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Research Article

Long-term temporal variability of chlorophyll-*a* and sea surface temperature in the southern Caspian Sea using MODIS satellite observations (2002–2020)

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Keywords

Caspian Sea,
Chl-*a*,
Sea surface temperature,
Remote sensing,
Time series analysis,
Phytoplankton biomass

Abstract

Sea surface temperature (SST) and chlorophyll-*a* (Chl-*a*) are important indicators of climatic variability and phytoplankton biomass. This study investigated temporal trends in SST and Chl-*a* and their relationship in the southern Caspian Sea at monthly and seasonal scales during 2002–2020. MODIS-Aqua and MODIS-Terra satellite data were used to construct long-term time series following standard image preprocessing, atmospheric correction, and retrieval using Multi-Channel SST (MCSST) for SST and OC3M for Chl-*a*. Seasonal trends were assessed using the Mann–Kendall test, while the Pettitt's test was applied to identify abrupt changes. Linear regression was used to examine the relationship between SST and Chl-*a*. Chl-*a* showed a significant increasing trend, with mean concentrations rising from 2.95 mg m^{-3} in 2002 to 4.52 mg m^{-3} in 2020. In contrast, mean SST increased slightly from 15.1°C to 16.1°C, but no significant monotonic trend was detected. The Pettitt's test identified a significant change point in Chl-*a* around mid-2006. Regression analysis indicated a moderate positive relationship between SST and Chl-*a*, with SST explaining 57.5% of the observed variability (R^2=0.575, p<0.05). The increasing Chl-*a* trend despite the absence of a significant SST trend suggests that factors beyond temperature, including nutrient inputs and river discharge, may contribute to phytoplankton variability. Overall, the findings highlight the value of long-term satellite observations for monitoring ecological changes in the southern Caspian Sea ecosystem.

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Introduction

Climate-driven changes in marine ecosystems have become a major concern because they directly affect primary productivity, biogeochemical cycles, and fisheries resources worldwide. In this context, climatic factors play a significant role in determining the extent and quality of this exploitation (Kostianoy and Pešić, 2024). Global climate change, including alterations in temperature, chemical composition, and biological characteristics of water in seas and oceans, is clearly evident (Tang *et al.,* 2011). These changes can redirect energy cycles from the production of valuable stocks toward harmful species-a trend that leads to the decline of aquatic resources. According to reports from 1997, there is a significant relationship between ocean primary production and climatic effects on marine ecosystems (Behrenfeld *et al.,* 2006); however, due to the vastness of marine ecosystems, the impacts of these changes often remain undetected in the short term, and when they do appear, they are frequently irreversible or difficult to mitigate.

In this regard, parameters such as chlorophyll-*a* (Chl-*a*) and sea surface temperature (SST) play a key role in biochemical and biological studies. Beyond examining biological cycles and climate change, these parameters serve as important indicators for assessing biological status and ecological changes in oceans and seas. SST holds particular importance in oceanography, as major changes in this index have significant biological impacts on the living conditions of marine organisms, including plankton, mollusks, fish, and marine mammals (Beaugrand *et al.,* 2009). Rising temperatures reduce dissolved oxygen levels in water, which in turn affects marine life and water quality. The standard depth for measuring SST is one meter below the water surface (Esfandiyarnzhad *et al.,* 2004; Donlon *et al.,* 2007).

Among semi-enclosed marine ecosystems, the southern Caspian Sea is particularly vulnerable to environmental change because of its restricted water exchange, large riverine inflows, and increasing anthropogenic pressures. Recent studies have reported substantial ecological changes in the basin, including fluctuations in primary productivity, changes in phytoplankton composition, sea-level decline, and alterations in thermal conditions. Therefore, understanding the long-term variability of Chl-*a* and SST is essential for assessing ecosystem health and supporting sustainable fisheries management in the region.

From a remote sensing perspective, Chl-*a* facilitates more precise observation due to sensor spectral capabilities (including high radiometric sensitivity (12 bits) and coverage of 36 spectral bands). These features enable better discrimination of Chl-*a* related signals within bands 1 to 19, at wavelengths ranging approximately from 0.4 to 0.9 µm, ultimately making Chl-*a* an effective tool for monitoring marine ecosystems.

Previous studies have demonstrated the broad applicability of satellite remote sensing for monitoring Chl-*a* and SST in marine ecosystems. Satellite-derived Chl-*a* has been widely used as an indicator of phytoplankton biomass and primary productivity, while SST has been recognized

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as a key environmental factor influencing phytoplankton dynamics and ecosystem functioning (Behrenfeld and Falkowski, 1997; Robinson, 2004; Martin, 2004). In the Caspian Sea, remote sensing studies have mainly focused on the spatial distribution and seasonal variability of Chl-*a*, regional phytoplankton blooms, and environmental changes associated with climate variability and biological invasions (Kideys *et al.,* 2008; Kopelevich *et al.,* 2009; Moradi, 2022; Vostokov *et al.,* 2023; Lavrova *et al.,* 2024a,b). Although these studies have substantially improved our understanding of the Caspian Sea ecosystem, comprehensive assessments integrating long-term temporal trends of Chl-*a* and SST together with their statistical relationship remain limited, particularly for the southern Caspian Sea.

Recent studies have highlighted substantial environmental and ecological changes in the Caspian Sea, including declining water levels, shifts in thermal structure, variations in phytoplankton biomass, algal bloom dynamics, and long-term changes in SST associated with climate variability and increasing anthropogenic pressures (Arpe *et al.,* 2020; Kostianoy and Pešić, 2024). In this context, satellite remote sensing has become an indispensable tool for monitoring ecosystem processes because it provides continuous observations over large spatial and temporal scales, particularly in semi-enclosed basins such as the Caspian Sea (Lavrova *et al.,* 2024a,b). Analyses based on MODIS and SeaWiFS observations have revealed pronounced seasonal and interannual variability in Chl-*a* concentrations across different regions of the Caspian Sea, emphasizing the importance of long-term assessments of ecosystem dynamics (Moradi, 2022; Vostokov *et al.,* 2023). Furthermore, advances in satellite-based monitoring have improved our understanding of the interactions between SST and phytoplankton productivity, allowing researchers to better evaluate ecosystem responses to environmental change (Tuzcu Kokal and Musaoğlu, 2021). Collectively, these findings highlight the need for comprehensive long-term investigations of SST and Chl-*a* variability to improve our understanding of ecological responses to ongoing climate and environmental changes in the Caspian Sea.

Although previous studies have investigated Chl-*a* variability in different regions of the Caspian Sea, most have focused on specific sub-basins or limited time periods. Comprehensive assessments of long-term SST– Chl-*a* relationships in the southern Caspian Sea using continuous MODIS observations remain relatively scarce. Therefore, an updated evaluation of spatio-temporal variability and the relationship between SST and Chl-*a* is needed to improve our understanding of ecosystem responses to ongoing environmental changes.

Therefore, the objective of this study was to investigate the long-term spatio-temporal variability of Chl-*a* and SST in the southern Caspian Sea using MODIS satellite observations from 2002 to 2020. In addition, the relationship between these two environmental variables was evaluated using trend analysis, change-point detection, and regression techniques to improve understanding of ecosystem dynamics in this ecologically important basin.

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Materials and methods

The Caspian Sea, as the largest enclosed basin in the world, holds particular importance in studies of Chl-*a* concentration changes and biological dynamics (Kosarev and Kostianoy, 2005). The meridional extent of this basin and its diverse climatic conditions create significant temperature gradients from north to south; in northern regions, due to the influence of riverine flows from polar areas, temperatures are lower, while southern regions at lower latitudes experience higher temperatures. Covering approximately 390,000 km², with a volume of close to 78,000 km³ and a maximum depth of approximately 1,025 m, this basin represents a unique ecosystem whose changes require continuous satellite-based monitoring (Fig. 1).

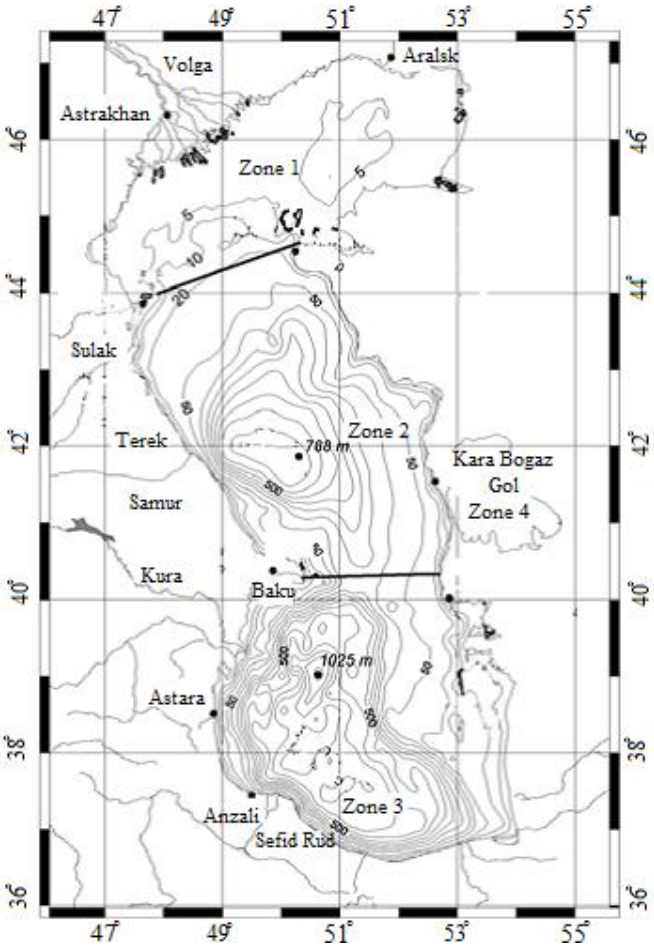

Figure 1: Caspian Sea regionalization (1. Northern zone; 2. Middle zone; 3. Southern zone; 4. Kara-Bogaz Gulf (Kosarev, 2005).

This study was designed to investigate the temporal trends of SST and Chl-*a* concentration, as well as to analyze the relationship between these two parameters in the southern Caspian Sea, on monthly and seasonal time scales. Satellite images acquired by the MODIS sensors onboard the Aqua and Terra platforms from July 2002 to December 2020 were used to retrieve SST and Chl-*a* concentration.

Globally calibrated algorithms with appropriate accuracy were employed to

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calculate SST and Chl-*a* concentration. For SST computation, the Multi-Channel SST (MCSST) model was used. This model is based on split-window algorithms, which provide high accuracy due to the inclusion of satellite zenith angle and atmospheric corrections (Equation 1):

$$\text{MODIS - SST} = C_1 + C_2 \times T_{31} + C_3 \times T_{3132} + C_4 \times (\sec(\theta) - 1) \times T_{3132} \quad (1)$$

Where, T_{31} is the brightness temperature of band 31, T_{3132} is the brightness temperature difference between bands 31 and 32, and θ is the satellite viewing angle, which is derived from the initial image metadata.

The brightness temperatures for bands 31 and 32 were then calculated using the numerical values of image emissivity and Planck's inverse law (Equation 2):

$$(2)\ T = \frac{\left(\frac{hc}{k}\right)}{\lambda * ln\left(\left(\frac{2hc^2}{L\lambda^5}\right)+1\right)}$$

Where, T is the brightness temperature, λ is the wavelength (m), h is Planck's constant, C is the speed of light, K is the Boltzmann constant, and L is the radiance.

To calculate and calibrate SST based on the MCSST model, coefficients derived from the outputs of the ECMWF model were used. These data are available with a spatial resolution of 0.25 degrees in longitude and latitude and have been collected at 00:00 and 12:00 UTC on the first and sixteenth days of every two months since 1996. The coefficients obtained from this process form the basis of the atmospheric correction algorithm used to calculate SST from satellite data. The estimated error for SST values is reported as 0.345 Kelvin (Brown and Minnett, 1999) (Table 1).

Table 1: ECMWF coefficients for estimating SST values with the MCSST algorithm.

	T30 - T31 > 0.7	T30 - T31 <= 0.7
1	1.18	1.11
2	0.99	0.96
3	0.13	0.17
4	1.62	0.87

The algorithm for generating Chl-*a* maps using MODIS sensor data is based on a semi-analytical and bio-optical model. To extract Chl-*a* concentration, the empirical OC3M algorithm for the absorption coefficient of Colored Dissolved Organic Matter (CDOM, also known as Gelbstoff), which was proposed by Carder *et al*. (2003), was used (Equation 3). This algorithm was designed and calibrated based on data from 32,550 points collected from seas and oceans as part of the global SeaBASS project. The predicted error in calculating Chl-*a* values is 0.554 mg/m³ (SeaBASS project, 2006), (Equation 3). The OC3M algorithm was selected because it is one of the most widely used MODIS Chl-*a* retrieval algorithms and has been employed in previous studies of in the southern Caspian Sea. However, in the southern Caspian Sea exhibits Case-2 optical characteristics, particularly in coastal regions affected by river discharge, suspended sediments, and CDOM. Consequently, Chl-*a* estimates in nearshore waters may contain additional uncertainty, which should be considered when

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interpreting the results. The OC3M and MCSST algorithms used in this study are standard MODIS retrieval algorithms that have been widely applied in previous ocean color and SST studies, providing a consistent basis for long-term environmental monitoring.

$$C_a = 10^{0.283-2.753R+1.457R^2+0.659R4} \quad (3)$$

$$R = \log 10 \left[\frac{R_{rs443} > R_{rs488}}{R_{rs551}}\right]$$

C_a is the Chl-*a* concentration in mg/m³, R_r is the remote sensing reflectance, and R is the blue-green band ratio.

In non-parametric trend analysis, no specific statistical distribution is assumed for the time series. The Mann-Kendall test was used to identify monotonic trends, while Pettitt's test was applied to detect abrupt changes in the time series. To reduce the influence of short-term seasonal variability, monthly observations were first aggregated into seasonal datasets prior to trend analysis. The Mann–Kendall test was then applied to the seasonal series, and Pettitt's test was used to identify potential change points.

Results

By applying the aforementioned algorithm, SST values were extracted and corresponding maps were prepared (Fig. 2). Examination of the SST map for January 2007 shows that during the cold season, the northern regions of the Caspian Sea have lower temperatures compared to the southern parts. This temperature pattern is mainly due to higher latitude, reduced solar radiation angle, and the inflow of cold waters from the subpolar regions of the Volga River.

By applying the described algorithm, Chl-*a* values were estimated (Fig. 3).

The Chl-*a* map of the Caspian Sea for January 2007 shows that the highest Chl-*a* concentrations occured in the northwestern regions, due to the proximity to the Volga River delta, the presence of shallow water depths, and the input of urban and agricultural pollutants into these areas (Europe's Environment, 2007). The maps presented for January 2007 are provided as representative examples of the spatial distribution of SST and Chl-*a* because this period exhibited relatively pronounced spatial variability. All statistical analyses, trend detection, and regression analyses were performed using the complete MODIS time series covering 2002–2020.

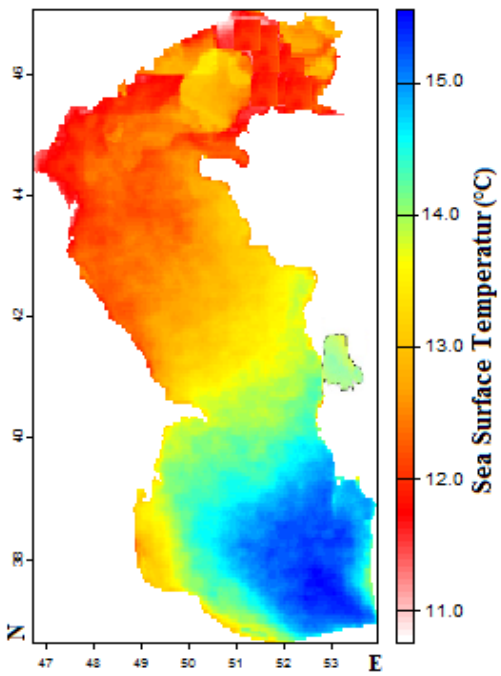

Figure 2: The Caspian Sea SST in January 2007. January 2007 is presented as a representative month to illustrate the spatial distribution patterns. All statistical analyses were based on the complete 2002–2020 MODIS dataset.

Analysis of the monthly Chl-*a* time series showed that the minimum and maximum

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Chl-*a* concentrations at the beginning of the study period had a smaller range compared to the end of the study period (Fig. 4). In other words, the range of variations in 2002 was smaller than that in 2020. The seasonal distribution of Chl-*a* during the study period indicated that winter had the minimum concentration and summer had the maximum concentration. Chl-*a* concentration exhibited an increasing trend, as the mean concentration increased from 2.95 mg/m³ in 2002 to 4.52 mg/m³ in 2020.

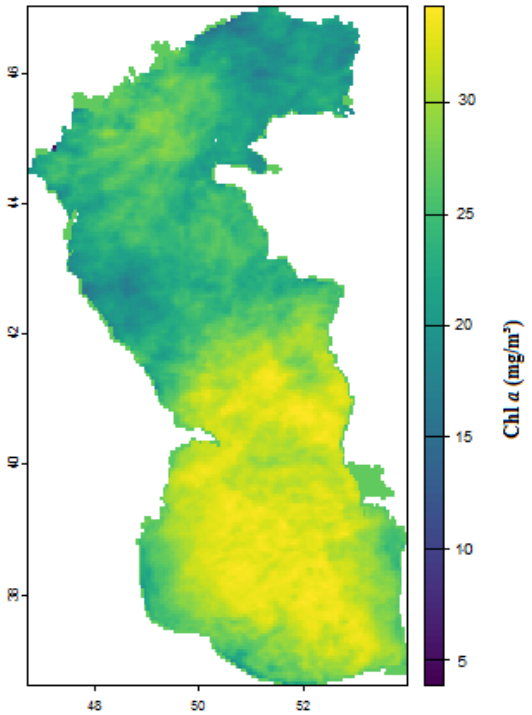

Figure 3: The Caspian Sea Chl-*a* in January 2007.

Due to the specific heat capacity of water, the minimum and maximum water temperatures occur with a time lag relative to land. The minimum monthly SST occurred in February, with one instance in March, while the maximum occurred in August, with one instance in October. The range of SST variations followed a more regular pattern compared to Chl-*a* (Fig. 5A). Furthermore, the minimum SST was observed in winter and the maximum in summer. The slope of temperature change showed a mild positive trend compared to Chl-*a*, with the mean SST increasing from 15.1°C to 16.1°C in 2020 (Fig. 5B).

Based on the calculated p-value for Chl-*a*, the alternative hypothesis (H_a), indicating the presence of a trend, is confirmed at the 1% significance level. However, the Mann-Kendall test for SST indicated rejection of the alternative hypothesis, thus showing no trend (Table 2).

In Pettitt's test, no assumption is made regarding the distribution of the data. This test is based on the Mann–Whitney test and enables the detection of changes in a time series (Pettitt, 1979). According to Table 3, the monthly SST time series did not show statistically significant changes, and H_1 (the alternative hypothesis indicating the presence of changes) is rejected at the 0.05 significance level. However, this hypothesis is confirmed for Chl-*a*, such that a change point (shift) is observable in Chl-*a* around mid-2006, indicating the presence of significant changes in the ecological conditions of the Caspian Sea (Fig. 6A). Based on the above test, no significant changes were observed for SST (Fig. 6B). This indicates that no shift in the temperature trend was observed in the Caspian Sea during the study period. In other words, there were no thermal anomalies in sea water over the study period.

Comparison of the monthly pattern of Chl-*a* concentration with the monthly pattern of SST revealed a correlation, such that as SST increased or decreased, Chl-*a* concentration also showed an increasing or decreasing trend, respectively (Fig. 7A, B). The seasonal moving average also illustrates this relationship (Fig. 8).

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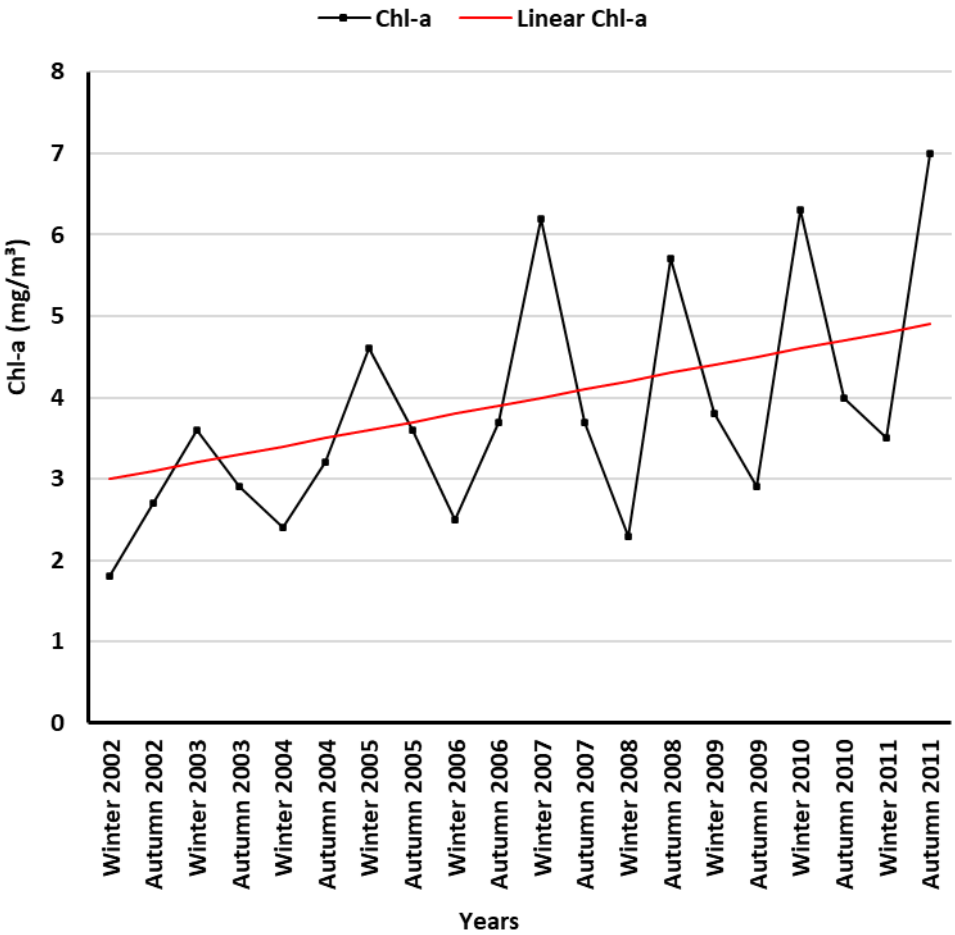
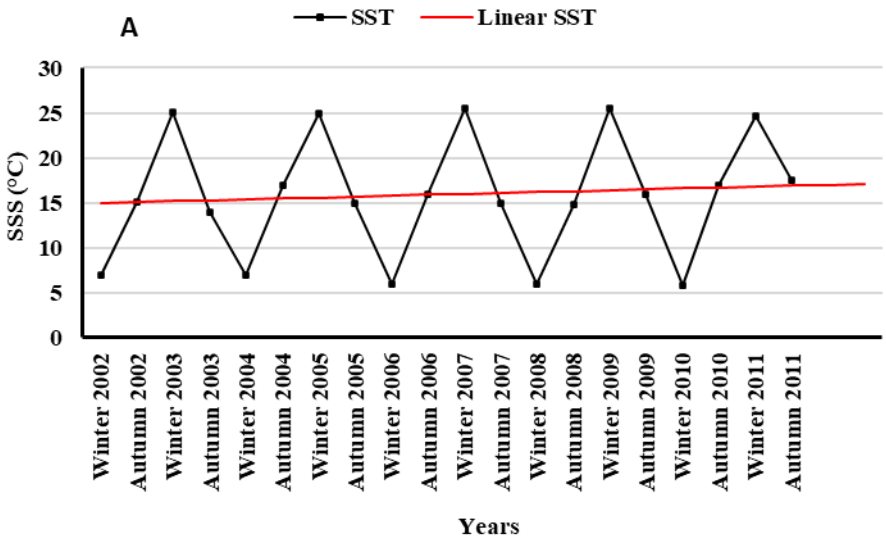


Figure 4: Time series of Chl-*a* in the Caspian Sea.



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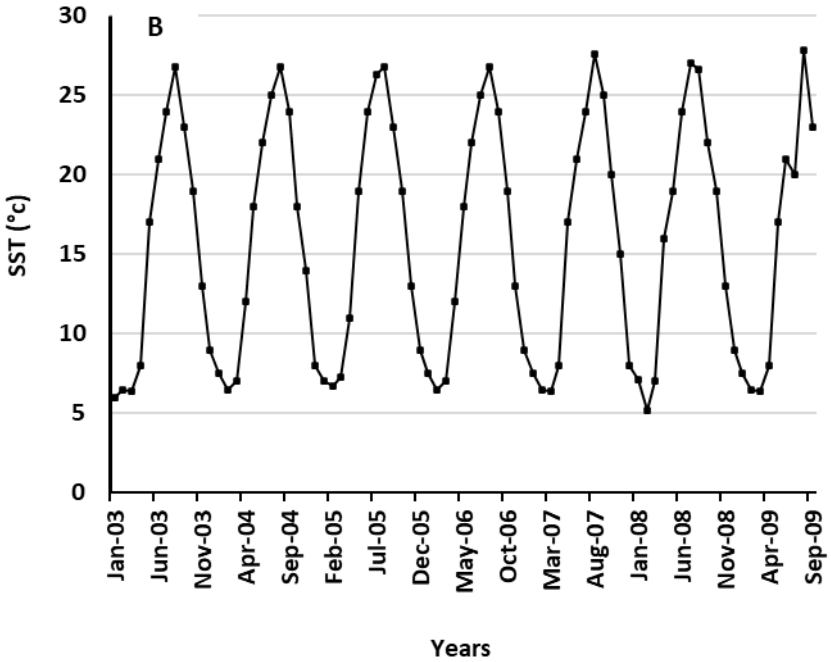


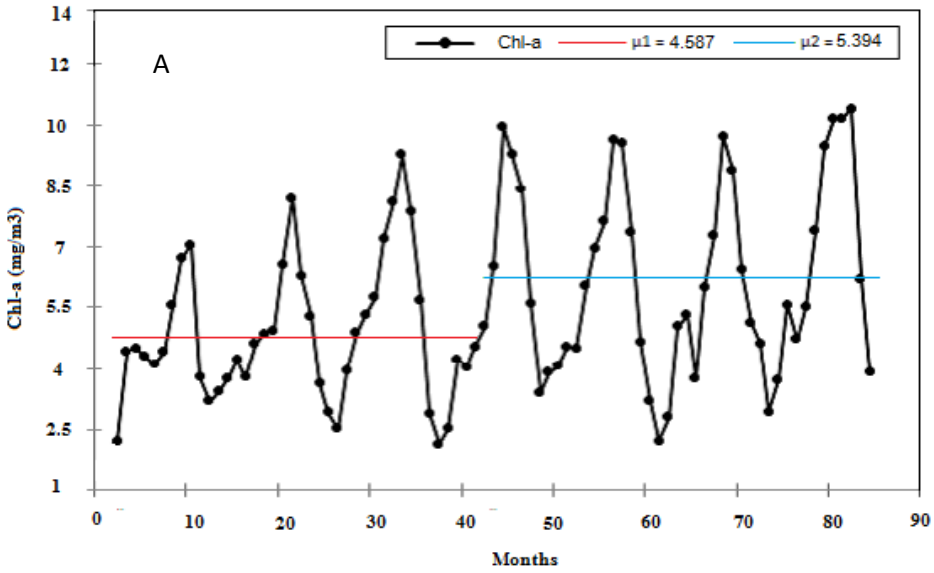
Figure 5: Time series of the Caspian Sea SST.

Table 2: Analyzing seasonal time series trends of Chl-*a* and SST of the Caspian Sea.

	Chl-*a*	SST
Kendall	0.524	0.024
p-value	0.004	0.658
Alpha	0.01	0.01

Table 3: Presenting time series changes of Chl-*a* and SST of the Caspian Sea.

	Chl-*a*	SST
t	35	30
p-value	0.016	0.758
Alpha	0.05	0.05



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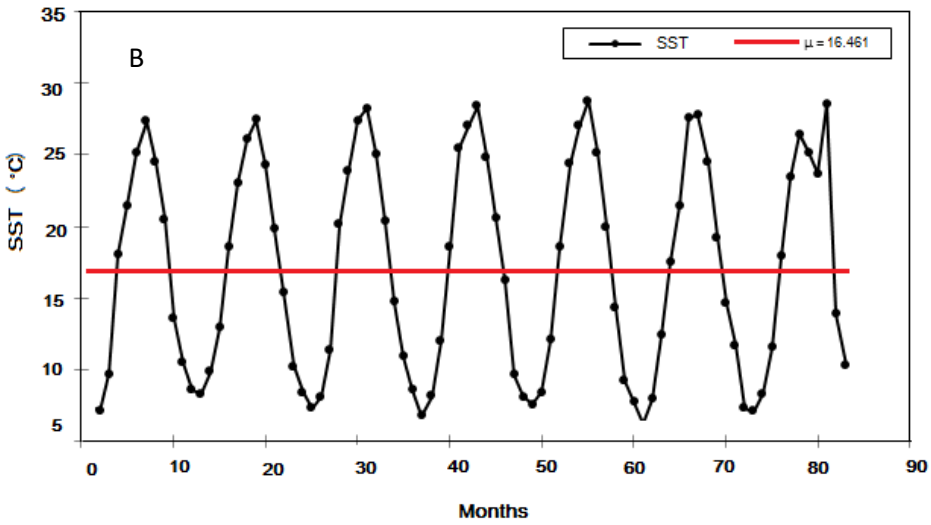

Figure 6: Time series changes of Chl-*a* and SST of the Caspian Sea.

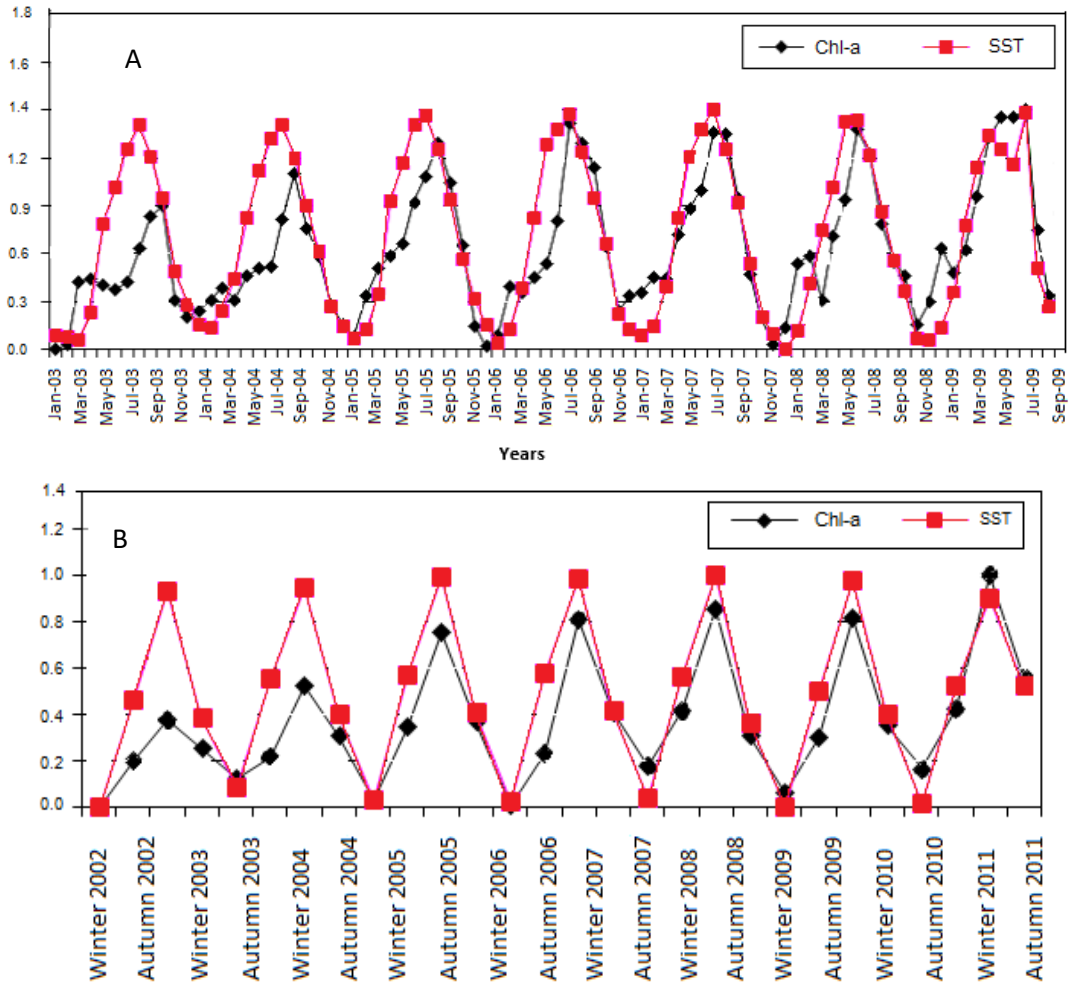

Figure 7: Spatial patterns of SST and Chl-*a* in the Caspian Sea.

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Therefore, linear regression was determined to be the best model for fitting and explaining this relationship (Equation 4, Fig. 8). The root mean square error (RMSE) of the model was 0.88 mg/m³. The adjusted R^2 value indicated that SST explained 56.7% of the observed variability in Chl-*a* concentration. Additionally, the Fisher's F-test confirmed the significance and validity of the relationship (Tables 4 and 5).

$$\text{Chl-}a_{\text{mg/m}^3} = 1.174 + 0.161 \times \text{SST} \quad (4)$$

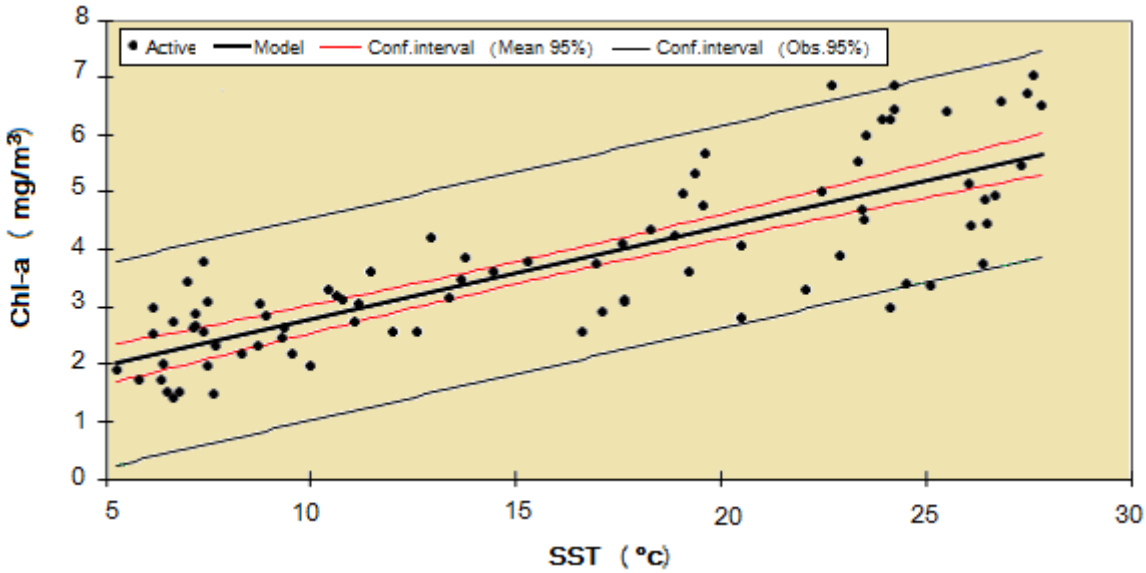

Figure 8: Linear regression relationship between surface temperature and Chl-*a* in the Caspian Sea.

Table 4: Statistical properties of the linear regression model for the the Caspian Sea.

R^2	R^2 Adjusted	RMSE	F	Pr>F
0.575	0.567	0.88	201	<0001

Table 5: Summary of the principal quantitative results for the 2002–2020 study period.

Variable **Study period**	**Main Result** **2002–2020**
Chl-*a*	Increased from 2.95 to 4.52 mg m⁻³
SST	Increased from 15.1 to 16.1 °C
Mann–Kendall (Chl-*a*)	Significant increasing trend ($p = 0.004$)
Mann–Kendall (SST)	No significant trend ($p = 0.658$)
Pettitt's test (Chl-*a*)	Significant change point around mid-2006
Pettitt's test (SST)	No significant change
Regression equation	Chl-*a* = 1.174 + 0.161 × SST
Adjusted R^2	0.567
RMSE	0.88 mg m⁻³
F-test	Significant ($p < 0.001$)

Discussion

Understanding the interactions between SST and Chl-*a* is essential for evaluating ecosystem responses to climate variability because these variables jointly regulate primary productivity and marine ecosystem

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functioning (Harding *et al.,* 1986; Marra *et al.,* 1990).

Long-term satellite observations provide a valuable framework for detecting gradual ecological changes that are difficult to identify through short-term field surveys. The significant increase in Chl-*a* observed in the present study suggests that biological productivity in the southern Caspian Sea has undergone measurable long-term changes during the study period. Because no significant monotonic trend was detected for SST, the observed increase in Chl-*a* is unlikely to be explained by temperature alone. Instead, it probably reflects the combined influence of nutrient availability, hydrological variability, and ecological changes that have been reported for the Caspian Sea during recent decades. Comparable long-term patterns have also been reported by Kideys *et al*. (2008) and Kopelevich *et al.* (2009), supporting the interpretation that Chl-*a* variability is governed by the interaction of multiple physical and biogeochemical processes rather than temperature alone.

Spatial variability in Chl-*a* has also been reported for different regions of the Caspian Sea (Kopelevich *et al.,* 2009), indicating that regional environmental conditions, including hydrology and nutrient availability, play an important role in regulating phytoplankton dynamics. Spatial variability is also evident in the magnitude of monthly and seasonal Chl-*a* fluctuations (Nasrollahzadeh Saravi and Hosseini, 2004), further highlighting the influence of local environmental conditions on phytoplankton dynamics. Since Chl-*a* is a widely accepted proxy for phytoplankton biomass and primary productivity (Longhurst, 1998), the increasing trend observed in this study likely reflects the combined effects of nutrient availability, hydrological variability, and broader ecosystem changes previously reported for the Caspian Sea. However, the present study did not directly evaluate nutrient concentrations or riverine inputs, and therefore no causal relationship can be confirmed. These processes may be further influenced by the enclosed nature of the Caspian Sea, where limited water exchange and relatively weak large-scale circulation can enhance nutrient retention and modify ecosystem dynamics.

The positive association between SST and Chl-*a* suggests that temperature contributes to regulating phytoplankton productivity in the southern Caspian Sea. Interestingly, this positive relationship differs from the inverse relationship commonly reported in many open-ocean environments. In enclosed and semi-enclosed basins, warmer conditions may enhance phytoplankton growth by increasing metabolic rates, prolonging the growing season, and promoting favorable light conditions. In addition, the southern Caspian Sea is influenced by riverine inputs and coastal processes that may contribute to nutrient availability during warm periods. Therefore, higher SST values do not necessarily imply nutrient limitation and may coincide with elevated phytoplankton biomass. Recent studies have reported substantial ecological changes in the Caspian Sea, including declining water levels, altered thermal conditions, and shifts in biological productivity associated with climate change and anthropogenic pressures (Arpe *et al.,* 2020; Kostianoy and Pešić, 2024; Lavrova *et al.,* 2024a). The observed

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increase in Chl-*a* may also reflect broader ecosystem responses to ongoing environmental change in the Caspian Sea, including alterations in stratification patterns, water level decline, and changes in nutrient cycling. Recent satellite-based investigations have likewise reported considerable spatial and temporal variability in Chl-*a* and thermal conditions across the Caspian Sea (Vostokov *et al.,* 2023; Lavrova *et al.,* 2024a,b). These studies suggest that ongoing climate variability, declining water levels, and changing hydrodynamic conditions are modifying ecosystem processes throughout the basin. The present findings are consistent with these observations and further indicate that long-term changes in Chl-*a* are likely driven by multiple interacting environmental factors rather than SST alone.

From an ecological perspective, the increasing Chl-*a* concentration may indicate enhanced primary productivity; however, persistent increases may also reflect a greater risk of eutrophication and harmful algal blooms in coastal areas of the southern Caspian Sea. Such changes could alter food-web structure, affect habitat quality, and influence fisheries resources by modifying the availability of primary food sources. Consequently, continuous satellite monitoring combined with field observations is essential for the early detection of ecosystem changes and for supporting sustainable fisheries management under ongoing climate change. These findings highlight the importance of integrating long-term satellite observations with in situ monitoring into ecosystem assessment programs for the Caspian Sea, thereby improving the assessment of climate-driven changes in primary productivity and supporting sustainable fisheries management in this unique ecosystem.

Conclusions

This study used MODIS satellite data (2002–2020) to analyze the temporal trends of Chl-*a* and SST in the Caspian Sea and to examine the relationship between these two parameters. The results revealed a significant increasing trend in Chl-*a* concentration over the study period, whereas SST showed no significant monotonic trend. The Pettitt's test detected a distinct shift in Chl-*a* dynamics around mid-2006, indicating a notable change in the ecological conditions of the Caspian Sea. Linear regression analysis showed that SST explained approximately 56.7% of the variability in Chl-*a* concentration based on the adjusted R^2, suggesting that temperature plays a modulating role in primary production in this ecosystem. The increasing trend in Chl-*a*, despite the absence of a significant SST trend, suggests that additional environmental drivers beyond temperature may be involved. These may include nutrient enrichment, hydrological variability, and anthropogenic pressures previously reported for the Caspian Sea. The enclosed nature of the Caspian Sea may enhance nutrient retention and potentially increase the susceptibility of the ecosystem to eutrophication and harmful algal blooms under favorable environmental conditions. These findings have important implications for fisheries management and environmental conservation. Future studies should integrate satellite data with in-situ measurements and focus on regional-scale analyses to better

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understand local drivers of Chl-*a* dynamics in this unique basin.

Conflicts of interest

The authors declare no conflicts of interest.

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