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ARTICLE

Assessing the Impact of Gas Flaring and Carbon Dioxide Emissions on Precipitation Patterns in the Niger Delta Region of Nigeria Using Geospatial Analysis

Otutu Anslem Onyebuchi[1*], *Eteh Desmond Rowland*[2], *Iluma Vieme Phoebe*[3]

[1] *Department of Physics, Niger Delta University, Wilberforce Island, Bayelsa State, 560001, Nigeria*

[2] *Department of Geology, Niger Delta University, Wilberforce Island, Bayelsa State, 560001, Nigeria*

[3] *Department of Biology, Niger Delta University, Wilberforce Island, Bayelsa State, 560001, Nigeria*

ABSTRACT

This research utilizes geospatial methodologies to investigate the influence of gas flaring and carbon dioxide emissions on precipitation patterns within the Niger Delta region of Nigeria. The study relies on average mean precipitation data sourced from CHRS at the University of Arizona and carbon dioxide emissions data from NASA's AIRS in Giovanni, spanning from July 2002 to November 2011. To carry out the analysis, ArcGIS 5.0 and SPSS 25, employing Inverse Distance Weighting (IDW), were employed to assess CO_2 emissions and rainfall for both November and July during the period from 2002 to 2011. Over the course of this study, it was observed that CO_2 emission exhibited an upward trend, increasing from 327.5226 parts per million (ppm) in July 2002 to 390.0077 ppm in November 2011. Simultaneously, the rainfall demonstrated an increase, rising from 56.66 millimeters to 390.78 millimeters for both July and November from 2002 to 2011. Noteworthy findings emerged from the correlation analysis conducted. Specifically, from July 2000 to 2011, there was a weak positive correlation (0.3858) observed between CO_2 emissions and minimum rainfall, while a strong negative correlation (–0.7998) was identified for maximum rainfall values. In November, both minimum and maximum CO_2 emissions displayed strong negative correlations with rainfall, with coefficients of –0.8255 and –0.7415, respectively. These findings hold significant implications for comprehending the environmental dynamics within the Niger Delta. Policymakers and stakeholders can leverage this knowledge to formulate targeted strategies aimed at mitigating CO_2 emissions and addressing potential climate change-induced alterations in rainfall patterns.

Keywords: Remote sensing; CO_2 emissions; Rainfall; Atmospheric infrared sounder (AIRS); Climate change; Impact; Gas flaring

*CORRESPONDING AUTHOR:

Otutu Anslem Onyebuchi, Department of Physics, Niger Delta University, Wilberforce Island, Bayelsa State, 560001, Nigeria; Email: otutuanslem@gmail.com

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1. Introduction

The Niger Delta region in Nigeria, often known as the "Heart of Nigeria", is famous not only for its abundant biodiversity and oil reserves but also for grappling with significant environmental challenges. Among these challenges, increasing attention has been focused on the detrimental effects of gas flaring and carbon dioxide emissions on both the local ecosystem and the global climate [1]. In response, the application of remote sensing technologies has emerged as a powerful tool for monitoring and examining the impacts of these environmental stressors on the delicate balance of rainfall patterns in the area. Remote sensing technologies provide a means to observe and assess the consequences of these environmental stressors on rainfall patterns. This approach enables data collection from a distance, allowing for the monitoring of changes in land cover, vegetation, and atmospheric composition. Such data are crucial in assessing the influence of gas flaring and CO_2 emissions on rainfall patterns. Ismail and Umukoro [2] present compelling evidence that gas flaring exerts a substantial influence on the climate, both at local and global scales. On a local level, gas flaring emits a spectrum of pollutants, encompassing greenhouse gases, particulate matter, and volatile organic compounds, thereby contributing to air pollution. These emissions can give rise to a range of adverse health outcomes, such as respiratory ailments, cardiovascular issues, and cancer. Furthermore, gas flaring can induce alterations in local climate dynamics, where the release of greenhouse gases can trap heat in the atmosphere, elevating temperatures. Although particulate matter can attenuate sunlight and cool the atmosphere, this effect is typically eclipsed by the warming potential of greenhouse gases. On a global scale, methane, a prominent gas emitted during gas flaring, is identified as a greenhouse gas with over 80 times the heat-trapping capability of carbon dioxide over a two-decade span. This underscores the substantial impact even small quantities of methane can have on global warming. Additionally, gas flaring releases black carbon, a pollutant that absorbs sunlight and contributes to atmospheric warming. Black carbon particles can traverse long distances in the atmosphere, influencing climate patterns in distant regions. The research by Ismail and Umukoro [2] also implies that gas flaring can lead to modifications in precipitation patterns. This phenomenon is attributable to the emissions of greenhouse gases and pollutants altering cloud formation and precipitation processes. For instance, greenhouse gases, by trapping heat in the atmosphere, foster increased evaporation and higher water vapor levels in the air, promoting heightened cloud formation and subsequently, increased precipitation. Conversely, particulate matter's capacity to block sunlight and cool the atmosphere can have the opposite effect, resulting in reduced cloud formation and diminished precipitation. Okpobiri et al. [1] utilized geospatial technology to monitor and quantify carbon dioxide emissions and their impact on marine ecosystems in the Niger Delta as indicators of climate change. The authors employed various methods, including satellite imagery, remote sensing, and GIS, to gather and analyze data on these factors. Their findings indicated that the Niger Delta is a significant source of carbon dioxide emissions, and sea surface temperatures are rising in the region. These changes are negatively affecting marine ecosystems, including coral reefs and mangrove forests. The authors concluded that geospatial technology can be a valuable tool for monitoring and assessing the impacts of climate change in the Niger Delta and other coastal regions. Word Bank [3] report, the Global Gas Flaring Reduction Partnership (GGFR) approximates that in the year 2022, gas flaring resulted in the emission of 357 million metric tons of carbon dioxide equivalent (CO_2e). Out of this total, approximately 315 million metric tons were in the form of carbon dioxide (CO_2), while the remaining 42 million metric tons were in the form of methane (CH_4). Additionally, a study by Nduka, et al. [4] revealed that the practice of gas flaring in the Niger Delta region could potentially lead to the development of acid rain, which in turn poses dangers to agricultural crops, woodlands, infrastructure, and the well-being of individuals. Anejionu et al. [5] and Earsel et al. [6] utilized remote sensing for detecting and mapping gas flares. MODIS is a multispectral instrument that collects data in a variety of wavelengths, including the thermal infrared band. The thermal infrared band is sensitive to the heat emitted by gas flares, so it can be used to detect and map flares. The primary aim of this study is to utilize remote sensing techniques to investigate the interplay between gas flaring, CO_2 emissions, and rainfall patterns and correlation between CO_2 and rainfall in the Niger Delta region of Nigeria. Advanced satellite-based tools will be employed to monitor changes in land cover, vegetation, and atmospheric composition. The results of this research endeavor will enhance our understanding of the environmental challenges facing the Niger Delta and emphasize the importance of adopting sustainable practices in the oil and gas extraction industry.

2. Study Area

The Niger Delta region is located in the South-South geopolitical zone of Nigeria. It is bounded by longitudes 5° 05'E and 7° 35'E and latitudes 4° 15'N and 6° 01'N. The region consists of 9 oil-producing states (Abia, Akwa Ibom, Bayelsa, Cross River, Delta, Edo, Ondo, Imo, and Rivers) and 185 local government areas [7]. It is home to over 800 oil-producing communities and has an extensive network of over 900 producing oil wells and petroleum production-related facilities [8]. According to Sakib [9], the ecological zones in the Niger Delta can be broadly divided into two: the tropical rainforest in the northern part of the delta and the mangrove forest in the warm coastlines of Nigeria. Mangrove forests and swamps, which are characterized by regular saltwater inundation, lie at the centre of a complex and sensitive ecosystem that is vital to the local economy and accommodates important flora and fauna. The Niger Delta is the largest mangrove forest in Africa and the third largest in the world. It is also the richest part of Nigeria in terms of petroleum resources and diverse natural ecosystems supportive of numerous species of terrestrial and aquatic fauna [10]. The Niger Delta is the catchment of the Niger River as it enters the Atlantic Ocean in the Gulf of Guinea in a delta form. Other rivers such as the Cross River, Qua Iboe River, and Imo River to the east and the Forcados and Ethiope Rivers to the west, which also empty into the Gulf of Guinea close to the Niger River, join to constitute the catchments.

2.1 Limitation

The major challenge of this research work is that data acquisition from 2018 to the present has been extremely difficult due to inadequate funding as the materials required for the research are very expensive.

2.2 Literature review

The impact of carbon dioxide (CO_2) on various environmental systems, including groundwater, lakes, ice caps, and oceans, is a critical concern in today's world. This literature review explores the relationship between CO_2 emissions, greenhouse gases, and their effects on the environment, particularly focusing on the Niger Delta region in Nigeria.

Rising CO_2 emissions

The alarming projection made in the World Energy Outlook [13], which foresaw a rise in CO_2 emissions from 26 billion tonnes in 2004 to 40 billion tonnes by 2030, has unfortunately become a reality. According to the Global Carbon Budget 2023, global CO_2 emissions reached 41 billion tonnes in 2022, marking a 1.4% increase from 2021 and representing the highest recorded level of emissions. This increase in CO_2 emissions can be attributed to various factors, including the growing energy demand in developing countries, the persistent reliance on fossil fuels for electricity and transportation, and the expansion of industrial activities. Consequently, this surge in CO_2 emissions is wreaking havoc on our planet, contributing to climate change, which in turn results in more frequent extreme weather events, rising sea levels, and the accelerated melting of glaciers. Evidently, there is an urgent need for action to curtail CO_2 emissions. This entails a shift away from fossil fuels in favour of cleaner energy sources like solar and wind power, as well as adjustments in our personal lifestyles such as reducing driving and minimizing energy consumption at home. Governments, businesses, and individuals all have a role to play in reducing CO_2 emissions. Governments can invest in renewable energy and energy efficiency initiatives, while businesses can transition to cleaner energy sources and adopt measures to decrease their carbon footprint. Individuals can also make changes to their daily routines, such as driving less, conserving energy at home, and adopting more sustainable dietary choices. While reducing CO_2 emissions presents a complex challenge, it is one that must be addressed to safeguard our planet for future generations.

Greenhouse gases and global warming

Raúl et al. [14] discuss the impact of greenhouse gases (GHGs) on plant oxidative stress. GHGs, such as CO_2, contribute to global warming by trapping heat in the Earth's atmosphere. This can lead to extreme climate events, such as floods, droughts, and heat waves, which can all stress plants and induce oxidative stress. Oxidative stress is a condition in which the production of reactive oxygen species (ROS) exceeds the capacity of the antioxidant system to detoxify them. ROS are highly reactive molecules that can damage cellular components, including DNA, proteins, and lipids. CO_2 can have both positive and negative effects on plant oxidative stress. On the one hand, CO_2 is a substrate for photosynthesis, and increased CO_2 concentrations can lead to increased photosynthetic rates and biomass production. This can help plants to cope with some abiotic stresses, such as drought. On the other hand, high CO_2 concentrations can also lead to increased ROS production. This is because high CO_2 concentrations can increase the activity of Rubisco, an enzyme that is involved in photosynthesis. Rubisco can also catalyze a reaction that produces ROS. Another GHG, nitric oxide (NO), can also have both positive and negative effects on plant oxidative stress. NO is a signaling molecule that can have a variety of effects on plant growth and development. At low concentrations, NO can act as an antioxidant and help to protect plants from oxidative stress. However, at high concentrations, NO can also become a ROS and contribute to oxidative damage. The overall effect of GHGs on plant oxidative stress is complex and depends on a number of factors, including the species of plant, the concentration of GHGs, and the presence of other environmental stressors.

The study conducted by Chiroma et al. [15], revealed that OPEC's carbon dioxide (CO_2) emissions stemming from petroleum consumption have been on the rise, significantly contributing to the issue of global warming. The research employed a combination of a hybrid cuckoo search algorithm and an artificial neural network to forecast OPEC's CO_2 emissions for various time frames: 3, 6, 9, 12, and 16 years into the future. The outcomes demonstrated that this novel model exhibited enhanced precision and efficiency when compared to contemporary methodologies. Furthermore, the investigation underscored that OPEC nations were responsible for 7% of the world's CO_2 emissions in 2010, a substantial proportion considering their 40% share of global oil production. This study's ultimate implication was that precise forecasting of OPEC's CO_2 emissions holds paramount importance for policymakers and stakeholders in crafting effective strategies to combat global warming. This cited passage highlights the profound impact of greenhouse gases like CO_2, which possess a significant global warming potential due to their ability to trap heat in the atmosphere and contribute to climate change. While the greenhouse effect is a natural phenomenon vital for maintaining Earth's temperature, human activities have escalated greenhouse gas levels, leading to detrimental global warming consequences. Global warming poses a grave threat to both the planet and its inhabitants, manifesting in extreme weather events, rising sea levels, and the rapid melting of glaciers. OPEC countries bear a significant responsibility in curtailing their CO_2 emissions to combat global warming effectively.

Gas flaring and pollution

Gas flaring in the Niger Delta constitutes a severe environmental predicament, discharging detrimental pollutants into the atmosphere, thereby exacerbating air pollution, fostering acid rain, and contributing to noise pollution. According to a study by Nwaichi and Uzazobona [16], the annual emissions of over 100 million tons of CO_2 due to gas flaring in the Niger Delta correspond to the emissions of more than 20 coal-fired power plants. The repercussions of gas flaring on both the environment and human well-being are substantial. The air pollution stemming from gas flaring can lead to respiratory ailments, cardiovascular diseases, and even cancer. Acid rain poses a threat to crops and forests, while noise pollution can result in hearing impairment and various health issues. Furthermore, gas flaring represents a squandering of a valuable resource. Natural gas, a clean-burning fuel, has myriad applications, including electricity generation, heating for homes and businesses, and fertilizer production. By dissipating this gas through flaring, Nigeria is forfeiting a significant source of revenue and opportunities for economic advancement. Several strategies can be employed to curtail gas flaring in the Niger Delta. Firstly, enhancing oil production technologies can facilitate the capture and utilization of more gas. Secondly, establishing gas processing facilities can transform flared gas into marketable commodities. Finally, the government can enforce stricter regulations concerning gas flaring and extend financial incentives to companies that reduce or eliminate their flaring emissions. Mitigating gas flaring in the Niger Delta stands to yield numerous advantages. It would ameliorate air quality, diminish the impact of acid rain, and safeguard human health. Additionally, it would preserve a valuable natural resource and invigorate the Nigerian economy. Legislation and penalties have been introduced to mitigate gas flaring, but challenges remain as seen in **Figure 1**.

Figure 1. Gas flaring site [12].

Rainfall and climate change

The study by Ideki and Weli [17] offers a valuable examination of rainfall fluctuations in North Central Nigeria, employing advanced techniques such as remote sensing and geographic information systems (GIS). Their research reveals a noteworthy decrease in rainfall in this region over recent decades, with an average annual rainfall fluctuation of 896.1 mm during their study period from 2000 to 2017. This decline is particularly pronounced in the early rainy season, displaying a significant negative trend. The study also identifies spatial disparities in rainfall variability, with certain areas witnessing more substantial declines than others. For instance, it notes that high-rainfall regions in the southern part of the area have experienced milder declines compared to low-rainfall zones in the north. These findings align with earlier research documenting rainfall variability in Nigeria and the Sahel region as a whole. Researchers attribute this decline to factors including climate change, shifts in land usage, and the El Niño Southern Oscillation (ENSO). The dwindling rainfall in North Central Nigeria carries a range of adverse consequences for the region, including diminished agricultural output, water scarcity, and heightened susceptibility to droughts and floods. This underscores the urgency of addressing rainfall variability and bolstering climate resilience in the area.

The study highlights the importance of monitoring both CO_2 levels and rainfall. Therefore, the research emphasizes the use of remote sensing to monitor CO_2 levels in the atmosphere and hydrosphere during wet and dry seasons in the Niger Delta region. This approach can provide valuable insights into the relationship between CO_2 and rainfall patterns. In conclusion, the literature review highlights the critical importance of addressing rising CO_2 emissions, understanding their impact on various environmental systems, and monitoring their effects on rainfall patterns, particularly in regions like the Niger Delta. Mitigating CO_2 emissions and managing their consequences on climate and ecosystems are essential steps in addressing the challenges posed by climate change.

3. Materials and method

3.1 Materials

The subsequent remote sensing data utilized comprise the average mean rainfall data, sourced from the Center for Hydrometeorology and Remote Sensing (CHRS) at the University of Arizona, spanning the period from July 2002 to November 2008. Additionally, the mean Carbon dioxide emissions data were acquired from the Atmospheric Infrared Sounder (AIRS) through NASA's Giovanni platform (accessible at: https://giovanni.gsfc.nasa.gov/giovanni/) for the time frame extending from July 2002 to November 2011. These emissions data were derived from the PERSIANN-CCS system, which enables the categorization of cloud-patch characteristics based on parameters such as cloud altitude, spatial coverage, and texture variability as inferred from satellite imagery. Notably, this system provides real-time, high-resolution (0.04° × 0.04° or 4 km × 4 km) global satellite precipitation data. Additionally, the Niger Delta area map, Mapping Gas Flares in the Niger Delta, and Code of Africa (Impact Africa) by Schick [11] delineates the locations of gas flaring sites and oil and gas fields within the area (**Figure 2**).

3.2 Methodology

Remote sensing data from 44 stations in the Niger Delta from July 2002 to November 2011 was processed using ArcGIS software and the Inverse Distance Weighting (IDW) spatial interpolation method [18]. This allowed us to monitor the trend of carbon dioxide in the region, check the influence of rainfall on carbon dioxide levels, and understand the effect of global warming due to gas flaring. The ArcGIS software was launched and the data was prepared in Microsoft Excel sheets and saved in CSV format. The necessary settings were made in the software, the study area (Niger Delta) was imported, and the CSV file was imported. Then, the Arc toolbox was opened, the spatial analyst tools were selected, and the interpolation option was chosen. The IDW method was selected and the various years were specified. The process extent was selected, the study area was selected, and the spatial analysis option was clicked. Finally, the mask option was selected and the study area was again selected.

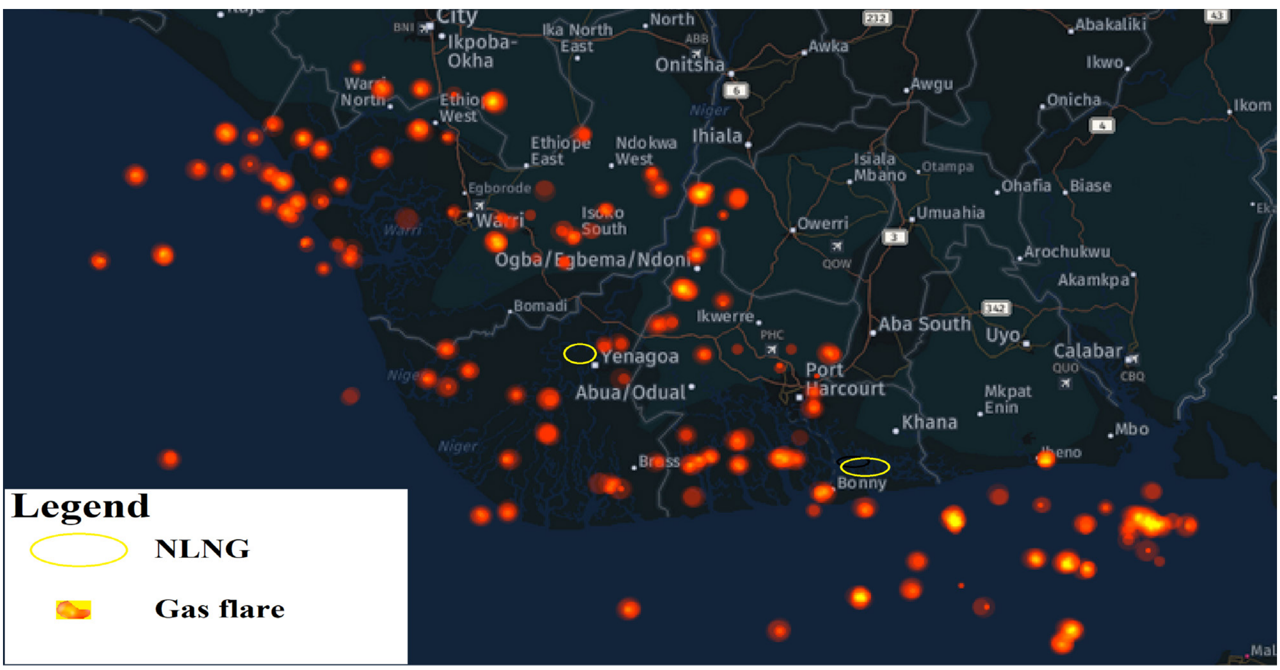


Figure 2. Location map of the Niger Delta region of Nigeria showing gas flaring fields (adapted from Schick [11]).

4. Results and discussions

The Niger Delta region in Nigeria is renowned for its abundant biodiversity and natural resources but confronts various environmental challenges, notably climate change [19]. Carbon dioxide (CO_2) emissions, primarily stemming from fossil fuel combustion, are a prominent driver of global climate change [20]. This study's objective is to assess CO_2 emission levels within the Niger Delta, with a specific focus on the years 2002, 2005, 2008, and 2011. **Table 1** provides data on the minimum and maximum CO_2 emissions for November and July during the years from 2002 to 2011. Numerous factors, including industrial activities, transportation, deforestation, and land-use changes, influence CO_2 emissions in the Niger Delta [20]. Analysing these emissions yields insights into the region's climate change impact, aiding policymakers and stakeholders in crafting effective mitigation and adaptation strategies [19]. July and November hold special significance for carbon dioxide levels and rainfall patterns in the Niger Delta from 2002 to 2011, due to its distinctive climate and environmental dynamics. July marks the height of the rainy season, when warm, moisture-laden air from the Atlantic Ocean migrates inland, resulting in substantial rainfall. This abundant rainfall plays a pivotal role in carbon dioxide regulation. The increased moisture fosters plant growth, enabling photosynthesis that absorbs CO_2 from the atmosphere while releasing oxygen. This process, combined with augmented cloud cover, helps stabilize CO_2 concentrations. Conversely, November signals the transition from the rainy to the dry season. As rainfall diminishes, vegetation loses its lushness, and photosynthesis rates decline. Consequently, CO_2 levels gradually rise as vegetation absorbs less CO_2. Additionally, this transition often ushers in unstable weather patterns and reduced rainfall, potentially impacting the region's water resources and agriculture. Monitoring these two critical months over the 2002-2011 decade is imperative for comprehending long-term climate trends and their consequences on the delicate balance between CO_2 levels and rainfall in the Niger Delta. Changes in these patterns could profoundly affect the region's ecosystems, agriculture, and overall environmental well-being. Thus, continuous monitoring and study of these fluctuations are essential for guiding sustainable practices and adapting to potential shifts in climate and carbon dynamics.

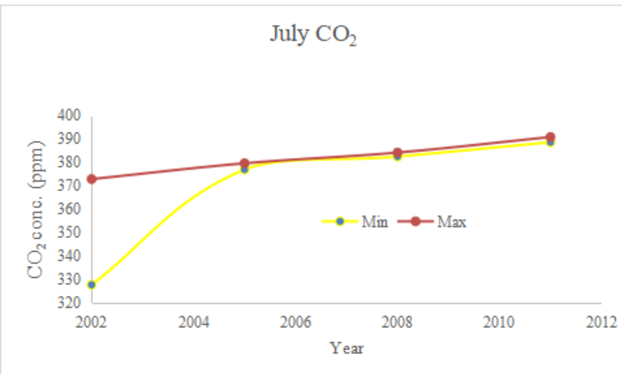
Table 1. Carbon dioxide emission for minimum and maximum.

Year	2002	2005	2008	2011
Min (November)	367.5351	378.1126	383.6403	390.0077
Max (November)	373.4932	380.1209	385.7512	391.608
Min (July)	327.5226	376.8556	382.3989	388.5471
Max (July)	372.7715	379.5303	384.1261	390.7832

Carbon dioxide emissions in July

Gas flaring has been a long-standing environmental problem in the Niger Delta region of Nigeria, resulting in the substantial release of carbon dioxide (CO_2) into the atmosphere. The effect of this practice on the region's CO_2 emissions can be evaluated by examining the data presented in **Table 1** and **Figure 3b**. **Table 1** provides data on the minimum and maximum CO_2 levels in parts per million for the years 2002, 2005, 2008, and 2011. These figures reveal a consistent increase in CO_2 emissions over the course of the decade. The minimum values rose from 327.52 ppm in 2002 to 388.55 ppm in 2011, while the maximum values increased from 372.77 ppm in 2002 to 390.78 ppm in 2011. This upward trend indicates that CO_2 emissions in the Niger Delta have steadily risen during this period. **Figure 3a** visually represents tropospheric CO_2 emissions from July 2002 to 2011. The graph likely exhibits a similar upward trend as observed in the table, confirming that gas flaring has had a significant impact on CO_2 emissions in the region.

These findings have concerning implications. Increasing CO_2 emissions contribute to global climate change, resulting in higher temperatures, rising sea levels, and extreme weather events. Additionally, the Niger Delta region itself faces adverse effects, including air pollution that can harm both human health and ecosystems. Addressing this issue requires a multifaceted approach, including the reduction of gas flaring through improved technology and regulations, as well as a transition to cleaner energy sources. Furthermore, international cooperation is essential to mitigate the global consequences of such emissions. The spatial distribution map in **Figure 4a** illustrates that in July 2002, areas such as Ondo, Edo, and parts of Delta State had elevated CO_2 levels. In 2005, sections of Edo, Delta, and Bayelsa states exhibited high CO_2 levels in July, as depicted in **Figure 4b**. By July 2008, as shown in **Figure 4c**, only portions of Cross River State displayed elevated CO_2 levels, and in July 2011 (**Figure 4d**), parts of Delta, Bayelsa, and Cross River State experienced increased CO_2 levels. The surge in July's CO_2 emissions can be attributed to various factors, including increased energy consumption for cooling due to rising temperatures, expanded agricultural activities, and potential changes in land-use patterns. Additionally, seasonal fluctuations in economic activities and energy demand may contribute to the observed variations.



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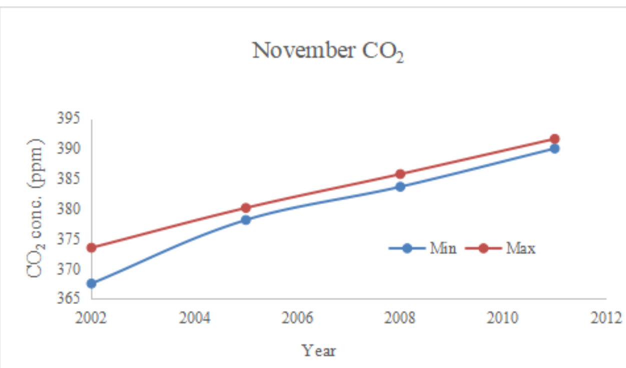


(b)

Figure 3. Tropospheric carbon dioxide emission from July, 2002-2011 (a) and November, 2002-2011 (b) in Niger Delta, Nigeria.

Carbon dioxide emissions in November

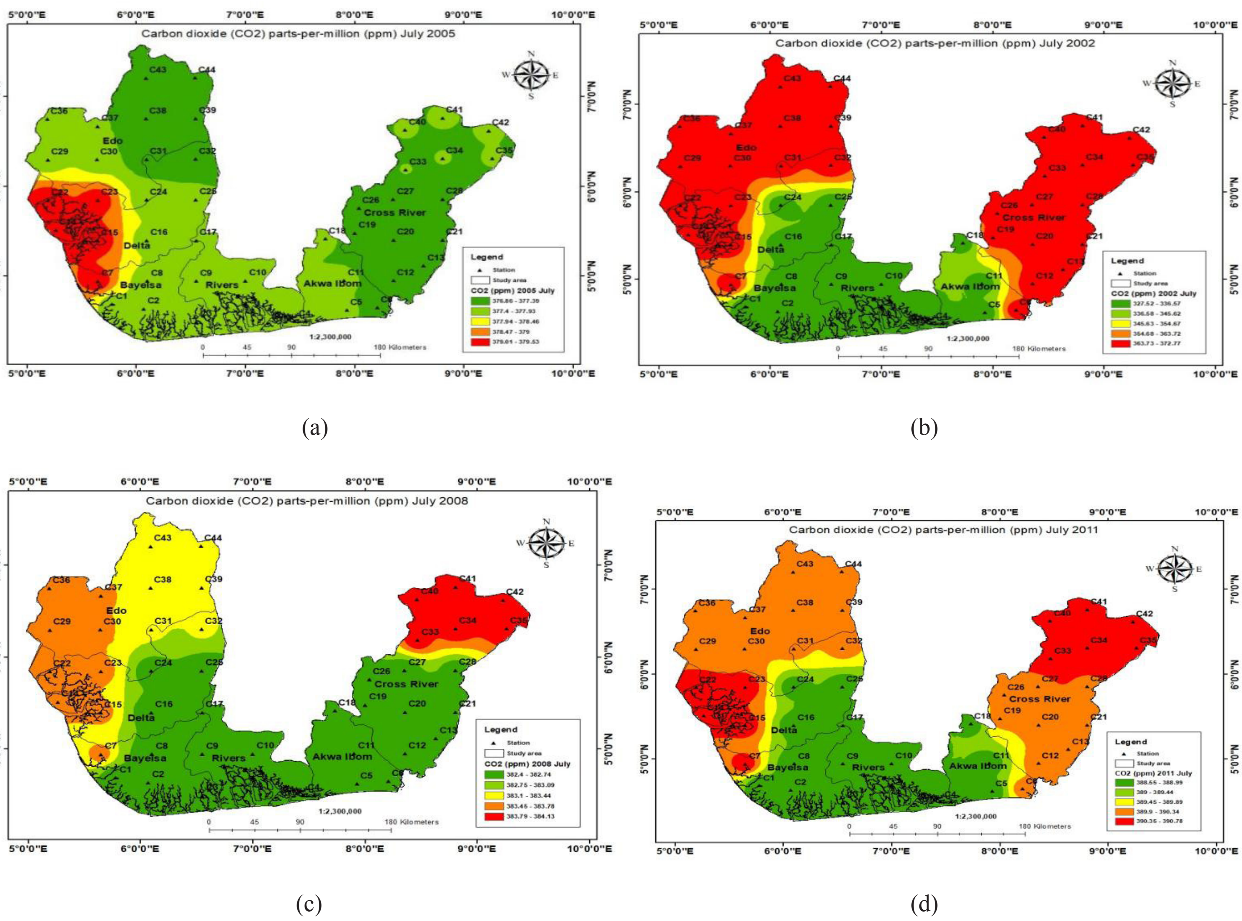
To evaluate the impact of gas flaring on CO_2 emissions in the Niger Delta region, we can analyse the data presented in **Table 1** and **Figure 3a**, which depicts the levels of tropospheric CO_2 emissions between November 2002 and 2011. **Table 1** provides information on the yearly minimum and maximum CO_2 emission values. It's evident that both the minimum and maximum emissions have gradually increased from 2002 to 2011. The minimum emissions range from 367.54 to 390.01 ppm, while the maximum emissions range from 373.49 to 391.61 ppm. This upward trajectory clearly indicates a consistent rise in CO_2 emissions during this period. **Figure 3b** visually illustrates this trend, showing a continuous increase in CO_2 emissions over the years. This trend aligns with the growing concerns regarding the impact of gas flaring in the Niger Delta. Gas flaring is a common practice in the region's oil extraction industry, where excess natural gas is burned off into the atmosphere, releasing CO_2 and other harmful pollutants. The increasing trend in CO_2 emissions has several adverse consequences. Firstly, it contributes to global warming and climate change since CO_2 is a greenhouse gas that traps heat in the atmosphere. This can lead to more severe weather events, rising sea levels, and disruptions to ecosystems. Moreover, higher CO_2 emissions can negatively affect human health by contributing to air pollution and respiratory diseases. It can also have detrimental effects on local ecosystems, including marine life and vegetation. The spatial distribution map presented in **Figure 5a** shows that in November 2002, regions encompassing Ondo, parts of Edo, and Delta State displayed elevated CO_2 levels. In **Figure 5b** for 2005, areas including Rivers, Bayelsa, parts of Delta, and Akwa Ibom States exhibited heightened CO_2 levels during November. Moving forward to November 2008 in **Figure 4c**, we observed that Rivers, Bayelsa, parts of Delta, and Akwa Ibom States continued to demonstrate elevated CO_2 levels. In **Figure 4d** for November 2011, parts of Delta, Bayelsa, Rivers, a small section of Akwa Ibom, and Cross River State experienced increased CO_2 levels. These findings collectively point to an overall escalation in CO_2 emissions within the Niger Delta region during the specified years. This rise in emissions can be attributed to a variety of factors, including population growth, economic development, and the expansion of the industrial sector. Rapid industrialization and urbanization typically lead to a greater demand for energy, resulting in increased burning of fossil fuels and subsequent CO_2 emissions. Identifying the specific sectors responsible for these emissions is crucial in order to develop targeted strategies for mitigation.

Rainfall

The Niger Delta, located in southern Nigeria, is a region characterized by a unique geological and environmental setting, making it susceptible to the impacts of climate change. Rainfall patterns are crucial in this area, as they directly influence vegetation growth, river systems, soil erosion, and overall ecosystem stability. Monitoring and interpreting rainfall trends are essential to understanding how climate change might be affecting this region and, consequently, its geological features.

Rainfall in July

To gain insights into the potential repercussions of gas flaring on precipitation, we can examine **Table 2**, which provides information on rainfall patterns in the Niger Delta during the month of July. **Table 2** illustrates the range of rainfall values for July over a specific timeframe, with values spanning from a minimum of 112.5 mm to a maximum of 463.38 mm. These fluctuations in rainfall are critical for assessing the impact of gas flaring since any increase or decrease in rainfall can significantly influence the region's ecosystems, agriculture, and water resources. For a deeper understanding, it is advisable to scrutinize **Figure 6a**, which depicts the July rainfall data from 2002 to 2011 in the Niger Delta. This dataset offers a temporal perspective on precipitation patterns, allowing us to identify trends and potential associations with gas flaring activities during this pe-



(a)

(b)

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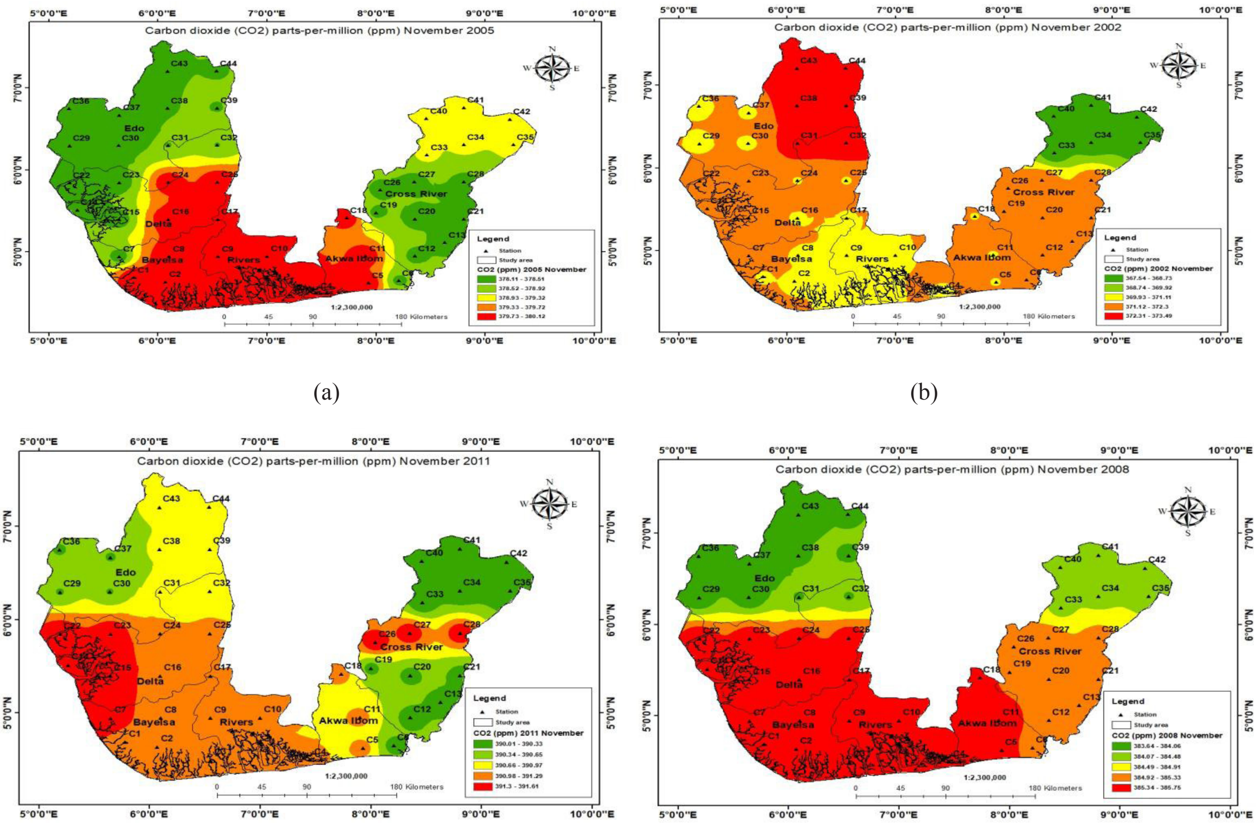
Figure 4. Tropospheric carbon dioxide emission in Niger Delta, Nigeria. July (a) 2002, (b) 2004, (c) 2008 and (d) 2011.



(a) (b)

(c) (d)

Figure 5. Tropospheric carbon dioxide emission in Niger Delta, Nigeria. November (a) 2002, (b) 2004, (c) 2008 and (d) 2011.

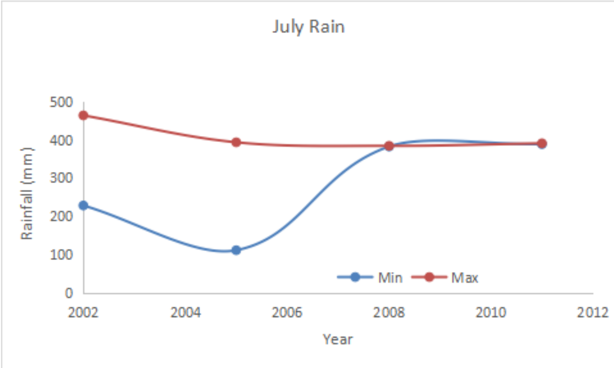
riod. Upon analyzing **Figure 6a**, we can potentially detect shifts or anomalies in rainfall patterns over the years. If there is a consistent trend of increasing or decreasing rainfall that corresponds to the intensity of gas flaring, it could indicate a causative link between the two. Nevertheless, it is crucial to consider other factors such as climate variability and changes in land use that may also impact precipitation. A spatial distribution map reveals that specific areas within Bayelsa, Delta, Akwa Ibom, and Cross Rivers States experienced elevated levels of rainfall in July 2002 (**Figure 7a**). In July 2005 (**Figure 7b**), high rainfall levels were observed in parts of Akwa Ibom and Cross River States. Similarly, in July 2008 (**Figure 7c**), regions within Rivers, Akwa Ibom, and Cross Rivers States displayed increased rainfall levels. In 2011 (**Figure 7d**), portions of Rivers, Edo, Delta, Bayelsa, and Akwa Ibom States witnessed higher levels of rainfall. It is important to note that the July rainfall data does not exhibit a clear and consistent trend. These fluctuations in rainfall can be attributed to various climate drivers and natural variability, underscoring the complexity of the factors influencing precipitation in this region.

Table 2. Rainfall for minimum and maximum.

Year	2002	2005	2008	2011
Min (November)	56.66	54.82	8.18	15.21
Max (November)	338.23	300.19	332.25	253.94
Min (July)	228.9	112.5	382.4	388.55
Max (July)	463.38	393.38	384.13	390.78

Rainfall in November

To comprehend this phenomenon, we can examine **Table 2**, which displays data regarding November's precipitation from 2002 to 2011, as well as **Figure 6b**, which illustrates rainfall trends over the same timeframe. **Table 2** uncovers significant fluctuations in rainfall patterns. In 2002 and 2005, the lowest monthly recorded rainfall stood at 56.66 mm and 54.82 mm, respectively. However, in 2008



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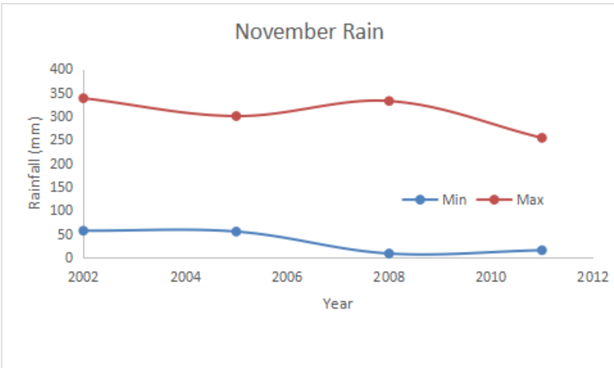


(b)

Figure 6. Rain for July 2002-2011 (a) and November 2002-2011 (b) in Niger Delta, Nigeria.

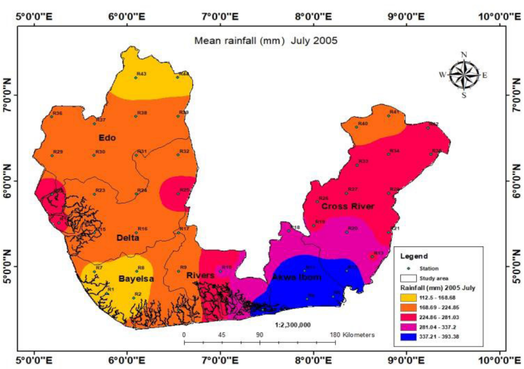
and 2011, this minimum dropped notably to 8.18 mm and 15.21 mm. This decline in minimum rainfall suggests the possibility of changes in the local water cycle, which could have detrimental impacts on agriculture and water resources. Furthermore, an examination of **Figure 6b** offers a more comprehensive view. Although the data spans from July 2002 to 2011, we can observe variations in rainfall trends. These fluctuations might be influenced by gas flaring activities, as the release of greenhouse gases such as methane can affect atmospheric conditions and modify precipitation patterns. Gas flaring emits pollutants like sulfur dioxide and nitrogen oxides, which can contribute to the formation of acid rain. This could explain the reduced minimum rainfall observed in specific years, notably 2008 and 2011. Acid rain can harm ecosystems, corrode infrastructure, and further disrupt regional climate patterns. When we look at the spatial distribution maps depicted in **Figures 8a-8d**, it becomes evident that particular areas within parts of Akwa Ibom, Cross Rivers, Bayelsa, and Delta States experienced increased levels of rainfall during the period from November 2002 to 2011.

Therefore, the variations observed in the rainfall patterns of the Niger Delta over the ten-year period may have several implications for the region's geological dynamics and environmental health. Changes in precipitation patterns can influence river systems, leading to alterations in sediment transport, erosion, and deposition processes. Additionally, fluctuations in rainfall can impact soil moisture content, potentially influencing groundwater levels and affecting local ecosystems, agriculture, and biodiversity.

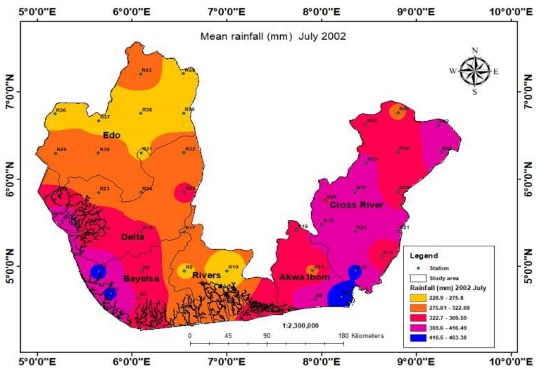
Pearson correlation coefficient between CO_2 and rainfall in the Niger Delta

This analysis is based on Pearson correlation coefficients calculated from CO_2 concentration and rainfall data for the Niger Delta region from July and November of 2002 to 2011. The correlation coefficient (r) measures the strength and direction of the linear relationship between the two variables. The values of r range from –1 to +1, with –1 indicating a perfect negative correlation, 0 indicating no correlation, and +1 indicating a perfect positive correlation.

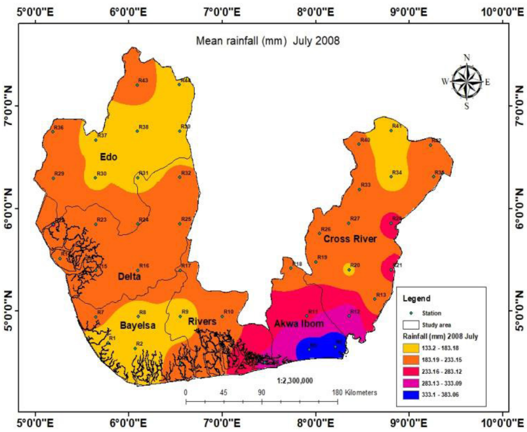
Table 3 presents the Pearson correlation coefficients for CO_2 and rainfall in the Niger Delta for the period of July 2000 to 2011. The minimum correlation coefficient recorded is 0.3858, indicating a weak positive correlation between CO_2 concentration and rainfall. The maximum correlation coefficient is -0.7998, revealing a strong negative correlation between the two variables. In **Table 4**, which covers the period of November 2000 to 2011, the minimum correlation coefficient is –0.8255, indicating a strong negative correlation between CO_2 and rainfall. The maximum correlation coefficient for this period is –0.7415, also indicating a strong negative correlation. Weak Positive Correlation (r = 0.3858): The weak positive correlation between CO_2 concentration and rainfall in the Niger Delta suggests that, to some extent, an increase in CO_2 levels might be associated with a slight increase in rainfall. However, it is important to note that this correlation is weak, meaning other factors likely play a more significant role in in-



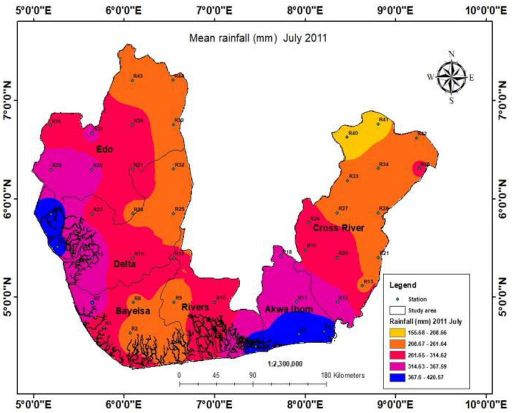
(a)



(b)

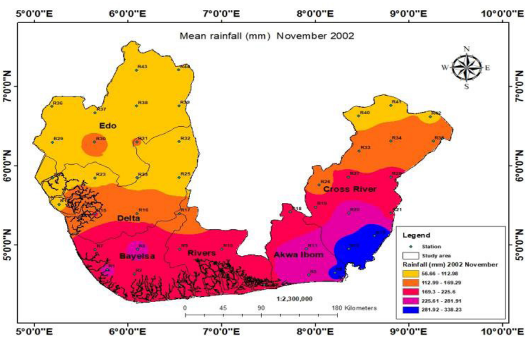


(c)

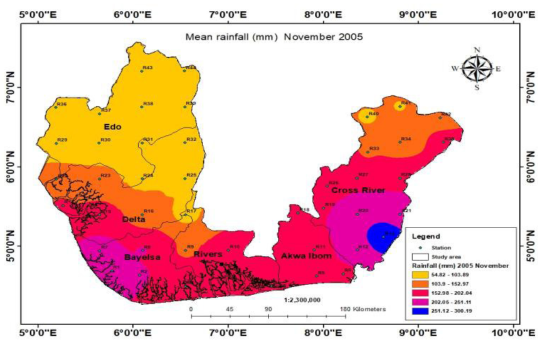


(d)

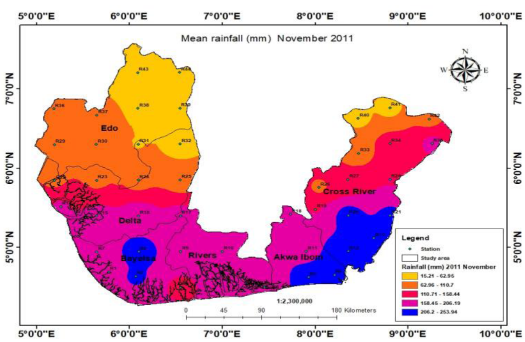
Figure 7. Rainfall in Niger Delta, Nigeria. July (a) 2002, (b) 2004, (c) 2008 and (d) 2011.



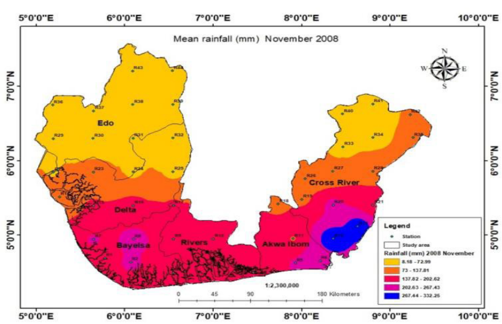
(a)



(b)



(c)



(d)

Figure 8. Rainfall in Niger Delta, Nigeria. November (a) 2002, (b) 2004, (c) 2008 and (d) 2011.

fluencing rainfall patterns in the region. Strong Negative Correlation (r = –0.7998 and r = –0.8255): The strong negative correlation observed in both July and November data indicates that as CO_2 concentration increases, there is a decrease in rainfall in the Niger Delta. This finding is particularly concerning, as it suggests that higher CO_2 levels might be associated with drier conditions in the region. Reduced rainfall can have severe consequences for agriculture, water availability, and ecosystem health. Therefore, the observed strong negative correlations between CO_2 concentration and rainfall in the Niger Delta have important implications for climate change in the region. While a weak positive correlation between CO_2 and rainfall might initially appear beneficial, it is essential to recognize that other factors likely have a more substantial impact on rainfall patterns.

Table 3. Pearson correlation coefficient between CO_2 and rainfall from July 2002 to 2011 in the Niger Delta.

2000-2011 (July)	r	Strength	Direction
Minimum	0.3858	Weak	Positive
Maximum	–0.7998	Strong	Negative

Table 4. Pearson correlation coefficient between CO_2 and Rainfall from November 2002 to 2011 in the Niger Delta.

2000-2011 (November)	r	Strength	Direction
Minimum	–0.8255	Strong	Negative
Maximum	–0.7415	Strong	Negative

The negative correlation raises concerns about potential feedback loops. As CO_2 concentrations rise due to human activities like burning fossil fuels and deforestation, it leads to higher temperatures and altered weather patterns. Reduced rainfall can result in decreased vegetation cover and changes in the hydrological cycle, further exacerbating climate change.

Factors such as sea surface temperatures, atmospheric circulation patterns, and local land use changes can influence rainfall in the Niger Delta. Additionally, the relatively short timescale of the data (2002 to 2011) might not fully capture long-term climate trends and variability.

Implications

The analysis of carbon dioxide emissions in the Niger Delta region provides valuable insights into the region's contribution to climate change. The upward trend in CO_2 emissions observed in both November and July indicates a potential increase in greenhouse gas concentrations, which can exacerbate global warming and its associated impacts. Understanding the factors driving CO_2 emissions is crucial for designing effective mitigation and adaptation strategies. Policymakers and stakeholders should focus on implementing sustainable practices and promoting renewable energy sources to reduce dependency on fossil fuels. Efforts should also be directed towards promoting afforestation, sustainable land-use practices, and enhancing public awareness about the consequences of carbon dioxide emissions. Additionally, international collaborations and financial support are necessary to assist countries, like Nigeria, in implementing climate change mitigation and adaptation measures. The findings of this study can serve as a baseline for future monitoring and assessment of carbon dioxide emissions in the Niger Delta region. The rainfall data analysis for the Niger Delta from 2002 to 2011 provides valuable insights into potential climate change impacts on the region. While the data reveals fluctuations in both minimum and maximum rainfall values, caution must be exercised in attributing these variations solely to climate change. Natural climate drivers and geological factors play significant roles in shaping rainfall patterns in the Niger Delta.

5. Conclusions and recommendations

5.1 Conclusions

The analysis of carbon dioxide emissions in the Niger Delta region during the years 2002-2011 reveals a notable increase in emissions. This finding highlights the urgency of taking immediate action to mitigate the adverse effects of climate change.

Encouraging sustainable practices that promote a low-carbon future is essential for fostering a more resilient and sustainable future for the Niger Delta and beyond. By addressing the factors contributing to carbon dioxide emissions, we can pave the way for a more environmentally conscious approach to development in the region. Examining the rainfall data for the Niger Delta from 2002 to 2011 provides valuable insights into potential climate change impacts on the region's hydrology. While the data shows fluctuations in both minimum and maximum rainfall values, it is crucial to exercise caution when attributing these variations solely to climate change. Natural climate drivers and geological factors play significant roles in shaping rainfall patterns in the Niger Delta, underscoring the complexity of the region's climate system. The observed strong negative correlation between CO_2 concentration and rainfall in the Niger Delta reinforces the need to consider this relationship in the context of climate change. The results suggest that increasing CO_2 levels may be associated with reduced rainfall, posing significant implications for the region's ecosystems and communities. Addressing the challenges posed by climate change demands comprehensive research that takes multiple variables into account and incorporates long-term data to develop effective strategies for climate adaptation and mitigation. Therefore, a holistic approach to understanding climate change impacts in the Niger Delta is crucial. The region's vulnerability to the changing climate underscores the importance of implementing sustainable practices and policies to ensure a more stable and sustainable future. This necessitates collaborative efforts across disciplines and sectors to develop adaptive and resilient solutions that can safeguard the Niger Delta's unique environment and support its communities.

5.2 Recommendations

Mitigating Carbon Dioxide Emissions: The overall increase in carbon dioxide emissions during the years 2002-2011 calls for urgent action to curb these emissions. Implementing policies and initiatives that reduce reliance on fossil fuels and promote the use of renewable energy sources, such as solar and wind power, can significantly contribute to lowering carbon dioxide emissions in the region. Sustainable Land Use Practices: Deforestation and land-use changes are significant contributors to carbon dioxide emissions. Encouraging sustainable land use practices, such as reforestation and afforestation, can help sequester carbon and mitigate emissions. Additionally, implementing sustainable agricultural practices that prioritize soil health and carbon sequestration can also play a crucial role in reducing emissions. Climate Resilience and Adaptation Strategies: Given the strong negative correlation between CO_2 concentration and rainfall, the Niger Delta must develop and implement climate resilience and adaptation strategies. These may include improved water management systems, the promotion of water conservation practices, and the development of drought-resistant crop varieties to cope with potential changes in rainfall patterns.

Author Contributions

Otutu, A.O. designed the study and contributed to its writing; Eteh, D.R. processed the data and did statistical analysis and writing; and Iluma, V.P. aided with writing and formatting. All writers contributed to the final draft.

Conflict of Interest

Authors have declared that no competing interests exist.

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