

Relationship between coral bleaching and large-scale oscillations in the Lakshadweep archipelago

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Abstract

The coral reef ecosystems in the Lakshadweep Sea are among the least studied due to the dearth of *in-situ* measurements. The objectives of this study were to compare the remote sensing datasets with the available *in-situ* measurements and confirm the reliability of the former for further studies in this region. The study also examines how the sea surface temperature and salinity triggered coral bleaching during El Niño Southern Oscillation (ENSO) /Indian Ocean Dipole (IOD) events. We found that satellite observations of sea surface temperature ($r = 0.94$) and salinity ($r = 0.81$) correlated well with *in-situ* measurements. Such a high degree of correlation enabled us to analyse satellite data for inter-annual variations like ENSO and IOD. In the study area, coral bleaching due to salinity variation was found to be negligible. The study delineates a coral bleaching threshold temperature and the prevalence of such warm waters in the coral environment. Analysis revealed a mass coral bleaching peak during the El Niño event in 2016, with a maximum prevalence of 78 days. Similarly, significant coral bleaching events were observed in 2010 (El Niño; 63 days) and 2019 (PIOD; 56 days). Maximum temperature was noticed during the spring inter-monsoon (March to May). But from 2015, intense warming in the coral region was also noticed in the fall inter-monsoon (October). Combined with global warming, the threat of thermal stress to corals may continue in the long term, which will negatively impact the health of reef ecosystems.

Keywords: Coral reefs, Bleaching threshold, SST, El Niño, IOD, Lakshadweep

1. Introduction

Coral reefs are considered comparable to tropical rainforests in terms of biodiversity, indicating their ecological importance on a global scale (Plaisance et al. 2011; Fisher et al. 2015). Coral reefs play an important role in host significant small-scale and artisanal fisheries, which account for 10% of global fishing production, and thus have great socio-economic importance. The majority of coral reefs are found in tropical latitudes between 22°S and 22°N, where the maximum seasonal variation of ocean temperatures will be within 4–5 °C and by about 30°C on average during the highest day's temperature (Kleypas et al. 1999).

The Lakshadweep Islands are among the least studied coral atolls located at a distance of 200–300 km from the southwest coast of India. Most of the islands' coral reefs are atoll-type, except for the platform type reefs at Androth (Mallik 2017). The total reef area of the Lakshadweep islands is 933.7 square kilometres, which includes a combined lagoon area of 510 square kilometres and a diverse range of flora and fauna can observe in the lagoons on each island (Hoon 1997). In recent decades coral reefs have been under threat due to local population-related pressures and global climate change (Hoegh-Guldberg et al. 2014; Nobi and Dinesh Kumar 2014; Stocker 2014; Kumaresan et al. 2018). Various environmental stressors, such as changes in temperature, increased solar radiation, and alterations in water chemistry, are known to cause coral bleaching. Additionally, physical stressors like sedimentation and increased turbidity can also contribute to coral bleaching (Hoegh-Guldberg 1999). Large-scale coral bleaching events are caused mainly by elevated sea surface temperature (SST) (Li and Reidenbach 2014). According to (Vivekanandan et al. 2008), coral bleaching episodes happen when surface waters become too warm and remain at that temperature for more than 28 days. Endosymbiotic microalgae (zooxanthellae), which normally provide the coral polyps with over 90% of their metabolic needs, are unable to withstand such high temperatures and are therefore expelled from the host (Eladawy et al. 2015).

The geographic setting of the Lakshadweep Islands favour the increase in sea surface temperatures, ultimately leading to coral bleaching (Shenoi et al. 1999). *In-situ* coral reef monitoring via snorkelling or scuba diving gives vital information about reef health at local scales. But, the paucity of resources limits the coverage and repeatability of such monitoring to a small percentage of coral reefs worldwide. Understanding anthropogenic and climate change impacts on coral reefs in remote or inaccessible areas is made possible using remote sensing techniques. Because comprehensive individual surveys may be costly and time-consuming, attempts to broader monitoring of the environmental status of coral reefs (e.g., local or globally) rely on satellites (Rowlands et al. 2012). Although satellites cannot directly monitor the health of coral reef ecosystems, satellite SST data can be used as a metric to indicate where

and when heat stress will cause corals to bleach (Hedley et al. 2016). Since 1980, global SST has been gradually increasing, which has increased in the frequency and intensity of El Niño Southern Oscillation (ENSO), and marine heatwave events (Bellwood et al. 2019). Such warming events have triggered massive coral bleaching (MCBE) and mortality (over 90% of coral reefs) worldwide since 1998 (Podestá and Glynn 2001; Baker et al. 2008; Kleypas et al. 2015; Morrison et al. 2020). Because of weak monsoons, high sea pressure, recurrent winds from the east and southeast, and colder SST in spring and early summer (which may become warmer than typical by late summer), El Niño frequently results in drier conditions (Lough 1994; Risbey et al. 2009). The Indian Ocean Dipole (IOD) has a variety of consequences and contributions to the environmental settings of the region at a large scale (Saji and Yamagata 2003). The Arabian Sea experiences dry conditions and severe increases in temperature during positive IOD episodes, resulting in coral bleaching (Abram et al. 2008; Jayakrishnan et al. 2014). General estimates reveal that approximately 10% of the world's coral reefs have already perished, and about 60% are at risk due to environmental and anthropogenic activities. Here we present an analysis of the SST and salinity variations in the Lakshadweep Sea and how these parameters trigger coral bleaching especially during ENSO and IOD events.

2. Materials and methods

The present study uses observational/satellite sea surface temperature and sea surface salinity datasets for a 12-year period (1st January 2010 to 31st December 2022) to elucidate environmental changes.

2.1 In-Situ measurements

Lakshadweep Islands are located in the Arabian Sea, about 225–450 km away from the southwest coast of India, between 8 °N and 12 ° 3' N latitude and 71 °E and 74 °E longitude (Figure 1). We conducted a total of four CTD surveys in the study area from 2021 to 2022. Two offshore surveys were carried out during cruises in the outer waters of the Lakshadweep islands in July 2021 and November 2022. Additionally, two surveys were conducted in the lagoon habitats at selected sites within the Agatti, Kavaratti, Perumal Par, and Bangaram Islands in January 2022 and December 2022. The selection of these sites was based on the environmental conditions of the lagoon habitats. A table detailing the location of each sampling site can be found in the Supplementary section (Table S.T1). *In-situ* temperature and salinity data have been measured using Seabird 19 plus CTD. This CTD probe can measure depths up to 600m with a temperature accuracy of $\pm 0.002^{\circ}\text{C}$ and a conductivity accuracy of $\pm 0.002 \text{ mS cm}^{-1}$. We utilized five years' 2017–2022 weekly salinity data and daily data of SST from drifting subsurface profiling float (latitude: 11.47°N, longitude: 71.22°E) and NIOT buoy (Latitude:

10.87°N, Longitude: 72.21°E). This data was used to compare and validate data derived from satellite observations.

2.2 Satellite observations

Daily (night-time) SST data with 5 km resolution was retrieved from NOAA Coral Reef Watch (CRW), commonly known as CoralTemp. CoralTemp SST datasets were constructed by combining two related reanalyses (reprocessed) SST products and a near real-time SST product. The CoralTemp SST is one of the finest and most internally consistent daily global SST products ever generated, and included data from 1st January 1985 to the present. Weekly salinity data has been obtained from the Aquarius Level 3 sea surface salinity version 5.0 with a 1-degree resolution from 2011- Aug-25 to 2015-Jun-07, and NASA Soil Moisture Active Passive (SMAP) version 3.0 with a resolution of 70 km from April-2015 to Dec 2021 Daily estimates of surface wind and precipitation datasets were obtained from the ECMWF-ERA-5 (<https://cds.climate.copernicus.eu/>).

2.3 Quantifying agreement between datasets

The *in-situ* measurements at 1 m depth were deemed the best/most reasonable to compare with remote sensing measurements (Thakur et al. 2018). A few metrics were used to assess the relationship between remote-sensing products and *in-situ* measurements. For this, we calculated the Pearson correlation coefficient (r), indicating the relation between the two variables. If the coefficient value lies between + 0.50 and + 1, it is said to be a strong correlation. Next, we calculated the difference between the two measurements (value from the overlapping pixel of the remote sensing product minus the *in-situ* measurement, referred to as "bias"), by which bias's standard deviation (S.D.) and root mean square errors (RMSE) were estimated. We evaluated *in-situ* data with satellite products using the Index of agreement (d-index) by using the ratio between RMSE and the potential error between the two measurements. This index is also dimensionless, with a value that ranges from 0 (no agreement at all) to 1 (perfect agreement), and is sensitive to differences between two measurements. To assess the robustness of the correlation between SST and sea surface salinity (SSS), a Monte Carlo simulation was conducted (Preacher and Selig 2012). This involved generating 20,000 random datasets based on the observed data, while maintaining the same sample size and distribution characteristics. The correlation coefficient was calculated for each simulated dataset, resulting in a distribution of correlation coefficients. From this distribution, a 95% confidence interval was derived to estimate the uncertainty associated with the correlation estimate.

2.4 Indian Ocean Dipole (IOD) and El Niño Southern Oscillation (ENSO)

We used the Dipole Mode Index (DMI) (Saji et al. 1999) for IOD and the Niño 3.4 index for ENSO to study their impact (Rasmusson and Carpenter 1982; Bamston et al. 1997; Trenberth 1997) on coral bleaching events. The IOD Index compares SST anomalies in a box that covers the western (50°E–70°E, 10°S–10°N) and eastern (90°E–110°E, 10°S–0°) Indian Oceans. The Niño 3.4 SST anomaly index is constructed from SST in the Pacific region between 170°W–120°W, 5°S–5°N. The variability of Niño 3.4 in the Pacific region plays a significant role in shaping the climate conditions in the Indian Ocean region; and the Niño 3.4 index for the December–February (DJF) period and the IOD index for the March–June (MAMJ) period is used for the present study. Both indices are based on the Reynolds Olv2 SST study and were collected from the NOAA State of the Ocean Climate webpage (NOAA, 2021).

3. Results and discussion

3.1 Statistical comparison

The statistical analysis revealed the concordance of satellite data with *in-situ* observations. Scatter plots between *in-situ* and satellite-derived SST (Figure 2a) showed a high positive correlation (Pearson correlation coefficient, r) of 0.94, while the correlation coefficient (r) for SSS was 0.81. In both cases, r values were statistically significant (p -value < 0.05). The S.D., mean, maximum, minimum, RMSE, Pearson correlation coefficient, and Index of agreement (d-index) between *in-situ* and satellite data in the study area are summarised in Table 1. The statistical analysis reveal a good agreement between the satellite and *in-situ* measurements. The S.D. bias for SST was 0.2°C. The SST had an RMSE range of 0.2°C, with an index of agreement (d-indices) of 0.96. Similarly, salinity also showed good agreement with *in-situ* measurements. The Index of the agreement for the satellite salinity was 0.84, and with RMSE of 0.38. The Monte Carlo simulation (Figure 2b) analysis also revealed a strong and statistically significant correlation between SST and SSS. The confidence interval for SST ranged from a lower limit of 0.9353 to an upper limit of 0.944, indicating that the true value of SST falls within this range with 95% confidence. This result was further supported by the exact confidence interval, which also showed consistent results with a lower limit of 0.9352 and an upper limit of 0.9444. Similarly, the analysis of SSS yielded a confidence interval with a lower limit of 0.7412 and an upper limit of 0.8616, suggesting that the true value of SSS falls within this range with 95% confidence. The exact confidence interval demonstrated consistent results, with a lower limit of 0.7415 and an upper limit of 0.8618. Overall, these findings indicate that the observed relationship between the variables is unlikely to be due to chance and is likely to be consistent across different datasets.

The results obtained from the both analyses enhance our confidence in the correlation and provide valuable insights into the association between SST and SSS in the study area. These results also justify further analysis using satellite data to understand inter-annual variations in ENSO and IOD and influence of these phenomena on coral bleaching events.

3.2 Hydrography of the Lakshadweep region

In the Lakshadweep Sea, the annual air temperature varies between 25 °C and 35 °C, with humidity above 70% for most of the year. The winds that prevail over the Lakshadweep are predominantly northwest throughout the year, with an average speed of 5–8 ms⁻¹, which peaks from June to August. The Lakshadweep receives the most rainfall during this period, with a total annual rainfall of 1600 mm (Vijaykumar et al. 2014; Sreekesh 2016). The tide in the Lakshadweep Sea is mixed and semi-diurnal, with a maximum range of 1.4 m (micro-tidal). Minimum wave activity was noticed from November to March, while high wave activity was during the southwest monsoon (June–September) period. But the presence of coral reefs dramatically decreases wave activity and provides calm regions inside the lagoon (Prakash et al. 2014). The southeastern Arabian Sea is a dynamic climatic region influenced by the seasonal reversal of surface currents driven by wind patterns. This region experiences multiple surface ocean currents, including the West India Coastal Current (WICC), East India Coastal Current, Winter Monsoon Current, and Summer Monsoon Current (Shankar et al. 2002). Along the southwest coast of India, which includes the Lakshadweep region, the seasonal monsoons play a significant role in determining physical dynamics of the region. During the summer monsoon season, strong upwelling occurs, while downwelling prevails during the winter monsoon. (Smitha et al. 2008; Yi et al. 2018) The downwelling associated with the winter monsoon leads to convective mixing and deepening of the mixed layer (Madhupratap et al. 1996). Notably, the early winter monsoon gives rise to a large anti-cyclonic eddy known as the Lakshadweep High (LH), which spans a diameter of 400 to 500 km and reaches depths of approximately 300 m (Shankar and Shetye 1997). Conversely, during the early summer monsoon, a cyclonic eddy called the Lakshadweep Low (LL) forms at the same location (McCreary Jr et al. 1993). The LH contributes to high SST and a deep thermocline, while the LL promotes lower SST and a shallower thermocline. The Arabian Sea is characterised by distinct water masses with varying temperature, salinity, and depth characteristics. The upper 100 m are dominated by the Arabian Sea High Saline Water (ASHSW), with temperatures ranging from 28°C to 24°C and salinity ranging from 36.7 to 35.3 PSU. Between 200 and 400 m, Persian Gulf Water (PGW) prevails, characterized by temperatures ranging from 19°C to 13°C and salinity ranging from 37.5 to 35.1 PSU (Kumar and Prasad 1999).

The intrusion of low salinity waters from the Bay of Bengal into the Arabian Sea is clearly observed in the data presented in Figure 3(a–e). In November, the study area exhibited high salinity values (>35 PSU), but it was noted that low salinity waters extended into the Arabian Sea up to a latitude of 6°N . However, in December, a patch of low salinity waters (<34 PSU) mixed with the higher salinity waters in the region and expanded to cover the study area, resulting in the entire region displaying a salinity < 35 PSU. By January, the salinity in the study area had dropped further (< 33.5 PSU), and the low salinity water mass had extended even further north. The analysis of SMAP data, capturing the annual variation in salinity from 2016 to 2022 in Agatti Island, also confirms the presence of low salinity waters originating from the Bay of Bengal in the study area. Additionally, the temperature-salinity (T-S) diagram (Figure 3(e)) near the Agatti site indicates water characteristics typical of the Bay of Bengal, with temperature ranging from 25 to 29°C , salinity from 28 to 35 PSU, and sigma-t between 21 and 22 . These findings align with the established understanding that the study area experiences the influx of low salinity waters from the Bay of Bengal during the November to January season (Rao et al. 2014).

Based on the CTD observations, Figure S1(a–d) illustrates the temperature variation along a selected transect off four islands of the Lakshadweep region. The water temperature in these islands exhibits a range between 28.6°C and 31°C . The highest temperature of 31°C is observed at the reef edge of Kavaratti Island. Agatti Island displays higher temperatures in the coastal region, while the lowest temperatures are observed in the reef edge region. On the other hand, Bangaram and Kavaratti Islands exhibit higher temperatures in both the coastal and reef edge stations. Kavaratti Island shows a similar temperature trend pattern as Bangaram Island. Perumal Par Island, on the other hand, displays a uniform water temperature throughout the entire water column. Figure S1(e–h) presents the variations in salinity in the four islands of the Lakshadweep region. The salinity values observed during the study range from 33.2 PSU to 34.9 PSU. Kavaratti Island exhibits the highest salinity value at the coastal station (34.9 PSU), Bangaram Island shows the lowest salinity value of 33.2 PSU.

Figure S2(a–d) displays the variation of ocean temperature along a selected transect in the four islands of the Lakshadweep region in December 2022. The water temperature in the four islands exhibits a range between 28.3°C and 30°C . The highest temperature of 30°C was recorded in Bangaram Island. In contrast, the waters of Perumal Par Island showed a consistent and uniform water temperature throughout the entire water column. Figure S2(e–h) presents the variation of salinity in the four islands of the Lakshadweep region. During the observation period, the salinity values ranged from 34.5 PSU to 35.3 PSU. Kavaratti Island recorded the maximum salinity value at the coastal station (35.3 PSU).

The higher salinity in this region indicates the presence of high saline waters from the Arabian Sea. On the other hand, Bangaram Island exhibited a lower salinity value of 33.2 PSU.

Figures S3 & S4 represent the offshore locations of the study area in July 2021 and November 2022. In both survey periods, the actual depth of each location was 700 m. However, due to the complex bathymetric gradient in the Lakshadweep atolls, the CTD was lowered only up to a depth of 75 m. From the Figure S3(a–h), it is evident that the mixed layer depth in the locations was about 55 m. The maximum temperature recorded at each location was around 29°C, while the minimum temperature was approximately 25°C. The salinity values ranged from 35.2 PSU to 35.7 PSU. In addition, from Figure S4(a–h), it can be observed that the mixed layer depth was below 20 m. The temperature values ranged from 29°C at the surface to 21°C at a depth of 75 m. The D26 was located at approximately 30 m depth. The salinity values ranged from 34.8 PSU to 35.3 PSU, with a maximum of 35.5 PSU observed at a depth of 37 m.

3.2.1 Climatology of the Lakshadweep reef region

The daily climatology of SST and salinity in the Lakshadweep Sea, as shown in Figure 4, exhibited seasonal variation. During the Southwest monsoon (June to September), the SST decreased from 29.5°C to 28.3°C, while the salinity varied from 35.3 PSU to 35.8 PSU. In the fall inter-monsoon (October), SST increased from 27.8°C to 28.5°C but remained unchanged during winter monsoon (November to February). Compared to the fall inter-monsoon (secondary heating period), the SST decreased from January to the first week of March. Further, a warming trend was noticed during the spring inter-monsoon (March to May; primary heating period), and the SST exceeded 30°C. The salinity showed the highest value (35.89 PSU) in August due to the presence of the Arabian Sea high saline water mass (Kumar and Prasad 1999). While during the winter monsoon, the salinity was minimum (33.9 PSU) in the Lakshadweep Sea region, which may be due to the intrusion of low salinity water from the Bay of Bengal (Rao et al. 2014). According to (Guan et al. 2015) the thermohaline tolerance limit of coral is 29.6°C and 28.7–40 PSU, respectively. In the Lakshadweep region, the inter-annual variation of SST is from 27.5 to 30.6°C and exceeds 29.6°C during the primary heating period. In contrast, salinity variation is minimum (33.9–35.89 PSU) and within the tolerance limit. Therefore, warm temperature periods can strengthen coral bleaching events compared to the salinity variation.

3.3 Effects of ENSO and IOD on SST and bleaching threshold

El Niño and positive IOD events can have a significant impact on coral (Saji and Yamagata 2003; Claar et al. 2018). During El Niño events, there is a notable increase in SST across the equatorial Pacific, leading to above-average temperatures. This warming is associated with changes in

atmospheric circulation patterns, resulting in widespread effects on climate, including shifts in rainfall patterns and the occurrence of extreme weather events in various regions around the world (Lough 1994; Risbey et al. 2009). Positive IOD leads to warmer SST in the western Indian Ocean, influencing atmospheric conditions and precipitation patterns in the surrounding regions. El Niño events are more common than IOD events, and they tend to be more severe. The 1997–98 El Niño event was one of the strongest on record, and it caused widespread coral bleaching and mortality around the world (Podestá and Glynn 2001; Vargas-Ángel et al. 2001). While positive IOD events are less common than El Niño, they can also cause severe coral bleaching. Several previous studies in the Lakshadweep region have identified the association between elevated SST induced coral bleaching and the teleconnection of El Niño and positive IOD events (Arthur 2000; Ahmad et al. 2011; Jayakrishnan et al. 2014). These studies have found that during these climate events, the SST in the region increases, which eventually leads to coral bleaching. During the last decade (2010–2022), there have been two El Niño events (2010, 2016) and one positive IOD event (2019) (Figure 5). Co-occurrences of IOD with El Niño are rare in observations (Meyers et al. 2007; Santoso et al. 2012).

Intense warming of the sea surface can cause coral bleaching, leading to coral death and reducing coral cover (Kumagai and Yamano 2018). The bleaching threshold approach estimates the number of days corals exceed a specific temperature limit. The term ‘bleaching threshold’ has been calculated as SST being 1°C higher than the maximum monthly mean SST for that location (<https://coralreefwatch.noaa.gov/>), which is widely used to detect heat stress in coral reefs and acts as a proxy for coral bleaching (Glynn and D’croz 1990). The results (Figure 6 upper panel) showed the persistence of warm waters above the coral bleaching threshold during the fall inter-monsoon (primary heating period) compared to the rest of the year. Further analysis revealed that during the years 2010, 2016, and 2019, the study area experienced the maximum durations with SST above the bleaching threshold. It also showed an increasing trend, indicating that the ocean temperature is increasing rapidly compared to the previous decades. In addition to that, the number of days exceeding the bleaching threshold in these years was significantly higher than in other years (Figure 6 lower panel). In the year 2016 the corals around the Lakshadweep islands were exposed to temperatures above the bleaching threshold limit for 78 days, and showed intense bleaching. Similarly, in 2010, the water temperature in this region was above the bleaching threshold for more than two months (63 days), and in 2019, it was for 56 days. During 2012 and 2013, warm waters persisted in the coral environment for less than two weeks (10 and 13 days, respectively). Since 2014, the study area has consistently encountered warm water exceeding the bleaching threshold for more than 30 days annually, which would exert significant stress on the resident corals.

Unprecedented warming of waters with decreased wind speed and precipitation (Figure 7) was noticed during 2010, 2016 and 2019. The year 2010 was considered an El Niño year, Figure 7(a–b) depicts how where intense warming above the bleaching threshold (0.5 to 2.8 °C) persisted for 63 days (The third week of March to the first week of June). Throughout this period, there was a noticeable decrease in wind speed ($<1.37 \text{ ms}^{-1}$ on average). Moreover, the rate of precipitation was exceptionally low ($<0.2 \text{ mm}$). The cooling of the water column by 2°C was noticed during the summer monsoon, and a marginal increase in wind speed and precipitation was noticed. This was followed by the fall inter-monsoon, when warming was noticed but SST did not reach the coral bleaching threshold. The year 2016 is considered the strongest El Niño year of the decade and witnessed the third mass coral bleaching in the 21th century (Idrees Babu and Kumar 2016; Head et al. 2019). A maximum of 3°C exceeded the bleaching threshold and lasted for more than 60 days at 2°C during the primary heating period (Figure 7c–d). The wind speed and precipitation rate also showed conditions favourable for the elevation of SST. The year 2019 stands out as the strongest IOD ever recorded in history (Ratna et al. 2021; Shi and Wang 2021), and it negatively affected the coral environment. During this year, a variation of 0.5–1.5°C of stress level was observed, which lasted for more than 40 days. After the last week of May, the temperature decreased below the bleaching threshold, coinciding with the onset of summer monsoon conditions over this region, as noticed in the higher wind speed ($>15 \text{ ms}^{-1}$) and rainfall ($>25 \text{ mm}$) (Fig 7 e–f).

The SST and SSS satellite products are typically suitable for monitoring offshore, and broad geographic regions; these may not always be accurate for coral reef ecosystems which occur in relatively shallow water (McClanahan et al. 2007; Castillo and Lima 2010; Stobart et al. 2015). Earlier comparisons of remote sensing SST datasets with *in-situ* temperature measurements in various geographical regions showed considerable discordance (Lathlean et al. 2011; Wu et al. 2016; Thakur et al. 2018). However, our study reveals a significant positive relationship between SST satellite products and *in-situ* measurements. Over the last 100 years, the SST in tropical regions has increased by nearly 1°C, and it is now increasing at rates of 1–2°C per century and also If the present rate of global warming continues, the coral reefs may diminish totally over the next 20 to 50 years (Hoegh-Guldberg 1999). Since 1989, 29 widespread bleaching events have occurred in Indian coral reefs (Vivekanandan et al. 2008, 2009). A 30-year SST record (1966–1995) concluded that the association between threshold SST and bleaching is area-specific (Winter et al. 1998). The Lakshadweep Islands are the only atoll reefs in India, and they are home to highly diverse coral reefs. Increase in SST poses a severe threat to these fragile ecosystems. Climatological variations in the salinity were found to be within the tolerance range (28.7–40 PSU) of corals. In a global warming scenario, SST over this

region during the primary heating period exceed the coral bleach limit (29.6°C), but the temperature remained below the ‘bleaching threshold’ during the secondary heating period. We also found that whenever the occurrence of ENSO or positive IOD induced an increase in SST, it resulted in intense coral bleaching events. Various studies have associated bleaching incidents with global warming and climate change (Glynn 1991; Sebens 1994; Hoegh-Guldberg 1999; Hughes et al. 2003; Sheppard 2003; Donner et al. 2005; Hoegh-Guldberg et al. 2007). The present study showed that since 2014, the warm waters above the bleaching threshold has persisted for more than 30 days per year in the primary heating period in the Lakshadweep atolls. This trend will be expected to continue in the coming years due to the combined effect of global warming and climate change, and this may cause the SST variability, and more bleaching events may also occur during the secondary warming period.

4. Conclusion

The present study illustrates that remote sensing data on SST and SSS, correlate well with *in-situ* measurements and can be used for future research. The SST variations are one of the factors influencing coral reef ecosystems, including the physical and chemical properties of the coral environment, as well as the distribution of flora and fauna. Coral bleaching events occur when surface waters temperatures surpass the threshold for bleaching and temperatures remain elevated above this threshold for more than 28 consecutive days. Our analysis indicates that the years 2010, 2016, and 2019 witnessed the prolonged prevalence of warm water around the reefs, with 63, 78, and 56 days respectively, leading to severe coral bleaching. Upon examining the decadal variability SST from 2010 to 2021, we found that since 2014, the SST exceeded the coral bleaching threshold for an average of 30 days per year during the primary heating period (March–May). The maximum duration with persistent temperatures above bleaching threshold was observed during ENSO/PIOD years. Additionally, we identified a significant increase in the duration with temperatures above bleaching threshold during the primary heating period in recent years, suggesting substantial warming of SST in the Lakshadweep region compared to the previous decade. This warming trend may be attributed to global warming, further exacerbating the seasonal warming in the Lakshadweep region. If the trend of increasing SST persists, the prolonged prevalence of high SST can result in extreme coral bleaching events and severe impacts on coral reef ecosystems. This study also surmises that during the secondary heating period, the temperature remained below bleaching threshold for coral reefs, while it also detected an increasing SST during this season in recent years. Coral bleaching is a significant threat to coral reefs worldwide, and the increasing trend in SST due to climate change poses a significant risk to these ecologically and economically important ecosystems. It is essential to monitor and understand

bleaching thresholds and their implications for coral reefs in order to develop effective management strategies to protect these valuable ecosystems.

Acknowledgements

The authors of the study are grateful to the Council of Scientific & Industrial Research (CSIR) for funding the project MLP 2013, and to the Director and Scientist in Charge of the National Institute of Oceanography in Goa and Kochi for providing facilities throughout the paperwork. Also, we thank the Department of Science and Technology (DST) in Lakshadweep and REEF NGO in Lakshadweep for their support in conducting the field survey and express acknowledge for the participation of the boat's crew. We wish to record a special thanks to the staffs who are working on the project MLP 2013.

Author contribution

Ravikumar C Nair managed the field survey, data analysis, and writing of the manuscript. Muraleedharan K R identified the problem, field survey, analysis, interpretation of the data. Ravikumar C Nair, and Abdul Azeez S were involved in downloading data and preparing the figures. Dinesh Kumar P K administered the project and contributed to discussion. All authors reviewed and approved the final manuscript.

Funding: The study was funded by the Council of Scientific & Industrial Research (CSIR), India and CSIR- National Institute of Oceanography, India

Data availability: The satellite data used in this study can be accessed freely from their respective websites, and the field survey data can be obtained by contacting the corresponding author, Muraleedharan K R, upon reasonable request.

Declarations

Ethical statement: This article does not contain any studies with human participants or animals performed by any of the authors.

Consent statement: For this type of study, formal consent is not required.

Conflict of interest: The authors declare no competing interests.

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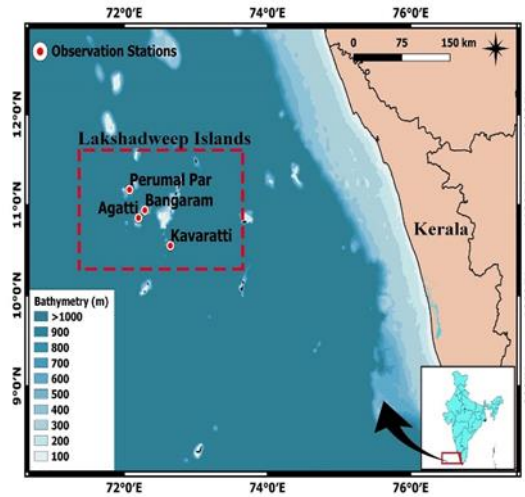


Figure 1. Map of the Lakshadweep islands (Perumal Par, Bangaram, Agatti and Kavaratti) showing the observation stations

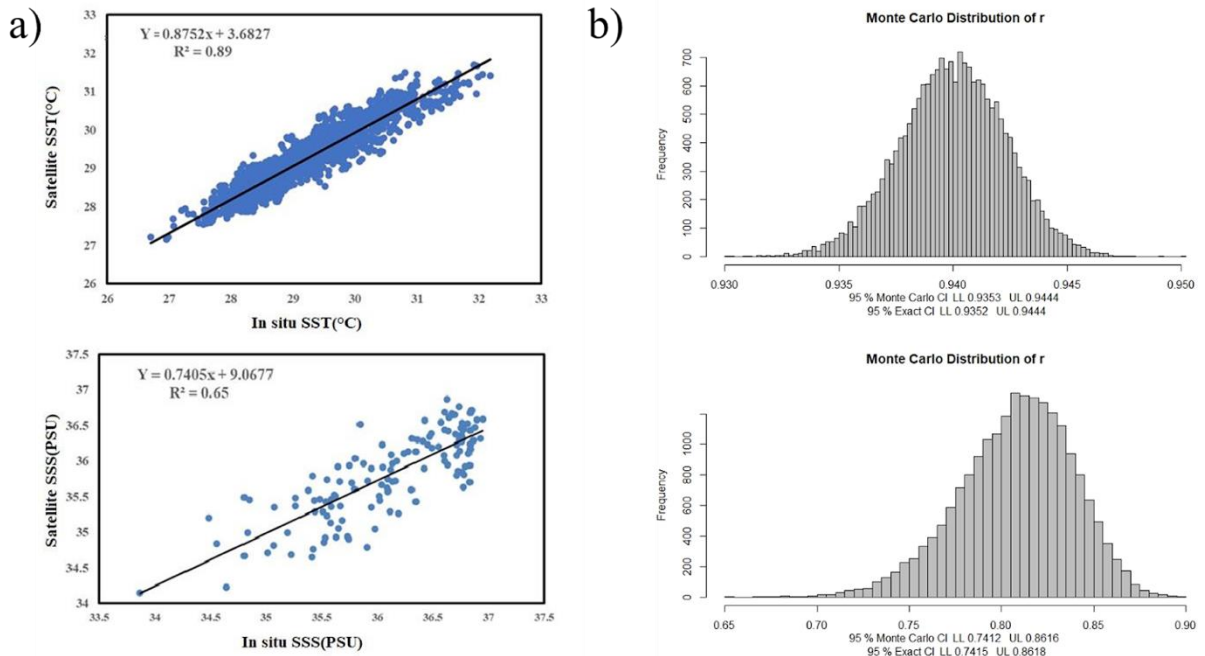


Figure 2. (a) Scatterplots of Satellite SST/SSS and In-situ SST/SSS, and (b) Monte Carlo Distribution of SST and SSS

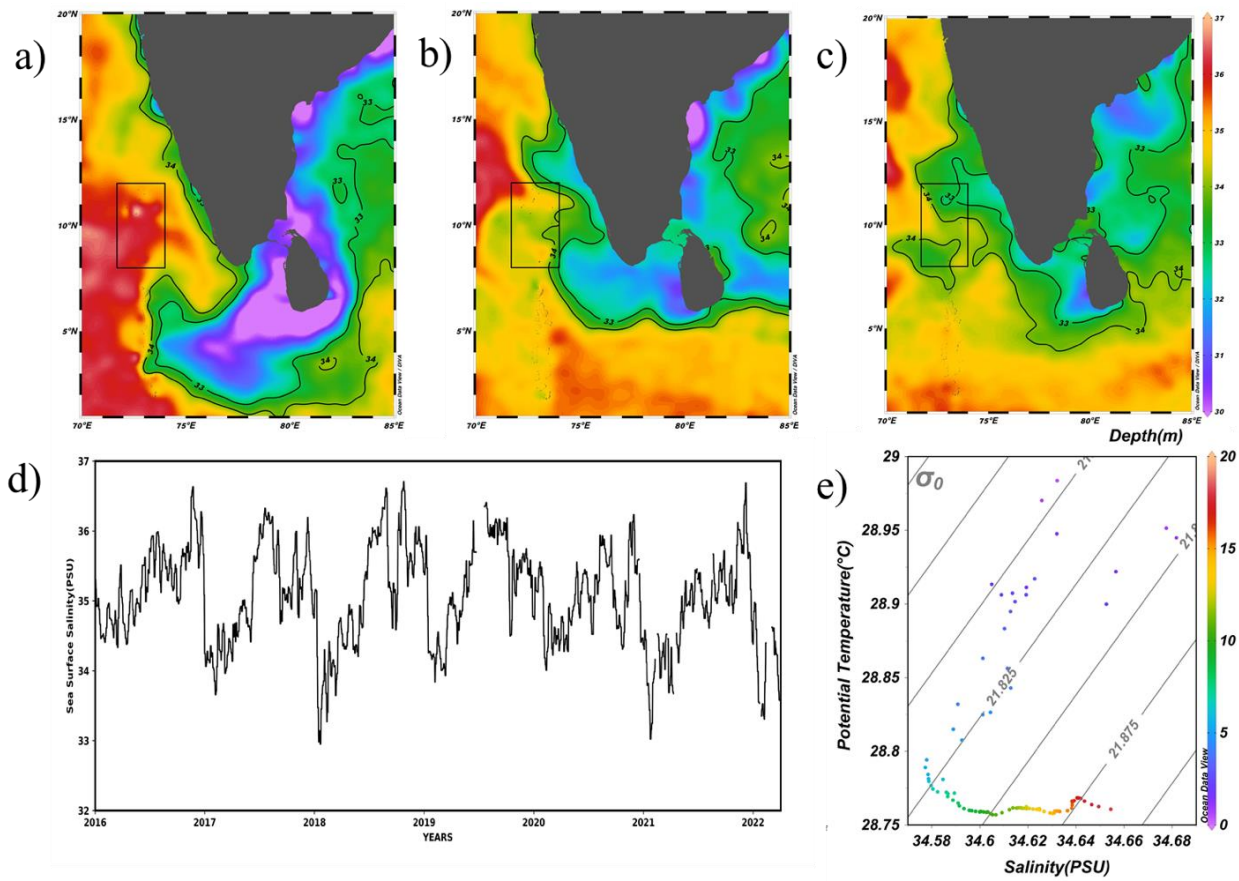


Figure 3. (a-c) Surface plot of SMAP SSS for November 2021-January 2022, (d) Annual Variation of SSS in the Lakshadweep region, and (e) T-S Diagram of January 2022 Survey.

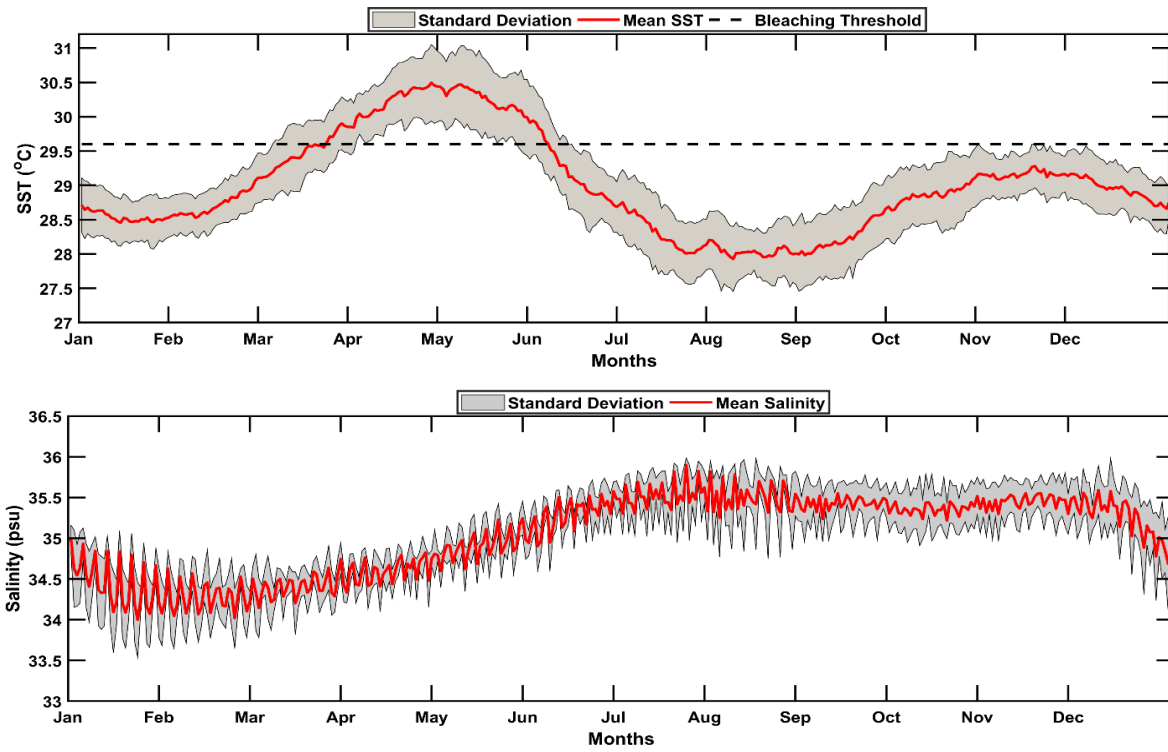


Figure 4. Daily climatology of SST ($^{\circ}\text{C}$) and salinity (PSU) in the Lakshadweep region (Latitude $9\text{--}12^{\circ}\text{N}$ and Longitude: $71.5\text{--}74^{\circ}\text{E}$)

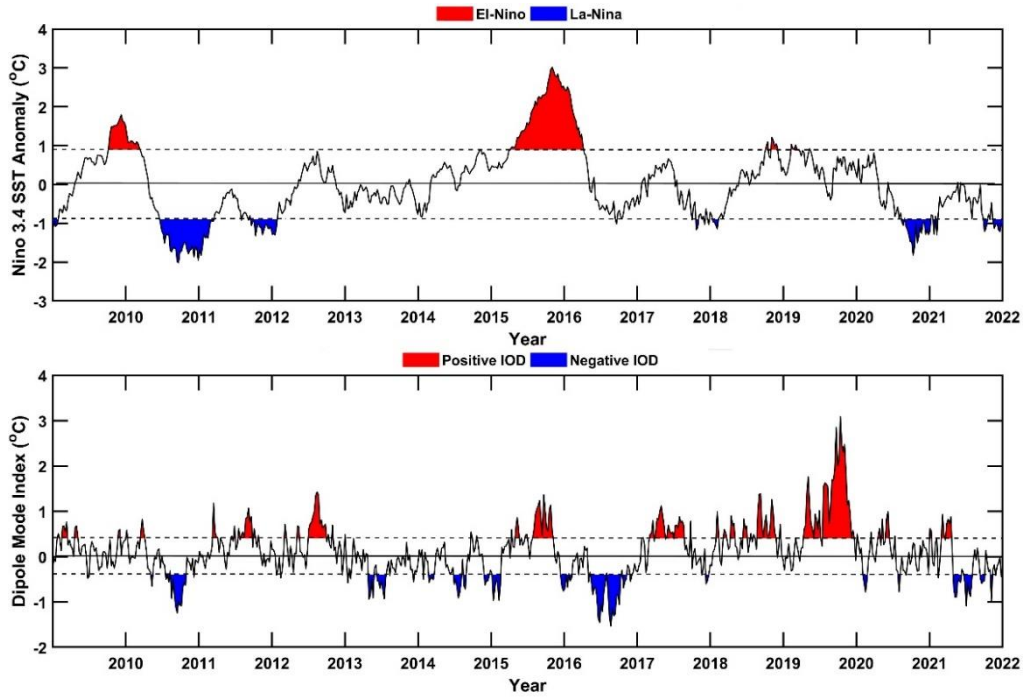


Figure 5. Niño 3.4 Index and Dipole Mode Index (DMI) (2010–2022)

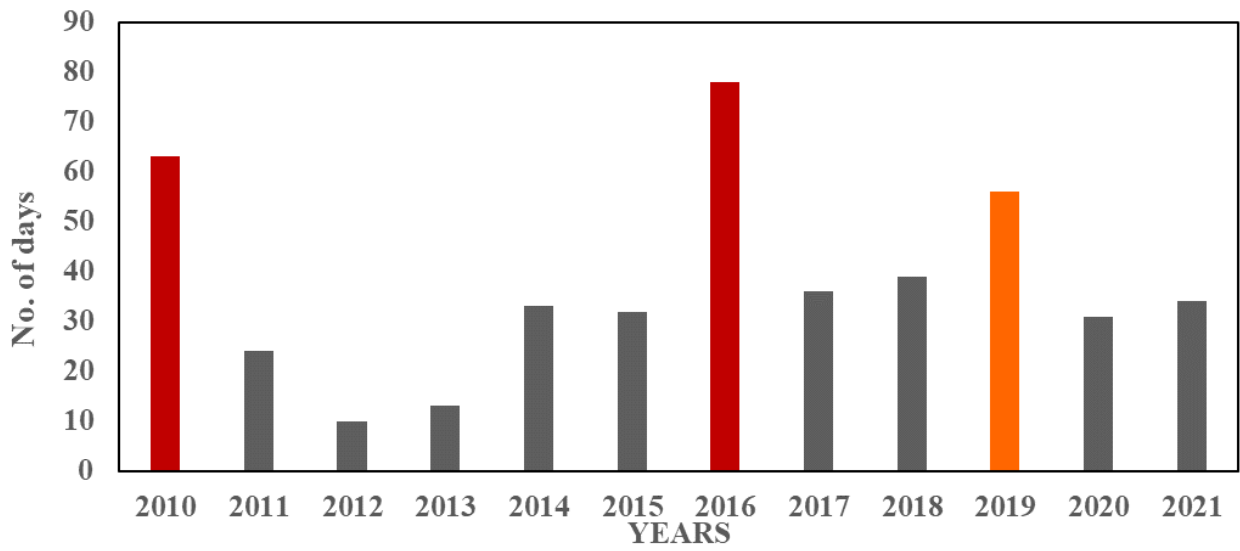
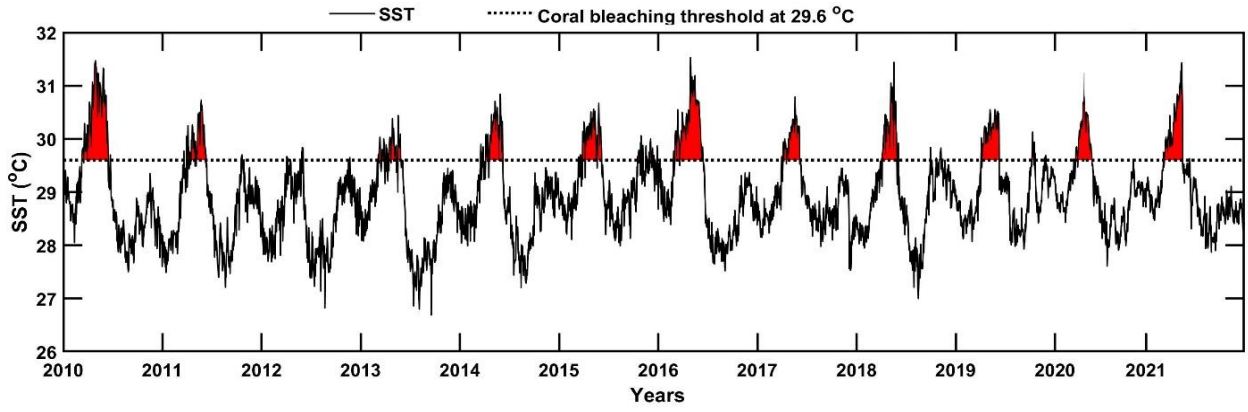


Figure 6. Decadal variation of SST (upper panel), total number of days corals spent above the threshold temperature (lower panel) from 2010 to 2021

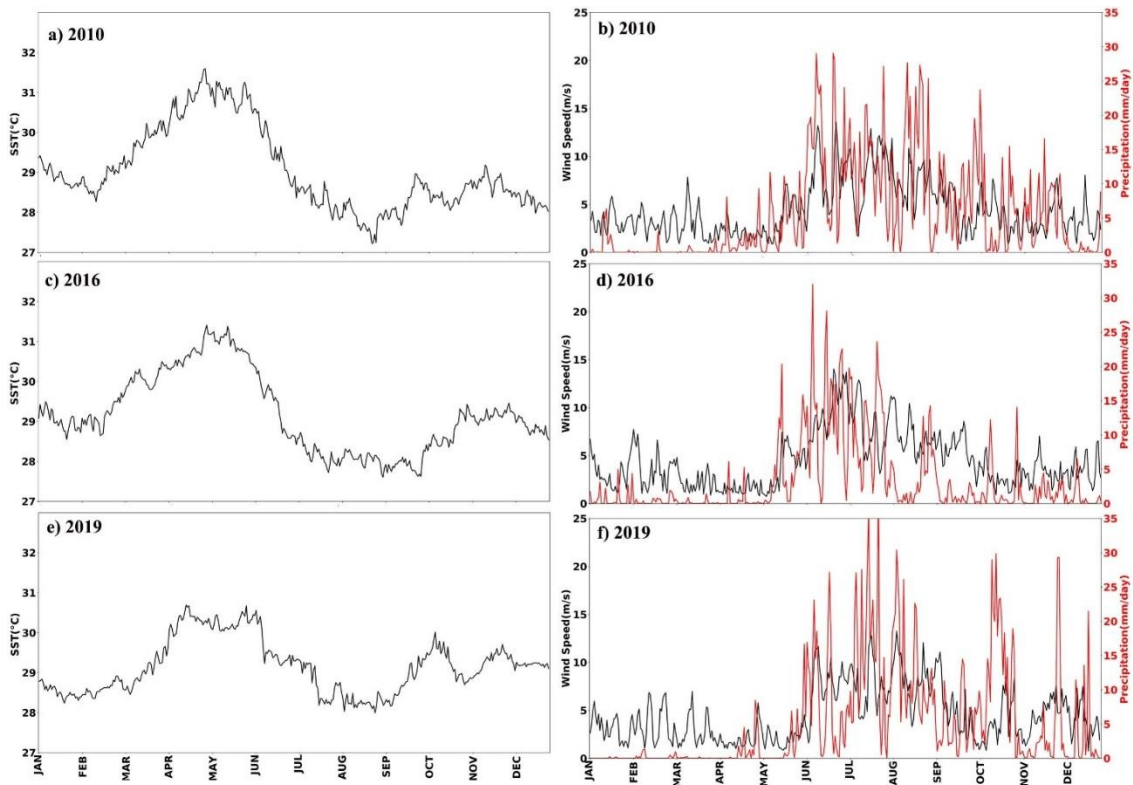


Figure 7. (a-f) Variation of SST, wind speed and precipitation in ENSO and IOD years (2010, 2016 and 2019)

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Table 1. Results of statistical analyses between *in-situ* and satellite data in the study area

	SST	SSS
Mean	29.17	35.8
Minimum	27.14	33.83
Maximum	31.6	36.87
Pearson correlation coefficient(r)	0.94	0.81
RMSE	0.29	0.38
SD Bias	0.28	0.3
Index of Agreement	0.96	0.84

Supplementary Figures

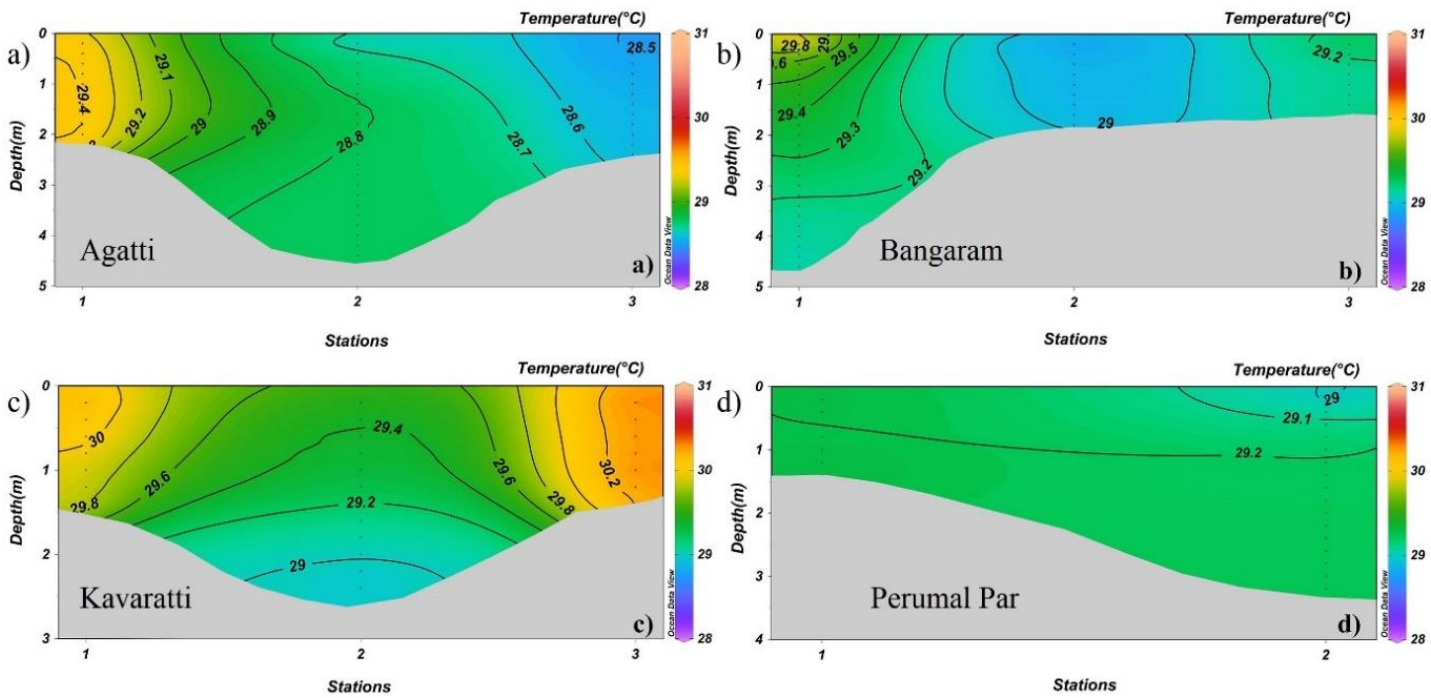


Figure S1 (a-d) variation of temperature along stations in Lakshadweep Island in January 2022

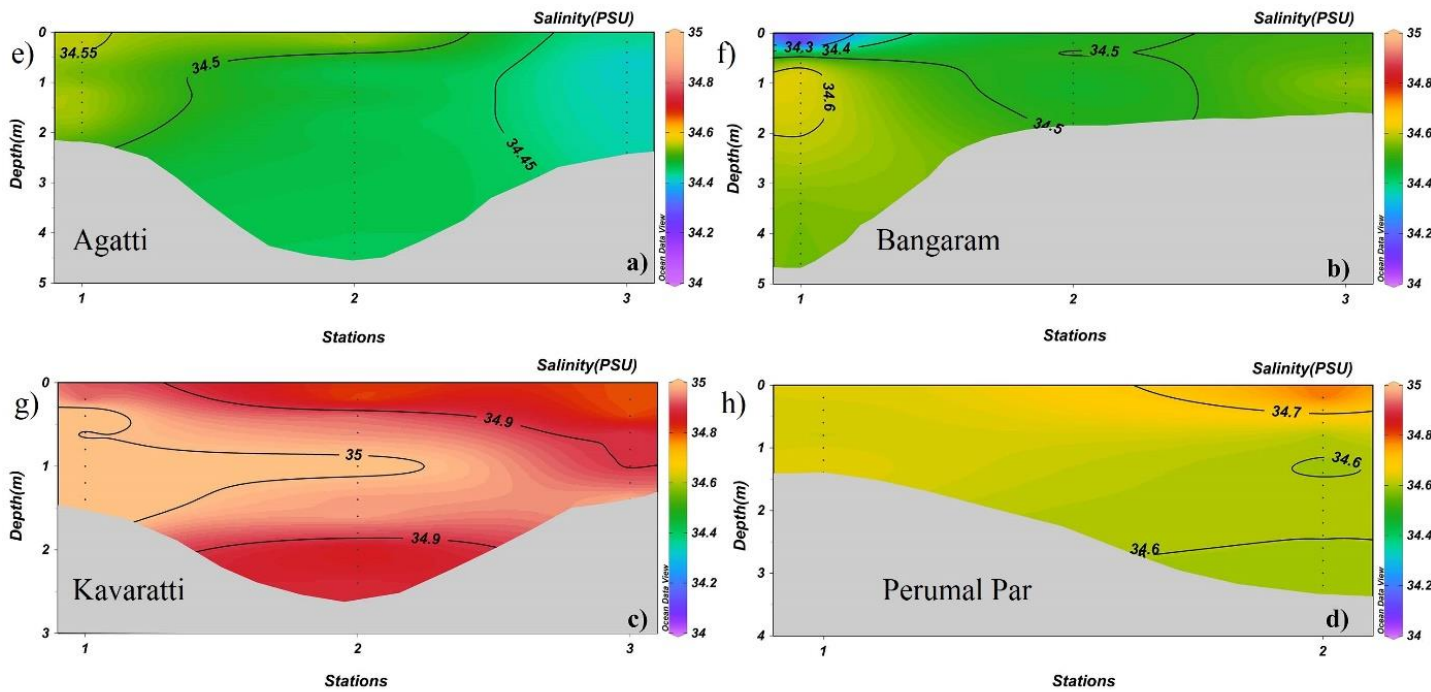


Figure S1 (e-h) variation of salinity along stations in Lakshadweep Islands in January 2022

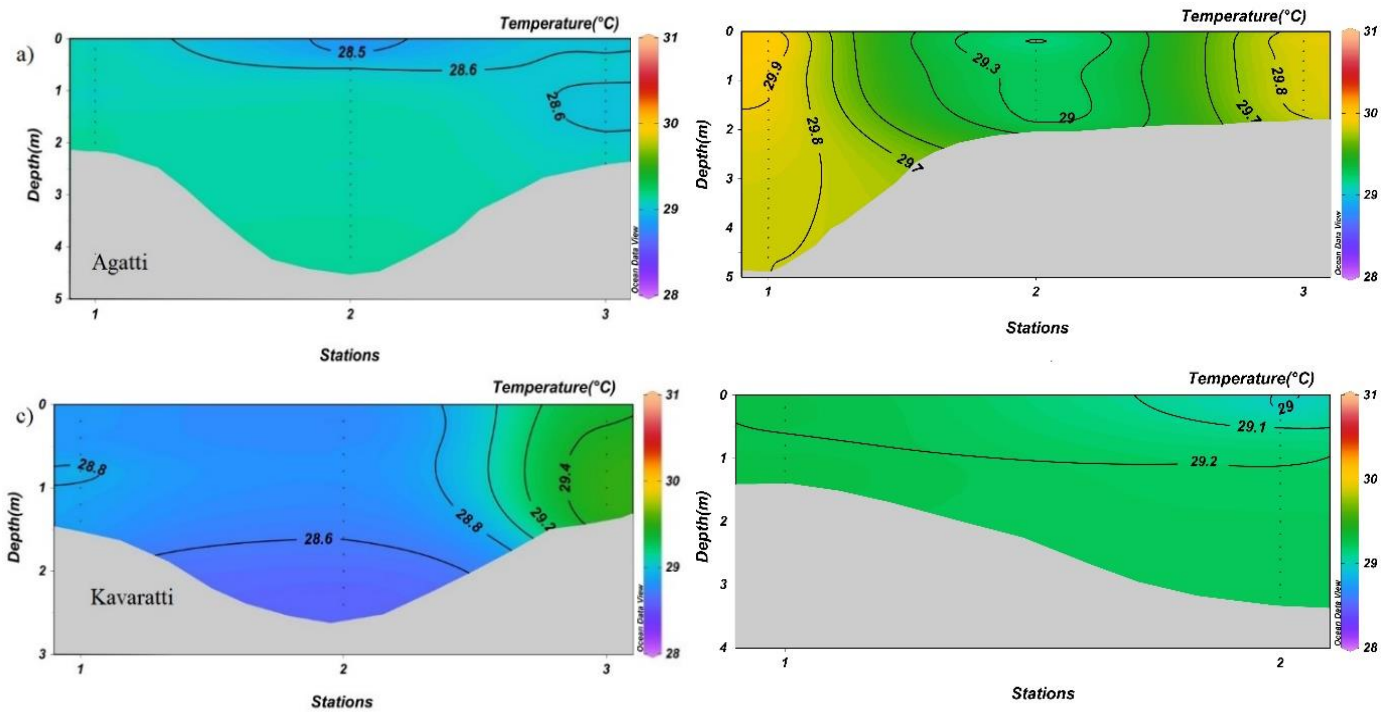


Figure S2 (a-d) variation of Temperature along stations in Lakshadweep Islands in December 2022

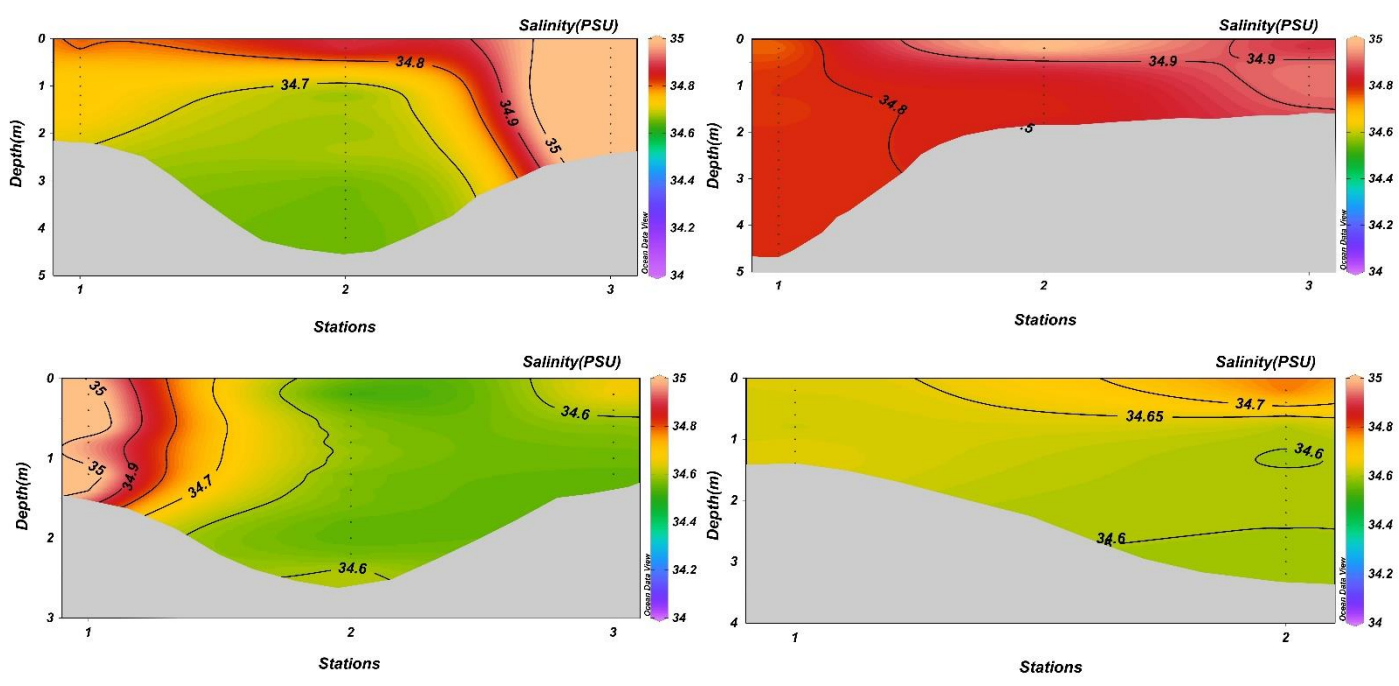


Figure S2 (e-h) variation of salinity along stations in Lakshadweep Islands in December 2022

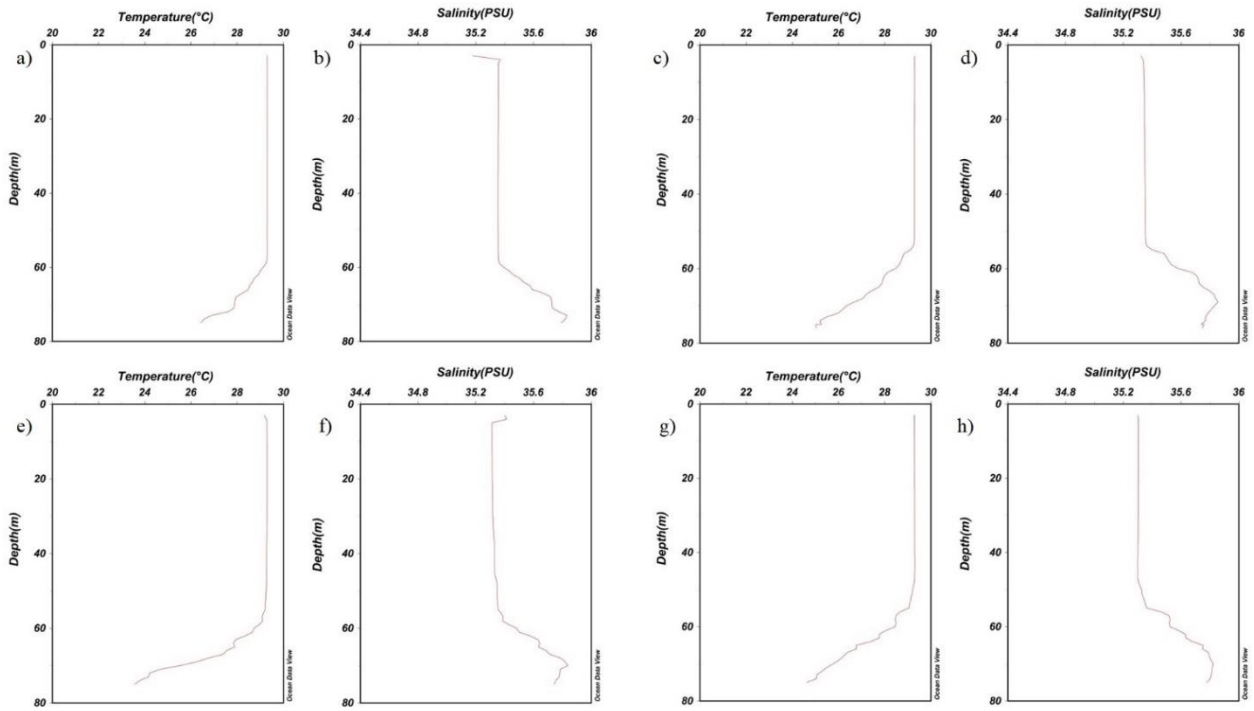


Figure S3 (a-h) Vertical variation of Temperature and Salinity along stations in Kavaratti Islands in July 2021

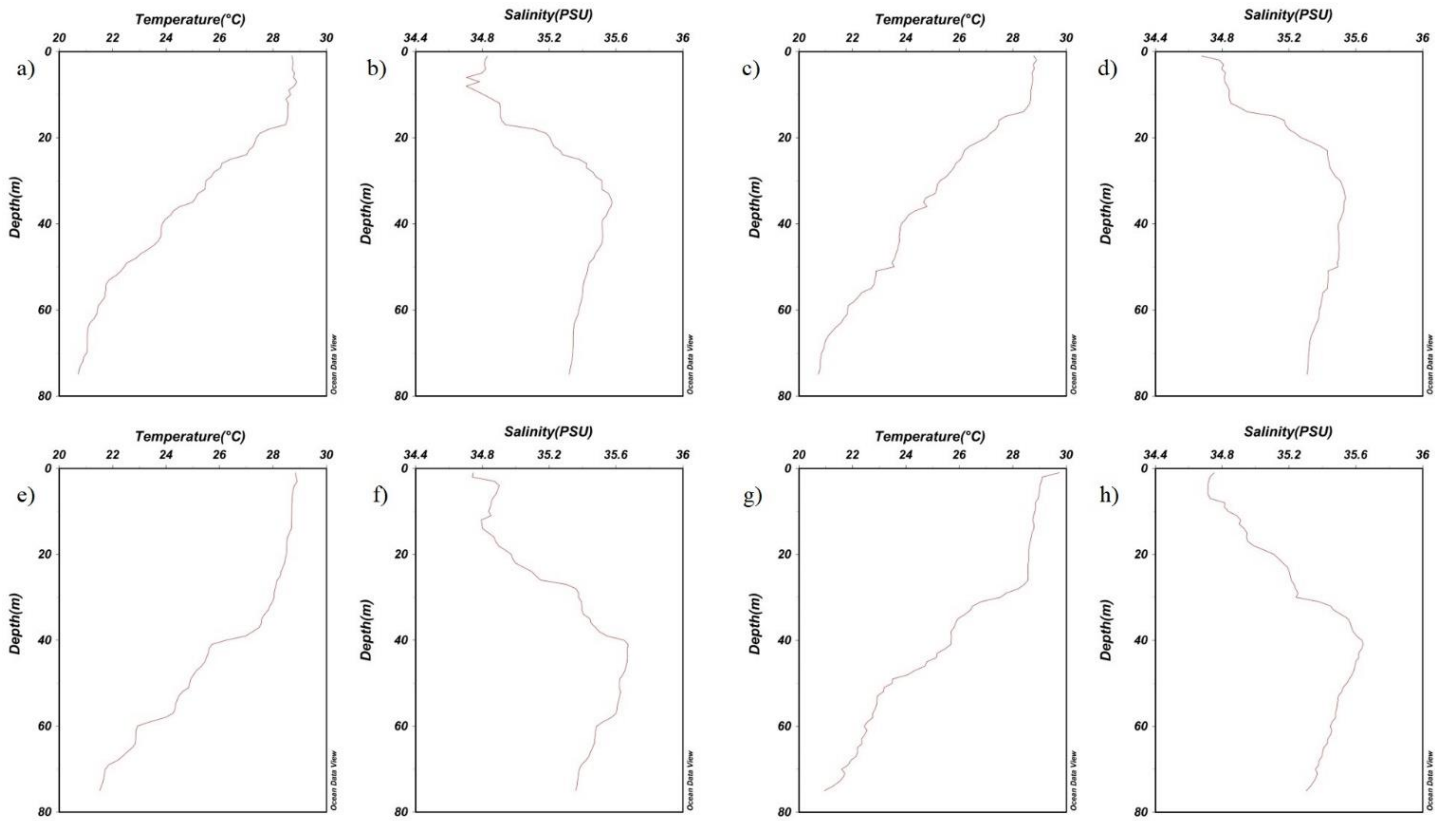


Figure S4 (a-h) Vertical variation of Temperature and Salinity along Four stations in Agatti Islands in November 2022

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Table S.T1 – Details of sampling Locations at Lakshadweep waters

Survey Type	Locations	Stations	Latitude(N)	Longitude(E)
Lagoon	Agatti	1	10.845	72.1839
		2	10.8489	72.1718
		3	10.8505	72.16
	Kavaratti	1	10.56119	72.63114
		2	10.56315	72.62742
		3	10.54848	72.61683
	Bangaram	1	10.94225	72.28905
		2	10.92709	72.28996
		3	10.92175	72.29358
	Perumal Par	1	11.20169	72.09487
		2	11.15421	72.086
	Off Shore	Kavaratti	1	10.576823
2			10.570325	72.606155
3			10.518648	72.612061
4			10.590944	72.660133
Agatti		1	10.79438	72.15553
		2	10.79542	72.15274
		3	10.87158	72.13668
		4	10.91565	72.1765