sea region, the DO ranges from 200-210 mmol/m^3, SST 28-28.5ºC, and SSS 36-36.5PSU. Similarly, in the eastern Arabian Sea, DO concentrations are slightly lower at around 198-200 mmol/m^3, with SST increasing from 27ºC in the north to28.5ºC in the south, and SSS decreasing southward from 34.5 PSU. In the central Arabian Sea, DO ranges from 190-200 mmol/m^3,with a declining trend from north to south.SST varies between 26.5-29ºC,increasing southward,while SSS decreases from37 PSU in the north to 35.5 PSU in the south. In the northern Bay of Bengal, DO concentration is highest near the Ganges-Brahmaputra river mouth, at 260 mmol/m^3 and decreasing southward. SST near the river mouth is 25.5ºC, with regional variations ranging from 25.5-26.5ºC north to south. SSS in the northern Bay of Bengal is relatively low at 32 PSU during pre-monsoon season, reflecting the influence of freshwater input. In the western Bay of Bengal, DO ranges from 210-220 mmol/m^3, with a decreasing trend from north to south. SST ranges from 27.5ºC in the north to 29ºC in the south, while SSS varies from 32 PSU in the north to 33.5PSU in the south.

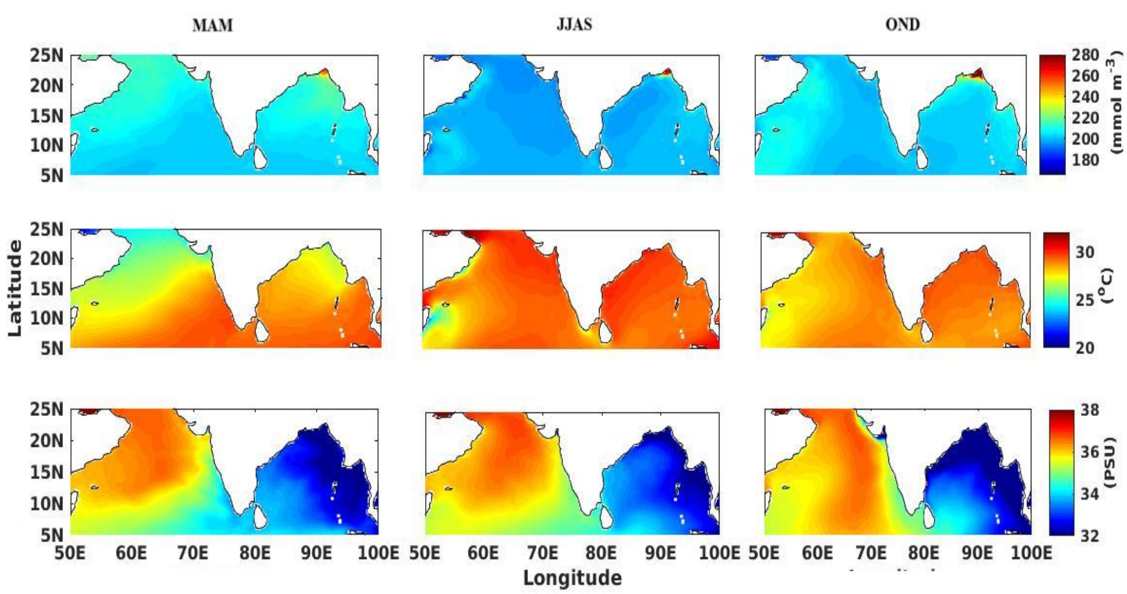

Figure 2. Seasonal mean climatology of dissolved oxygen, sea surface salinity, and sea surface temperature over the Arabian Sea and Bay of Bengal.

In the eastern Bay of Bengal, DO concentration ranges from 200-215 mmol/m^3, slightly higher than those observed in the western Bay of Bengal and central Bay of Bengal. SST varies between 26.5-27ºC in the northern segment of the eastern Bay of Bengal with a slight increase toward the south. SSS remains steady at 32 PSU in this region. In the central Bay of Bengal, DO concentration show a declining trend, ranging from 205 mmol/m^3 in the north to 196 mmol/m^3 in the south. SST increases from 27.7ºC in the northern region to 29ºC in the southern region, while SSS is 32 PSU in the north, slightly increasing to 33.5 PSU in the southern central Bay of Bengal. During the monsoon season, the DO concentrations decline in the northern Arabian Sea to 190-195 mmol/m^3. SST rises to 30ºC, and SSS remains at 37 PSU. In the western Arabian Sea, DO levels are slightly higher, ranging from 200-210 mmol/m^3, with values near the Arabian coast reaching 210 mmol/m^3. This elevated DO spreads from the Arabian coast to the Socotra region. SST increases to (27.5ºC), although lower temperatures are recorded near the Arabian coast (26.5ºC) and in the Socotra region (26ºC). SSS in the western Arabian Sea varies from 36 PSU in the north to 37 PSU in the south, showing a decreasing trend from north to south. In the eastern Arabian Sea, DO levels vary from 190-200 mmol/m^3, with a decreasing trend from north to south. SST ranges from 25.5ºC - 29ºC, with the Arabian coast experiencing temperatures of 26.5ºC and the Socotra region 25.5ºC. SSS varies from 35.5 PSU near the coast to 36 PSU farther offshore, increasing toward the central Arabian sea. Salinity generally decreases from north to south in the eastern Arabian sea region. In the central Arabian Sea, DO levels range from 190 to 200 mmol/m^3, with a slight increase observed southward. SST during the monsoon season ranges from 29.5ºC in the north to 30ºC in the south. SSS starts at 37 PSU in the northern central Arabian Sea and decreases southward to 35.5 PSU.

During the pre-monsoon season of the northern Arabian Sea, the DO is 200-210 mmol/m^3, the SST is 24.5 - 25ºC and SSS in the range of 37 - 37.5 PSU. In the western Arabian Sea region, the DO is 200-210 mmol/m^3, SST is 28-28.5ºC, and the SSS value is 36-36.5 PSU. In the eastern Arabian Sea, DO concentration is 198-200 mmol/m^3, The SST varies from 27-28.5ºC, showing a gradual increase from the northern to southern segment of the eastern Arabian Sea. The SSS decreases southward, starting at 34.5 PSU in the northern region. In the central Arabian Sea, the DO is 190-200 mmol/m^3.There is a decreasing trend in DO from north to south in the central Arabian Sea region. SST ranges from 26.5-29ºC, showing an increase from north to the south. The SSS in the central Arabian Sea region varies from 35.5-37 PSU, decreasing gradually from north to south. In the northern Bay of Bengal, dissolved oxygen is highest near the Ganges-Brahmaputra river mouth (260 mmol/m^3), decreasing southward (230–260 mmol/m^3). Sea surface temperature (SST) ranges from 25.5°C near the river mouth to 26.5°C in the south, while sea surface salinity (SSS) is 32 PSU during pre-monsoon. In the western Bay of Bengal, DO ranges from 210–220 mmol/m^3, also decreasing southward. SST in the western Bay of Bengal varies from 27.5ºC-29ºC.The SST is 27.5ºC in the northern region and increases to 29ºC in southern segment of western Bay of Bengal. The SSS in north-western Bay of Bengal is 32 PSU increasing to 33.5 PSU in southern segment of western Bay of Bengal region. The DO concentration in eastern Bay of Bengal region is 200-215 mmol/m^3, slightly higher than in western Bay of Bengal and central Bay of Bengal. SST in the eastern Bay of Bengal ranges from 26.5-27ºC. The northern segment of the eastern Bay of Bengal has a lower SST, which slightly increases toward the south. The SSS is 32 PSU in eastern Bay of Bengal. In the central Bay of Bengal, it is 205 mmol/m^3 in the northern region, showing a decreasing trend toward the south, where it drops to 196 mmol/m^3. The SST in the northern central Bay of Bengal is 27.7ºC and increases to 29ºC toward the south. The SSS starts at 32 PSU in the northern region and increases slightly toward the southern region, reaching 33.5 PSU.

During the monsoon season, the DO declines to190-195 mmol/m^3 in the northern Arabian Sea region. The temperature in the northern Arabian Sea is 30ºC, and the SSS is 37 PSU. In the western region of the Arabian Sea, DO is slightly more than northern Arabian Sea 200-210 mmol/m^3 and 210 mmol/m^3 reported near the Arabian coast. This increase in DO extends from the Arabian coast to the Socotra region. SST increases to 27.5ºC, but low temperature is found near the Arabian coast, where SST is 26.5ºC, and in the Socotra region, where it is 26ºC. SSS varies from 36 PSU to 37 PSU, showing a decreasing trend from north to south in the western Arabian Sea region. The DO in the eastern Arabian Sea varies from 190-200 mmol/m^3, with a decreasing trend observed from north-to-south in the eastern Arabian Sea region. SST ranges from 25.5ºC to 29ºC during monsoon season. Near the Arabian coast, the SST is 26.5ºC and in the Socotra region, it is 25.5ºC. SSS ranges from 35.5 PSU to 36 PSU, with lower salinity observed near the coast areas of eastern Arabian Sea. Salinity increases toward the central Arabian Sea region within eastern Arabian Sea. In the central Arabian Sea region, DO ranges from 190 to 200 mmol/m^3, with a slight increase in concentration observed from north to south. SST during the monsoon season varies from 29.5ºC to 30ºC. SSS in the northern central Arabian Sea 37 PSU, which decreases southward, reaches 35.5 PSU. In the monsoon season, the northern Bay of Bengal near the Ganges-Brahmputra river mouth has a DO of 280 mmol/m^3, which decreases as it moves away from the northern coastal region. SST in the northern region is above 27.5-28ºC, and SSS is 32 PSU. In the western Bay of Bengal region, the DO near the coastal area is

195 mmol/m^3, decreasing toward the central and eastern directions, reaching 190 mmol/m^3. SST is about 29ºC near the western Bay of Bengal coastal region, showing a prolonged decreasing trend toward the central and southern western Bay of Bengal region, reaching 33.5 PSU. In the eastern Bay of Bengal region, DO is 198 mmol/m^3. With only a slight variation during the monsoon season. SST is around 29ºC, showing only slight variation southward in the eastern Bay of Bengal. SSS in the eastern Bay of Bengal is 32 PSU during the monsoon season. In the central Bay of Bengal region, the DO is 196 mmol/m^3,with a slight increase to 196.8 mmol/m^3 from southern to the northern segment central Bay of Bengal. SST is 28ºC, decreasing to 27.8ºC toward the southern region of the central Bay of Bengal. SSS in the northern Bay of Bengal is 33.1 PSU, decreasing to 32 PSU toward the south, then increasing again in the same direction.

In the post-monsoon season, the DO in the northern Arabian Sea region is 200 mmol/m^3. In the western region northern Arabian Sea region, the DO concentration is higher compared to the eastern part of the northern Arabian Sea region. SST in the northern Arabian Sea is 27 – 27.5ºC, and SSS is 37 PSU during the post-monsoon season. In the western Arabian Sea, the DO is 210 mmol/m^3, slight decrease to 207 mmol/m^{3}in the mid-western Arabian Sea. The SST near the coast of the western Arabian Sea is 26.5ºC, and the DO increases to 21 mmol/m^{3}in the southern western Arabian Sea. Salinity in the western Arabian Sea region from 35.7 - 35.5 PSU with slight variations. The northern western Arabian Sea exhibits elevated salinity (+0.2 PSU) compared to southern freshening (−0.1 to −0.3 PSU), driven by evaporation-precipitation and riverine contrasts. In the eastern Arabian Sea, DO ranges from 192-197 mmol/m^3. The DO concentration increases southward along coastal region. SST in eastern Arabian Sea is 27.5ºC,with slight decrease in the SST observed in the coastal and central regions of the eastern Arabian Sea. The SSS in the eastern Arabian Sea varies from 32.2-36PSU, with the lowest salinity (32 PSU) found near the Gulf of Khambhat. It slightly increases to 34 PSU toward the southern eastern Arabian Sea and reaches 36 PSU in the central-eastern Arabian Sea. In the central Arabian Sea, the DO is 200 mmol/m^3, which is lower than the eastern Arabian Sea region. A slight increase in DO is observed from east to west, while it decreases from north to south in the central Arabian Sea region. SST in the central Arabian Sea region varies from 27-29ºC, with lower SST in the northern central Arabian Sea and decreases toward the southern central Arabian Sea. The SSS is 37 PSU and decreases toward the western Arabian Sea region. In the northern Bay of Bengal, highest DO concentration is 280 mmol/m^3, present in the broad northern region near the Ganges-Brahmaputra river mouth. This high DO concentration gradually decreases toward the central open region of the Bay of Bengal. SST in northern Bay of Bengal is slower than during monsoon season, ranging from 27-28ºC, and it declines toward the central Bay of Bengal. The SSS in the northern Bay of Bengal is very low, at 32 PSU, and slightly increases toward the central Bay of Bengal.

Annual variability of dissolved oxygen, sea surface temperature and sea surface salinity

During the pre-monsoon season (Figure 3), DO levels in the Arabian Sea decline from 206 mmol/m^3 to 197 mmol/m^3. Simultaneously, SST increases from 26°C at the onset of pre-monsoon to 29.7°C in mid-pre-monsoon, followed by a further rise during the transition from pre-monsoon to monsoon. Throughout the monsoon season, DO levels rise from 197 mmol/m^3 to 204 mmol/m^3, while sea surface salinity experiences an initially increase but shows a slight decline from July onwards. Meanwhile, SST decreases consistently from 29.8°C to 27.5°C during the monsoon period. In the post-monsoon season, DO levels in the Arabian Sea remain relatively stable, showing a slight increase from 197 mmol/m^{3}to 204 mmol/m^3. Sea surface salinity exhibits a marginal increase initially, followed by a gradual decline. Concurrently, Sea surface temperature decreases steadily from 29.8°C to 27.5°C throughout the post-monsoon period.

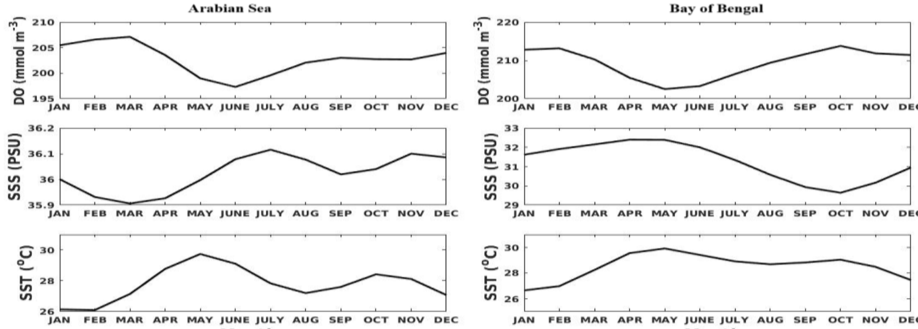

Figure 3. Annual cycle of the dissolvedoxygen (mmol/m^3), sea surface salinity(PSU) and sea surface temperature(˚C) over the Arabian Sea and Bay of Bengal.

In Contrast to the Arabian Sea region, the Bay of Bengal displays different trends in dissolved oxygen, sea surface salinity, and sea surface temperature. During the pre-monsoon season, dissolved oxygen levels decline rapidly from 214 mmol/m^3 to 204 mmol/m^3, while sea surface salinity and sea surface temperature increases from 0.5 PSU to 27.8°C and 28.8°C, respectively. Throughout the monsoon season, dissolved oxygen levels steadily raise from 203 mmol/m^3 to 214 mmol/m^3, In contrast, sea surface salinity decreases from 32.1 PSU to 29.9 PSU and sea surface temperature shows an initial slight decline followed by an increase towards the end of the monsoon period. In the post-monsoon season in the Bay of Bengal region, DO levels experience a slight decrease from 215 - 213 mmol/m^3 initially, stabilizing toward the end of the season. Conversely, sea surface salinity exhibits an increasing trend from 29.8 PSU to 31 PSU, while sea surface temperature decreases from 29°C to 27.5°C.

Inter-annual trend of dissolved oxygen, sea surface temperature and sea surface salinity

A decreasing trend in the concentration of dissolved oxygenin the Arabian Sea is observed (Figure 4). The plot indicates a yearly decrease in DO concentration of 0.0061 mmol/m^3, alongside an increase in sea surface temperature is 0.0017 and an increase in sea surface salinityto 0.00026 PSU. During the study period, the concentration of dissolved oxygen varied from 195.5 to 209 mmol/m^3, sea surface salinityranged from 35.8 to 36.3 PSU, and sea surface temperature fluctuated between 25.4 and 30.1ºC.

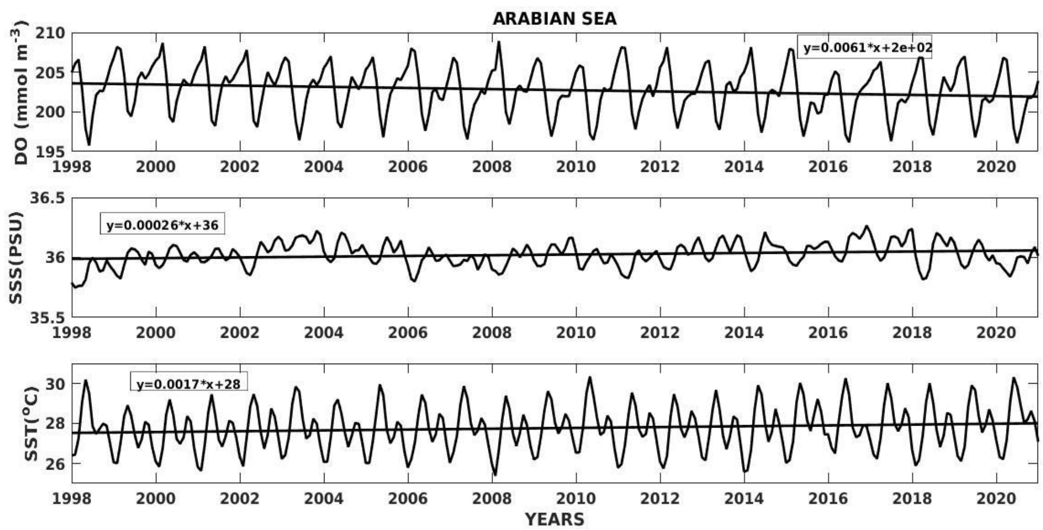

Figure 4. Temporal trend of DO (mmol/m^3), SSS (PSU) and SST (˚C) from 1998 to 2020 in the Arabian Sea.

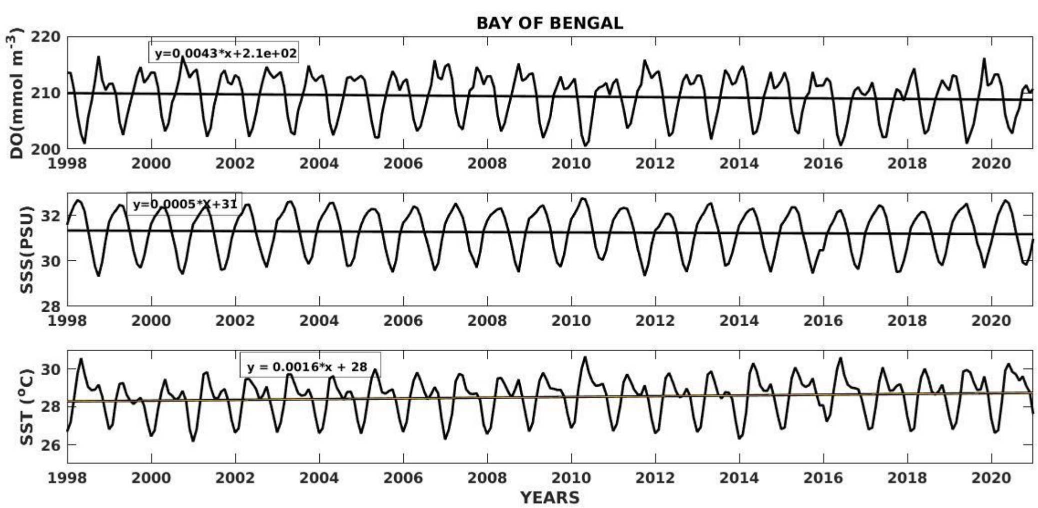

Figure 5. Temporal trend of DO (mmol/m^3), SSS (PSU) and SST (˚C) from 1998 to 2020 in Bay of Bengal region.

A decreasing trend in the concentration of dissolved oxygenin the Bay of Bengal is also observed (Figure 5). The plot indicates a yearly decrease in dissolved oxygen concentration of 0.0043 mmol/m^3, an increase in sea surface temperature is 0.0016ºC, and a decrease in sea surface salinity of 0.00059 PSU. During the study period, the concentration of DO varied from 200.5 to 216 mmol/m^3, sea surface salinity ranged from 29.5 to 32.8 PSU, and sea surface temperature fluctuated between 26.4 and 30.5ºC.

Anomaly of dissolved oxygen, sea surface temperature and sea surface salinity The dissolve oxygen anomaly (Figure 6) shows both increasing and decreasing trends, with dissolve oxygen and sea surface salinity exhibiting an increasing trend or vice versa. Sea surface salinity is influenced by global warming, IOD (Indian Ocean Dipole), monsoon and ENSO (El Niño-Southern Oscillation),while precipitation, cold currents or the winter season negatively impact Sea surface salinity. Cold current increase SSS or dissolve oxygen due to presence of high nutrient levels and a positive anomaly in dissolve oxygen, seasurface salinity and SST reflects an increase in dissolve oxygen, sea surface salinity concentration, and temperature. The line plot of the Arabian Sea anomaly indicates difference between actual dissolve oxygen, sea surface salinity, SST and the long-term average.An increase in the anomaly of dissolve oxygen may suugest the water is becoming more eutrophic or nutrient-rich, leading to increased primary productivity, decreased decomposition, mixing of water layers, reduced water temperature, improved and support of aquatic life growth. Similarly, an increase in the sea surface salinity anomaly indicates changes such as increased evaporation, decreased precipitation, or altered ocean currents, potentially harming marine life, altering food webs, and reducing water quality. An increase in the SST anomaly reflects influences from phenomenon like El Niño-Southern Oscillation (ENSO), increased stratification, and changes in ocean currents, alongside climate-related impacts, such as rising sea levels, ocean acidification, and shifts in precipitation patterns.

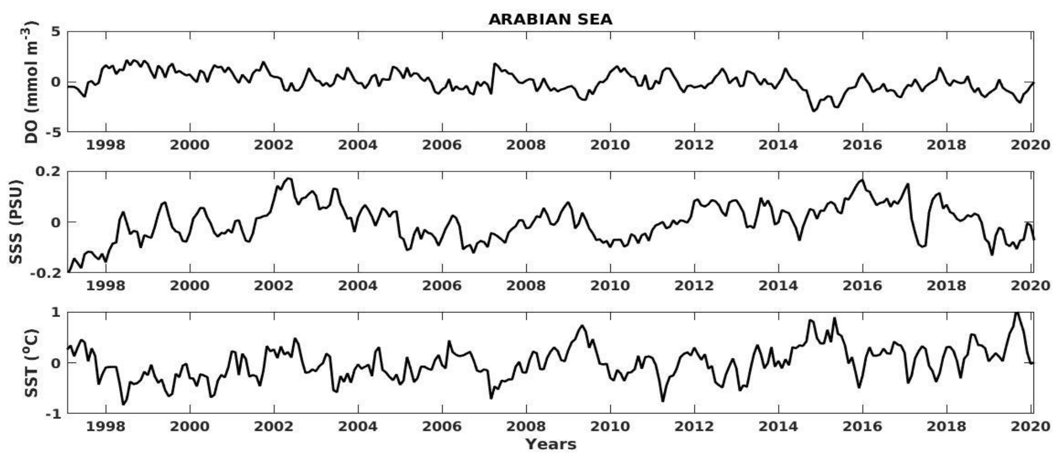

Figure 6. Anomaly of the dissolved oxygen (mmol/m^3), sea surface salinity (PSU) and sea surface temperature (˚C) from 1998 to 2020 in Arabian Sea.

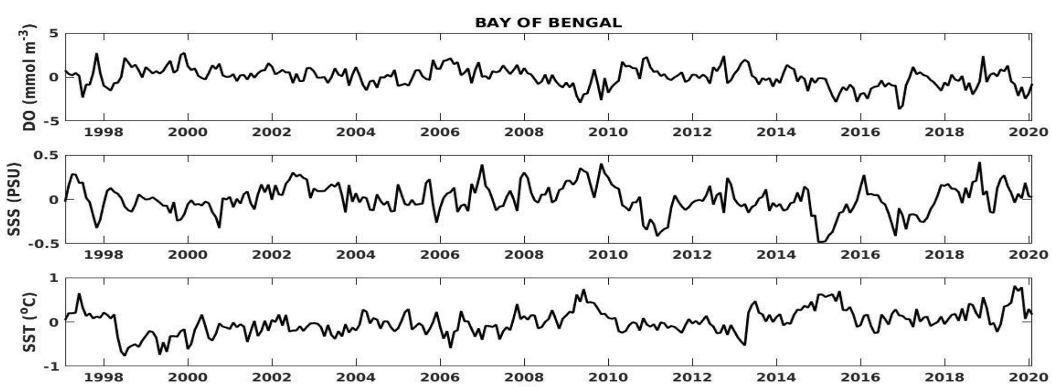

Figure 7. Anomaly of the dissolved oxygen (mmol/m^3), sea surface salinity(PSU) and sea surface temperature(˚C) from 1998 to 2020 in the Bay of Bengal region.

The line plot (Figure 7) illustrates anomalies in the Bay of Bengal (BoB), representing deviations from the long-term average in DO, sea surface salinity, and SST. These anomalies carry significant implications for the marine ecosystem. Specifically, we observe notable increases in DO anomalies during various periods. Such elevated DO anomalies may indicate a shift toward eutrophic conditions, characterized by increased nutrient enrichment. These conditions tend to enhance primary productivity, reduce decomposition rates, promote vertical mixing of water layers, and lower water temperatures, thereby improving overall water quality and supporting aquatic life. Additionally, the anomalies in sea surface salinity suggest changes in ocean conditions. These anomalies align with increased evaporation, decreased precipitation, and alterations in ocean currents, which may harm marine life and disrupt the marine food web. Such changes can ultimately lead to reduced water quality. In this case, SST anomalies variations may be linked to climatic phenomena such as the El Niño-Southern Oscillation (ENSO) and monsoonal influences. For instance, significant rainfall during the summer monsoon reduces salinity levels in the Bay of Bengal, while lower rainfall during the winter monsoon results increased salinity. These fluctuations can lead to stratification, shifts in ocean currents, and broader climate-related impacts, including rising sea levels, ocean acidification, and changes in precipitation patterns.

Statistics of dissolved oxygen, sea surface temperature and sea surface salinity

This comprehensive descriptive analysis of key environmental parameters in the Arabian Sea region (Table 1a), including dissolved oxygen in Arabian sea, sea surface salinity, and sea surface temperature, provides valuable insights into the current state of the region's environmental conditions. These parameters play a fundamental role in determining the health, sustainability and dynamics of the marine ecosystem. This analysis has revealed important results: The mean dissolved oxygen in the Arabian Sea is calculated to be 202.50 ± 2.61 mmol/m³, indicating relatively low variability. Sea surface salinity Arabian Sea exhibits an average value of 35.90 PSU, with a small standard deviation of 0.14. Sea surface temperature records a mean value of 27.91ºC; with a standard deviation is 1.03ºC.These findings underscore the relatively stable environmental conditions of the Arabian Sea, critical for maintaining its marine ecosystem.

Pearson correlation (Table 1b**)** analysis of key environmental parameters in the Arabian sea region, including dissolved oxygen, sea surface salinity, and sea surface temperature was conducted to examine the relationships between these variables. The study aims to unravel potential associations and their implications for marine ecosystem dynamics in the Arabian sea region. The dissolved oxygen exhibits a weak negative correlation with sea surface salinity (r = -0.294), indicating that higher sea surface salinity is associated with slightly lower dissolved oxygen levels. Furthermore, dissolved oxygen shows a strong negative correlation with sea surface temperature (r = -0.711), implying that higher sea surface temperature corresponds to significantly lower DO levels. In contrast, sea surface salinity and sea surface temperature demonstrate a weak negative correlation (r = -0.102).

Table 1(a).Analysis of key environmental parameters in the Arabian Sea

Serial number	Parameters	Mean	Standard deviation
1.	Dissolved oxygen	202.50	2.61
2.	Sea surface salinity	35.89	0.13
3.	Sea surface temperature	27.90	1.03

Table 1(b). Pearson correlation and Sigma (1-tailed) over the Arabian Sea

Correlation		Dissolved oxygen	Sea surface salinity	Sea surface temperature
Pearson correlation	Dissolved oxygen	1.00	-0.29	-0.71
	Sea surface salinity	-0.29	1.00	-0.10
	Sea surface temperature	-0.71	-0.10	1.00
Note:Significance: $p < 0.05$; $p < 0.001$.				

Table 1(c) Multiple linear regression models predicting dissolved oxygen in Arabian Sea

Multiple linear regression model								
Data	R	R square	Adjusted R square	Std. error of the estimate	Change statistics			
					R square change	F Change	Degree of freedom 1	Degree of freedom 2
	0.800	0.640	0.638	1.5726232	0.640	243.940	2	274
a. Dependent variable: Dissolved oxygen [mmol/m³] b. Predictors: Sea surface temperature [°C], Sea surface salinity [PSU]								

Table 2(a). Descriptive statistics of the Bay of Bengal

Serial number	Parameters	Mean	Standard deviation
1.	Dissolved oxygen	204.14	2.73
2.	Sea surface salinity	32.44	0.41
3.	Sea surface temperature	28.71	0.82

Table 2(b). Pearson correlation matrix for environmental parameter in Bay of Bengal.

Correlation		Dissolved oxygen	Sea surface salinity	Sea surface temperature
Pearson correlation	Dissolved oxygen	1.000	-0.272	-0.837
	Sea surface salinity	-0.272	1.000	-0.272
	Sea surface temperature	-0.837	-0.224	1.000
Note: Significance: p < 0.05; p < 0.001.				

Table 2(c). Multiple linear regression models statistics Bay of Bengal.

Multiple linear regression model								
Data	R	R Square	Adjusted R Square	Std. error of the estimate	Change statistics			
					R Square change	F change	Degree of freedom 1	Degree of freedom 2
	0.842	0.709	0.707	1.4832988	0.709	333.798	2	274
a. Dependent Variable: Dissolved oxygen [mmol/m³] b. Predictors: Sea surface temperature [°C], Sea surface salinity [PSU]								

A multiple linear regression model (Table 1c) was developed to predict dissolved oxygen (DO) variability in the Arabian Sea using sea surface temperature (SST) and salinity (SSS) as predictors. The model explains 64% of the variance in DO levels ($R^2 = 0.640$, Adjusted $R^2 = 0.638$) and demonstrates strong statistical significance ($F = 243.940$, $p < 0.001$). The high correlation coefficient ($R = 0.800$) and low standard error (1.573 mmol/m³) underscore the model's precision and confirm that SST and SSS are critical drivers of dissolved oxygen dynamics in the region, indicating that the inclusion of the predictor variables has significantly improved the model's fit.

Bay of Bengal exhibits (Table 2a) stable environmental conditions, with dissolved oxygen averaging 204.15 mmol/m³ (±2.73), sea surface salinity at 32.45 PSU (±0.41), and sea surface temperature of 28.71°C (±0.82). Low variability across these parameters suggests consistent hydrological and thermal regimes. These stable conditions likely enhance ecological resilience, supporting complex marine ecosystems. Such equilibrium underscores the Bay's role as a vital refuge for marine life amid global environmental changes.

Dissolved oxygen in the Bay of Bengal (Table 2b) declines significantly with rising sea surface temperature ($r = -0.837$, $p < 0.001$) and moderately with increasing salinity ($r = -0.272$, $p < 0.05$). Salinity and temperature show no significant correlation ($r = -0.224$, $p > 0.05$), highlighting sea surface temperature as the dominant driver of oxygen variability. These results align with the thermodynamic principle that warmer waters reduce oxygen solubility. The findings emphasize sea surface salinity critical role in predicting climate-driven oxygen depletion, vital for managing marine ecosystems.

The multiple linear regression model (Table 2c) accounted for 70.9% of the variance ($R^2 = 0.709$, $F(2, 274) = 333.80$, $p < 0.001$) in dissolved oxygen concentrations within the Bay of Bengal, with sea surface temperature and sea surface salinity emerging as statistically significant predictors. Sea surface temperature demonstrated the strongest inverse association, consistent with the thermodynamic regulation of oxygen solubility in aqueous systems, wherein elevated temperatures reduce gas retention capacity. Sea surface salinity exhibited a moderate negative correlation, suggesting salinity-driven stratification or mixing processes may marginally attenuate oxygen availability. These results underscore sea surface temperature as the principal determinant of oxycline variability, with critical implications for predicting hypoxia under anthropogenic warming scenarios and informing adaptive management of pelagic ecosystems.

CONCLUSIONS

Following major conclusions can be drawn from the present study

1. Significant decline in dissolved oxygen levels in both the Arabian sea and the Bay of Bengal, with Arabian sea experiencing a sharper decrease compared to Bay of Bengal. This oxygen loss coincides with increasing sea surface temperature in both regions, with Arabian sea also showing a slight rise in sea surface salinity, while Bay of Bengal exhibits freshening.

2. A strong inverse correlation between sea surface temperature and dissolved oxygen is observed, with regression models attributing dissolved oxygen variability to sea surface temperature changes.

3. Regionally, Arabian sea maintains higher salinity with moderate dissolved oxygen, while Bay of Bengal, influenced by freshwater influx, has lower salinity but slightly higher dissolved oxygen.

4. Seasonal dynamics reveal a pre-monsoon dissolved oxygen drop in Arabian Sea, as sea surface temperature rises, followed by a monsoon-induced recovery, while Bay of Bengal, experiences post-monsoon dissolved oxygen peaks due to mixing but pre-monsoon stratification-induced declines.

5. Anthropogenic influences and climate drivers, including warming, salinification, and monsoon variability, exacerbate hypoxia risks, with Arabian sea show increased stratification and reduced ventilation, while Bay of Bengal freshening trends intensify oxygen loss.

6. Predictive models confirm sea surface temperature and SSS as major dissolved oxygen determinants, with Arabian sea regression model indicating moderate predictive power, whereas Bay of Bengal model underscores sea surface temperature dominant influence.

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Author Credit Statement

Siddharth Srivasatv, Vivek Kumar Pandey, Yaduvendra Singh, and Prabha Kushwaha conducted data analysis and wrote the manuscript. Siddharth Srivasatv contributed to data analysis and interpretation.

Data Availability Statement

The data sets used in this study are publicly available Global ocean analysisv3.6 NEMO (EU, 2023).

Compliance with Ethical Standard

The authors declare that they have no conflict of interest and adhere to copyright norms.

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