water

MDPI

Article

Multivariate Environmental Factors and Seasonal Spatial Dynamics Affecting the Phytoplankton Community in Yazhou Bay, South China Sea

Zhida Yu [1,2,3], Zhiyuan Ouyang [1,2,4], Chuanyang Zheng [1,2,4], Zhen Wang [1,2,4], Xiaoming Fu [1,2,4], Haiping Cui [1,2,4], Yadong Huang [1,2,4], Zitao Zhang [1,2,4] and Chenhui Xiang [1,2,4,*]

1 CAS Key Laboratory of Tropical Marine Bio-Resources and Ecology, Guangdong Provincial Key Laboratory of Applied Marine Biology, South China Sea Institute of Oceanology, Chinese Academy of Sciences, Guangzhou 510301, China; brownmain@163.com (Z.Y.); ouyangzhiyuan@scsio.ac.cn (Z.O.); zhengchuanyang@scsio.ac.cn (C.Z.); wangzhen@scsio.ac.cn (Z.W.); xmfu@scsio.ac.cn (X.F.); cuihp@scsio.ac.cn (H.C.); hyd@scsio.ac.cn (Y.H.); zhangzitao@scsio.ac.cn (Z.Z.)
2 Sanya Institute of Ocean Eco-Environmental Engineering, Hainan 572004, China
3 Department of Ecology and Institute of Hydrobiology, Jinan University, Guangdong 510632, China
4 Nansha Marine Ecological and Environmental Research Station, Chinese Academy of Sciences, Guangzhou 511458, China
* Correspondence: chxiang92@scsio.ac.cn

Abstract: This study investigated phytoplankton and water environmental factors in Yazhou Bay, South China Sea, during the winter, spring, and summer of 2023. It examined phytoplankton community structure, subgroup heterogeneity, and key environmental drivers. Phytoplankton abundance ranged from 0.08 to 14.30 $\times$ 10^4 cells·L^{-1}, with high concentrations in estuary and nearshore zones. In summer, currents carry phytoplankton offshore, with stratification leading to high sedimentation in southern offshore waters. RDA results indicated that in winter and spring, inorganic nitrogen mainly influences phytoplankton distribution, while silicate is the primary factor in summer. Although seasonal differences in total phytoplankton abundance are minimal, significant horizontal and vertical distribution variations exist. Diverse preferences of different phytoplankton species for temperature, salinity, nitrogen, and phosphorus result in high species diversity. The Shannon–Wiener diversity index (H') averages 3.96 $\pm$ 0.09, and the Pielou evenness index (J) averages 0.82 $\pm$ 0.01. Dominant species include *Pseudo-nitzschia pungens*, *Skeletonema costatum*, and *Rhizosolenia sinica*. Influenced by external oceanic water masses, estuary input, and islands, phytoplankton subgroups show regional and seasonal variations. Despite recorded harmful algal blooms (HABs) in adjacent waters, Yazhou Bay's high biodiversity and low cell density suggest a low HAB risk, though future risks due to climate change and human activities remain.

Keywords: phytoplankton community; environmental drivers; seasonal variation; biodiversity; Yazhou Bay

check for updates

Citation: Yu, Z.; Ouyang, Z.; Zheng, C.; Wang, Z.; Fu, X.; Cui, H.; Huang, Y.; Zhang, Z.; Xiang, C. Multivariate Environmental Factors and Seasonal Spatial Dynamics Affecting the Phytoplankton Community in Yazhou Bay, South China Sea. *Water* **2024**, *16*, 3181. https://doi.org/10.3390/w16223181

Academic Editor: Marina Marcella Manca

Received: 9 October 2024
Revised: 4 November 2024
Accepted: 5 November 2024
Published: 6 November 2024

Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

The coastal ecosystem is a vital component of the marine ecosystem and is concurrently influenced by multiple factors such as human activities, terrestrial inputs, and oceanic water masses [1–3]. Phytoplankton, as primary producers, are highly sensitive to environmental changes, which affect their growth, metabolism, and reproduction. Consequently, the community structure and metabolic characteristics of phytoplankton often reflect the health of the aquatic environment and are vital for water quality monitoring, environmental assessment, water productivity estimation, and fishery production forecasting [4,5].

The bay ecosystem, characterized by strong land–sea interactions, has hydrodynamic processes and material transport that significantly impact the phytoplankton community. For example, terrestrial nutrient inputs or nearshore upwelling can stimulate phytoplankton

growth [6–9]. However, excessive phytoplankton growth can lead to harmful algal blooms (HABs), reduced biodiversity, and a sharp decline in biological resources, resulting in structural changes and potential imbalances in the bay ecosystem [10–12].

In general, environmental factors such as the temperature, salinity, dissolved oxygen, light intensity, and nutrient concentration of seawater, as well as physical factors like hydrological processes, exert significant influences on the shaping of the phytoplankton community structure [13–15]. In different coastal waters, in view of the combined effects of oceanic water masses and terrestrial influences including human activities, the environmental factors closely related to the growth of phytoplankton present diverse and complex environmental characteristics in different bays, and they lead to considerable spatio-temporal differences in the community structure and abundance characteristics of phytoplankton. Different phytoplankton groups, such as diatoms, dinoflagellates, and cyanobacteria, can each become dominant species in bays and even cause HABs under specific environmental conditions [16–18]. Moreover, environmental changes can drive the evolution of dominant phytoplankton species in bays, leading to shifts such as the transition from diatom dominance to dinoflagellate dominance [19]. Consequently, investigating the seasonal composition, regional variations, and key environmental factors influencing phytoplankton community structure in specific regions can offer critical insights into the structure, function, and evolutionary patterns of bay ecosystems [20,21].

Yazhou Bay is situated in the west of Sanya City, Hainan Province, China. It is a typical tropical open bay that connects to the South China Sea. The wide openness of this bay implies that the area is significantly influenced by the oligotrophic open ocean water masses of the South China Sea [22], yet this does not signify that the impact of terrestrial input on phytoplankton can be disregarded. The eastern region of Sanya, encompassing Sanya Bay and areas adjacent to Yazhou Bay, has undergone economic development and high levels of human activity. Research indicates that nutrient availability is the primary regulatory factor influencing the distribution of phytoplankton in this region [23]. Additionally, the ecological risks associated with HABs of dinoflagellate *Noctiluca scintillans* have been documented on multiple occasions [24,25].

Nevertheless, there are currently no relevant reports on the phytoplankton community in Yazhou Bay. The structural characteristics of the phytoplankton community, potential seasonal variation patterns, and associated ecological risks remain unknown. Presently, Yazhou Bay experiences relatively less human activity pressure compared to the eastern region of Sanya. However, this area is designated as a key zone for scientific and technological innovation and economic development in Sanya City, Hainan Province. The coastal waters are potentially subject to runoff inputs from industrial, agricultural, and domestic sources. The northeastern corner of Yazhou Bay is the estuary of the Ningyuan River, the longest river in southern Hainan [26], which contributes additional environmental pressures and challenges.

Amid the escalating trends of global climate change and increasing regional human activity, the seasonal variations in hydrodynamic processes driven by the East Asian monsoon [27], combined with terrestrial inputs, may exert complex influences on the diversity and community distribution of phytoplankton in this area. Phytoplankton in open bays often exhibit significant seasonal and regional disparities [28]. For the tropical open bay of Yazhou Bay, which has yet to be thoroughly studied, there is a pressing need for in-depth research to elucidate the spatiotemporal distribution patterns, key driving factors, and their indicative effects on marine physical processes and ecological risks within its phytoplankton community.

In consideration of this, based on in situ observations during different monsoon periods, this study aimed to assess the temporal and spatial structures of phytoplankton communities and identify dominant species in Yazhou Bay. It sought to analyze the main environmental factors influencing the composition and distribution of these dominant phytoplankton species. Additionally, this research explored the impact of complex physical processes and terrestrial inputs on community structure. Special attention was given to

potential algal bloom species, to evaluate whether riverine nutrient inputs fuel their growth and pose future ecological risks. Ultimately, the findings are intended to inform strategies for maintaining the ecosystem balance and mitigating HAB threats in Yazhou Bay.

2. Materials and Methods

2.1. Study Area

This research was conducted in Yazhou Bay, located in Sanya City, Hainan Province, China (Figure 1), with coordinates ranging from 108.989° E to 109.153° E longitude and from 18.299° N to 18.369° N latitude. The water depth in this area varies from 0 to 25 m. The annual average temperature is 25.4 °C. The region experiences distinct dry and wet seasons, with the majority of rainfall occurring during the southwest monsoon period from May to October. The tidal regime in Yazhou Bay is primarily characterized by diurnal tides, with irregular diurnal tides being predominant. The bay is influenced by both the East Asian monsoon and ocean current systems from the South China Sea [29].

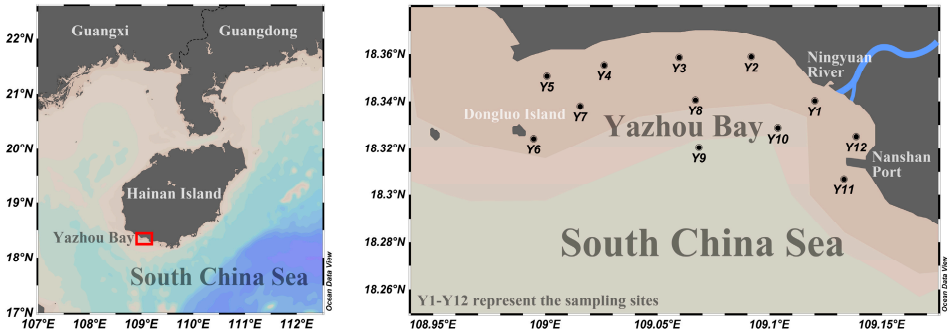


Figure 1. Sampling sites in Yazhou Bay.

2.2. Sample Collection and Processing

Twelve sites were deployed in Yazhou Bay, encompassing the Ningyuan River Estuary, Nanshan Port, other nearshore waters, Dongluo Island, and the offshore area. Field observations of phytoplankton and related ecological environmental indicators, as well as water sample collections, were conducted once during each of three distinct periods: the winter northeast monsoon (January 2023), the spring monsoon transition (April 2023), and the summer southwest monsoon (August 2023).

The environmental parameters and water samples were detected and collected from the surface and bottom water layers of 12 sites in each season, with a total of 72 water samples collected. Environmental parameters such as water temperature, salinity, dissolved oxygen (DO), pH, and turbidity were measured in situ using a YSI (Yellow Springs Instruments) EXO2 multi-parameter water quality detector. Surface water samples (approximately 0.5 m below the water surface) and bottom water samples (approximately 2 m above the seabed) were collected using a cylindrical plexiglass water collector.

For fractionated chlorophyll a (Chl a) analysis, 250 mL water samples, after removing large organisms with a 200 µm sieve, were filtered sequentially through 20 µm (Meck Millipore, Burlington, MA, USA), 3 µm (Meck Millipore), and 0.7 µm (GF/F-Whatman, Sigma-Aldrich, St. Louis, MO, USA) membranes, to collect the samples of micro- (>20 µm), nano- (3–20 µm), and pico- (<3 µm) phytoplankton cells, respectively. For unfractionated Chl a analysis, 250 mL water samples filtered through a 200 µm sieve were directly filtered through a 0.7 µm membrane [30]. All filters containing phytoplankton cells were stored at −20 °C for subsequent analysis. Chl a concentration was measured fluorometrically using a Turner Designs Model 10 fluorometer [30], following extraction in the dark for 24 h at 4 °C in 10 mL of 90% (*v*/*v*) acetone.

For nutrient analysis, water samples were filtered through a 0.7 µm pore size GF/F filter membrane (25 mm, Whatman GF/F), aliquoted into 80 mL polycarbonate bottles, and stored frozen at −20 °C. Concentrations of NH_4^+, NO_2^-, NO_3^-, PO_4^{3-}, and SiO_3^{2-}

were determined using a nutrient autoanalyzer (AA3, Seal Instruments, Norderstedt, Germany) based on the colorimetric method [31]. The dissolved inorganic nitrogen (DIN) concentration was calculated as the sum of NH_4^+, NO_2^-, and NO_{3-} concentrations.

For phytoplankton analysis, the Utermöhl method for the identification of phytoplankton in water samples was adopted [32], and 1 L water samples were collected in the field and treated with 1% Lugol's solution for fixation for more than 24 h. The samples were then concentrated to 30 mL. Subsequently, 0.1 mL of the concentrated sample was used for species identification and cell counting using a 0.1 mL counting chamber under an optical microscope (BX43, Olympus, Microscope Central, Feasterville, PA, USA). Species identification of phytoplankton was based on the World Register of Marine species (https://www.marinespecies.org/) (accessed on 23 August 2024).

2.3. Data Analysis

The Shannon–Wiener diversity index (H'), Pielou's evenness index (J), and the dominance index (Y) were calculated based on the data of phytoplankton abundance at each site, without any pre-transformation of the abundance data. The equations are listed below [33]:

$$H' = -\sum_{i=1}^{X} p_i log_2^{p_i} \quad (1)$$

$$J = H'/log_2^S \quad (2)$$

$$p_i = n_i/N \quad (3)$$

$$Y = p_i * f_i \quad (4)$$

where X denotes the number of species, n_i represents the number of individuals of the i-th species, N represents the total number of all species at the sample points, and f_i represents the frequency of the i-th species occurring at each sample point. A species is regarded as dominant when $Y > 0.02$.

The spatial distribution of environmental factors was visualized using Ocean Data View 5.7.1 and GraphPad Prism 8 software. Hierarchical clustering analysis of phytoplankton community was conducted using the "Vegan" package in R 4.4.0 software. One-way ANOVA in environmental factors among different subcommunities was calculated by the "pwr" package in R software. Redundancy analysis (RDA) was performed using the "Vegan" package in R software to explore the relationships between the abundance of each of the top 20 dominant species in each season and each water layer, total phytoplankton abundance, and environmental factors.

3. Results

3.1. Phytoplankton Species Composition and Diversity

Across three seasons, phytoplankton communities in Yazhou Bay were analyzed at 12 stations, identifying 71 genera and 125 species in winter, 44 genera and 111 species in spring, and 65 genera and 146 species in summer. Diatoms consistently dominated the phytoplankton community, comprising 81.6% of the species in winter, 74.8% in spring, and 82.2% in summer. Dinoflagellates were the second most prevalent group, accounting for 15.2%, 23.4%, and 16.4%, respectively. Additionally, 1–2 species from the Chrysophyta and Cyanobacteria phyla were present in each season (Table 1).

The phytoplankton community exhibited relatively high Shannon–Wiener diversity index (H') and Pielou's evenness index (J) values in all three seasons, with the highest levels observed in winter and the lowest in spring (Table S1). The lowest values of H' (3.23) and J (0.61) in winter appeared in the surface water of the Ningyuan River estuary (Y1B) (Figure 2), whereas the bottom water layer showed a high biodiversity distribution area (H' of 5.05). In spring, both H' and J were low in the estuary and adjacent waters. In summer, H' and J in both surface and bottom water layers were slightly lower than in winter, with

the highest H' value (4.74) and the lowest value (3.47) appearing at the bottom water layer of Nanshan Port (Y12D) and offshore waters (Y8B), respectively.

Table 1. Phytoplankton genus and species richness in Yazhou Bay across three seasons.

Seasons	Bacillariophyta		Dinoflagellates		Chrysophyta		Cyanophyta	
	Genus	Species	Genus	Species	Genus	Species	Genus	Species
winter	40	102	10	19	1	2	1	2
spring	33	83	13	26	1	1	1	1
summer	49	120	16	24	1	1	1	1

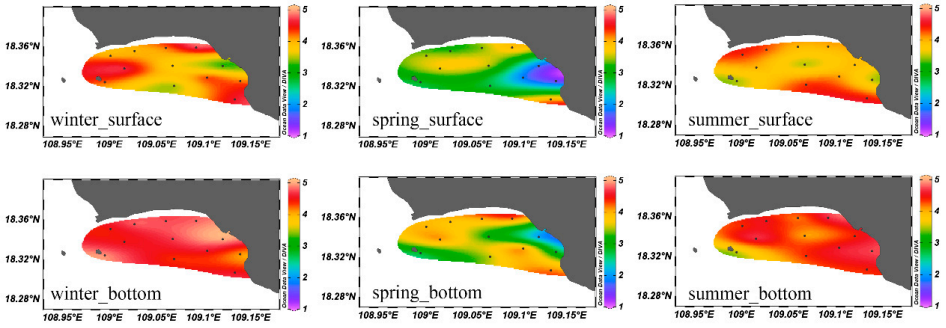


Figure 2. Seasonal variation in Shannon–Wiener diversity index (H') at surface and bottom water layers in Yazhou Bay. The color bars indicate the level of the Shannon–Wiener diversity index.

3.2. Distribution Characteristics of Phytoplankton Abundance

Phytoplankton abundance in Yazhou Bay peaked in summer and was lowest in spring. The average phytoplankton abundance in surface and bottom water layers across the three seasons were $2.91 \pm 0.28 \times 10^4$ cells·L^{-1} (winter), $1.32 \pm 0.53 \times 10^4$ cells·L^{-1} (spring), and $3.96 \pm 0.76 \times 10^4$ cells·L^{-1} (summer) (Table S1). The highest abundance in winter and spring was found at the Ningyuan River estuary, showing a gradual decrease towards the open sea southwest. There was no significant difference in phytoplankton abundance between the surface and bottom water layers (Figure 3). In summer, the abundance pattern was unique; the bottom water layer's average abundance ($6.34 \pm 1.19 \times 10^4$ cells·L^{-1}) was significantly higher than the surface layer ($1.59 \pm 0.43 \times 10^4$ cells·L^{-1}), nearly four times that of the surface layer. The highest summer abundance was observed in the bottom waters in the far south of Yazhou Bay (Y9).

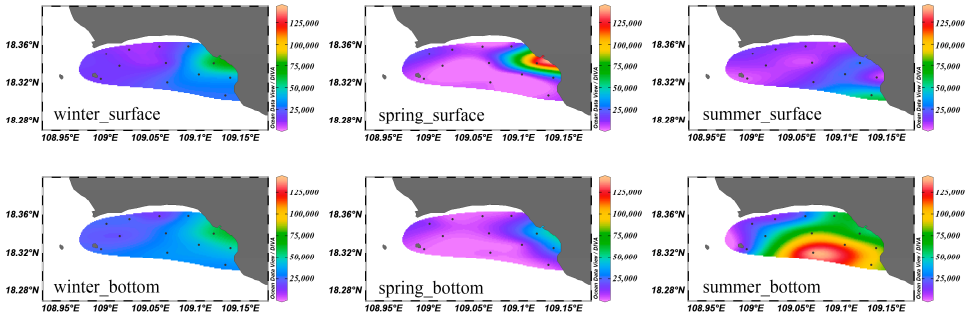


Figure 3. Seasonal abundance distribution at surface and bottom water layers in Yazhou Bay. The color bars indicate the level of phytoplankton abundance (cells·L^{-1}).

3.3. Phytoplankton Subcommunities and Their Corresponding Environmental Characteristics in Yazhou Bay

A hierarchical clustering method was used to analyze the phytoplankton community structure, delineating different subgroups based on geographic locations and environmental features (Figures 4 and S1). These subcommunities displayed distinct regional

characteristics—estuary, nearshore, island, and open sea—reflecting varying influences from open ocean water masses and terrestrial inputs. The corresponding habitats were classified into an Offshore Zone (OZ), Mixed Zone (MZ), Estuary and Nearshore Zone (ENZ), and Island Zone (IZ). In winter, the estuarine and nearshore area was further divided into an Estuary Zone (EZ) and Nearshore Zone (NZ) based on subcommunity differences.

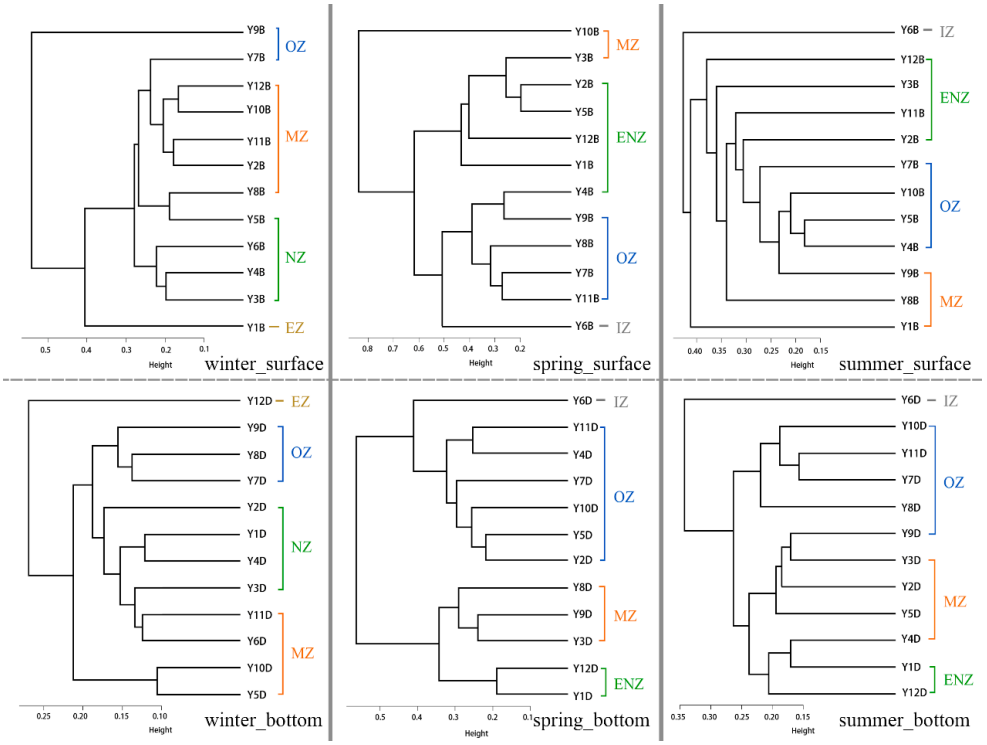


Figure 4. Hierarchical clustering of phytoplankton communities in surface and bottom water layers of Yazhou Bay. Subgroups include an Offshore Zone (OZ), Mixed Zone (MZ), Estuary and Nearshore Zone (ENZ), and Island Zone (IZ). In winter, the estuarine and nearshore area is further divided into an Estuary Zone (EZ) and Nearshore Zone (NZ) based on subcommunity differences.

In winter, phytoplankton were classified into four subgroups: EZ, NZ, MZ, and OZ. Compared to MZ, NZ exhibited significantly higher concentrations of SiO_3^{2-}, DIN, and a greater N:P ratio ($p \leq 0.05$). Additionally, in the bottom water layer, NZ demonstrated a notably elevated Chl a concentration ($p \leq 0.05$) (Figure 5). The EZ, adjacent to the Ningyuan River estuary, exhibited relatively low temperatures and salinities in both surface and bottom water layers, with high total Chl a concentrations. Diatoms *Pseudo-nitzschia pungens* and *Leptocylindrus danicus* were dominant here. The NZ had higher temperatures and fewer dominant species compared to the EZ. The MZ covered most of the eastern bay's surface waters, featuring a broad salinity range and balanced Chl a fractions. Dominant species included diatoms *P. pungens* and *Rhizosolenia sinensis*, with cyanobacterium *Trichodesmium thiebautii* also present. In the OZ, far from the coast, temperatures and salinities were higher, Chl a concentrations were the lowest, the pico-phytoplankton fraction reached 40%, and *T. thiebautii* dominated the surface waters (Figure 5, Table S2).

In spring and summer, the phytoplankton were classified into four subgroups: IZ, ENZ, MZ, and OZ. In the ENZ in spring, silicate concentrations were low, and total Chl a concentrations were significantly higher. Diatoms *Skeletonema costatum* and *P. pungens* dominated, particularly at stations Y1 and Y12, where they constituted over 68% of the abundance. The MZ, which is more influenced by external oceanic waters than the ENZ, exhibited a higher N:Si ratio, particularly in the surface layer ($p \leq 0.05$), and elevated pi-co-Chl a concentrations, especially in the bottom layer ($p \leq 0.001$), compared to the ENZ and OZ. Diatom *Melosira sulcata* was the dominant species, absent in other areas. In the OZ,

the overall salinity was higher, and its pico-phytoplankton fraction exceeded 60%, which was significantly greater than in the ENZ ($p \leq 0.001$). *S. costatum* was present only in the bottom water layer of a few stations (Y5D, Y10D). The IZ conditions resembled those of the OZ, with the lowest phytoplankton abundance, and Diatoms *Nitzschia* spp. was the dominant group (Figure 6, Table S2).

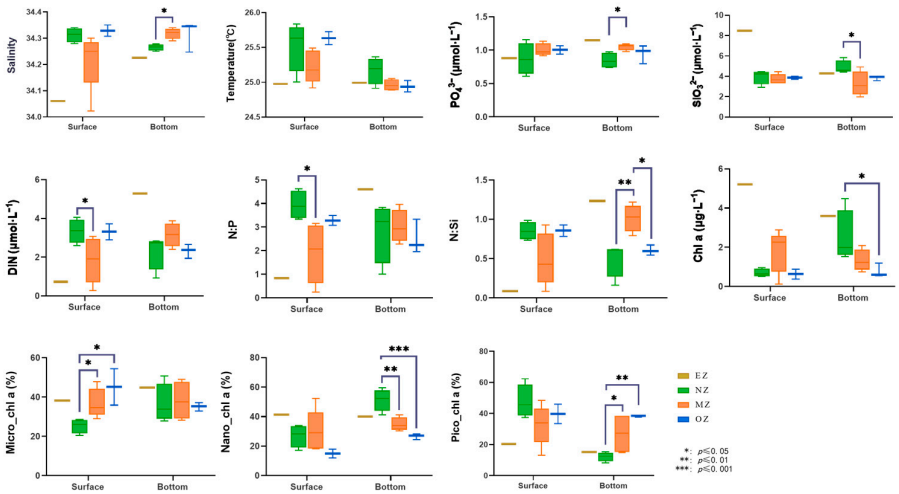


Figure 5. Regional variation in environmental and biological parameters in the surface and bottom water layers of Yazhou Bay during winter: salinity, temperature, phosphate (PO_4^{3-}), silicate (SiO_3^{2-}), ammonium (NH_4^+), oxynitride (NO_X), dissolved inorganic nitrogen (DIN), nitrogen phosphorus ratio (N:P), nitrogen silicon ratio (N:Si), chlorophyll a (Chl a), percentage of micro-phytoplankton (Micro_chl a (%)), percentage of nano-phytoplankton (Nano_chl a (%)), percentage of pico-phytoplankton (Pico_chl a (%)). One-way ANOVA was conducted for the environmental factors of the zones covering 2 or more stations (NZ, MZ, and OZ). * represents p-value ≤ 0.05, ** represents p-value ≤ 0.01, *** represents p-value ≤ 0.001.

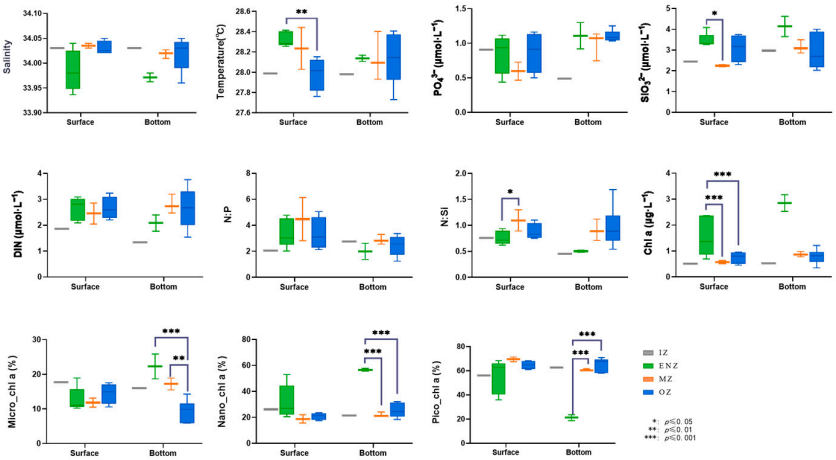


Figure 6. Regional variation in environmental and biological parameters in the surface and bottom water layers of Yazhou Bay during spring salinity, temperature, phosphate (PO_4^{3-}), silicate (SiO_3^{2-}), ammonium (NH_4^+), oxynitride (NO_X), dissolved inorganic nitrogen (DIN), nitrogen phosphorus ratio (N:P), nitrogen silicon ratio (N:Si), chlorophyll a (Chl a), percentage of micro-phytoplankton (Micro_chl a (%)), percentage of nano-phytoplankton (Nano_chl a (%)), percentage of pico-phytoplankton (Pico_chl a (%)). One-way ANOVA was conducted for the environmental factors of the zones covering 2 or more stations (NZ, MZ, and OZ). * represents p-value ≤ 0.05, ** represents p-value ≤ 0.01, *** represents p-value ≤ 0.001.

In the ENZ in summer, temperatures and N:Si and N:P ratios were high, with diverse dominant groups showing balanced abundances. In the MZ, salinity and nitrogen con-

centrations were high, and total Chl a concentrations were elevated compared to other areas. Diatom *Chaetoceros* spp. dominated, with *Chaetoceros lorenzianus* and *Chaetoceros curvisetus* jointly exceeding 22% abundance at each station. The OZ bottom water layer exhibited significantly higher salinity ($p \leq 0.001$) and lower temperature ($p \leq 0.05$), with high abundances of diatoms *Chaetoceros affinis* and *P. pungens*. Phytoplankton abundances in the IZ were low, with the proportions of each phytoplankton size class around 30%. Dominant species were diatoms *Bacteriastrum comosum* and *Asterionella glacialis*, particularly at station Y6 near the island (Figure 7, Table S2).

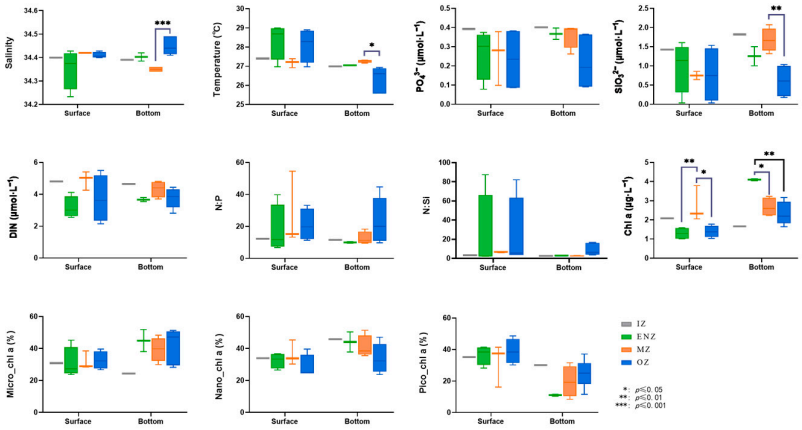


Figure 7. Regional variation in environmental and biological parameters in the surface and bottom water layers of Yazhou Bay during summer: salinity, temperature, phosphate (PO_4^{3-}), silicate (SiO_3^{2-}), ammonium (NH_4^+), oxynitride (NO_X), dissolved inorganic nitrogen (DIN), nitrogen phosphorus ratio (N:P), nitrogen silicon ratio (N:Si), chlorophyll a (Chl a), percentage of micro-phytoplankton (Micro_chl a (%)), percentage of nano-phytoplankton (Nano_chl a (%)), percentage of pico-phytoplankton (Pico_chl a (%)). One-way ANOVA was conducted for the environmental factors of the zones covering 2 or more stations (NZ, MZ, and OZ). * represents *p*-value ≤ 0.05, ** represents *p*-value ≤ 0.01, *** represents *p*-value ≤ 0.001.

3.4. Dominant Species and Their Relationship with Environmental Factors: RDA Results

The seasonal succession of dominant species was clearly observed. In winter surface waters, *P. pungens* and *R. sinensis* were predominant, collectively accounting for 28% of the total phytoplankton abundance. However, in the bottom water layer, their prevalence dropped to 21%, with *C. affinis* and *Chaetoceros socialis* becoming more dominant (Table 2). During spring, *P. pungens* and *S. costatum* were highly dominant, making up 78% and 59% of the surface and bottom water layer populations, respectively, with dominance indices exceeding 0.2. In summer, the dominance shifted towards the *Chaetoceros* spp., which included numerous species but with lower dominance levels. The surface layer was primarily dominated by *C. affinis*, while in the bottom water layer, *C. curvisetus* and *P. pungens* were more prevalent (Table 2).

Figure 8 presents the RDA results, illustrating relationships between dominant phytoplankton species and environmental factors such as water temperature, salinity, and nutrient concentrations (Figure 8). In winter, the surface temperature and salinity are the main contributors to the silicate explanatory variable score of RDA1, while DO and nutrients (NH_4^+, SiO_3^{2-}, and DIN) are main contributors to that of RDA2. The total abundance of phytoplankton had a strong correlation with nitrate and silicate. *L. danicus* showed a negative correlation with salinity, *R. sinensis* had a strong positive correlation with nitrogen, and *T. thiebautii* positively correlated with salinity. In spring, the surface temperature and salinity are also the main contributors to the explanatory variable score of RDA1, while nutrients (SiO_3^{2-}, PO_{4-}, and DIN) are the main contributors to that of RDA2. The total abundance of phytoplankton had a strong correlation with nitrate and nitrogen.

S. costatum had significant negative and positive correlations with salinity and temperature, respectively, while *P. pungens* was positively correlated with temperature and silicate.

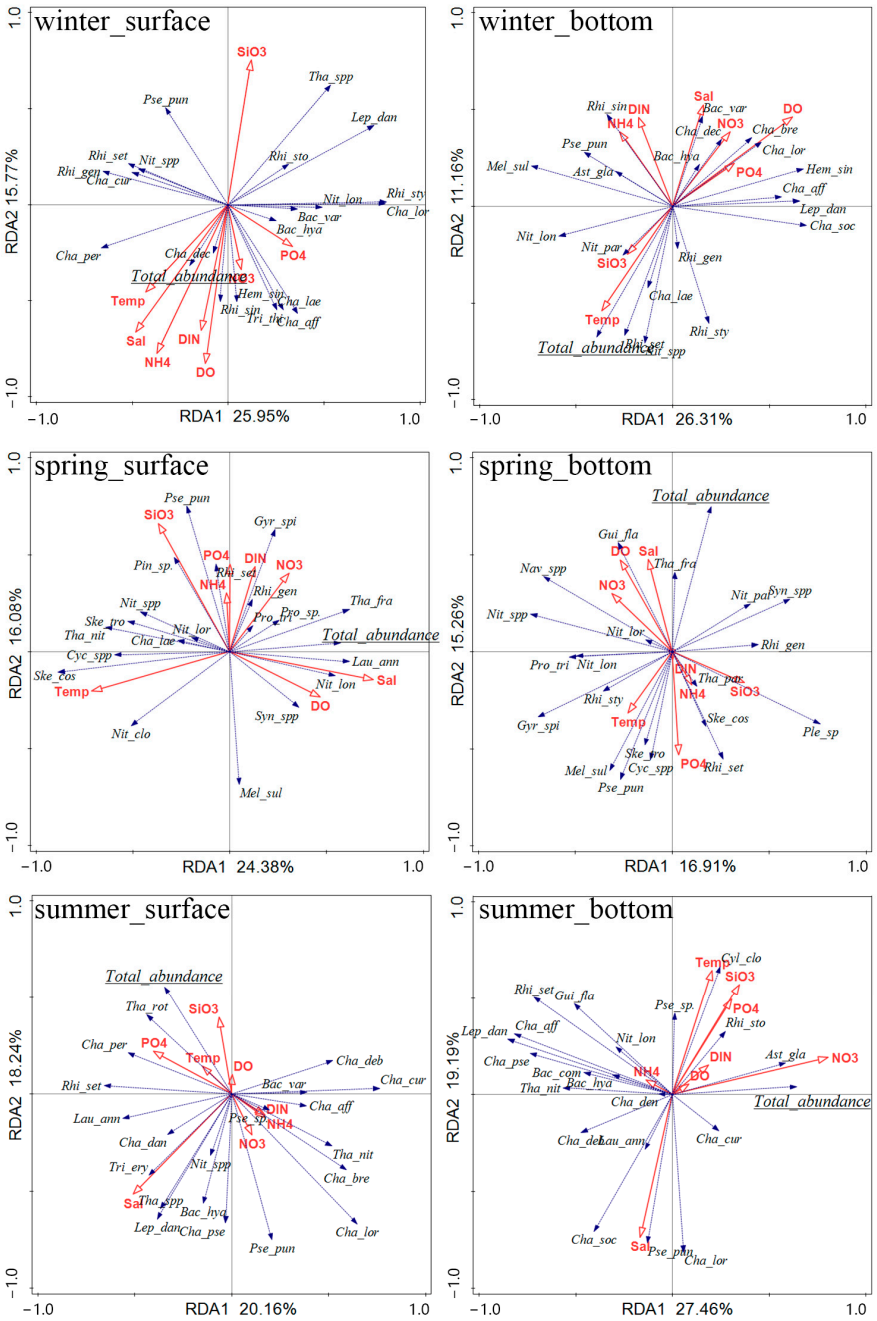


Figure 8. Results of redundancy analysis (RDA) of dominant species abundance and environmental factors (Temp represents temperature, Sal represents salinity, DO represents dissolved oxygen, NO3 represents nitrate, NH4 represents ammonium, DIN represents dissolved inorganic nitrogen, PO4 represents phosphate, SiO3 represents silicate) in surface and bottom water layers of Yazhou Bay across three seasons.

In summer, the surface salinity was the main contributor to the explanatory variable score of RDA1, while SiO_3^{2-} was the main contributor to the explanatory variable score of RDA2. The total abundance of phytoplankton had a strong correlation with silicate. The nearshore species *P. pungens* in the bottom water layer showed a strong correlation with salinity.

Table 2. Dominant species in the surface and bottom water layers of Yazhou Bay (dominance > 0.05).

Season	Layer	Species	Dominance	Proportion	Average Abundance
Winter	surface	*P. pungens*	0.17	18.59	4682.43
		R. sinensis	0.11	10.54	2654.51
		C. affinis	0.05	5.12	1288.96
	bottom	*R. sinensis*	0.14	14.16	4673.75
		P. pungens	0.07	7.73	2549.44
		C. affinis	0.06	6.35	2095.35
		C. socialis	0.05	5.7	1880.21
Spring	surface	*P. pungens*	0.28	37.57	6319.72
		S. costatum	0.20	40.44	6802.01
	bottom	*P. pungens*	0.22	23.62	2275.97
		S. costatum	0.21	35.97	3465.73
Summer	surface	*C. affinis*	0.08	8.58	1361.75
		C. pseudocurvisetus	0.05	7.64	1212.50
		C. lorenzianus	0.05	5.9	936.33
		P. pungens	0.05	6.29	997.92
		Pseudo-nitzschia sp.	0.05	5.46	866.25
	bottom	*C. curvisetus*	0.15	15.37	9742.25
		P. pungens	0.13	12.9	8177.92
		Pseudo-nitzschia sp.	0.07	7.2	4565.92
		L. danicus	0.05	5.85	3707.92
		C. socialis	0.05	6.77	4291.17

4. Discussion

4.1. Overall Distribution Patterns and Environmental Drivers of Phytoplankton in Yazhou Bay

Coastal phytoplankton typically exhibit distribution patterns influenced by terrestrial nutrient inputs, often showing higher abundance and biomass in estuarine and nearshore areas compared to the open sea [34–37]. In this study, the overall distribution pattern aligned with this trend, except for the phytoplankton distribution in the bottom waters during summer. During this season, strong stratification [38] can cause phytoplankton to settle and accumulate in the bottom waters, resulting in significantly higher abundance and biomass in the bottom layers compared to the surface layers. Similarly, in the adjacent Sanya Bay, Zhang (2010) observed that bottom water Chl a concentrations in summer were more than three times those in surface waters, primarily due to larger-sized diatoms and dinoflagellates [23]. The ocean current characteristics observed during this study (Figure S2b) suggest that a large number of coastal phytoplankton may be transported offshore and settle to the bottom, leading to high phytoplankton abundance in offshore areas. The high-value phytoplankton areas in this study were located in the offshore waters of the southern part of the bay, which has the deepest water depth, rather than in nearshore waters, indicating that water column stratification significantly influences the distribution of bottom phytoplankton.

The environmental factors influencing phytoplankton distribution vary seasonally [39–41]. A significant correlation between phytoplankton abundance and any single environmental factor in Yazhou Bay is difficult to pinpoint (Table S3), highlighting the complexity of these influences. Generally, temperature is not a limiting factor for phytoplankton growth in tropical bays like Yazhou Bay. Instead, the correlation between temperature and salinity mainly reflects the indirect effects of freshwater runoff or the intrusion of offshore oceanic water masses. RDA results indicate that in the dry season (winter and spring), phytoplankton abundance distribution is primarily affected by inorganic nitrogen (Figure 8). Specifically in winter, strong vertical mixing in offshore waters allows the upper water layer to receive DIN supplementation from nutrient release from bottom sediments [42], resulting in relatively small differences in phytoplankton abundance between nearshore and offshore areas. In summer, phytoplankton

abundance is mainly influenced by silicate distribution (Figure 8), suggesting that terrestrial inputs magnify the distribution differences between nearshore and offshore areas in the upper water layer during the wet season. The bottom water layer, restricted by light availability, is not conducive to active phytoplankton photosynthesis. Consequently, it is challenging to link phytoplankton distribution in this area to a single environmental factor. Instead, their distribution is influenced by a combination of vertical mixing, sea current transport, and sedimentation. Overall, these influencing factors indicate that phytoplankton in Yazhou Bay have suitable growth temperatures and nutrient supplies throughout the year. Although there is no significant seasonal variation in total phytoplankton abundance (both surface and bottom), there are notable seasonal differences in their horizontal and vertical distribution characteristics.

4.2. Regional Characteristics of Phytoplankton Community Structure and the Indicative Role of Dominant Species

The open bay environment is influenced by various complex factors such as river runoff, coastal human activities, terrestrial inputs, island effects, and the dynamic changes in oceanic water masses [28,43] (Figure S2a). The varied environmental conditions create a complex setting that affects the growth of different phytoplankton species. RDA results indicate that the preferences of phytoplankton in this area for environmental factors like temperature, salinity, nitrogen, and phosphorus exhibit diverse and heterogeneous differences, leading to a high number of phytoplankton species and biodiversity indices.

Comprehensive analysis of phytoplankton community clustering and RDA reveals that the phytoplankton in Yazhou Bay form subgroups with distinct regional differences, influenced by varying degrees of external oceanic water masses, river and nearshore terrestrial inputs, and island effects. The regional coverage, community structure, and dominant species of these subcommunities show strong seasonal fluctuations (Figures 4–7 and S1, Table S2). For instance, the distribution of *L. danicus*, *S. costatum*, and *Nitzschia* spp. is often significantly negatively correlated with salinity. These dominant algal species are more adapted to the low-salinity areas of estuaries or nearshore zones and form population dominance by utilizing nutrients from terrestrial inputs, making them effective indicator species of terrestrial influence [44,45].

In winter, terrestrial inputs have a relatively minor influence on offshore waters, which exhibit characteristics of external oceanic water masses. *Trichodesmium* spp., which possesses the capacity for nitrogen fixation, is typically distributed in the surface waters of the expansive ocean [46]. The fact that *T. thiebautii* occupies an absolute dominance in the surface water body of Yazhou Bay supports this observation. In contrast, during spring and summer, even areas dominated by oceanic water masses are affected to varying degrees by terrestrial inputs. This is evident from the widespread presence of nearshore species such as *S. costatum* and *P. pungens*. Spring, in particular, is unique because not only do far offshore areas show signs of terrestrial influence, but nearshore areas are also affected by the intrusion of external oceanic water masses. Real-time ocean current modeling results (Figure S2a), the relatively high salinity observed on-site, and the distinct distribution of dominant phytoplankton species (e.g., *M. sulcata*) all confirm this, highlighting the complex impact of ocean currents during the monsoon transition period.

Compared to the dry season, the offshore waters of Yazhou Bay in summer are more affected by precipitation and terrestrial inputs, making the influence of external oceanic water masses on the phytoplankton community less prominent. Dongluo Island often shows unique phytoplankton community distribution characteristics, especially in spring and summer, where the dominant species differ significantly from other areas. This phenomenon may be attributed to the varying intensity and nature of human activities originating from the island compared to terrestrial sources along the coastline of Yazhou Bay, as well as the unique hydrological conditions created by the island's barrier effect [29,47,48].

4.3. Potential Risks of HABs in Yazhou Bay

HABs have frequently occurred along the coast of Hainan Island. Between 1991 and 2022, there have been 33 documented events, with most attributed to dinoflagellates.

Species such as the dinoflagellate *N. scintillan* and haptophyte *Phaeocystis globosa* have been primary contributors [49]. While HABs predominantly occur in the island's northern waters [50], open bays along the southern coast have also experienced outbreaks. For instance, in the nearshore waters of Sanya, east of Yazhou Bay, red tides caused by *N. scintillans* have been recorded twice. Factors contributing to these outbreaks may include relatively low water temperatures (23.6–24.4 °C), low salinity (under 33.0), and substantial terrestrial nutrient input [24,25]. In our study, *N. scintillans* was detected only sporadically in winter and summer in nearshore waters, with minimal abundance (under 240 cells·L^{-1}), insufficient to form dominant populations. This correlates with the high salinity and temperature observed during the study period. Compared to historical data from the eastern Sanya waters, the nutrient levels in the nearshore regions of Yazhou Bay indicate a lesser degree of terrestrial influence [51,52], suggesting the area's environment is generally unfavorable for *N. scintillans* growth, with a low likelihood of blooms occurring.

Common phytoplankton species in Yazhou Bay, like *P. pungens* and *S. costatum*, have been known to cause HABs in other parts of the South China Sea; these dominant species have triggered HABs in the relevant sea areas, resulting in adverse effects on local fisheries and the utilization of nuclear power resources. Additionally, *P. pungens* can produce neurological toxin domoic acid, which is harmful to marine organisms and humans [53,54]. Our findings show the phytoplankton community in Yazhou Bay displays high species richness, diversity, and evenness (Table S1). This complexity and stability in community structure prevent any single species from gaining a competitive edge that could lead to a bloom [55,56]. However, potential HAB species often have high cell densities in estuarine and nearshore zones. For example, in spring, *P. pungens* can reach a cell density of 6.29×10^5 cells·L^{-1} in the surface layer, and *S. costatum* exceeds 10^5 cells·L^{-1} near the estuary. Although these densities have not met historical thresholds for HAB outbreaks [57–59], they remain significantly high. With rapid economic growth and increased human activities, continued nutrient input and eutrophication could potentially boost the dominance of nutrient-dependent species like *P. pungens*, increasing the risk of HABs. Therefore, it is crucial to enhance dynamic monitoring of phytoplankton and related ecological indicators, and to conduct timely assessments and risk warnings, ensuring the sustainable development of Yazhou Bay's economy and ecology.

5. Conclusions

This study comprehensively examined the phytoplankton communities in Yazhou Bay across three distinct seasons, revealing significant insights into species composition, diversity, abundance, and their interrelationships with environmental factors. Our findings highlight that diatoms are the dominant phytoplankton group throughout the year, consistently surpassing dinoflagellates in both species richness and abundance. The high Shannon–Wiener diversity and Pielou's evenness indices underscore a resilient and stable phytoplankton community, particularly pronounced in winter, whereas spring exhibited the lowest diversity, likely influenced by varying nutrient dynamics and environmental conditions.

Seasonal variations played a crucial role in shaping phytoplankton abundance and distribution patterns. Summer emerged as the period with peak phytoplankton abundance, notably in the bottom layers, attributed to strong water column stratification and subsequent sedimentation processes. In contrast, spring experienced the lowest abundance, reflecting the transitional impacts of nutrient availability and oceanic influences during this period. Spatially, the estuarine and nearshore zones consistently supported higher phytoplankton densities, driven by terrestrial nutrient inputs, while offshore areas displayed lower abundances except during summer when stratification facilitated phytoplankton accumulation in deeper waters.

The hierarchical clustering and RDA elucidated distinct subcommunities within Yazhou Bay, each responding uniquely to environmental gradients such as temperature, salinity, and nutrient concentrations. Dominant species acted as effective indicators of specific environmental conditions, with species like *P. pungens* and *S. costatum* signaling terrestrial influence and nutrient-rich environments. The complex interplay of vertical mixing,

water mass transport, and sedimentation processes further emphasizes the multifaceted drivers governing phytoplankton distribution.

Importantly, this study identified potential risks for HABs in Yazhou Bay, particularly associated with high cell densities of certain phytoplankton species in nutrient-rich estuarine and nearshore areas. While current conditions do not favor widespread HAB occurrences, ongoing anthropogenic activities and nutrient loading pose future risks. The high species diversity and community stability observed may currently mitigate bloom formation; however, continued monitoring and dynamic management are essential to prevent potential ecological disruptions.

In conclusion, Yazhou Bay hosts a diverse and dynamically responsive phytoplankton community influenced by seasonal and spatial environmental factors. The resilience and complexity of this community provide a robust foundation for sustaining the bay's ecological health. Future research should focus on long-term monitoring and the incorporation of additional environmental variables to further elucidate the mechanisms driving phytoplankton dynamics. Active management strategies aimed at controlling nutrient inputs will be crucial in maintaining the ecosystem balance and preventing the onset of HABs, thereby ensuring the sustainable development of Yazhou Bay's marine resources.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/w16223181/s1, Figure S1. Phytoplankton subcommunity division in the surface and bottom water layers of Yazhou Bay; Figure S2. Schematic illustration of ocean currents in spring (a) and summer (b), adapted from real-time ocean current model results; Table S1. Abundance (10^4 cells·L^{-1}), Shannon–Wiener diversity index (H'), and Pielou evenness index (J) in the surface and bottom water layers of Yazhou Bay across three seasons; Table S2. Dominant species of subcommunities in the surface and bottom water layers of Yazhou Bay; Table S3. Pearson correlation analysis between total abundance and environmental factors (*: $p < 0.05$). Reference [60] is cited in Supplementary Materials.

Author Contributions: Conceptualization, Z.Y. and C.X.; methodology, C.X.; validation, C.X. and Z.Y.; formal analysis, Z.Y.; investigation, Z.O., C.Z., Z.W., X.F., H.C., Y.H. and Z.Z.; data curation, C.X. and Z.Y.; writing—original draft preparation, Z.Y.; writing—review and editing, Z.Y. and C.X.; visualization, Z.Y.; supervision, C.X. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the Hainan Provincial Joint Project of Sanya Yazhou Bay Science and Technology City, Grant No: 2021CXLH0011, the National Key Research and Development Program of China, Grant No: 2022YFC3103802, the Guangzhou Basic and Applied Basic Research fund, Grant No: 2023A04J0900; the Guangdong Basic and Applied Basic Research Foundation (2023A1515110550); and the Science and Technology Planning Project of Guangdong Province, China (2023B1212060047).

Data Availability Statement: The original contributions presented in this study are included in the article/Supplementary Materials, and further inquiries can be directed to the corresponding authors.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Grand, A.L.; Maxime, V.; Kedzierski, M.; Duval, H.; Douzenel, P.; Sire, O.; Tilly, V.L. Assessment and monitoring of water quality of the gulf of Morbihan, a littoral ecosystem under high anthropic pressure. *Mar. Pollut. Bull.* **2017**, *124*, 74–81. [CrossRef] [PubMed]
2. Nakajima, T.; Kusunoki, T.; Takao, Y.; Yamada, K.; Yokoyama, K.; Sugimoto, R. Saline groundwater discharge accelerates phytoplankton primary production in a Sanriku ria coastal embayment, Japan. *Mar. Ecol. Prog. Ser.* **2023**, *712*, 21–34. [CrossRef]
3. Liu, D.; Xu, Y.Y.; Junaid, M.; Zhu, Y.G.; Wang, J. Distribution, transfer, ecological and human health risks of antibiotics in bay ecosystems. *Environ. Int.* **2022**, *158*, 106949. [CrossRef]
4. Song, X.Y.; Huang, L.M.; Zhang, J.L.; Huang, H.H.; Li, T.; Su, Q. Harmful algal blooms (HABs) in Daya Bay, China: An in situ study of primary production and environmental impacts. *Mar. Pollut. Bull.* **2009**, *58*, 1310–1318. [CrossRef] [PubMed]
5. Linacre, L.; Sánchez-Robles, C.; Mirabal-Gómez, U.; Lara-Lara, J.R.; Bazán-Guzmán, C. Cell carbon content and biomass assessments of dinoflagellates and diatoms in the oceanic ecosystem of the Southern Gulf of Mexico. *PLoS ONE* **2021**, *16*, e0247071. [CrossRef] [PubMed]

6. Oziel, L.; Baudena, A.; Ardyna, M.; Massicotte, P.; Randelhoff, A.; Sallée, J.-B.; Ingvaldsen, R.B.; Devred, E.; Babin, M. Faster Atlantic currents drive poleward expansion of temperate phytoplankton in the Arctic Ocean. *Nat. Commun.* **2020**, *11*, 1705. [CrossRef] [PubMed]
7. Kanna, N.; Sibano, Y.; Toyota, T.; Nishioka, J. Winter iron supply processes fueling spring phytoplankton growth in a sub-polar marginal sea, the Sea of Okhotsk: Importance of sea ice and the East Sakhalin Current. *Mar. Chem.* **2018**, *206*, 109–120. [CrossRef]
8. Ochoa, N.; Taylor, M.H.; Purca, S.; Ramos, E. Intra- and interannual variability of nearshore phytoplankton biovolume and community changes in the northern Humboldt Current system. *J. Plankton Res.* **2010**, *32*, 843–855. [CrossRef]
9. Song, X.Y.; Lai, Z.G.; Ji, R.B.; Chen, C.S.; Zhang, J.L.; Huang, L.M.; Yin, J.Q.; Wang, Y.S.; Lian, S.M.; Zhu, X.M. Summertime primary production in northwest South China Sea: Interaction of coastal eddy, upwelling and biological processes. *Cont. Shelf Res.* **2012**, *48*, 110–121. [CrossRef]
10. Song, X.-Y.; Liu, H.-X.; Zhong, Y.; Tan, Y.-H.; Qin, G.; Li, K.-Z.; Shen, P.-P.; Huang, L.-M.; Wang, Y.-S. Bacterial growth efficiency in a partly eutrophicated bay of South China Sea: Implication for anthropogenic impacts and potential hypoxia events. *Ecotoxicology* **2015**, *24*, 1529–1539. [CrossRef]
11. Kang, N.S.; Lee, K.H.; Jeong, H.J.; Yoo, Y.D.; Seong, K.A.; Potvin, É.; Hwang, Y.J.; Yoon, E.Y. Red tides in Shiwha Bay, western Korea: A huge dike and tidal power plant established in a semi-enclosed embayment system. *Harmful Algae* **2013**, *30*, S114–S130. [CrossRef]
12. Ando, H.; Maki, H.; Kashiwagi, N.; Ishii, Y. Long-term change in the status of water pollution in Tokyo Bay: Recent trend of increasing bottom-water dissolved oxygen concentrations. *J. Oceanogr.* **2021**, *77*, 843–858. [CrossRef]
13. Xu, C.; Ma, Y.; Zhang, H.; Li, X.; Chen, Q. The impact of environmental factors on the spatiotemporal heterogeneity of phytoplankton community structure and biodiversity in the Qiongzhou Strait. *Water* **2023**, *15*, 3792. [CrossRef]
14. Yoon, J.N.; Lee, M.; Jin, H.; Lim, Y.K.; Ro, H.; Park, Y.G.; Baek, S.H. Summer Distributional Characteristics of Surface Phytoplankton Related with Multiple Environmental Variables in the Korean Coastal Waters. *J. Mar. Sci. Eng.* **2022**, *10*, 850. [CrossRef]
15. Pang, H.; Yongo, E.; Lu, Z.; Li, Q.; Liu, X.; Li, L.; Guo, Z. Spatio-temporal dynamics of phytoplankton community structure in the coastal waters of the Southern Beibu Gulf. *Environ. Monit. Assess.* **2024**, *196*, 721. [CrossRef] [PubMed]
16. Rajaneesh, K.M.; Naik, R.K.; Roy, R.; D'Costa, P.M. Chapter 3—Cyanobacteria in tropical and subtropical marine environments: Bloom formation and ecological role. In *Advances in Cyanobacterial Biology*; Singh, P.K., Kumar, A., Singh, V.K., Shrivastava, A.K., Eds.; Academic Press: Cambridge, MA, USA, 2020.
17. Ryan, J.P.; Fischer, A.M.; Kudela, R.M.; Gower, J.F.R.; King, S.A.; Marin, R.; Chavez, F.P. Influences of upwelling and downwelling winds on red tide bloom dynamics in Monterey Bay, California. *Cont. Shelf Res.* **2009**, *29*, 785–795. [CrossRef]
18. Lange, P.K.; Ligowski, R.; Tenenbaum, D.R. Phytoplankton in the embayments of King George Island (Antarctic Peninsula): A review with emphasis on diatoms. *Polar Rec.* **2018**, *54*, 158–175. [CrossRef]
19. Song, Y.; Guo, Y.; Liu, H.; Zhang, G.; Zhang, X.; Thangaraj, S.; Sun, J. Water quality shifts the dominant phytoplankton group from diatoms to dinoflagellates in the coastal ecosystem of the Bohai Bay. *Mar. Pollut. Bull.* **2022**, *183*, 114078. [CrossRef] [PubMed]
20. Araújo, C.A.S.; Belzile, C.; Tremblay, J.É.; Bélanger, S. Environmental niches and seasonal succession of phytoplankton assemblages in a subarctic coastal bay: Applications to remote sensing estimates. *Front. Mar. Sci.* **2022**, *9*, 1001098. [CrossRef]
21. Wang, Y.; Wang, W.; Huang, Y.; Chang, L.; Tang, X.; He, X.; Lin, H. Scenarios of temporal environmental alterations and phytoplankton diversity in a changing bay in the East China Sea. *Front. Mar. Sci.* **2023**, *10*, 1303497. [CrossRef]
22. Du, C.; Liu, Z.; Kao, S.J.; Dai, M. Diapycnal fluxes of nutrients in an oligotrophic oceanic regime: The South China Sea. *Geophys. Res. Lett.* **2017**, *44*, 11510–11518. [CrossRef]
23. Zhang, Y.Y.; Dong, J.; Ling, J.; Wang, Y.; Zhang, S. Phytoplankton distribution and their relationship to environmental variables in Sanya Bay, South China Sea. *Sci. Mar.* **2010**, *74*, 783–792. [CrossRef]
24. Yin, A.Q.; Wang, X.H. Specific spatial-temporal and biological features of red tide in coastal waters around Hainan Island. *J. Saf. Environ.* **2019**, *19*, 1456–1460, (In Chinese with English Abstract).
25. Lv, S.G.; Tang, D.L.; Guan, X.B.; Cen, J.Y.; Lv, S.H. Identification of susceptibility of harmful algal blooms and determining the key monitoring zones in the coastal water of Hainan Island. *Mar. Environ. Sci.* **2016**, *35*, 580–586, (In Chinese with English Abstract).
26. Qu, H.; Gou, P.; Sun, L.; Liu, G.; Han, X.; Long, G. Spatial distribution and its controlling mechanism of surface sediments in the Yazhou Bay, Hainan Island. *Haiyang Xuebao* **2021**, *43*, 70–81, (In Chinese with English Abstract).
27. Wu, M.L.; Ling, J.; Long, L.J.; Zhang, S.; Zhang, Y.; Wang, Y.S.; Dong, J. Influence of human activity and monsoon dynamics on spatial and temporal hydrochemistry in tropical coastal waters (Sanya Bay, South China Sea). *Chem. Ecol.* **2012**, *28*, 375–390. [CrossRef]
28. Santos, M.; Moita, M.T.; Oliveira, P.B.; Amorim, A. Phytoplankton communities in two wide-open bays in the Iberian upwelling system. *J. Sea Res.* **2021**, *167*, 101982. [CrossRef]
29. Li, D.R.; Li, L.; Shen, F.Z.; Liu, B.J.; Shi, H.B.; He, Z.G. Numerical Simulation of Three-dimensional Ocean Hydrodynamic Characteristics in Yazhou Bay. *Bull. Sci. Technol.* **2024**, *40*, 6–14, (In Chinese with English Abstract).
30. Parsons, T.R.; Maita, Y.; Lalli, C.M. *A Manual of Chemical and Biological Methods for Seawater Analysis*; Elsevier: Amsterdam, The Netherlands, 1984.
31. Hansen, H.P.; Koroleff, F. Determination of nutrients. In *Methods of Seawater Analysis*; Grasshoff, K., Kremling, K., Ehrhardt, M., Eds.; Wiley Professional, Reference & Trade: Hoboken, NJ, USA, 1999.

32. Utermöhl, H. Zur vervollkommung der quantitativen phytoplankton-methodik. *Mitteilungen Int. Ver. Limnol. Stuttgard* **1958**, *9*, 263–272.
33. Dhanalakshmi, M.; Akter, S.; Gogoi, P.; Deshmukhe, G.; Landge, A.T.; Bhushan, S.; Layana, P.; Shivkumar, R.N.; Wanjari, R.N.; Nayak, B.B. The effect of the tidal cycle on the phytoplankton community assemblage in a mangrove-dominated tropical tidal creek. *Environ Monit Assess.* **2024**, *196*, 795. [CrossRef] [PubMed]
34. Elser, J.J.; Bracken, M.E.S.; Cleland, E.E.; Gruner, D.S.; Harpole, W.S.; Hillebrand, H.; Ngai, J.T.; Seabloom, E.W.; Shurin, J.B.; Smith, J.E. Global analysis of nitrogen and phosphorus limitation of primary producers in freshwater, marine and terrestrial ecosystems. *Ecol. Lett.* **2007**, *10*, 1135–1142. [CrossRef] [PubMed]
35. Lewis, W.M.; Wurtsbaugh, W.A.; Paerl, H.W. Rationale for control of anthropogenic nitrogen and phosphorus to reduce eutrophication of inland waters. *Environ. Sci. Technol.* **2011**, *45*, 10300–10305. [CrossRef] [PubMed]
36. Paerl, H.W.; Scott, J.T.; McCarthy, M.J.; Newell, S.E.; Gardner, W.S.; Havens, K.E.; Hoffman, D.K.; Wilhelm, S.W.; Wurtsbaugh, W.A. It takes two to tango: When and where dual nutrient (N&P) reductions are needed to protect lakes and downstream ecosystems. *Environ. Sci. Technol.* **2016**, *50*, 10805–10813. [PubMed]
37. Ozuem, F.O.; Chigbu, P.; Oghenekaro, E.; Waguespack, Y.; Chen, N. Spatiotemporal patterns of phytoplankton composition and abundance in the Maryland Coastal Bays: The influence of freshwater discharge and anthropogenic activities. *Estuar. Coast. Shelf Sci.* **2018**, *207*, 119–131.
38. Huang, L.M. Vertical distribution characteristics of seawater temperature and DIN in Sanya Bay. *Trop. Oceanogr.* **2002**, *21*, 40–47.
39. Xu, S.N.; Xiao, Y.Y.; Xu, Y.W.; Su, L.; Cai, Y.C.; Qi, Z.H.; Liu, Y.; Chen, Z.Z.; Lakshmikandan, M. Effects of seasonal variations and environmental factors on phytoplankton community structure and abundance in Beibu Gulf, China. *Ocean Coast. Manag.* **2024**, *248*, 106982. [CrossRef]
40. Xu, Q.; Huang, M.; Yang, S.; Li, X.; Zhao, H.; Tang, J.; Jiang, G.; Li, Z.; Huang, Y.; Dong, K.; et al. Ecological stoichiometry influences phytoplankton alpha and beta diversity rather than the community stability in subtropical bay. *Ecol. Evol.* **2022**, *12*, e9301. [CrossRef]
41. Guo, S.; Zhu, M.; Zhao, Z.; Liang, J.; Zhao, Y.; Du, J.; Sun, X. Spatial-temporal variation of phytoplankton community structure in Jiaozhou Bay, China. *J. Ocean. Limnol.* **2019**, *37*, 1611–1624. [CrossRef]
42. Wihsgott, J.U.; Sharples, J.; Hopkins, J.E.; Woodward, E.M.S.; Hull, T.; Greenwood, N.; Sivyer, D.B. Observations of vertical mixing in autumn and its effect on the autumn phytoplankton bloom. *Prog. Oceanogr.* **2019**, *177*, 102059. [CrossRef]
43. Gao, J.; Guo, X.; Yoshie, N.; Ding, X. Occurrence of surface phytoplankton bloom as the Kuroshio Current passes an island. *J. Geophys. Res. Oceans.* **2022**, *127*, e2021JC018242. [CrossRef]
44. Marić, D.; Frka, S.; Godrijan, J.; Tomažić, I.; Penezić, A.; Djakovac, T.; Vojvodić, V.; Precali, R.; Gašparović, B. Organic matter production during late summer–winter period in a temperate sea. *Cont. Shelf Res.* **2013**, *55*, 52–65. [CrossRef]
45. Gallouli, E.; Mahjoub, O.A.; El Hafa, M.; Aamiri, A. Spatiotemporal variability of phytoplankton in the Aglou-Sidi Ifni coastline (Moroccan Atlantic Coast). *Mar. Biol. Res.* **2022**, *18*, 203–214. [CrossRef]
46. Eichner, M.; Inomura, K.; Pierella Karlusich, J.J.; Shaked, Y. Better Together? *Lessons on Sociality from Trichodesmium. Trends Microbiol.* **2023**, *31*, 1072–1084. [CrossRef]
47. Hasegawa, D.; Yamazaki, H.; Lueck, R.G.; Seuront, L. How islands stir and fertilize the upper ocean. *Geophys. Res. Lett.* **2004**, *31*, L16303. [CrossRef]
48. Hasegawa, D.; Lewis, M.R.; Gangopadhyay, A. How islands cause phytoplankton to bloom in their wakes. *Geophys. Res. Lett.* **2009**, *36*, L20605. [CrossRef]
49. Wang, M. Distribution Characteristics of Planktonic Dinoflagellates in Coastal Waters of Sanya Bay and Establishment of Detection Methods for Red Tide Species. Master's Thesis, Hainan Tropical Ocean University, Hainan, China, 2024. (In Chinese with English Abstract).
50. Fu, C.H. Study on the Occurrence Regularity and Influencing Factors of *Phaeocystis globosa* Bloom in the Northwestern Sea of Hainan Island. Master's Thesis, Hainan University, Hainan, China, 2023. (In Chinese with English Abstract).
51. Dong, J.D.; Zhang, Y.Y.; Zhang, S.; Wang, Y.S.; Yang, Z.H.; Wu, M.L. Identification of temporal and spatial variations of water quality in Sanya Bay, China by three-way principal component analysis. *Environ. Earth Sci.* **2010**, *60*, 1673–1682. [CrossRef]
52. Fu, H. Analysis of Water Pollution Characteristics and Load of Non-point Source Pollution in Yazhou Section of Ningyuan River. Master's Thesis, Southwest University, Chongqing, China, 2020. (In Chinese with English Abstract).
53. He, R.; Jiang, R.; Zhu, X.P.; Guo, W.; Li, Z.X.; Xu, N. Seasonal variation of phytoplankton and its relationship with environmental factors in sea waters near Taishan. *Chin. J. Ecol.* **2018**, *37*, 2727–2736.
54. Liu, H.; Song, X.; Huang, L.; Zhong, Y.; Shen, P.; Qin, G. Diurnal variation of phytoplankton community in a high frequency area of HABs: Daya Bay, China. *Chin. J. Ocean. Limnol.* **2011**, *29*, 800–806. [CrossRef]
55. Wang, H.; Li, Y.; Li, Y.; Liu, H.; Wang, W.; Zhang, P.; Fohrer, N.; Li, B.L.; Zhang, Y. Phytoplankton Communities' Response to Thermal Stratification and Changing Environmental Conditions in a Deep-Water Reservoir: Stochastic and Deterministic Processes. *Sustainability* **2024**, *16*, 3058. [CrossRef]
56. Chen, W.; Gao, J.; Xu, Z.; Yan, Y.; Yang, S. Phytoplankton Community Diversity and Its Environmental Driving Factors in the Northern South China Sea. *Water* **2022**, *14*, 3777. [CrossRef]
57. Tas, S.; Lundholm, N. Temporal and spatial variability of the potentially toxic Pseudo-nitzschia spp. in a eutrophic estuary (Sea of Marmara). *J. Mar. Biol. Assoc. UK* **2017**, *97*, 1483–1494. [CrossRef]

58. Lorenzo, J.I.; Nieto-Cid, M.; Álvarez-Salgado, X.A.; Pérez, P.; Beiras, R. Contrasting complexing capacity of dissolved organic matter produced during the onset, development and decay of a simulated bloom of the marine diatom *Skeletonema costatum*. *Mar. Chem.* **2007**, *103*, 61–75. [CrossRef]
59. Shikata, T.; Nagasoe, S.; Matsubara, T.; Yoshikawa, T.; Yamasaki, S.; Shimasaki, Y.; Oshima, Y.; Jenkinson, I.R.; Honjo, T. Factors influencing the initiation of blooms of the raphidophyte *Heterosigma akashiwo* and the diatom *Skeletonema costatum* in a port in Japan. *Limnol. Oceanogr.* **2008**, *53*, 2503. [CrossRef]
60. Archive of the 1/12° Global HYCOM+CICE—South China Sea Speed + Currents. Available online: https://www7320.nrlssc.navy.mil/GLBhycomcice1-12/navo/arc_list_schinaspdcur.html (accessed on 21 July 2024).

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.