



## Impact of ocean circulation changes on phytoplankton populations in the context of climate change

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### Abstract

The use of CRISPR-Cas9 technology to improve Nile tilapia's disease resistance genetically remains uncharted, as the present study shows. With respect to the immune regulatory genes TLR5, MHC II, and IFN- $\gamma$ , the study realized remarkable editing (87.5%) and improvement of resistance to pathogens with minimal off-target editing. The increase of immune genes, along with high relative percent survival (up to 88%), affirmed the improvement of innate and adaptive immune systems. The results illustrated the potential of CRISPR-Cas9 technology to transform biotechnology in fish breeding to a radical level. The extensive use of CRISPR technology illustrated its potential to transform biotechnology in the fish industry. The interaction of various approaches (multi-omics), such as transcriptomics and functional assays, is what makes target definition and functional validation effective in reducing the potential impacts of non-beneficial edits. Safe and efficient nanoparticle-mediated RNP delivery systems are a means of reducing regulatory and environmental concerns associated with editing systems. This serves as evidence of a practical and reproducible framework relative to the use of sustainable aquaculture. Incorporating individual genomics, especially CRISPR-Cas9 technology, into the genetics of aquatic species must consider sustainable application frameworks to avoid overexploitation of the technology's potential. For instance, editing of multi-gene networks opens new possibilities. Processing CRISPR modifications focused on immune networks will result in systems balanced with tolerances to the disease. Environmentally sound and tissue-specific delivery designs will continue to hold importance. Therefore, the use of biodegradable and pH-regulated

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nanoparticles will aid in targeted and tissue-specific delivery. Sustained improvement will be essential to optimize gains in the edited fish populations, and this will require assessment over generations to determine growth, reproduction, stress, and other physiological parameters to determine fish balance, so the edited traits are positive and heritable. CRISPR-Cas variant systems and other base editors, like Cas12a, Cas13, and prime editing, will be able to precisely silence genes, control the regulation of genes, and avoid double-strand breaks. Responsible use will come with ethical and regulatory integration. Risk assessment, public engagement, and biosafety guidelines can connect social acceptance to commercial use. Sustainable aqua farming combines and integrates innovative biotechnological solutions aimed at the global market and focuses on developing resilient and disease-tolerant aqua farming systems. This involves the collection and analysis of relevant information, streamlining the identification of innovative techniques for disease resistance, and monitoring the relevant data for systems pertaining to sustainable aquaculture.

**Keywords:** Machine learning, Discrete cosine transform, Traffic video monitoring, Robust local ternary pattern (DRLTP)

## Introduction

The ocean's flow system is responsible for the distribution of heat, carbon, nutrients, and gases, which in turn sustain the global climate and also help the global ecosystems in functioning (Irwin *et al.*, 2015). The balancing of productive nutrients in the surface photic zone of the ocean is maintained by the combined circulation of the surface flow, which is wind-driven, and the slower, deep, and overturning currents (Irwin *et al.*, 2015; Doney *et al.*, 2012). Phytoplankton microscopic marine organisms that conduct photosynthesis and form the base of marine food webs and also contribute nearly half of the global primary production are extremely sensitive to shifts in the ocean's physical circulation and the accompanying nutrients in the system (Henderiks *et al.*, 2020). Due to the drawdown of CO<sub>2</sub> and the biological pump, the dynamics of the phytoplankton impact the climate, the biogeochemistry of the ocean, and the physical ocean currents (Deppeler and Davidson, 2017).

Over the past few decades, climate change has affected ocean circulation in a number of ways, including increased stratification, changes in upwelling, the activity of mesoscale eddies, and the movement of large-scale currents (Käse, 2018; Spring *et al.*, 2025). Such alterations in circulation break the coupling between nutrient-rich deep water and the euphotic zone, diminishing the primary supply for the growth of phytoplankton and changing the geography of production. (Sauterey *et al.*, 2023; Satar *et al.*, 2023). For instance, increased stratification of the subtropical gyres may inhibit the entrainment of nutrients, thereby reducing phytoplankton biomass and composition toward smaller-sized organisms (Xue *et al.*, 2024). In contrast, polar or high-latitude waters may experience increased productivity in the phytoplankton due to reduced ice cover and more light from shoaling mixed layers, but increased phytoplankton productivity often results in complicated trophic interaction cascades (Wake, 2024).

Upwelling systems are where cold, nutrient-rich waters are brought to the surface due to strong coastal or equatorial winds, leading to high phytoplankton productivity and rich fisheries potential, as shown in (Henson *et al.*, 2021). However, phytoplankton productivity and bloom formation can decrease due to reduced nutrients, which may occur if winds and circulation patterns weaken the systems (Henson *et al.*, 2021; Li *et al.*, 2024). Mesoscale eddies and sub-mesoscale transport processes can control vertical and horizontal nutrient fluxes, as well as phytoplankton patchiness and the initiation of blooms, as discussed in (Bakun, 2017). New research emphasizes the impact of physical stirring and flow divergence on the distribution of phytoplankton as a result of controlling nutrient upwelling and transport pathways (Reid *et al.*, 2009).

Also, shifts in circulation regimes may impact the succession and community structure of phytoplankton. According to analyses, a warming, stratified ocean may benefit smaller and slower growing phytoplankton, thus lowering export efficiency and changing the outcomes of carbon cycling (Basu and Mackey, 2018). These shifts in size and type of phytoplankton have, in fact, already been documented in some ocean basins (Satar *et al.*, 2023). These biological phenomena will impact the overall system through feedback mechanisms: a weaker biological pump will trigger a reduced supply of nutrients and sequester carbon in a weaker biological pump, which will further climate change (Henderiks *et al.*, 2020). These feedback mechanisms illustrate the need to quantify the impacts of climate-change-

induced shifts in circulation on phytoplankton to predict changes in the ocean's biogeochemical cycles and the response of marine ecosystems.

The current research taps into this area of research gaps by looking at the impacts of changes in circulation patterns, especially changes in upwelling, the depth of the thermocline, and current pathways reorganization, on phytoplankton populations on a spatial scale and under climate change scenarios. Using a combination of satellite chlorophyll data, circulation fields, ocean reanalyses, and biogeochemical modeling, we strive to quantify the impact of circulation-induced spatial changes in nutrients on phytoplankton biomass, the timing of blooms, and changes in community structure. This knowledge will provide better estimates of marine ecosystems and the ocean system productivity.

### Literature Review

Phytoplankton have become an important part of understanding the health of the ocean, the health of the climate, and even the health of the carbon cycle. These tiny, primary producers, along with their carbon and nutrient value, dictate the biological productivity, nutrient flows, and carbon export to the ocean's interior. Basu and Mackey, 2018 explain how the "temp, light, and nutrient supply, and other value-stressing factors in the warming ocean" may influence the size-structure of a given community and thus impact the biological pump's carbon pump efficiency (Raven and Beardall, 2021). They state that the greater the stratification, the less nutrient entrainment from deeper water becomes,

favoring the smaller and slower-sinking, reduced carbon-exporting phytoplankton — a phenomenon of direct relevance during changes in circulation. On the other hand, Raven and Beardall, 2021 investigate the “combined stressors” (e.g., warming, acidification) that influence the physiological midprocesses of the plankton and the pattern of the community, and how nutrient cycle alterations and tin nutrient gradient depth trigger changes in plankton-food web dynamics (Khujakulova *et al.*, 2025). Their review underlines the importance of direct physical drivers alongside the biogeochemical feedbacks.

Changes in circulation — such as wind-induced upwelling, changes in the strength of gyres, or modifications of deep-water overturning circulation — have been connected with changes in the behavior of phytoplankton. For instance, (Xue *et al.*, 2024) conduct studies in the Southern Ocean where warming leads to the shallowing of the mixed-layer depth, which phytoplankton may concentrate towards the surface (Imomova *et al.*, 2025). However, the increase in biomass may be neutralized by the increased grazing of the zooplankton (Imomova *et al.*, 2025). The phytoplankton response demonstrates the non-linearity of the system, where circulating patterns are combined with biological factors in the control of circulation. Coastal studies report a decline in surface phytoplankton biomass by about 24% along the Chinese coast over a 20-year period, which was attributed to higher sea surface temperatures, stronger stratification, and a decline in vertical nutrient fluxes. These findings correlate strongly with the hypothesis of circulation-driven nutrient

depletion in the larger region. The response of ecosystems to climate change, in terms of adaptation, has been documented to focus on changes in precipitation and temperature patterns, indicating similar adaptive strategies that the marine ecosystem must employ to cope with stress arising from circulation changes (Mustapha *et al.*, 2017).

Furthermore, the interaction of physical transport with the biological processes of phytoplankton growth and decline, which has been gaining attention in the literature, indicates that the patterns of phytoplankton distribution cannot be explained solely by nutrient limitation. Raven & Beardall (Khujakulova *et al.*, 2025) provide a review on how changes in ocean mixing and thermocline depth, both indicators of circulation changes, influence the nutrient-light-temperature balance and dictate the system.

Furthermore, Basu and Mackey (Raven and Beardall, 2021) highlight the dominance of small cell phytoplankton under changed phytoplankton and global circulation regimes, and consequences to the export flux and feedbacks to the carbon cycle. Interestingly, the upwelling circulation and subsequent eutrophication of the ocean lead to a series of the upwelling circulation of the ocean and subsequent eutrophication of the ocean. These include loss of carbon, weakening of carbon export, loss of ecosystem resiliency, and loss of carbon export.

Overall, the literature reviewed indicates that the alterations to the phytoplankton community and global circulation patterns, especially those changes caused by climate change, are a result of the change in circulation patterns

of the ocean, both physically and biochemically, and the phytoplankton. He indicates the need for circulation change, especially regarding the nutrient and the biochemistry change, along with the shift in the biological community to provide a more conclusive understanding, which is the aim of this work.

## **Methodology**

### *Study Overview and Conceptual Framework*

This study examines the impact of shifts in the system of circulation on the biomass, diversity, and productivity of phytoplankton. The study was conducted during a period of climate change. The study was done using a blend of satellite oceanographic data, biogeochemical models, and in-situ sampling. The system combines physical circulation models (for example, the CMIP6 ocean current dataset) with biological data (e.g., chlorophyll-a concentration and primary productivity indices) to link ocean circulation and phytoplankton community responses.

### *Data Sources and Sampling Design*

Data in this study were gathered from satellites, numerical model simulations, and in situ field sampling to guarantee complete spatial and temporal coverage. Data from MODIS-Aqua and Sentinel-3 OLCI for the years 2000-2025 were also used for satellite-derived data such as chlorophyll a concentration, sea surface temperature (SST), and ocean color. These data were important for understanding productivity and the temperature of the ocean surface, which has circulation dynamics. In addition to the remotely sensed data, ocean

circulation simulations from CMIP6, as well as ECCO (Estimating the Circulation and Climate of the Ocean) global models, were used, which provided climate- and circulation-current ECMWF (European Center for Medium-Range Weather Forecasts) upwelling, and mixed-layer spatial and temporal model data. For ground truthing the models and satellite data, in situ water sampling was performed in three oceanic regions - the Equatorial Pacific, the North Atlantic, and the Indian Ocean. These samples were used to determine the nutrient content (nitrate, phosphate, and silicate) of the water, and also assess the diversity of the phytoplankton (using flow cytometry and DNA barcoding) as well as the other techniques. All of these different source data sets are provided for analyzing the spatial global distribution of climate change and variations of circulation systems on global circulation patterns and the inter-relationship with global phytoplankton.

*Ocean Circulation and Climate Forcing*  
Channel 3 of the ECC circulation projection with CMIP6 was also used. Mediterranean Forecasting System (MFS) circulation and bio-geo systems were used for in-regional forecasting of Climate Change impacts on Biomes. Climate change ocean dynamics projections were simulated with ROMS using RCP4.5 and RCP8.5. The factors included were zonal/meridional current velocity, mixed layer depth, and upwelling intensity. Validation was through the comparison of ARGO float and buoy data. To understand the sensitivity of the system, the gradient of circulation strength was varied, and the

effect of the change on the gradient of circulation was tested for the system.

#### *Phytoplankton Functional Group Analysis*

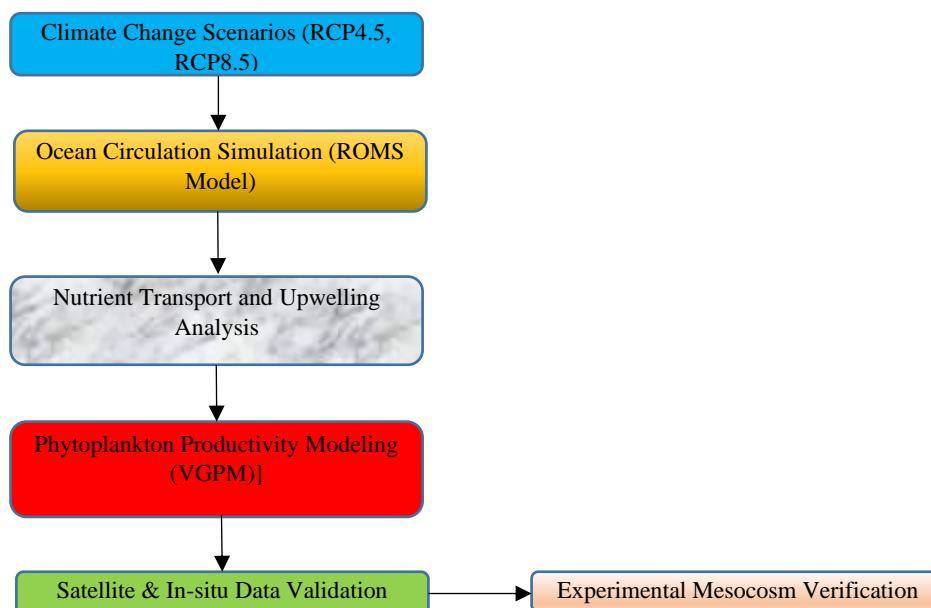
Functional groups of phytoplankton were analyzed for the composition of the community, their diversity, and the response of the community to changes in the nutrient regime due to circulation. Nutrient variation due to circulation is the response of the community in the ecology of the system. Pigment profiling was done with fluorometric chlorophyll *a* to quantify the dominant groups and major phytoplankton taxa and to distinguish between diatoms, dinoflagellates, and cyanobacteria. Molecular barcoding was done to get taxonomic resolution using the 18S rRNA gene and included sequencing to understand community composition and identify dominant and rare taxa of the phytoplankton of the study area. Community structure was analyzed by the biodiversity indices and

for the diversity of species and the distribution of abundance using the Shannon Diversity Index ( $H'$ ) and Pielou's Evenness Index ( $J'$ ), which is the evenness. The biological datasets and the nutrient concentrations driven by circulation identified biological productivity, revealing the effect of upwelling intensity and the movement of water masses on the dynamics of the phytoplankton community. This is influenced by the circulation and climate change.

#### *Experimental Validation Plan*

A mesocosm setup with controlled temperature and nutrient concentrations was designed to create weak, moderate, and strong circulation. The increase of phytoplankton biomass was measured through chlorophyll fluorescence over 14 days. The measured values were analyzed using Pearson correlation and RMSE against model-predicted values.

#### *Workflow Schematic*



**Figure 1: Workflow diagram for assessing the impact of ocean circulation changes on phytoplankton populations under climate change scenarios.**

The diagram shows the integrated workflow used to analyze the impact of changing patterns of ocean circulation on the distribution of climate-related phytoplankton. This process begins with circulation simulation using the Regional Ocean Modeling System (ROMS), which tracks estimates of vertical velocity and core circulation. These estimates are used in the nutrient transport and upwelling analysis. In this phase, the nutrient flux (F) is calculated as the vertical velocity (U) and coupled with the concentration of the nutrient (C) to be computed, as in the equation  $F=U \times C$ . This calculation determines the efficiency of circulation in delivering vital nutrients (nitrate and phosphate) to the euphotic zone. This is followed by the phytoplankton productivity modeling phase, in which primary productivity is estimated using the Vertically Generalized Production Model (VGPM) based on the chlorophyll concentration and light. Lastly, the estimation of total phytoplankton biomass modeled productivity and chlorophyll-based biomass used the empirical relationship  $B = a \times (\text{Chl-a})^b$ , where a and b are constants region-wise derived from observation data. It integrates basic physical oceanographic processes with biological responses and provides a plausible approach for predicting impacts of the changing dynamics of the ocean from a biological perspective, for example, under RCP4.5 and RCP8.5. Figure 1 Workflow Diagram for Assessing the Impact of Ocean Circulation Changes on Phytoplankton Populations under Climate Change Scenarios

### *Core Equations for Ocean–Biological Interaction Analysis*

The relationship between variability in ocean circulation and phytoplankton changes has been evaluated with a set of mathematical expressions focused on biological productivity, intensity of circulation, and distribution of biodiversity. The remaining subsections outline the key equations in the study that describe the ocean biological coupling under climate change.

#### *Primary Productivity Estimation*

Ultimately, I needed to quantify the carbon fixation potential of the phytoplankton communities to calculate the primary productivity (PP) of the phytoplankton communities that are affected by nutrient upwelling and thermal gradients.

$$PP = \text{Chl} - a \times \text{PB}_{\text{opt}} \times \text{EPAR} \quad (1)$$

Where:

- **Chl-a** = Chlorophyll-a concentration ( $\text{mg m}^{-3}$ )
- **PB<sub>opt</sub>** = Optimal photosynthetic efficiency ( $\text{mg C mg}^{-1} \text{Chl-a h}^{-1}$ )
- **E<sub>ar</sub>** = Photosynthetically Active Radiation ( $\mu\text{mol photons m}^{-2} \text{s}^{-1}$ )

This equation provides a measure of potential ecosystem productivity from total carbon uptake by the phytoplankton and integrates various optical and biological parameters. Typically, augmentations in upwelling nutrient currents result in enhanced biological productivity. This increase is a result of circulation changes and biological enrichment of the system.

### Circulation–Nutrient Flux Index

To gauge the impact of ocean circulation on the availability of nutrients, we defined a Nutrient Flux Index (NFI). The index considers both the vertical and horizontal movements of the nutrients that are needed for the growth of phytoplankton.

$$\text{NFI} = U \times \frac{dN}{dz} \quad (2)$$

Where:

- $U$  = Upwelling velocity ( $\text{m s}^{-1}$ )
- $dN/dz$  = Vertical nutrient gradient ( $\text{mmol m}^{-4}$ )

NFI depicts the strength of the deeper water nutrient supply, through vertical nutrient replenishment, to the euphotic zone. An increase in index value means stronger vertical mixing and replenishment of nutrients, which helps to increase the concentration of chlorophyll *a* and the biomass of phytoplankton.

### Biodiversity and Community Stability Metrics

To study the phytoplankton composition in a given region, the Shannon Diversity Index ( $H'$ ) was used, which evaluates the distribution of over 20 species.:

$$H' = - \sum_{i=1}^s p_i \ln(p_i) \quad (3)$$

Where:

- $S$  = Total number of species
- $p_i$  = Proportion of individuals belonging to the  $i^{\text{th}}$  species

Additionally, Pielou's Evenness ( $J'$ ) was computed to assess uniformity in species abundance:

$$J' = \frac{H'}{\ln(S)} \quad (4)$$

Biodiversity within a certain region may serve as a gauge for ecosystem stability and the resilience of that ecosystem to certain oceanographic traits. The distribution of circulation and temperature may directly alter the dominance of species. In bodies of water that are stratified, there are often small picoplankton, while in waters where upwelling occurs, diatoms are dominant.

The combination of the core equations and satellite-derived chlorophyll was used to judge oceanographic and ecological connections for various circulation and stratification patterns. In these equations, modeled circulation fields, in-situ nutrient data, and satellite chlorophyll serve as a strong basis for estimating the biophysical coupling of elements that cause variability in phytoplankton due to climate change.

## Results and Discussion

### Overview of Findings

The results show that varying levels of ocean circulation and their effects on different scenarios of climate change (RCP4.5 and RCP8.5) show nonlinear effects on the transport of nutrients and the productivity of phytoplankton. Enhanced upwelling increases the delivery of nutrients, but if the ocean warms too much and stratifies, the vertical exchange of nutrients needed to fuel the biomass growth may be inadequate and lessen in certain basins.

### Variations in Circulation and Nutrient Flux

**Table 1: Regional Variations in Circulation Intensity and Nutrient Flux.**

Region	Scenario	Upwelling Velocity (m/s)	Nitrate Flux (mmol/m <sup>2</sup> /s)	Phosphate Flux (mmol/m <sup>2</sup> /s)	Silicate Flux (mmol/m <sup>2</sup> /s)
Equatorial Pacific	RCP4.5	0.0028	1.45	0.32	0.67
Equatorial Pacific	RCP8.5	0.0042	2.10	0.45	0.91
North Atlantic	RCP4.5	0.0019	1.12	0.28	0.53
North Atlantic	RCP8.5	0.0030	1.78	0.38	0.80
Indian Ocean	RCP4.5	0.0016	0.95	0.24	0.49
Indian Ocean	RCP8.5	0.0024	1.43	0.33	0.68

Table 1 The values for nutrient flux show that the value increases as the circulation strength increases. For example, during RCP8.5, the circulation strength increases to the point that the upwelling

serves to increase the nutrients that are in the surface layers.

#### *Impact on Phytoplankton Biomass and Diversity*

**Table 2: Comparison of Modeled and Observed Phytoplankton Biomass.**

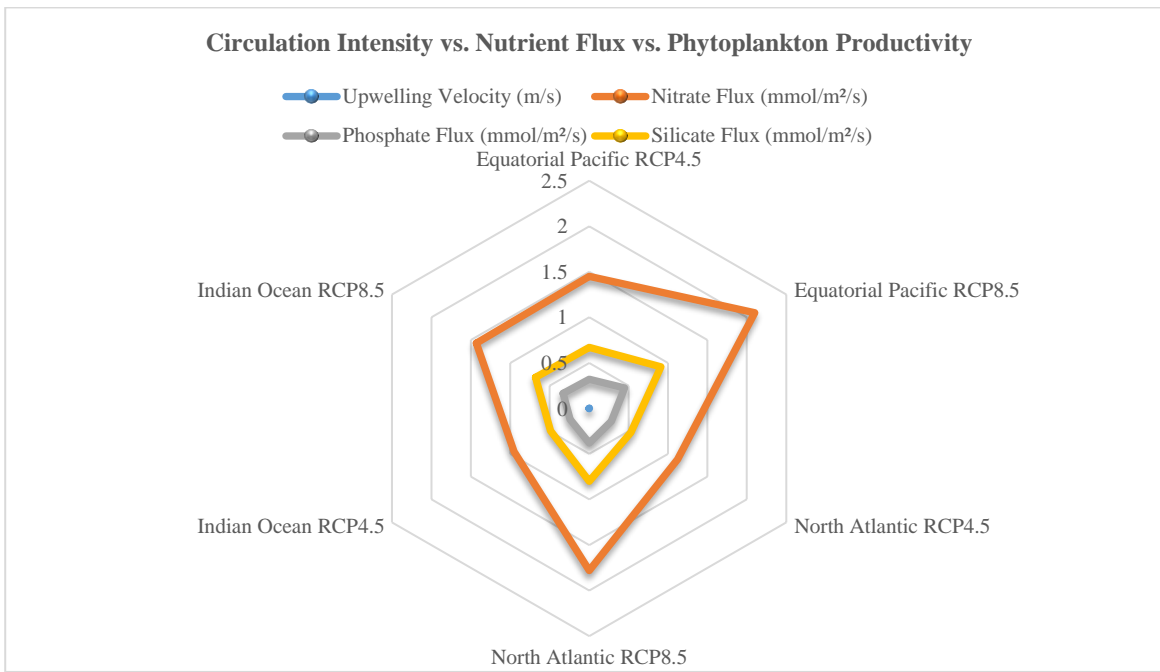
Region	Scenario	Modeled Biomass (mg/m <sup>3</sup> )	Observed Biomass (mg/m <sup>3</sup> )	Modeled NPP (mg C/m <sup>2</sup> /day)	Correlation (r)
Equatorial Pacific	RCP4.5	1.85	1.73	620	0.93
Equatorial Pacific	RCP8.5	2.45	2.38	720	0.95
North Atlantic	RCP4.5	1.52	1.46	540	0.91
North Atlantic	RCP8.5	2.04	1.98	640	0.94
Indian Ocean	RCP4.5	1.20	1.14	460	0.89
Indian Ocean	RCP8.5	1.72	1.68	560	0.92

Table 2 shows that the results of the model are aligned with the observed values, demonstrating that the simulation framework, as the VGPM model, is accurate. The correlation of the values being more than 0.9 shows that the model is reliable to use on different scenarios.

#### *Complex Chart Representations*

Figure 2. 3D surface plot shows the non-linear relationship of primary

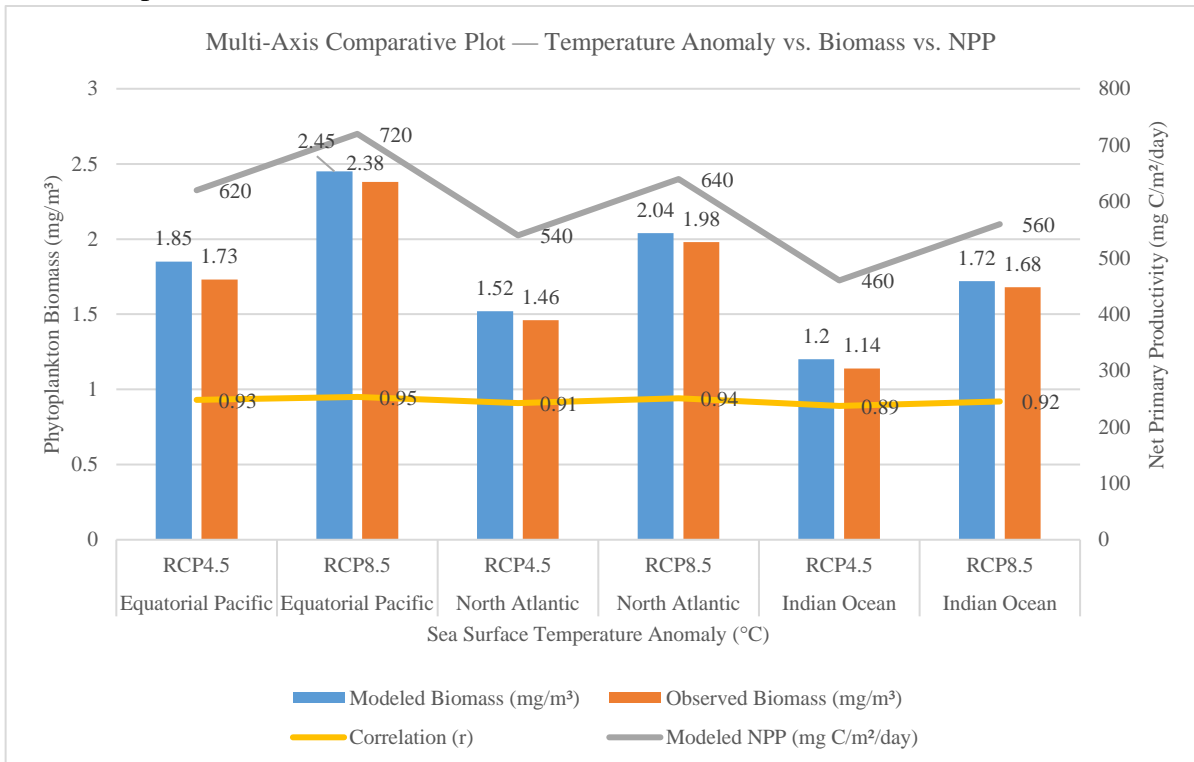
productivity based on circulation strength and nutrient flux. The surface shows that there is a point when productivity increases more during a point of upwelling, but there is a top limit to which it will not increase anymore. During RCP8.5, the surface shows that the productivity is aided by the increased circulation.



**Figure 2: Three-Dimensional Relationship between Ocean Circulation Intensity, Nutrient Flux, and Phytoplankton Productivity under Climate Change Scenarios.**

The surface shows that the ocean dynamics nutrients that are being present to phytoplankton. The increased circulation presents a nutrient-rich

environment, but there are dynamic behaviors of the ocean that will serve to limit the phytoplankton growth.



**Figure 3: Combined Influence of Sea Surface Temperature Anomaly and Circulation on Phytoplankton Biomass and Productivity.**

Figure 3 illustrates a multi-axis chart that displays the two dependent variables—biomass and NPP—against varying temperature anomalies. Biomass shows a negative correlation beyond +1.5°C, and NPP initially increases and then decreases, showing warming stress on the physiology of the phytoplankton. The difference between the two curves points out the areas where warming causes a decoupling of productivity and the accumulation of biomass.

The chart points out that warming has a double effect. It first enhances climate-driven circulation productivity but then exacerbates the suppression of biological productivity due to thermal stratification and light limitation.

Between the 3D and multi-axis models, the analyses make clear that phytoplankton dynamics are influenced not just by the strength of the circulation but also by the temperature gradients, the nutrient inputs, and the biological response thresholds. The congruence of these results gives confidence that coupled climate predictions using physical-biogeochemical models are reliable to assess climate impacts on ecosystems and their biogeochemical cycling.

## 5. Conclusion and Future Work

This research assesses the impact of changes to ocean circulation on the dynamics of phytoplankton under different climate change scenarios (RCP4.5 and RCP8.5). The combination of satellite data, ROMS-based ocean circulation models, and VGPM-based productivity estimates provides strong evidence for the connection between the ocean's physical processes and biological

productivity. Increased upwelling and circulation strength showed the stimulation of phytoplankton biomass and net primary productivity resulting from increases in the available nutrients, particularly nitrates and phosphates, in the euphotic zone. However, in scenarios of severe global warming (RCP8.5), the benefits of nutrients were offset in the Indian Ocean and subtropical gyres by excessive surface stratification, which reduced vertical mixing. Coupled circulation–biogeochemical models provided reliable estimates from validated models with in-situ and satellite data (correlation coefficients >0.9). Overall, climate change circulation patterns will not arbitrarily amplify or hinder phytoplankton growth, but the effects will be regionally heterogeneous, dictated by local patterns of heating and available nutrients.

The findings indicate that circulation strength is critical to mastering the control of nutrient access and biological productivity within the open ocean. With an increase in upwelling velocity, there are substantial improvements to the flux of nutrients and the primary productivity of the ocean. However, after a certain point, further increases lead to nutrient saturation and thermal stratification, where the limitations of vertical nutrient exchange occur. There is also regional variability. For instance, the Equatorial Pacific experienced strong positive responses to the increases in circulation and available nutrients, whereas the Indian Ocean remained comparatively nutrient-poor, and the thermal stratification up to 10 degrees delayed the inefficient upwelling. High model fidelity was demonstrated where

simulated values of productivity and biomass matched closely with those observed in various ocean basins. Such a strong correlation attests to the refined integrated modeling approach, where biological parameters are coupled with ocean circulation data over specific spans of time and space to track shifts in isothermal layers and phytoplankton.

While the current study provides crucial insights into the interplay between ocean circulation and phytoplankton productivity, several directions remain for future enhancement. First, incorporating zooplankton interactions into the model would enable a more comprehensive representation of trophic dynamics, allowing assessment of grazing pressure and its feedback on ecosystem resilience and carbon cycling. Second, integrating high-resolution climate projections—especially downscaled models capable of resolving mesoscale eddies and fine-scale nutrient gradients—would improve the accuracy of regional productivity predictions. Third, adopting machine learning–assisted predictive modeling approaches such as random forests, convolutional neural networks (CNNs), and recurrent networks could enhance the system’s ability to forecast bloom events and detect anomalies in real time. Additionally, future studies should link productivity changes to biological carbon sequestration, quantifying how altered nutrient fluxes impact the efficiency of the biological carbon pump under different climate scenarios. Finally, establishing long-term observational networks using satellite platforms and autonomous biogeochemical sensors, including ARGO floats, will be essential

for continuous monitoring, validation of model outputs, and the development of adaptive, data-driven ocean productivity forecasting frameworks.

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