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TEMPORAL TRENDS OF OCEAN ACIDIFICATION IN THE GULF OF GUINEA AND THE POTENTIAL IMPACT ON SOCIOECONOMIC DEVELOPMENT

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ABSTRACT

Ocean acidification, primarily driven by increased atmospheric CO_2, poses significant environmental and socioeconomic threats, particularly in vulnerable regions like the Gulf of Guinea. This study analyses historical pH trends, spatial variations, and projected acidification scenarios using data from CMIP6 models and NOAA observational records, focusing on the Gulf of Guinea's unique ecological and economic challenges. Findings indicate a steady decline in pH from 8.20 to 8.08 between 1750 and 2010, with pronounced deviations linked to industrial activities and rising atmospheric CO_2 concentrations. Seasonal fluctuations and upwelling events exacerbate acidification in this high-productivity region, intensifying the vulnerability of marine biodiversity and fisheries. Projections for 2050–2100 under SSP2-4.5 and SSP5-8.5 scenarios reveal further pH declines, with potential hotspots emerging in coastal areas. These changes threaten critical ecosystems, such as shellfish habitats, and threaten food security and economic stability for communities dependent on marine resources. The study underscores the necessity of regional monitoring programs, international collaboration, and mitigation strategies, including carbon emission reductions, ecosystem-based adaptation, and sustainable aquaculture practices. This research highlights the Gulf of Guinea's heightened sensitivity to acidification due to its unique biogeochemical processes and socioeconomic dependencies. It advocates for integrating science, policy, and local initiatives to address these challenges. Targeted interventions, such as

mangrove restoration and regional partnerships, can strengthen resilience and provide valuable insights for global ocean acidification management efforts.
Keywords: Coastal vulnerability; Marine ecosystem; Mitigation; West Africa, Biodiversity.

1.0 INTRODUCTION

Ocean acidification, driven by absorbing atmospheric carbon dioxide (CO_2) by seawater, decreases oceanic pH levels, posing significant threats to marine ecosystems and the human communities that depend on them. Globally, the oceans have absorbed approximately 30% of anthropogenic CO_2 emissions, resulting in a 0.1 unit decline in surface ocean pH since the pre-industrial era (Kubin *et al.,* 2024). This process adversely affects marine organisms, particularly those that rely on calcium carbonate for their skeletal structures, such as corals, molluscs, and certain plankton species. Dissolving calcium carbonate under lower pH conditions impairs these organisms' growth and survival, leading to broader ecological consequences. Foundational studies, such as those by Caldeira and Wickett (2003), Mathis *et al.* (2024), highlighted the rapid chemical changes occurring in the oceans due to increased CO_2 emissions, while Jiang *et al*., (2019) have shown that air-sea CO_2 disequilibrium is the dominant mode of spatial variability for surface pH, and important metrics for ocean acidification alongside calcium carbonate. However, the global decline in pH is not uniform, and regional variations are influenced by factors such as local oceanic CO_2 uptake capacity and natural dissolved inorganic carbon (DIC) changes (Gregor & Gruber, 2023). Upwelling zones, such as those off the coast of West Africa, are susceptible to changes in ocean chemistry due to their high biological productivity and CO_2 exchange rates (Hagens & Middelburg, 2016). Thus, the buffering capacity of these waters is often lower, making them more susceptible to acidification. The interplay between natural and anthropogenic factors results in complex pH dynamics, with potential implications for marine ecosystems and fisheries in the region (Lauvset *et al*., 2015). Doney *et al*. (2020) provided a comprehensive analysis of the cascading effects of acidification on marine food webs and ecosystems. These studies establish the global context for understanding the regional dynamics of ocean acidification. In West Africa's context, ocean acidification is particularly concerning. The region's coastal communities rely heavily on marine resources for food security, economic activities, and cultural practices. Recent study (Chukwuka *et al*., 2023) have highlighted significant pH declines in surface waters of the

West African coast, notably around the Niger Delta in Nigeria and the coastal regions of Guinea and Guinea-Bissau. These areas have experienced lower pH trends, indicating increased acidification, which poses risks to local marine biodiversity and fisheries.

The Gulf of Guinea, a critical component of the West African marine ecosystem, is recognised as a hotspot for climate change-driven oceanic alterations, including rising temperatures, acidification, and deoxygenation (Jewett & Romanou, 2017; Lam & De Fontaubert, 2019; Yavo *et al*., 2024). These changes are anticipated to profoundly affect marine life, potentially disrupting ecological balance and diminishing fish stocks. The region's high productivity, driven by nutrient-rich upwelling systems, may be compromised, leading to socioeconomic challenges for communities dependent on fishing and related industries (Capson *et al*.,2022).

While the global trend of ocean acidification is well-documented, regional variations, such as those in West African upwelling zones, highlight the complexity of oceanic responses to anthropogenic CO_2. Moreover, the Gulf of Guinea is already vulnerable to multiple stressors, including overfishing, pollution, and rising sea temperatures due to climate change (Hauser *et al*., 2023; Andrews *et al*., 2021; Asiedu *et al*., 2015). Ocean acidification adds another layer of complexity, affecting biodiversity and ecosystem services. These areas require targeted research to understand the full impact of acidification on local marine ecosystems and to develop effective adaptation strategies. Despite the evident risks and increasing research on ocean acidification, a notable lack of comprehensive monitoring and impacts of ocean acidification in West Africa exists. This gap hinders the development of effective mitigation and adaptation strategies tailored to the region's unique environmental and socioeconomic contexts. Addressing this deficiency is crucial for safeguarding marine ecosystems and the livelihoods of millions who depend on them. This study aims to address the existing knowledge gap by conducting a detailed analysis of pH trends in West African marine waters, focus on the Gulf of Guinea. It seeks to examine temporal and spatial variations in ocean acidity using available observational and satellite-derived datasets, and to explore the potential implications of these trends for marine ecosystems, coastal communities, and regional climate resilience. Nnaemeka (2024) and Chuku et al. (2022) have highlighted the critical dependence of West African coastal communities on marine resources for livelihoods and food security. By comparing regional pH levels to global averages, examining temporal changes, and assessing the potential impacts on marine ecosystems and coastal economies, this research seeks

to inform policy and conservation efforts. The findings are intended to support the development of targeted mitigation strategies and promote international collaboration to address the challenges posed by ocean acidification in West Africa.

2.0 METHODOLOGY

2.1 Study Area

The Gulf of Guinea is located in the eastern part (20˚W-10˚E; 10˚S-10˚N) of the tropical Atlantic Ocean (Figure 1). The region experiences significant concerns regarding ocean acidification, primarily due to its location in the tropical Atlantic Ocean, making it particularly susceptible to absorbing high levels of carbon dioxide, which leads to a decrease in pH levels and impacts marine life in the region. This issue is further exacerbated by factors like coastal development, river discharge, and potential upwelling events (Djakouré *et al*., 2020), highlighting the need for dedicated monitoring and mitigation strategies.The Guinea Current is the dominant ocean surface current in the northern part of the Gulf of Guinea. It plays a vital role in marine productivity and the coastal upwelling in the region (Bosson *et al*., 2023).

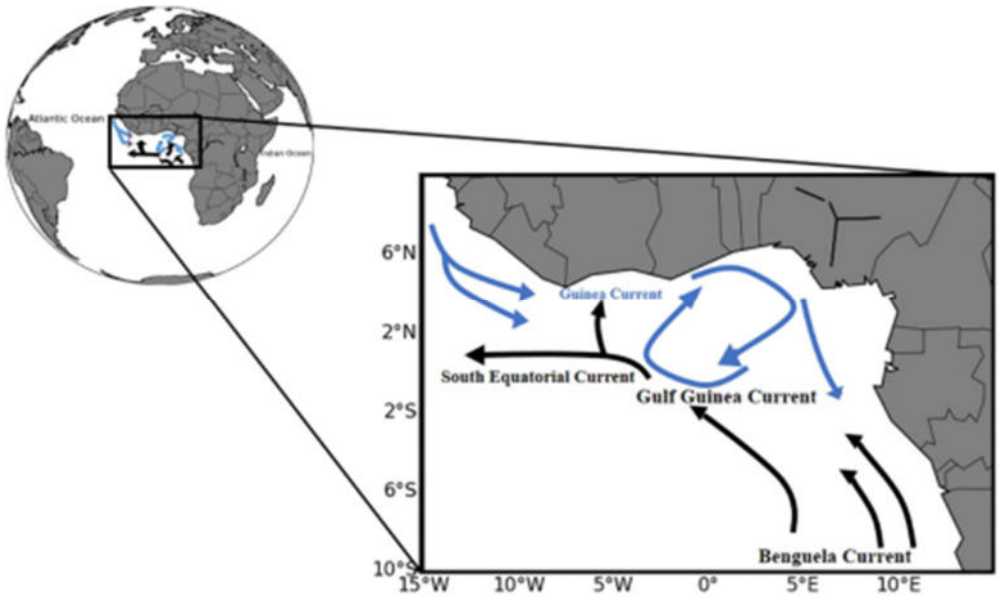


Fig. 1: Location of the Gulf of Guinea in West Africa (Source: Koffi *et al*., 2024).

2.2 Data and Methods

This study employed pH data (pH Total Scale and Total hydrogen ion content pHT) extracted from modelled indicators of ocean acidification from the sixth phase of the Coupled Model Intercomparison Project (CMIP6), combined with observational records for historical validation from NOAA National Centers for Environmental Information (Jiang *et al.,* 2023; Eyring *et al*., 2016). Sea surface temperature (SST) and CO_2 concentration from the NOAA Global Monitoring Laboratory and Coupled Model Intercomparison Project (CMIP) were also utilised. Temporal changes were analysed over 1750-2010, and projections for future (2020-2100) acidification trends were based on Shared Socioeconomic Pathways (SSP) 2-4.5 and 5-8.5 scenarios. SSP scenarios are projections used in climate modelling to describe different possible futures based on global socioeconomic trends, such as population growth, energy use, and policy decisions, which influence greenhouse gas emissions and climate change impacts. Spatial patterns and variations were analysed using statistical (mean and standard deviation) and visualisation techniques such as time series plots to identify long-term changes and periodic fluctuations. The regional pH values were averaged spatially for West Africa (Gulf of Guinea) and compared against global means. Spatial maps were shown to illustrate the spatial distribution of the pH. The Python programming language was used for processing and analysing the datasets, including time series trends, statistical evaluation, and plotting.

3.0 RESULTS

3.1 Temporal Changes

Figure 2 shows the global ocean surface pH trend and ocean pH over West Africa (Gulf of Guinea). Temporal analysis indicates a steady decline in pH levels from 8.20 to 8.08 from 1750-2010, with pronounced drops between 1960 and 2010 (Figure 2).

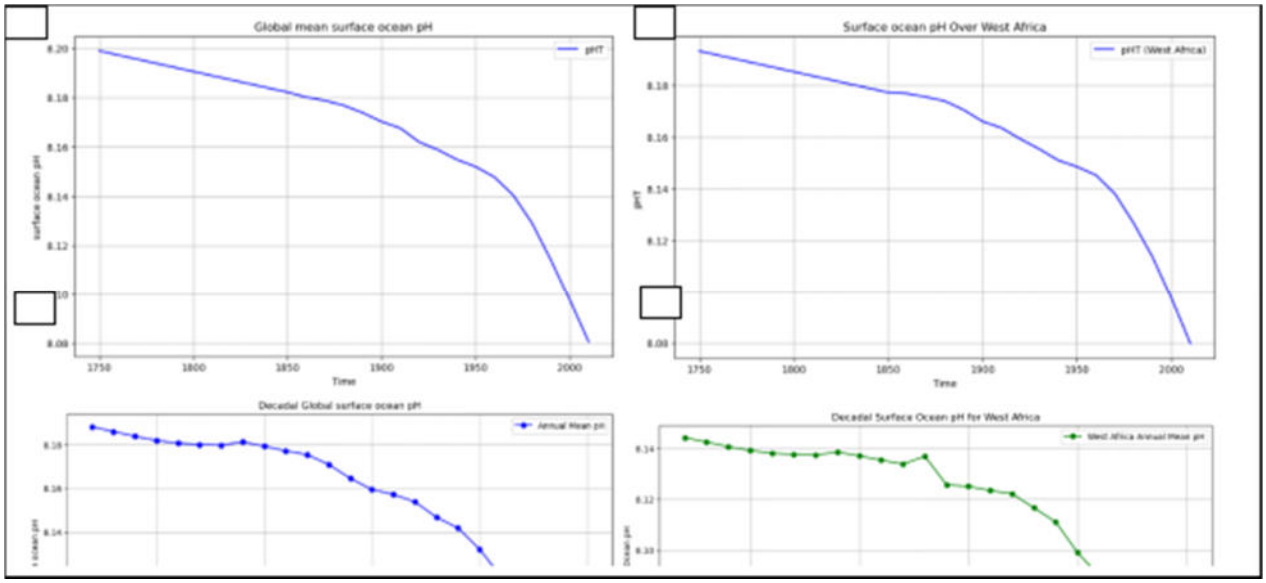


Fig. 2: Global Ocean Surface pH and Ocean pH around West Africa (Gulf of Guinea)

PH trend in Figure 2b over West Africa indicates the same trend as the global mean but shows increased deviations in 1900, 1960, and 1990. These declines align with periods of heightened industrial activity and carbon emissions presented in Figure 3a, emphasising the regional impact of anthropogenic CO_2. Atmospheric CO_2 concentrations have increased to about 425 parts per million (ppm) since 1980 from an initial value of approximately 338 ppm (Figure 3a). Global mean SST values (Figure 3b) over the period indicate a similar trend of increase (1.2℃), representing climate impacts on the region's waters.

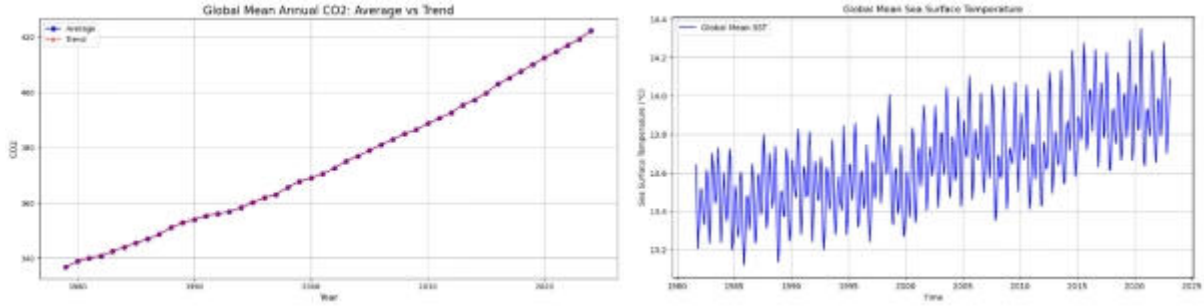


Fig. 3: Global mean **a.** Annual atmospheric CO_2 concentrations (ppm) and **b.** Sea surface temperature (SST).

3.2 VARIATIONS OVER WEST AFRICA AND COMPARISON WITH GLOBAL TRENDS

Over West Africa, an increasing trend in SST from 23.5 to 28.5 ℃ is seen in Figure 4a. Seasonal fluctuations are evident, with pH levels dipping during upwelling seasons represented in the oceanic Niño Index (Figure 4b).

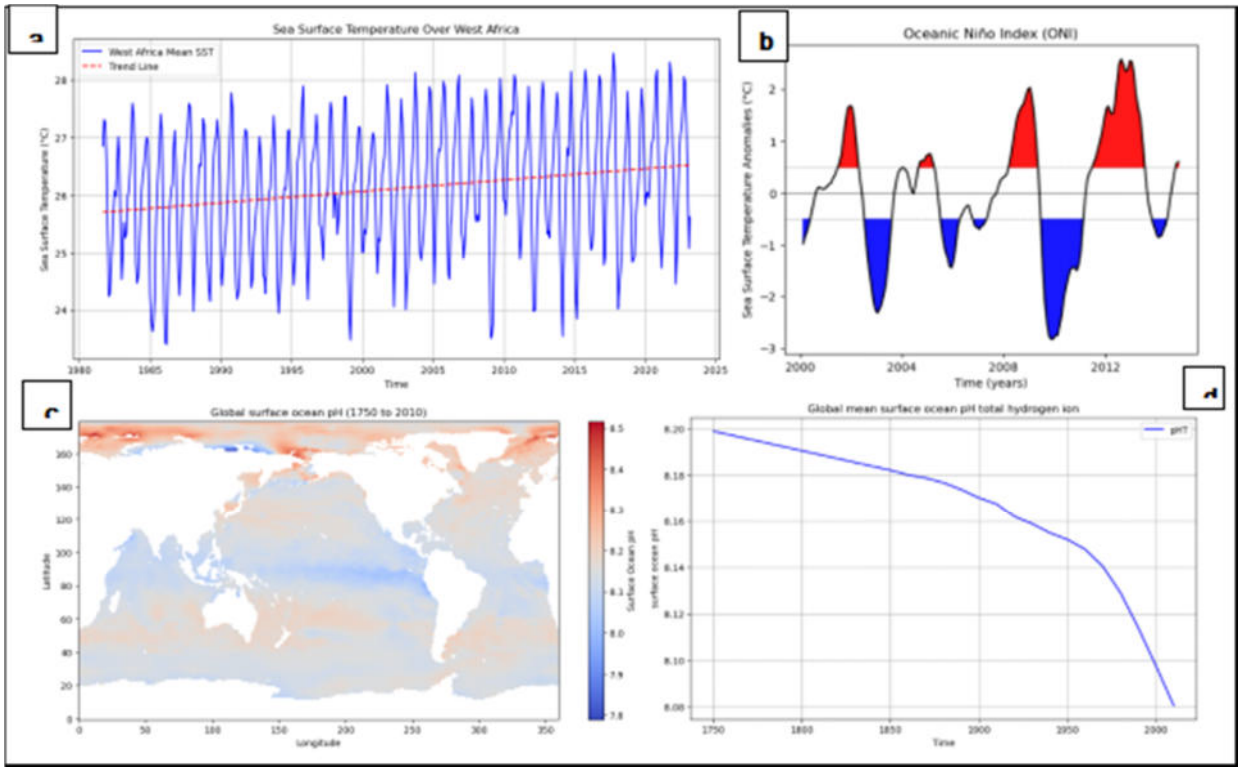


Fig. 4**:** a. and b. Surface ocean Ph c. SST and d. Oceanic Nino Index

The global mean surface ocean pH and Oceanic Niño Index calculated from SST anomalies are shown in Figures 4c and 4d. Sharp anomalies in the SST between 2005 and 2015 correlate with extreme weather events (Figure 4d), likely driven by climate variability such as ENSO (El Niño-Southern Oscillation) events. These periods highlight the interplay between natural variability and anthropogenic influences on ocean chemistry. Figure 5a shows the spatial mean sea surface pH across the global oceans and the variability (standard deviation) of pH values over time. The lower mean pH values (~8.0–8.2) are observed in the tropical and subtropical regions where the Gulf of

Guinea is located. Tropical regions show lower variability, indicating more stable pH levels over time. Figure 5b shows the spatial mean sea surface pH across West Africa.

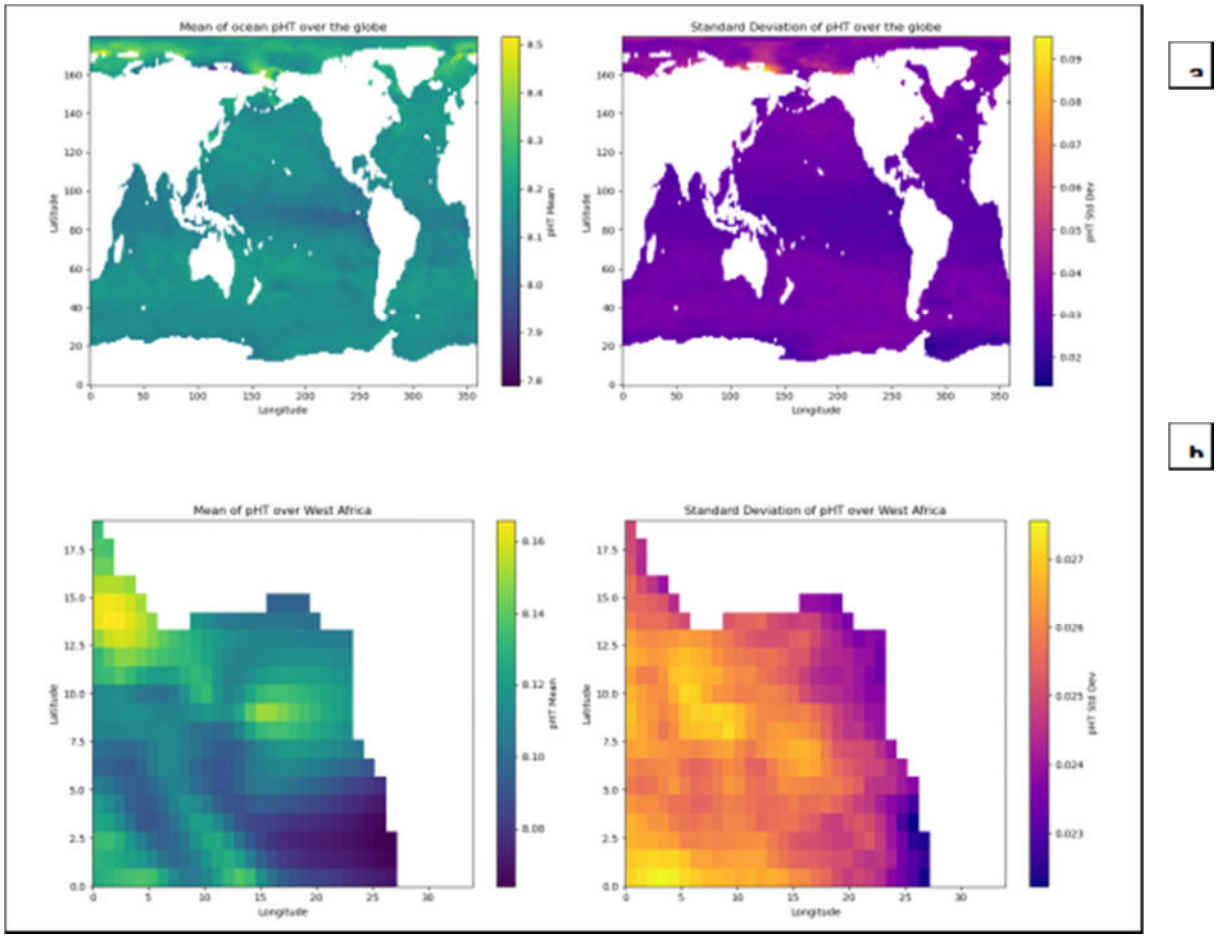


Fig. 5: Mean and standard deviation over **a.** the Globe and **b.** West Africa.

Figure 6 displays variability in pH across the West African region. There is a gradual and consistent decline in the mean pH from about 8.14 in 1750 to below 8.06 in 2020. The standard deviation (a measure of spatial variability) begins around 0.0228 in 1750 and generally declines over time. Variability was relatively stable before 1900, then began to fluctuate more afterwards. There are noticeable fluctuations between 1850 and 2000, with spikes near 1875, 1900, and 1950.

Peaks in variability could indicate regional changes in ocean circulation, temperature, or biological activity affecting carbonate chemistry.

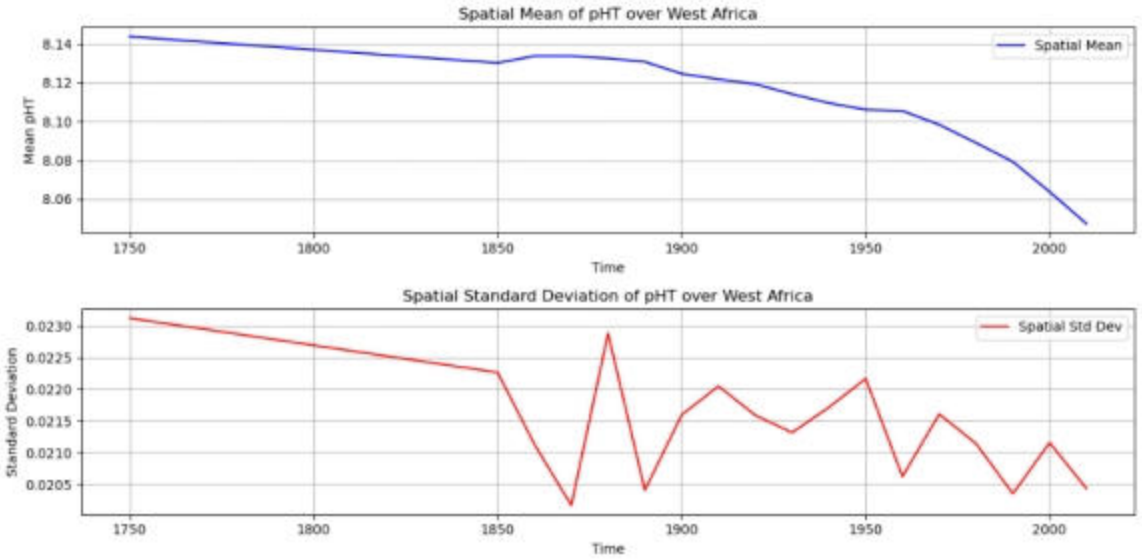


Fig. 6: Spatial mean trend and standard deviation of pH over West Africa.

3.3 Projected Changes in pH

The projected pH of total hydrogen ions from 2020 to 2100 under two climate scenarios (SSP2-4.5 and SSP5-8.5) can be found in Figure 7. By 2050, under scenario 4.5 (Figure 7a), pH is expected to decrease to 8 across the Atlantic Ocean, while a decrease to 7.7 is expected by 2100. Projections indicate further declines in pH under SSP5-8.5 (Figure 7b), with potential acidification hotspots emerging in the Gulf of Guinea. These changes are expected to exacerbate stress on marine ecosystems and dependent industries.

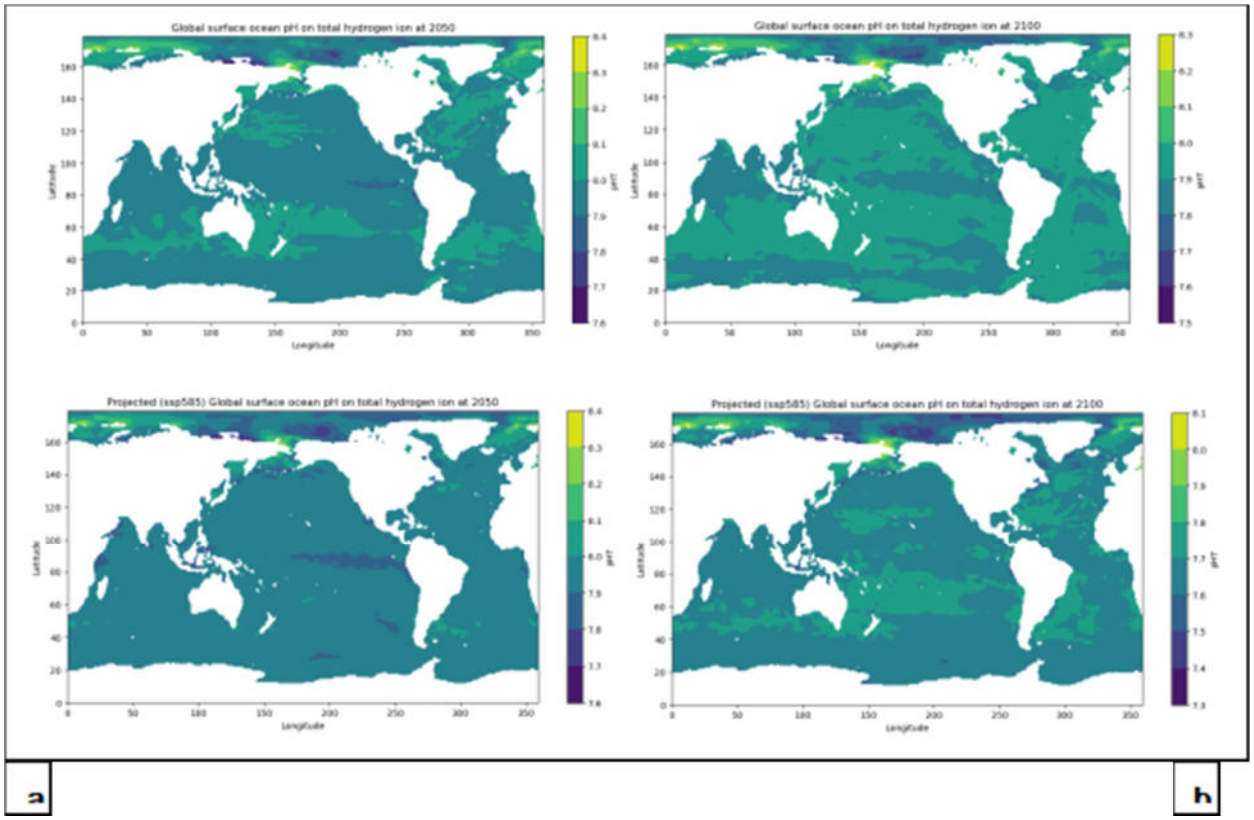


Fig.7a: Projected Global Surface Ocean pH by 2050 and 2100 under **a.** SSP2-4.5 **b.** SSP5-8.5

3.3.1 Comparison to Historical Observations:

In this section, the projected trend of pH (Figure 8) is compared to the historical pH values in Figure 2. Modelled trends align with historical data, confirming the robustness of projected acidification patterns. Observational records show similar rates of decline i.e. 8.06 – 7.9 (SSP2-4.5) and 8.05-7.7 (SSP5-8.5), reinforcing the urgency of mitigation.

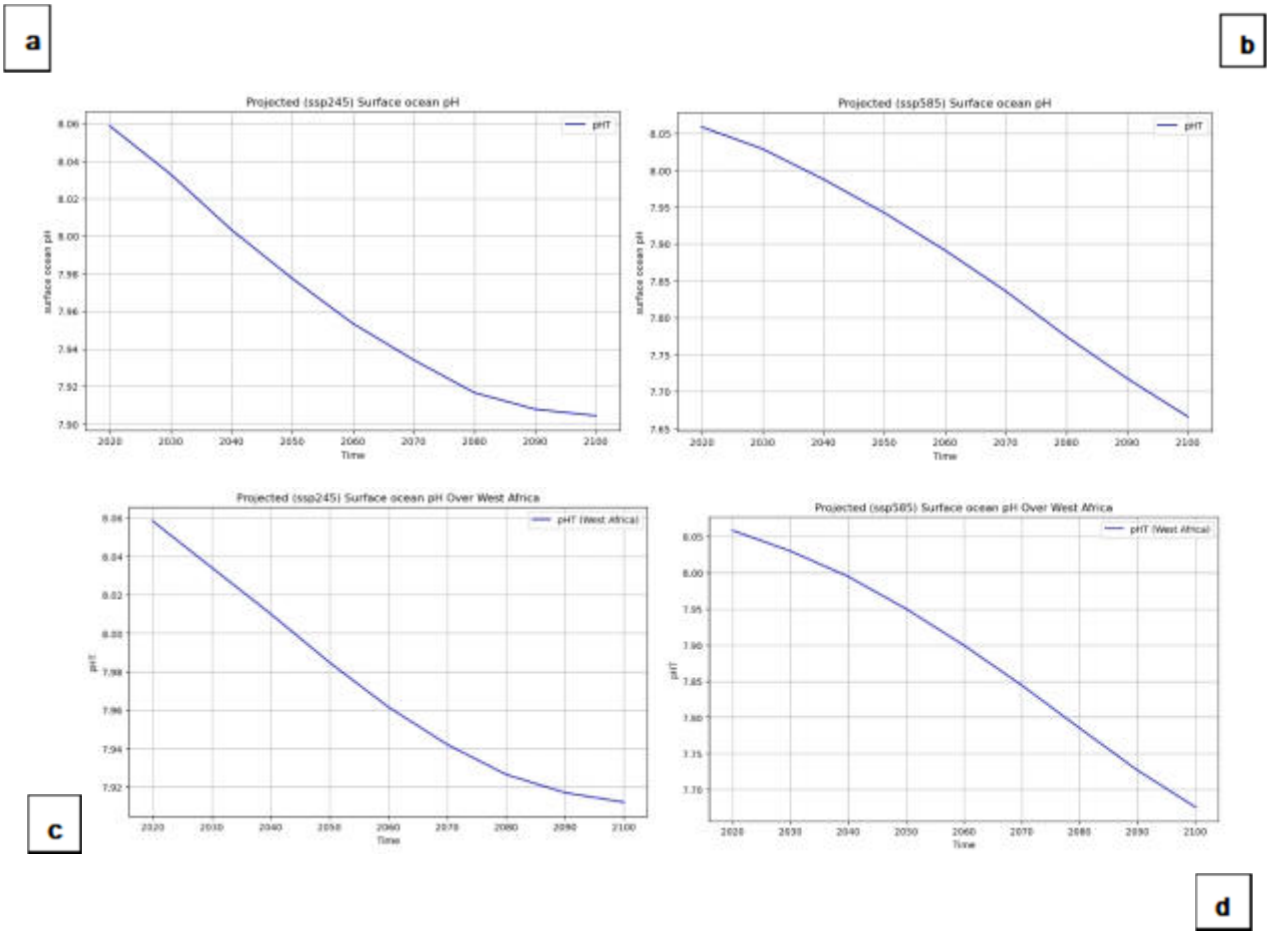


Fig. 8: Projected Surface Ocean pH from 2020 to 2100 under SSP2-4.5 and SSP5-8.5 over the **a.** Globe **b.** West Africa

4.0 DISCUSSION

The study findings indicate a consistent pH decline during the 1960-2010 period, aligning with the increasing carbon emissions and ocean temperatures in recent times. This is supported by Gregor & Gruber (2021), who reported that global mean surface ocean pH has been decreasing due to increased atmospheric CO_2, with a decline of about 0.016 per decade from 1990 to 2018. West Africa, particularly in the Gulf of Guinea, exhibits distinct characteristics when compared to the global mean. There is a consistent decline in surface ocean pH, highlighting the regional sensitivity to global climate change and carbon emissions. Results indicate long-term ocean acidification over the West African marine zone. The steeper drop after 1950 aligns with the Industrial Revolution and increased atmospheric CO_2 emissions due to rapid fossil fuel burning and land-use changes. Comparing Figures 5 and 6, the mean pH over West Africa was marginally lower than the global

mean, reflecting heightened sensitivity in this region due to warmer waters and intense processes regulating ocean chemistry, nutrients, and ecosystem health. This regional deviation suggests that ecosystems in West Africa may experience accelerated acidification effects compared to global averages. In Ghana, Kpaliba & Mbage (2024) reported a mean annual pH of 8.01, slightly lower than the global mean as found in this study. The study observed variations throughout the year due to fluctuating CO_2 concentrations reflecting its impact on ocean acidification in the region. The decreasing trend shows that pH across West Africa's waters is becoming more spatially uniform, resulting in a relatively stable climate and biogeochemical variability (like upwelling, freshwater input, and CO_2 fluxes) in the region. Similarly, Loucaides *et al*. (2012) in their study noted pH values in West Africa, particularly in upwelling zones, tend to be lower than the global mean due to natural upwelling processes that bring CO_2-rich waters to the surface. Unlike stronger and more persistent upwelling systems such as the Canary or Benguela currents, the Gulf of Guinea experiences weaker, intermittent upwelling events, leading to less intense but still significant fluctuations in carbonate chemistry. Additionally, heavy riverine discharge from the Niger and Congo rivers introduces large amounts of organic matter and nutrients possibly linked to natural climate variability (e.g., El Niño/Atlantic Niño events), enhancing microbial respiration and CO_2 production, further lowering pH levels. Compared to upwelling zones with lower human impact, the Gulf of Guinea also faces compounded acidification from coastal pollution, oil spills, and industrial runoff, which introduce additional stressors to marine ecosystems (Scheren *et al*., 2002). These combined factors create a more complex and variable acidification pattern, necessitating region-specific monitoring and mitigation strategies. Temperature projections for West Africa under the Shared Socioeconomic Pathways (SSP) 2-4.5 and 5-8.5 scenarios indicate significant warming trends, with varying impacts across the region (Macadam *et al*., 2020; Limantol *et al*., 2023). This is seen in the projected declining pH trend over the region, with potential acidification hotspots emerging in the Gulf of Guinea under 5-8.5 scenarios. Rising temperatures can exacerbate acidification by reducing the ocean's capacity to buffer changes in pH, particularly in coastal areas where salinity and alkalinity are lower (Makuch *et al.,* 2023). In addition, observational records show similar rates of decline, i.e. 8.06 – 7.9 (ssp245) and 8.05 - 7.7 (ssp585), reinforcing the urgency of mitigation. In West Africa, the Gulf of Guinea, a biodiversity hotspot recognised for climate change-driven oceanic alterations, including rising temperatures, acidification, and deoxygenation, exhibits the most extreme pH variations (Chukwuka *et al*., 2023). As the ocean

acidifies, it may be flattening natural spatial gradients, possibly reducing ecological niches and affecting biodiversity. These changes are anticipated to profoundly affect marine life, potentially disrupting ecological balance and diminishing fish stocks (Kubin *et al.,* 2024). Shellfish, which rely on calcium carbonate for shell formation, are particularly vulnerable. The region's high productivity, driven by nutrient-rich upwelling systems, may be compromised, leading to socioeconomic challenges for coastal livelihoods and food security in communities dependent on marine resources. A preliminary study on Ghana's artisanal and semi-industrial fisheries suggests that ocean acidification could impact fish populations, potentially affecting local livelihoods, though more comprehensive data is needed (Nunoo *et al*., 2016). Environmental degradation in Nigeria's Niger Delta, driven by oil and gas activities, has led to increased acidity in rain and surface waters, affecting ecosystems and human health (Nduka *et al*., 2016). Gas flaring and refinery operations release acidic aerosols, causing acid rain, which contributes to soil degradation, deforestation, and reduced agricultural productivity, impacting local livelihoods (Nduka *et al*., 2016). Research shows surface water bodies in the region have slightly acidic pH levels—rivers (5.97), creeks (6.29), streams (5.67), and lakes (6.10)—indicating a trend toward acidification (Rim-Rukeh, 2018). This poses risks to aquatic life, threatening fisheries essential to the local economy, while contaminated water consumption endangers public health. Addressing these issues requires robust environmental monitoring and pollution mitigation strategies. To address the region's ocean acidification data gap, the Building Capacity in Ocean Acidification Monitoring in the Gulf of Guinea (BIOTTA) (https://pogo-ocean.org/innovation-in-ocean-observing/activities/biotta/) project was launched to develop a sustainable OA observing system, equipping local scientists with essential skills for data acquisition. These efforts highlight the need for region-specific research and local capacity-building to address the challenges posed by ocean acidification in the Gulf of Guinea. The observed and projected trends underscore the critical need for regional interventions. Regional strategies must incorporate findings from Gattuso *et al*. (2015), which emphasize the importance of coordinated international and local efforts to mitigate ocean acidification through emission reductions and ecosystem-based adaptation. Additionally, recommendations by the IPCC highlight the role of integrated coastal zone management and marine conservation in strengthening resilience (IPCC, 2023). Implementing these strategies in West Africa could involve establishing comprehensive monitoring networks, fostering regional collaboration, and promoting carbon sequestration initiatives such as mangrove restoration. Large-scale mangrove reforestation in the

Gulf of Guinea and conservation efforts can enhance carbon sequestration, while a regional ocean acidification observatory would enable standardised monitoring and policy coordination. Promoting resilient aquaculture species, reducing nutrient runoff, and adopting habitat-friendly farming practices can further strengthen coastal ecosystem resilience and protect fisheries-dependent communities. These approaches mitigate acidification effects and provide co-benefits like biodiversity conservation and carbon storage. Enhanced monitoring of pH and CO_2 levels and regional cooperation can improve adaptation strategies. Examples of successful regional monitoring programs include those implemented in the Pacific Ocean, which leverages community-based observation systems, and the European Marine Observation and Data Network (EMODnet) (https://emodnet.ec.europa.eu/en) and BIOTTA, which integrates large-scale data collection efforts. These programs provide valuable frameworks for developing similar initiatives in West Africa to enhance the understanding and management of ocean acidification impacts. Socioeconomic resilience must be bolstered by diversifying livelihoods and investing in sustainable aquaculture practices. Case studies, such as those by Froehlich *et al.* (2018), have highlighted the potential of integrating low-trophic species and multi-trophic aquaculture systems to mitigate acidification impacts on aquaculture. Furthermore, FAO (2020) reports emphasise the importance of adopting adaptive practices, including breeding acidification-resistant species and promoting policy frameworks that support sustainable aquaculture initiatives. Collaborating with local stakeholders, such as fishers and industry representatives, ensures that solutions are practical and aligned with economic interests, fostering adoption. Public awareness campaigns and participatory citizen science initiatives can empower coastal communities with knowledge and tools to advocate for policies that protect their livelihoods.

5.0 Conclusion

Ocean acidification presents a pressing challenge for West Africa, particularly in the Gulf of Guinea. This study proffers the critical need for regional analyses of ocean acidification to inform policy and conservation strategies. The region's heightened vulnerability to acidification necessitates immediate action to mitigate impacts on marine ecosystems and dependent communities. To address these challenges, we recommend reducing CO_2 emissions globally and regionally, strengthening marine protected areas (MPAs) to safeguard biodiversity, promoting regional collaboration for monitoring and mitigation efforts, and supporting adaptive aquaculture

techniques resilient to changing pH conditions. Collaborative strategies integrating science, policy, and local efforts will be crucial to addressing this global threat while enhancing the resilience of marine ecosystems and the communities that depend on them. Further research should focus on understanding the complex interactions between ocean acidification and other stressors, such as rising sea temperatures and pollution, by using satellite remote sensing and autonomous underwater sensors to enhance the spatiotemporal resolution of these stressors in the Gulf of Guinea. Additionally, studies investigating the socio-economic costs of acidification and the effectiveness of mitigation measures in this region are critical. Finally, developing predictive models tailored to West African waters could improve future adaptation planning and policy-making.

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REFERENCES

Andrews Nathan, Nathan J. Bennett, Philippe Le Billon, Stephanie J. Green, Andrés M. Cisneros-Montemayor, Sandra Amongin, Noella J. Gray, U. Rashid Sumaila (2021). Oil, fisheries and coastal communities: A review of impacts on the environment, livelihoods, space and governance. *Energy Research & Social Science*, Volume 75, 102009, ISSN 2214-6296, https://doi.org/10.1016/j.erss.2021.102009.

Asiedu, Berchie & Nunoo, F.. (2015). Declining Fish Stocks in the Gulf of Guinea: Socio-Economic Impacts. In Patrick K. Ofori–Danson, Elvis Nyarko, Kwasi Appeaning Addo, Dzidzornu K. Atsu, Benjamin O. Botwe, Eunice K. Asamoah, Physical and Life Science Series No. 2, (pp.201-218). The University of Ghana, Department of Marine and Fisheries Sciences Reader. (https://www.sciencedirect.com/science/article/pii/S221462962100102X)

Bosson, K., Aman, A., Toualy, E. and Arnault, S. (2023). The Surface Guinea Current Variability from Satellite Data. *Regional Studies in Marine Science*, 64, Article ID: 103045.https://doi.org/10.1016/j.rsma.2023.103045

Caldeira, K. & Wickett, M. (2003). Anthropogenic carbon and ocean pH. *Nature* **425**, 365. https://doi.org/10.1038/425365a

Chuku, E. O., Effah, E., Adotey, J., Abrokwah, S., Adade, R., Okyere, I., Aheto, D. W., Kent, K., Osei, I., Omogbemi, E. D., Adite, A., Ahoedo, K., Sankoh, S., Soro, Y., Wélé, M., Saine, D. F., & Crawford, B. (2022). Spotlighting Women-Led Fisheries Livelihoods Toward Sustainable Coastal Governance: The Estuarine and Mangrove Ecosystem Shellfisheries of West Africa. *Frontiers in Marine Science*, *9*. https://doi.org/10.3389/fmars.2022.884715

Chukwuka, A. V., Omogbemi, E. D. & Adeogun, A. O. (2023). Habitat sensitivity in the West African coastal area: inferences and implications for regional adaptations to climate change and ocean acidification. *Environmental Monitoring Assessment*. Dec 23;196(1):79. doi: 10.1007/s10661-023-12171-z. PMID: 38141112.

Doney, S., Busch, S. D., Cooley, S. R. & Kroeker, K. J. (2020). The Impacts of Ocean Acidification on Marine Ecosystems and Reliant Human Communities. *Annual Review of Environment and Resources*. 45. 11.1-11.30. 10.1146/annurev-environ-012320-083019.

Djakouré, S. , Konaté, Y. , Koné, V. , Bosson, K. , Koné, M. and Kouadio, K. (2024) Relationship between the Guinea Current and the Coastal Upwelling in Northern of Gulf of Guinea. *Open Journal of Marine Science*, **14**, 63-77. doi: 10.4236/ojms.2024.144004.

Eyring, V., Bony, S., Meehl, G. A., Senior, C. A., Stevens, B., Stouffer, R. J., and Taylor, K. E.: Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization, *Geoscientific Model Development*, 9, 1937-1958, doi:10.5194/gmd-9-1937-2016, 2016.

FAO. (2020). The State of World Fisheries and Aquaculture 2020. Sustainability in action. Rome. https://doi.org/10.4060/ca9229en

Froehlich, H. E., Jacobsen, N. S., Essington, T. & Clavelle, T. & Halpern, B. (2018). Avoiding the ecological limits of forage fish for fed aquaculture. Nature Sustainability. 1. 10.1038/s41893-018-0077-1.

Gattuso JP, Magnan A, Billé R, Cheung WW, Howes EL, Joos F, Allemand D, Bopp L, Cooley SR, Eakin CM, Hoegh-Guldberg O, Kelly RP, Pörtner HO, Rogers AD, Baxter JM, Laffoley D, Osborn D, Rankovic A, Rochette J, Sumaila UR, Treyer S, & Turley C. (2015). OCEANOGRAPHY. Contrasting futures for ocean and society from different anthropogenic CO_2 emissions scenarios. *Science*. Jul 3;349(6243):aac4722. doi: 10.1126/science.aac4722. PMID: 26138982.

Gregor, L., & Gruber, N. (2023). Four decades of trends and drivers of global surface ocean acidification. *Global Biogeochemical Cycles*. https://doi.org/10.1029/2023gb007765.

Hauser Leon, Boni Roberta, Minderhoud Philip S.J., Teatini Pietro, Woillez Marie-Noëlle, Almar Rafael, Avornyo Selasi Yao (2023). *Agence Francaise De Development AFD Research Papers*, No. 283.

Kwasi Appeaning AddoA scoping study on coastal vulnerability to relative sea-level rise in the Gulf of Guinea

Hagens, M., & Middelburg, J. J. (2016). Generalised expressions for the response of pH to changes in ocean chemistry. *Geochimica et Cosmochimica Acta*, *187*, 334–349. https://doi.org/10.1016/J.GCA.2016.04.012

IPCC (2023). *Climate Change 2023: Synthesis Report.* Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland, pp. 35-115, doi: 10.59327/IPCC/AR6-9789291691647.

Jewett, L., & Romanou, A. (2017). *Ocean changes – warming, stratification, circulation, acidification, and deoxygenation*. https://digitalcommons.unl.edu/cgi/viewcontent.cgi?article=1583

Kubin, E., Lipizer, M., Molina Jack, M. E., French, M., & Giorgetti, A. (2024). *Ocean Acidification: Weaves to be tied on European and global scale*. https://doi.org/10.5194/egusphere-egu24-19568

Jiang, L.-Q., Dunne, J., Carter, B. R., Tjiputra, J. F., Terhaar, J., Sharp, J. D., Olsen, A., Alin, S., Bakker, D. C. E., Feely, R. A., Gattuso, J.-P., Hogan, P., Ilyina, T., Lange, N., Lauvset, S. K., Lewis, E. R., Lovato, T., Palmieri, J., Santana-Falcón, Y., Schwinger, J., Séférian, R., Strand, G., Swart, N., Tanhua, T., Tsujino, H., Wanninkhof, R., Watanabe, M., Yamamoto, A., and Ziehn, T. (2023). Global surface ocean acidification indicators from 1750 to 2100.

Journal of Advances in Modeling Earth Systems, 15, e2022MS003563. https://doi.org/10.1029/2022MS003563.

Jiang, L.-Q., Carter, B. R., Feely, R. A., Lauvset, S. K., & Olsen, A. (2019). Surface ocean pH and buffer capacity: past, present and future. *Scientific Reports*, *9*(1), 18624. https://doi.org/10.1038/S41598-019-55039-4

Koffi, K. U., Konan, E. S., Hassoun, A. R., Kouadio, Y. (2024). Relationship between the carbonate system and phytoplankton community in the Gulf of Guinea-Africa. *Frontiers in Marine Science*, 11. DOI:10.3389/fmars.2024.1286338, ISSN: 2296-7745, https://www.frontiersin.org/journals/marine-science/articles/10.3389/fmars.2024.1286338.

Lam, V., & De Fontaubert, C. (2019). *Climate Change and Marine Fisheries in Africa : Assessing Vulnerability and Strengthening Adaptation Capacity*. 1–76. https://documents.worldbank.org/curated/en/280891580715878729/Climate-Change-and-Marine-Fisheries-in-Africa-Assessing-Vulnerability-and-Strengthening-Adaptation-Capacity.

Lauvset, S. K., Lauvset, S. K., Gruber, N., Landschützer, P., Olsen, A., Olsen, A., & Tjiputra, J. (2015). Trends and drivers in global surface ocean pH over the past 3 decades. *Biogeosciences*, *12*(5), 1285–1298. https://doi.org/10.5194/BG-12-1285-2015

Loucaides, S., Tyrrell, T., Achterberg, E. P., Torres, R., Nightingale, P. D., Kitidis, V., Serret, P., Woodward, M., & Robinson, C. V. (2012). Biological and physical forcing of carbonate chemistry in an upwelling filament off northwest Africa: Results from a Lagrangian study. *Global Biogeochemical Cycles*, *26*(3). https://doi.org/10.1029/2011GB004216

Mathis, M., Lacroix, F., Hagemann, S., Nielsen, D., Ilyina, T., & Schrum, C. (2024). Enhanced CO_2 uptake of the coastal ocean is dominated by biological carbon fixation. *Nature Climate Change*. https://doi.org/10.1038/s41558-024-01956-w

Nduka, J., Okafor, V. & Odiba, I. (2016). Impact of Oil and Gas Activities on Acidity of Rain and Surface Water of Niger Delta, Nigeria: An Environmental and Public Health Review. *Journal of Environmental Protection*, **7**, 566-581. doi: 10.4236/jep.2016.74051.

Nnaemeka, E. I. (2024). Sustainable Practices and Economic Impacts of Small Scale Fisheries in Coastal Communities of West Africa. *IAA Journal of Arts and Humanities*, *11*(2), 43–45. https://doi.org/10.59298/iaajah/2024/11.4345.33

Nunoo, F. & Quansah, Edna & Patrick, Ofori-Danson. (2016). Preliminary Studies on Impacts of Ocean Acidification on Diversity of Fish Species Landed By Artisanal and Semi-Industrial Fisheries in Ghana. International Journal of Marine Science. 10.5376/ijms.2016.06.0027.

Rim-Rukeh, A. (2018). Acidification Status of Surface Waters in the Niger Delta, Nigeria: A Review of Results and Predictions for the Future. *Equatorial Journal of Agriculture and Earth Sciences*, 2(1); Available at SSRN: https://ssrn.com/abstract=3159407

Scheren, Peter & Ibe, Chidi & Janssen, F & Lemmens, A.M. (2002). Environmental pollution in the Gulf of Guinea - A regional approach. *Marine Pollution Bulletin*. 44. 633-41. 10.1016/S0025-326X(01)00305-8.

Todd, L. Capson, Marie Boye. Climate change: West Africa's oceans at risk because of a lack of monitoring. 2022. HAL-04030179. https://hal.science/hal-04030179v1

Yavo, F. P. R., Tiemele, J., Koffi, K. U., Djagoua, É. V., & Ochou, A. D. (2024). Influence of Climatic and Oceanographic Parameters on CO_2 Exchanges at the Air-sea Interface in the Gulf of Guinea. *International Journal of Environment and Climate Change*. https://doi.org/10.9734/ijecc/2024/v14i114583.