

First Study of Seawater Carbonate Chemistry Variability in a Portion of the Southern Atlantic Coast of Cameroon: Impact of Organic Pollution

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Abstract

The carbonate system variability and acidification process remain little understood in the coastal ocean of Cameroon. The aim of this study was to assess the variability of the carbonate system in a portion of the southern coast of Cameroon, and the influence of local seawater physicochemical and biological properties on keys parameters of this system. The study was carried out at three fixed sampling stations (Bp, Kb, and Eb), from September 2021 to August 2022 involving all the seasons encountered in the study area. The carbonate system was determined from Total alkalinity (TA), pH, temperature and salinity, using the CO₂SYS_xls program. In addition, nutrients (nitrate, nitrite, phosphate and nitrogen ammonia) and chlorophyll-a data were collected simultaneously at each station. The results showed a high variability of the carbonate system parameters on both temporal and spatial scale. TA and bicarbonate ions (HCO₃⁻) were significantly different between the large rainy season (LRS) and small rainy season (SRS), while CO₂ and CO₂ partial pressure (pCO₂) were significantly different between Kb and Eb sampling stations (p-value < 0.05). The critical thresholds for ocean acidification (OA) seems to not been reached in the southern coastal ocean of Cameroon, given the means values of pH (8.14 ± 0.17), aragonite (3.31 ± 1.3 Ω) and calcite (5.3 ± 2.05 Ω) saturation states obtained. Salinity appears as the main driver of the variability of TA in the study area, while, nitrogen ammonia and the dissolved carbon

dioxide from the degradation of organic matter, respiration and atmospheric absorption, appears as the drivers of pH variation. The large rainy season (LRS) seems to be the most critical period for OA sensitive organisms, while the Bp station looks most vulnerable.

Keywords

Carbonate System, Variability, Coastal Ocean, Ocean Acidification, Cameroon

1. Introduction

The carbonate system contributes to the regulation of seawater pH, and controls the carbon dioxide (CO₂) cycle between the lithosphere, atmosphere and ocean [1]. Understanding the variability of carbonate chemistry parameters in seawater is important to predict potential impact of ocean acidification (OA) on biodiversity and marine ecosystems [2]. Since the advent of industrial revolution and the burning of fossil fuels, anthropogenic carbon dioxide (CO₂) emission into the atmosphere has significantly increased. Each year, the oceans absorb about a quarter of emitted CO₂ by fossil fuel consumption, cement manufacturing and land use change, contributing to mitigate the impacts of climate change on the planet [3] [4]. This absorption causes significant changes in the seawater carbonate chemistry by increasing the concentration of bicarbonate ions (HCO₃⁻) and dissolved inorganic carbon (DIC), and lowering pH, carbonate ions (CO₃²⁻) concentration, aragonite (ΩAr.) and calcite (ΩCal.) saturation (biogenic form of calcium carbonate (CaCO₃) useful in the construction of shells and skeletons of marine crustaceans) [5] [6]. This process known under the term “Ocean Acidification” could have varied effects on different marine taxa, ultimately leading to possible changes in ecosystem services [7] [8]. Global seawater pH has declined approximately by 0.1 units on average since the pre-industrial period [9]. Furthermore, the Representative Concentration Pathway (RCP) 8.5 is projected to decline by a further ~0.30 units by the end of the century [10]. In the coastal ocean, variability in carbonate system can be influenced by biological metabolism, river input, and water mass mixing [11]. Biogeochemical and anthropogenic processes can also result in heterogeneity in coastal water chemistry, including carbonate system parameters [12]. Eutrophication due to excess nutrient runoff (e.g., nitrate and phosphate), biological production of organic matter and their subsequent microbial degradation release CO₂ and can also contribute to acidify subsurface water in coastal ocean regions [13] [14]. In order to gain a deeper comprehension of coastal acidification and its potential impacts for biological organisms and the functioning of ecosystems, it is essential to investigate the variability and drivers of the carbonate system within the specified region [12] [15] [16]. Although carbonate chemistry and acidification processes have been the subject of considerable study and analysis in the open ocean at the global scale, the paucity of data and uncertainties remain a

significant challenge in coastal oceans [12] [17]. In the Gulf of Guinea, few studies and monitoring campaigns have been conducted to gain an understanding of the variability of carbonate system [18]-[21]. The majority of studies conducted in the region have examined air-sea CO₂ flux in conjunction with the analysis of data collected during monitoring campaigns undertaken on research cruises, and very few have been conducted in the coastal ocean. In Cameroon, OA research remains at the early stage. Little is known about the variability of the carbonate chemistry. This is mostly due to the fact that the country is classified among those with no infrastructure or having few equipment to monitor OA [22]. Nevertheless, OA resulting from alterations in seawater carbonate chemistry may have detrimental impact on the fishing of a multitude of marine species, including molluscs, crustacea and small pelagic fish within the country. This could lead to adverse economic consequences for coastal communities, reducing their incomes and livelihoods [23]. Over the past decade, the southern Atlantic coast of Cameroon, with a particular focus on the city of Kribi and its surrounding areas, has witnessed a significant acceleration in industrialisation and uncontrolled urbanisation. The potential for this economic development to contribute to the degradation of marine ecosystems and accelerate the adverse effects of global environmental threats, including climate change, is a significant concern. Therefore, it is crucial to understand the evolution of ocean changes in the area, including the potential for acidification. The aim of this preliminary study was to assess the variability of the carbonate system in the southern coastal ocean of Cameroon at Kribi, and the effect of local variation of physicochemical and biological variables on keys parameters of this system (TA and pH). Our hypothesis was that the local variation of physicochemical variables could exert an influence on pH and TA. The study constituted the initial phase of an observational programme and vulnerability assessment of local marine ecosystems to ocean change and ocean acidification in an area that is insufficiently documented.

2. Methods

2.1. Study Area and Description of the Sampling Stations

The study was conducted in the coastal ocean of the southern Atlantic coast of Cameroon at Kribi and its surrounding areas. Kribi is a coastal city situated between 2°33'N and 2°57'N, and 9°18'E and 9°54'E. The climate of the southern coast of Cameroon is an equatorial Guinean type influenced by south-west monsoon from the Atlantic Ocean, characterized by high and constant temperature. The region exhibits a four-season climate: 2 rainy seasons, the long rainy season (LRS) from September to November, the short rainy season from and April to June; and 2 dry seasons, the long dry season (LDS), from December to March, and the short dry season from July to August [24] [25]. The average annual temperature is around 25.7°C and precipitation is about 2957 mm per year [26]. The tidal cycle in the area is semidiurnal with moderate constituents, ranging between 0.5 m and 0.85 m [27].

Three sampling stations, each situated at about 3 km from the shore, were selected for this study according to anthropogenic activities in its proximity and importance for small pelagic fishing (Figure 1). The Bp ($3^{\circ}06'5.22''\text{N}$, $9^{\circ}55'50.66''\text{E}$) sampling station was situated in the continuum of the ocean to the locality called Bipaga, around the marine gas pipeline carrying natural gas from the offshore to the liquefaction plant located on the coastline within 5 km. It has been established that the process of gas liquefaction results in the emission of CO_2 and sulphur dioxide (SO_2) [28]. Furthermore, there is a possibility that this could contribute to the acidification of near-surface seawater. The station was also in close proximity to an artisanal fishermen camp and fish market on the coastline, and watered by several small rivers that carry litter from the coastal forest to the ocean. The Kb ($2^{\circ}57'4.82''\text{N}$, $9^{\circ}52'40.08''\text{E}$) sampling station was located in the vicinity of the mouth of the Kienke river, an important river that traverses the urban zone of Kribi city and the surrounding agro-industrial area. The river carries organic matter and pollutants from land to the ocean. The Eb ($2^{\circ}48'25.20''\text{N}$, $9^{\circ}51'44.96''\text{E}$) sampling station was located off the coast of the village Eboundja. This village is situated less than 10 km from the Kribi deep-sea port and an oil exploitation platform, and is known to be a sea turtles feeding area [29]. The distance between the Bp station and the Kb station is approximately 20 km and the distance between the Kb station and the Eb station is also approximately 20 km. The Bp station is located in the North of Kb and Eb in the South.

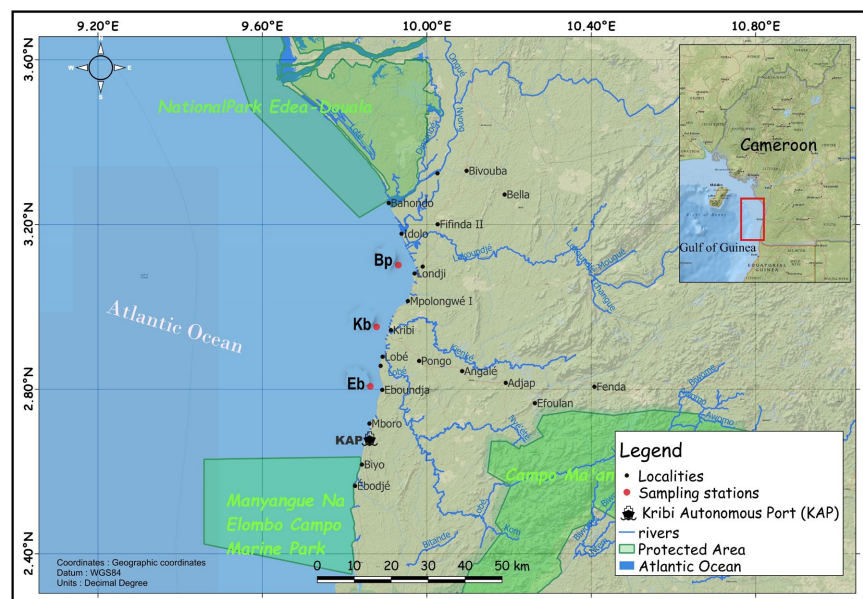


Figure 1. Study area and location of sampling stations (Modified from [30]).

2.2. Sampling

A sampling programme was conducted at each station from September 2021 to August 2022, during the months of September, November, December, March, April, June, July and August, thereby encompassing all the seasons type encoun-

tered in the study area.

Seawater samples for total alkalinity (TA) analysis were collected from the surface at each sampling station in duplicate per campaign using a 500 ml double-sealed polyethylene bottle and preserved for biological activity with 100 µl of saturated mercuric chloride solution ($HgCl_2$) as recommended by [31].

Seawater samples (500 ml each) for nutrients (nitrate, nitrite, nitrogen ammonia and phosphate) and chlorophyll-a analysis were collected at the same time and same frequency at each sampling station and preserved in a refrigerated container prior to laboratory analysis within the following 48 hours.

2.3. *In Situ* Measurement of pH, Salinity, Temperature, Dissolved Oxygen, Electrical Conductivity and Total Dissolved Solids (TDS)

Physicochemical parameters including pH, salinity, temperature, dissolved oxygen (D.O), electrical conductivity (E.C) and total dissolved solids (TDS) of surface seawater were measured *in situ* at each sampling point using a well calibrated water quality multimeter probe (Hanna Instrument, HI 9829). Calibration was carried out once for each sampling campaign, using the different buffer solutions provided and the recommended method of the manufacturer. The probes measure pH with ± 0.02 accuracy, ± 0.01 PSU for salinity and $\pm 0.15^\circ C$ for temperature. Each measurement was made three times for data quality control.

2.4. Laboratory Analysis of Chlorophyll-a and Nutrients

Chlorophyll-a (Chl-a) was extracted in the laboratory using acetone at 90% in the darkness after filtration of 200 ml of seawater sample, then optical density was read using a HACH DR/3900 spectrophotometer at 630 nm, 645 nm and 663 nm wave length. Chlorophyll-a concentration was calculated in mg/L following the Equation (1).

$$\text{Chl.a (mg.l}^{-1}\text{)} = \frac{[(11.64 \times \text{O.D} \times 663) - (2.16 \times \text{O.D} \times 645) - (0.10 \times \text{O.D} \times 630)] \times v}{V \times l} \quad (1)$$

where: O.D = optical density; v = volume of the acetonic extract (ml);
V = volume of filtered sample (ml); l = optical length

In the laboratory, nitrate was determined using HACH method N°8171 with detection level between 0.1 mg/L NO_3^- and 10 mg/l NO_3^- . Nitrite concentration was measured using HACH method N°8507, with detection level up to 0.30 mg/l. Ammonia was evaluated using the ammonia salicylate method, HACH method N°8155. Orthophosphate concentrations were determined using the HACH method N°8048, the ascorbic acid method. The detection level was between 0.02 mg/l PO_4^{3-} , and 2.50 mg/l PO_4^{3-} . These parameters were measured on a HACH DR/3900 spectrophotometer.

2.5. Laboratory Analysis of Total Alkalinity (TA)

TA was measured in the laboratory by titration of 50 ml of the seawater sample

with 0.1 N hydrochloric acid (HCl) using methyl orange 0.1% w/v solution as dye [32]. The volume of acid necessary to induce change of the solution colour was recorded and used to calculate the corresponding TA. The analysis was repeated twice for each sample to reduce manipulation error.

All laboratory analyses were made at the laboratory of water analysis and at the Fisheries Research Laboratory of the Cameroon Agricultural Research Institute for Development.

2.6. Carbonate System Parameters Determination

To characterise the carbonate system, two of the four commonly measured parameters (TA, DIC, pH and carbon dioxide partial pressure ($p\text{CO}_2$)) must be considered and measured simultaneously with temperature and salinity [33] [34]. In this study, we used total alkalinity (TA), pH, temperature and salinity, as recommended by the Integrated Carbon Observation System [35] [36], to characterize the carbonate system, using the $\text{CO}_2\text{SYS_xls}$ program [37]. Carbonate speciation calculations were done according to [38] for K_1 and K_2 dissociation constants, [39] for bisulphate (KHSO_4) dissociation constants and [40] for borate concentration.

2.7. Statistical Analysis

All statistical analyses were performed using RStudio, version 4.4.0 [41]. The normal distribution of measured and calculated carbonate system parameters as well as the other environmental variables was checked using the Shapiro-Wilk test. Data collected were presented per month in each sampling station, and were also grouped according to the seasons of the study area to analyse the seasonal variability of considered variables. Then, to compare mean variation of parameters between seasons, sampling months, as well as sampling stations, data which did not follow the normal distribution were analysed using the Kruskal-Wallis test followed by a pairwise Dunn's test when a significant difference resulted, and the variables that satisfied the normality assumption were analysed using the ANOVA test, followed by a Tukey's HSD (honestly significant difference) pairwise multiple comparison test in case of significant difference. Dunn's test was performed with Bonferroni correction for p-values. All statistical tests were performed at a 5% significance level. Pearson correlation analysis was performed to assess relationships among environmental variables and carbonate system parameters. We then used linear regression to show how strong relationship between correlated variable was and the confidence limit of this relation, mostly between hydrological variables having a strong correlation with TA and pH.

3. Results

3.1. Physicochemical Characteristics of Seawater of the Study Area

During the study period, the variation of physicochemical parameters was a function of sampling stations and seasons. **Table 1** shows the mean values and standard deviation of each parameter at each sampling station and season. The sea sur-

face water remained warm throughout the study period, with a mean value of $28.57^{\circ}\text{C} \pm 0.37^{\circ}\text{C}$. This temperature varied very little between sampling stations, but showed the highest mean value during the long dry season (LDS) of $30.4^{\circ}\text{C} \pm 0.66^{\circ}\text{C}$, and the lowest mean value during the short dry season (SDS), $26.0^{\circ}\text{C} \pm 0.76^{\circ}\text{C}$. Salinity varied with rainfall during the study period with a mean value of 18.28 ± 1.24 PSU. The lowest mean value was observed during the long rainy season (LRS) (10.8 ± 0.96 PSU), and the highest during the short rainy season (SRS), (24.3 ± 0.55 PSU).

Table 1. Mean values of physicochemicals parameters at each season and station LRS = long rainy season; LDS = long dry season; SRS = short rainy season; SDS = short dry season.

Parameters	Spatial mean values			Seasonal mean values			
	Kb	Bp	Eb	LRS	LDS	SRS	SDS
Salinity (PSU)	18.1 ± 6.35	17.5 ± 6.27	19.3 ± 6.4	10.8 ± 0.96	18.1 ± 7.28	24.3 ± 0.55	19.8 ± 2.10
Temp. ($^{\circ}\text{C}$)	28.3 ± 2.12	29.1 ± 1.78	28.3 ± 1.78	28.8 ± 0.87	30.4 ± 0.66	29.0 ± 1.2	26.0 ± 0.76
D.O (mg/l)	4.74 ± 3.0	5.11 ± 3.67	5.63 ± 3.73	2.25 ± 0.91	4.50 ± 3.9	5.11 ± 2.91	8.78 ± 0.79
E.C (mS/cm)	29.4 ± 9.66	28.9 ± 9.78	31.7 ± 10.1	18.4 ± 1.50	29.2 ± 10.8	39.6 ± 1.43	32.7 ± 3.63
TDS (g/l)	15.4 ± 5.21	15.0 ± 5.23	16.7 ± 5.89	9.19 ± 0.76	14.6 ± 5.39	20.2 ± 1.14	18.8 ± 2.83
Nitrate (mg/l)	2.34 ± 1.09	2.08 ± 2.23	1.98 ± 0.82	3.15 ± 2.15	1.39 ± 0.54	1.42 ± 1.11	2.55 ± 0.86
Phosphate(mg/l)	1.63 ± 1.50	0.50 ± 0.75	1.66 ± 2.77	2.12 ± 3.19	1.62 ± 1.42	1.23 ± 1.06	0.09 ± 0.15
Chl.a (mg/l)	0.12 ± 0.1	0.23 ± 0.16	0.134 ± 0.12	0.053 ± 0.04	0.097 ± 0.15	0.2 ± 0.12	0.3 ± 0.061
Nitrite (mg/l)	0.02 ± 0.015	0.025 ± 0.02	0.02 ± 0.009	0.012 ± 0.01	0.026 ± 0.03	0.012 ± 0.01	0.02 ± 0.007
Ammonia (mg/l)	1.07 ± 0.76	0.78 ± 0.97	0.93 ± 1.05	1.38 ± 1.19	1.33 ± 1.09	0.54 ± 0.41	0.46 ± 0.37

Temp = temperature; D.O = dissolved oxygen; E.C = electrical conductivity; TDS = total dissolved solids; Chl.a = chlorophyll-a.

The mean value of dissolved oxygen was 5.16 ± 0.68 mg/l, with the lowest mean value observed during LRS (2.25 ± 0.91 mg/l) and the highest during SDS (8.78 ± 0.79 mg/l). Dissolved oxygen varied slightly between sampling sites with the Kb site presenting the lowest mean value (4.74 ± 3.0 mg/l) and the Eb site presenting the highest mean value (5.63 ± 3.73 mg/l). Nitrate showed a mean concentration of 2.13 ± 1.45 mg/l, and phosphate 1.27 ± 1.87 mg/l. At the seasonal level, nitrate showed the lowest mean value during the LDS (1.39 ± 0.54 mg/l), and the highest during the LRS (3.15 ± 2.15 mg/l). Phosphate showed the highest mean value during the LRS (2.12 ± 3.19 mg/l), and the lowest during the SDS (0.09 ± 0.15 mg/l). At the sampling site level, the lowest concentration of nitrate was found in the Eb site (1.98 ± 0.82 mg/l) and the highest in the Kb site (2.34 ± 1.09 mg/l). Phosphate concentration was lowest in the Bp site (0.5 ± 0.75 mg/l) and the highest in the Eb site (1.66 ± 2.77 mg/l). Based on all the data collected, chlorophyll-a (Chl-a) concentration presented a mean value of 0.16 ± 0.14 mg/l during the study period. For each season, Chl-a presented the lowest concentration during the LRS (0.053 ± 0.04 mg/l) and the highest during SDS (0.3 ± 0.06 mg/l). At sampling site level,

the lowest concentration was found in Kb (0.12 ± 0.1 mg/l) and the highest in Bp (0.23 ± 0.16 mg/l). Nitrite concentration shows the lowest mean value during the LRS (0.012 ± 0.01 mg/l), and the highest during the LDS (0.0267 ± 0.0294 mg/l). At the sampling point level, nitrite presented the lowest mean value at Eb (0.0162 ± 0.009 mg/l) and the highest mean value at Bp (0.0251 ± 0.02 mg/l). Ammonia concentration was lowest at the Bp sampling site (0.786 ± 0.97 mg/l) and highest at Kb (1.07 ± 0.76 mg/l). At seasonal scale, the lowest concentration was observed during the SDS (0.465 ± 0.37 mg/l), and the highest concentration during the LRS (1.38 ± 1.19 mg/l).

The Shapiro-Wilk test for normality was applied to all physicochemical parameters, and the results demonstrated that only temperature (p-value = 0.11) followed a normal distribution ($\alpha = 0.05$). The Kruskal-Wallis test applied to parameters that did not satisfy the normality assumption (salinity, D.O, TDS, conductivity, nitrate, phosphate, nitrite, ammonia and chlorophyll-a) showed that these variables were not significantly different between sampling sites (p-value > 0.05) at 5% significance level. While, salinity, dissolved oxygen, TDS, conductivity, nitrate and chlorophyll-a were significantly different between seasons (p-value < 0.05) at 5% significance level. Dunn's test applied to these parameters showed that, salinity was significantly different between LRS and SRS (adjusted p-value = 0.0016) and dissolved oxygen was significantly different between LRS and SDS (adjusted p-value = 0.009). While significant difference was observed between LRS and SDS for chlorophyll-a (adjusted p-value = 0.02), LRS and SRS for TDS (adjusted p-value = 0.003) and conductivity (adjusted p-value = 0.0006). No significant difference was observed for nitrate (p-value > 0.05) between seasons.

The result of the ANOVA test on temperature indicated that this parameter was not statistically significant different between the sampling stations (p-value > 0.05). However, a significant difference was observed between the LRS and LDS, SDS and LDS, SDS and LRS, SRS and SDS (p-value < 0.05), as determined by the Tukey HSD test.

3.2. Spatio Temporal Variation of Carbonate System Parameters in the Southern Coast of Cameroon

The carbonate system parameters showed a large variability during the study period at each sampling station. The variation of TA, bicarbonate ions, carbon dioxide and carbonate ions are presented in **Figure 2**. At the spatial scale, the lowest mean value of TA (2225 ± 210 $\mu\text{mol/kg}$) was observed at the Bp sampling station, and the highest mean value (2448 ± 219 $\mu\text{mol/kg}$) at the Eb station. September and December were the months with the lowest TA mean value observed (2070 ± 52.7 $\mu\text{mol/kg}$ and 2069 ± 52.2 $\mu\text{mol/kg}$ respectively), April and June the months with the highest TA mean values (2530 ± 58 $\mu\text{mol/kg}$ and 2531 ± 115 $\mu\text{mol/kg}$ respectively). At the level of each sampling station, TA varied at the Bp station between 2009 $\mu\text{mol/kg}$ and 2597 $\mu\text{mol/kg}$, with a mean value of 2225 ± 210 $\mu\text{mol/kg}$. The lowest value was observed in December (2008.8 $\mu\text{mol/kg}$) and

the highest value in April (2597.2 $\mu\text{mol/kg}$). At the Kb station, the mean value of TA observed was $2325 \pm 251 \mu\text{mol/kg}$. The lowest value was $2009 \mu\text{mol/kg}$ observed during the months of September and November, and the highest value was $2597 \mu\text{mol/kg}$ obtained during the months of June and August. At the Eb station, TA varied between $2100 \mu\text{mol/kg}$ (in September and December) and $2597 \mu\text{mol/kg}$ (in June, July and August), with a mean value of $2448 \pm 219 \mu\text{mol/kg}$.

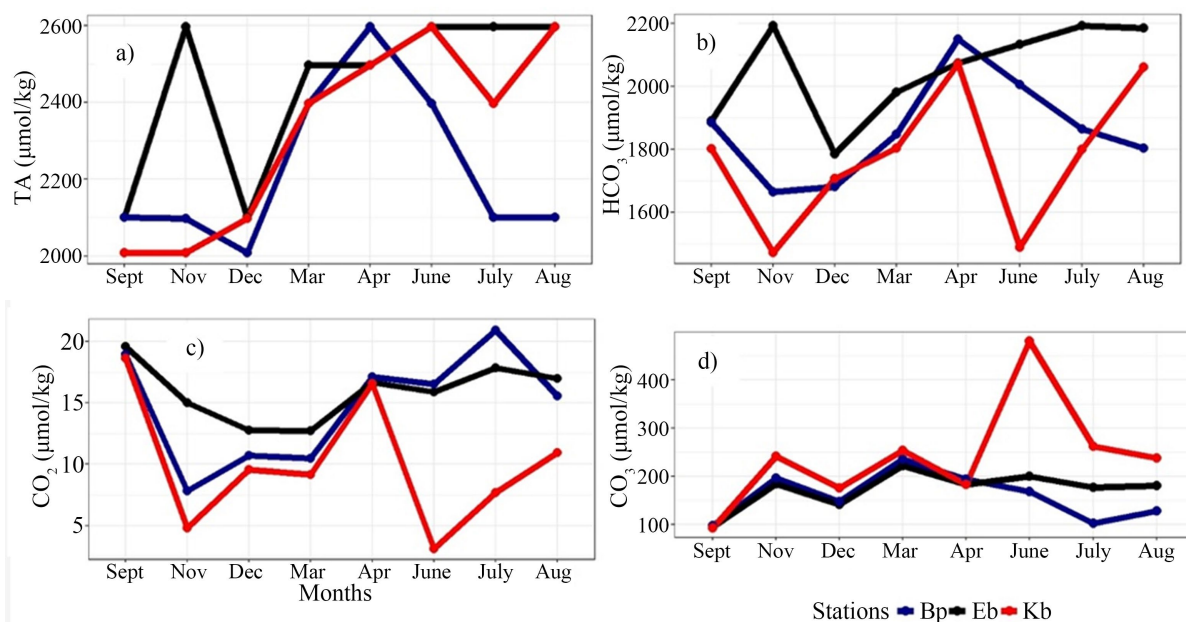


Figure 2. Monthly variation of (a) Total alkalinity; (b) Bicarbonate ions HCO_3^- ; (c) Carbon dioxide CO_2 and (d) Carbonate ions CO_3^{2-} in the southern coast of Cameroon.

The bicarbonate ions (HCO_3^-) showed a large variability during this study at all the sampling stations. At the sampling stations level, the lowest mean value ($1776 \pm 224 \mu\text{mol/kg}$) was obtained at the Kb station, and the highest mean value ($2054 \pm 155 \mu\text{mol/kg}$) at the Eb station. December was the month with the lowest mean value ($1724 \pm 53.6 \mu\text{mol/kg}$), and April the month with the highest mean value ($2098 \pm 44.3 \mu\text{mol/kg}$). At each sampling station, HCO_3^- presented at the Bp station, a mean value of $1863 \pm 160 \mu\text{mol/kg}$, with the lowest value ($1664 \mu\text{mol/kg}$) obtained during the month of November, and the highest value ($2150 \mu\text{mol/kg}$) during the month of April. At the Kb station, the mean value obtained was $1776 \pm 224 \mu\text{mol/kg}$. The minimum value ($1472 \mu\text{mol/kg}$) was observed during the month of November, and the maximum value ($2072 \mu\text{mol/kg}$) was obtained during the month of April.

The lowest mean value of Carbonate ions (CO_3^{2-}) was observed at the Bp sampling station ($159 \pm 48.7 \mu\text{mol/kg}$), and the highest at the Kb sampling station ($241 \pm 112 \mu\text{mol/kg}$). September was the month where lowest mean value ($95.4 \pm 2.17 \mu\text{mol/kg}$) was observed, and June the month where the highest mean value (283.3

$\pm 171 \mu\text{mol/kg}$) was collected. At the level of each station, CO_3^{2-} presented a mean value of $159 \pm 48,7 \mu\text{mol/kg}$ at the Bp station, $173.12 \pm 38.7 \mu\text{mol/kg}$ at Eb station, and a mean value of $241.22 \pm 112 \mu\text{mol/kg}$ at the Kb station. At the Bp sampling station, the lowest value ($97.6 \mu\text{mol/kg}$) was observed in September, and the highest ($235.73 \mu\text{mol/kg}$) in March. At Eb, the lowest value ($95.32 \mu\text{mol/kg}$) was obtained in the month of September, and the highest value ($222.02 \mu\text{mol/kg}$) obtained in the month of March. At the Kb sampling station, the minimum value ($93.3 \mu\text{mol/kg}$) was recorded in September, and the maximum value ($480.14 \mu\text{mol/kg}$) recorded in June.

The lowest mean value of Carbon dioxide (CO_2) during the study period was observed at the Kb station ($10.1 \pm 5.33 \mu\text{mol/kg}$) and the highest at the Eb station ($15.9 \pm 2.39 \mu\text{mol/kg}$). The month of November presented lowest mean value of CO_2 ($9.2 \pm 5.23 \mu\text{mol/kg}$), and the month of September the highest mean value ($19.04 \pm 0.5 \mu\text{mol/kg}$). At each station, Carbon dioxide (CO_2) varied with a mean value of $14.8 \pm 4.6 \mu\text{mol/kg}$ at the Bp sampling station, $15.9 \pm 2.39 \mu\text{mol/kg}$ at Eb, and $10.1 \pm 5.33 \mu\text{mol/kg}$ at Kb. At Bp the lowest value ($7.81 \mu\text{mol/kg}$) was obtained in November, and the highest ($20.9 \mu\text{mol/Kg}$) obtained in July. At the Eb station, the minimum value ($12.7 \mu\text{mol/kg}$) was observed in March, and the maximum value ($19.6 \mu\text{mol/kg}$) observed in November. At the Kb station, the lowest value observed was $3.12 \mu\text{mol/kg}$ during the month of June, and the highest value ($18.6 \mu\text{mol/kg}$) observed during the month of November.

Figure 3 illustrate the variation of pH, partial pressure of carbon dioxide (pCO_2), aragonite and calcite saturation state during the study period in the southern Atlantic coast of Cameroon.

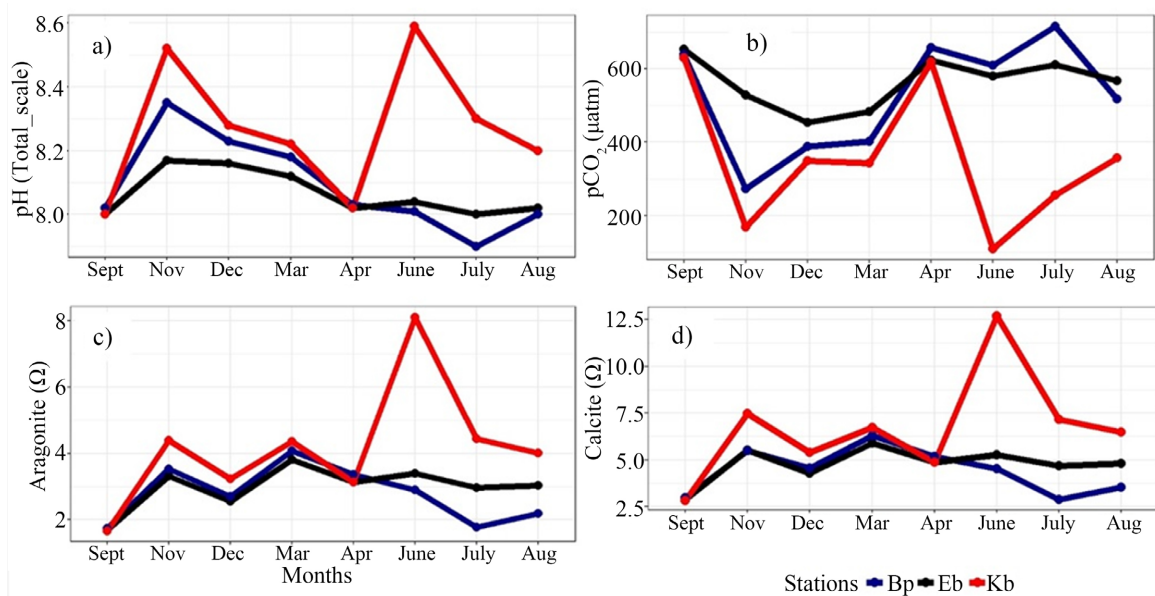


Figure 3. Monthly variation of pH (a), pCO_2 (b), aragonite (c) and calcite (d) saturation state in the southern coast of Cameroon.

At the spatial scale, minimal mean value of pH was obtained at the Eb sampling station (8.07 ± 0.07), and the maximum mean value at the Kb station (8.27 ± 0.2). September was the month where the lowest pH mean value was observed (8.01 ± 0.01), and November the month with the highest mean value (8.35 ± 0.17). At the level of each sampling station, pH variation presented a mean value of 8.09 ± 0.15 at the Bp station, 8.07 ± 0.07 at Eb and a mean value of 8.27 ± 0.21 at Kb. The lowest value observed at Bp was 7.9 in July, and highest 8.35 in November (**Figure 3(a)**). At Eb, the minimum value recorded was 8.00 during the month of September, and the maximum value 8.17 was recorded during the month of November. At the Kb station, the lowest value of pH (8.0) was obtained in September, and the highest (8.59) obtained in June.

The $p\text{CO}_2$ varied at the spatial scale in the study area with the minimal mean value ($354 \pm 189 \mu\text{atm}$) obtained at the Kb sampling station, and the maximal mean value ($562 \pm 7 \mu\text{atm}$) obtained at the Eb sampling station. At the time scale, September was the month with the highest $p\text{CO}_2$ mean value ($640.15 \pm 11.3 \mu\text{atm}$), and November the month with the lowest $p\text{CO}_2$ mean value ($323.5 \pm 185.2 \mu\text{atm}$). When considering the variability inside each station, the mean value obtained at the Bp sampling station was $525.04 \pm 156 \mu\text{atm}$, $562 \pm 7 \mu\text{atm}$ at the Eb station, and $354 \pm 189 \mu\text{atm}$ at the Kb station. The lowest value obtained at the Bp station was $273.22 \mu\text{atm}$ in November and the highest $715.01 \mu\text{atm}$ in July (**Figure 3(b)**). At the Eb station the minimum value of $p\text{CO}_2$ ($453 \mu\text{atm}$) was observed during the month of December, and the maximum ($652 \mu\text{atm}$) during the month of September. At the Kb sampling station, the lowest value was $110 \mu\text{atm}$ during the month of June, and the highest value was $630 \mu\text{atm}$ during the month of September.

For aragonite saturation, the lowest mean value ($1.7 \pm 0.04 \Omega$) was observed during the month of September and the highest ($4.8 \pm 2.87 \Omega$) during the month of June. The means values obtained in each sampling station were $2.78 \pm 0.84 \Omega$ at Bp, $2.9 \pm 0.63 \Omega$ at Eb and $4.17 \pm 1.85 \Omega$ at Kb. The lowest aragonite saturation state value (1.74Ω) at Bp station was obtained in September and the highest value (4.08Ω) in March. At Eb, the minimum value of aragonite (1.69Ω) was observed in September and the maximum value (3.82Ω) in March. At the Kb station, the lowest aragonite value (1.66Ω) was obtained during the month of September, and the highest (8.1Ω) during the month of June.

Calcite saturation followed the same variation as aragonite in each sampling station. The means values observed during the study period were $4.43 \pm 1.23 \Omega$ at Bp, $4.78 \pm 0.9 \Omega$ at Eb, and $6.7 \pm 2.84 \Omega$ at Kb sampling station.

Shapiro-Wilk normality test applied to the measured and calculated carbonate system parameters showed that, HCO_3^- (p-value = 0.071), CO_2 (p-value = 0.067) and $p\text{CO}_2$ (p-value = 0.104) follows a normal distribution ($\alpha = 0.05$).

To understand whether or not variables were significantly different between the months of measurement, or between the sampling stations, the ANOVA test was applied to parameters with a normal distribution. The results revealed that, in one

hand, the means of CO_2 and pCO_2 were significantly different between sampling stations (p -value < 0.05), while HCO_3^- was not significantly different between sampling stations (p -value > 0.05). In the other hand, the above variables were not significantly different between sampling months. The Tukey HSD test applied on CO_2 and pCO_2 shows that, the difference was between Kb and Eb (p -value = 0.01 and p -value = 0.02 respectively) for both variables.

The Kruskal Wallis test applied to variables that do not follow the normal distribution (TA, pH, CO_3^{2-} , calcite, and aragonite) showed that all these parameters were not significantly different between sampling stations and sampling months (p -value > 0.05 at 5% significance level).

3.3. Seasonal Variation of Carbonate Systems

Carbonate system data collected was grouped according to the four seasons encountered in the southern coast of Cameroon. The boxplots of results showed a seasonal variation of TA, HCO_3^- , CO_2 and CO_3^{2-} as presented in **Figure 4**. During the LRS and the SRS, interquartile range of total alkalinity were less spread than in the other two seasons, showing an appreciable level of homogeneity of the alkalinity during these seasons. Lowest alkalinity was observed during the LRS with a mean value of $2152 \pm 222 \mu\text{mol/kg}$, and highest during the SRS with a mean value of $2530 \pm 81.6 \mu\text{mol.kg}$. Bicarbonate ions (HCO_3^-) also exhibited a seasonal variation. During the LRS and SDS, interquartile range were highest spread than in the other seasons. The lowest median ($1794 \mu\text{mol/kg}$) was observed during the LDS, with a range of $300 \mu\text{mol/kg}$, and the highest median ($2073 \mu\text{mol/kg}$) during the SRS with a range of $662 \mu\text{mol/kg}$. Carbonate ions (CO_3^{2-}) presented the highest median value ($199 \mu\text{mol/kg}$) during the LDS with a range of $112 \mu\text{mol/kg}$, and the lowest median value ($141 \mu\text{mol/kg}$) during the LRS with a range of $149 \mu\text{mol/kg}$. For carbon dioxide, we obtained the lowest median value ($10.6 \mu\text{mol/kg}$) during the LDS with a range of $3.64 \mu\text{mol/kg}$, and the highest value ($16.8 \mu\text{mol/kg}$) during the LRS with the highest range of $14.8 \mu\text{mol/kg}$.

Figure 5 show the seasonal variation of pH, pCO_2 , aragonite, and calcite saturation state in the southern coast of Cameroon. The pH showed a large range of variation during the LRS (range = 0.52) and the SRS (range = 0.58). Median variation showed the lowest value (8.01) during the SDS, and the highest value (8.2) during the LDS. The pCO_2 interquartile range were less spread during the LDS and the SRS. A large range of variation was observed during the SRS (range = $547 \mu\text{atm}$), LRS (range = $483 \mu\text{atm}$), and the SDS (range = $459 \mu\text{atm}$). The smallest median value ($395 \mu\text{atm}$) was obtained during the LDS, and the highest value ($613 \mu\text{atm}$) during the SRS. Aragonite and calcite followed approximately the same seasonal trend with a large spread of interquartile during the LRS and SDS than the other two seasons. Analysis of medians values showed the smallest value during the LRS for aragonite and calcite (2.53Ω and 4.24Ω respectively) and the highest during the LDS (3.52Ω and 5.65Ω respectively).

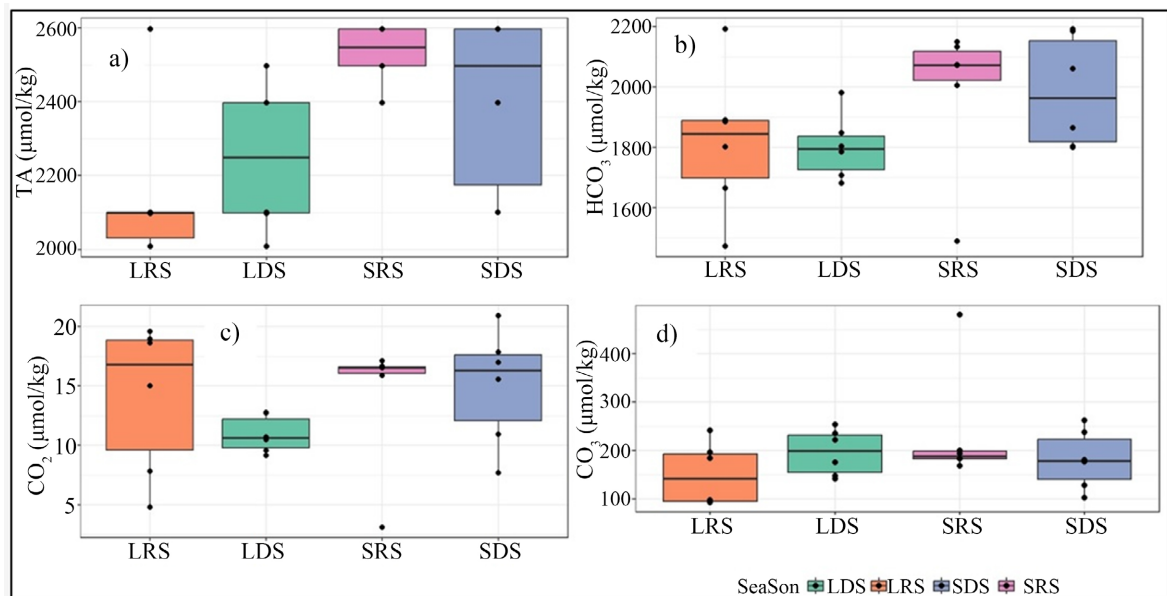


Figure 4. Seasonal variation of Total alkalinity (a), Bicarbonate ions (b), Carbon dioxide (c), and Carbonate ions (d) in the southern coast of Cameroon.

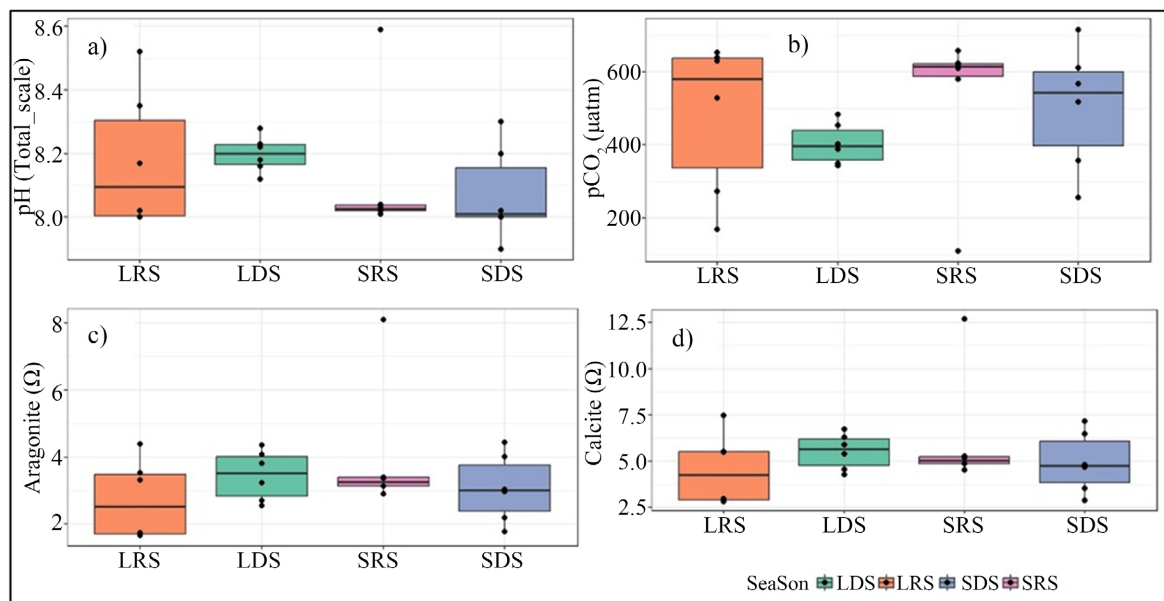


Figure 5. Seasonal variation of pH (a), pCO_2 (b), Aragonite (c) and Calcite (d) in the southern coast of Cameroon.

The ANOVA test revealed that, HCO_3^- was significantly different between SRS and LRS (adjusted p-value < 0.05). In the other hand, the Kruskal Wallis test showed that TA was also significantly different between LRS and SRS (adjusted p-value < 0.05). No significant difference was found between seasons for the others carbonate system parameters.

3.4. Correlation Analysis

The analysis of Pearson correlations showed that some physicochemical variables

were significantly correlated with carbonate system parameters. Salinity expressed a positive correlation with TA ($r = 0.8$). Positive correlations were also founded between salinity and both HCO_3^- and CO_3^{2-} ($r = 0.5$). Nitrogen ammonia (NH_4) presented a positive correlation with pH ($r = 0.6$), and a negative correlation with pCO_2 ($r = -0.5$) and CO_2 ($r = -0.5$). In addition, significant correlations were founded between carbonate system variables. TA was positively correlated to HCO_3^- ($r = 0.7$), CO_3^{2-} ($r = 0.5$) and aragonite ($r = 0.5$). pH was negatively correlated to pCO_2 ($r = -1$), HCO_3^- ($r = -0.7$), and positively correlated to aragonite and calcite ($r = 0.8$). pCO_2 was positively correlated to HCO_3^- ($r = 0.7$) and negatively correlated to CO_3^{2-} ($r = -0.7$), aragonite ($r = -0.8$) and calcite ($r = -0.8$).

The linear representation of the influence of salinity on TA variation (**Figure 6(a)**), and nitrogen ammonia influence on pH (**Figure 6(b)**) is presented below. As salinity increase, TA also increase. The linear equation showed that salinity have explained 63% of the TA variation in the southern coast of Cameroon during the study period. A significant relationship was founded between nitrogen ammonia and pH in the study area. This suggest that organic matter runoff in the coastal region could have an effect on the pH variation in the area. However, the linear equation showed that only 34% of the variation of the pH can be explained by nitrogen ammonia concentration in the area, suggesting the importance of other factors on pH variation.

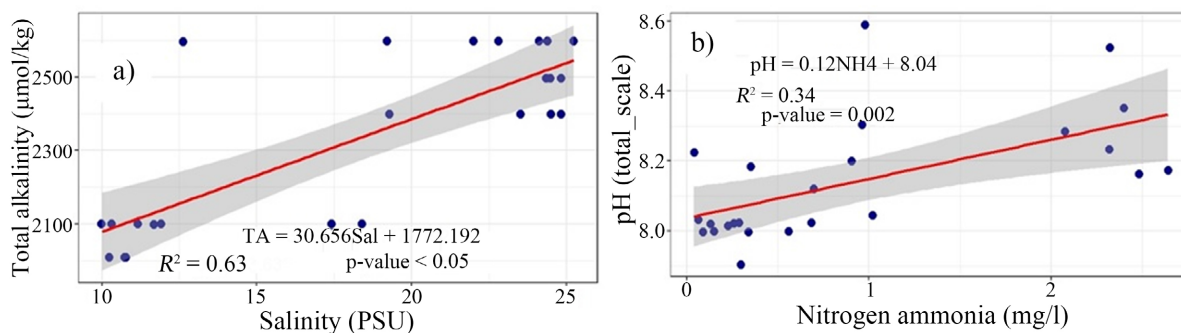


Figure 6. Linear regression of the influence of salinity on TA (a), and the influence of nitrogen ammonia on pH (b) at the southern coast of Cameroon. The grey area represents the 95% confidence limit.

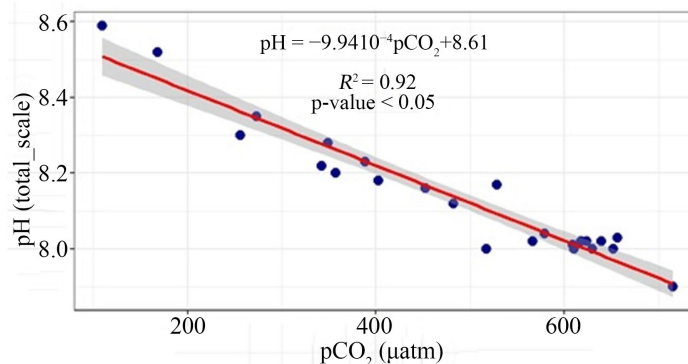


Figure 7. Linear regression of the influence of pCO_2 on the pH variation at the southern coast of Cameroon.

Among the other factors likely to influence pH variation, $p\text{CO}_2$, which expresses the quantity of carbon dioxide absorbed by the ocean, appears to be very important as presented in **Figure 7**. In fact, $p\text{CO}_2$ strongly and negatively influence the variation of pH explaining about 92% of its variance. Thus, dissolved carbon dioxide resulting from atmospheric absorption or other process appears to be the main factor influencing pH variation in the study area.

4. Discussion

4.1. Variability of the Carbonate System

The carbonate system showed spatial and temporal variability in the southern coastal ocean of Cameroon during the study period. At the temporal level, the fluctuation of carbonate system parameters had some specificities for each season. This seasonal variability was highlighted in marine ecosystems of other regions of the world [17] [42] [43]. During the LRS, the TA appears lower, with lowest values observed during the month of September, affected by the reduction in salinity due to the large amount of freshwater that is brought into the area by rivers and adjacent streams. As salinity decreased in this period, TA also decreased, affecting the buffering capacity of seawater in the area. During the other seasons, this relationship was conserved with TA increasing when salinity increases. Many studies in other world regions mentioned this variation of TA associated with changes in salinity even in coastal ocean [44]-[46]. The highest variability range of TA observed during the SDS, reveal the complexity of coastal ocean processes happened during this period, with alternating periods of light rain and great sunshine. This fluctuation affects the stability of salinity during this period driving the large range of TA. The pH also showed seasonal variability but the ANOVA analysis shows that this variability was not significative. The pH was correlated to the $p\text{CO}_2$ and the nitrogen ammonia during the study period. The lowest mean value of pH (8.01 ± 0.01) obtained during the month of September which correspond to the large rainy season (LRS), highlight the fact that, during this period, more acidic freshwater added to the area through river and streams, accompanied by organic matter, as the largest mean value of nitrogen ammonia was also obtained during the same period, contribute in decreasing the pH. Degradation of organic matter produce CO_2 and can contribute to the lowering of pH [13]. This presence of large amount of CO_2 in the seawater at this period was corroborated by the highest mean value of $p\text{CO}_2$ ($640 \pm 11.3 \mu\text{atm}$) obtained in September. Indeed, an increase in $p\text{CO}_2$ directly induced a lowering of pH in the area, since a strong negative correlation between both parameters was found in all seasons. It is therefore difficult to say at this stage of the study whether it is the input of organic matter ocean-atmosphere CO_2 exchange that is responsible for the drop in pH at this period. The saturation state of aragonite and calcite followed the same trend at both seasonal and months level and could be linked to the variability of pH, $p\text{CO}_2$ and TA. The large rainy season (LRS) appears to be the most critical period for the carbonate

system in the study area, recording the lowest mean TA value, the lowest concentration of carbonate ions, the lowest saturation states for calcite and aragonite, and elevated $p\text{CO}_2$. This period of about four months could be stressful for marine calcifier organisms, affecting their shell construction ability. Most of the carbonate system parameters were not significantly different between sampling stations except for $p\text{CO}_2$ which showed a significant difference between Eb and Kb sampling stations. However, we found the lowest pH value (7.9) at the Bp sampling site. This lowest pH value in this zone could be the effect of human activities, mostly activities of the gas liquefaction plant in the coastal area in addition to the CO_2 uptake. Sulphur dioxide rejected by the plant could contribute to acidify near seawater in the area. This could also be due to organic matter runoff from rivers and their subsequent microbial degradation. The Bp sampling station appears to be the most vulnerable of the three stations, as the lowest mean values of carbonate ions (CO_3^{2-}), aragonite and calcite were found there. The site could be considered as a potential hotspot of acidification in the study area, and should be monitored over a long term, so as to be able to anticipate early the irreversible effects of acidification on the local ecosystem.

4.2. Factors Driving the Carbonate System Variability

Correlations analysis between carbonate system and physicochemical parameters revealed the existence of some strong relationship among them. Salinity appears to be strongly correlated to TA, bicarbonate and carbonate ions. This strong relation between salinity and TA was mentioned in many others studies around the world [42] [44] [47] [48]. However, the linear regression analysis in this study showed that 63% of TA variation was explained by salinity. Contrary to the work of [19], who showed that only a quarter of TA variation in coastal region can be attributed to salinity in the Gulf of Guinea. The difference observed could be attributed to the hydrography of the coastal area and the importance of freshwater input in the ocean at the target area. pH and nitrogen ammonia were positively correlated showing an influence of organic matter to the variation of the pH in the area. Although linear regression showed that only 34% of the pH variation could be explained by nitrogen ammonia, it is known that the degradation of organic matter in coastal region could influence the variation of pH through the eutrophication process [49]. However, a strong negative correlation was found between pH and $p\text{CO}_2$ confirmed by the linear regression, showing that about 92% of pH variation could be attributed to CO_2 concentration in the seawater. This relationship between pH and $p\text{CO}_2$ in seawater is at the basis of ocean acidification process [3] [8] [10] [50] [51]. The other environmental variables contributed very little to the change in pH in the study area. At the end, salinity variation, organic matter input in the area, linked to local hydrography, and carbon dioxide concentration in seawater, appears as the main driving factors of the variation of carbonate system parameters in the study area.

4.3. Implications for Ocean Acidification Process and Research in the Study Area

Observations made during the study period indicate that the critical thresholds for ocean acidification have not yet been reached in the portion of southern coastal ocean of Cameroon studied, given the means values of pH (8.14 ± 0.17), aragonite ($\Omega > 1$) and calcite ($\Omega > 1$) saturation states obtained. The pH observed was in line with the global average pH currently observed in the ocean. The values of aragonite and calcite saturation are indicators of the fact that calcifiers organisms in the study area still retain their ability to form shells and exoskeletons. However, during the LRS when the lowest mean values of pH, aragonite and calcite saturation have been observed, particular care should be taken to avoid aggravating factors related to human activities that could increase the vulnerability of these organisms during this period. This means that adequate environmental management policies must be implemented upstream to prevent the discharge of acidic pollutants or organic matter into the ocean, which could increase carbon dioxide levels in the environment through microbial degradation, leading to a more pronounced lowering of the pH in the area. The potential impacts of ocean acidification on the Cameroon marine ecosystems have been analysed in a previous study [23]. As the study area represent an important fishery zone [52], in a long term, acidification process could in the long term affect the development of fish larval stages, particularly small pelagic, with serious socio-economic consequences for local communities. It is admitted that the biological impact of OA will occur at the molecular and cellular level, but the expression of this impact may lead to changes in relative species composition or to reduction in productivity at a given trophic level [53]. Local environmental conditions can therefore act as stimulating factors of the potential effect of OA in the area [54]. The large variability of carbonate system parameters observed during this study give an overview of changing conditions experienced by organisms living in this ecosystem. Futures laboratory studies of the potential impact of ocean acidification on local organisms will need to take into account the range of variation of carbonate system parameters in the area, in order to prepare realistic experiments that take local conditions into account. As one of the actual challenges of the scientific community is to assess the impacts of OA on marine diversity as they occur in real situations [55], monitoring and observations then provide a context and the understanding of environment to complement experimental studies.

5. Conclusion

The coastal ocean is a high variable system with complex interactions and processes. This study highlighted the high variability of carbonate system parameters in a portion of the southern coastal ocean of Cameroon, and presented the variation in salinity related to the hydrography and the seasonal rainfall, as a major driver of the variation of TA, while organic matter input and its degradation affect the variation of pH. Studying the variability of carbonate systems remains challenging in the context of a developing country with few observational infrastruc-

tures. To capture all the processes affecting the variability of carbonate systems, high frequency and long-term measurements on representatives sampling stations will be necessary. It will be important to distinguish processes linked to eutrophication that can influence the variation of pH in the area, to the potential effect of rising atmospheric carbon dioxide uptake. The use of Certified Reference Material (CRMs) in TA measurements in future monitoring campaigns will improve the data quality. The study was an opportunity and step toward to somewhat describe, analyse and understand the current variability of carbonate system and the chemical condition experiencing by organisms in the study area. We are very hopeful that the research team will soon receive the donation of GOA-ON kits in Box from The Ocean Foundation through the BIOTTA (Building Capacity in Ocean Acidification Monitoring in The Gulf of Guinea) project, which will enable us to improve the quality and quantity of measurements and go further in observing ocean acidification in Cameroon.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

- [1] Millero, F.J. (2000) The Carbonate System in Marine Environments. In: Gianguzza, A., Pelizzetti, E. and Sammartano, S., Eds., *Chemical Processes in Marine Environments*, Springer, 9-41. https://doi.org/10.1007/978-3-662-04207-6_2
- [2] Cai, W., Xu, Y., Feely, R.A., Wanninkhof, R., Jönsson, B., Alin, S.R., *et al.* (2020) Controls on Surface Water Carbonate Chemistry along North American Ocean Margins. *Nature Communications*, **11**, Article No. 2691. <https://doi.org/10.1038/s41467-020-16530-z>
- [3] IOC-UNESCO (2022) State of the Ocean Report, Pilot Edition. IOC-UNESCO, Report No. IOC Technical Series, 173.
- [4] Von Schuckmann, K., Moreira, L., Grégoire, M., Marcos, M., Staneva, J., Brasseur, P., *et al.* (2024) 8th Edition of the Copernicus Ocean State Report (OSR8). Copernicus GmbH. <https://doi.org/10.5194/sp-4-osr8>
- [5] Gattuso, J.P. and Hansson, L. (2011) Ocean Acidification. Oxford University Press. <https://doi.org/10.1093/oso/9780199591091.001.0001>
- [6] Stark, J.S., Roden, N.P., Johnstone, G.J., Milnes, M., Black, J.G., Whiteside, S., *et al.* (2018) Carbonate Chemistry of an *In-Situ* Free-Ocean CO₂ Enrichment Experiment (antFOCE) in Comparison to Short Term Variation in Antarctic Coastal Waters. *Scientific Reports*, **8**, Article No. 2816. <https://doi.org/10.1038/s41598-018-21029-1>
- [7] Aze, T., Barry, J., Bellerby, R. and Secretariat of the Convention on Biological Diversity (2014) An Updated Synthesis of the Impacts of Ocean Acidification on Marine

Biodiversity. CBD Technical Series No. 75.

- [8] Hurd, C.L., Lenton, A., Tilbrook, B. and Boyd, P.W. (2018) Current Understanding and Challenges for Oceans in a Higher-CO₂ World. *Nature Climate Change*, **8**, 686-694. <https://doi.org/10.1038/s41558-018-0211-0>
- [9] Leung, J.Y.S., Zhang, S. and Connell, S.D. (2022) Is Ocean Acidification Really a Threat to Marine Calcifiers? A Systematic Review and Meta-analysis of 980+ Studies Spanning Two Decades. *Small*, **18**, Article ID: 2107407. <https://doi.org/10.1002/smll.202107407>
- [10] Intergovernmental Panel on Climate Change (IPCC) (2019) The Ocean and Cryosphere in a Changing Climate: Special Report of the Intergovernmental Panel on Climate Change. Cambridge University Press. <https://doi.org/10.1017/9781009157964>
- [11] McGarry, K., Siedlecki, S.A., Salisbury, J. and Alin, S.R. (2021) Multiple Linear Regression Models for Reconstructing and Exploring Processes Controlling the Carbonate System of the Northeast US from Basic Hydrographic Data. *Journal of Geophysical Research: Oceans*, **126**, e2020JC016480. <https://doi.org/10.1029/2020jc016480>
- [12] McCutcheon, M.R., Yao, H., Staryk, C.J. and Hu, X. (2021) Temporal Variability and Driving Factors of the Carbonate System in the Aransas Ship Channel, TX, USA: A Time Series Study. *Biogeosciences*, **18**, 4571-4586. <https://doi.org/10.5194/bg-18-4571-2021>
- [13] Cai, W., Hu, X., Huang, W., Murrell, M.C., Lehrter, J.C., Lohrenz, S.E., *et al.* (2011) Acidification of Subsurface Coastal Waters Enhanced by Eutrophication. *Nature Geoscience*, **4**, 766-770. <https://doi.org/10.1038/ngeo1297>
- [14] Morrell, B. (2019) Coastal Ocean Acidification: Carbonate Chemistry and Ecosystem Effects. *Encyclopedia of Ocean Sciences*, **1**, 671-674. <https://doi.org/10.1016/b978-0-12-409548-9.11289-8>
- [15] Gear, J.S., Rynearson, T.A., Montalbano, A.L., Govenar, B. and Menden-Deuer, S. (2017) pCO₂ Effects on Species Composition and Growth of an Estuarine Phytoplankton Community. *Estuarine, Coastal and Shelf Science*, **190**, 40-49. <https://doi.org/10.1016/j.ecss.2017.03.016>
- [16] Pajusalu, L., Dupont, S., Lainela, S. and Martin, G. (2019) Ocean Acidification Research in Estonia: Challenges and Opportunities. *Proceedings of the Estonian Academy of Sciences*, **68**, 22-31. <https://doi.org/10.3176/proc.2019.1.05>
- [17] Enochs, I.C., Manzello, D.P., Jones, P.R., Stamates, S.J. and Carsey, T.P. (2019) Seasonal Carbonate Chemistry Dynamics on Southeast Florida Coral Reefs: Localized Acidification Hotspots from Navigational Inlets. *Frontiers in Marine Science*, **6**, Article 160. <https://doi.org/10.3389/fmars.2019.00160>
- [18] Lefèvre, N. (2009) Low CO₂ Concentrations in the Gulf of Guinea during the Upwelling Season in 2006. *Marine Chemistry*, **113**, 93-101. <https://doi.org/10.1016/j.marchem.2009.01.001>
- [19] Koffi, K.U., Konan, E.S., Hassoun, A.E.R. and Kouadio, Y. (2024) Relationship between the Carbonate System and Phytoplankton Community in the Gulf of Guinea-Africa. *Frontiers in Marine Science*, **11**, Article 1286338. <https://doi.org/10.3389/fmars.2024.1286338>
- [20] Koffi, K.U. (2014) Distribution des paramètres du carbone et du flux de CO₂ à l'interface air-mer dans l'Est de l'Atlantique tropical. Université Pierre et Marie Curie-Paris VI, Université de Cocody Abidjan. Université De Cocody Abidjan.
- [21] Kwame Kpaliba, R. and Bawa, M. (2022) Variability of Carbonate Chemistry of Sea-

- water of the Central Atlantic Coastline of Ghana. *Journal of Phase Change Material*, **2**, 12-23.
- [22] Tilbrook, B., Jewett, E.B., DeGrandpre, M.D., Hernandez-Ayon, J.M., Feely, R.A., Gledhill, D.K., *et al.* (2019) An Enhanced Ocean Acidification Observing Network: From People to Technology to Data Synthesis and Information Exchange. *Frontiers in Marine Science*, **6**, Article 337. <https://doi.org/10.3389/fmars.2019.00337>
- [23] Bilounga, U.J.F., Onana, F.M. and Efole E., T. (2022) Potential Impacts of Ocean Acidification in Cameroon Marine and Coastal Ecosystems (Central Africa). *Academia Letters*. <https://doi.org/10.20935/al1482>
- [24] Molua, E. (2006) Climatic Trends in Cameroon: Implications for Agricultural Management. *Climate Research*, **30**, 255-262. <https://doi.org/10.3354/cr030255>
- [25] Pouokam, G. and Lemnyu, W.B. (2012) Cameroon Climate Compatible Development: Cameroon Case Study. <https://doi.org/10.13140/RG.2.1.2202.0326>
- [26] climate-data.org (2019) Kribi Climate: Average Temperature, Weather by Month, Kribi Water Temperature.
- [27] Onguene, R., Pemha, E., Lyard, F., Du-Penhoat, Y., Nkoue, G., Duhaut, T., *et al.* (2015) Overview of Tide Characteristics in Cameroon Coastal Areas Using Recent Observations. *Open Journal of Marine Science*, **5**, 81-98. <https://doi.org/10.4236/ojms.2015.51008>
- [28] Yuan, X., Zhang, B., Liang, R., Wang, R. and Sun, Y. (2020) Environmental Impact of the Natural Gas Liquefaction Process: An Example from China. *Applied Sciences*, **10**, Article 1701. <https://doi.org/10.3390/app10051701>
- [29] Ayissi, I., Aksissou, M., Tiwari, M. and Fretey, J. (2014) Caractérisation des habitats benthiques et ponte des tortues marines autour du parc national de Campo-Ma'an (Cameroun). *International Journal of Biological and Chemical Sciences*, **7**, 1820-1828. <https://doi.org/10.4314/ijbcs.v7i5.3>
- [30] Esri National Geographic (2025) NatGeo_World_Map (MapServer).
- [31] Dickson, A.G., Sabine, C.L., Christian, J.R. and Barger, C.P. (2007) Guide to Best Practices for Ocean CO₂ Measurements. North Pacific Marine Science Organization.
- [32] Pimenta, A. and Grear, J. (2018) Guidelines for Measuring Changes in Seawater pH and Associated Carbonate Chemistry in Coastal Environments of the Eastern United States. EPA/600/R-17/483, 59.
- [33] Dickson, A. (2010) Standards for Ocean Measurements. *Oceanography*, **23**, 34-47. <https://doi.org/10.5670/oceanog.2010.22>
- [34] Fassbender, A.J., Sabine, C.L. and Feifel, K.M. (2016) Consideration of Coastal Carbonate Chemistry in Understanding Biological Calcification. *Geophysical Research Letters*, **43**, 4467-4476. <https://doi.org/10.1002/2016gl068860>
- [35] Dickson, A.G. (2010) Part 1: Seawater Carbonate Chemistry. Guide to Best Practices for Ocean Acidification Research and Data Reporting. Publications Office of the European Union, 36.
- [36] ICOS (Ocean Thematic Centre) (2018) Calculation Uncertainty of pCO₂ from Discrete Samples of TA, DIC, and pH.
- [37] Pierrot, D., Lewis, E. and Wallace, D.W.R. (2006) MS Excel Program Developed for CO₂ System Calculations. Carbon Dioxide Information Analysis Center (CDIAC) Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tennessee.
- [38] Millero, F.J., Graham, T.B., Huang, F., Bustos-Serrano, H. and Pierrot, D. (2006) Dissociation Constants of Carbonic Acid in Seawater as a Function of Salinity and Temperature. *Marine Chemistry*, **100**, 80-94.

- <https://doi.org/10.1016/j.marchem.2005.12.001>
- [39] Dickson, A.G. (1990) Standard Potential of the Reaction: $\text{AgCl(s)} + 12\text{H}_2\text{(g)} = \text{Ag(s)} + \text{HCl(aq)}$, and the Standard Acidity Constant of the Ion HSO_4^- in Synthetic Sea Water from 273.15 to 318.15 K. *The Journal of Chemical Thermodynamics*, **22**, 113-127. [https://doi.org/10.1016/0021-9614\(90\)90074-z](https://doi.org/10.1016/0021-9614(90)90074-z)
- [40] Uppström, L.R. (1974) The Boron/Chlorinity Ratio of Deep-Sea Water from the Pacific Ocean. *Deep Sea Research and Oceanographic Abstracts*, **21**, 161-162. [https://doi.org/10.1016/0011-7471\(74\)90074-6](https://doi.org/10.1016/0011-7471(74)90074-6)
- [41] R Core Team (2024) R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing.
- [42] McGrath, T., McGovern, E., Gregory, C. and Cave, R.R. (2019) Local Drivers of the Seasonal Carbonate Cycle across Four Contrasting Coastal Systems. *Regional Studies in Marine Science*, **30**, Article ID: 100733. <https://doi.org/10.1016/j.rsma.2019.100733>
- [43] Jones, E.M., Renner, A.H.H., Chierici, M., Wiedmann, I., Lødemel, H.H. and Biuw, M. (2020) Seasonal Dynamics of Carbonate Chemistry, Nutrients and CO_2 Uptake in a Sub-Arctic Fjord. *Elem Sci Anth*, **8**, Article 41. <https://doi.org/10.1525/elementa.438>
- [44] Baldry, K., Hardman-Mountford, N. and Greenwood, J. (2017) Estimating Total Alkalinity for Coastal Ocean Acidification Monitoring at Regional to Continental Scales in Australian Coastal Waters. *Biogeosciences Discussions*.
- [45] Jiang, Z., Tyrrell, T., Hydes, D.J., Dai, M. and Hartman, S.E. (2014) Variability of Alkalinity and the Alkalinity-Salinity Relationship in the Tropical and Subtropical Surface Ocean. *Global Biogeochemical Cycles*, **28**, 729-742. <https://doi.org/10.1002/2013gb004678>
- [46] Koziorowska-Makuch, K., Szymczycha, B., Thomas, H. and Kuliński, K. (2023) The Marine Carbonate System Variability in High Meltwater Season (Spitsbergen Fjords, Svalbard). *Progress in Oceanography*, **211**, Article ID: 102977. <https://doi.org/10.1016/j.pocean.2023.102977>
- [47] Fassbender, A.J., Alin, S.R., Feely, R.A., Sutton, A.J., Newton, J.A. and Byrne, R.H. (2016) Estimating Total Alkalinity in the Washington State Coastal Zone: Complexities and Surprising Utility for Ocean Acidification Research. *Estuaries and Coasts*, **40**, 404-418. <https://doi.org/10.1007/s12237-016-0168-z>
- [48] Millero, F.J., Lee, K. and Roche, M. (1998) Distribution of Alkalinity in the Surface Waters of the Major Oceans. *Marine Chemistry*, **60**, 111-130. [https://doi.org/10.1016/s0304-4203\(97\)00084-4](https://doi.org/10.1016/s0304-4203(97)00084-4)
- [49] Wallace, R.B., Baumann, H., Grear, J.S., Aller, R.C. and Gobler, C.J. (2014) Coastal Ocean Acidification: The Other Eutrophication Problem. *Estuarine, Coastal and Shelf Science*, **148**, 1-13. <https://doi.org/10.1016/j.ecss.2014.05.027>
- [50] Friedrich, T., Timmermann, A., Abe-Ouchi, A., Bates, N.R., Chikamoto, M.O., Church, M.J., *et al.* (2012) Detecting Regional Anthropogenic Trends in Ocean Acidification against Natural Variability. *Nature Climate Change*, **2**, 167-171. <https://doi.org/10.1038/nclimate1372>
- [51] Thor, P. and Dupont, S. (2017) Ocean Acidification. In: Salomon, M. and Markus, T., Eds., *Handbook on Marine Environment Protection*, Springer, 375-394. https://doi.org/10.1007/978-3-319-60156-4_19
- [52] Ebango Ngando, N., Regis Christian, M.N., Song, L.M., Achille, N.P., Li, C.H. AND Minette, T.E. (2021) Catch Statistics from Artisanal Marine Fishing: A Case of the

South Coast. *African Journal of Fisheries Sciences*, **9**, 1-13.

- [53] Le Quesne, W.J.F. and Pinnegar, J.K. (2011) The Potential Impacts of Ocean Acidification: Scaling from Physiology to Fisheries: Potential Acidification Impacts on Fisheries. *Fish and Fisheries*, **13**, 333-344. <https://doi.org/10.1111/j.1467-2979.2011.00423.x>
- [54] Mostofa, K.M.G., Liu, C., Zhai, W., Minella, M., Vione, D., Gao, K., *et al.* (2016) Reviews and Syntheses: Ocean Acidification and Its Potential Impacts on Marine Ecosystems. *Biogeosciences*, **13**, 1767-1786. <https://doi.org/10.5194/bg-13-1767-2016>
- [55] Widdicombe, S., Isensee, K., Artioli, Y., Gaitán-Espitia, J.D., Hauri, C., Newton, J.A., *et al.* (2023) Unifying Biological Field Observations to Detect and Compare Ocean Acidification Impacts across Marine Species and Ecosystems: What to Monitor and Why. *Ocean Science*, **19**, 101-119. <https://doi.org/10.5194/os-19-101-2023>