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Seasonal and Interannual Variability of Coastal Black Sea Waters off Bulgaria (2022–2025): A Copernicus Marine Reanalysis Assessment

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Abstract

This study assessed spatial, seasonal, and interannual variability in physical and biogeochemical indicators in surface waters along the Bulgarian Black Sea coast during 2022–2025 to provide an integrated characterization of coastal marine conditions. Copernicus Marine Level 4 multiyear reanalysis products at $0.025^\circ \times 0.025^\circ$ resolution were aggregated into four climatological seasons and summarized for a 25 km coastal strip divided at Cape Emine into northern and southern sectors. Sea-water potential temperature increased from a four-year winter mean of 9.02°C to 24.70°C in summer, with the southern sector warmer in all 16 season–year comparisons. Salinity peaked in winter (18.276×10^{-3}) and was lowest in summer (17.684×10^{-3}), with consistently higher values in the south. Current-vector magnitude was highest in summer (0.0614 m s^{-1}), without persistent sectoral predominance. Chlorophyll-a, net primary production, phytoplankton carbon biomass, and dissolved molecular oxygen peaked in spring and were consistently higher in the northern sector; nitrate was also higher there in 15 of 16 comparisons. Biological productivity peaked in spring 2024, while 2025 showed lower biological indicators than 2022 across all season–sector combinations. The four-year series does not support long-term trend inference but provides a reproducible framework for integrated coastal assessment.

Keywords: Bulgarian Black Sea coast; Copernicus Marine; marine reanalysis; coastal oceanography; seasonal variability; coastal circulation; biogeochemical indicators; phytoplankton productivity



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1. Introduction

The Black Sea is one of the world's largest semi-enclosed marine basins. It is characterised by a distinctive vertical structure, limited water exchange with the Mediterranean Sea, and complex interactions among atmospheric processes, riverine inflow, marine circulation, and biological productivity [1–3]. Substantial freshwater inflow, persistent haline stratification, and restricted exchange through the Bosphorus make the Black Sea ecosystem particularly sensitive to natural variability and anthropogenic pressures. The western basin, including the Bulgarian Black Sea coast, exhibits pronounced spatial, seasonal, and interannual variability in its physical and biogeochemical conditions [4,5].

The hydrographic regime of the western Black Sea is governed by atmospheric circulation, air–sea heat exchange, river discharge, vertical mixing, and the regional current system. The main Black Sea current, commonly known as the Rim Current, together with associated mesoscale circulation structures, plays an important role in controlling water-mass transport [6–8]. Seasonal and interannual variations in the intensity and spatial position of these currents influence the transport and distribution of heat, salts, nutrients, suspended matter, and biological components.

Freshwater inflows from the Danube, Dnieper, and Dniester strongly influence the northwestern Black Sea shelf by supplying nutrients and suspended material that affect surface-water salinity, transparency, and biological productivity [5,9]. Although the Bulgarian coast lies south of the major river mouths, river-influenced waters and associated substances may be transported southward along the western shelf. Bulgarian coastal waters are also affected more locally by smaller rivers, including the Kamchiya, and by exchanges with coastal lakes and bays [10,11].

Seasonal variations in temperature, vertical mixing, and upper-layer stability are among the principal controls on the coastal marine environment. During the cold season, surface-water cooling generally enhances vertical mixing and the redistribution of dissolved substances and gases within the water column. During the warm season, increasing temperatures promote thermal stratification and restrict vertical exchange. These processes affect nutrient availability, phytoplankton biomass, chlorophyll-a, and dissolved oxygen [2,3]. However, relationships between physical conditions and biological productivity are complex. Increased temperature and light availability may favour phytoplankton growth, whereas prolonged stratification may restrict nutrient supply from deeper layers. Conversely, winter mixing may replenish nutrients in surface waters and establish conditions favourable for subsequent phytoplankton development. Seasonal changes in chlorophyll-a and phytoplankton biomass therefore need to be interpreted in relation to the combined effects of light availability, nutrients, vertical mixing, riverine inputs, and horizontal water-mass transport rather than temperature alone [12,13].

The Black Sea ecosystem has undergone substantial long-term changes in biological productivity and ecological state. During the second half of the twentieth century, increased nutrient inputs, eutrophication, overfishing, and changes in trophic structure resulted in major ecosystem transformations [9,14–16]. Subsequent changes in anthropogenic pressures and climatic conditions contributed to partial recovery, although considerable spatial and temporal variability has persisted [17,18]. Studies of Bulgarian coastal waters have similarly documented variability in temperature, salinity, dissolved oxygen, nutrients, and phytoplankton biomass. Shtereva et al. [19] identified seasonal and spatial differences in hydrochemical and biological characteristics in the Varna Bay and Galata area, while Dineva [10] demonstrated the importance of river discharge for long-term variations in surface salinity. Together, these findings underline the need to consider physical and biogeochemical indicators jointly rather than in isolation.

The Bulgarian coastal marine environment is subject to multiple anthropogenic pressures, including urbanisation, agriculture, port activities, shipping, tourism, and wastewater discharges [10,11,20,21]. Recent studies have also documented plastic litter and microplastics along the Bulgarian coast and in marine sediments, particularly near urbanised areas and river mouths [22–25]. However, the physical and biogeochemical indicators analysed here cannot identify specific pollution sources or quantify pollution levels. Elevated chlorophyll-a or phytoplankton biomass may reflect nutrient inputs, but may also arise from natural seasonal dynamics, circulation, or interannual variability; potential anthropogenic influences therefore require cautious interpretation alongside targeted field observations.

Conventional in situ observations provide detailed information at specific locations and depths, but their spatial and temporal coverage is often limited. Remote sensing, numerical modelling, and data-assimilation systems complement these observations by providing spatially and temporally consistent information on physical and biogeochemical variables [26–28].

Copernicus Marine products integrate numerical modelling, satellite and in situ observations, and data assimilation to provide consistent datasets for analysing temperature, salinity, circulation, nutrients, oxygen conditions, and biological productivity. This makes them particularly suitable for regional comparisons among seasons, years, and coastal sectors, although their model-based nature and spatial resolution must be considered in heterogeneous nearshore environments.

Despite the increasing availability of spatial oceanographic datasets, previous investigations of Bulgarian Black Sea waters have frequently focused on individual monitoring stations, specific bays or coastal sections, particular time periods, or limited groups of physical or biogeochemical variables. Consequently, the extent to which persistent north–south spatial contrasts interact with seasonal cycles and interannual fluctuations along the Bulgarian coast remains insufficiently characterised within a single, internally consistent analytical framework.

The novelty of this study lies in jointly assessing physical and biogeochemical surface-water characteristics across the Bulgarian coastal zone using a consistent Copernicus Marine Level 4 multiyear reanalysis framework. By integrating multiple physical, nutrient, oxygen, and biological-productivity indicators with seasonal, interannual, and north–south sector comparisons, the analysis enables persistent spatial contrasts to be distinguished from seasonal variability and year-to-year fluctuations. This integrated approach provides a broader coastal-scale perspective than studies restricted to individual stations, bays, coastal sections, or separate groups of environmental indicators.

The primary objective of this study was therefore to assess the spatial, seasonal, and interannual variability of selected physical and biogeochemical surface-water indicators along the Bulgarian Black Sea coast during 2022–2025 using Copernicus Marine Level 4 multiyear reanalysis products. The analysis included seawater potential temperature, salinity, surface circulation, chlorophyll-a, phytoplankton carbon biomass, net primary production, dissolved oxygen, nitrate, and phosphate, with particular attention to seasonal contrasts and differences between the northern and southern coastal sectors.

Accordingly, the study addressed four research questions: (1) How do the main physical and biogeochemical surface-water indicators vary seasonally along the Bulgarian Black Sea coast? (2) Are there persistent differences between the northern and southern coastal sectors? (3) How do the observed physical and biogeochemical patterns vary among individual years during 2022–2025? (4) What qualitative correspondence can be identified between seasonal physical conditions, nutrient concentrations, and indicators of biological productivity?

The four-year study period permits assessment of interannual fluctuations but is insufficient for identifying long-term climatic trends. The results are therefore interpreted as characteristics of spatial, seasonal, and interannual variability during 2022–2025, while potential longer-term climatic influences are considered only in the context of previous research.

2. Materials and Methods

2.1. Study Area and Spatial Delineation

The study covered the coastal marine strip along the Bulgarian Black Sea coast, extending from the national border with Romania in the north to the national border with Türkiye in the south. The analytical area was defined as a 25 km-wide marine coastal

strip measured from the shoreline. This width was chosen to represent the near-coastal zone under the strongest direct terrestrial and riverine influence, as distinct from the wider shelf regime (the Bulgarian shelf itself extends approximately 40–60 km offshore), while retaining sufficient raster coverage (582 and 432 valid cells in the northern and southern sectors, respectively) for stable sector-level statistics. The landward portion of the buffer was removed, and the final marine polygon was restricted to the Bulgarian coastal section. For spatial comparison, the area was divided at Cape Emine into northern and southern sectors (Figure 1).

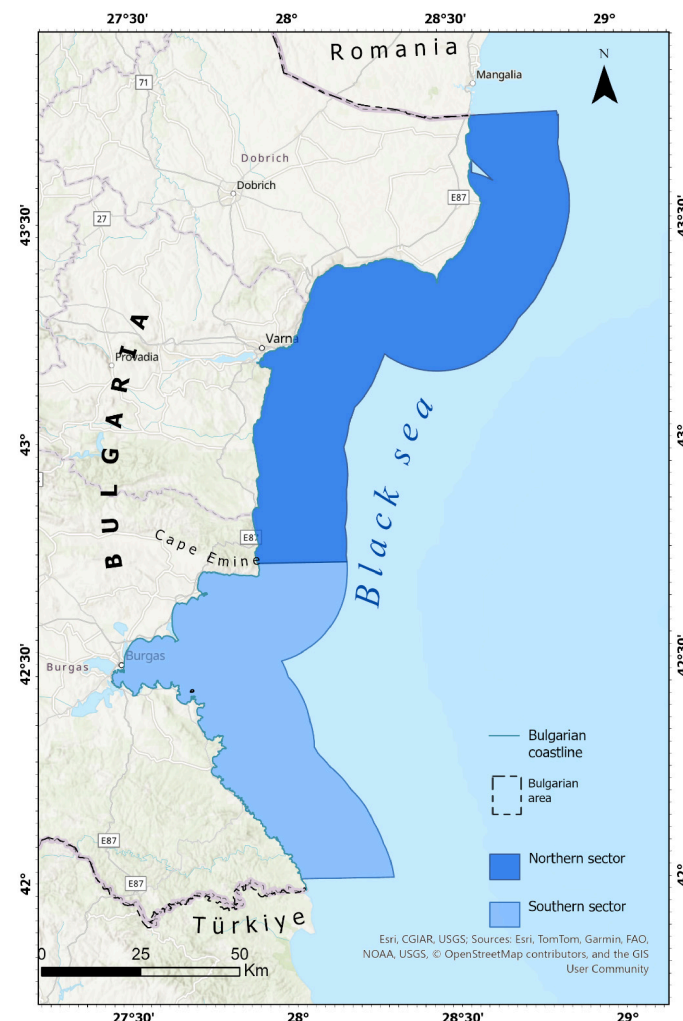


Figure 1. Study area and coastal sectors.

The northern sector extended from the Bulgarian-Romanian border to Cape Emine, and the southern sector from Cape Emine to the Bulgarian-Turkish border. Cape Emine was selected as the sectoral boundary because it marks the point where the Balkan Mountain range (Stara Planina) terminates at the Black Sea coast, and it is widely recognised in the regional geographical literature as the conventional divide between the northern and southern Bulgarian Black Sea coast, corresponding to a shift in coastal geomorphology from predominantly rocky, cliff-bound shores in the north to lower-lying sandy shores in the south.

The shoreline and sector polygons were processed in—ArcGIS Pro 3.1.0 (Esri, Redlands, CA, USA) using the WGS 1984 UTM Zone 35N projected coordinate system (EPSG:32635). The final polygon layers were used as zones for statistical aggregation. The initial rectan-

gular extent of the downloaded data was 27.4–29.5° E and 41.8–44.0° N; only raster cells within the two coastal sectors were included in the analysis.

2.2. Data Sources and Characteristics

Copernicus Marine Service Level 4 multiyear reanalysis products were used as the primary data source. The datasets were downloaded through the Copernicus Marine Data Store in NetCDF-4 format compliant with CF-1.11. These products are outputs of numerical modelling and data-assimilation procedures rather than direct measurements at individual monitoring stations.

Physical variables were obtained from the Black Sea Physics Reanalysis product (Product ID: BLKSEA_MULTIYEAR_PHY_007_004; [29]), whereas biogeochemical variables were obtained from the Black Sea Biogeochemistry Reanalysis product (Product ID: BLKSEA_MULTIYEAR_BGC_007_005; [30]). Both products have a spatial resolution of $0.025^\circ \times 0.025^\circ$ (approximately 2.5 km) and a monthly temporal resolution. The specific datasets, variables, units, and surface levels used in the analysis are summarised in Table 1.

Table 1. Copernicus Marine datasets used in the analysis.

Indicator	Variable	Unit	Dataset ID	Surface Level
Sea-water potential temperature	thetao	°C	cmems_mod_blk_phy-temp_my_2.5km_P1M-m_202411	0.5002 m
Salinity	so	10^{-3}	cmems_mod_blk_phy-sal_my_2.5km_P1M-m_202411	0.5002 m
Eastward current component	uo	m s^{-1}	cmems_mod_blk_phy-cur_my_2.5km_P1M-m_202411	0.5002 m
Northward current component	vo	m s^{-1}	cmems_mod_blk_phy-cur_my_2.5km_P1M-m_202411	0.5002 m
Chlorophyll-a	chl	mg m^{-3}	cmems_mod_blk_bgc-plankton_my_2.5km_P1M-m_202311	0.2546 m
Phytoplankton carbon biomass	phyc	mmol m^{-3}	cmems_mod_blk_bgc-plankton_my_2.5km_P1M-m_202311	0.2546 m
Net primary production	nppv	$\text{mg m}^{-3} \text{ day}^{-1}$	cmems_mod_blk_bgc-bio_my_2.5km_P1M-m_202311	0.2546 m
Dissolved molecular oxygen	o2	mmol m^{-3}	cmems_mod_blk_bgc-bio_my_2.5km_P1M-m_202311	0.2546 m
Nitrate	no3	mmol m^{-3}	cmems_mod_blk_bgc-nut_my_2.5km_P1M-m_202311	0.2546 m
Phosphate	po4	mmol m^{-3}	cmems_mod_blk_bgc-nut_my_2.5km_P1M-m_202311	0.2546 m

The physical variables were extracted from the uppermost available model level at 0.5002 m, whereas the biogeochemical variables were obtained from the uppermost model level at 0.2546 m. The physical files were downloaded on 6 and 7 August 2026, and the biogeochemical files on 7 August 2026.

Each source file contained 48 monthly time slices covering the period from 1 December 2021 to 1 November 2025. December 2021 was included to construct the winter season of 2022. The original datasets were arranged on a regular geographic longitude–latitude grid. Projection to WGS 1984 UTM Zone 35N was used for vector-based spatial operations and cartographic presentation without interpolation or modification of the values on the native raster grid.

2.3. Seasonal Aggregation and Multidimensional Raster Processing

The NetCDF files were imported into ArcGIS Pro as multidimensional rasters. For all variables, only the downloaded surface level was selected (StdZ = 1). Monthly values were aggregated using the Aggregate Multidimensional Raster tool with the Mean statistic into four climatological seasons: DJF (December of the preceding year, January, and February), MAM (March, April, and May), JJA (June, July, and August), and SON (September, October, and November).

This procedure produced 16 seasonal time slices for each variable, corresponding to four seasons for each year from 2022 to 2025, and one vertical level (StdTime = 16; StdZ = 1). Intermediate and final multidimensional rasters were stored in Cloud Raster Format (CRF).

NoData values, land cells, and raster cells outside the final coastal-sector polygons were excluded from statistical processing. No spatial interpolation, smoothing, or conversion of raster cells into artificial sampling stations was performed. The analysis therefore retained the values represented on the native model grid.

For the seasonal temperature climatology map, the four seasonal rasters corresponding to each climatological season were averaged across 2022–2025. A common colour-scale range was applied to all seasonal panels to facilitate direct spatial comparison.

2.4. Sector-Level Statistics and Comparative Analysis

Sector-level statistics were calculated for each indicator, season, and year using the Zonal Statistics as Table tool in ArcGIS Pro. The resulting tables included the number of valid raster cells (COUNT), area, minimum, maximum, range, mean, standard deviation, sum, median, and 90th percentile. The sectoral arithmetic mean was used as the principal metric for subsequent spatial, seasonal, and interannual comparisons.

The northern sector contained 582 valid raster cells and the southern sector 432. Each of the ten primary variables yielded 32 sector–season–year observations, corresponding to two sectors, four seasons, and four years. Together with the derived current-vector magnitude, the analytical dataset contained 352 records.

Current-vector magnitude was calculated separately for each raster cell from the seasonally averaged eastward and northward current components as:

$$S_i = \sqrt{(\bar{u}_i)^2 + (\bar{v}_i)^2} \quad (1)$$

where $\bar{u}_i$ and $\bar{v}_i$ are the seasonal means of the u_o and v_o components in cell i ; the S_i values were subsequently averaged spatially within each sector.

The indicator represents the mean magnitude of the local seasonal vectors and is not equivalent to the mean instantaneous current speed within the season.

The sectoral difference was defined as the northern-sector value minus the southern-sector value:

$$\Delta X = X_N - X_S \quad (2)$$

where X_n and X_s are the respective sectoral means.

A positive value indicates a higher value in the northern sector, whereas a negative value indicates a higher value in the southern sector. The symmetric relative sectoral difference was calculated relative to the mean absolute value of the two sectors:

$$D = (X_n - X_s) / ((X_n + X_s) / 2) \times 100\% \quad (3)$$

Relative differences were interpreted cautiously for values close to zero and for the sign-changing current components. Interannual change was represented primarily by the difference between 2025 and 2022 for identical season–sector combinations. Four-

year seasonal means, interannual standard deviations, minima, maxima, and coefficients of variation were also calculated. To assess whether the direction of the north–south differences departed from an even split across the 16 season–year pairs, a two-tailed exact sign test was applied separately to each indicator ($\alpha = 0.05$). Given the short four-year time series, no statistical significance tests for long-term trends or correlation analyses were performed; the results are descriptive and comparative.

2.5. Quality Control and Reproducibility

Following the merging of the sectoral statistical tables, data quality and structural consistency were checked before comparative analysis. The uniqueness of each indicator–sector–year–season combination, the total number of records, and the presence of missing values were verified. No duplicate indicator–sector–year–season combinations or missing sectoral seasonal means were identified.

The analytical workbook was organised into separate worksheets containing the source data, seasonal climatology, interannual changes, and north–south comparisons. Maps and graphs were prepared using consistent terminology for sectors, seasons, indicators, and measurement units.

The workflow was designed to support reproducibility. The Copernicus Marine Product IDs and Dataset IDs, temporal coverage, spatial resolution, selected vertical levels, seasonal aggregation procedure, coordinate reference system, and spatial delineation of the coastal sectors are reported above. These parameters, together with the sector polygons, provide the information required to reproduce the principal processing and statistical steps.

2.6. Methodological Scope

The analysis was designed to characterize regional-scale spatial, seasonal, and interannual variability in surface waters using the spatial and temporal resolution of the selected Copernicus Marine reanalysis products. Accordingly, the results represent broad coastal-sector patterns rather than local conditions at individual beaches, bays, river mouths, or monitoring stations. The analysis was restricted to the selected surface model levels and did not address the vertical structure of the water column. These methodological boundaries were considered when interpreting the results.

3. Results

3.1. Seasonal Variability of Physical Indicators

Sea-water potential temperature in the surface layer followed a pronounced annual cycle (Figure 2). The mean across both sectors and the entire study period increased from 9.02 °C in winter to 11.35 °C in spring and reached a maximum of 24.70 °C in summer. The autumn mean remained relatively high at 19.95 °C. The highest sectoral value, 25.85 °C, occurred in the southern sector in summer 2024, whereas the lowest, 8.46 °C, occurred in the northern sector in winter 2022. The southern sector was warmer than the northern sector in all 16 season–year comparisons. The mean difference between the two sectors was 0.36 °C, with individual values ranging from 0.15 to 0.64 °C. Thus, the spatial differentiation in temperature persisted throughout the study period, although its absolute magnitude was substantially smaller than that of the seasonal variation.

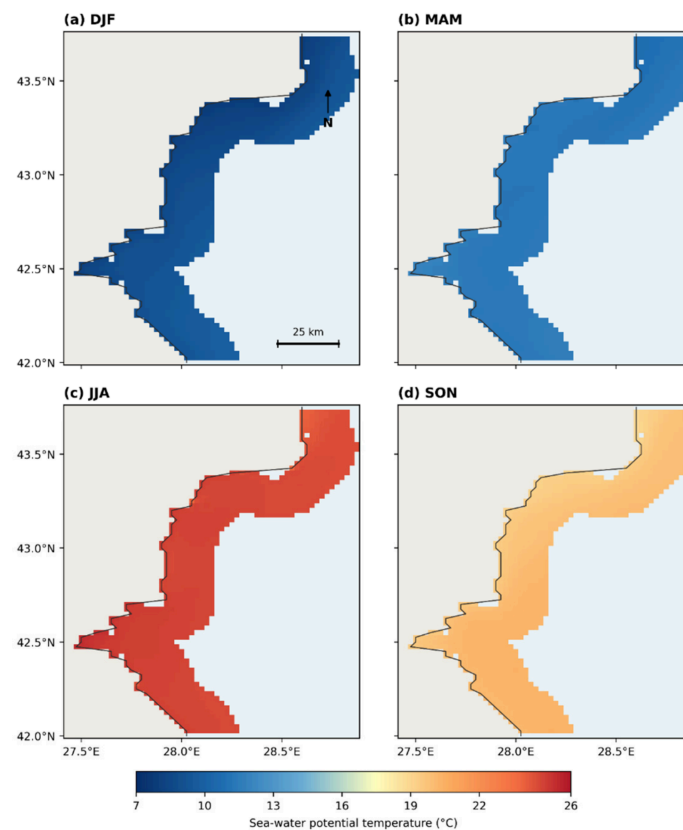


Figure 2. Seasonal climatology of surface-water temperature along the Bulgarian Black Sea coast during 2022–2025: (a) DJF, (b) MAM, (c) JJA, and (d) SON. White cells within the analysed marine area represent NoData values.

Salinity displayed a less pronounced, yet clearly distinguishable, seasonal cycle (Figure 3). The highest mean value occurred in winter (18.276×10^{-3}), followed by autumn (18.214×10^{-3}). Lower values occurred in spring (17.789×10^{-3}) and summer (17.684×10^{-3}). The absolute maximum, 18.613×10^{-3} , was recorded in the southern sector in winter 2024, and the minimum, 17.244×10^{-3} , in the northern sector in summer 2023. As with temperature, salinity was higher in the southern sector in all 16 comparisons. The mean difference between the northern and southern sectors was 0.198×10^{-3} and reached 0.525×10^{-3} in individual season–year combinations. The magnitude of the seasonal-mean current vector ranged from 0.0465 m s^{-1} in spring to 0.0614 m s^{-1} in summer. The winter and autumn means were 0.0546 and 0.0497 m s^{-1} , respectively. The highest value, 0.1014 m s^{-1} , occurred in the northern sector in summer 2025, whereas the lowest, 0.0155 m s^{-1} , occurred in the southern sector in spring of the same year. Unlike temperature and salinity, current speed showed no persistent sectoral predominance: it was higher in the southern sector in 10 of the 16 comparisons and in the northern sector in the remaining six. The components of the seasonal-mean vector varied in both magnitude and direction (Figure 3). The eastward component, u_0 , ranged from -0.0448 to 0.0256 m s^{-1} , and the northward component, v_0 , from -0.0853 to 0.0878 m s^{-1} . Sign reversals in both components among seasons and years indicate changes in the prevailing direction of the seasonally averaged current.

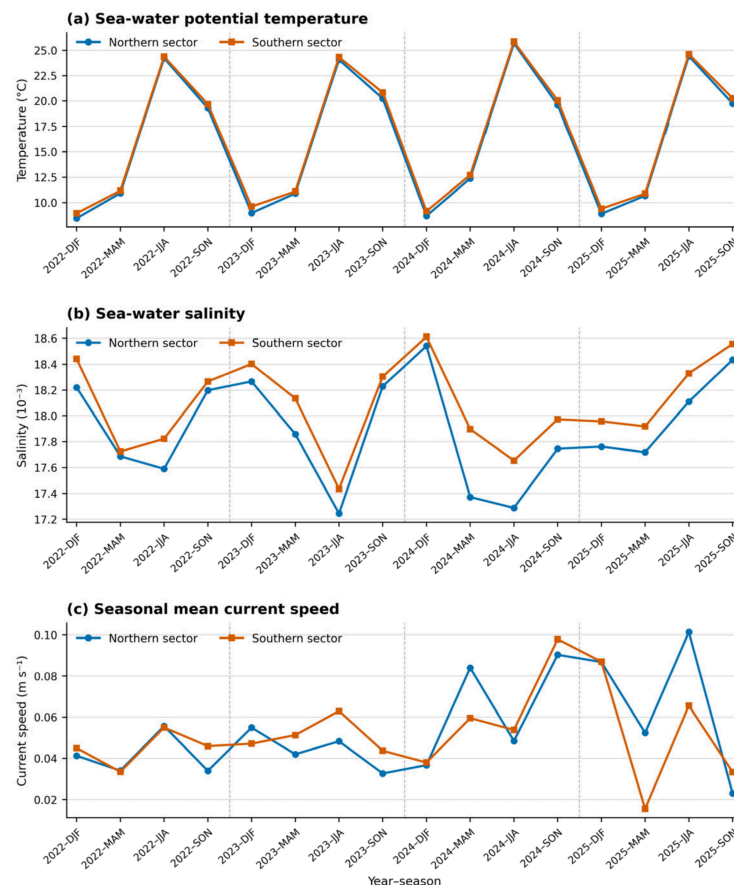


Figure 3. Seasonal and interannual variability of physical indicators in the northern and southern sectors of the Bulgarian Black Sea coast during 2022–2025: (a) sea-water potential temperature, (b) salinity, and (c) magnitude of the seasonal-mean current vector. Vertical dashed lines separate consecutive years.

3.2. Seasonal Variability of Biogeochemical Indicators

Chlorophyll-a exhibited a spring maximum, with a mean value of 2.875 mg m^{-3} (Figure 4). The mean concentration was 2.041 mg m^{-3} in winter and 1.887 mg m^{-3} in autumn, while the seasonal minimum of 1.350 mg m^{-3} occurred in summer. The highest value for the entire period, 5.608 mg m^{-3} , was recorded in the northern sector in spring 2024. The minimum of 0.290 mg m^{-3} occurred in the southern sector in summer 2025. Net primary production also reached its maximum in spring, averaging $44.021 \text{ mg m}^{-3} \text{ day}^{-1}$. The mean was $35.313 \text{ mg m}^{-3} \text{ day}^{-1}$ in autumn and $26.726 \text{ mg m}^{-3} \text{ day}^{-1}$ in winter, decreasing to $23.367 \text{ mg m}^{-3} \text{ day}^{-1}$ in summer. The absolute maximum of $80.666 \text{ mg m}^{-3} \text{ day}^{-1}$ occurred in the northern sector in spring 2024. The minimum of $8.195 \text{ mg m}^{-3} \text{ day}^{-1}$ occurred in the southern sector in summer 2025. Phytoplankton carbon biomass displayed a spring maximum of $25.370 \text{ mmol m}^{-3}$. The mean was $17.247 \text{ mmol m}^{-3}$ in summer and $15.940 \text{ mmol m}^{-3}$ in autumn, while the lowest seasonal value, $10.544 \text{ mmol m}^{-3}$, occurred in winter. The maximum for an individual season-sector combination was $53.979 \text{ mmol m}^{-3}$ in the northern sector in spring 2024. The minimum of $3.367 \text{ mmol m}^{-3}$ occurred in the southern sector in summer 2025. Dissolved molecular oxygen also exhibited pronounced seasonality. The highest mean concentration, $333.407 \text{ mmol m}^{-3}$, occurred in spring, followed by $314.643 \text{ mmol m}^{-3}$ in winter. The mean decreased to $255.344 \text{ mmol m}^{-3}$ in autumn and reached a minimum of $248.364 \text{ mmol m}^{-3}$ in summer. The highest value during the study period, $347.747 \text{ mmol m}^{-3}$, occurred in the northern sector in spring 2022, and the lowest, $241.624 \text{ mmol m}^{-3}$, in the southern sector in summer 2024. Spring therefore

emerged as the season with the highest mean chlorophyll-a, net primary production, phytoplankton biomass, and dissolved-oxygen values. Chlorophyll-a, net primary production, and oxygen reached their seasonal minima in summer, whereas phytoplankton biomass had its lowest four-year seasonal mean in winter.

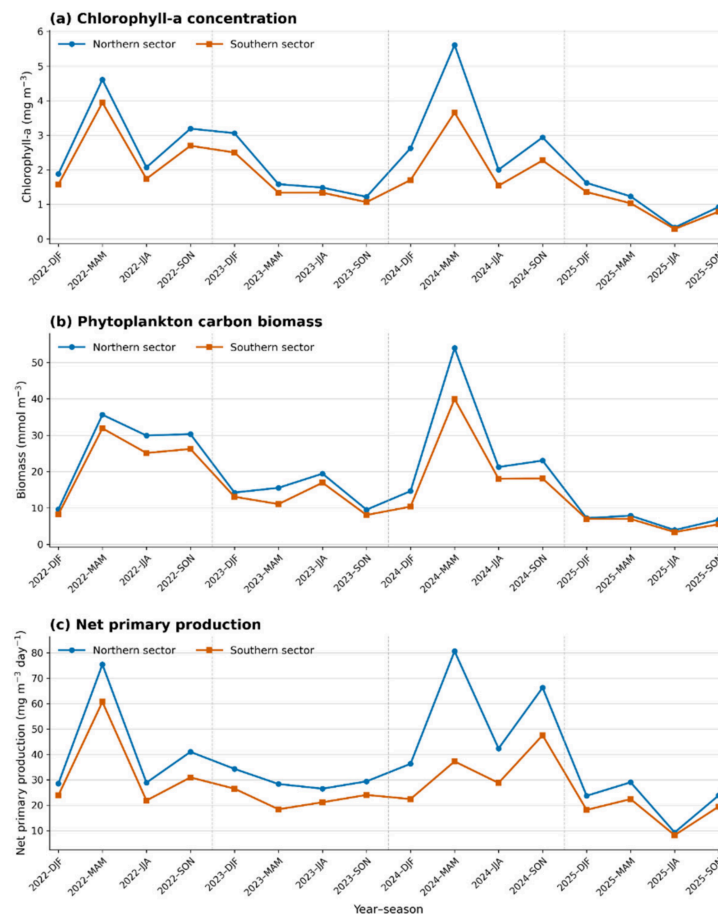


Figure 4. Seasonal and interannual variability of biological indicators: (a) chlorophyll-a concentration, (b) phytoplankton carbon biomass, and (c) net primary production. Vertical dashed lines separate consecutive years.

3.3. Variability of Nutrients

Nitrate had its highest mean concentration in spring, at $13.410 \text{ mmol m}^{-3}$ (Figure 5). The mean decreased to $8.586 \text{ mmol m}^{-3}$ in summer and was $5.222 \text{ mmol m}^{-3}$ in winter, while the seasonal minimum of $2.809 \text{ mmol m}^{-3}$ occurred in autumn. The highest value, $17.528 \text{ mmol m}^{-3}$, was recorded in the northern sector in spring 2024. The lowest value, $0.339 \text{ mmol m}^{-3}$, occurred in the southern sector in winter of the same year. The seasonal pattern of phosphate differed from that of nitrate. The highest mean concentration, $0.286 \text{ mmol m}^{-3}$, occurred in winter. It decreased to $0.155 \text{ mmol m}^{-3}$ in spring and $0.038 \text{ mmol m}^{-3}$ in autumn, reaching a minimum of $0.016 \text{ mmol m}^{-3}$ in summer. The absolute maximum of $0.388 \text{ mmol m}^{-3}$ was recorded in the northern sector in winter 2025, and the minimum of $0.004 \text{ mmol m}^{-3}$ in the same sector in summer 2022.

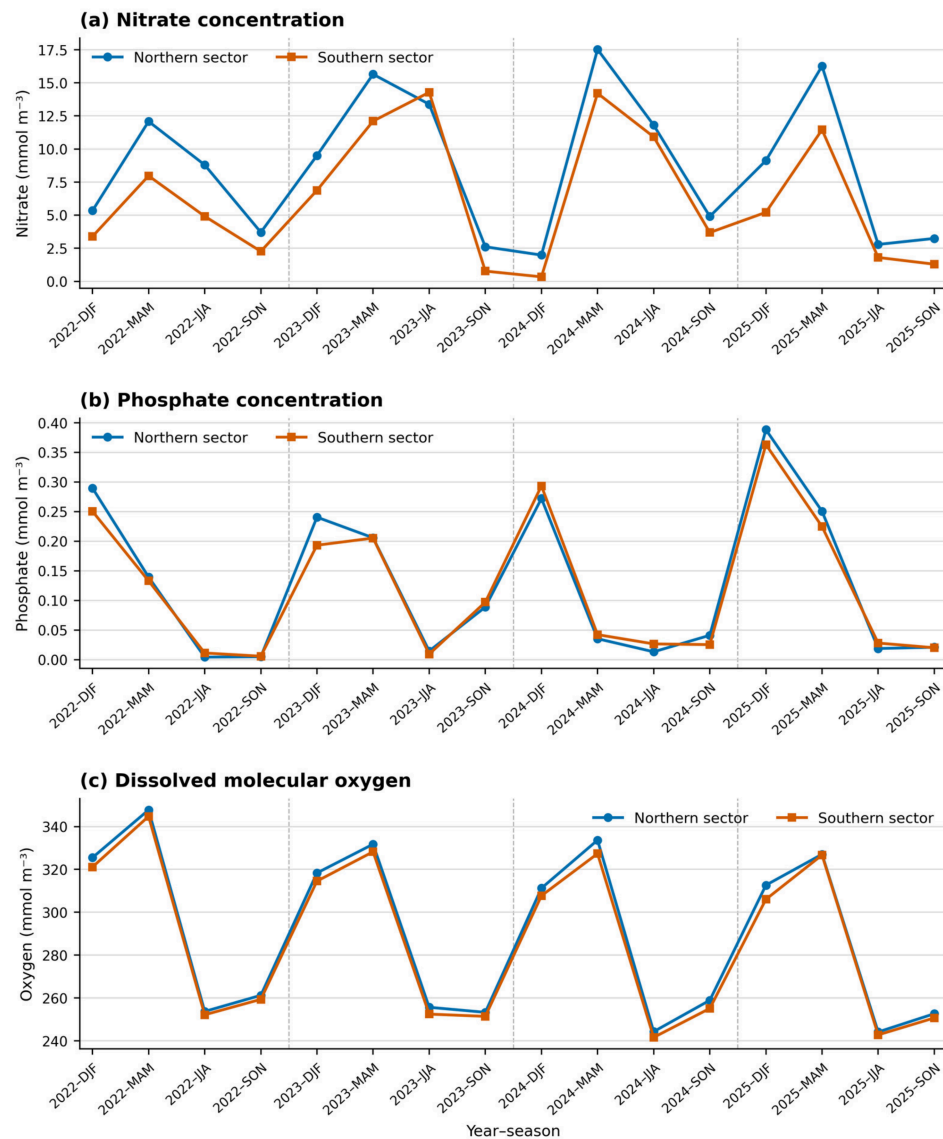


Figure 5. Seasonal and interannual variability of nutrients and oxygen: (a) nitrate, (b) phosphate, and (c) dissolved molecular oxygen. Vertical dashed lines separate consecutive years.

3.4. Differences Between the Northern and Southern Sectors

The most persistent spatial differences were observed for the indicators associated with biological productivity. Chlorophyll-a, net primary production, phytoplankton biomass, and dissolved oxygen were higher in the northern sector in all 16 season–year comparisons.

The mean difference between the northern and southern sectors was:

- 0.471 mg m⁻³ for chlorophyll-a;
- 10.759 mg m⁻³ day⁻¹ for net primary production;
- 3.311 mmol m⁻³ for phytoplankton biomass;
- 3.109 mmol m⁻³ for dissolved oxygen.

Nitrate was also higher in the northern sector in 15 of the 16 comparisons, with a mean sectoral difference of 2.327 mmol m⁻³. A two-tailed exact sign test applied to the direction of the 16 paired sector–season–year differences confirmed that the sectoral predominance was statistically significant for temperature, salinity, chlorophyll-a, net primary production, phytoplankton biomass, and dissolved oxygen (16 of 16 comparisons; $p \approx 0.00003$ in each case) and for nitrate (15 of 16; $p \approx 0.0005$), whereas phosphate (9 of 16) and current speed

(10 of 16) did not differ significantly from an even split ($p > 0.4$), consistent with the absence of persistent sectoral predominance described above.

The spatial distribution of phosphate was more heterogeneous: values were higher in the northern sector in nine comparisons and in the southern sector in seven. Temperature and salinity showed opposite yet entirely consistent spatial patterns. The southern sector was warmer and more saline in all analysed seasons and years. Neither current speed nor the current components exhibited persistent predominance in either sector.

3.5. Interannual Changes

The comparison between 2022 and 2025 showed a consistent decrease in four biogeochemical indicators. Chlorophyll-a, net primary production, phytoplankton biomass, and dissolved oxygen were lower in 2025 than in 2022 in all eight season–sector combinations. The choice of 2022 and 2025 as comparison years reflects their position as the first and last years of the four-year record, providing the longest available interval for describing overall change. This comparison should not be read as identifying the extreme years of the record: for chlorophyll-a, net primary production, and phytoplankton carbon biomass, the four-year maximum occurred in spring 2024 rather than 2022, while the four-year minimum occurred in summer 2025 in all three cases. Dissolved oxygen showed the opposite asymmetry, reaching its four-year maximum in spring 2022 and its minimum in summer 2024, plausibly reflecting the added influence of temperature-dependent solubility during the warm 2024 summer.

The mean absolute change between the two years was:

- 1.765 mg m^{−3} for chlorophyll-a;
- 19.643 mg m^{−3} day^{−1} for net primary production;
- 18.550 mmol m^{−3} for phytoplankton biomass;
- 12.860 mmol m^{−3} for dissolved oxygen.

Phosphate showed the opposite pattern. Values in 2025 were higher than those in 2022 in all eight season–sector comparisons, with a mean absolute increase of 0.059 mmol m^{−3}. Relative phosphate changes should be interpreted cautiously because the initial concentrations were very low in some seasons.

Sea-water potential temperature and salinity were higher in 2025 than in 2022 in six of the eight comparisons. Their mean increases were 0.231 °C and 0.105×10^{-3} , respectively. Nitrate changes were bidirectional, increasing in four and decreasing in the other four season–sector combinations. Similar heterogeneity was observed in the current components. Particularly high spring values occurred in 2024, when maxima in chlorophyll-a, net primary production, phytoplankton biomass, and nitrate were recorded in the northern sector. By contrast, the minima in chlorophyll-a, net primary production, and phytoplankton biomass occurred in the southern sector in summer 2025.

Given the limited four-year period, the observed interannual changes should be regarded as descriptive differences among individual years rather than evidence of long-term statistically significant trends. Their ecological interpretation and the possible relationships between the physical and biogeochemical indicators are considered in the Discussion.

4. Discussion

4.1. Interrelationships Between Seasonal Physical and Biogeochemical Changes

The seasonal patterns observed in the physical and biogeochemical indicators are consistent with the established seasonal evolution of the Black Sea upper layer. Winter cooling and stronger wind forcing intensify vertical mixing, whereas summer warming promotes more persistent stratification [2,3,31]. Although we did not analyse mixed-layer

depth and thermocline structure directly, the temperature and salinity cycles observed here are consistent with this seasonal sequence.

The spring maxima in chlorophyll-a, net primary production, and phytoplankton biomass were probably associated with improved light conditions combined with nutrients accumulated or redistributed into the surface layer during the cold season. Mikaelyan et al. [12], Silkin et al. [32], and Yunev et al. [33] have discussed similar links among winter mixing, nutrient supply to the euphotic layer, and subsequent phytoplankton development. Mechanistically, this coupling reflects the classical convective-mixing pathway: reduced buoyancy and stronger wind stress during winter deepen the surface mixed layer, entraining nutrient-rich subsurface water into the euphotic zone; the onset of spring stratification then traps these nutrients near the surface under improving light conditions, producing the observed spring maxima in nitrate, chlorophyll-a, and net primary production [12,31–33]. Interannually, the anomalously strong spring 2024 signal is consistent with either intensified winter convective mixing or enhanced mesoscale/Rim-Current-driven transport of shelf and riverine waters that year [6,8,34]; distinguishing between these mechanisms would require independent wind-stress, mixed-layer-depth, or current-velocity validation data beyond the scope of the present reanalysis-based assessment.

The concurrence of elevated nitrate and biological-productivity indicators in spring suggests functional coherence between nutrient availability and biological activity, although it does not establish causality. Conversely, the summer temperature maximum did not coincide with maximum chlorophyll-a or net primary production, indicating that high temperature alone was insufficient to enhance productivity. The summer phosphate minimum and lower production may reflect nutrient depletion or restricted nutrient availability in the stratified surface layer. Changes in phytoplankton community structure, grazing pressure, and horizontal transport may also contribute, but these processes cannot be distinguished using the aggregated data employed here.

Phytoplankton carbon biomass did not fully mirror chlorophyll-a seasonality, indicating that the two variables should not be treated as interchangeable indicators. Their relationship may vary with species composition, physiological state, and light adaptation; without taxonomic information, however, these mechanisms remain hypotheses for future investigation.

4.2. Seasonal Variability of Dissolved Oxygen

The seasonal oxygen pattern is consistent with the combined influence of biological production, temperature-dependent solubility, and vertical mixing. The spring oxygen maximum coincided with enhanced biological productivity, whereas lower summer concentrations occurred under warmer, more stratified conditions. Similar seasonal behaviour has been observed in Bulgarian Black Sea waters, although the timing of minimum concentrations varies among stations and depths [10,19].

The results apply exclusively to the surface layer and cannot be used to assess oxygen conditions at depth. They do not demonstrate the presence of hypoxia or a shift in the oxic–anoxic boundary, the investigation of which requires vertical profiles and targeted observations [3,34].

4.3. Spatial Differences Between the Northern and Southern Sectors

One of the most consistent findings was the north–south differentiation of the coastal zone. The warmer and more saline conditions in the southern sector are compatible with geographic and hydrographic differences, whereas the combination of lower salinity, higher nitrate concentrations, and enhanced biological-productivity indicators in the northern sector is consistent with a stronger influence of freshwater and shelf waters. River discharge

from the northwestern Black Sea, including the Danube, can be transported southward along the western shelf depending on circulation, wind forcing, and mesoscale structures, and its importance for salinity and biogeochemical conditions has been demonstrated previously [4,5,10]. The reanalysis-derived summer surface-temperature maximum (24.70 °C four-year mean; 25.85 °C absolute maximum) is consistent with the summer surface ranges reported for Bulgarian coastal waters from direct in situ measurements [10,11]. Nevertheless, the observed contrasts cannot be attributed solely to the Danube. Local rivers, coastal lakes, urbanised areas, wastewater discharges, ports, and agricultural runoff may also contribute, while the two-sector aggregation does not allow these influences to be separated quantitatively. The absence of persistent spatial predominance in phosphate further suggests that nitrate and phosphate should not be interpreted as a single nutrient signal, given their different sources, cycling, and biological uptake.

4.4. Currents and Horizontal Transport

Seasonal changes in the sign and magnitude of the u_0 and v_0 components indicate variable directions of seasonally averaged water transport (Figure 6), consistent with the complex circulation of the western Black Sea and the established roles of atmospheric forcing, coastal configuration, the Rim Current, and mesoscale eddies [6,8,35]. The present analysis does not, however, allow the contribution of individual circulation mechanisms to be isolated.

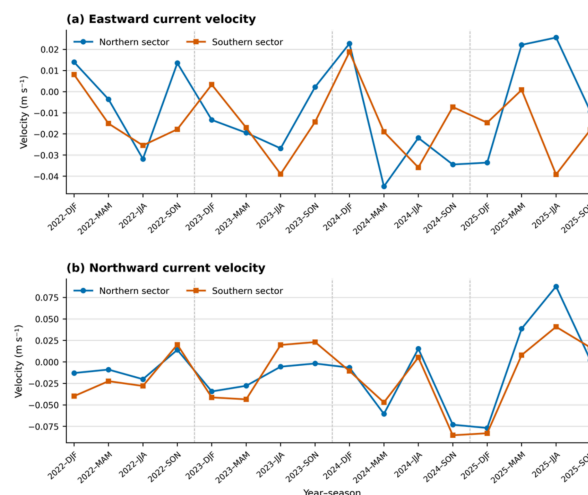


Figure 6. Seasonal and interannual variability of the current components: (a) eastward component, u_0 , and (b) northward component, v_0 . Vertical dashed lines separate consecutive years.

The calculated speed represents the magnitude of the seasonal-mean vector derived from the averaged u_0 and v_0 components. It is not equivalent to the mean instantaneous current speed. Oppositely directed currents within a season may partly cancel during averaging. A low seasonal-mean vector magnitude should therefore not necessarily be interpreted as an absence of dynamic activity.

4.5. Interannual Variability During 2022–2025

The coherent 2022–2025 changes across all season–sector combinations indicate that the interannual differences in biological indicators were not restricted to a particular season or coastal sector. However, the simultaneous increase in phosphate and decrease in biological-productivity indicators shows that variation in a single nutrient cannot explain the observed response. The molar N:P ratio, calculated from the seasonal mean nitrate and phosphate concentrations, was close to the Redfield ratio of 16 in winter (≈ 18) but far above it in spring (≈ 87), autumn (≈ 74), and especially summer (≈ 540 ; this value is highly sensitive to

the very low summer phosphate concentrations and should be interpreted cautiously). This pattern is consistent with potential phosphate limitation outside the winter mixing period, although N:P ratios alone do not demonstrate nutrient limitation. The pronounced spring 2024 signal further demonstrates that the magnitude of the spring production period can vary substantially among years. Because the record spans only four years, these differences should be interpreted as interannual variability rather than evidence of a long-term trend, regime shift, or change in ecological status; such conclusions require longer time series and appropriate statistical testing.

4.6. Relevance to Marine Recreation and Coastal Management

The results provide regional context relevant to marine recreation and coastal management, particularly through information on surface-water temperature, biological activity, and circulation. However, monthly and seasonal averages may not resolve short-lived local blooms, and the indicators analysed here do not permit direct assessment of bathing-water quality or safety. Such assessments require targeted observations of microbiological contamination, harmful phytoplankton, petroleum products, plastics, and other pollutants. The present results should therefore complement, rather than replace, specialised coastal monitoring.

4.7. Limitations of the Interpretation

Several methodological limitations should be considered. First, the analysis relies on Copernicus Marine model reanalysis rather than independent field observations. The approximately 2.5 km spatial resolution supports regional comparisons but cannot fully resolve local conditions in small bays, estuaries, ports, river mouths, or the immediate nearshore zone.

Second, the analysis was restricted to fixed surface model levels of approximately 0.5 m for physical variables and 0.25 m for biogeochemical variables. The findings therefore characterise surface waters and should not be extrapolated to vertical water-column structure or deeper processes.

Third, monthly data and seasonal averaging emphasise persistent patterns but may obscure short-lived anomalies, extreme events, rapid circulation changes, and brief phytoplankton blooms. Likewise, division into northern and southern sectors facilitates systematic comparison but inevitably aggregates substantial within-sector variability.

Finally, the four-year period supports comparison of seasonal conditions and interannual fluctuations during 2022–2025 but is too short for robust identification of long-term trends or regime shifts.

Future research should extend the temporal coverage, as a minimum of approximately ten years is likely necessary to characterise ecological-scale variability and change rather than climatological-scale variability. Copernicus Marine products should also be combined with in situ observations, satellite-derived information, river-discharge records, meteorological data, and spatially explicit indicators of anthropogenic pressure. The use of satellite ocean-colour products in such comparisons should account for the optical complexity of coastal waters [36] and the atmospheric correction of remotely sensed signals [37]. Satellite-based approaches to distinguishing phytoplankton functional types could also be explored as a complement to the bulk biological indicators analysed here [38]. Analyses using smaller coastal units could further clarify local variability and the processes underlying the north–south contrasts identified here.

5. Conclusions

This study provides an integrated assessment of spatial, seasonal, and interannual variability in physical and biogeochemical surface-water conditions along the Bulgarian Black

Sea coast during 2022–2025 using Copernicus Marine reanalysis products. The combination of seasonal aggregation and systematic comparison of the northern and southern coastal sectors enabled persistent spatial contrasts to be distinguished from seasonal and year-to-year variability, while providing a reproducible framework for regional-scale coastal assessment.

The results reveal two dominant features of the coastal system: pronounced seasonal organization and persistent north–south differentiation. Temperature showed the clearest annual cycle, whereas the southern sector remained consistently warmer and more saline. Biological productivity was most pronounced in spring, and the northern sector consistently showed higher chlorophyll-a, net primary production, phytoplankton carbon biomass, and dissolved oxygen, together with generally higher nitrate concentrations. In contrast, seasonal-mean current vectors showed substantial variability in magnitude and direction without a persistent sectoral predominance. These spatial patterns are consistent with differences in freshwater influence, nutrient availability, and coastal circulation, but the present analysis does not establish direct causal relationships.

Interannual differences were also evident: chlorophyll-a, net primary production, and phytoplankton carbon biomass reached their four-year maxima in spring 2024 and their minima in summer 2025, whereas dissolved oxygen reached its four-year maximum in spring 2022 and its minimum in summer 2024. Because the study covers only four years, these changes should be interpreted as interannual variability rather than long-term trends. Overall, the results demonstrate the value of Copernicus Marine reanalysis for spatially and temporally consistent assessment of broad coastal patterns. Extending the time series and integrating reanalysis with in situ observations, satellite products, river-discharge and meteorological data, and spatially explicit information on anthropogenic pressures would allow the mechanisms underlying the observed variability to be tested more directly and strengthen future long-term coastal assessments. Thus, by combining physical and biogeochemical indicators within a single, reproducible framework, this dataset can serve as a regional reference baseline for future comparative and remote-sensing-based coastal-monitoring studies and can support tracking of the coupling between hydrographic conditions and surface-water ecology over time.

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