Original Research Article

Influence of Climatic and Oceanographic Parameters on CO2 Exchanges at the Air-Sea Interface in the Gulf of Guinea

ABSTRACT

Aims: Analyze the climatic and oceanographic parameters influencing oceanic CO_2.

Place and Duration of Study: Gulf of Guinea, 2010-2018

Methodology: Analysis of Monthly Satellite Data from the Gulf of Guinea on Sea Surface Temperature, Sea Surface Salinity, Sea Surface Chlorophyll, Sea Surface Partial Pressure of CO_2, Sea Surface Wind Speed at 10 meters, Dry Air Molar Fraction (xCO2), and Sea Level Pressure. Numerical Data Processing on a One-Degree Spatial Resolution Grid Using Python 3.11 through Bilinear Interpolation. The data are then averaged monthly, allowing for an assessment of the intra-monthly variability of oceanic parameters.

Results: Physical parameters (salinity, temperature, wind speed), hydrological parameters (chlorophyll-a and ocean surface partial pressure of CO_2) are characterized by strong seasonal and spatial variability, modulated by phenomena such as seasonal upwelling and thermal stratification, which directly influence CO_2 fluxes at the air-sea interface, with minor differences between coastal areas and offshore regions.

Conclusion: Climatic and oceanographic parameters act synergistically to modulate CO_2 exchanges between the ocean and the atmosphere. Integrating these parameters into climate models will improve the accuracy of global climate change predictions.

Key words *: Oceanographic parameters, Gulf of Guinea, Python,* CO_2*.*

1. INTRODUCTION

The Gulf of Guinea, located along the west coast of Africa, is a region of significant ecological and economic importance. This portion of the tropical Atlantic Ocean exhibits characteristics that influence climatic and oceanographic factors through complex interactions. Among these factors, air-sea interface interactions play a crucial role in the carbon cycle, particularly in the transfer of carbon dioxide (CO_2) between the atmosphere and the ocean [1]. Understanding these parameters is therefore essential for assessing the impact of climate change on carbon cycles and, consequently, on global climate [2]. These parameters include sea surface temperature (SST), sea surface salinity (SSS), sea surface chlorophyll-a (Chl-a), sea surface wind speed (U10), as well as sea surface partial pressure of CO_2 (pCO2sw). In the lower atmosphere, the dry air mole fraction of CO_2 (xCO_2) and sea level pressure (SLP) also influence CO_2 exchange behavior at the air-sea interface, impacting the processes of absorption and emission of this greenhouse gas. Studies by [3] and [4] highlight the importance of these parameters in modeling CO_2 fluxes at the air-sea interface. Sea surface temperature influences CO_2 solubility, while salinity affects seawater alkalinity and buffering capacity [5]. Chlorophyll-a, as an indicator of biological productivity, plays a key role in CO2 absorption through photosynthesis [6]. Wind speed is a determining factor for CO_2 transfer between the atmosphere and the ocean, as it influences turbulence at the air-sea interface [7]. In the lower atmosphere, the dry air mole fraction of CO_2 (xCO_2) and sea level pressure (SLP) are key variables modulating the partial pressure gradients necessary for CO_2 fluxes [8]. These atmospheric parameters, combined with oceanographic conditions, determine the net CO_2 exchanges between the ocean and the atmosphere. Studies have shown that the Gulf of Guinea may act as a source of CO2 to the atmosphere, despite high phytoplankton productivity, which could have implications for ecosystem management and food security in the region. Unfortunately, the in situ data available for this area are often sparse and discontinuous, making precise evaluation of CO2 fluxes challenging. Therefore, the use of geospatial data from remote sensing is essential to address these gaps, providing more comprehensive spatial and temporal coverageThe objective of this work is to analyze how each parameter influences CO_2 behavior at the air-sea interface in the Gulf of Guinea. This analysis aims to provide a detailed understanding of the interactions between climatic conditions and oceanic processes that modulate the carbon cycle in this region, thus allowing a better grasp of their climatic implications at the regional scale.

Study Area Presentation

The Gulf of Guinea is a maritime region located along the west coast of Africa (Figure 1). This vast body of water, covering an area of approximately 3146000 km², extends from the southwest of the African continent to the central part of West Africa. It is located on either side of the Equator, between longitudes 15°W and 10°E, and latitudes 3°S and 10°N.This region is influenced by seasonal upwellings that occur along the equator and its coasts.

The Gulf of Guinea holds major strategic and economic importance. It is rich in natural resources, particularly hydrocarbons (oil and natural gas), making this region a key hub for the energy industries. Additionally, it is renowned for its marine biodiversity and coastal ecosystems, which include mangroves, estuaries, and coral reefs.

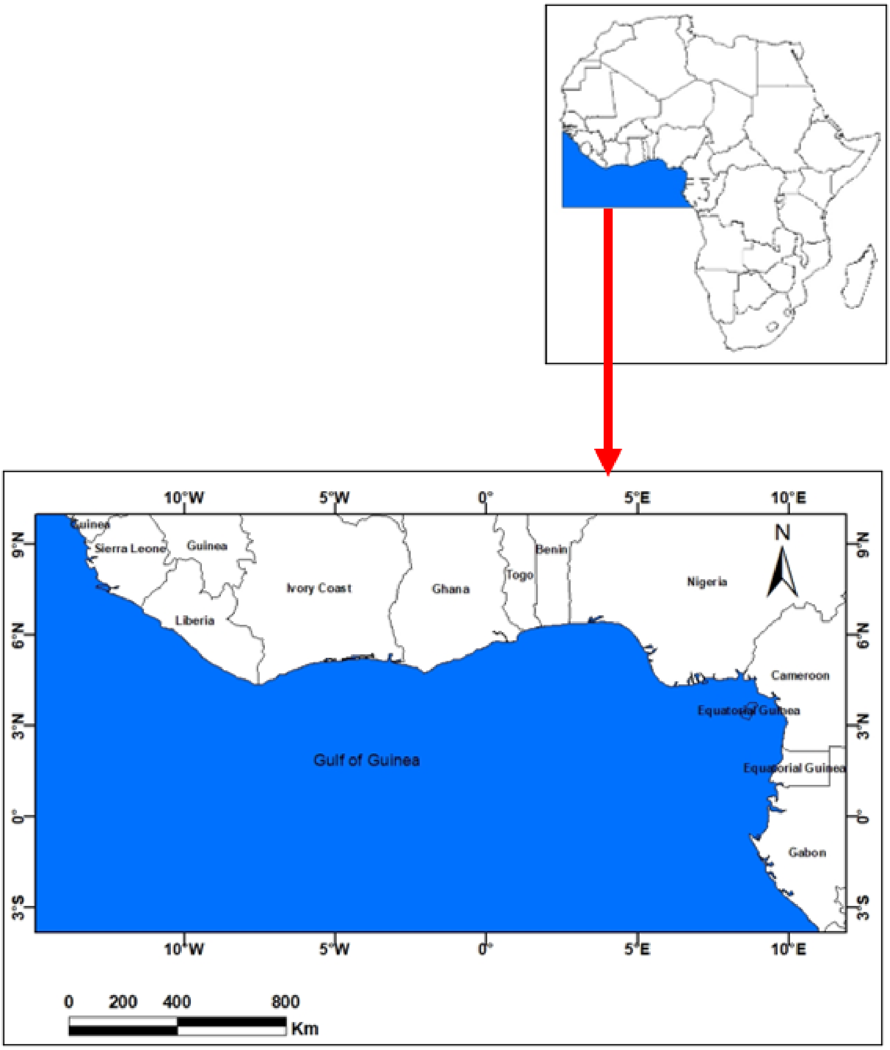

Fig.1. Geographical Location of the Gulf of Guinea

MATERIAL AND METHODS

2.1 Data collection

Various types of satellite data were used in this study, all sourced from different open-access repositories. These data include, on one hand, ocean surface parameters such as sea surface temperature, chlorophyll-a, sea surface salinity, and sea surface wind speed. On the other hand, atmospheric data from the lower atmosphere layer include the dry air mole fraction and air pressure. These datasets are essential for determining gas transfer velocity, solubility, as well as pCO_{2w} and pCO_{2a} values. The data have a spatial resolution of 0.25° x 0.25° in longitude and latitude and a temporal resolution of 6 hours, except for salinity and chlorophyll-a (4 and 8 days, respectively) and are provided in netCDF-4 format. The 2010-

2018 period was chosen due to data availability for salinity and oceanic partial pressure of CO_2. The data download sites are as follows:

- Sea surface temperature (https://www.ncei.noaa.gov/data/sea-surface-temperature-optimum-interpolation/v2.1/access/avhrr)
- Sea surface salinity (ftp://ftp.ifremer.fr/Ocean_products/GRIDDED/L3OS/RE06/MIR_CSQ3B_/${yr}/${mth}/*.tgz)
- Sea surface wind speed (www.remss.com/measurements/ccmp)
- Sea surface chlorophyll-a (http://www.oceancolour.org)
- Atmospheric partial pressure of CO_2 (https://www.esrl.noaa.gov/gmd/ccgg/mbl/).

2.2 Methods

Data processing was carried out using a custom script written in Python and executed on a Linux operating system. For each year, climate-ocean data were sorted, and records containing anomalies or missing values were removed, thereby ensuring data integrity. Once valid files were identified, they were interpolated onto a new spatial grid with a resolution of 1 degree, aligned with the target grid for analysis. This interpolation relied on resampling functions and tools available within relevant Python libraries. The data were then averaged on a monthly basis, facilitating an assessment of intra-monthly variability of oceanic parameters. The results were subsequently stored in a netCDF file for optimal preservation, with detailed documentation including authors' names, institution, data source, and spatial resolutions used.

3. RESULTS AND DISCUSSION

3.1 Spatio-temporal Variability of Sea Surface Temperature

From January to March, temperatures are relatively high, ranging between 28 and 30°C. From April to June, a slight drop in temperatures is observed, particularly along the coast, with values ranging from 27 to 28°C. From July to September, temperatures are lower, oscillating between 25 and 27°C, especially along the southern coast. However, from October to December, they gradually begin to rise, reaching the levels observed at the beginning of the year (28 to 30°C) (Figure 2A).

3.2 Spatio-temporal Variability of Sea Surface Salinity

Figure 2B shows salinity generally ranging from 34 to 37 psu (Practical Salinity Units) in the Gulf of Guinea. Coastal areas exhibit lower salinity, while offshore regions show higher salinity values. Specifically, from January to March, salinity is relatively low (between 34 and 35 psu), especially near the northern part of the equator. From April to June, salinity slightly increases, particularly south of the equator, reaching up to 36 psu. Between July and September, salinity continues to rise, reaching 36.3 psu, especially in August and September. From October to December, salinity decreases again, returning to lower values.

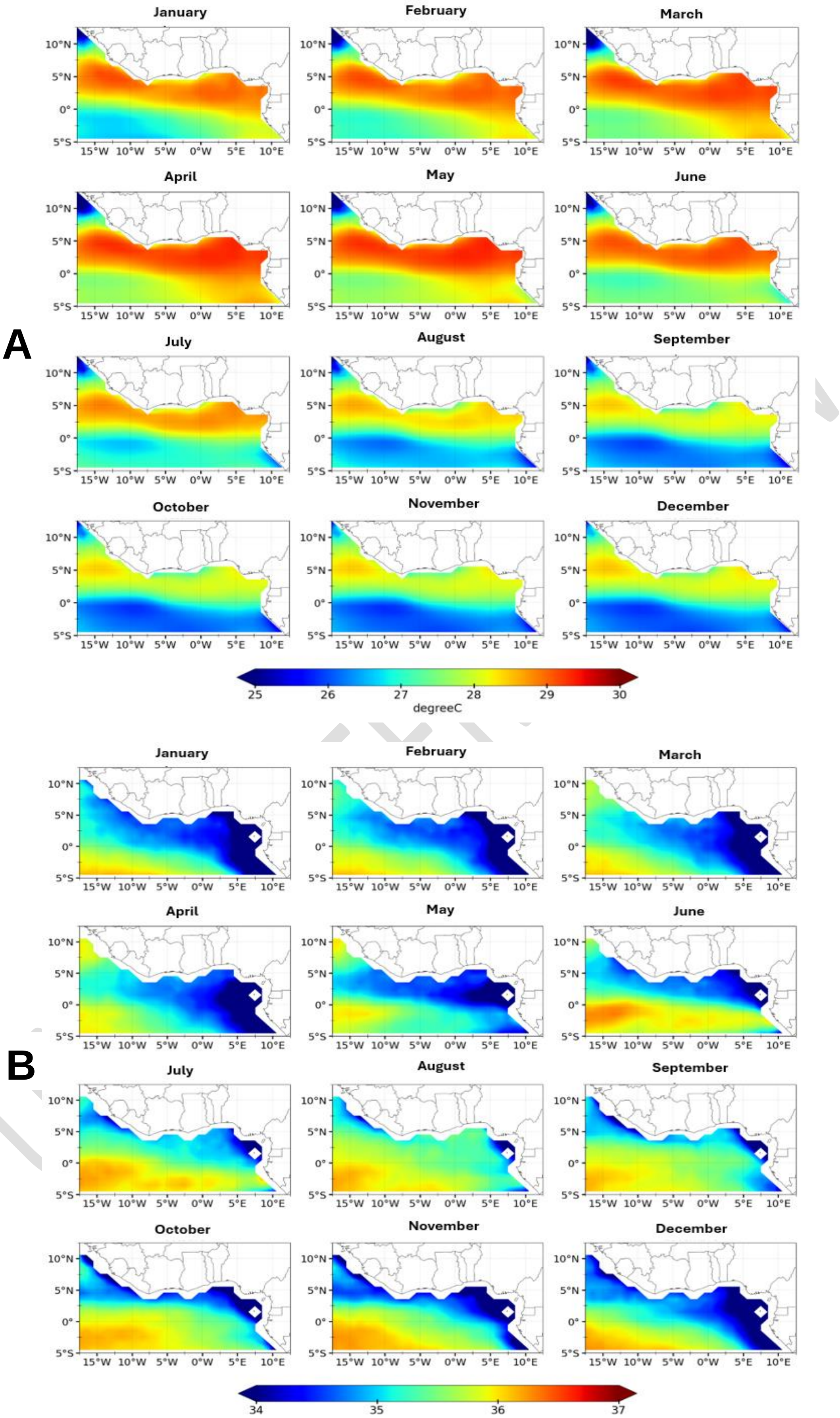

Fig.2. Spatial distribution of the monthly average of SST (A) and SSS (B) in the Gulf of Guinea from. 2010 to 2018

3.3 Spatio-temporal Variability of Sea Surface Chlorophyll-a

The variability of sea surface Chlorophyll-a shows high chlorophyll concentrations along the coasts of the Gulf of Guinea, ranging between 0.9 and 1 $mg.m^{-3}$ during the period from 2010 to 2018. The areas of high chlorophyll concentration are primarily located along the coasts and around the equator, particularly visible from January to March and from July to September, with values around 0.7-1.0 mg.m–3. In contrast, the areas of low chlorophyll concentration cover most of the oceanic zone, with a decrease in chlorophyll observed from April to June and from October to December, with near-zero values (Figure 3C).

3.4 Spatio-temporal Variability of 10-meter Sea Surface Wind Speed

Figure 3D shows extreme wind speed values in the study area. Indeed, very high speeds range from 6 to 8 m/s, while the lowest are between 0 and 2 m/s. From January to March, wind speeds are lower, generally between 2 and 4 m/s. Between April and June, a gradual increase in wind speed occurs, reaching 4 to 6 m/s. From July to September, wind speeds continue to increase, peaking in August (up to 8 m/s). However, from October to December, a return to initial values is observed.

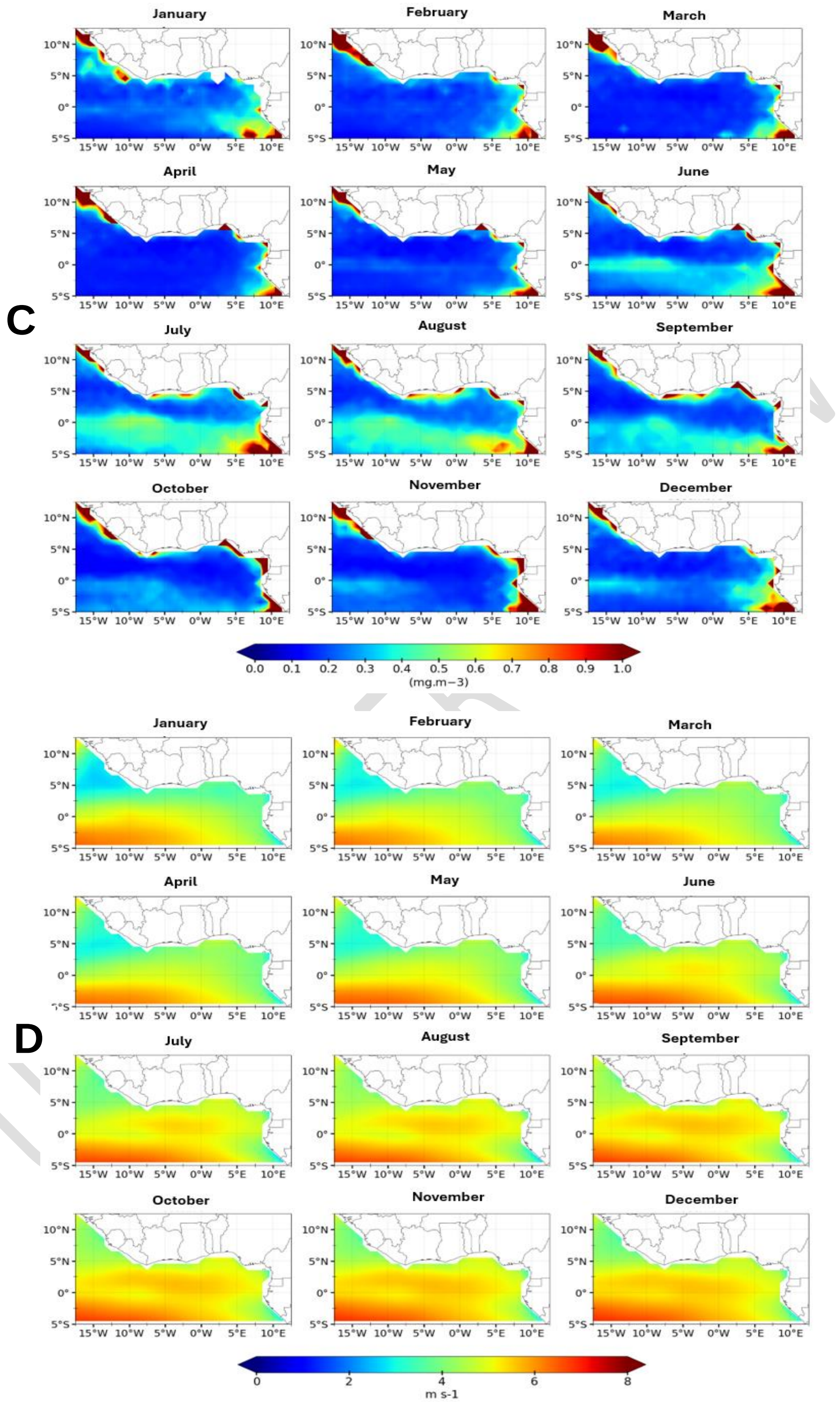

Fig.3. Spatial distribution of the monthly average of sea surface chlorophyll (C) and wind speed (D) in the Gulf of Guinea from 2010 to 2018.

3.5 Spatio-temporal Variability of Sea Surface Partial Pressure of CO_2

Figure 4 shows the variation in sea surface partial pressure of CO_2 (PCO2sw) in the Gulf of Guinea, ranging from 300 to 650 µatm. From January to March, relatively high concentrations are observed along the coast, ranging between 400 and 500 µatm. From April to June, PCO2sw concentrations remain high along the coast, but a downward trend is observable in May. In June, PCO2sw increases significantly along the coast, with values reaching up to 550 µatm in certain regions. From July to September, PCO2sw concentrations rise even further, particularly in August, peaking at over 600 µatm. In September, concentrations remain high along the coast but tend to decline from October to December. This decline intensifies in November and December, although concentrations of 500 µatm are still present in some areas.

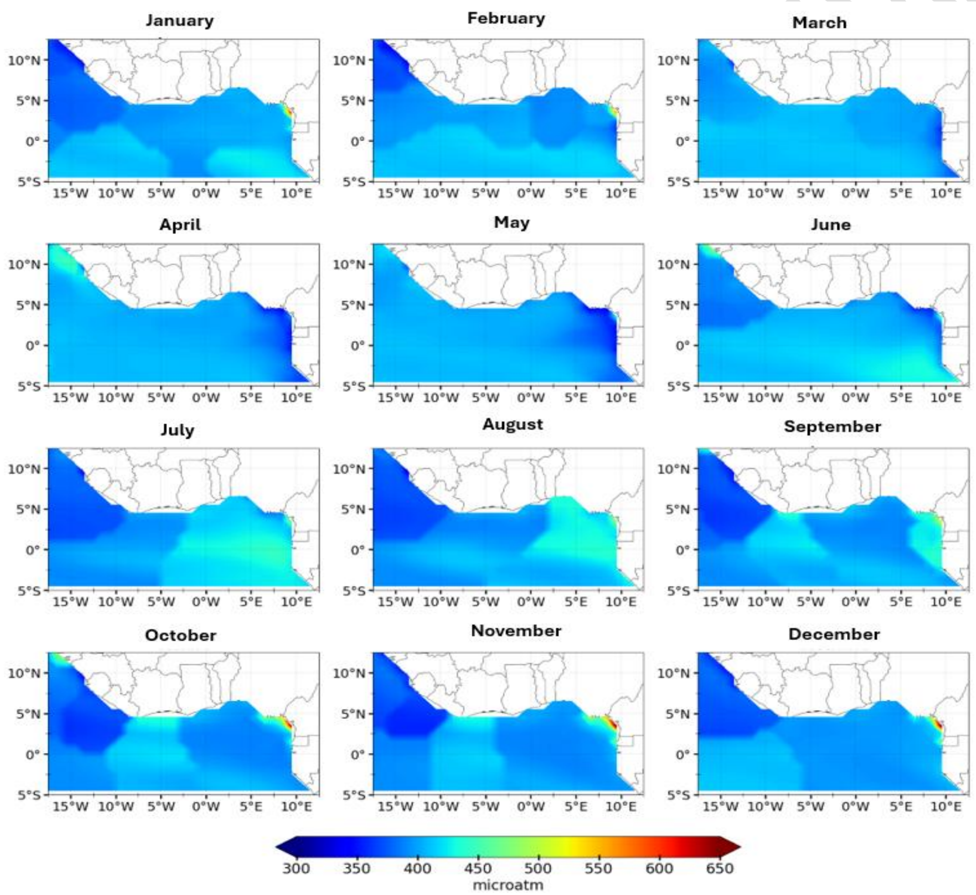

Fig.4. Spatial distribution of the monthly average of sea surface partial pressure of CO_2 (PCO2sw) in the Gulf of Guinea from 2010 to 2018.

3.6. Discussion

The study primarily relied on custom scripts written in Python. These scripts allowed for efficient data rescaling. Indeed, each parameter studied is interconnected and often influences biogeochemical processes at the air-sea interface in various ways. The monthly and seasonal variations in sea surface temperature reveal that during periods of high temperatures (from January to March and from October to December), the ocean's capacity to absorb CO_2 decreases. This suggests weak thermal stratification, leading to increased CO_2 emissions into the atmosphere, as confirmed by the studies of

[9] and [10]. These studies address the methods and estimates of anthropogenic CO_2 inventories in the ocean, while considering the effects of temperature on CO_2 solubility. In contrast, during periods of lower temperatures (notably from July to September), the decrease in temperature is attributed to seasonal upwelling, where coastal winds promote the upwelling of colder waters from the depths to the surface, causing a drop in temperatures. [11], [12], and [13] have demonstrated that upwelling brings CO_2-rich and more acidic waters to the surface, affecting marine ecosystems. Regarding sea surface salinity, it is relatively low, particularly near the northern part of the equator, mainly between January and March, as well as between October and December. This low salinity is attributed to heavy rainfall and freshwater inputs from rivers, such as the Congo River, which reduce salinity, as confirmed by recent studies from [14] and [15]. These authors show that rainfall and riverine inputs have a significant impact on surface salinity in the Gulf of Guinea. Moreover, salinity reaches very high values in August and September, marking the cold season. This increase is due to reduced freshwater inputs as well as increased evaporation. This dynamic is also reinforced by upwelling, which can bring saltier water from the depths to the surface. [15] and [16] confirm that the seasonal variations in salinity in the Gulf of Guinea are strongly influenced by weather conditions and river flows. The monthly and seasonal variations in 10-meter wind speeds in the Gulf of Guinea show that during the major dry season (January-March), weak winds (2-4 m/s), predominantly from the northeast trade winds, bring relatively stable but weak wind conditions. [17] highlighted a correlation between decreased wind speeds and reduced gas fluxes. On the other hand, the strong winds observed during the major cold season, peaking in August (up to 8 m/s), are often linked to the African monsoon, which brings stronger winds and more turbulent conditions, promoting increased CO_2 transfer. The work of [18] and [19] shows how monsoons influence CO_2 fluxes in coastal regions. Chlorophyll-a concentrations, ranging from 0.7 to 1.0 mg/m³ along the coasts, are corroborated by recent studies. [20] have shown that nutrient inputs, similar to upwelling, increase chlorophyll-a concentrations. Additionally, the decrease in chlorophyll-a concentrations during periods of thermal stratification is confirmed by [21], who demonstrate how seasonal variations influence marine biogeochemical cycles. Sea surface partial pressure of CO_2 (pCO2sw) remains slightly elevated along the coasts during the major warm season, then significantly decreases in May. This is explained by lower biological productivity and increased oceanic thermal stratification during this period, as suggested by [3], [22], [23], [24], and [25]. However, during the major cold season, pCO2sw is higher from July to September, a period when upwelling currents bring CO_2-rich waters from the depths, promoting phytoplankton growth and indicating an increase in pCO2sw. These results are in agreement with the research of [12], [26], and [27], which showed that intense upwelling events bring CO_2-rich waters to the surface, thereby increasing pCO2sw concentrations.

4. Conclusion

In conclusion, it is clear that climatic and oceanographic parameters such as sea surface temperature, salinity, chlorophyll-a, wind speed, and partial pressure of CO_2 play a fundamental role in CO_2 exchanges at the air-sea interface in the Gulf of Guinea. The analysis of data from the 2010-2018 period reveals significant spatio-temporal variations, modulated by phenomena such as seasonal upwelling and thermal stratification, which directly influence CO_2 fluxes at the air-sea interface, as higher temperatures reduce the water's ability to absorb CO_2. Regions with high salinity due to strong evaporation or low freshwater input can alter CO_2 exchanges, as saltier waters can dissolve less CO_2 than less saline waters, although this effect is relatively small. Areas with stronger winds promote more efficient CO_2 absorption by the ocean. High pCO2 levels in the water lead to CO_2 degassing into the atmosphere. Thus, these climatic and oceanographic parameters act synergistically to modulate CO_2 exchanges between the ocean and the atmosphere. Integrating these parameters into climate models could improve the accuracy of global climate change predictions.

Disclaimer (Artificial intelligence)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this ma

References

[1] Resplandy L., Hogikyan A., Müller J. D., Najjar R. G., Bange H. W., Bianchi D., ... & Regnier P. (2024). A synthesis of global coastal ocean greenhouse gas fluxes. *Global biogeochemical cycles*, *38*(1), e2023GB007803.

[2] Gutiérrez-Loza, L. (2020). Mechanisms controlling air-sea gas exchange in the Baltic Sea. Licentiate dissertation, Uppsala University, 39 pages.

[3] Takahashi T., Sutherland S. C., Wanninkhof R., Sweeney C., Feely R. A., Chipman D. W., ... & de Baar H. J. (2009). Climatological mean and decadal change in surface ocean pCO2, and net sea–air CO2 flux over the global oceans. Deep Sea Research Part II: Topical Studies in Oceanography, 56(8-10), 554-577.

[4] Wanninkhof R. (2014). Relationship between wind speed and gas exchange over the ocean revisited. Limnology and Oceanography: Methods, 12(6), 351-362. https://doi.org/10.4319/lom.2014.12.351

[5] Landschützer P., Gruber N., Bakker D. C., Stemmler I., & Six K. D. (2018). Strengthening seasonal marine CO2 variations due to increasing atmospheric CO2. Nature Climate Change, 8(2), 146-150.

[6] Behrenfeld M. J., Boss E. S., & Halsey K. H. (2021). Phytoplankton community structuring and succession in a competition-neutral resource landscape. *ISME communications*, *1*(1), 12

[7] Watson A. J., Schuster U., Shutler J. D., Holding T., Ashton I. G. C., Landschützer P., et al. (2020). Revised estimates of ocean-atmosphere CO2 flux are consistent with ocean carbon inventory. Nature Communications, 11(1), 1–6. https://doi.org/10.1038/s41467-020-18203-3

[8] Hoegh-Guldberg O., & Bruno J. F. (2010). The impact of climate change on the world's marine ecosystems. *Science*, *328*(5985), 1523-1528.

[9] Sabine C. L., & Tanhua T. (2010). Estimation of anthropogenic CO2 inventories in the ocean. Annual review of marine science, 2(1), 175-198.

[10] Goodwin P., & Lenton T. M. (2009). Quantifying the feedback between ocean heating and CO2 solubility as an equivalent carbon emission. Geophysical research letters, 36(15).

[11] Djagoua É. V., Larouche P., Kassi J.B., Affian K., et Saley B. (2011). Variabilité saisonnière et interannuelle de la concentration de la chlorophylle dans la zone côtière du golfe de Guinée à partir des images SeaWiFS. Revue internationale de télédétection, 32 (14), 3851-3874.

[12] Gruber N., Landschützer P., & Lovenduski N. S. (2019). The Variable Southern Ocean Carbon Sink. Annual Review of Marine Science, 11, 159-186. DOI : 10.1146/annurevmarine-121916-063407

[13] Feely, R. A., Doney, S. C., & Cooley, S. R. (2009). Ocean acidification: Present conditions and future changes in a high-CO_2 world. *Oceanography*, *22*(4), 36-47.Ocean acidification: Present conditions and future changes in a high-CO_2 world. Oceanography, 22(4), 36-47.

[14] Djakouré S., Penven P., Bourlès B., Koné V., & 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, 47(6), 1367-1387. https://doi.org/10.1175/JPO-D-16-0126.1

[15] Da-Allada C. Y., Jouanno J., Gaillard F., Kolodziejczyk N., Maes C., Reul N., & Bourlès B. (2017). Importance of the Equatorial Undercurrent on the sea surface salinity in the eastern equatorial Atlantic

in boreal spring. Journal of Geophysical Research: Oceans, 122(1), 521–538. https://doi.org/10.1002/2016JC012342

[16] Jouanno J., Marin F., du Penhoat Y., Sheinbaum J., and Molines J. M. (2011). Seasonal heat balance in the upper 100 m of the equatorial Atlantic Ocean, J. Geophys. Res., 116, C09003, doi :10.1029/2010JC006912.

[17] Lenton A., Matear R. J., & Tilbrook B. (2006). Design of an observational strategy for quantifying the Southern Ocean uptake of CO_2. Global Biogeochemical Cycles, 20(4).

[18] Koffi K.U. (2011). Distribution des paramètres du carbone et du flux de CO_2 à l'interface air-mer dans l'Est de l'Atlantique tropical (Thèse de doctorat, Université Pierre et Marie Curie-Paris VI).

[19] Coëtlogon, G.D., Janicot S., & Lazar A. (2010). Variabilité intersaisonnière du couplage océan-atmosphère dans le golfe de Guinée au printemps et en été boréaux. Revue trimestrielle de la Royal Meteorological Society, 136 (S1), 426-441.

[20] Thibodeau P. S., Puggioni G., Strock J., Borkman D. G., & Rynearson T. A. (2024). Long-term declines in chlorophyll a and variable phenology revealed by a 60-year estuarine plankton time series. Proceedings of the National Academy of Sciences, 121(21), e2311086121.

[21] Signorini S. R., Franz B. A., & McClain C. R. (2015). Chlorophyll variability in the oligotrophic gyres : mechanisms, seasonality and trends. Frontiers in Marine Science, 2, 1.

[22] Landschuetzer P., Gruber N., Bakker D.C. (2016). Decadal variations and trends of the global ocean carbon sink. Global Biogeochemical Cycles 30(10) :1396–1417.

[23] Bourgeois T., Orr J. C., Resplandy L., Terhaar J., Ethé C., Gehlen M., & Bopp L. (2016). Coastal-ocean uptake of anthropogenic carbon. *Biogeosciences*, *13*(14), 4167-4185.

[24] Henson S. A., Beaulieu C., & Lampitt R. (2016). Observing climate change trends in ocean biogeochemistry: when and where. Global change biology, 22(4), 1561-1571.

[25] DeVries, T. (2022). The Ocean Carbon Cycle. Annual Review of Environment and Resources, 47, 317-341. https://doi.org/10.1146/annurev-environ-120920-111307

[26] Feely R.A., Sabine C.L., Lee K., Berelson W., Kleypas J., Fabry V.J., and Millero F.J. (2004). Impact of anthropogenic CO_2 on the $CaCO_3$ system in the oceans. Science 305(5682):362–366, doi:10.1126/ science.1097329.NOAA, 1959

[27] Wanninkhof, R. (1992). Relationship between wind speed and gas exchange over the ocean. Journal of Geophysical Research: Oceans, 97(C5), 7373-7382.