Computational Modeling of Phytoplankton Dynamics with Climatic and Ecological Ramifications

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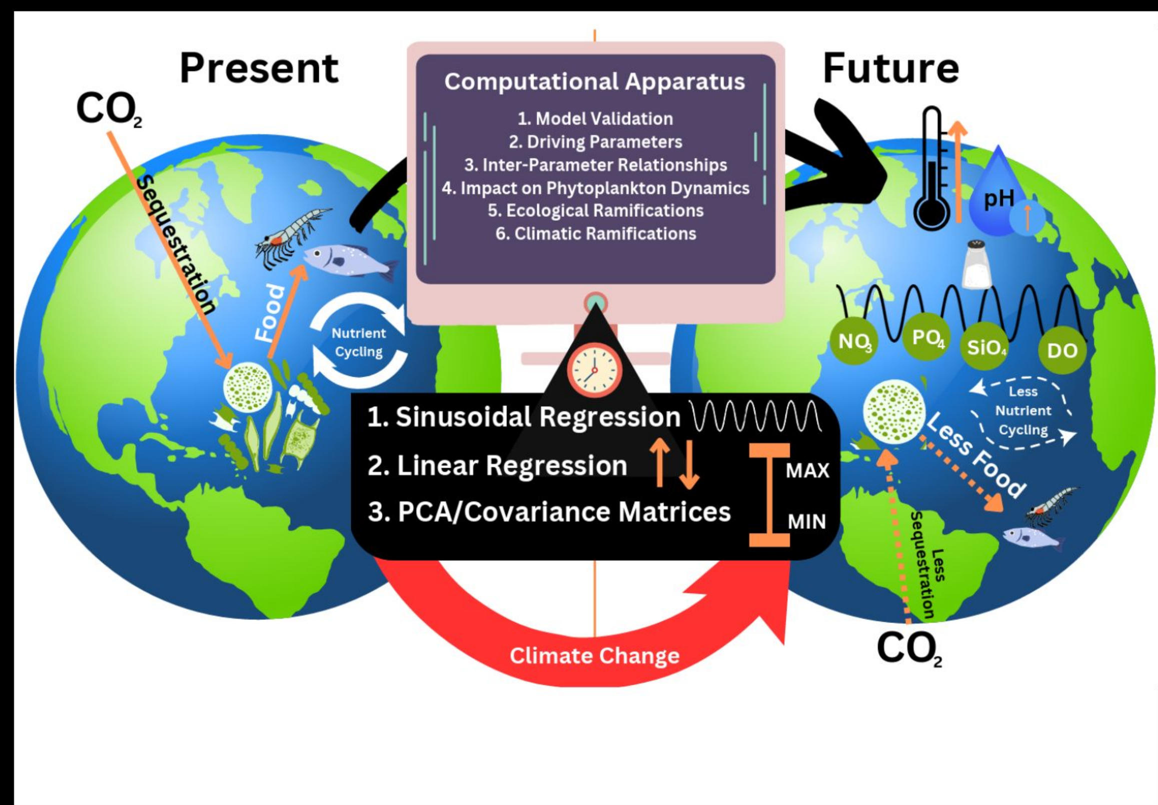
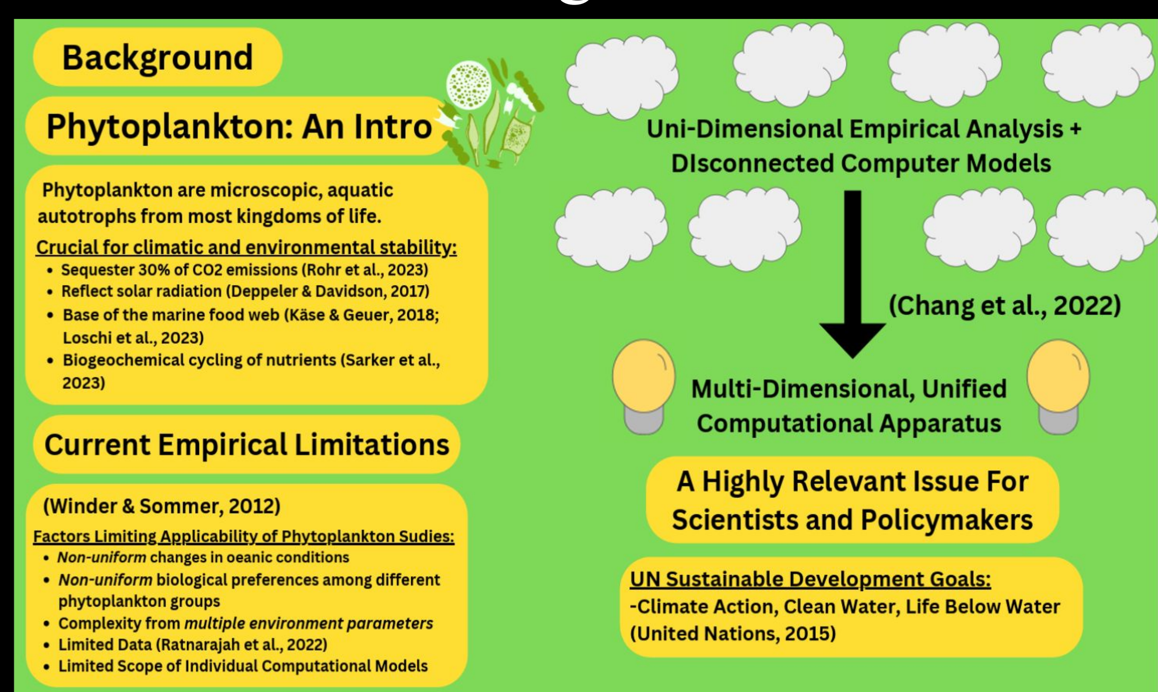
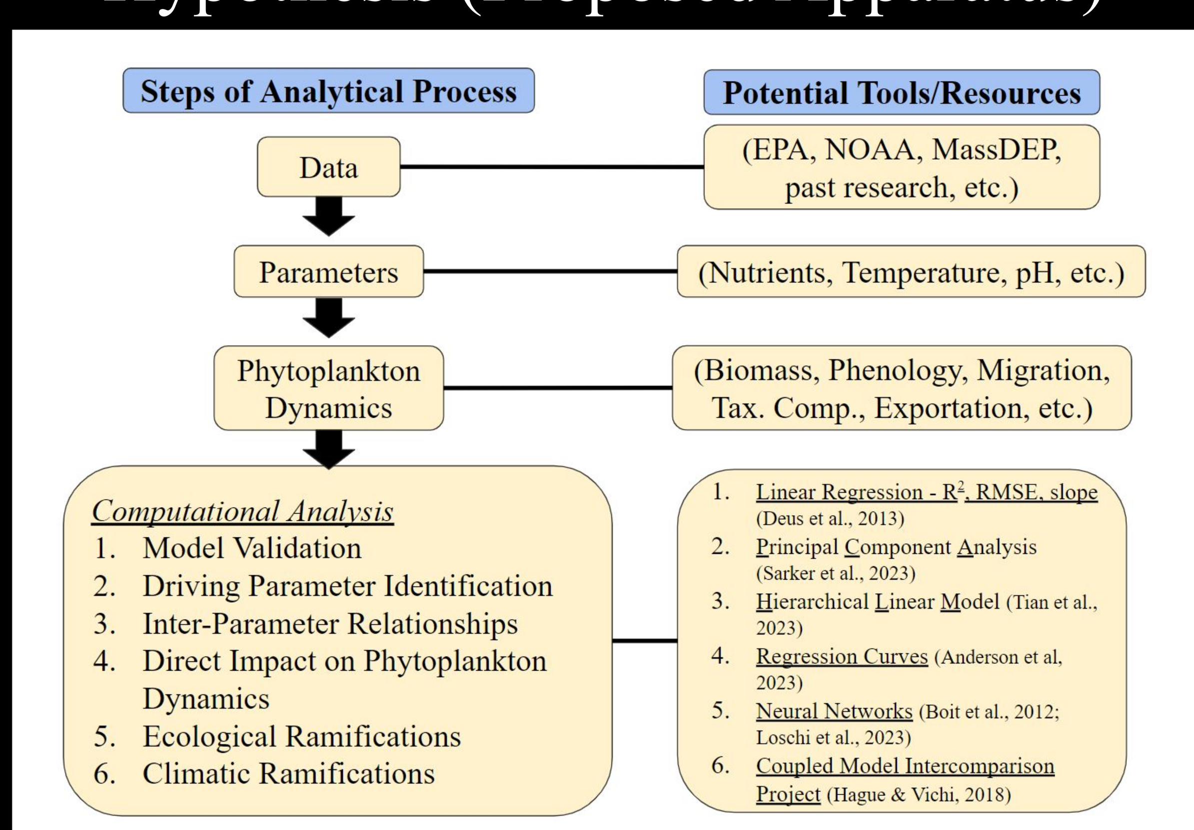
Graphical Abstract



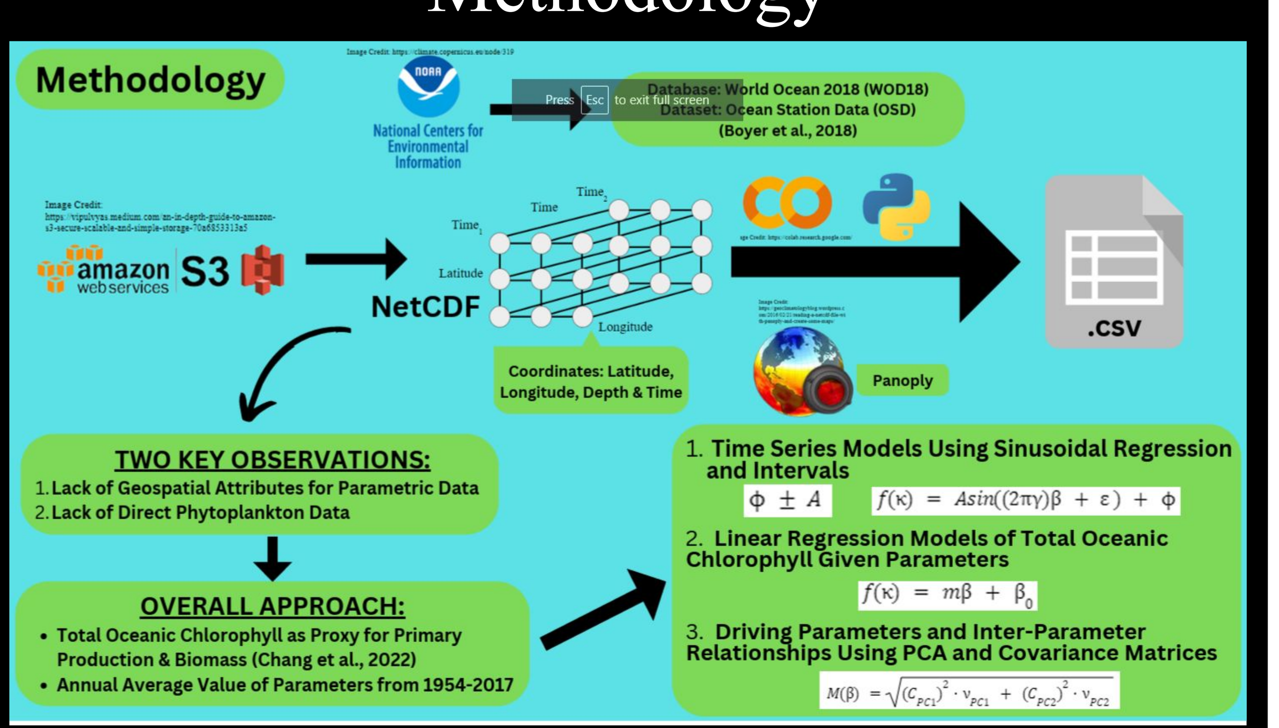
Background



Hypothesis (Proposed Apparatus)



Methodology



Researchable Question:

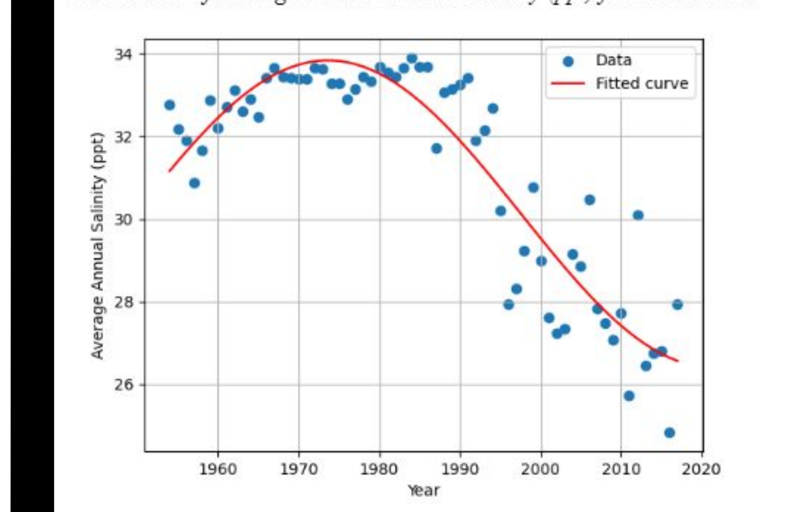
How can the causes and effects of changing phytoplankton dynamics be computationally modeled?

Key Findings:

1. Accuracy of time series models for environmental parameters tested (e.g., oxygen, pH, etc.) varies greatly.
2. There exist significant directional relationships between parameters and phytoplankton primary production and biomass, though they are not effective predictors of these metrics.
3. At a global scale, pH, followed by salintiy and pressure, are the most influential parameters for these aspects of phytoplankton populations.

Figure 1

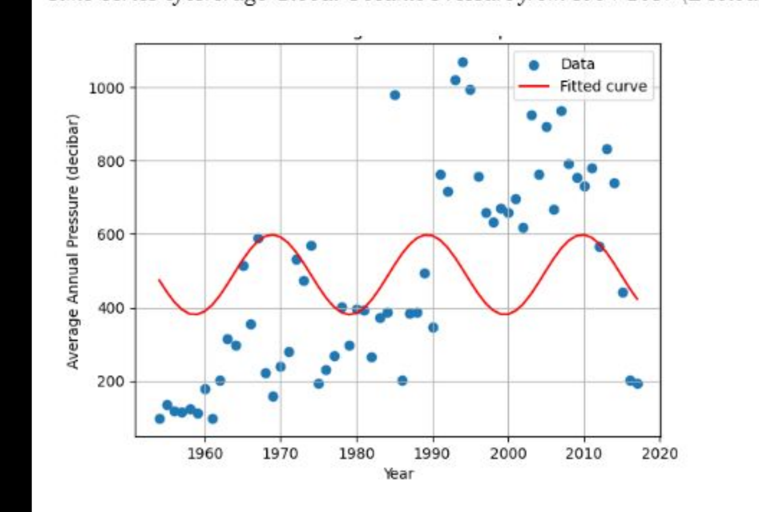
Time Series of Average Global Oceanic Salinity (ppt) from 1954-2017



Note. Note. The time series for salinity (s) for year (y) is described by the sinusoidal regression function of f(s) = 3.724*sin(6.220y + 80.552) + 30.112; $R^2 = 0.847$. Sinusoidal Interval: (26.388, 33.836)

Figure 2

Time Series of Average Global Oceanic Pressure from 1954-2017 (Decibars)



Note. Note. The time series for pressure (ρ) for year y is described by the sinusoidal regression function of f(ρ) = 109.099*sin(6.951y + 43.661) + 489.463; $R^2 = 0.077$ Sinusoidal Interval: (380.364, 598.562)

Table 1

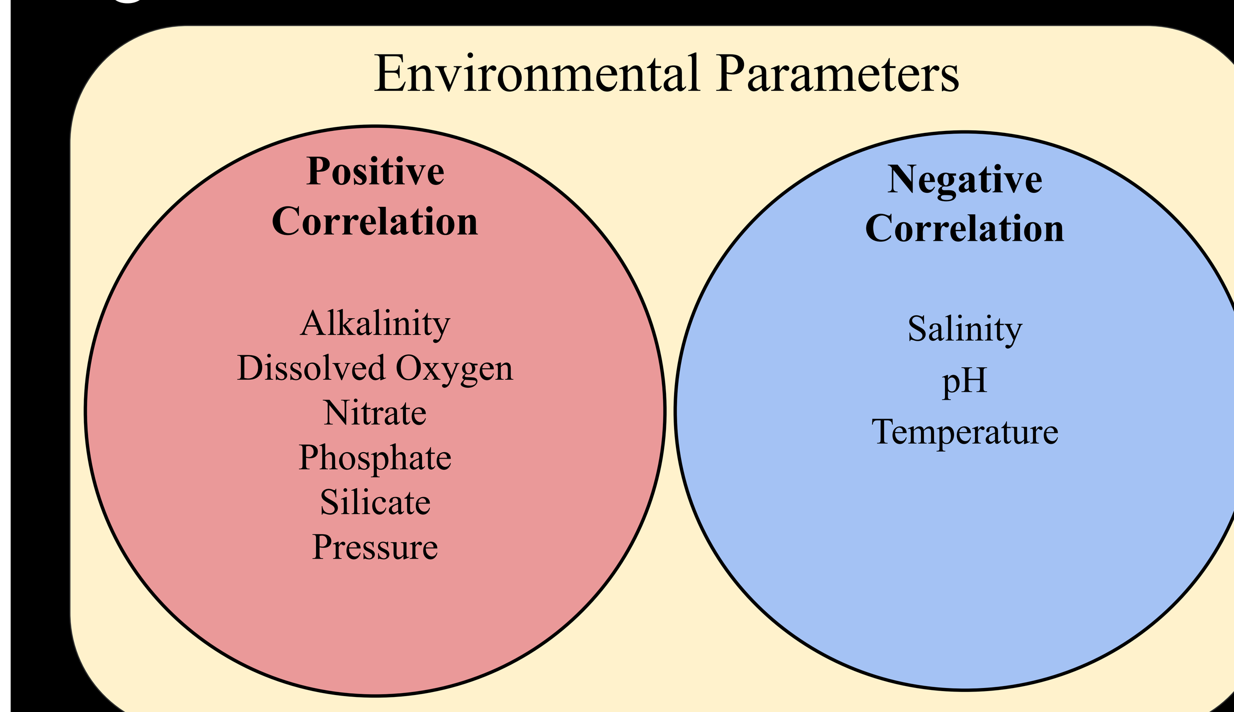
Linear Regression Information of Parametric Factors Related to Total Oceanic Chlorophyll

Parameter	Variable	R^2 Value (r)	p-value (single-tailed p-value) α = 0.05	Equation
Salinity (ppt)	s	0.54 (0.735)	0.0000 (0.0000)***	f(κ) = -0.2248s + 8.6275
pH	φ	0.27 (0.520)	0.0000 (0.0000)***	f(κ) = -3.9346φ + 33.0813
Dissolved Oxygen (μmol/kg)	d	0.25 (0.500)	0.0000 (0.0000)***	f(κ) = 0.0333d - 5.6467
Pressure (decibars)	ρ	0.22 (0.469)	0.0001 (0.00005)***	f(κ) = 0.0014ρ + 0.9536
Phosphate (μmol/kg)	q	0.10 (0.316)	0.0130 (0.0065)*	f(κ) = 1.8526q - 0.5389
Nitrate (μmol/kg)	η	0.09 (0.300)	0.0171 (0.0086)*	f(κ) = 0.0634η + 0.8126
Silicate (μmol/kg)	h	0.08 (0.283)	0.0244 (0.0122)*	f(κ) = 0.0324h + 0.6060
Temperature (°C)	t	0.07 (0.265)	0.0318 (0.0159)*	f(κ) = -0.1641t + 3.2049
Alkalinity (milli-equivalent/liter CaCO3)	c	0.07 (0.265)	0.0368 (0.0184)*	f(κ) = 1.4551c - 1.6810

Note. From highest to lowest R^2 value, the parameters are: salinity, pH, dissolved oxygen, pressure, phosphate, nitrate, silicate, temperature, and

Note. A color gradient is used to show the progression of parameters by decreasing R2 values. With a lower p-value, temperature is placed above alkalinity in the table, given their tied R2 values. α = 0.05 for all significance levels.

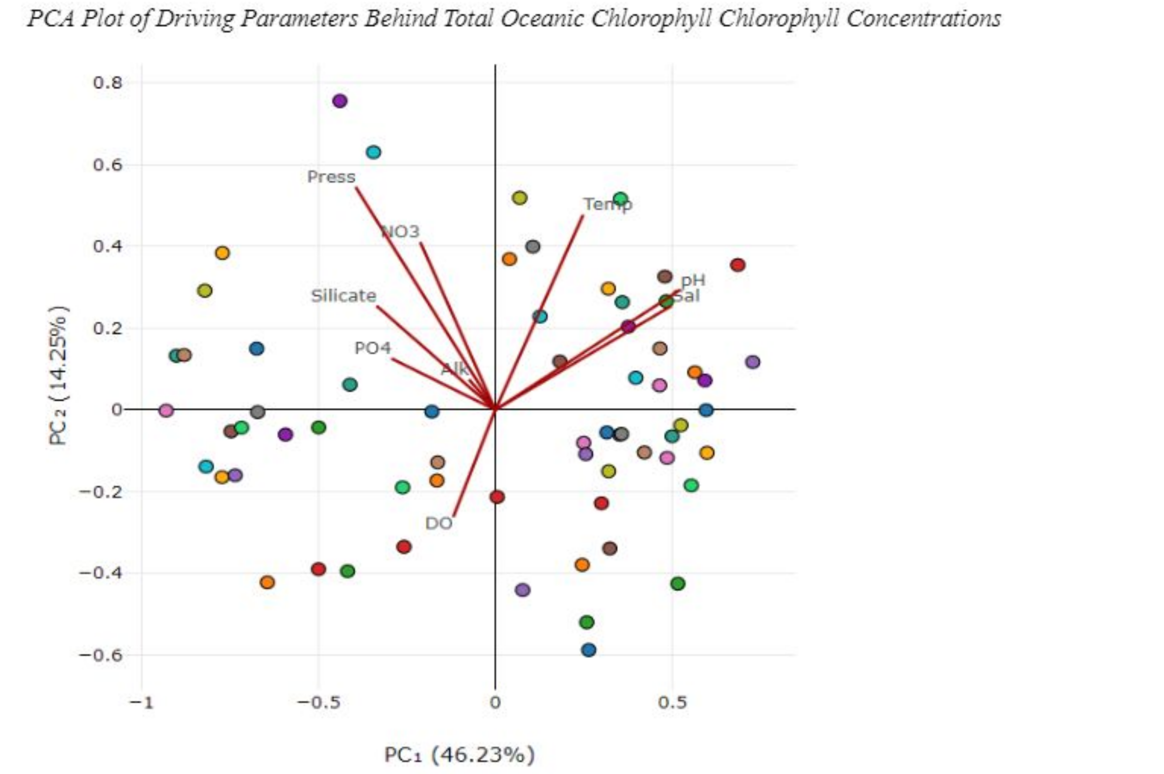
Figure 3



Note. This diagram sorts parameters by their directional relationship with total oceanic chlorophyll. These relationships suggest notable climatic and ecological ramifications.

Figure 4

PCA Plot of Driving Parameters Behind Total Oceanic Chlorophyll Chlorophyll Concentrations



Note.. The individual dots of varying color represent various instances of chlorophyll measurements relative to the first two principal components following dimension reduction. The red lines sprouting from the origin represent the vectors of each parameter's contribution to the variance of the first two principal components. Parametric abbreviations are designated as follows: pH (pH), salinity (sal), temperature (temp), nitrate (NO3), pressure (Press), silicate (Silicate), phosphate (PO4), alkalinity (alk), and dissolved oxygen (DO).

Table 2

Covariance Among Oceanic Parameters in OSD Dataset of WOD18, 1954-2017

	Temperature (°C)	Salinity (ppt)	Dissolved O_2 (μmol/kg)	Pressure (decibars)	pH	Alkalinity (meq/L $CaCO_3$)	NO_3 (μmol/kg)	PO_4 (μmol/kg)	Silicate (μmol/kg)
Temperature (°C)	0.05679								
Salinity (ppt)	0.03166	0.08317							
Dissolved O_2 (μmol/kg)	-0.01647	-0.01959	0.04698						
Pressure (decibars)	-0.005877	-0.03823	0.01677	0.08013					
pH	0.03188	0.06853	-0.01324	-0.03891	0.09541				
Alkalinity (meq/L $CaCO_3$)	0.006023	-0.01187	0.001403	0.009997	-0.01088	0.02999			
NO_3 (μmol/kg)	-0.001303	-0.01835	0.003703	0.03955	-0.01663	0.0009591	0.03353		
PO_4 (μmol/kg)	-0.0178	-0.02756	-0.003317	0.02564	-0.03468	0.002638	0.017	0.05649	
Silicate (μmol/kg)	-0.02261	-0.03465	-0.007556	0.029	-0.03073	0.004527	0.02327	0.02543	0.06992

Note. Green cells represent the diagonal cells of the covariance matrix. These quantities, rather than inter-parameter covariance, represent the

Note. All values are rounded to four decimal places. Green cells represent diagonal cells. These quantities represent the variance observable within the specified parameter. For example, the cell 0.0801 represents the variance seen within water pressure. By contrast, the cell below, -0.0389, represents the covariance between pH and water pressure.

Analysis

Sinusoids:
- Highly Variable R^2 Values: 0.077- 0.847 (Figure 1; Figure 2)
  → **Model Fitness Varies Depends Upon Parameter**
- **Impractical Sinusoidal Intervals** (Figure 1; Figure 2; Supporting Figures)
- **Alternative Regression Methods Necessary**
- **Viable Forecasting Strategy**—Crucial For Decision-Making (e.g., Algal blooms)

Linear Regression Models:
- Low R^2 Values + Low p-values = **poor predictors, but significant directional relationships** (Table 1)
- Negative correlation with temperature (Figure 3) suggests a **loss in phytoplankton biomass and reduction in primary production capabilities** (Berwyn, 2018)
- This means **less CO_2 sequestration, nutrient cycling,** and **trophic energy for marine food webs**
- Salinity and nutrient concentrations are predicted to become less spatially homogeneous (Berwyn, 2018), meaning **the degree to which biomass and primary production increase/decrease will vary, decreasing ecological stability** (Figure 3)

Analysis (Con.)

PCA:
- **pH, followed by salinity and pressure, are driving parameters of** phytoplankton **biomass and primary production** (Figure 4)
  - (With total oceanic chlorophyll as a proxy)
- **Positive Relationships: Among Nutrients; Pressure & Nutrients; pH & Salinity** (Figure 4)
- **Negative Relationships: Temperature & DO** (Figure 4)
- **Limited applicability:** PCs 1 and 2 only account for 60% of variance (Figure 4)
- **Case-by-Case Variability**

Covariance Matrix:
- **Strong Independence Among Parameters** (Table 2)— low variance values
  - *Confounding variables for phytoplankton dynamics, but not one another*
- **Strong Homogeneity Within Parameters** (Table 2)— low diagonal values
- **Global Scale Homogeneity vs. Specific Ecosystem Variations**

Conclusions and Extensions

- **Apparatus appears to be viable**
  - **Critical for addressing climate change, marine ecosystem health, and understanding climatic and ecological patterns**
- **Limitations**:
  - **Geography as a confounding variable**: lack of geospatial data for parametric data
  - **Specific Temporal Scale**
    - 1954-2017, using the OSD Dataset
  - **Greater Data Integration & Apparatus Modification Required**
- **Extensions:**
  - Integration of Neural Networks for Food Web Modeling (Boit et al., 2012; Loschi et al., 2023)
  - Forming Mechanistic Connections with CMIP and other climate models (Hague & Vichi, 2018)

References

Amazon Web Services. (2024). *Registry of Open Data on AWS*. Registry.opendata.aws; Amazon Web Services, Inc. https://registry.opendata.aws/

Anderson, S. I., Barton, A. D., Clayton, S., Dutkiewicz, S., & Rynearson, T. A. (2021). Marine phytoplankton functional types exhibit diverse responses to thermal change. *Nature Communications*, *12*(1). https://doi.org/10.1038/s41467-021-26651-8

Berwyn, B. (2018, May 7). *Scientists Say Ocean Circulation Is Slowing. Here's Why You Should Care.* Inside Climate News. https://insideclimatenews.org/news/07052018/atlantic-ocean-circulation-slowing-climate-change-heat-temperature-rainfall-fish-why-you-should-care/?gclid=CjwKCAjw2K6lBhBXEiwA5RjtCZMQVm0nxKHzSuutQ_Cgz9mZ1peI8xnzAhVnN0VCr8vudXHq2Sa3IhoC5O0QAvD_BwE

Boyer, T.P., O.K. Baranova, C. Coleman, H.E. Garcia, A. Grodsky, R.A. Locarnini, A.V. Mishonov, C.R. Paver, J.R. Reagan, D. Seidov, I.V. Smolyar, K. Weathers, M.M. Zweng,(2018): World Ocean Database 2018. A.V. Mishonov, Technical Ed., NOAA Atlas NESDIS 87. https://www.ncei.noaa.gov/sites/default/files/2020-04/wod_intro_0.pdf

Chang, C.-W., Miki, T., Ye, H., Souissi, S., Adrian, R., Anneville, O., Agasild, H., Ban, S., Be'eri-Shlevin, Y., Chiang, Y.-R., Feuchtmayr, H., Gal, G., Ichise, S., Kagami, M., Kumagai, M., Liu, X., Matsuzaki, S.-I. S., Manca, M. M., Nõges, P., & Piscia, R. (2022). Causal networks of phytoplankton diversity and biomass are modulated by environmental context. *Nature Communications*, *13*(1), 1140. https://doi.org/10.1038/s41467-022-28761-3

Dedman, C. J., Barton, S., Fournier, M., & Rickaby, R. E. M. (2023). The cellular response to ocean warming in Emiliania huxleyi. *Frontiers in Microbiology*, *14*. https://doi.org/10.3389/fmicb.2023.1177349

Deppeler, S. L., & Davidson, A. T. (2017). Southern Ocean Phytoplankton in a Changing Climate. *Frontiers in Marine Science*, *4*. Frontiers. https://doi.org/10.3389/fmars.2017.00040

Deus, R., Brito, D., Kenov, I. A., Lima, M., Costa, V., Medeiros, A., Neves, R., & Alves, C. N. (2013). Three-dimensional model for analysis of spatial and temporal patterns of phytoplankton in Tucuruí reservoir, Pará, Brazil. *Ecological Modelling*, *253*, 28–43. https://doi.org/10.1016/j.ecolmodel.2012.10.013