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# A two-decade remote sensing assessment of sea surface temperature trends in Pakistan's exclusive economic zone

Afsheen Ashraf[1], Anila Kausar[1*], Asad Maqsoom[1], Ghuffran Saeed[1], Amrin Hina Khan[1], Altaf Hussain Lahori[2], Yuliia Kravchenko[3], Mykola Andrienko[3], Petro Gaman[3], Oksana Boiko[3]

[1] Department of Geography, University of Karachi, 75270 Karachi, Pakistan
[2] Department of Environmental Sciences, Sindh Madressatul Islam University Karachi, 74000Karachi, Pakistan
[3] Civil Protection Research Center, Institute of Scientific Research on Civil Protection of the National University of Civil Protection of Ukraine, Kyiv, Ukraine
* Corresponding author's e-mail: anilak78@yahoo.com

## ABSTRACT

Climate-induced changes in sea surface temperature (SST) have become an important indicator for assessing marine environmental variability and its ecological consequences. This study investigated seasonal and interannual SST variability within Pakistan's exclusive economic zone (EEZ) using moderate resolution imaging spectroradiometer (MODIS) satellite observations acquired between 2002 and 2022. The analysis focused on five representative months (January, March, May, August, and October) to characterize seasonal thermal variability, compare decadal changes, and evaluate temporal patterns using linear regression and the non-parametric Mann–Kendall trend test. The results revealed distinct seasonal differences in SST variability across the study period. The highest SST values were consistently observed during May and August, while January represented the coldest conditions. Over the 20-year observation period, SST changes reached 1.00 °C in January, 0.90 °C in March, 1.53 °C in May, 1.50 °C in August, and 1.32 °C in October, with an overall average change of 0.52 °C. Decadal comparison indicated enhanced thermal variability during 2012–2022, particularly in January. Statistical analyses showed that significant temporal changes were limited to specific thermal indicators: March exhibited significant decreases in annual maximum SST and temperature difference, whereas August showed a significant increase in annual minimum SST. Most remaining variables displayed substantial interannual variability without statistically significant monotonic trends. The findings indicate that SST variability within Pakistan's EEZ is season-dependent and cannot be adequately described by a uniform warming pattern. By combining long-term satellite observations with statistical trend assessment, this study provides one of the first comprehensive evaluations of seasonal and decadal SST variability for Pakistan's EEZ, helping to address the limited availability of long-term regional assessments. Although the analysis was based on representative seasonal observations rather than continuous monthly records, it establishes a valuable baseline for future investigations of thermal variability and contributes scientific evidence to support marine environmental monitoring, climate-change assessment, and sustainable management of Pakistan's coastal and marine ecosystems.

**Keywords:** climate change, sea surface temperature, MODIS, exclusive economic zone, Arabian Sea.

## INTRODUCTION

Earth's surface is covered mostly with oceans i.e., 71%. Compared to continents, oceans are the main constituent of Earth's surface (Turbuck, 1997). Pakistan lies in the Northern Hemisphere, where the percentage of continental land is higher than water surfaces, the land-water heat contrast is thus sharp at Pakistan's coastal area (Ali, 2023). 990km coastline (Rabbani et al., 2008); making Pakistan fortunate enough, in terms of its length (Ali 2023). Sea surfaces are dynamic they take time to become warm and vice versa. The reason is water's mobility and transparency. Apart from these natural characteristics, it has been observed that due to global warming, the oceans are getting warmer (National Geographic, 2023). Near the surface, an increase in average air temperature has been an international phenomenon for around two centuries (Brittanica, 2024). Since the industrial revolution, air temperature over the Earth has been rising (NASA, 2024). Moreover, in recorded history, the last decade is the warmest (Figure 1).

Oceans are bodies of heat storage on a large scale. Heat is absorbed by water layers of the surface penetrating the deep ocean and circulated across the deep ocean basins called ocean currents (Copernicus, 2024).

Approximately 28% of the world's population's homes are along coasts (IPCC, 2024). Therefore 1 quarter of livelihood is directly influenced by the weather and climate variations due to the ocean waters' warmth. The Arabian Sea is connected with the Indian Ocean (Ali, 2023); a comparatively large water reservoir. The Arabian Sea has a total area of 3,862,000 square km with 2.734 meters mean and 5.803 meters maximum depth (Brittanica, 2024). The existing study encompasses the exclusive economic zone (EEZ) of Pakistan. The overall area is 50,000 km$^2$ after adding continental shelf zone (NIO, 2024). Sea surface temperatures (SST) are thus an important indicator for monitoring climate change (Ali, 2023). The standing investigation is monitoring SST over the exclusive economic zone of Pakistan through remote sensing. Obtaining information from a distance is remote sensing (Earth Data, 2024). MODIS (moderate resolution imaging spectroradiometer) has been used to analyze SST for the study. MODIS has 36 discrete spectral bands that cover almost every point on Earth's surface every one to two days with a swath of 2,330 km wide (NASA, 2024). The objective is "to monitor the historical variations in the SST through analysis of MODIS satellite product of SST during the study period over EEZ" on the available data i.e., 2002–2022. The hypothesis is; that surface temperatures of the sea are progressive. The oceans cover over 70% of the Earth's surface, significantly influencing weather, climate, and human activities. Coastal areas are attractive for tourism and contribute to the GDP. Oceans serve as a source of minerals and petroleum but are also susceptible to climate change. Recent research has highlighted the substantial impact of ocean depths on driving climate change and reshaping the Earth's ecosystem (Azmi et al., 2015). Understanding SST is crucial for monitoring marine and coastal ecosystem health and modeling regional and global weather patterns Akbari et al. (2017). The Terra and Aqua satellites, integral parts of the NASA Earth Observing System, are equipped with advanced sensors designed to measure the climate system precisely. These satellites provide crucial SST data and offer various products suitable for diverse research applications. Covering 70% of the Earth's surface, they are vital in assessing ocean climate change. Since their launch, NASA has consistently delivered global SST from MODIS on a daily to decadal basis, supporting various atmospheric and oceanic studies (Dong et al., 2011). The Moderate Resolution Imaging Spectroradiometer (MODIS), launched by NASA in December 1999 onboard Terra and in May 2002 onboard Aqua, represents a significant advancement in imaging technology Koner and Harris (2016). The exclusive economic zone of Pakistan offers a valuable opportunity to study the impact of climate change in coastal areas, particularly in Sindh and throughout Pakistan.

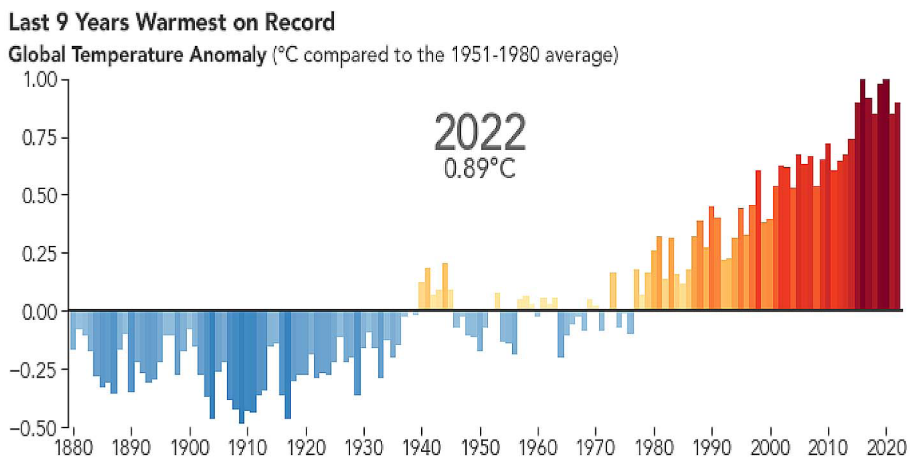


**Figure 1.** Temperature changes 1880–2020 (NASA, 2024)

This research can enhance our understanding of ocean-related disasters such as cyclone formation in the Arabian Sea. Additionally, sea surface temperature (SST) is a critical parameter for monitoring the health of marine and coastal ecosystems and is essential for regional and global weather modeling (Azmi et al., 2015). Leveraging satellite remote sensing can provide valuable insights into ecosystem changes on a larger scale and enable a more comprehensive risk assessment process at provincial, national, and continental levels (Maier et al., 2024).

Researchers have made significant progress in mapping various crucial elements of the marine environment from space. Satellite remote sensing is the most reliable method for accurately measuring ocean-wide sea surface temperatures on a daily to decadal scale (Zhang and Yin, 2023). Satellite sensors provide data for oceanographic and climate models, aiding in forecasting fisheries and aquaculture management. Active and passive satellite remote sensing can measure variables at the ocean surface, such as surface roughness, wave height, suspended particulate matter, SST, Sea Surface Salinity (SSS), and ocean color (Tyagia et al., 2017). Ecological research has made significant strides in utilizing digital and satellite technologies, particularly remote sensing tools. There has been a strong focus on improving satellite-derived SSTs, given their crucial role in studying climate, weather, and oceans (Ditri et al., 2018).

The MODIS on the Terra and Aqua satellites has provided valuable data on global sea-surface temperatures for over a decade. Understanding sea surface temperatures is crucial for gaining insights into the climate system and its impact on coastal areas and ocean-related disasters like cyclones in the Arabian Sea. Studying local sea surface temperature changes is important for understanding potential impacts and developing effective predictive methods (Kilpatrick et al., 2015). SST monitoring over the EEZ of Pakistan is crucial due to its implications for climate studies, marine biodiversity, and fisheries management. Recent studies have also demonstrated the growing applicability of remote sensing techniques for environmental monitoring and water resource assessment in Pakistan (Khan and Lahori, 2024). The EEZ, which extends approximately 290,000 km$^2$ in the Arabian Sea, is categorized by exclusive oceanic phenomena that pointedly affect local ecosystems and economies. Although previous studies have demonstrated the usefulness of satellite-derived SST products for climate and oceanographic applications, few studies have systematically evaluated long-term SST variability specifically across Pakistan's exclusive economic zone using a consistent multi-decadal dataset. Consequently, important questions remain regarding the magnitude, seasonal variability, and long-term evolution of SST within this region.

Despite the increasing availability of satellite-derived SST products, comprehensive long-term assessments of SST variability over Pakistan's EEZ remain limited. Previous studies have primarily focused on the Arabian Sea at broader spatial scales or on specific coastal sectors, whereas systematic evaluation of multi-decadal SST variability across the entire Pakistani EEZ has received comparatively little attention. Furthermore, limited information is available regarding the spatial and seasonal differences in SST trends that may influence regional marine ecosystems, fisheries, and coastal climate processes.

Therefore, this study aims to quantify and evaluate long-term spatio-temporal variations in sea surface temperature over Pakistan's EEZ using MODIS satellite observations for the period 2002–2022. The study seeks to identify seasonal SST trends, assess decadal changes, and determine whether statistically consistent warming patterns can be detected across the study area.

We hypothesize that (i) SST over the Pakistan EEZ has exhibited a significant warming trend during the study period; (ii) the magnitude of warming differs among seasons; and (iii) satellite-derived SST observations can provide reliable evidence for characterizing long-term thermal changes in the region and contribute to climate-related marine environmental assessments.

## MATERIALS AND METHODS

### Study area

The study was conducted within Pakistan's EEZ, located in the northeastern Arabian Sea. The EEZ extends along approximately 1050 km of coastline and covers nearly 240,000 km$^2$ of marine waters (Figure 2). Geographically, the study area is situated between approximately 23–26°N latitude and 61–68°E longitude (please provide the exact coordinates used for the analysis).

The region is characterized by a tropical to subtropical climate and is influenced by the seasonal southwest and northeast monsoon systems.

Sea surface temperature exhibits pronounced seasonal variability associated with atmospheric circulation, coastal upwelling, solar radiation, and ocean-atmosphere interactions. The northern Arabian Sea is recognized as one of the most dynamically variable regions of the Indian Ocean, where SST strongly influences marine productivity, fisheries, cyclone formation, and regional climate.

The coastal line (Figure 3) has a remarkable impact, predominately on the environment of coastal cities i.e., daily temperature ranges and rainfall profoundly followed by economic resources, livelihood, fauna and flora with and within coastline features, etc. Pakistan's EEZ was selected because long-term SST variability in this region has important implications for marine ecosystem dynamics, coastal environmental management, fisheries resources, and climate change adaptation. The study area therefore represents an important natural laboratory for evaluating long-term thermal changes using satellite observations.

## Research methodology

The methodological workflow consisted of four consecutive stages: (i) acquisition of satellite-derived SST data, (ii) image preprocessing and extraction of the study area, (iii) calculation of spatial and temporal SST characteristics, and (iv) assessment of long-term SST variability between 2002 and 2022.

Monthly MODIS Aqua SST products with a spatial resolution of 4 km were obtained from the NASA Ocean Color database. Only cloud-screened and quality-controlled observations were used for the analysis. Images corresponding to January, March, May, August, and October were selected to represent seasonal variability during the study period. (Please specify the exact MODIS product name, collection version, temporal resolution, and download link.)

All satellite images were clipped to the boundary of Pakistan's EEZ. Land pixels were excluded from the analysis using the EEZ boundary mask. SST values were extracted for each observation period, and descriptive statistics, including minimum, maximum, mean, and spatial variability, were calculated for every year. Long-term SST variability was evaluated by comparing annual observations throughout the 2002–2022 period. Decadal changes were assessed by comparing two time intervals (2003–2012 and 2012–2022). Temporal changes were quantified using annual SST differences and decadal averages.

To improve the robustness of the analysis, long-term SST trends should be evaluated using appropriate statistical methods, such as linear regression and the Mann-Kendall trend test with Sen's slope estimator, to determine the significance and magnitude of observed changes. (If these analyses were not performed, they are strongly recommended before publication.) Figure 4 summarizes the complete methodological workflow adopted in this study.

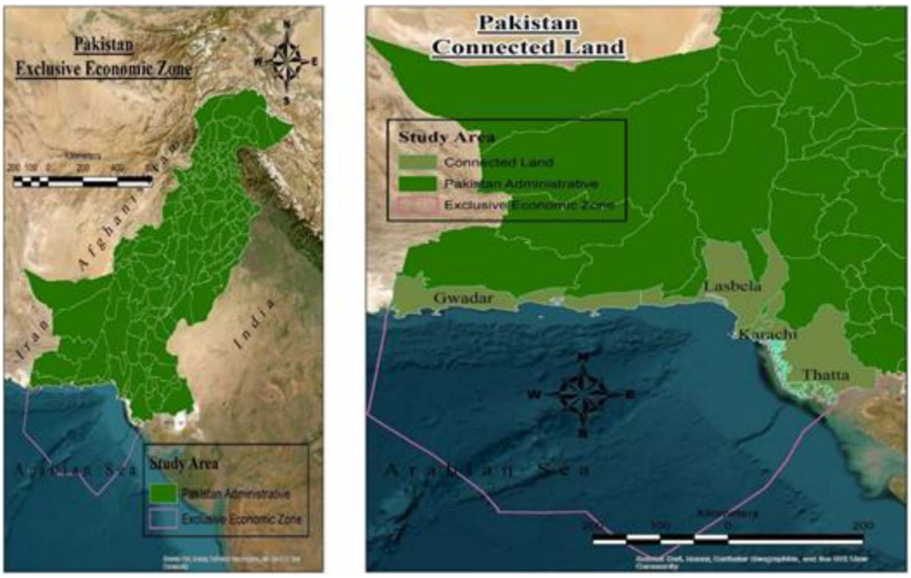


**Figure 2.** Study area – exclusive economic zone


**Figure 3.** Coasts and beaches in Pakistan: (a) sea view Karachi-Sindh, (b) Port Grand Karachi-Sindh, (c) Mubarak Village Karachi-Sindh, (d) Golden Beach Ras Malan Lasbela-Balochistan, (e) Native Jetty Karachi-Sindh, (f) Balochistan, (g) Kund Malir Lasbela Balochistan, (h) Mubarak Village – Charna Island Sindh, (i) Paradise Point Karachi-Pakistan

## Data processing

The SST analysis was performed using remotely sensed satellite observations acquired from the MODIS sensor operated by the National Aeronautics and Space Administration (NASA). Satellite-derived SST data were obtained from the NASA Ocean Color Web repository using the MODIS-Aqua Level-3 SST product (MYD28), Collection 6.1 (Reprocessing R2019.0). The dataset consisted of monthly mapped (gridded) Level-3 observations with a spatial resolution of 4 km and covered the period from January 2002 to October 2022. The data were downloaded from the NASA Ocean Color Web (https://oceancolor.gsfc.nasa.gov/) and were provided in NetCDF (.nc) format. All datasets were referenced to the World Geodetic System 1984 (WGS

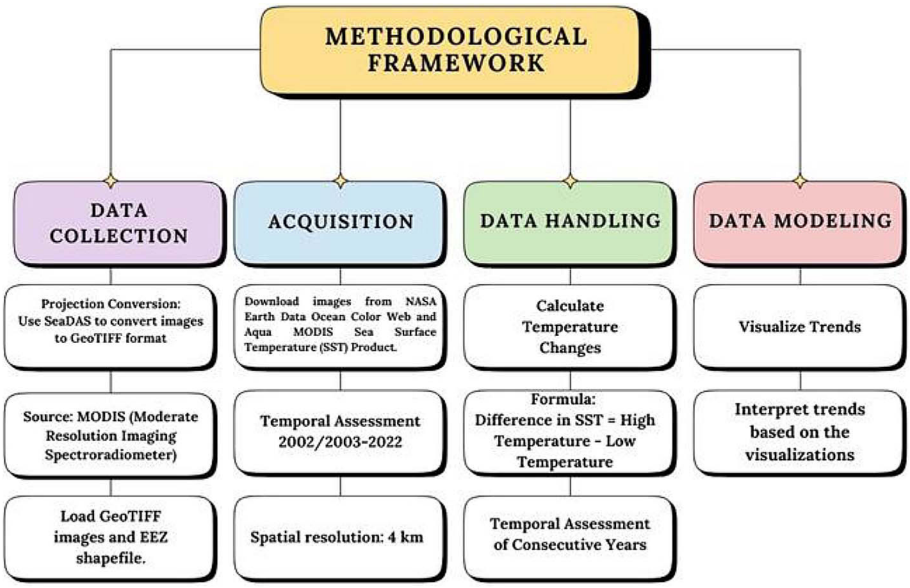


**Figure 4.** Methodological framework

84; EPSG:4326), which was also used as the coordinate reference system throughout all data processing and analysis.

Prior to analysis, satellite images underwent standard preprocessing procedures using SeaDAS software. Satellite scenes containing missing or invalid SST observations were excluded from further analysis. Standard quality control procedures recommended for MODIS-Aqua Level-3 SST products (MYD28, Collection 6.1) were applied, including the use of the built-in MODIS quality flags (QA), cloud masking, and the removal of low-quality, contaminated, and land pixels prior to statistical analysis.

The study area was extracted by clipping the SST rasters using the boundary of Pakistan's EEZ. The EEZ boundary shapefile was obtained from the Marine Regions database and was referenced to the World Geodetic System 1984 (WGS 84; EPSG:4326), which was also used as the coordinate reference system throughout the analysis. Since both the SST data and the EEZ boundary were referenced to the same geographic coordinate system, no additional reprojection was required. Spatial data processing and map preparation were performed using ArcMap 10.8.

For each monthly observation, SST values were extracted for the entire study area. According to the methodology adopted in this study, annual minimum and maximum sea surface temperatures were determined from the monthly mean SST values averaged over the entire EEZ. Thus, the reported low and high SST values represent area-averaged extrema rather than absolute pixel-based minimum or maximum temperatures. In addition, descriptive statistics, including the mean SST, standard deviation, and the number of valid observations, may be reported for each observation period to provide a more comprehensive statistical characterization of the dataset. Statistical analyses and graphical visualization were performed using SeaDAS, ArcMap 10.8, and Microsoft Excel.

The SST analysis was based on five representative months (January, March, May, August, and October) selected to capture key seasonal phases of the regional monsoon-driven climate system. These months were analyzed as independent temporal snapshots and were not used to reconstruct full annual SST cycles. Therefore, the results represent seasonal-to-interannual variability based on selected monthly observations rather than continuous annual SST time series. January, March, May, August, and October were selected to represent the principal seasonal phases of the annual oceanographic cycle in the northern Arabian Sea. January characterizes the northeast monsoon (winter) conditions, March represents the pre-monsoon transition, May corresponds to the pre-summer maximum SST period, August reflects the southwest monsoon season, while October represents the post-monsoon transition. This selection allows the assessment of SST variability under contrasting seasonal climatic conditions while reducing redundancy associated with analysing all twelve monthly datasets.

Temporal variability was evaluated by comparing annual SST observations throughout the study period. In addition, decadal changes were assessed by comparing two periods (2003–2012 and 2012–2022). The magnitude of SST change was calculated as the difference between corresponding annual and decadal values.

The present study employed descriptive statistical analysis to summarize temporal variations in sea surface temperature. Annual and decadal changes were evaluated using minimum and maximum SST values and their graphical comparison. As no inferential statistical tests were conducted, statistical significance (e.g., p-values or confidence intervals) was not assessed. Consequently, the reported changes represent observed temporal patterns rather than statistically confirmed trends. The application of inferential statistical methods, such as linear regression, the Mann–Kendall trend test, or Sen's slope estimator, would further strengthen the quantitative assessment of long-term SST variability.

All image processing, spatial analyses, and statistical calculations were performed using SeaDAS software. Spatial data processing, map preparation, and visualization were conducted using ArcMap 10.8, while statistical summaries and graphical representations were prepared using Microsoft Excel.

## Data collection and acquisition

Satellite-derived SST data were obtained from the NASA Ocean Color Web repository using the MODIS-Aqua Level-3 Sea Surface Temperature product (MYD28), Collection 6.1 (Reprocessing R2019.0). The dataset covered the period from January 2002 to October 2022, providing approximately 20 years of SST observations for the Pakistan EEZ. Satellite data were acquired with a spatial resolution of 4 km and a monthly temporal resolution.

Only observations corresponding to January, March, May, August, and October were included in the analysis to represent the principal seasonal phases of the annual oceanographic cycle in the northern Arabian Sea. January represents the northeast monsoon (winter), March the pre-monsoon transition, May the pre-summer warming period, August the southwest monsoon season, and October the post-monsoon transition.

Monthly MODIS-Aqua Level-3 sea surface temperature (SST) data (MYD28, Collection 6.1, Reprocessing R2019.0) with a spatial resolution of 4 km were obtained from the NASA Ocean Color Web repository for the period from August 2003 to October 2022 (Table 2). The study area was delineated using the Pakistan Exclusive Economic Zone (EEZ) boundary obtained from the Marine Regions database. All spatial datasets were referenced to the World Geodetic System 1984 (WGS 84; EPSG:4326), which was used consistently throughout the analysis.

To ensure data reliability, only quality-controlled SST observations were included in the analysis. The built-in MODIS Level-3 quality flags (QA) were applied during preprocessing, together with cloud masking and the exclusion of low-quality and contaminated pixels prior to statistical analysis.

A summary of the satellite dataset and its principal characteristics is presented in Table 1.

## Key calculations

The processed SST datasets were used to quantify temporal variability within the Pakistan EEZ. The analysis focused on descriptive characterization of annual and decadal SST variations using satellite-derived observations.

For each selected observation month (January, March, May, August, and October), SST values were extracted for the entire study area. Monthly mean SST values were calculated for the Pakistan EEZ, from which the annual minimum (Low SST) and maximum (High SST) values were identified. Thus, the reported Low and High SST values represent area-averaged extrema rather than absolute pixel-based minimum and maximum temperatures.

Annual SST variability was evaluated by comparing the minimum and maximum SST values between consecutive years throughout the study period (2002–2022). Long-term changes were further assessed by comparing two decades (2003–2012 and 2012–2022). The decadal SST difference (ΔSST) was calculated as

$$\Delta SST = SST_{(2012\text{–}2022)} - SST_{(2003\text{–}2012)} \quad (1)$$

where: $SST$ represents the annual area-averaged sea surface temperature statistic, expressed as either the annual minimum (Low $SST$) or annual maximum (High $SST$), depending on the analysis.

Temporal SST variability was summarized using descriptive statistical measures. The calculated variables included annual minimum SST, annual maximum SST, annual SST range, and decadal SST differences. Graphical

**Table 1.** Information about the satellite dataset

| Parameter | Description |
|---|---|
| Satellite | MODIS aqua |
| Product | Sea surface temperature (SST), Level-3 (MYD28) |
| Collection | Collection 6.1 (Reprocessing R2019.0) |
| Processing level | Level-3 (mapped/gridded) |
| Data provider | NASA Ocean Color Web |
| Study period | January 2002 – October 2022 |
| Spatial resolution | 4 km |
| Temporal resolution | Monthly |
| Study area | Pakistan Exclusive Economic Zone (EEZ) |
| Projection | WGS 84 (EPSG:4326) |
| Software | SeaDAS, ArcMap 10.8, Microsoft Excel |

**Note:** MODIS.

**Table 2.** MODIS specification

| Instrument | Operating system | Swath width | Earth coverage | Bands | Band width | Available spatial resolution |
|---|---|---|---|---|---|---|
| MODIS | Terra and aqua | 2.330 km | In 2 days | 36 | 0.405 and 14.385 µm | 250 m, 500 m, 1.000 m |

visualization was used to examine temporal changes and identify long-term patterns within the study area.

This study employed a comparative analysis of satellite-derived sea surface temperature (SST) indicators, including annual minimum (Low SST), annual maximum (High SST), and decadal differences, to characterize temporal variability over the study period.

## RESULTS

### Seasonal variability of sea surface temperature

The seasonal analysis of MODIS-derived SST revealed pronounced thermal variability across the Pakistan exclusive economic zone throughout the 2002–2022 observation period (Table 3). Sea surface temperatures followed a clear seasonal cycle, with the lowest values occurring during January and the highest temperatures consistently observed during May and August. These seasonal differences reflect the regional influence of solar radiation, atmospheric circulation, and the northeast and southwest monsoon systems. Although seasonal variability was evident throughout the study period, the magnitude of warming was not uniform among the selected months. The greatest long-term changes were observed during the pre-monsoon (May) and southwest monsoon (August) periods, whereas October exhibited comparatively smaller variations. March showed a distinct behaviour compared with the remaining months, suggesting differences in seasonal ocean-atmosphere interactions. Overall, the results indicate that SST variability within Pakistan's EEZ is characterized by both strong seasonal contrasts and long-term warming patterns.

### Interannual SST variability (2002–2022)

The interannual analysis demonstrated that SST variability differed considerably among seasons (Figures 5–9). January exhibited the largest reduction in maximum SST between the beginning and the end of the observation period, whereas minimum SST changed only slightly. Similar behaviour was observed during March, where maximum temperatures decreased while minimum temperatures showed comparatively smaller changes. In contrast, May and August displayed the highest thermal variability

**Table 3.** Sea surface temperatures in January, March, May, August, and October (2002–2022)

| Year | January | | | March | | | May | | | August | | | October | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Temperature ℃ | | | Temperature ℃ | | | Temperature ℃ | | | Temperature ℃ | | | Temperature ℃ | | |
| | High | Low | TD* | High | Low | TD* | High | Low | TD* | High | Low | TD* | High | Low | TD* |
| 2002/2003 | 29.96 | 20.32 | 9.65 | 37.13 | 22.17 | 14.96 | 37.98 | 25.06 | 12.92 | 33.86 | 20.64 | 13.22 | 39.01 | 24.43 | 14.59 |
| 2004 | 28.545 | 18.35 | 10.2 | 34.55 | 24.52 | 10.04 | 38.72 | 26.26 | 12.46 | 36.45 | 20.73 | 15.72 | 36.51 | 25.03 | 11.48 |
| 2006 | 27.165 | 18.5 | 8.67 | 30.83 | 23.56 | 7.27 | 37.69 | 23.8 | 13.89 | 35.77 | 21.73 | 14.04 | 32.95 | 26.37 | 6.575 |
| 2008 | 24.93 | 17.92 | 7.02 | 28.61 | 22.62 | 5.99 | 37.45 | 24.97 | 12.49 | 37.85 | 22.55 | 15.3 | 36.73 | 25.12 | 11.62 |
| 2010 | 27.765 | 19.79 | 7.98 | 29.6 | 22.76 | 6.84 | 38.51 | 25.58 | 12.93 | 35.67 | 23.76 | 11.91 | 32.27 | 26.16 | 6.105 |
| 2012 | 25.295 | 18.45 | 6.85 | 28.74 | 21.61 | 7.135 | 37.22 | 25.35 | 11.87 | 38.49 | 20.86 | 17.63 | 32.01 | 26.47 | 5.54 |
| 2014 | 26.38 | 18.02 | 8.37 | 30.92 | 22.34 | 8.585 | 33.9 | 27.04 | 6.86 | 32.82 | 25.28 | 7.54 | 37.91 | 25.72 | 12.19 |
| 2016 | 25.81 | 20.89 | 4.93 | 29.84 | 23.22 | 6.625 | 33.21 | 26.48 | 6.73 | 32.57 | 22.53 | 10.04 | 32.45 | 23.93 | 8.52 |
| 2018 | 28.845 | 19.14 | 9.71 | 30.28 | 23.65 | 6.625 | 40 | 25.17 | 14.83 | 33.52 | 22.3 | 11.22 | 34.72 | 26.09 | 8.635 |
| 2020 | 25.895 | 16.53 | 9.37 | 26.91 | 22.46 | 4.455 | 34.04 | 26.73 | 7.31 | 37.43 | 27.75 | 9.68 | 34.65 | 25.28 | 9.365 |
| 2022 | 24.795 | 19.67 | 5.13 | 30.62 | 24.64 | 5.985 | 35.69 | 24.56 | 11.13 | 34.4 | 23.97 | 10.43 | 30.61 | 25.4 | 5.215 |

**Note:** *TD (°C) = temperature difference (°C) = high (°C) – low (°C).

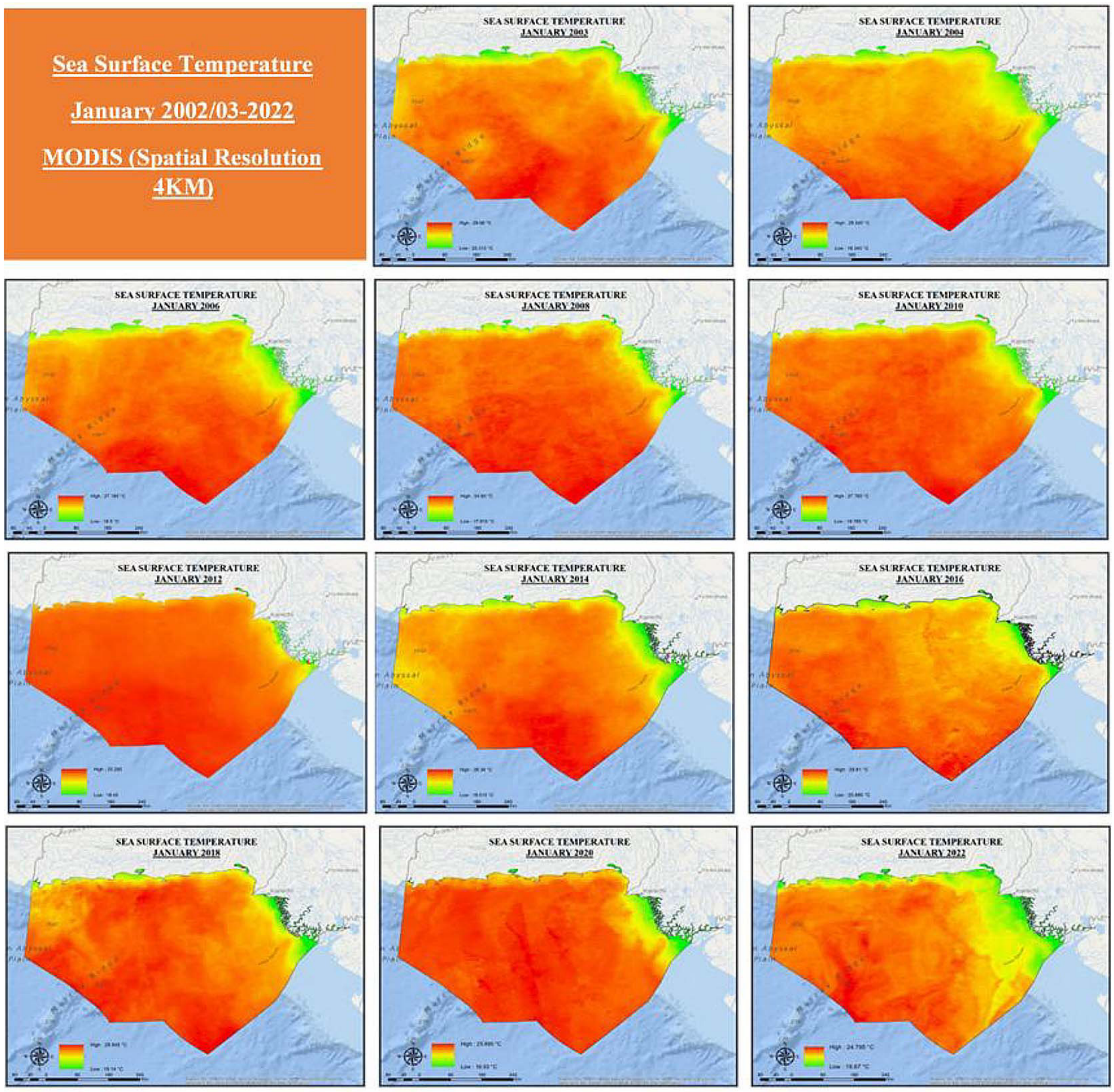


**Figure 5.** SST January 2002/03-2022

throughout the study period. Although annual fluctuations were evident, both months maintained the highest SST values among all observation periods, confirming that late spring and summer represent the warmest phases of the regional thermal cycle.

October exhibited relatively stable SST conditions compared with the other seasons. Interannual fluctuations were present but their overall magnitude remained considerably smaller than those observed during May and August.

Collectively, these observations demonstrate that long-term SST variability is season-dependent and that the response of the Pakistan EEZ differs substantially between winter and summer conditions.

## Decadal changes in SST

Comparison of the two observation decades revealed clear differences in SST variability (Table 4). January showed the largest increase in average temperature difference between decades, indicating enhanced thermal variability during winter conditions. Moderate increases were also observed during May, August, and October, whereas March was the only month exhibiting a reduction in decadal temperature difference.

The strongest decadal increase was identified during May and August, where the average temperature difference increased from approximately 1.45°C during the first decade

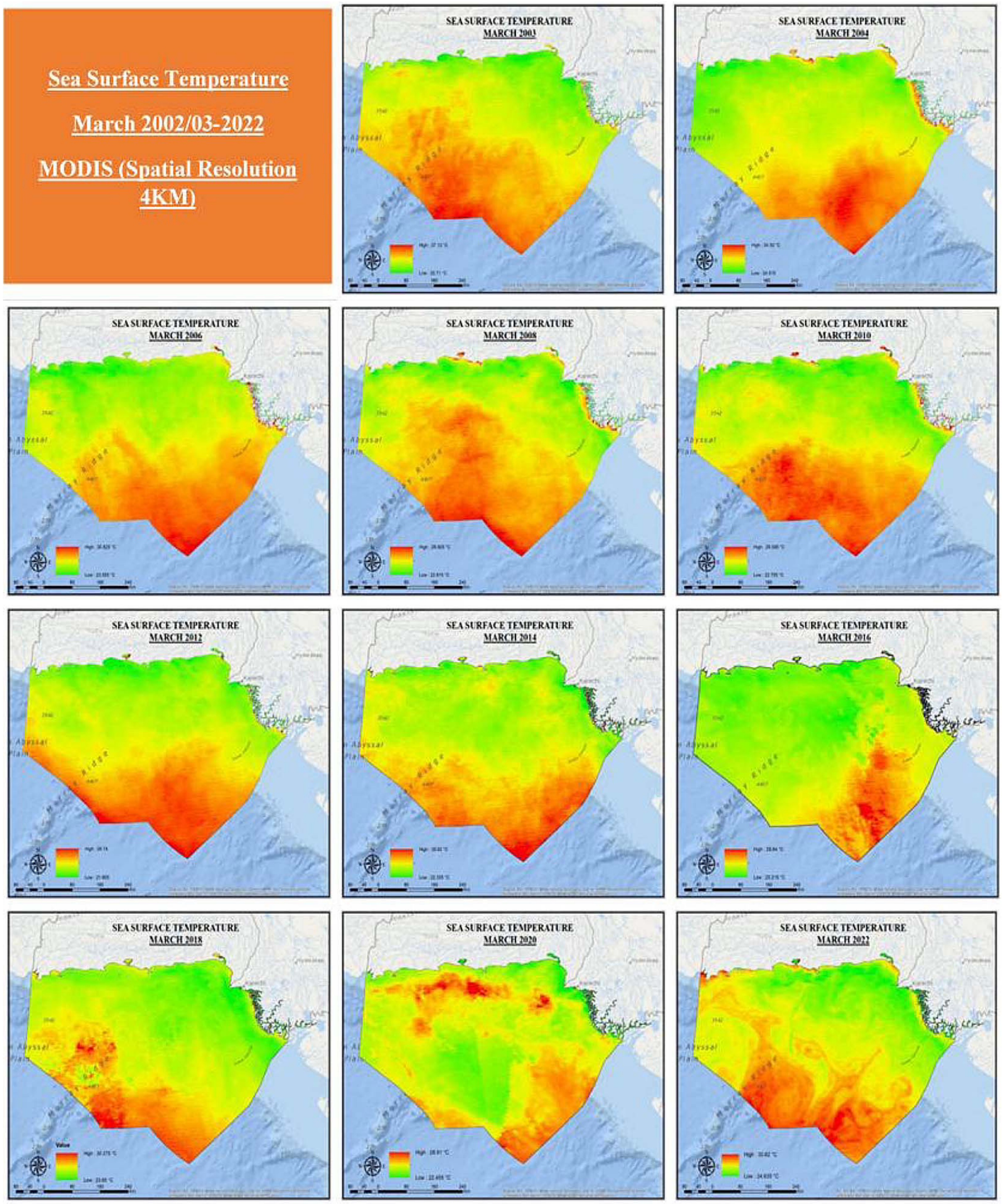


**Figure 6.** SST March 2002/03-2022

to 1.61 °C during the second decade. October showed only minor changes between decades, suggesting comparatively stable thermal conditions during the post-monsoon period.

Overall, the comparison indicates that SST variability intensified during the second decade (2012–2022), although the magnitude of change differed considerably among seasons (Figure 10).

## Statistical assessment of temporal changes

To complement the descriptive analysis, linear regression and the non-parametric Mann–Kendall trend test were applied to the annual maximum SST, minimum SST, and temperature difference (TD) for each observation month during 2002/03–2022.

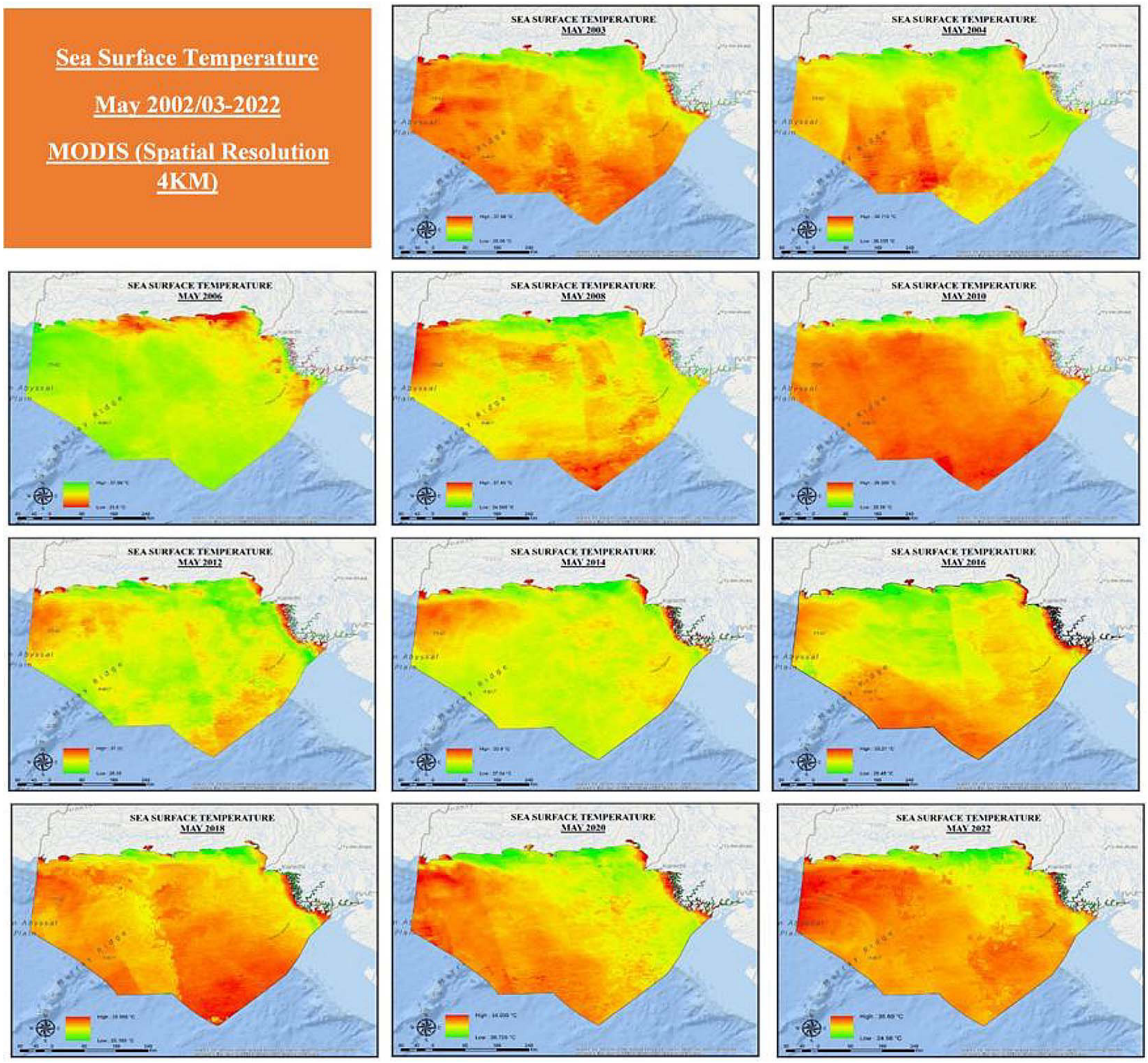


**Figure 7.** SST May 2002/03-2022

The analysis identified statistically significant temporal changes only for selected variables (Table 5). March exhibited a significant decline in both annual maximum SST and temperature difference according to linear regression ($p = 0.039$ and $p = 0.020$, respectively), while the Mann–Kendall test confirmed a significant decreasing trend only for temperature difference ($p = 0.008$). In contrast, August showed a significant increase in annual minimum SST according to both linear regression ($p = 0.026$) and the Mann–Kendall test ($p = 0.017$). Although the temperature difference in August showed a significant linear decrease ($p = 0.042$), this pattern was not confirmed by the Mann–Kendall test ($p = 0.087$). For the remaining months and variables, no statistically significant temporal trends were detected ($p > 0.05$), indicating that interannual variability exceeded any consistent monotonic changes over the study period.

## DISCUSSIONS

The present study provides a comprehensive assessment of seasonal and interannual SST variability within Pakistan's exclusive economic zone over the period 2002–2022 using MODIS satellite observations. Although pronounced seasonal variability characterized all observation months, statistical analyses demonstrated that persistent temporal changes were limited to specific thermal indicators rather than being uniformly distributed throughout the annual cycle. This finding suggests that SST variability in the northern Arabian Sea is governed by complex regional

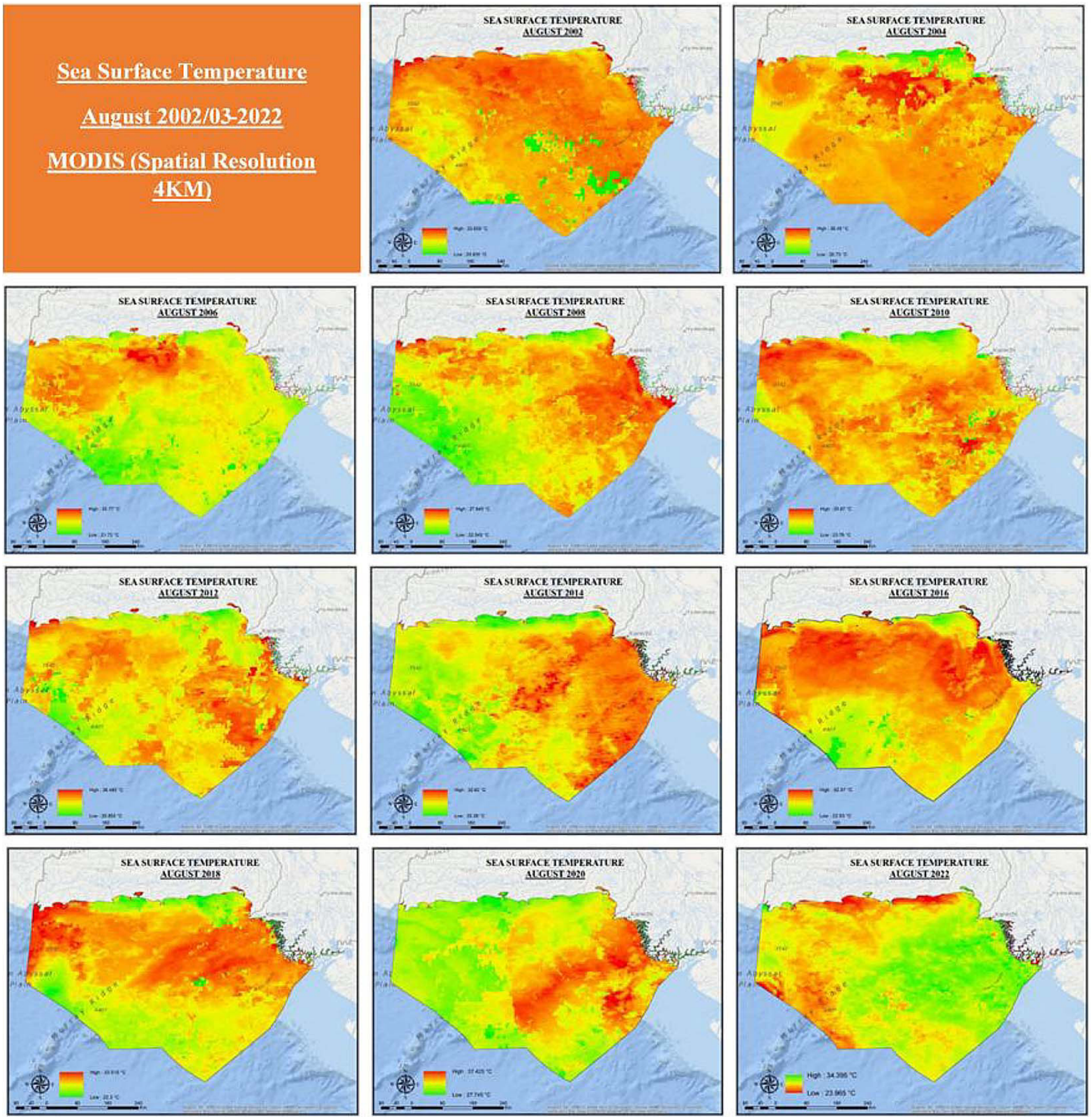


**Figure 8.** SST August 2002/03-2022

oceanographic processes rather than by a simple, continuous warming pattern.

The observed seasonal differences are consistent with the climatic characteristics of the northern Arabian Sea. May and August consistently exhibited the highest SST values, reflecting the combined influence of increasing solar radiation, pre-monsoon heating, and southwest monsoon circulation. In contrast, January represented the coolest conditions due to enhanced winter cooling and the northeast monsoon. Such seasonal contrasts have been widely recognized as dominant controls of thermal variability in the Arabian Sea and indicate that regional atmospheric forcing remains the primary driver of SST distribution (Albert et al., 2023; Nisha et al., 2024).

The statistical analyses further revealed that significant temporal changes were restricted to March and August. March demonstrated a significant decrease in both annual maximum SST and temperature difference, while August showed a significant increase in annual minimum SST. These results suggest that seasonal thermal characteristics have evolved differently over the last two decades, with winter–spring transition periods exhibiting different responses from the peak monsoon season. The absence of statistically significant trends for most remaining variables indicates that substantial interannual variability continues

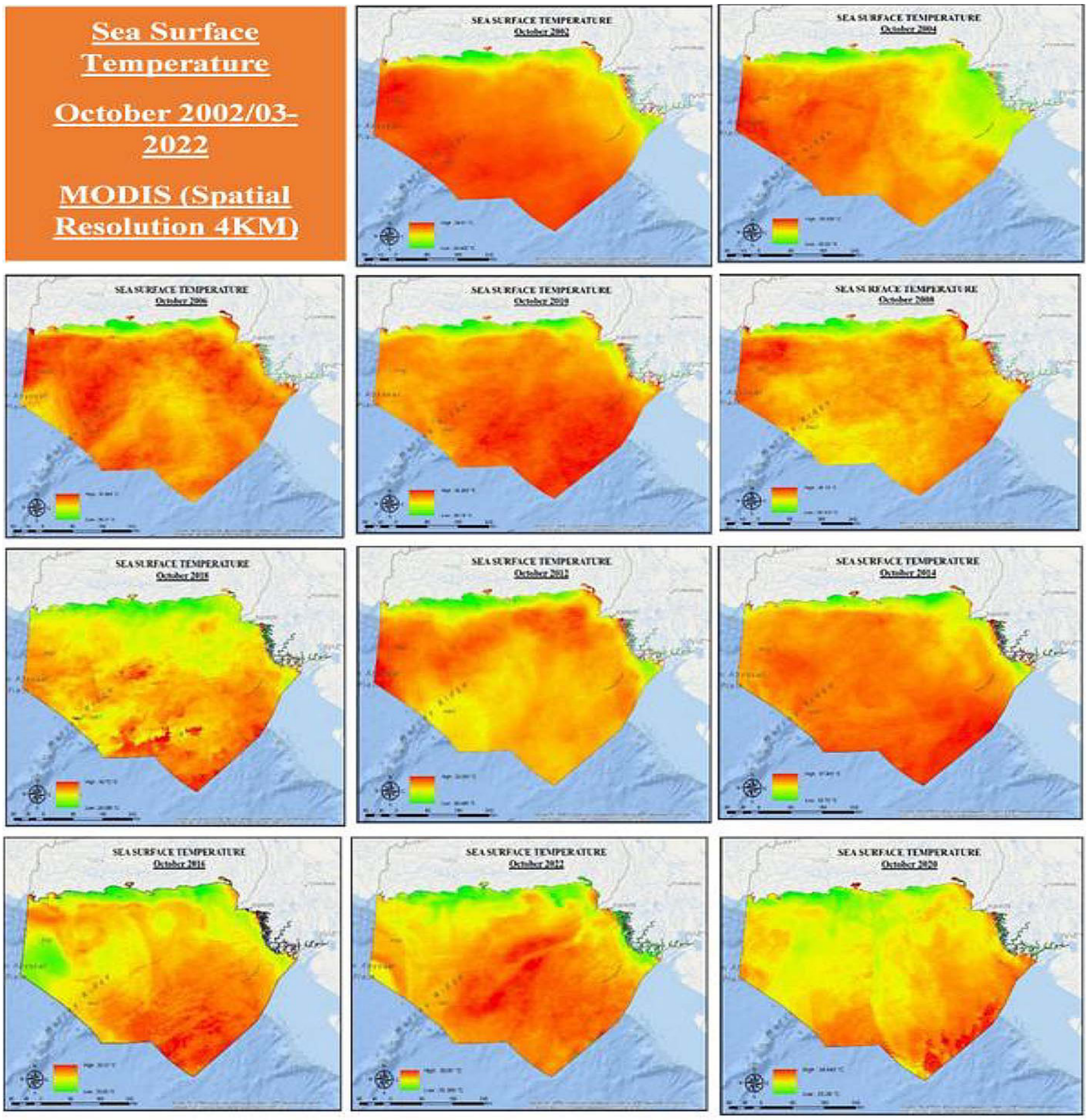


**Figure 9.** SST October 2002/03-2022

to characterize SST dynamics within Pakistan's EEZ (Roxy et al., 2015; Saranya et al., 2022).

These findings agree with previous studies reporting that SST changes in the Arabian Sea are spatially and seasonally heterogeneous rather than temporally uniform (Schott et al., 2009; Kumar et al., 2009). Moreover, the obtained findings are consistent with recent studies emphasizing the importance of long-term climate analyses for understanding regional environmental change (Odiana et al., 2026). These observations complement broader evidence of climate-related environmental changes reported for Pakistan (Anwar et al., 2024). Regional SST variability has been associated with interactions among monsoon intensity, coastal upwelling, ocean circulation, air–sea heat exchange, and large-scale climate variability. Consequently, different portions of the annual cycle may respond differently to changing atmospheric and oceanographic conditions, explaining why statistically significant changes were detected only for selected months and variables.

The comparison between the two observation decades nevertheless indicates that thermal conditions within Pakistan's EEZ have evolved over time. Although monotonic trends were not identified for most variables, the decadal analysis demonstrated changes in the magnitude of seasonal temperature differences and confirmed

**Table 4.** Decade-wise sea surface temperature change

| Months | Difference between years | High (°C) | Avg of decade (°C) | Low (°C) | Avg of Decade(°C) | Difference | Avg of difference in decade (°C) |
|---|---|---|---|---|---|---|---|
| January | 2003–2004 | 1.415 | 1.0335 | 1.97 | 0.5915 | -0.555 | 0.584 |
| | 2004–2006 | 1.38 | | -0.155 | | 1.535 | |
| | 2006–2008 | 2.235 | | 0.585 | | 1.65 | |
| | 2008–2010 | -2.835 | | -1.87 | | -0.965 | |
| | 2010–2012 | 2.47 | | 1.335 | | 1.135 | |
| | 2012–2014 | -1.085 | 0.874 | 0.435 | 1.08 | -1.52 | 1.432 |
| | 2014–2016 | 0.57 | | -2.87 | | 3.44 | |
| | 2016–2018 | -3.035 | | 1.745 | | -4.78 | |
| | 2018–2020 | 2.95 | | 2.61 | | 0.34 | |
| | 2020–2022 | 1.1 | | -3.14 | | 4.24 | |
| March | 2003–2004 | 2.58 | 1.037 | -2.345 | 0.5535 | 4.925 | 1.0115 |
| | 2004–2006 | 3.725 | | 0.96 | | 2.765 | |
| | 2006–2008 | 2.22 | | 0.94 | | 1.28 | |
| | 2008–2010 | -0.99 | | -0.14 | | -0.85 | |
| | 2010–2012 | 0.855 | | 1.15 | | -0.295 | |
| | 2012–2014 | -2.18 | 1.077 | -0.73 | 0.542 | -1.45 | 0.711 |
| | 2014–2016 | 1.08 | | -0.88 | | 1.96 | |
| | 2016–2018 | -0.435 | | -0.435 | | 0 | |
| | 2018–2020 | 3.365 | | 1.195 | | 2.17 | |
| | 2020–2022 | -3.71 | | -2.18 | | -1.53 | |
| May | 2002–2004 | -2.592 | 1.0337 | 0.095 | 0.603 | -2.497 | 1.4547 |
| | 2004–2006 | 0.68 | | 1 | | 1.68 | |
| | 2006–2008 | -2.075 | | 0.815 | | -1.26 | |
| | 2008–2010 | 2.175 | | 1.215 | | 3.39 | |
| | 2010–2012 | -2.815 | | 2.905 | | -5.72 | |
| | 2012–2014 | 5.665 | 1.38 | 4.425 | 1.663 | 10.09 | 1.605 |
| | 2014–2016 | 0.25 | | 2.75 | | -2.5 | |
| | 2016–2018 | -0.945 | | 0.23 | | -1.175 | |
| | 2018–2020 | -3.91 | | 5.445 | | 1.535 | |
| | 2020–2022 | 3.03 | | 3.78 | | -0.75 | |
| August | 2002–2004 | -2.592 | 1.0337 | 0.095 | 0.603 | -2.497 | 1.4547 |
| | 2004–2006 | 0.68 | | 1 | | 1.68 | |
| | 2006–2008 | -2.075 | | 0.815 | | -1.26 | |
| | 2008–2010 | 2.175 | | 1.215 | | 3.39 | |
| | 2010–2012 | -2.815 | | 2.905 | | -5.72 | |
| | 2012–2014 | 5.665 | 1.38 | 4.425 | 1.663 | 10.09 | 1.605 |
| | 2014–2016 | 0.25 | | 2.75 | | -2.5 | |
| | 2016–2018 | -0.945 | | 0.23 | | -1.175 | |
| | 2018–2020 | -3.91 | | 5.445 | | 1.535 | |
| | 2020–2022 | 3.03 | | 3.78 | | -0.75 | |
| October | 2002–2004 | 2.505 | 1.4575 | -0.605 | 0.187 | 1.9 | 1.2795 |
| | 2004–2006 | 3.56 | | -1.34 | | 4.9 | |
| | 2006–2008 | -3.785 | | 1.255 | | 2.53 | |
| | 2008–2010 | 4.465 | | -1.045 | | 3.42 | |
| | 2010–2012 | 0.26 | | -0.305 | | 0.045 | |
| | 2012–2014 | -5.9 | 1.7735 | 0.745 | 0.561 | 5.155 | 1.3585 |
| | 2014–2016 | 5.455 | | 1.79 | | 3.665 | |
| | 2016–2018 | -2.27 | | -2.155 | | 0.115 | |
| | 2018–2020 | 0.075 | | 0.805 | | 0.73 | |
| | 2020–2022 | 4.035 | | -0.115 | | 3.92 | |

**Note:** (-) Represents the forthcoming year having a higher temperature than the previous year..

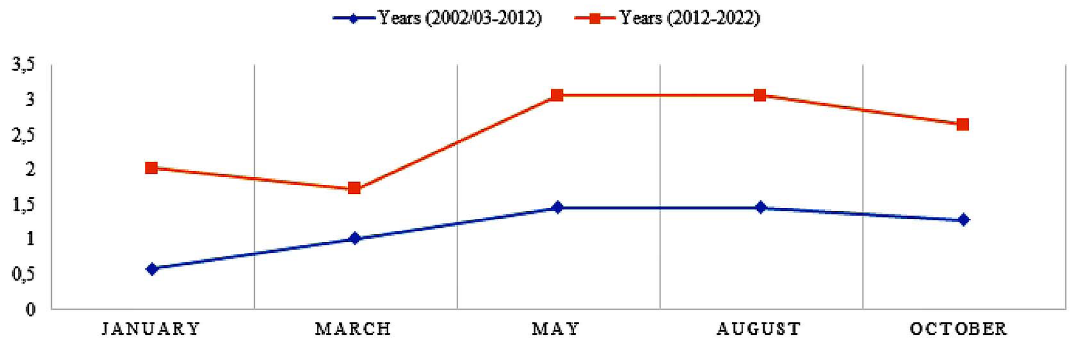


**Figure 10.** Decade-wise temperature differences

**Table 5.** Summary of statistical trend analysis of annual SST extremes and temperature difference (2002/03–2022)

| Month | Variable | Linear regression (p) | Mann–Kendall (p) | Interpretation |
|---|---|---|---|---|
| March | High SST | 0.039 | 0.218 | Significant decrease (LR only) |
| March | TD | 0.020 | 0.008 | Significant decrease |
| August | Low SST | 0.026 | 0.017 | Significant increase |
| August | TD | 0.042 | 0.087 | Significant in LR only |
| All remaining variables | — | >0.05 | >0.05 | No significant temporal trend |

that the thermal regime has not remained stationary throughout the study period. This distinction between long-term temporal variability and statistically significant monotonic trends is important because environmental changes in coastal marine systems often occur through non-linear fluctuations rather than continuous linear warming (Seekell et al., 2022).

From an environmental perspective, even moderate modifications in seasonal SST characteristics may influence ecosystem functioning within the northern Arabian Sea (Schott et al., 2009). Sea surface temperature regulates primary productivity, nutrient availability, fish distribution, coral health, and the ecological functioning of mangrove ecosystems. Changes in seasonal thermal conditions may therefore affect fisheries resources, biodiversity, and the resilience of coastal ecosystems that support both regional livelihoods and marine conservation (Hoegh-Guldberg and Bruno, 2010).

The present study also demonstrates the value of long-term satellite observations for monitoring thermal variability in Pakistan's EEZ. The effectiveness of remote sensing for long-term environmental monitoring has also been demonstrated in studies of atmospheric pollution, land-cover dynamics, climate variability, and water resource assessment, highlighting the versatility of satellite observations for detecting spatio-temporal environmental changes across diverse ecosystems (Amaechi et al., 2026; Okoduwaet al., 2026). Satellite-derived SST provides consistent spatial coverage over extensive marine areas and enables the identification of seasonal and interannual patterns that are difficult to resolve using conventional in situ observations alone. The integration of remote sensing with statistical trend analysis therefore represents an effective framework for long-term marine environmental assessment.

Despite these findings, several limitations should be acknowledged. The analysis focused on five representative months rather than continuous monthly observations and evaluated annual maximum and minimum SST values together with their temperature differences. Additional investigations incorporating complete monthly time series, multiple satellite products, in situ measurements, and coupled atmospheric–oceanographic variables would provide a more comprehensive understanding of long-term thermal variability within the northern Arabian Sea.

Future research should therefore focus on integrating SST observations with indicators of monsoon dynamics, coastal upwelling, chlorophyll-a concentration, and marine ecosystem responses to better understand the mechanisms controlling thermal variability within Pakistan's EEZ. Such integrated approaches will improve regional climate assessments and support evidence-based management of marine resources under changing environmental conditions.

## CONCLUSIONS

The objectives of this study were successfully achieved through the analysis of MODIS-derived sea surface temperature data for Pakistan's exclusive economic zone covering the period 2002–2022. The results support the proposed hypothesis that SST variability has changed over the last two decades; however, these changes are season-dependent rather than spatially or temporally uniform. Statistical analyses demonstrated that significant temporal changes were limited to specific thermal indicators, while most seasonal variables exhibited considerable interannual variability without consistent monotonic trends.

The study provides new quantitative evidence of seasonal and decadal SST variability within Pakistan's EEZ by combining long-term satellite observations with statistical trend assessment. Unlike previous regional studies that primarily described general warming patterns in the Arabian Sea, the present analysis identifies the months in which statistically significant thermal changes occur and distinguishes between short-term variability, decadal differences, and persistent temporal trends. This contributes to a more nuanced understanding of thermal dynamics in the northern Arabian Sea.

The findings help address the limited availability of long-term, region-specific assessments of SST variability for Pakistan's marine waters and establish a baseline for future environmental monitoring. The observed seasonal differences emphasize that changes in marine thermal conditions cannot be adequately characterized using annual averages alone, highlighting the importance of season-specific analyses for regional climate assessments.

The findings of this study establish a baseline for future investigations of SST variability within Pakistan's EEZ. Integrating satellite-derived SST observations with oceanographic and atmospheric variables, including monsoon dynamics, coastal upwelling, chlorophyll-a concentration, and in situ measurements, may further improve understanding of the mechanisms controlling regional thermal variability and strengthen the scientific basis for ecosystem assessment and sustainable management under changing climatic conditions.

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