Journal of Earth and Atmospheric Research

PARTICULATE INORGANIC CARBON AND CHLOROPHYLL VARIABILITY OFF LAGOS COAST: AS INFERRED FROM MODIS-AQUA MONTHLY TIME SERIES (2018-2021)

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Article History
Received: 11-11-24
Accepted: 12-12-24

Keywords:
Phenology, Remote sensing, Lagos coast, Annual cycle, Gulf of Guinea

ABSTRACT

The intensity of anthropogenic carbon dioxide emissions is increasing. It influences marine ecosystems by shifting the particulate inorganic carbon (PIC) to particulate organic carbon (POC) ratio. In the present study, MODIS-AQUA products were used to investigate the four-year (2018-2021) average annual variability in PIC and chlorophyll biomass in association with other environmental controls across three sites off Lagos coastal waters, Gulf of Guinea. On annual time scale environmental variables demonstrated a strong cycle with PIC, Chlorophyll, sea surface temperature (SST) and photosyntethically active radiation (PAR) demonstrating a peak in June (0.0078 mol C m-3), November (7.052 mgm-3;29.6°C) and March (48.68 E m-2 day-1) respectively. The spatial gradient in all the environmental variables was not statistically significant ($p>0.05$).A significant positive relationship between PIC and chlorophyll ($p<0.05$; $r= 0.657$) indicates strong coupling between organic matter production and carbon dioxide uptake and incorporation into inorganic carbon pools. This phenological study has shown that continued observation of ocean colour is crucial for understanding and predicting environmental ecological changes at local scales within coastal waters off Lagos.

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1.0 INTRODUCTION

The marine ecosystem is the largest reservoir of carbon on earth (DeVries,2022) with a substantive proportion being contributed by planktonic calcifiers including pteropods, foraminifers and coccolithophores (Anglada-Ortiz *et al*., 2021; Ziveri *et al*., 2023). By far, coccolithophores contribute the most (30-90%) to the biogenic carbon pool in the form of particulate inorganic carbon (PIC) export to the deep-sea floor (Mitchell *et al*., 2017; De Vries *et al.,* 2021). These unicellular algae also supply approximately 1-40% of global ocean primary production (Poulton *et al.,* 2013). The magnitude and gradient of air-

sea CO_2 flux are dependent on the relative ratio of PIC production to particulate organic carbon (POC) export. Higher PIC : POC constitutes efflux of $CO_2$to the atmosphere while organic carbon transport efficiency is enhanced through the ballast effect and vice versa for lower PIC : POC. Through this process, coccolithophores play a crucial role in the earth's climate system and marine carbon biogeochemistry (Brewin *et al*., 2021). The dynamic interplay between chlorophyll biomass and PIC has significant ramifications for marine ecosystems. Particulate inorganic carbon production influences the carbon cycle by sequestering carbon to the ocean seafloor and regulating climate (Balch *et al*., 2005). In a comprehensive x-ray of global ocean primary productivity, Siegel *et al*. (2013) elucidated the significance of chlorophyll biomass as a crucial indicator of ecosystem health across different marine regions. Multiple studies have however demonstrated that changes in particulate inorganic and organic carbon production and export can compromise marine ecosystem resilience and biodiversity (Doney *et al*., 2009; Beaugrand *et al*., 2010).

The ocean biological carbon pump is significantly influenced by PIC:POC ratio as it has a cascading effects on surface ocean carbonate chemistry, air-sea CO_2 flux and the climate system. The production of POC reduces surface water partial pressure of carbon dioxide (pCO_2) acting as a CO_2 sink from the atmosphere whereas PIC production acts a as source of CO_2 to the atmosphere lowering total alkalinity (Frankignoulle *et al*., 1994). The opposing impact of calcification on CO_2 uptake via the 'rain ratio' (PIC:POC) has been shown to significantly reduce the efficiency of the biological carbon pump (Rost and Riebesell, 2004). Changes in the PIC:POC ratio caused by ocean acidification have the potential to cause substantial influence on future climate scenarios. Furthermore, investigations using ocean colour remote sensing have found considerable geographical and seasonal variability in the PIC:POC ratio, which has implications for climate modeling and global carbon cycling (Balch *et al*., 2005).Coccolithophores possess light backscattering properties owing to the optical effect of calcium carbonate coccoliths.

The scattering of spectrally resolved light by coccoliths from the ocean (water leaving radiance-nLw) serves as input for satellite sensors to measure coccolithophore biomass concentration in the surface ocean. Ocean primary production is dominated by non-calcifying phytoplankton largely represented by siliceous diatoms and dinoflagellates. The standing stock of phytoplankton in the surface ocean can be quantified by satellite remote sensing of chlorophyll reflectance based on a 2B/3BOC algorithm (Yu *et al*., 2020). Chlorophyll as a proxy for phytoplankton biomass when remotely sensed enables high temporal and spatially resolved data of the ocean biological carbon pump (OBCP) at a synoptic scale not achievable by *in-situ* observation (Brewin *et al*., 2021). The application of ocean colour remote sensing to characterize trends of PIC and chlorophyll (Chl-a) biomass is rare off the coastal waters of Lagos. The objectives of the present study are to; i) understand the annual cycle of coccolithophore biomass off the coast of Lagos using PIC as a proxy as well as in Chl-a, sea surface temperature (SST), and photosynthetically active radiation

(PAR), ii) investigate the spatial distribution of PIC, Chl-a, SST, and PAR in the study stations, iii) investigate the interconnections between PIC, Chl-a, SST and PAR iv) understand the key environmental factors that control the seasonal chl-a and PIC biomass in the waters off Lagos, and v)examine how PIC:POC ratio influence air-sea CO_2 flux and carbon cycling processes in the study area.

2.0 MATERIALS AND METHODS

2.1 Study Area

The study area comprises a transect of three georeferenced sites off the coast of Lagos adjacent to the Lagos harbour entrance situated in southwestern Nigeria, Gulf of Guinea (Figure 1). The farthest station, Beyond Lagos Anchorage (BLA) is 18nautical miles away from the coastline while the station midpoint, Lagos Anchorage (LA) is 12 nautical miles and the closest station Lagos Break Waters (LBW) is six nautical miles away from the coast. The environment is bordered to the North by the Lagos Lagoon and the barrier beach which runs along the entire 180 km Lagos coastline. Oceanographic dynamics are influenced by a dominant year-round warm Guinea Current (GC) that is subject to seasonal upwelling which has a weak signal on the westernmost flank of Lagos (Sohou *et al*., 2020). The tidal cycle is semi-diurnal and influences the flux of materials and energy between the Atlantic waters and the Lagos Lagoon. The sampling stations were selected across the shelf to capture spatial heterogeneity of the hydrophysical and hydrochemical parameters in the coastal environment. The area is climatologically

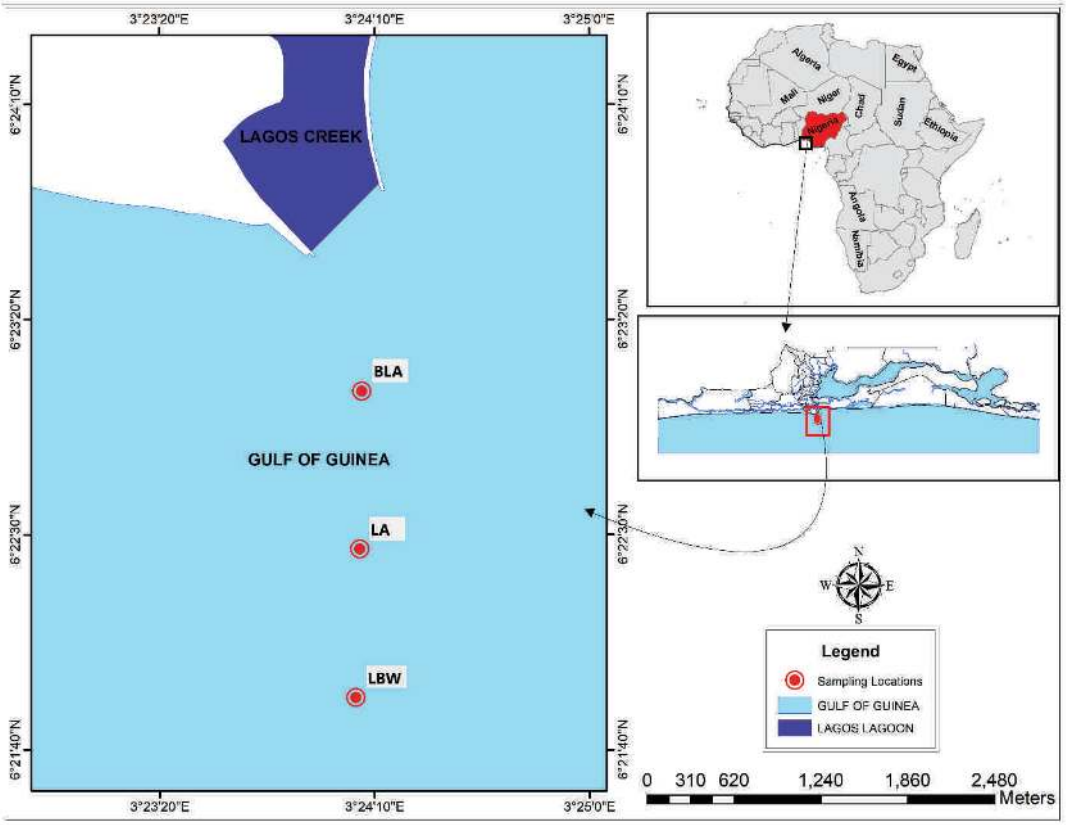


Figure 1: Study stations off Lagos coast: BLA-Beyond Lagos Anchorage, LA-Lagos Anchorage, and LBW-Lagos Break Waters.

influenced by the tropical maritime and tropical continental air masses (Odekunle and Eludoyin, 2008).The dynamic position of the intersection point between both air masses known as the Intertropical Convergence Zone (ITCZ) determines the onset of the Wet (May-November) and Dry (December-April) seasons over the region. The coastal waters off Lagos coast area eutrophic marine environment that shows seasonal variability in its primary production.

2.2 Data Collection

Measurements of SST and collection of seawater for Chl-a analyses was embarked upon periodically from December 2018 to April 2021 covering the Wet and Dry seasons. Surface seawater for Chl-a was collected in 1-litrepolyethylene bottles with a Niskin bottle while SST measurement was conducted simultaneously with a calibrated YSI Pro 1030 probe at 5m water depth. For each sample, 200mL of seawater was filtered through Whatman GF/F, glass fiber filter (nominal pore size 0.45 µm, 47 mm diameter). If immediate filtration was impossible, the water samples were kept on ice in the dark and filtered within 24 hours. Filter homogenization and pigment extraction were carried out with 90% acetone overnight in the dark at 4°C following standard protocols (Arar and Collins, 1997). The concentration of Chl-a was then determined with a Lamotte Smart Spectro spectrophotometer. Results were validated with calibration standards, and squared correlation coefficients $r^2 > 0.9990$ were considered acceptable (Wurl, 2009). If the r^2 is less than acceptable, new standards are made and samples re-analyzed.

Standard monthly SST, Chl-a, PIC and PAR data for (2018-2021) were obtained from the NASA Ocean Colour Web (https://oceancolor.gsfc.nasa.gov/l3/,accessed on 06 January 2023). The 4km spatial resolution Modis-Aqua (Moderate Resolution Imaging Spectroradiometer) Level 3 data were downloaded as Standard Mapped Images (SMI) NetCDF files and pixel extraction was done with the SeaDAS software version 8.2.0 developed by the Ocean Biology Processing Group (OBPG). The algorithms used to estimate PIC concentrations from MODIS-Aqua data are based on the observed relationship between water remote sensing reflectance (Rrs) and PIC concentration. This algorithm uses two bands near 443 and 555 nm and calculates PIC in units of mol C m^{-3} (Vostokov *et al*., 2021). However, the algorithm can be subject to atmospheric correction errors and contamination from the sun's glint. To overcome these limitations, a new algorithm based on reflectance differences between green, red and near-infrared (NIR) bands was used (Mitchell *et al.*, 2017).

2.3 Data Analyses and Validation

Extracted satellite data for the three stations which contained missing value points due to cloud cover were filled using the R statistics package, imputeTS (Moritz and Bartz-Beielstein 2017). The imputation of missing values in the satellite dataset is conservative (Wang *et al*., 2020). Validation of satellite data with *in situ* data (Chl-a and SST) was evaluated by root mean square error (RMSE) following (Poddar *et al*., 2019). Statistical analyses were done on the dataset using the software JAMOVI Statistics version 2.3.18. Descriptive statistics was used to analyse the

monthly time series data of the respective stations. Multivariate analyses which include analysis of variance (ANOVA)were performed to investigate significant spatial differences in the variables, correlation analyses showed the strength and direction of the relationships between variables while regression analyses and principal component analyses (PCA) was used to predict and investigate the factors that controlled seasonal variation in PIC biomass. Validation of *in-situ* and satellite data was evaluated by calculating the root mean square error between satellite and *in-situ* data using the formula in Eq 1.To our knowledge, there is no study within Nigerian waters available to quantify the possible bias that is introduced to the PIC concentration made by ocean colour remote sensing.

$$RMSE = \sqrt{\frac{\sum_{I=1}^{N}\left(X_{obs,i}-X_{sensor,i}\right)^2}{n}} \quad \text{Eq 1}$$

Where;

$X_{obs,i}$=*in-situ* observation

$X_{sensor,i}$ = satellite observation

Using Chl-a data as proxy for POC (Legendre *et al*., 1999; Gardner *et al*., 2006; Sathyendranath *et al*., 2020), the PIC: POC ratio for the study area was calculated according to the formula in Eq 2.

PIC:POC = PIC / POC Eq2

Where;

PIC = Particulate Inorganic Carbon

POC = Particulate Organic Carbon

3.0 RESULTS

3.1 Validation of *in-situ* and satellite SST and Chl-a data

Ground-truthing satellite SST and chl-a data with *in situ* data showed RMSE of 1.37°C and 8.55 mgm^{-3} respectively. These differences between field and satellite data can be partly explained by mismatches in the time and spatial scales between the two variables (Zibordi *et al*., 2019). Over the sampling period, *in situ,* measurements and sample collection were done periodically at seasonal time scale. On the other hand, to investigate the long-term trend in both variables continuous satellite data was utilized which perhaps can result in the discrepancy observed.

3.2 Annual cycles of Chl-a, PIC, SST, and PAR

As presented in Figure 2a, monthly average of environmental parameters for the studied period (2018-2021) showed strong seasonal cycles for chl-a, PIC, SST and PAR in the waters off Lagos. From January to May Chl-a biomass remained fairly constant. It was observed to be relatively stable at 1.534 – 1.539 mgm^{-3}.Biomass increased steadily from 2.294 mgm^{-3} in June to 3.622 mgm^{-3}in September. A steep rise in productivity for the annual cycle was observed from September to the peak in November at 7.052 mgm^{-3}. In December biomass declined but remained high at 6.019 mgm^{-3}. Particulate inorganic carbon showed an annual cycle similar to Chl-a biomass especially between January and May when the average biomass was lowest at 0.0003 to 0.0004 mol C m^{-3}respectively.Figure 2b shows that the highest PIC was observed in June with an average biomass of 0.0078 mol C m^{-3}. Between July and September, PIC biomass demonstrated average annual fluctuation from 0.0033 to 0.0048 and 0.0031 mol C m^{-3} in July, August, and September respectively. In October an upshoot in PIC to 0.0068 mol C m^{-3} was recorded while values remained high in November and December at 0.0072 and 0.0067

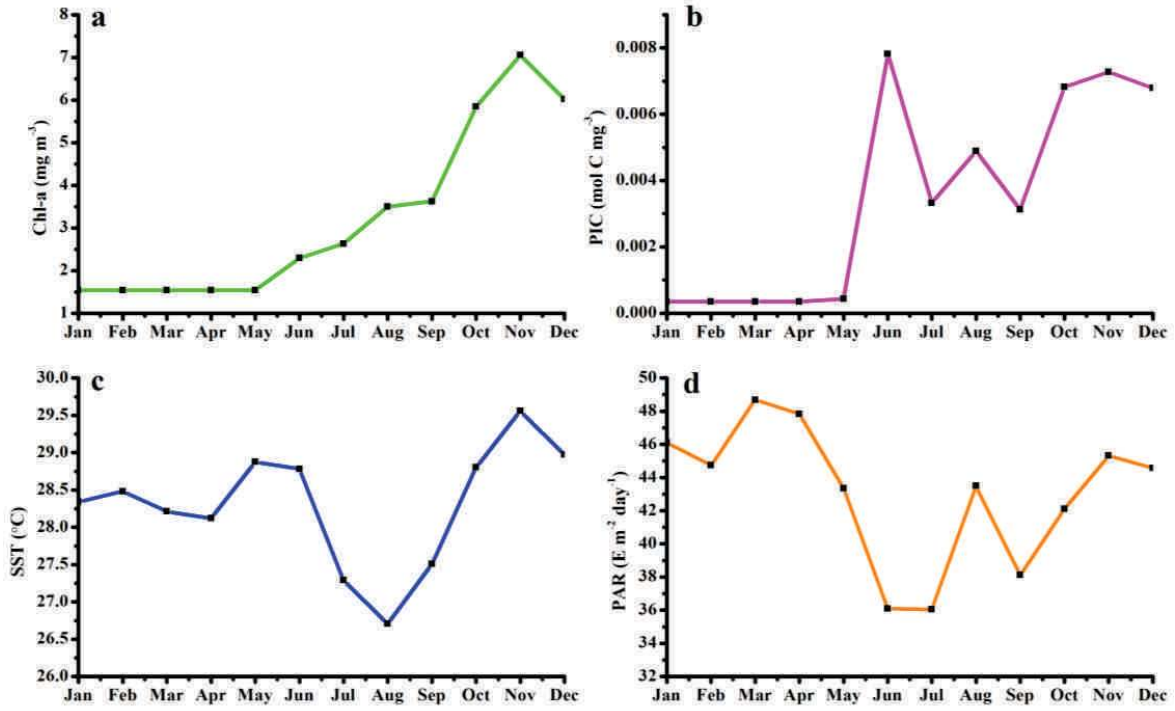


Figure 2 Average annual cycle of (a) Chla-a (b) PIC(c) SST and (d) PAR off Lagos coast during 2018-2021.

mol C m^{-3} respectively. Figure 2c shows that SST displayed a strong annual signal with lowest average temperature of 26.7°C recorded in August while the warmest temperature of 29.6°C was observed in November. As shown in Figure 2d, PAR showed a sinusoidal pattern with an average annual maximum radiation of 48.68 E m^{-2} day^{-1} in March and lowest radiation of 36.08 and 36.04 E m^{-2} day^{-1} in June and July respectively. As depicted in Table 1, Independent student t-tests indicate significant seasonal differences ($p<0.05$) in Chl-a, PIC, SST, and PAR.

3.3 Spatial Variability of Chl-a, PIC, SST and PAR

Figure 3a-d and Table 2 demonstrates the distribution of environmental variables in the study area off the coast of Lagos. In Figure 3a, the spatial variation of Chl-a was not apparent between the three stations observed for the period (2018-2021). However, the coastal-most station LBW had the highest Chl-a record (4.517 mgm^{-3})

Table 1: Independent t-test showed a significant seasonal difference in Chl-a, PIC and PAR

		Statistic	df	p
Chl-a	Student's t	-3.09	34.0	0.004
PIC	Student's t	-4.29	34.0	<.001
SST	Student's t	1.35[a]	34.0	0.187
PAR	Student's t	5.66[a]	34.0	<.001

Levene's test is significant ($p <0.05$), suggesting a violation of the assumption of equal variances.

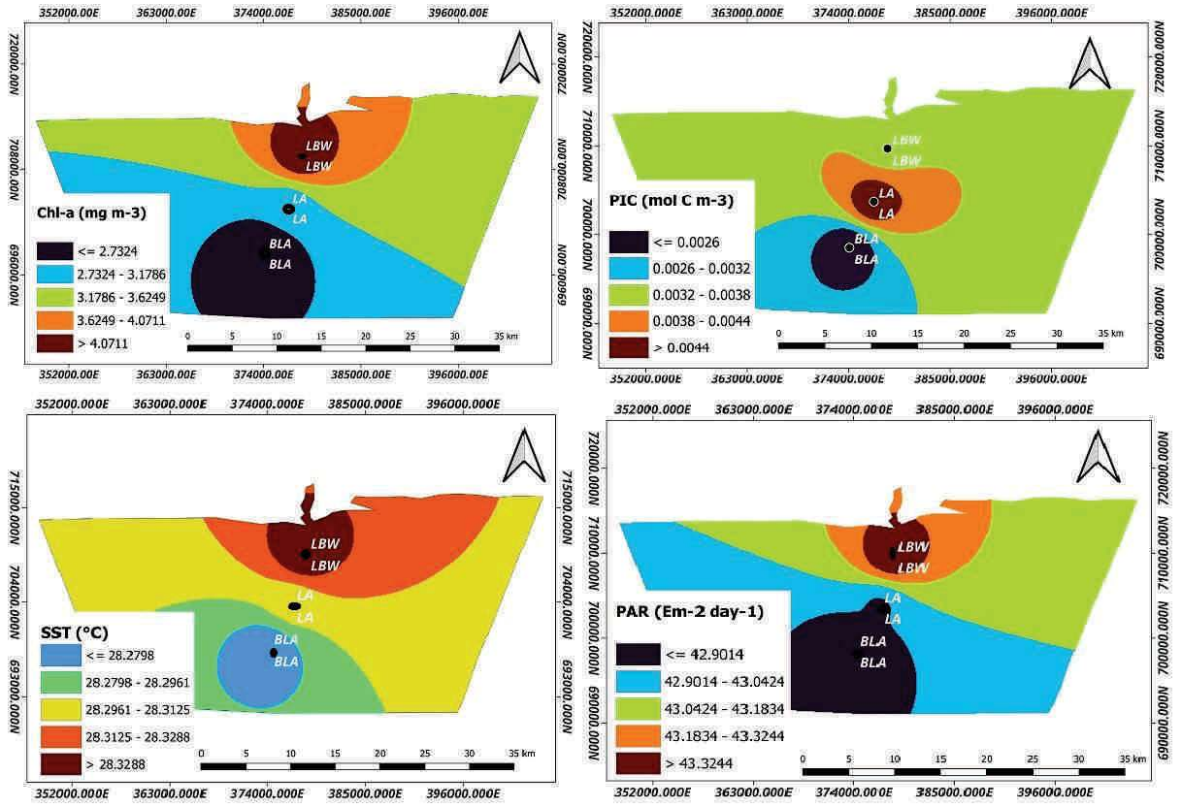


Figure 3: Graphical representation of the distribution of variables across stations off the coast of Lagos, (a) Chl-a (b) PIC (c) SST and (d) PAR.

Table 2: Summary Statistics of Chl-a, PIC, PAR and SST at Stations BLA, LA and LBW off Lagos coastal waters

	Station	Minimum	Maximum	Mean	Std. Deviation
Chl-a (mgm^{-3})	BLA	0.739	6.130	2.286	1.927
	LA	0.915	6.432	2.856	1.953
	LBW	2.562	8.596	4.517	2.254
PIC (mol C m^{-3})	BLA	1.910e-4	0.005	0.002	0.002
	LA	5.085e-4	0.011	0.005	0.005
	LBW	3.498e-4	0.008	0.003	0.003
SST(°C)	BLA	26.672	29.535	28.263	0.855
	LA	26.679	29.584	28.303	0.802
	LBW	26.762	29.555	28.345	0.773
PAR (Em^{-2} day^{-1})	BLA	35.607	48.309	42.760	4.216
	LA	35.892	48.136	42.883	4.022
	LBW	35.559	49.613	43.465	4.508

which was not always significantly different from other stations ($p>0.05$) as indicated in Table 3. The lowest Chl-a ($0.739mgm^{-3}$) was usually observed at the southernmost station BLA. According to Table 2 and 3 respectively, PIC biomass was the highest (0.011 mol C m^{-3}) at the intermediate station LA and was not significantly different from other stations ($p>0.05$). The biomass of PIC in the stations was generally observed to be low (0.00019 – 0.011 mol C m^{-3}). Also Table 2and 3

Table 3: One-way ANOVA (Welch's) of spatial variability inChl-a, PIC, PAR and SST off Lagos coastal waters

	F	df1	df2	p
Chl-a (mgm^{-3})	3.4327	2	21.9	0.050
PIC (mol C m^{-3})	2.9435	2	19.5	0.076
SST(°C)	0.0295	2	22.0	0.971
PAR (Em^{-2} day^{-1})	0.0856	2	22.0	0.918

F=F-statistic; df=Degrees of Freedom

respectively showed that SST records at the three stations over the period studied demonstrated spatial homogeneity ($p>0.05$) which ranged from 28.26 to 29.58°C. As evident from Table 2 and 3, PAR throughout the observed period also exhibited homogeneous variability ($p>0.05$) across the three stations and ranged from 35.55 to 49.61 E m^{-2} day^{-1} in station LBW.

3.4 Inter-relationships between variables and control on Particulate Inorganic Carbon seasonal biomass

As shown in Table 4, the inter-relationships between the environmental variables were explored by the Pearson correlation coefficient matrix which indicated their strength and direction. Chl-a, had a significantly strong positive relationship with PIC ($p<0.05$; $r= 0.657$). Sea surface temperature showed an insignificant and weak positive correlation with Chl-a. Particulate inorganic carbon and PAR had a significant but weak inverse correlation.

Table 5 displays the linear regression model which showed that 57% in PIC variance was predicted by all variables with Chl-a, and PAR

Table 4: Pearson coefficient matrix showing the association between the different variables in the stations off Lagos

		Chl-a(mgm^{-3})	PIC(mol C m^{-3})	SST(°C)	PAR(E m^{-2} day^{-1})
Chl-a (mgm^{-3})	Pearson's r	—			
	p-value	—			
PIC (mol C m^{-3})	Pearson's r	**0.657**	—		
	p-value	**< .001**	—		
SST (°C)	Pearson's r	**0.344**	0.246	—	
	p-value	**0.040**	0.148	—	
PAR (E m^{-2} day^{-1})	Pearson's r	0.038	**-0.378**	0.253	—
	p-value	0.828	**0.023**	0.136	—

having a significant effect ($p < 0.05$) on PIC biomass. Further confirmation of the control on PIC biomass by PCA also showed that Principal Component 1 (PC1) explained 76.9% of the variance while PC2 explained 20.9% of the variance. The loading score of PAR in PC1 is 0.998 while in PC2 Chl-a had a loading value of 0.988. As depicted in Table 6 and Figure 4, PCA biplot showed PAR controlled the variability observed in Dry season while Chl-a strongly influenced variability in the Wet season.

Table 5: Regression model of the mean environmental variables controlling seasonal PIC biomass

Model	R	R^2		
1	0.756	0.572		
Predictor	Estimate	SE	t	p
Intercept	-0.00308	0.0153	-0.201	0.842
Chla-a (mgm^{-3})	9.43e-4	1.98e-4	4.773	< .001
SST (°C)	6.29e-4	5.72e-4	1.099	0.280
PAR (E m^{-2} day^{-1})	3.32e−4	1.02e-4	-3.240	0.003

Table 6: Principal component (PC) loadings of environmental variables controlling PIC biomass off Lagos coast

	PC 1	PC 2	PC 3	PC 4
PIC	-0.00032851	0.00097	0.00055663	1
SST	0.041282	0.1443	0.98867	0.00067677
Chl-a	-0.042672	0.98887	-0.14255	-0.0008941
PAR	0.99824	0.036304	-0.04698	0.00031885

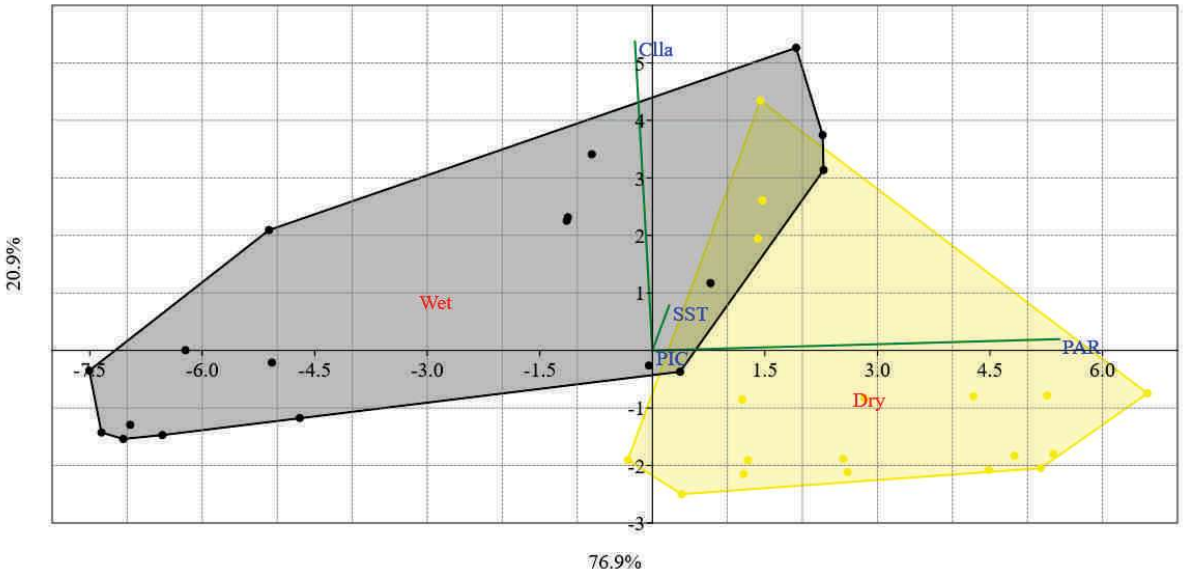


Figure 4: Principal component analyses biplot of environmental variables controlling PIC biomass off Lagos coast

Table 7: Descriptive statistics of PIC: POC ratio across stations in the study area off Lagos

Station	Minimum	Maximum	Mean	SD
BLA	1.67e-4	0.00529	9.74e-4	0.00143
LA	3.90e-4	0.00468	0.00150	0.00123
LBW	1.37e-4	0.00213	6.66e-4	5.93e-4

Table 8: One-way ANOVA of PIC :POC ratio between stations across the study area off Lagos

	F	df1	df2	p
PIC:POC	2.21	2	18.9	0.137

3.5 PIC:POC Ratio

Table 7 shows the descriptive statistics of calculated PIC:POC ratio and Table 8 presents One-way ANOVA statistics used to better understand the significance of PIC:POC ratio between stations. The results demonstrate PIC:POC ratio < 1 which was not statistically significant ($p > 0.05$) across all stations in the study area off Lagos.

4.0 DISCUSSION

Over four years, Chl-a biomass off Lagos coast showed a distinct seasonal cycle where the seawater was less productive in the Dry season while maximum productivity occurred in the Wet season between September and November annually. Nieto and Melin (2017) observed a clear chlorophyll peak in October along the western coast of Nigeria. This is in congruence with the annual cycle obtained in our satellite data where off the coast of Lagos chlorophyll was found to increase from June to reach a maximum in November. The trajectory of chlorophyll increasing from March/April and attaining maximum in later months between September and November broadly follows the pattern of annual chlorophyll in Nigeria's coastal waters as presented in the work of Nieto and Melin (2017). Some studies have expressed a weak connection between the occurrence of low SST (and increased productivity here) off the Lagos coast to coastal upwelling (Oyewo *et al*., 1982; Ibe and Ajayi, 1985; Nieto and Melin, 2017).

Suffice it to say that the horizontal distribution of chlorophyll in the surveyed area is intuitive. The station closest to the shore had the highest recorded chlorophyll and can be associated withthe proximity of this station to the outlet of the Lagos lagoon at the Lagos harbour where it discharges a concoction of nutrients including nitrate and phosphate received from the Lagos lagoon (Elegbeleye and Onyema, 2019). As the nutrient is used up there is a corresponding reduction in chlorophyll biomass as seen in the range of chlorophyll values at stations LBW (2.562-8.596 mgm^{-3}) LA (0.915-6.432 mgm^{-3})and BLA (0.739-6.130 mgm^{-3})away from the shore.

Particulate inorganic carbon biomass as a proxy for coccolithophore displayed an annual cycle that featured maximum value recorded in June. This pattern suggests a possible successional relationship with the (diatom) chlorophyll maximum recorded between September and November in relation to nutrient availability.

Coccolithophore production is favoured by low nutrient levels especially relative to diatoms which can bloom in eutrophic conditions (Godrijan *et al*., 2013). As reported by the works of Onyema and Popoola (2013), and Elegbeleye and Onyema (2019), the phytocoenos is off the Lagos coast is diatom dominated which translates to high chlorophyll level of the seawater. In addition, seasonal peaks in chlorophyll and coccolithophore have been reported in the Black Sea during anomalously warm wintertime in connection to nutrient dynamics (Vostokov *et al*., 2021). The values returned by the PIC algorithm for the present study (0.00019 – 0.011 mol C m^{-3}) are within range as observed by Signorini *et al*., 2006 in the Patagonian shelf break (1 x 10^{-5} – 0.00325 mol C m^{-3}) during austral summer, 0.21 – 1.1 mol C m^{-3} in the open and coastal waters of the northeastern Black Sea (Vostokov *et al*., 2019) and 0.00 – 0.010 mol C m^{-3} in the Black Sea (Vostokov*et al*., 2021), during boreal summer respectively. Spatially, PIC distribution manifested maximum biomass at station LA intermediate to the coastal-most and offshore stations indicating the ubiquity of coccolithophores, especially *Emiliania huxleyi* in coastal environments (Godrijan *et al*., 2018).The biogeochemical production and export of carbon in the ocean depend on the relationship between particulate inorganic carbon and chlorophyll biomass. Chlorophyll demonstrates the contribution of primary production and carbon fixation, whereas PIC biomass indicates coccolithophore formation. Light, turbulence, and nutrient variability are only a few examples of the environmental factors that affect how PIC and chlorophyll dynamics are coupled. Since coccolithophore have a lower chlorophyll-to-carbon ratio than other phytoplankton groups like diatoms and exhibit less nutrient limitation than light limitation, these organisms may not exhibit synchronous peaks in their chlorophyll and PIC biomass due to divergent phenological characteristics. Hopkins *et al*. (2015) reported that they had detected notable differences in the geographical pattern of coccolithophore blooms, which tended to start later and last shorter at higher latitudes.In the Patagonian shelf zone, where coccolithophores predominate in the spring and summer, Signorini *et al*.(2006) discovered a high link between PIC and chlorophyll biomass. Furthermore, in the North Atlantic bloom of 1991, PIC and chlorophyll biomass showed strong correlations and peaked in June (Balch *et al*., 1996).

The pattern of seasonal cycle of SST has been ascribed to various physical processes in the coastal/marine waters off Lagos (Oyewo *et al*., 1982). Olaniyan (1969) related the maximum temperature around the Lagos harbour to the effect of insolation. At the stations off Lagos the steady rise in temperature from January to reach the warm period in May is an indication of a relative cooling of harmattan which gradually increased as atmospheric temperature continued to rise until its maximum in May. Longhurst (1964) have ascribed the warming period to the migration of isotherms which synergize with the thermocline to cause a temperature increase in the water mass. The lowest annual temperature in August has been associated with the cooling effect of water influx during rain events entering into the Atlantic Ocean from the Lagos lagoon (Olaniyan, 1969), combined with a general cooling of the Gulf of Guinea during the major coastal upwelling

period around July-September (Longhurst, 1964). The SST seasonal variability as seen in this study is in conformity with the reports of Arfi *et al*. (1991) and Sohou *et al*. (2020). In a study of the seasonal temperature cycle in four counties (Côte d'Ivoire, Ghana, Benin, and Nigeria) in the northern Gulf of Guinea using a combination of *in-situ* ONSET thermometer, satellite and reanalysis data, Sohou *et al*. (2020) observed temperature pattern similar to our study off the coast of Lagos. Specifically, the thermal feature obtained for Lagos from2018-2021 showed strong seasonal oscillation. While the mean minimum temperature in our study was recorded as 26.7°C in August, Sohou *et al*. (2020) reported a minimum temperature of 26.5°C. This confirms the consistency of satellite SST measurement in the present work with *in-situ* observations. The mechanism for the minimum temperature (cooling) signal in August has been hypothesized as induced by: i) geostrophic adjustment of the Guinea Current (Ingham, 1970), ii) the presence of cyclonic eddies downstream of Cape Three Points and Cape Palmas,(Marchal and Picaut, 1977), iii) The Ekman pumping caused by wind stress curl(Colin, 1991) and iv) propagation of equatorial Kelvin waves (Picaut, 1983). One or a combination of these hypotheses have been suggested to be responsible for the seasonal cooling in August in the northern Gulf of Guinea (Colin 1988; Roy 1995), and by implication specifically at the study location off the coast of Lagos between 2018-2021. However, Djakouré*et al*. (2014; 2017) has refuted the hypothesis of Marchal and Picaut (1977).

The annual structure of PAR over the coast off Lagos showed a typical seasonal pattern observed across tropical oceans. In a multi-satellite mission analysis of twenty-year PAR variability data, Tan and Frouin (2019) were able to show that temporal (seasonal) patterns were dependent on latitude. The authors reported that within the tropical band, higher latitudes have larger seasonal fluctuation in PAR than lower latitudes, with regions around the equator showing maximum intensities in March and September as the sun passes across the equator (i.e., during equinoxes). In June the intensity of PAR is reduced as the sun has moved from the northern hemisphere to the southern hemisphere. Broadly, in accordance with the seasonal pattern in the tropical Atlantic, PAR off Lagos coast attained its peak in March. However, in contrast to the observation by Tan and Froiun (2019) an obvious peak in September is not evident at the study stations. Rather the intensity remained relatively high until December. A similar PAR annual structure was documented in a model study across six tropical ecological zones in Nigeria (Sunday *et al*., 2016). The general high PAR values area reflection of the influence of sunlight that passes the equator in March, which leads to a higher sun altitude at the equator at noon, increasing the quantity of solar radiation hitting the ocean surface daily. The Intertropical Convergence Zone (ITCZ) is coupled with high cloudiness (Tan and Frouin 2019), and thus suggests the cause of the lowest PAR intensity observed between June and July when rain clouds are mostly prevalent over the coastal waters off Lagos. The position of the sun at any time during the year hasa strong influence on the spatial distribution of PAR. As observed in Table 3, the distribution of PAR between the three stations had values that were spatially insignificant.

Corresponding variation between SST and PAR is connected to the generation of solar radiation and heat energy reaching the ocean surface from sunlight. Due to the high specific heat capacity of seawater, a gradual heating and warming of the surface ocean occurs as radiative energy from PAR increases from January to reach peak in March. Thus the lag between PAR and SST in the coastal stations off Lagos is an indication of the time it takes for the ocean water to get warmed up in response to PAR incidence. Conversely, the low PAR intensity and cooling observed in June and July respectively also demonstrate time dependent processes. In addition, high cloudiness coupled with intense precipitation in the form of rainfall that characterizes the tropical rainforest further contributes to low photosynthetic radiation and temperature observed during the period.

The PIC:POC ratio of less than 1 reported in this study has implications for carbon dynamics. This suggests that organic carbon generation from photosynthesis surpasses inorganic carbon production from calcification, implying increased carbon sequestration to the sea floor and efficient atmospheric CO_2 drawdown. This low ratio also indicates a non-calcifying phytoplankton population, which leads to an effective biological carbon export (Falkowski *et al*., 1998; Sathyendranath *et al*., 2020). This process plays a critical part in marine carbon cycling, as biological systems play an important role in regulating atmospheric CO_2 concentrations.

5.0 CONCLUSION

Key oceanographic variables were remotely sensed by satellite for four years at coastal sites off Lagos to investigate their temporal and spatial variability. Results showed that there is a strong relationship between particulate inorganic carbon and chlorophyll biomass suggesting the coupling between coccolithophores and the major phytoplankton groups. Strong annual cycle in the environmental variables reflects the dynamic nature of physical and biogeochemical processes inherent in the coastal waters off Lagos. Spatial homogeneity in almost all environmental variables observed stems from hydrodynamic processes such as tidal regime and wind stress causing effective mixing. Understanding complex biogeochemical processes is critical for forecasting future carbon cycling responses to climate change, especially in marine environments where biological carbon transformation is critical to global carbon dynamics. The current study emphasizes the need for continuous observation employing ocean colour remote sensing to supplement the dearth of *in-situ* observations of variables necessary for the understanding of carbon cycling in the study area.

REFERENCES

Anglada-Ortiz, G., Zamelczyk, K., Meilland, J., Ziveri, P., Chierici, M., Fransson, A., and Rasmussen, T. L. (2021). Planktic foraminiferal and pteropod contributions to carbon dynamics in the Arctic Ocean (North Svalbard Margin). *Frontiers in Marine Science*, vol. 8, p. 1-18.661158.

Arar, E. J., and Collins, G. B. (1997). Method 445.0: In vitro determination of chlorophyll a and pheophytin a in marine and freshwater algae by fluorescence (p.

22). *United States Environmental Protection Agency,* Office of Research and Development, National Exposure Research Laboratory. 26 p.

Arfi, R., Pezennec, O., Cissoko, S., and Mensah, M. (1991). Variations spatiale et temporelle de la résurgence ivoiro-ghanéenne. In P. Cury and C. Roy (Eds.), *Pêcheries Ouest-Africaines Variabilité, Instabilité et Changement*, p. 162-172). ORSTOM

Balch, W. M., Kilpatrick, K. A., and Trees, C. C. (1996). The 1991 coccolithophore bloom in the central North Atlantic. 1. Optical properties and factors affecting their distribution. *Limnology and Oceanography*, vol. 41(8), p. 1669-1683.

Balch, W. M., Gordon, H. R., Bowler, B. C., Drapeau, D. T., and Booth, E. S. (2005). Calcium carbonate measurements in the surface global ocean based on Moderate-Resolution Imaging Spectroradiometer data. *Journal of Geophysical Research: Oceans*, vol. 110(C7), p. 1-21.

Beaugrand, G., Edwards, M., and Legendre, L. (2010). Marine biodiversity, ecosystem functioning, and carbon cycles. *Proceedings of the National Academy of Sciences*, vol. 107(22), p. 10120-10124.

Brewin, R. J., Sathyendranath, S., Platt, T., Bouman, H., Ciavatta, S., Dall'Olmo, G., ... and Walker, P. (2021). Sensing the ocean biological carbon pump from space: A review of capabilities, concepts, research gaps and future developments. *Earth-Science Reviews*, vol. 217, p. 1-32. 103604.

Colin, C., (1988). Coastal upwelling events in front of the Ivory Coast during the FOCAL program. *Oceanologica. Acta*, vol. 11, p. 125–138.

Colin, C. (1991). Sur les upwellings équatorial et côtier (5°N) dans le Golfe de Guinée. *Oceanologica acta,* vol. 14(3), p. 223-240.

De Vries, J., Monteiro, F., Wheeler, G., Poulton, A., Godrijan, J., Cerino, F., Merlinverno, E., Langer. G., and Brownlee, C. (2021). Haplo-diplontic life cycle expands coccolithophore niche. *Biogeosciences,* vol. 18(3), p. 1161-1184.

DeVries, T. (2022). The Ocean Carbon Cycle. *Annual Review of Environment and Resources*, vol. 47, p. 317-341.

Djakouré, S., Penven, P., Bourlès, B., Veitch, J., and Koné, V. (2014). Coastally trapped eddies in the north of the Gulf of Guinea. *Journal of Geophysical Research: Oceans*, vol. 119(10), p. 6805-6819.

Djakouré, S., Penven, P., Bourlès, B., Koné, V., and Veitch, J. (2017). Respective roles of the Guinea Current and local winds on the coastal upwelling in the northern Gulf of Guinea. *Journal of Physical Oceanography*, vol. *47*(6), p. 1367-1387.

Doney, S. C., Lima, I., Feely, R. A., Glover, D. M., Lindsay, K., Mahowald, N. and Wanninkhof, R. (2009). Mechanisms governing interannual variability in upper-ocean inorganic carbon system and air–sea CO2 fluxes: Physical climate and atmospheric dust. *Deep Sea Research Part II: Topical Studies in Oceanography*, 56(8-10), 640-655.

Elegbeleye, O. W., and Onyema, I. C. (2019). Phytoplankton diversity and Stoichiometric nutrient limitation in the Lagos Harbour and adjacent sea, Southwestern Nigeria. *Ife Journal of Science*, vol. 21(3), p. 139-155.

Falkowski, P. G., Barber, R. T., and Smetacek, V. (1998). Biogeochemical controls and feedbacks on ocean primary production. *Science*, vol. 281(5374), p. 200-206.

Frankignoulle, M., Canon, C., and Gattuso, J.-P. (1994). Marine calcification as a source of carbon dioxide: Positive feedback of increasing atmospheric CO_2. *Limnology and Oceanography*, vol. 39(2), p. 458–462.

Gardner, W. D., Mishonov, A. V., and Richardson, M. J. (2006). Global POC concentrations from *in-situ* and satellite data. *Deep Sea Research Part II: Topical Studies in Oceanography*, vol. *53*(5-7), p. 718-740.

Godrijan, J., Marić, D., Tomažić, I., Precali, R., and Pfannkuchen, M. (2013). Seasonal phytoplankton dynamics in the coastal waters of the north-eastern Adriatic Sea. *Journal of Sea Research*, vol. 77, p. 32-44.

Godrijan, J., Young, J. R., Marić Pfannkuchen, D., Precali, R., and Pfannkuchen, M. (2018). Coastal zones as important habitats of coccolithophores: A study of species diversity, succession, and life-cycle phases. *Limnology and Oceanography*, vol. *63*(4), p. 1692-1710.

Hopkins, J., Henson, S. A., Painter, S. C., Tyrrell, T., and Poulton, A. J. (2015). Phenological characteristics of global coccolithophore blooms. *Global Biogeochemical Cycles*, vol. 29(2), p. 239-253.

Ibe, A.C., andAjayi, T.O., 1985. Possible Upwelling Phenomenon off the Nigerian Coast. Technical Paper 25. *Nigerian Institute for Oceanography and Marine Research*, 31 p.

Ingham, M. C. (1970). Coastal upwelling in the northwestern Gulf of Guinea. *Bulletin of Marine Science*, vol. 20(1), p. 1-34.

Legendre, L., and Michaud, J. (1999). Chlorophyll a to estimate the particulate organic carbon available as food to large zooplankton in the euphotic zone of oceans. *Journal of Plankton Research*, vol. *21*(11), p. 2067-2083.

Longhurst, A.R., (1964). The coastal oceanography of Western Africa. *Bull. Inst. Afr. Noire*vol. 2, p. 337–402.

Marchal, E., and J. Picaut, (1977). Répartition et abondance évaluées par écho-integration des poissons du plateau ivoiro-ghanéen en relation avec les upwellings locaux. *J. Rech. Oceanogr*., vol. 2, p. 39–58.

Mitchell, C., Hu, C., Bowler, B., Drapeau, D., and Balch, W. M. (2017). Estimating particulate inorganic carbon concentrations of the global ocean from ocean color measurements using a reflectance difference approach. *Journal of Geophysical Research: Oceans,* vol. 122(11), p. 8707-8720.

Moritz, S., and Bartz-Beielstein, T. (2017). imputeTS: time series missing value imputation in R. *The R Journal,* vol. 9(1), 207p.

Nieto, K., and Mélin, F. (2017). Variability of chlorophyll-a concentration in the Gulf of Guinea and its relation to physical oceanographic variables. *Progress in oceanography*, vol. 151, p. 97-115.

Odekunle, T. O., andEludoyin, A. O. (2008). Sea surface temperature patterns in the Gulf of Guinea: their implications for the spatio-temporal variability of precipitation in West Africa. *International Journal of Climatology*, vol. *28*(11), p. 1507–1517.

Olaniyan, C.I.O. (1969). The seasonal variation in the hydrography and total plankton of the Lagoons of South West Nigeria. *Nigerian Journal of Science*, vol. 3 (2) p. 101 – 119.

Onyema, I. C., and Popoola, R. T. (2013). The physico-chemical characteristics, chlorophyll a levels and phytoplankton dynamics of the east mole area of the Lagos Harbour, Lagos. *Journal of Asian Scientific Research*, vol. *3*(10), p. 995-1010.

Oyewo E .O., Ajao E.A, and Orekoya, T. (1982), Seasonal variations in surface temperature and salinity around Lagos Harbour, Nigeria. *NIOMR Technical Paper* No. 10.

Picaut, J. (1983). Propagation of the seasonal upwelling in the eastern equatorial Atlantic. *Journal of Physical Oceanography*, vol. *13*(1), p. 18-37.

Poddar, S., Chacko, N., and Swain, D. (2019). Estimation of chlorophyll-a in Northern Coastal Bay of Bengal using Landsat-8 OLI and Sentinel-2 MSI sensors. *Frontiers in Marine Science*, vol. 6(598), p. 1-11.

Poulton, A. J., Painter, S. C., Young, J. R., Bates, N. R., Bowler, B., Drapeau, D., Lyczsckowski, E., and Balch, W. M. (2013). The 2008 Emiliania huxleyi bloom along the Patagonian Shelf: Ecology, biogeochemistry, and cellular calcification. *Global Biogeochemical Cycles*, vol. 27(4), p. 1023-1033.

Rost, B., and Riebesell, U. (2004). Coccolithophores and the biological pump: Responses to environmental

changes. In H. R. Thierstein and J. R. Young (Eds.), Coccolithophores: From molecular processes to global impact *Springer Berlin Heidelberg*. 565 p.

Roy, C.,(1995). The C^ote d'Ivoire and Ghana coastal upwellings: Dynamics and changes. Dynamics and Use of Sardinella Resources from Upwelling off Ghana and Ivory Coast, X. Bard and K. A. Koranteng, Eds., ORSTOM, 346–361.

Sathyendranath, S., Platt, T., Kovač, Ž., Dingle, J., Jackson, T., Brewin, R.J.W., et al. (2020). Reconciling models of primary production and photoacclimation. *Applied Optics*, vol. *59*(10), p. C100-C114.

Siegel, D. A., Behrenfeld, M. J., Maritorena, S., McClain, C. R., Antoine, D., Bailey, S. W., ... and Yoder, J. A. (2013). Regional to global assessments of phytoplankton dynamics from the SeaWiFS mission. *Remote Sensing of Environment*, vol. 135, p. 77-91.

Signorini, S. R., Garcia, V. M., Piola, A. R., Garcia, C. A., Mata, M. M., and McClain, C. R. (2006). Seasonal and interannual variability of calcite in the vicinity of the Patagonian shelf break (38 S–52 S). *Geophysical research letters*, vol. 33(16), p. 1-5.

Sohou, Z., Koné, V., Da-Allada, Y. C., Djakouré, S., Bourlès, B., Racape, V., Degbe, G., and Adje, C. (2020). Seasonal and inter-annual ONSET Sea Surface Temperature variability along the northern coast of the Gulf of Guinea. *Regional Studies in Marine Science*, vol. 35, p. 1-11. 101129.

Sunday, S. E., Samuel, N. C., Agbasi, O. E., and Sylvia, J. J. A. (2016). Analysis of photosynthetically active radiation over six tropical ecological zones in Nigeria. Journal of Geography, *Environment and Earth Science International*, vol. 7(4), p. 1-15.

Tan, J., and Frouin, R. (2019). Seasonal and interannual variability of satellite-derived photosynthetically available radiation over the tropical oceans. *Journal of Geophysical Research: Oceans,* vol. 124(5), p. 3073-3088.

Vostokov, S. V., Lobkovskiy, L. I., Vostokova, A. S., and Solov'ev, D. M. (2019). Seasonal and interannual variability of phytoplankton in the Black Sea on the basis of remote sensing data and in situ measurements of chlorophyll-a. *Doklady Earth Sciences*, vol. 485, p. 293-297.

Vostokova, A. S., Lobkovskiy, L. I., and Vostokov, S. V. (2021). Anomalous Phenomena in the Development of Phytoplankton in the Black Sea on the Basis of Remote Sensing Data. In *Doklady Earth Sciences,* vol. 497, p. 261-265.

Wang, X., Yu, J., and Fan, H. (2020). Spatial and seasonal variability of surface particulate inorganic carbon and relationship with particulate organic carbon in the Yellow-

Bohai Sea. *Journal of Oceanography*, vol. 76, p. 327-339.

Wurl, O. (2009). Sampling and sample treatments. In Practical guidelines for the analysis of seawater. *CRC Press*. p. 1-32.

Yu, Y., Chen, S., Qin, W., Lu, T., Li, J., and Cao, Y. (2020). A Semi-Empirical Chlorophyll-a Retrieval Algorithm Considering the Effects of Sun Glint, Bottom Reflectance, and Non-Algal Particles in the Optically Shallow Water Zones of Sanya Bay Using SPOT6 Data. *Remote Sensing*, vol. *12*(17), p. 1-34.

Zibordi, G., Voss, K. J., Johnson, B. C., and Mueller, J. L. (2019). IOCCG Ocean optics and biogeochemistry protocols for satellite ocean colour sensor validation. *IOCCG Protocols Series*, *3*, 67p.

Ziveri, P., Gray, W. R., Anglada-Ortiz, G., Manno, C., Grelaud, M., Incarbona, A., ... and Berelson, W. (2023). Pelagic calcium carbonate production and shallow dissolution in the North Pacific Ocean. *Nature communications*, vol. 14(1), p. 1-14.