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Geospatial assessment of climate sensitivity in Ibarapa North, Oyo State, Nigeria

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ABSTRACT

This study employed remote sensing and geographic information system (GIS) to evaluate the spatial pattern of carbon(iv)oxide (CO_2) concentration and the resulting climate sensitivity in Ibarapa North local government areas of Oyo State, Nigeria. The evaluation was carried out using Landsat images of 2003 and 2023, digital elevation model, as well as CO_2 data collected with CO_2. meter. Surface temperature and radiative forcing were generated from the satellite images using random forest algorithm in *R* software environment, while the climate sensitivity was evaluated using Drakes' Sensitivity Linear Model. The results revealed mean air temperature of 31.5°C and 32.7°C in 2003 and 2023 respectively. The area experienced positive radiative forcing mean value of about $2.69W\ m^{-2}$, which indicates more energy being trapped on the earth's surface that could cause warming. The climate sensitivity in 2023 was 0.4°C $m^{-2}s^{-2}$ which falls below global average of about 3°C $m^{-2}s^{-1}$. The CO_2 concentration was extrapolated based on the mathematical function derived from the regression function between the variable and elevation. The results revealed positive radiative forcing and low climate sensitivity value. This may seem positive, but that doesn't negate the need for action to mitigate adverse effects of climate change.

Keywords: Remote sensing; GIS; CO_2; climate sensitivity; climate change

INTRODUCTION

In the era of climate change, it is important to measure how responsive the Earth's atmosphere is to a change in the concentration of atmospheric carbon dioxide (CO_2) (Pulsell *et al*, 2008). It is typically quantified as the change in global mean surface temperature resulting from a doubling of atmospheric CO_2 concentration compared to pre-industrial levels (IPCC, 2021). This measure is often referred to as climate sensitivity, which is crucial for predicting future climate conditions and is usually expressed in degrees Celsius (°C) (National Research Council, 2016). Climate sensitivity typically refers to the equilibrium climate sensitivity (ECS), which is the global average surface temperature change resulting from a doubling of atmospheric CO2 concentrations compared to pre-industrial levels (IPCC, 2021). Examples of responses or sensitivity of the climate to CO_2 concentration, according to (IPCC, 2019), include equilibrium sensitivity (ES): This is the long-term temperature

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increase after CO_2 levels have doubled and the climate system has reached a new equilibrium. Estimates of ES typically range from 1.5 to 4.5°C. Another form is the Transient Response (TR), which measures the temperature change at the time of CO_2 doubling, assuming a gradual increase of CO_2 at 1% per year, typically realized over a 70-year period. TR values are generally lower than ES values due to the shorter timescale. Every form of sensitivity affects the climate by increasing temperature (IPCC, 2019), Higher e sensitivity implies greater temperature increases for a given rise in CO_2. This can exacerbate the warming of the immediate environment, leading to more intense and frequent heatwaves. It can also cause changes in weather patterns. Increased temperatures influence weather patterns, potentially causing more extreme weather events, including stronger storms, heavier rainfall, and prolonged droughts (Hansen *et al,* 1984). This can disrupt agriculture, water supply, and overall human livelihoods. It also leads to shifts in ecosystems and biodiversity. Species may be forced to migrate to cooler areas, and those that cannot adapt quickly enough may face extinction (Boer *et al*, 2003).

The sensitivity of the climate is influenced by feedback mechanisms, such as the ice-albedo feedback (where melting ice reduces the Earth's reflectivity (Boer *et al*, 2000a), causing more absorption of solar radiation and further warming and water vapor feedback (where warming increases water vapor, a potent greenhouse gas, thus amplifying the warming effect). Despite advancements in climate modelling, there is still uncertainty in the exact value of such responses, largely due to complex interactions within the climate system. Policymakers rely on these estimates to make informed decisions about emissions reductions and climate mitigation strategies. Understanding and reducing these uncertainties is vital for effective climate action. Therefore, this study is set to examine how responsive the Earth's atmosphere is to a change in the concentration of atmospheric CO_2, with the objectives to (i) estimate CO_2 concentration, (ii) calculate radiative forcing and (iii) determine the response of the local climate to the greenhouse gas concentration.

MATERIALS AND METHOD

Study Area

The study area falls within latitudes 7^0.15' N and 7^0.55' N and longitudes 3^0E and 3^0.3' E, within Oyo State, Nigeria. It has an area of 1218km^2 and a population of 143,300 according to the 2022 population census. Their major occupation is farming. Most of the land lies at elevations ranging between 120 and 200 meters above sea level. The predominant occupation of the people is farming. Soil type: Lateritic clay soil, loamy sand, and sandy loam. vegetation: Mixed deciduous and semi-deciduous forest, with grassland and shrubs in open areas. The region has a tropical climate with two distinct seasons, the rainy season and the dry season. This could be a good opportunity to assess the radiant flux in the region and its impact on agricultural productivity.

Data Collection and Processing

Landsat satellite images of 2003 and 2023 were obtained from US Geological Survey (USGS). The study area is within the Landsat path 191 and row 55 with pixel sizes of images 30×30m with the exception for the thermal IR bands (bands 6 and 10) respectively, which has 100-m resolution bands (Chander, 2003). Table 1 describes the Landsat ETM+ and OLI images used, as well as the DEM of 30m resolution. Field data at various locations randomly selected were used to validate information derived from remote images. The locations were selected based on land cover types and elevation to account for different terrains. Carbon(iv)oxide (CO_2) concentration in part per million of atmospheric gases ((ppm) was collected randomly at 50 locations using handheld Neutron Air Quality Meter (AQ-9901SD).

The study focused on the spatial dynamics of climate variables such as net solar radiation, climate sensitivity, radiative forcing, CO_2, evapotranspiration and air temperature for the periods of 2003 and 2023, spanning twenty (20) years. The ground CO_2 data was obtained from 50 randomly selected locations within the study area. The study involved data retrieval from satellite images and cause-effect analysis using regression tool. between CO_2 and climate sensitivity, as well as elevation (Makinde *et al,* 2019; Ibrahim *et al.*, 2022). The software package used are R-studio for image processing, excel for statistical analysis, and ArcGIS 10.5 for final map outputs.

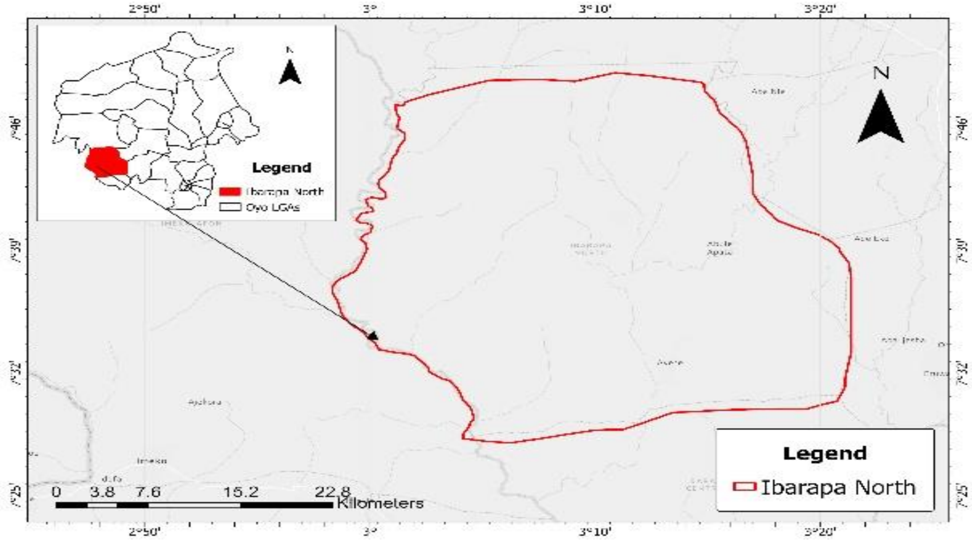

Fig. 1: The study area map

Estimation of Climate Variables

Radiative forcin*g***:** Radiative forcing is a measure of how the energy balance of the earth–atmosphere system is influenced. The presence of greenhouse gases (GHGs) naturally affects the climatic equilibrium of the earth (Pulsell *et al*, 2008; IPCC, 2013). The ability of the anthropogenic GHGs to absorb Infrared radiation coming from the earth (which would otherwise be lost to space), determines the increase of the radiative forcing (Pulsell *et al*, 2008). The atmospheric concentration of greenhouse gases such as CO_2, CH_4 and water vapour, is a primary indicator of greenhouse effect and it varies continuously. In general, radiative forcing is positive when GHG concentrations increase (Solomon *et al*, 2007; Robert *et al*, 2020). The R_f at any concentration was calculated in equation 9, **(**Douglas *et al*, 2014)

$$R_f = 5.35\ln\left(\frac{C}{Co}\right) \qquad 1$$

Where C is measured CO_2 and C_O represents the pre-industrial CO_2, estimated to be about 260 parts per million (ppm) **(**IPCC, 2013).

Climate sensitivity**:** This is typically the temperature rise following a doubling of CO_2 concentration in the atmosphere compared to pre-industrial levels. Pre-industrial CO_2 was about 260 parts per million (ppm), so a doubling would be at roughly 520 ppm (National Research Council, 2005, IPCC, 2013 and *Larson et al, 2019*). The sensitivity was evaluated using the linear relationship between radiative forcing (R_f) and the surface temperature (T_a) according to Drakes (2000) as:

$$T_a = \partial R_f \qquad 2$$

where ∂ is the sensitivity in kelvin per watts per square meter which accounts for feedback of global warming. The CO_2 concentration was determined using CO_2 Meter at different locations between 10/00am and 10:55am, which correspond with the time the Landsat images were acquired. The values obtained were used to extrapolate the CO_2 concentration in the study area.

The surface temperature**:** The air surface temperature T_a was estimated in equation 3.

$$T_a = \frac{K_2}{\left(\ln\left(\frac{k_1}{TOAr} + 1\right)\right)} \qquad 3$$

Where $TOAr$ is Top of Atmosphere radiance, K1 is calibration constant 1 (666.09 for ETM+) and (774.89 for OLI band 10) and K2 the calibration constant 2 (1282.71 for ETM+) and (1321.08 for OLI band 10) (Lillesand *et al*, 2008 and Makinde *et al.*, 2019)

Data Extrapolation

Data extrapolation involves predicting values outside the range of known data based on existing data points. One common method is linear extrapolation, which assumes a linear relationship between data points. The formula for linear extrapolation adopted in this study is in equation 11 (Makinde *et al*, 2019).

$$y = mx + b \qquad 4$$

Where y is the predicted CO_2 value, m is the slope of the line, x is the independent variable (the extrapolating DEM), b is the y-intercept of the line (calculated using one of the known data points)

Validation of Extrapolated CO_2

The extrapolated CO_2 is being validated to estimate the accuracies of the operational products and understanding of the potential and limitations of methods and instruments used. It involves a direct comparison of extrapolated CO_2 with CO_2 collected with ground-based instruments. This approach allows the uncertainties in CO_2 products to be determined. The ground CO_2 data were obtained from 50 locations randomly selected within the study area. This study employed mean absolute percentage error (MAPE) as a metric to evaluate the performance of forecasting model. MAPE measures the accuracy of a forecasting method of evaluating the average percentage difference between actual and predicted values as in equation 12 (DeLayne, 2012):

$$MAPE = \frac{1}{n}\sum_{k=1}^{n}\left|\frac{A_k - f_k}{A_k}\right| \times 100 \qquad 5$$

Where n is the number of observations, A_k is the actual value at time k, f_k is the predicted value at time k.

RESULTS

Table 3 shows the results obtained from Figures 2-6 for 2003 and 2023, while Figures 7 and 8 present the relationships between variable in 2023 only. Table 3 revealed that there was increase in surface air temperature T_a from 31.5°c in 2003 to 32.7°c in 2023. The statistics also show a higher concentration of CO_2 in Ibarapa north above the pre-industrial CO_2, with mean value of 658,6 ppm. Radiative forcing across the area was relatively high, though higher in the central area, averaging $2.92W\ m^{-2}$. The average climate sensitivity ∂ was about $0.4W$ ^{O}C m^{-2} with higher values in most parts of the study area. Figures 7 and 8 present the effect of elevation on carbon dioxide concentration and the rise in temperature following a doubling of CO_2 concentration in the atmosphere compared to the pre-industrial levels in 2023. There was a perfect positive response of the earth's climate system changes to atmospheric condition. Result also revealed a strong positive relationship of 88% between the surface elevation (DEM) and greenhouse gas (CO_2) concentration (Fig 8).

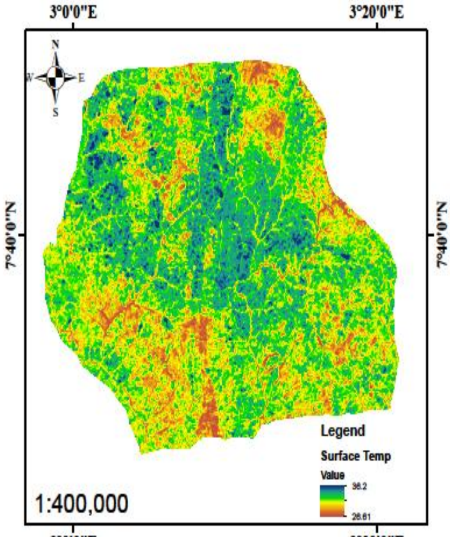

Fig. 2: 2003 Surface temperature (°C)

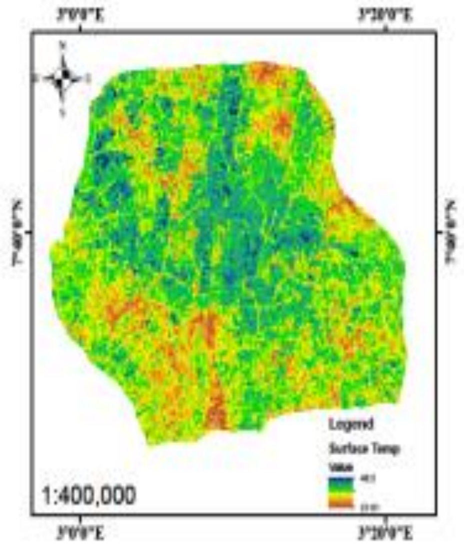

Fig. 3: 2023 Surface temperature (°C)

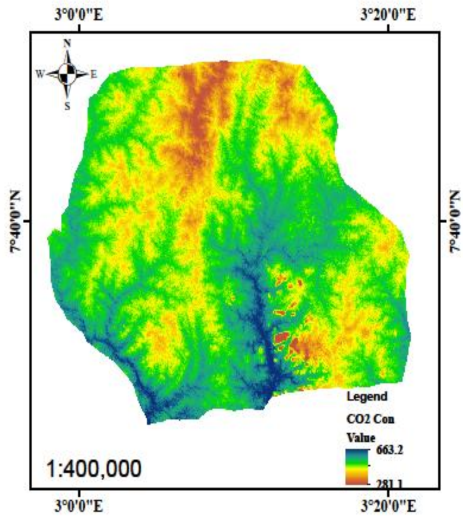

Fig 4: Atmospheric C0₂ concentration (ppm)

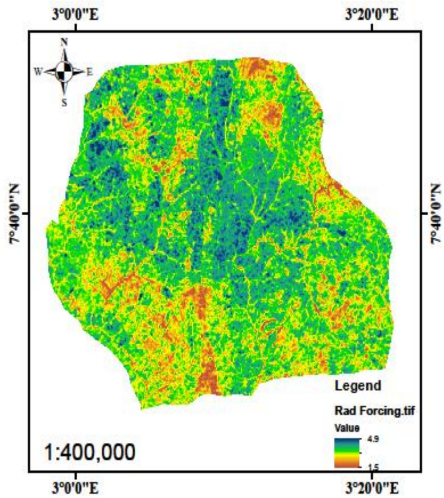

Fig 5: Radiative forcing ($W \quad m^{-2}$)

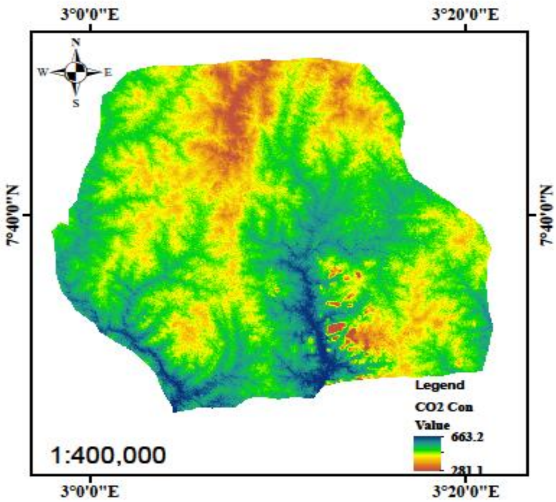

Fig. 6: Climate sensitivity map (^{O}C $m^{-2}s^{-1}$)

Table 3. Mean temperature, CO_2, radiative forcing and climate sensitivity.

Locations	**Mean T_a (°C)**		$\boldsymbol{Mean}$ ΔT_a **(°C)**	CO_2 (ppm)	R_f $(W\ m^{-2})$	∂ ^{O}C $m^{-2}s^{-1}$
	2003	2023	2003-2023	2023	2023	2023
Ibarapa North	31.5	32.7	1.2	691.1	2.92	0.4

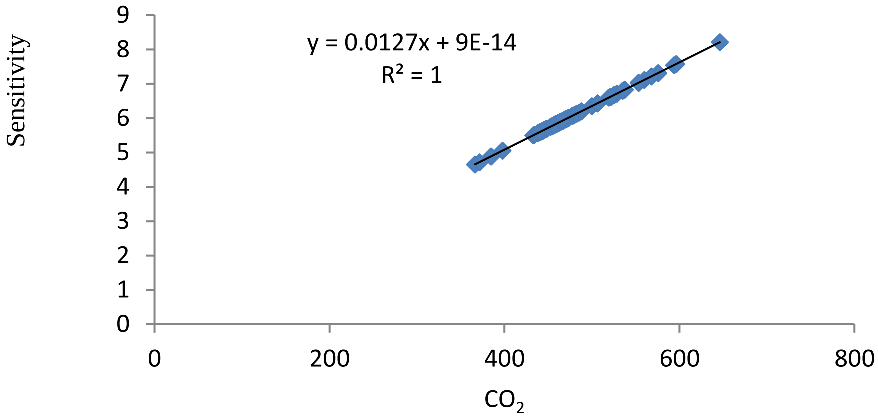

Fig 7: Relationship between climate sensitivity (^{O}C $m^{-2}s^{-1}$) and CO_2 (ppm)

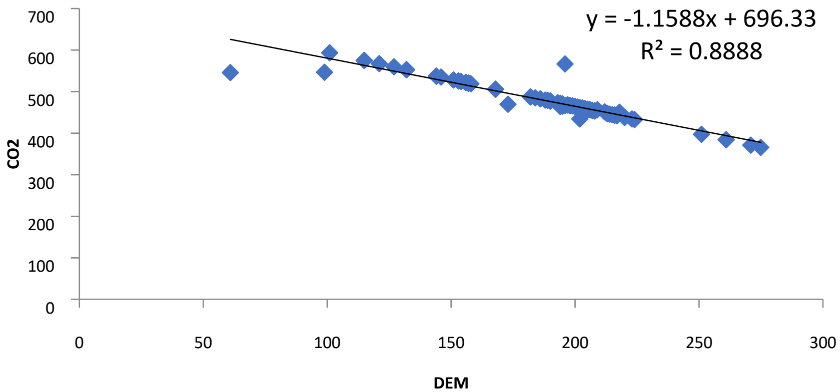

Fig 8: Relationship between elevation (meters) and CO_2 (ppm)

Validation satellite-derived CO_2 result

The performance of the extrapolation model was evaluated for bias, measured by $MAPE$. This was obtained by first calculating relative error as 0.016, then $MAPE$ as 0.0002. This MAPE value obtained is not so substantial as to undermine the robustness and validity of the extrapolated values (DeLayne, 2012).

DISCUSSION

This study examined how the concentration of greenhouse gas (GHG) in the atmosphere affects re the atmospheric equilibrium in the study area, which is the rate at which temperature rises following a doubling of CO_2 concentration in the atmosphere/ The study revealed very strong positive relationship between CO_2 concentration and sensitivity. A positive relationship was observed between CO_2 and sensitivity underscores the urgent need for reducing greenhouse gas emissions and implementing mitigation and adaptation measures to minimize the adverse environmental impacts of climate change (IPCC, 2013). Furthermore, the mean sensitivity of $0.4^0C\ m^{-2}$ shows the rate at which air surface temperature is expected to rise for every doubling of CO_2 concentration. A climate sensitivity value of 0.4 is extremely low and significantly below the widely accepted range from 1.5 to 4.5°. The commonly accepted range for ECS, according to the Intergovernmental Panel on Climate Change (IPCC, 2021), is between 2.5 and 4°C, with a likely range of 1.5 to 4.5°C. Climate sensitivity value of 0.4°C per doubling of CO_2 implies that the micro-climate system is much less responsive to increases in greenhouse gas concentrations than current scientific consensus suggests (Knutti *et al*, 2008). Some potential climatic implications of such a low climate sensitivity value would include less surface warming. The temperature rise due to increased CO_2 would be much smaller than the predicted values by most climate models. This would mean less severe impacts from global warming, such as insignificant increases in heatwaves, less intense storms, and milder changes in weather patterns (Roe *et al.,* 2007). Another implication is that the stress impact on natural ecosystems, such as forests and aquatic habitats, would be less severe. Biodiversity loss might be slower and less pronounced (Sherwood *et al*, 2020). Again, the urgent need for aggressive climate mitigation policies might be reduced. Adaptation strategies could also be less extensive and costly. However, a lower sensitivity value may seem positive, and that doesn't negate the need for action to mitigate climate change.

CONCLUSION

Climate sensitivity is a key factor in determining the extent and severity of climate change impacts. This study revealed very strong influence of CO_2 concentration on the local climate of Ibarapa North. The positive radiative forcing is a pointer to the fact that the incident solar energy is higher that the reflected energy, and this could lead to temperature increase. However, the climate sensitivity falls below commonly accepted range for equilibrium climate sensitivity. As good the result may appear, a positive relationship between CO_2 and climate sensitivity calls for urgent need to reduce greenhouse gas emissions and implementing mitigation and adaptation measures to minimize the adverse environmental impacts of climate change.

The study revealed interesting facts about the study area, such as the positive relationship between carbon dioxide and climate sensitivity. This is an important factor that should be monitored at regular interval. There is an indication that incident energy is higher than that reflected. Therefore, it is imperative that stakeholders across various sectors prioritize investments in research in climate studies. Prioritizing this can enhance our capacity to effectively win the global fight against climate change, ultimately contributing to a more suitable environment for all.

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