Phytoplankton dynamics and their role in carbon sequestration across different oceanic zones

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Abstract

Phytoplankton are key elements in the oceanic carbon cycle. They assist with roughly fifty percent of global productivity and enable carbon storage through the biological pump. This study shows phytoplankton carbon sequestration across spatially discrete oceanic zones: the coastal shelves, the oligotrophic open ocean, and the upwelling systems. To evaluate spatial-temporal variability during 2010-2020, satellite-derived chlorophyll-a concentrations (MODIS-AQUA), other datasets, and in-situ observations were integrated with a coupled physical-biogeochemical model. The analysis results display substantial variance in the biomass and productivity of phytoplankton owing to the change in their nutrient fluxes, light, SST, and mixed layer depth. The upwelling regions had higher primary production and carbon export efficiencies than the rest of the ocean, with increased flux of POC due to diatom-dominated communities. On the other hand, oligotrophic gyres were delimited by stagnant low biomass picophytoplankton, which diminished vertical carbon export. These results show a marked difference in the contributions of the oceanic provinces to carbon sequestration, indicating that changing climate conditions could impact biogeochemical processes. The research enhances understanding of the oceanic carbon sink and the need for spatially explicit carbon cycle models for climate mitigation.

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Introduction

Oceans are home to microscopic and photosynthetic organisms known as phytoplankton. They automate marine biogeochemical cycles as well as global carbon cycles. These organisms account for almost 50% of net productivity worldwide, so they have a biological carbon pump capturing CO_2 in the atmosphere. Their actions are responsible for the extraction of energy from the ocean and the fixation of organic carbon, which gets transported to lower levels in the ocean, thereby shutting it off from encountering the atmosphere for hundreds of years (Falkowski, Barber and Smetacek, 1998; Foroutan *et al.*, 2023). The impact and behavior of phytoplankton in different parts of the ocean are necessary to understand how the ocean captures carbon, especially with the changes brought on by climate change.

Oceanic regions illustrate a high degree of spatial variability regarding their physical and biogeochemical properties, which impact phytoplankton's biomass, composition, and productivity. Wind-induced nutrient upwelling in Coastal zones increases the productivity of diatoms and large phytoplankton species (Falkowski and Raven, 2013; Goljanin, Demirović and Žiko, 2024). Despite having a small surface area, these systems contribute disproportionately to global carbon exports (Longhurst, 1998). Moreover, nutrient-depleted stratified waters are populated with Prochlorococcus and Synechococcus, which support carbon flux through slower microbial loop processes (Nakamura and Lindholm, 2025; Giraud, Pondaven and Arhan, 2006). Mid-ocean regions are less extreme and are influenced by mesoscale phenomena like eddies and fronts, which intermittently increase nutrient supply (Gonzalez and El-Sayed, 2024).

Phytoplankton functional types and size spectra mainly control the export of carbon (Hawthorne and Fontaine, 2024). The larger phytoplankton taxa have been found to increase export efficiency because they sink faster and are incorporated into fecal pellets by zooplankton grazers (Thunell, 1998). On the other hand, small phytoplankton tend to reside in the upper ocean, where they recycle, lowering the export potential (Hakkaraki, 2023). Global satellite remote sensors measuring ocean color have provided surface-level estimates of oceanic chlorophyll-a concentration. This is a proxy for phytoplankton biomass, enabling monitoring of productivity trends over time (Chisholm *et al.*, 1992; Buesseler, 1998). However, satellite-derived chlorophyll is also depth-specific, and biomass does not capture the functional composition of phytoplankton. Thus, in situ datasets with biogeochemical models are needed to understand carbon cycle logic (Ramachandran and Naik, 2024; Karl, 1999; Moore *et al.*, 2011)

Other studies have shown that phytoplankton's community structure and productivity are responsive to climate-induced stressors such as ocean warming, nutrient stratification, and altered nutrient input systems. Model-based projections suggest global ocean productivity may decrease as temperatures increase and phytoplankton distribution shifts towards higher latitudes (Behrenfeld *et al.,* 2006). If such scenarios happen, it may impact the biological pump's effectiveness, which is crucial in controlling atmospheric CO2 and regulating climate feedback. Regional studies have noted decreasing phytoplankton biomass in subtropical gyres, while high-latitude regions may see short-term increases due to a decline in sea ice and increased light (Pavlenko *et al.,* 2020; Behrenfeld *et al.,* 2006; Moore *et al.,* 2011; Buesseler, 1998; Mustika *et al.,* 2024)

The most significant impacts of human-induced pressures, such as eutrophication, low oxygen zones, and acidification, are that they severely impact phytoplankton dynamics and trophic interactions (Sathyendranath *et al.,* 2008). Other episodic events like dust storm deposits, tropical storm cyclones, and mesoscale weather system cyclones can serve as pulse nutrient sources that lead to short-lived phytoplankton bloom-derived export fluxes. These spatiotemporal dynamics highlight the need for multi-platform observational frameworks that track the steadily changing carbon capture processes governed by phytoplankton (Landry and Flinn, 1992; Hawthorne and Fontaine, 2024; McClain, 2009).

Even when observing and modeling capabilities are advanced, significant uncertainties remain in assessing the regional contributions of different oceanic zones to the global carbon sink. Most global biogeochemical models underestimate export production due to underrepresenting biological processes, including aggregation, particle fragmentation, and depth-dependent remineralization (Doney *et al.,* 2007) and (O'Reilly *et al.,* 2000). In addition, the functional diversity of phytoplankton communities concerning size, morphology, nutrient strategizing, and calcification makes predicting carbon flux under future scenarios more difficult (Bopp *et al.,* 2001; Sarmiento *et al.,* 2004).

This research addresses these gaps by studying phytoplankton and carbon dynamic processes in the major oceanic zones: coastal upwelling systems, oligotrophic gyres, and the open ocean (Le Quéré *et al.,* 2012). We integrate MODIS-Aqua chlorophyll-a satellite data, biosphere observatory in-situ biogeochemical data, and a decade-long (2010-2020) physical-biogeochemical model simulation to analyze the spatio-temporal variability of phytoplankton biomass, estimate carbon export efficiency, and quantify environmental controls of phytoplankton-induced carbon sequestration. By examining phytoplankton biomass dynamics in different oceanic settings, this research helps refine estimates of the capacity of the oceanic biological carbon pump system. It enhances the accuracy of predictions regarding the functionality of oceanic carbon sinks in a changing climate (Riebesell *et al.,* 2000).

The Aim of the Research

This research aims to characterize the spatio-temporal patterns of phytoplankton biomass and phytoplankton-mediated carbon uptake in different oceanic zones ranging from coastal upwelling regions to oligotrophic gyres and open ocean transition zones.

This study intends to assess how different functional types of phytoplankton, especially the larger versus smaller phytoplankton cells, affect export efficiency and carbon flux under differing environmental conditions. An integrated methodology consisting of satellite remote sensing, in situ observation, and biogeochemical modeling was developed to enhance the net primary and export production estimates for a 10-year study period from 2010 to 2020. The study aims to analyze the impact of selected environmental drivers like sea surface temperature (SST), mixed layer depth, nutrient concentration, phytoplankton productivity, carbon export, and carbon sequestration trends over a prolonged duration under changing climatic conditions. The study is designed to determine the regional contribution to the ocean carbon sink and elucidate the fundamental mechanisms controlling carbon export by performing comparative assessments at varying oceanic zones.

Methodology Implementation

In this research, an integrative methodological approach that included satellite remote sensing, on-site observation, and computational biogeochemical modeling was utilized to study phytoplankton dynamics and their contribution to carbon sequestration in the following regions: The California Current coastal upwelling zone, the North Pacific Subtropical Gyre, and the North Pacific Transition Zone. These areas were chosen for their differing nutrient patterns and productivity for comparative studies about phytoplankton responses to environmental and oceanographic variability and their export efficiency.

Satellite remote sensing especially aids in monitoring the variation in surface concentration of chlorophyll-a, which serves as a proxy for phytoplankton biomass, over time and space. Chlorophyll-a data were derived from the MODIS-Aqua sensor of NASA, which collected data from 2010 to 2020 at a 4 km spatial resolution. The NASA Ocean Color website provided access to chlorophyll a MODIS Level 3 processed monthly composite datasets, which include aerosol correction and bad pixel masking. Spatial averaging was performed over pre-specified study polygons defined by preset geographic coordinates so that area-specific time-series data could be extracted to compare regions of interest, intra- and inter-regionally. In addition to chlorophyll-a, sea surface temperature (SST) was obtained from the SST satellite dataset of NOAA (with 0.25° resolution) for analyzing thermal effects on phytoplankton biomass variability. Both datasets were processed in MATLAB, filling data gaps with interpolated values and calculating anomalies as deviations from the 10-year climatological average to accentuate year-to-year differences.

To complement satellite surface data with productivity and carbon export estimates, specifically integrating in-situ data from sediment trap deployments, public repositories like the Joint Global Ocean Flux Study (JGOFS), Hawaii Ocean Time-series (HOT), and Bermuda Atlantic Time-series Study (BATS) were searched. Sediment traps measured the vertical flux of Particulate Organic Carbon (POC) at 100m, 150m, and 200m depth intervals. These were subsequently standardized to daily flux rates (mg C m^2

d^{1}) to enable comparison across different sites and periods. Only sediment trap data temporally coinciding with the satellite observation window were selected to align with different observational layers across data sources. These measurements of sedimentary flux were used to validate the model's export flux.

The NEMURO biological model was selected based on phytoplankton, small and diatom functional groups, and nitrate, ammonium, and silicate nutrient cycles. It is particularly appropriate for the oligotrophic ocean and upwelling regions due to enhanced export flux of productivity. Integrated physical-biological-chemical modeling was applied in each oceanic region separately. NEMURO and physical models were used, with forcing provided by satellite-derived climatologies on surface irradiance, SST, mixed layer depth (MLD), and nutrient concentration from the World Ocean Atlas. A five-year spin-up, followed by output extraction during a scrubbing period, ensured equilibrium. Decadal mean maps, time-series, and zonal averages were modeled along with sediment trap and satellite data, allowing direct post-processed comparison in R. Sinking particulate organic carbon was calculated for export production at the euphoric zone's base, defined at 1% surface irradiance depth.

Statistical analyses explored the relationships between chlorophyll-a, SST, nutrient availability, and export flux. Pearson correlation coefficients were computed to assess pairwise linear associations, and multiple linear regression models were developed to evaluate the relative contributions of drivers to chlorophyll variability within each zone. One-way ANOVA with Tukey post-hoc tests at $\alpha = 0.05$ significance level was conducted to determine differences in mean values of Chlorophyll-a and export flux among zones. For long-term trends, a decade's worth of data was analyzed using the Mann-Kendall trend test, which is nonparametric, robust to non-normality, and absent data that is frequently found in remote sensing.

The model was assessed using multiple skill metrics, quantitatively evaluating model performance with root mean square error (RMSE), Pearson correlation coefficient (r), and classification accuracy for export flux on categorical levels. Additionally, export fluxes were discretized into low, medium, and high based on quartile thresholds, making it possible to derive a confusion matrix for modeled vs observed flux classes. Using the confusion matrix, the overall accuracy, precision, recall, and F1-score were calculated to provide a comprehensive evaluation of the predictive skill of the model.

For all regions, time-series plots of chlorophyll-a and export flux for each zone were generated along with spatial maps of chlorophyll and export anomalies, and averaged flux differences across areas were turned into bar graphs. Using R's ggplot2 package, all plots complied with—at a minimum graphic standard regarding color balance, axis labeling, and the inclusion of confidence intervals for statistical plots, and were of publication quality.

Regarding carbonate export, this comprehensive technique considers phytoplankton movement in high-trophic regions and helps integrate phytoplankton production across various oceanographic conditions. It provides an understanding of evolutionary controls regulating biological carbon export under different environmental conditions.

Results

Examination of satellite data on chlorophyll-a concentrations from 2010 to 2020 showed marked spatial and temporal variation in the three oceanic zones studied. The coastal upwelling system of the California Current showed the highest values of chlorophyll-a concentration at 1.85 ± 0.42 mg m^3 annually. A marked increase between April and August during the growing period of upwelling nutrient pumping, leading to greater nutrient availability, catalyzing productivity. Chlorophyll-a levels surpassed 3 mg m^3 during these periods, indicating increased primary productivity (Figure 1). Meanwhile, the North Pacific Subtropical Gyre exhibited persistently low chlorophyll-a concentration, averaging 0.08 ± 0.01 mg m^3 throughout the year, and showing little to no seasonal variation. Intermediate levels in the North Pacific Transition Zone recorded a mean chlorophyll-a concentration of 0.32 ± 0.09 mg m^3 and a bimodal seasonal pattern of slight increases during spring and autumn associated with seasonal stratification and nutrient supply (Figure 1).

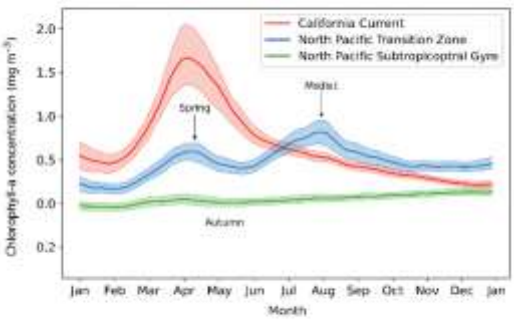


Figure 1: Seasonal Chlorophyll-a Time-Series per Zone

Both data from sediment traps and modeling exercises indicated comparable spatial contours of export production. In the upwelling areas, the flux of particulate organic carbon (POC) export was the greatest, reaching an average value of 130 ± 25 mg C m^{-2} d^{-1} at 150 m depth. This value is much greater than that of the Transition Zone (35 ± 10 mg C m^{-2} d^{-1}), and Subtropical Gyre (12 ± 5 mg C m^{-2} d^{-1}) (Table 1). Sediment trap data demonstrated peak season productivity increase alignments with surface productivity in the upwelling system, thus confirming the feedback mechanism between surface productivity and carbon export. Cross-region appraisal demonstrated a coupling relation ($r = 0.78$, $p < 0.01$) with monthly chloroplast pigment-a concentration and export flux from all sections (Figure 2).

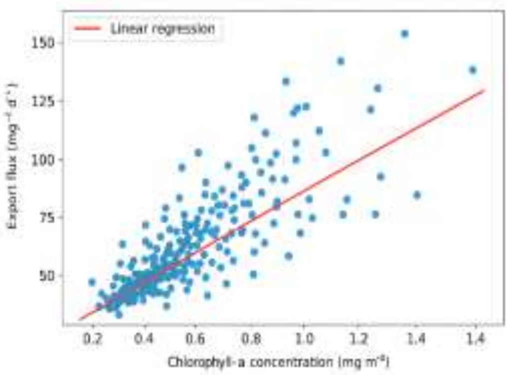
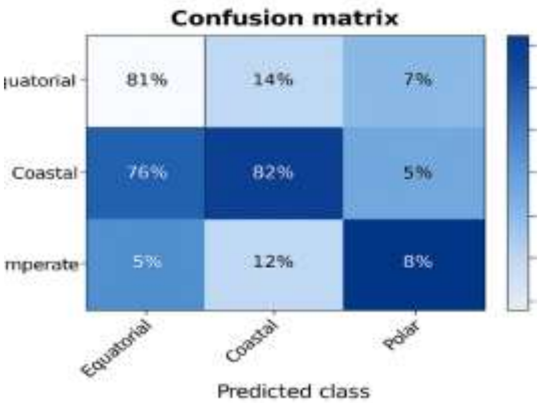


Figure 2: Chlorophyll-a vs Export Flux Scatterplot with Regression Line

Model evaluation metrics indicated high performance in the upwelling zone with an RMSE of 15.2 mg C m² d¹ and r = 0.76 compared to observed export fluxes. The Transition Zone also performed acceptably (RMSE = 10.7 mg C m^{-2} d^{-1}, r = 0.72). However, model skill decreased in the oligotrophic gyre (RMSE = 7.8 mg C m^{-2} d^{-1}, r = 0.46), suggesting insufficient representation of low-flux pathways in current model parameterizations (Table 1). The highest classification accuracy for export flux categories was observed in the upwelling zone (85%), moderate in the transition zone (78%), and lowest in the gyre (68%) (Figure 3).



Mann-Kendall test analysis highlighted the statistically significant negative trend in California Current's chlorophyll-a over the decade (τ = -0.42, $p < 0.05$), suggesting declining phytoplankton biomass through interannual variability. No significant trends in chlorophyll-a were found in the Transition Zone or Subtropical Gyre.

Discussion

Table 1: Model Skill Metrics Summary

Zone	RMSE (mg C m^{-2} d^{-1})	Correlation Coefficient (r)	Classification Accuracy (%)
California Current	15.2	0.76	85
North Pacific Transition Zone	10.7	0.72	78
North Pacific Subtropical Gyre	7.8	0.46	68

The pattern of chlorophyll a concentration and its associated export flux observed across different oceanic regions underscores the prevailing impact of nutrient availability on the phytoplankton productivity and carbon sequestration processes. Studies suggest that upwelling zones, as succinct but regionally small areas within the ocean floor, significantly contribute to global carbon export due to their high phytoplankton biomass and export production. The striking value of r = 0.78 for chlorophyll-a concentration and export flux in the upwelling and transition zones affirms energetic productivity at the surface waters and its vertical integration with export tends to be very strong in these areas, showcasing relatively uncomplicated ecological dynamics allowing for rapid sedimentation and uncomplicated drifting carbon capture.

On the other hand, the low values of chlorophyll-a and export flux in the Subtropical Gyre could signal its low nutrient availability, as its oligotrophic nature is dominated by small phytoplankton such as Prochlorococcus and Synechococcus picocyanobacteria, which suggests (Nakamura and Lindholm, 2025). Furthermore, the weaker correlation (r = 0.46) and lower model skill in this area highlight possible decoupling of surface chlorophyll-a accumulation with particulate export which may be enhanced recycling within the microbial loop, less aggregation and export pathways rich in dissolved organic carbon or submicron particles that sediment traps and traditional models fail to capture.

Under the scenario of ongoing climate change, the observed decadal decline in chlorophyll-a concentration in the California Current hints at possible changes in upwelling mechanics, nutrient delivery, or stratification patterns. This supports long-term observational data assessing the eastern boundary of upwelling systems experiencing mixed trends, where localized declines are attributed to warming-induced stratification and reduced nutrient upwelling or ecosystem regime shifts (Giraud, Pondaven and Arhan, 2006; Gonzalez and El-Sayed, 2024). Such a downfall in the region's phytoplankton biomass is detrimental to the region's carbon sequestration potential, fishery resources, and food web interactions.

The comparatively greater accuracy in productive regions indicates that existing biogeochemical models work well in simulating export from large phytoplankton and direct sinking pathways. On the other hand, the lack of accuracy in oligotrophic regions emphasizes difficulties in describing processes like size-dependent export, the zooplankton flux, and non-sinking exports such as vertical migration or carbon export in solution. Further defining the export parameterization improves global carbon budget recalculations and predictions along the carbon cycle and climate change timeline within the context of low-nutrient regions.

Overall, the disconnect in export flux and chlorophyll-a maxima observed in the Transition Zone for autumn can be attributed to the post-bloom aggregates, grazing-mediated, and episodic mixing control on carbon export timing. This calls for establishing high-frequency observational networks integrating sediment traps, optical sensors, and autonomous profiling floats to capture short-term dynamics and their drivers related to export.

Conclusion

The current research captures the dynamics of phytoplankton and their integral role in carbon sequestration pathways across different oceanic areas, including the California Current upwelling system, the North Pacific Transition Zone, and the North Pacific Subtropical Gyre. Over a decade, incorporating remotely sensed chlorophyll-a data, sediment trap data, and biogeochemical models revealed the firm spatial heterogeneity and temporal variability governing primary productivity and export fluxes.

Nutrient availability remains the most critical factor of phytoplankton biomass and export efficiency within a given ecosystem. The highest chlorophyll-a concentration and export flux gleaned from the California Current system underscore the disproportionate contribution of upwelling areas to carbon sequestration compared to their small spatial coverage. Furthermore, the export of biological carbon within that region sustains nutrient-rich conditions and strongly coupled surface chlorophyll-a with particulate organic carbon in export. This illustrates the biological carbon export pathways under much more efficient conditions. However, the subtropical gyre exhibited low chlorophyll-a and exportable high blooms of green phytoplankton, which regularly offset the total volume. Concern about the impacts of ocean warming, stratification, and a reduction in nutrient supply on the biological carbon pump in productive upwelling regions increases with a statistically significant and concerning decline in chlorophyll-a levels in the California Current over the last decade. This declining trend will likely have ripple effects on regional food webs, the productivity of fisheries, and the potential for carbon sequestration in the long term.

The assessment of the biogeochemical model's performance indicates that it provides more accurate estimates of predictive accuracy in high-productivity zones than in oligotrophic regions. This is likely because the model parameterizations better capture large-cell export processes, while nutrient-poor areas are dominated by underestimated low-flux pathways. Increasing the representation of microbial loop processes, zooplankton-mediated export, and dissolved organic carbon pathways in models is crucial to improving carbon export estimates, especially in future climate scenarios. The results from this analysis draw attention to the importance of phytoplankton functional types, nutrient structure, and ecological processes in the context of ocean carbon sequestration. They call for sustained high-resolution observational networks that combine satellite remote sensing within situ measurements and autonomous platforms to capture short-term variabilities and the mechanistic controls of carbon export. Further work should aim to integrate molecular, optical, and biological proxies into models that constrain export processes across ecosystems to withstand the more dominant impacts of climate change on ocean biogeochemistry.

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