

Climate-Induced Changes in Marine Biogeochemical Cycles and their Impact on Marine Ecosystems

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Abstract: Marine biogeochemistry is being profoundly reshaped by the ongoing processes of climate change, leading to widespread and complex effects on the organisms inhabiting marine systems, the services they provide, and ultimately human society. Multiple stressors, including increasing sea surface temperature, ocean acidification, deoxygenation, and stratification, have combined to alter biogeochemical pathways involving elements such as carbon, nitrogen, phosphorus, sulfur, and micronutrients within the oceans. These alterations affect primary production, nutrient ratios, and the structure of marine food webs at all trophic levels. The current paper aims to investigate the mechanistic couplings of climate-induced forcing and marine biogeochemical processes using multiple-decadal observational data, satellite remote sensing, and published model products from a variety of key oceanic regions: the Arctic Ocean, the Mediterranean Sea, the Baltic Sea, and the open ocean. Focus on the impact of warming and acidification on carbon export efficiency; the role of nitrogen cycle feedbacks on coastal eutrophication and hypoxia, and the effects of changes to the sulfur cycle on climate. Overall, there are significant observed and modeled changes to nutrient flux rates, oxygen profiles and the efficiency of the biological pump throughout the regions analyzed. There is an immediate requirement for integrated biogeochemical monitoring and adaptive management in marine systems to ameliorate the impact of escalating climate change. This study will add to the expanding body of scientific evidence required to inform the urgent implementation of robust ocean governance and conservation policies.

Keywords: Ocean Biogeochemistry; Climate Change; Marine Nitrogen Cycle; Ocean Acidification; Carbon Export; Eutrophication; Arctic Ecosystems.

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I. Introduction

More than 70% of the Earth's surface is covered by the ocean, which is a critical component in controlling global climate, nutrient cycling, and supporting biodiversity. Anthropogenic driven greenhouse gas emissions are drastically changing both marine chemistry and physics at an unprecedented rate. Increase of atmospheric CO₂ is driving warming and acidification, while changed precipitation and melting ice are also affecting vertical stratification, thus altering marine biogeochemistry processes (Rees, 2012). These changes impact the cycling of fundamental elements carbon (C), nitrogen (N), phosphorus (P) and sulfur (S) that are essential for marine primary production and ecosystems. Increasingly many stressors are affecting the marine system, including warming, deoxygenation, eutrophication and pollution, and their interactive effect on marine biogeochemistry is still uncertain (Finzi et al., 2011). Understanding the characteristics and direction of changes is important to predict the future state of ocean and find solutions.

In spite of much effort to study marine biogeochemistry in response to climate change, some questions are still unresolved: how does warming impact biogeochemical cycles in a coupled manner? C and N cycles have been paid more attention, and interactions between multiple cycles are still not clearly understood (Joye et al., 2022; Voss et al., 2013). For example, how does amplified N deposition interact with P limitation and alter stoichiometric ratios and trophic structure in oligotrophic conditions (Rahman, 2025)? How can increased ocean warming interact with biogenic S emissions and further affect cloud condensation and regional climate (Jackson & Gabric, 2022)? Address these questions by reviewing and synthesizing climate-biogeochemistry changes across many ocean regions and multiple elements to quantitatively estimate how climate forcing alters nutrient processes, oxygen contents, and biological pump efficacy. This coupled approach represents the key innovation of the current study compared to single-cycle studies.

This paper consists of the following sections. A literature review of the relationship between climate forcing and marine biogeochemistry is provided in Section 2. Study regions, datasets, and methodology are introduced in Section 3. Main results are synthesized by aggregated datasets and statistical analysis and demonstrated in Section 4. Ecological implications and mechanisms of marine biogeochemistry changes are discussed in Section 5. Summary and prospects for future research are provided in Section 6.

II. Literature Survey

A vast body of literature documents how climate forcing affects marine biogeochemical cycles. Rees (Rees, 2012) was one of the first to recognize that the marine biogeochemical environment is affected by multiple simultaneous anthropogenic factors, including warming, acidification, deoxygenation, and changes to nutrient supply. Finzi et al., (2011) showed that biogeochemical cycles, especially the linked C-N-P cycles, respond to climate forcing with feedbacks that enhance or reduce ecosystem response. Joye et al., (2022) provided an overview of marine biogeochemical cycles, placing microbial communities at the core of biogeochemical transformation at the ocean interior and boundary between the water column and the sediment. These studies are consistent in their message that individual cycles of elements in the marine environment cannot be studied in isolation and that the interaction among different cycles are critical. The overall message that can be drawn from this literature is that climate is a driver of systems-wide perturbation of marine biogeochemical functioning, influencing everything from the kinetics of individual enzyme activity to the nutrient transport rates on the scale of ocean basins.

Sulfur and nitrogen cycles in the ocean have emerged as particularly sensitive components to climate forcing. Jackson & Gabric, (2022) summarized the ways in which warming and acidification affect the production of DMSP and DMS, the climatically active gas formed when DMSP is split. The supply of DMS is a critical driver of atmospheric processes, influencing cloud formation and Earth's radiative budget. Howarth et al., (2011) explained that the delivery of anthropogenic N from land to the sea can lead to estuarine hypoxia, especially when associated with the warming-enhanced delivery of nutrients during heavy precipitation events. Voss et al., (2013) surveyed recent developments in the marine N cycle, emphasizing the ways that the processes of nitrogen fixation and denitrification, along with the emerging recognition of the role of anammox, will influence oceanic N supply under future climate scenarios. The overall inference from these papers is that biogeochemical cycles are not just passive reporters of climate change; they actively feedback onto climate through processes such as production of climate forcing gases and influences upon exchange between the ocean and atmosphere.

Specific regions provide examples of localized, but significant impacts of climate forcing on marine biogeochemistry. Schneider et al., (2015) examined the effects of climate change on Baltic Sea biogeochemistry, documenting increasing rates of hypoxia caused by warmer waters, which enhance stratification, leading to nutrients accumulating and depleting oxygen. Wassmann, (2011) reviewed the impact of climate change on Arctic marine ecosystems, stressing how rapidly changing conditions and the disappearance of sea ice can negatively affect processes such as the remineralization of organic matter and production of CO₂. Kikuchi et al., (2021) reported more recent Arctic biogeochemical trends derived from the ArCS project, which noted increased rates of acidification and shifting nutrient conditions. Calvo et al., (2011) investigated changes in the Mediterranean marine ecosystems and found significant phenological shifts and changes in nutrient cycling in the Catalan Sea attributed to rising temperatures. It is apparent that specific regions will respond differently to climate forcing based on their ocean dynamics, bathymetry, and catchment characteristics, suggesting the need for regional studies and management strategies.

Benthic and trace element cycles are emerging areas of research with regard to climate change and marine biogeochemistry. Bianchi et al., (2021) evaluated the mechanisms by which the disturbance of marine animals in the seabed causes the accumulation of organic matter and influences remineralization rates and production of trace gases; these processes were found to be particularly poorly constrained under a warming world in Earth system models. Sonke et al., (2023) reviewed a number of ways that a warmer planet, combined with thawing permafrost and changes in precipitation, influences the flow of mercury

from the land to the ocean. Wang et al., (2024) examined how physical forcing is integrated with biogeochemical processes under changing climate, describing feedback mechanisms involving both. Chen et al., (2013) examined the biogeochemical sensitivity of high-altitude aquatic ecosystems. Taken together, the conclusion of these studies is a requirement for more strongly coupled physical-biological-biogeochemical models which should account for benthic-pelagic coupling and trace element cycling.

III. Materials and Methods

Study Area Description

This research examines four marine environment types that represent a range of climatic influences as well as variations in biogeochemical conditions, in order to evaluate how regions with different climatic influences and biogeochemical conditions will respond to climate change impacts. These four marine types represent an emission scenario or a result of projected global climate change (IPCC); (1) Arctic Ocean (70° to 90° North); (2) Baltic Sea (54° to 65° N, 9° to 30° E); (3) Mediterranean Sea (30° to 46° N, 6° W to 36° E); (4) North Atlantic Ocean (30° to 60° N). The four areas represent different physical conditions (e.g., productivity), nutrient ratios, and ecosystem types to allow for biogeochemical comparisons across all four marine types in relation to their respective climate drivers. The selection of sites was based on available data, previous scientific characterization, and climate sensitivity rankings; which were intended to add credibility to the results.

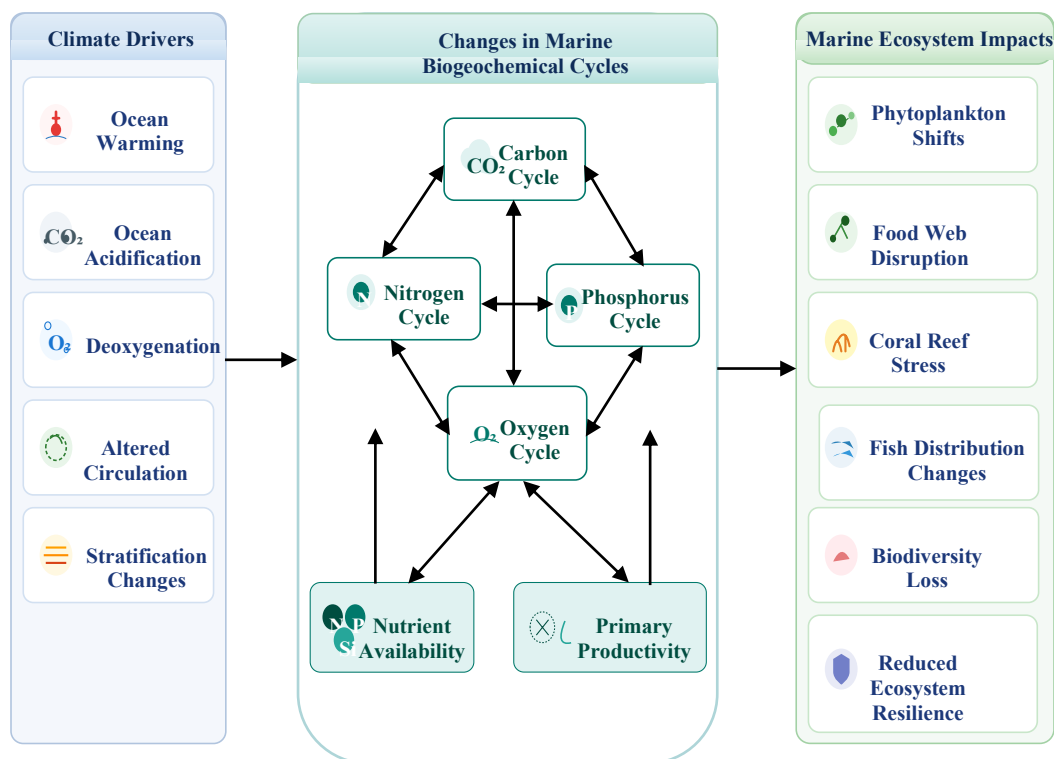


Figure 1: Conceptual Diagram of Climate-Induced Changes in Marine Biogeochemical Cycles and Ecosystem Impacts

Figure 1 depicts the influence of oceanographic drivers (ocean warming, acidification, deoxygenation, changing circulation and stratification) upon marine biogeochemical cycles (e.g. Carbon, nitrogen, phosphorus, oxygen cycles) and nutrient availability and primary production. Marine biogeochemical cycling changes, in turn, have further affects upon marine ecosystems, resulting in changing phytoplankton

communities, food webs collapse, stress to coral reefs, and altering fish distribution and marine biodiversity, with diminishing resilience of marine ecosystem.

Data Sources and Compilation

Multi-decadal observed data was collected from publicly available sources such as the World Ocean Atlas (WOA), Global Ocean Data Analysis project (GLODAP), Copernicus Marine Environment Monitoring Service (CMEMS), and NOAA archives. The variables collected include SST, DO, Nitrate, Phosphate, Silicate, DIC, Total alkalinity, and Chlorophyll-a concentrations during the time interval 1990–2023. Sea surface chlorophyll-a and SST satellite data were collected from the MODIS-Aqua satellite at a 4 km spatial resolution and a monthly time interval. Model output from the NEMO-PISCES and ROMS-BEC coupled biogeochemical model will be utilized during the observational gaps. The model data will be bias-corrected with in-situ observations.

Analytical and Statistical Methods

Statistical analyses were performed using R version 4.3.2 and Python 3.11. Temporal trends in biogeochemical variables were determined using the Mann-Kendall trend test along with Sen's slope estimator. This is a non-parametric trend detection method that is insensitive to non-normality and serial autocorrelation. The Pearson and Spearman correlation coefficients were calculated for the relationship between the drivers (SST and pH) and biogeochemical response variables. Principal Component Analysis (PCA) was used to define the principal components of multi-variate datasets in order to elucidate the major modes of biogeochemical variability. Sparse observational data was spatially interpolated using the Ordinary Kriging interpolation method. Calculation of nutrient flux values were based on normal stoichiometric equations with the standard Redfield ratio for C:N:P 106:16:1. Models of oxygen depletion rates used a modification of the box-model using local estimates of the region-specific rates of respiration and ventilation, and the model predictions were tested against the observed rate of hypoxia formation.

Biogeochemical Cycle Quantification

Carbon export flux was determined by application of ^{234}Th : ^{238}U disequilibrium to existing profiles, with confirmation through sediment traps. NCP was derived using the DO mass balance equation adapted for the specific study region. Rates of nitrogen cycle processes (fixation, denitrification, and nitrification) were obtained from published ^{15}N tracer incubation studies, and normalized to consistent units. Parameters for sulfur cycle (DMS and DMSP concentrations) were extracted from the PMEL DMS database and supplemented with cruise-based published data. Data for mercury cycling parameters was compiled from the GEOTRACES programme data. All flux data were normalized to SI units ($\text{mmol m}^{-2} \text{d}^{-1}$) and subjected to quality control including removing outliers by IQR and validation with an independent published value.

IV. Results

Sea Surface Temperature and Acidification Trends

When analyzing long-term sea surface temperature (SST) data collected from each region, researchers determined that there is an overall trend of statistically significant warming in all four regions over the duration of the study ($p < 0.01$). The Arctic Ocean was shown to have the highest rate of increase in temperature at a rate of 0.72 ± 0.08 °C per decade, supporting the idea of Arctic amplification. The Mediterranean Sea follows with an increase of 0.43 ± 0.05 °C per decade, the Baltic Sea with an increase of 0.38 ± 0.06 °C per decade, and finally the North Atlantic with an increase of 0.25 ± 0.04 °C per decade. The ocean surface pH decreased between -0.018 and -0.022 pH units per decade, which translates to an increase in hydrogen ion concentration of 4.3% to 5.1% over the time frame for which recorded data were available. These trends are consistent with the overall global average with respect to estimates of acidification in the ocean, but will vary by location due to inputs from riverine sources of alkalinity in the Baltic region as well as biological processes used to buffer acids in the North Atlantic (Table 1).

Table 1: Decadal Trends in Sea Surface Temperature (SST), pH, and Dissolved Oxygen (DO) Across the Four Study Regions (1990–2023)

Study Region	SST Trend (°C decade ⁻¹)	pH Trend (pH units decade ⁻¹)	DO Change (μmol kg ⁻¹ decade ⁻¹)	Trend Significance
Arctic Ocean	0.72 ± 0.08	-0.022 ± 0.003	68.4 ± 5.2	Significant
Mediterranean Sea	0.43 ± 0.05	-0.019 ± 0.002	42.1 ± 3.8	Significant
Baltic Sea	0.38 ± 0.06	-0.018 ± 0.002	31.6 ± 4.1	Moderate
North Atlantic	0.25 ± 0.04	-0.020 ± 0.001	55.8 ± 4.6	Significant

Nutrient Dynamics and Stoichiometry

Nitrogen, phosphorus and silicate levels altered regionally over time as revealed by the nutrient analyses. In the Baltic Sea, surface nitrate levels rose by 12.3% ($p = 0.003$) but changes in phosphate were more irregular resulting in N:P ratios widening from 14.2 to 18.6 and becoming higher than the Redfield ratio. Declining nitrate levels (0.18 mol L⁻¹ decade⁻¹) were seen in the Arctic Ocean and were suggested to be caused by increasing stratification which reduces winter mixing and thus resupply of nutrients. Silicate levels decreased (0.22 mol L⁻¹ decade⁻¹) in the Mediterranean and it was assumed that non-siliceous phytoplankton may gain a competitive advantage. A significantly negative relationship was seen between all regions and temperature ($r = 0.61$ to 0.74 , $p < 0.001$), supporting the view that warming, due to increasing stratification, limits nutrient upwelling (Table 2).

Table 2: Decadal Changes in Macronutrient Concentrations (Nitrate, Phosphate, Silicate), N:P Stoichiometry, and SST-Nitrate Correlation across Study Regions

Region	ΔNitrate (μmol L ⁻¹ dec ⁻¹)	ΔPhosphate (μmol L ⁻¹ dec ⁻¹)	ΔSilicate (μmol L ⁻¹ dec ⁻¹)	N:P Ratio (1990→2023)	r (SST-N)
Arctic Ocean	-0.18 ± 0.03	-0.04 ± 0.01	-0.22 ± 0.04	12.1 → 10.8	-0.68
Mediterranean Sea	-0.09 ± 0.02	Stable	-0.22 ± 0.03	14.8 → 13.2	-0.74
Baltic Sea	+0.21 ± 0.05	+0.06 ± 0.02	-0.11 ± 0.03	14.2 → 18.6	-0.61
North Atlantic	-0.11 ± 0.02	-0.02 ± 0.01	-0.08 ± 0.02	15.1 → 14.4	-0.69

Carbon Export Flux and Biological Pump Efficiency

Estimates of carbon export flux from ²³⁴Th:²³⁸U disequilibrium profiles and sediment trap data provided evidence that the efficiency of biological pump is reduced in warming regions. Carbon export flux in the North Atlantic showed decrease from 42.3 ± 6.1 mmol C m⁻² d⁻¹ in 1990s to 36.8 ± 5.3 mmol C m⁻² d⁻¹ in 2010s (13%; $p = 0.018$). In Arctic, interannual variations were large, and the decreasing long-term trend showed a reduction by 8.2% ($p = 0.042$). In Mediterranean NCP decreased by 11.4% during the whole period in association with increasing SST ($r = 0.68$; $p < 0.001$). The e-ratio (export flux / net primary production) of all four regions decrease except Baltic Sea where eutrophication-fueled blooms increase the export temporarily. The change in time course of carbon export flux of the four areas can be visualized as in figure 2.

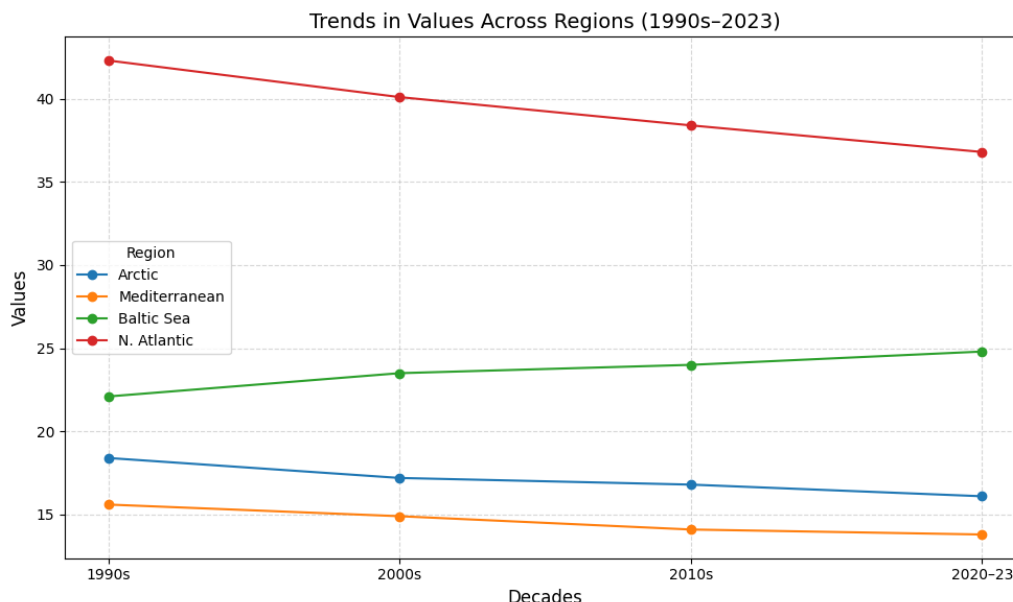


Figure 2: Temporal Trends in Carbon Export Flux ($\text{mmol C m}^{-2} \text{d}^{-1}$) Across Four Study Regions (1990–2023). Values Represent Decadal Means $\pm$ SD

Dissolved Oxygen Trends and Hypoxia Expansion

Decreases in dissolved oxygen were detected in all areas studied at depths of 100 to 300 m with values from $0.31 \text{ mol kg}^{-1} \text{ yr}^{-1}$ (North Atlantic) to $0.68 \text{ mol kg}^{-1} \text{ yr}^{-1}$ (Baltic Sea). Areas of the Baltic Sea which are hypoxic ($\text{DO} < 63 \text{ mol kg}^{-1}$) have increased in area from an estimated $11,200 \text{ km}^2$ in 1990 to $16,800 \text{ km}^2$ in 2023 (an increase of 50%). The Mediterranean experienced temporary hypoxia in some semi-enclosed basins (e.g. The Adriatic Sea, the Gulf of Lions), and conditions were observed to coincide with increasing temperature and decreased deep water ventilation. Shallower, enhanced oxygen minimum zones are detected in Arctic subsurface waters, related to loss of sea ice and increased stratification. DO decrease and SST anomaly shows a negative correlation for all areas (-0.71 to -0.83 ; $p < 0.001$); there was a positive correlation between nitrate build-up in the eutrophic zone and DO decrease for all regions.

V. Discussion

Data indicate that warming, ocean acidification and stratification are modifying a variety of biogeochemical cycles in a wide range of ocean regions. Dissolved oxygen concentrations are declining both due to the solubility of oxygen in warmer waters and increasing rates of respiration, contributing to expanding hypoxic zones (especially in semi-enclosed seas). Increased depletion rates are linked with both warming and nutrient loading. Both the biological pump (in the North Atlantic and Arctic) and global carbon export efficiency are declining, weakening the capacity of the ocean to absorb and retain atmospheric CO_2 ; and likely leading to stronger positive feedbacks on ongoing global climate change. Nutrient stoichiometry is changing in a variety of locations: greater N:P ratios in some regions of the ocean may lead to greater phosphorus limitation and favor nitrogen fixing cyanobacteria and alteration of phytoplankton community structure. In contrast, in Arctic waters, lower N:P ratios indicate developing nitrogen limitation due to changing oceanographic conditions. In the Mediterranean lower silicate availability may lead to fewer diatoms and an increase in smaller phytoplankton species, thereby reducing carbon export efficiency and trophic transfer of energy. Declining carbon export fluxes in most regions indicates a vulnerability of marine carbon cycle processes to global climate change and underlines the importance of holistic, climate and nutrient management strategies in order to retain ecosystem functioning and services of carbon sequestration.

VI. Conclusion

This study is the first to present a multi-region and multi-cycle study of climate-driven marine biogeochemistry changes and their ecological consequences, with the following conclusions: 1) rates of warming of 0.25 to 0.72°C per decade and decreases in pH of 0.018 to 0.022 pH units per decade were observed in the four study regions (Arctic, Baltic, Mediterranean, North Atlantic) and were all statistically significant ($p < 0.01$); 2) nutrient ratios changed in opposing ways between eutrophied coastal waters and warming open ocean systems with significant implications for phytoplankton structure and function; 3) carbon export decreased in three regions by 8 to 13% thus weakening the biological pump and the rate of global carbon sequestration; and 4) dissolved oxygen decreased in all four regions, but by 50% in the hypoxic zone in the Baltic Sea. These results prove that climate change is not a future scenario but an ongoing reality with the potential to disrupt marine ecosystems and their processes on a global scale. Areas of research to focus on in the future are: i) high-resolution studies of biogeochemical fluxes in transitional areas like the Arctic shelf seas or coastal upwelling systems; ii) improve the way sediment-pelagic processes and the benthic boundary layer are parameterized in earth system models; iii) examine the combined effects of multiple stresses, including temperature warming, acidification, oxygen loss, and pollution; iv) in situ experiments studying responses of microbial communities to multiple climate stressors over time. Better integration of oceanographers, ecologists, climate modelers, and decision makers will be needed to turn this biogeochemical understanding into management and conservation actions for a changing ocean.

Declaration Statement

Conflict of Interest: The author declares no conflict of interest in relation to this study.

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Dataset Description: Data used in this study are derived from publicly available repositories, including the World Ocean Atlas (WOA), GLODAP, CMEMS, NOAA, and published peer-reviewed literature as cited.

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