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Unmasking climate vulnerability in Africa: the role of CO_2 and CH_4 emissions on rising temperatures and sea levels

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Climate change influenced by anthropogenic emissions is a global occurrence affecting the Mean Surface Temperature (MST) and Mean Sea Level (MSL) patterns. The African continent contributes to the lowest Greenhouse Gas (GHG) emissions globally. However, GHG emissions, particularly Carbon Dioxide (CO_2) and Methane (CH_4) emission patterns, show a continuous increase in the African region, reflecting the importance of practising economic growth in the continent with sustainable environmental policies to meet future global climate targets. Given Africa's increasing emissions and the continent's vulnerability to climate change, this study contributes to the existing literature by assessing the continental and country-wise impact of CO_2 and CH_4 emissions on MST and the resulting impact on MSL through Fixed Effect (FE) panel estimation and Simple Linear Regression (SLR). The research employs data from 1993 to 2020 for fifty-four African countries. The study's main findings show that CO_2 and CH_4 positively impact MST at a 1% significance level, and MST positively impacts MSL at a 5% significance level. This study focuses on continent-specific and country-specific emissions and their impacts and proposes policy measures to mitigate the emissions in the African continent.

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Introduction

Climate change from anthropogenic emissions imposes a significant threat to African countries, affecting inhabitants and ecosystems across the continent. The African continent is subdivided into five main regions: Northern Africa (NA), Central Africa (CA), Southern Africa (SA), Eastern Africa (EA), and Western Africa (WA), encompassing a total of fifty-four countries with immense geographical, social, and economic differences. Many countries in the African region are especially vulnerable to climate change because of their reliance on rain-fed agriculture, scarcity of water resources, frequent extreme weather events like droughts and heatwaves, rising incidences of diseases, limited access to infrastructure and financial resources, outdated technologies, and climate-sensitive vital economic sectors (Bedair et al. 2023). Given the region's vulnerability, determining the role of anthropogenic emissions on regional climate would prove useful for climate adaptation.

Anthropogenic emissions affect the surface temperature levels, causing sea level rise (Zickfeld et al. 2017). Mean Sea Level (MSL) can be defined as the average height of the ocean surface (NASA 2024a). The surge in sea levels is primarily caused by thermal expansion and the melting of land-based ice sheets. The African continent covers about one-fifth of Earth's total surface and is bounded by the Atlantic Ocean on the west side and the Indian Ocean on the east side (Dickson et al. 2024). The African coastline showcases a steady growth in ocean height and is expected to increase by 1 m in a 4 °C global warming scenario. Rising sea levels threaten many African countries, reducing land areas and increasing coastal floods. The African coastal regions are expected to experience the highest growth of population and urbanisation in the world, and elevated sea levels will affect approximately 174 million African inhabitants by 2060 (Bernardino et al. 2023; Neumann et al. 2015). Hence, it is essential to understand and monitor MSL for climate research and proactive measures in the region.

Mean Surface Temperature (MST) is the average temperature of the earth's surface, including the landmass and ocean (IPCC 2023a). Human activities and natural causes drive global warming on Earth. However, anthropogenic emissions dominate the contributors' scale for the MST rise mainly through Carbon Dioxide (CO_2) emissions and Methane (CH_4) emissions (IPCC 2021). MST shows a drastic increase in African regions, particularly in subtropical and central tropical Africa, over the past five decades (Engelbrecht, Adegoke et al., 2015a). Anthropogenic climate change has led to a noticeable shift in MST levels in Africa from an average rate of +0.2 °C in 1961–1990 to +0.3 °C from 1991 to 2022, which is more than the global average rate (WMO 2023). CO_2 is the leading Greenhouse Gas (GHG) contributor to anthropogenic climate change, followed by CH_4 and other GHGs (Lindsey 2024). Human activities, such as burning fossil fuels, industrial processes, transportation, agriculture, livestock management, waste management, changes in land use, and deforestation, contribute primarily to the increase of GHG concentrations in the atmosphere.

The primary objective of this study is to investigate the impact of CO_2 and CH_4 on MST and how the changes in MST impact MSL at a regional scale for the African continent to bring about a novel and enhanced understanding of regional climate dynamics. To achieve this objective, the research explores the hypothesis that in Africa, CO_2 and CH_4 emissions have a significant impact on MST, which in turn influences MSL. Subsequently, this highlights the importance of quantitative examination of interrelated dynamics of anthropogenic emissions, temperature variation, and the fluctuations in sea level. The study contributes to the existing body of literature in three ways. First, the study focuses on fifty-four African countries to investigate the continental and country-wise impact of the variables rather than focusing only on a few selected countries, generating a larger set of results open for future research and discussions. This approach moves beyond the limitations of previous studies that often focus on a limited number of countries, offering a broader perspective on the regional effects of climate change. Second, contrary to the prevailing climate-related literature that utilises climate model simulations, this study employs econometrics to assess the regional impact of selected climate variables in a quantitative approach. The authors intend to provide a different lens to understand the regional interactions between the variables of CO_2, CH_4, MST, and MSL, seeking to determine whether a regional impact is caused by CO_2 and CH_4 emissions. Furthermore, the study provides current knowledge regarding the African continent-specific anthropogenic emissions of CO_2 and CH_4, which may be crucial for policymakers and researchers working to address the pressing issues of climate change on the continent. Finally, the study proposes policy recommendations tailored to the unique challenges and opportunities within the African context, contributing to African climate resilience and sustainability.

The subsequent sections of this research paper are organised as follows. Section "Literature Review" will outline a literature review covering existing empirical evidence in the African context, followed by Section "Data and Methodology", data and the implemented methodology, Section "Results and Discussions", results and discussion, which will analyse the research findings. Section "Conclusion" covers the conclusion and the limitations, and finally, Section "Policy Implication" explores the policy implications.

Literature review

Temperature rise led by anthropogenic activities is evident across the globe for all four seasons (Fomby and Vogelsang 2003; Kaufmann 2002; Vogelsang and Franses 2005). Studies prove that non-anthropogenic natural forcings only influence marginal levels of global temperature change in the past 15 decades (Joos and Spahni 2008; Stips et al. 2016). The global temperature shows a sharp increase and will potentially reach 4.8 °C by 2100, influenced by human activities, posing a significant challenge to the world (Hamdan, Al-Salaymeh et al., 2023). Specifically, since the industrial revolution, the Earth's temperature has increased with the growth of GHG emissions, and MST shows irreversible changes to CO_2 forcing (Kim et al. 2022). There is an evident phase relationship between changes in global CO_2 levels and global temperature levels (Humlum, Stordahl et al., 2013). The concept of transient climate response to cumulative CO_2 emissions offers a clear metric linking CO_2 emissions to temperature changes over time (MacDougall and Friedlingstein, 2015).

Climate change poses a significant threat to the African continent due to its diverse ecosystems, socio-economic factors, and unusual weather patterns, affecting agriculture and water resources. Although Africa contributes to a smaller proportion of global GHG emissions, it is disproportionately affected by the impact of climate change, including rising temperatures and fluctuations in weather conditions (Bedair et al. 2023). Hence, increasing anthropogenic emissions in the African continent could amplify the warming effect in the region and may worsen the negative consequences already experienced in the region.

Increasing emissions from anthropogenic activities are responsible for the increasing CO_2 concentrations in the atmosphere in recent years (Harde 2017). The global surface temperature increase due to rising CO_2 levels affects precipitation patterns in Africa (James and Washington 2013). Further, the elevation of CO_2 concentration leads to warming in the lower troposphere, which influences temperature patterns in WA (Wang and Eltahir 2002). Under the low mitigation scenarios, increased CO_2 emissions could lead to severe changes in biodiversity, water sources, and agriculture in WA (Engelbrecht et al. 2015b). Hence, it is essential to understand the heterogeneous short-term, medium-term, and long-term impact of CO_2 emissions on the increasing temperature levels in Africa (Espoir et al. 2022). Further, recognising human-induced climate change, along with the significant impact of CO_2 as a major anthropogenic gas, and gaining insights into the regional contributions of CO_2 emissions, their driving factors, and trends would prove critical for creating effective and targeted mitigating strategies (Canadell et al. 2009). Authors have widely studied top CO_2 emitters in the continent and their drivers and trends of CO_2 emissions, such as economic growth, urbanisation, population, renewable energy, and trade (Abid 2016; Acheampong et al., 2021; Adebayo and Odugbesan 2021; Bamisile et al. 2021; Chakamera and Alagidede 2018; Maji 2019). A similar focus on present low emitters on the continent may prove beneficial, given that emissions are likely to increase in least developed and developing nations.

There is a positive relationship between energy consumption, economic growth, and CO_2 emissions, indicating an increase in economic activities results in an increase of GHG (Silva et al. 2024). Similarly, Dao et al. (2024) Dao et al. (2024) also discuss how economic expansion and dependence on natural resources results in environmental degradation highlighting the importance of strengthening the green financial policies. As a continent with a fast-growing economy, Africa should consider the relationship between these factors. The results of a study done by Kazemzadeh, Fuinhas et al. (2023) for the G7 countries showcase that CO_2 emissions per capita and economic complexity positively impact the death rates due to air pollution and suggest policymakers take actions to mitigate the emissions. Similarly, Koengkan et al. (2023) also discuss how the increase in CO_2 emissions increases premature deaths from air pollution. Policymakers in the African continent should also consider these factors when imposing policies to mitigate emissions.

CH_4 can be considered one of the most potent GHGs due to its significant impact on climate change (Mar et al. 2022; Nyasulu et al. 2021). The main GHG's including CH_4 play an important role in controlling the surface temperature patterns (Rafique et al. 2014). Despite the potency of CH_4 as a GHG, rising CH_4 emissions in the continent and their consequences have often been overlooked (Djoumessi and Any 2021; Hickman et al. 2014). Therefore, the study aims to contribute to the existing literature by examining the impact and trends of both CO_2 and CH_4 emissions in the continent not only for the primary, industrialised emitters but also for the least developed rural countries to develop targeted policy implications and promote sustainable development in the continent.

Followed by global warming, sea level rise is a primary global concern that impacts the capacity of the world's resources and the coastal regions. The Intergovernmental Panel on Climate Change (IPCC) declared a rapid increase in sea level rise from the year 1901 to the present times (IPCC 2023c). The regional variations of MSL are exhibiting increasing trends and will continue to grow in the long term if mitigation is not enacted to reduce emissions (Griggs and Reguero 2021). Global sea level rise was 1.7 ± 0.2 mm a year from 1900 to 2009 but has increased to 3.2 ± 0.4 mm per year since the 20th century (Mimura 2013). The global temperature rise causes thermal expansion and glacier melting, resulting in sea level rise at an average of 3 mm a year (Jabir et al. 2021). A decrease in emissions early in this century will be more effective in controlling MSL rise than the latter part of the century (Vermeer and Rahmstorf 2009). The MSL rise is observed across Africa, affecting coastal tourism in the country (Dube et al. 2021). The limitation of GHG emissions would benefit in reducing the rising 21st-century MSL levels in Africa (Allison et al. 2022). The sea level in the WA coastal line is increasing each year, affecting the commercial hubs and rapidly growing population (Nyadzi et al. 2020). Rising sea levels increasingly threaten African coastal heritage sites that hold remarkable historical and cultural significance (Vousdoukas et al., 2022). Due to the continuous MSL rise, 16–27 million people will be flooded per year early, costing about US $5 to $9 billion annually in 2100 (Hinkel et al. 2012). Hence it is clear that urgent actions are necessary to mitigate sea level rise. Implementing measures to reduce CO_2 and CH_4 emissions may prove crucial in tackling this issue.

Past literature highlights the undeniable impact of CO_2 and CH_4 on climate dynamics, particularly on the MST and MSL, using climate models and simulations. However, the focus on regional studies is minimal, specifically regarding the impact of anthropogenic emissions on the continent and individual countries. Climate models provide only a broad perspective lacking the specificity to facilitate an understanding of regional climate dynamics (Elshall et al. 2022). Using econometrics on time series data gathered for individual countries can uncover a deeper understanding of how regional emissions affect regional climate variations over time. Addressing this gap in climate research using econometrics helps uncover localised climate dynamics and their consequences. It provides a different perspective in understanding short-term climate variations broadening the existing knowledge on regional climate dynamics.

Data and methodology

A panel dataset consisting of fifty-four African countries for twenty-eight years, from 1993 to 2020, has been used for the study. Emission data for CO_2 measured in kilotons (kt) and CH_4 measured in kiloton of CO_2 equivalent (ktCO2e) were obtained from the World Bank (WB) Development Indicators. MST change in degrees Celsius (°C) based on the average temperature from 1951 to 1980 as the baseline, and MSL change measured in millimetres (mm) were obtained from the International Monetary Fund (IMF) climate indicators dashboard. The data used for this study are presented in the Supplementary Table S1.

To investigate the impact of MST on MSL via CO_2 and CH_4 emissions, the following model was developed using three equations. Firstly, the impact of CO_2 emissions on MST was computed as shown in Eq. (1), where MST change is represented by MST_1 and the logarithmic value of CO_2 is represented by $\log CO2$.

$$MST1_{it} = \alpha_0 + \alpha_1 \log CO2_{it} + \varepsilon_{it} \quad (1)$$

Secondly, the impact of CH_4 emissions on MST was computed as shown in Eq. (2), where MST change is represented by MST_2 and the logarithmic value of CH_4 is represented by $\log CH4$.

$$MST2_{it} = \alpha_0 + \alpha_1 \log CH4_{it} + \varepsilon_{it} \quad (2)$$

The predicted values of MST_1 and MST_2 from Eqs. (1) and (2) are averaged to obtain the average MST change denoted by $\widehat{MST}$ as shown below,

$$\widehat{MST}_{it} = (MST1_{it} + MST2_{it})/2$$

Finally, to determine the impact of the MST on MSL, the obtained average predicted MST change denoted by $\widehat{MST}$ will be used as shown in Eq. (3)

$$MSL_{it} = \alpha_0 + \alpha_1 \widehat{MST}_{it} + \varepsilon_{it} \quad (3)$$

Given that ideal climate studies would incorporate both temporal and spatial elements, the model employs a panel regression analysis as shown in Eqs. (1), (2) and (3) where "i" represents the country, with "t" denoting the period. Further, a panel dataset offers numerous data points, thus improving the accuracy of estimation and providing the ability to derive robust hypotheses and uncover dynamic relationships (Hsiao 2014).

Additionally, the above model has several advantages. Using two equations, Eqs. (1) and (2), allows for quantifying the specific individual impact of CO_2 and CH_4 on MST. Furthermore, this approach overcomes the multicollinearity between the independent variables of CO_2 and CH_4 when using both variables together in a single equation. The logarithmic form of CO_2 and CH_4 used in the model helps to capture the non-linear relationship between the emissions and MST, hence accounting for the marginal diminishing effect of emissions on MST.

The analysis was initiated by conducting the Levin Lin and Chu (LLC) test to verify the presence of stationarity or long-term trends in variables. The LLC's test application for pooled data sets results in higher test power, thus improving the robustness of the findings (Levin et al. 2002). Panel Vector Auto-Regression (PVAR) was used to model the interactions of variables over time across countries to determine the stability of variables in response to exogenous shocks (Sims 1980).

Three-panel analysis techniques were considered for the model, including Pooled Ordinary Least Squares (POLS) estimation, Random Effect (RE) estimation, and Fixed Effect (FE) estimation. To determine the optimum panel analysis technique for the model, individual specification tests were carried out for Eqs. (1), (2) and (3). The specification tests included the F-test, Hausman test, and Lagrange Multiplier test. The F-test was used to decide between the FE and the POLS estimation. The Hausman test determined the more suitable estimation technique between the RE and the FE estimations. Finally, the Lagrange Multiplier test was utilised to decide between the RE and POLS estimations (Dharmapriya et al. 2024).

Results and discussions

Descriptive statistical analysis. Descriptive statistics for CO_2, CH_4, MST, and MSL variables of the African region are shown in Table 1. Accordingly, The African continent emitted 18,978 kt of CO_2 on average from 1993 to 2020. Furthermore, in the same period, on average, 17,939ktCO2e of CH_4 has been emitted by the region. CO_2 and CH_4 emissions are spread out by 57,745 kt and 25,995ktCO2e, respectively, indicating high variability in the region across different periods. On average, MST has changed by 0.87°C relative to the baseline. MSL shows an average change of 22 mm relative to the baseline, indicating that the region has undergone a substantial average MST and MSL increment during the considered twenty-eight-year period. Country-level descriptive statistics for 1993–2020 are provided in Supplementary Table S2. Accordingly, South Africa has the highest CO_2 emissions, followed by Egypt, Algeria, Nigeria, and Libya. Regarding CH_4 emissions, Nigeria ranks the highest, followed by Algeria, South Africa, Ethiopia, Egypt, and Libya.

Table 1 Descriptive Statistics for the African Continent.

	CO_2 (Kilotons)	CH_4 (Kilotons of CO_2 equivalent)	MST (Degree Celsius)	MSL (Millimetres)
Obs.	1512	1512	1512	1,512
Mean	18,978.191	17,939.800	0.870	22.018
Min.	12,189.643	14,290.048	−16.507	−16.307
Max.	25,543.645	21,181.146	69.315	69.014
SD	57,745.201	25,995.343	0.432	26.108

Source: Authors' Calculations Based on WB Indicators and IMF Dashboard Data.
Note: Obs. denotes Observations, Min. denotes Minimum, Max. denotes Maximum, and SD denotes Standard deviation.

Consequently, South Africa, Nigeria, Egypt, Algeria, and Libya are the major contributors to the continent's GHG emissions, collectively accounting for approximately 60% of Africa's total CO_2 and CH_4 emissions.

By 2020, the Indian and Atlantic oceans show a significant increase of 67.99 mm and 70 mm, respectively, relative to the baseline, as depicted in Fig. 1. Although not perfectly linear, this rise shows fluctuations influenced by other factors, such as ocean currents, and seasonal and climatic events. Despite such fluctuations, the MSL of both oceans throughout the overall period has accelerated alarmingly. Given that the African continent comprises thirty-eight coastal countries, including small island nations, this substantial rise in MSL underscores the urgent need for comprehensive local and regional actions. Addressing the underlying causes of sea level rise, especially anthropogenic emissions and the consequent MST changes, is critical to mitigate its impact.

A decadal comparison of average CO_2 emissions, CH_4 emissions, and MST change of the five African regions between the two decades of 1993–2002 and 2011–2020 are presented in Fig. 2. Respective percentage change values for the same variables are presented in Supplementary Table S3. All five regions in the continent show increased CO_2 emissions over the two decades. EA has experienced the most significant growth in CO_2 emissions, with a 110% increase over the two decades. In the latter decade, NA has accounted for more than 41% of the average CO_2 emissions on the continent and has shown an increase of 91% in CO_2 emissions over the considered two decades. SA has emitted 34% of the average CO_2 emissions on the continent in the latter decade, with a rise of 52% over the two decades. Followed by SA are WA, EA, and CA accounting for approximately 13%, 6%, and 4% of total average CO_2 emissions in the latter decade. CH_4 emissions in EA are the highest in Africa in the latter decade and show the fastest growth of 50% amongst all the regions. CA has the second highest CH_4 emission growth over the two decades, followed by WA, NA, and SA.

There is an increase in MST for all regions in the continent, indicating a general warming trend. NA has the highest average MST amongst all areas of the continent in the latter decade. This warming is followed by the increased frequencies of warm days and occurrences of heat waves (Fontaine et al. 2013). The WA region shows the second-highest average MST in the latter decade. The region is witnessing the same phenomena, specifically with the Sahara Desert warming rapidly (Vizy and Cook 2017). EA and CA have the highest percentage increase in MST over the two decades, with 150% and 121% increases, respectively. EA has experienced an MST increase of 0.7 °C–1 °C in the last decade (Camberlin 2018). CA region faces a 0.75 °C–1.2 °C increase since the 1960s (IPCC 2023b). The continent's increasing emissions and warming trends necessitate a study of the primary causes of emissions on a country-level basis.

The percentage change in average CO_2 and CH_4 emissions of African countries between the two decades of 1993–2002 and 2011–2020 are presented in Fig. 3. Respective percentage change values for CO_2 are presented in Supplementary Table S4, and percentage change values for CH_4 are presented in Supplementary Table S5. Despite the decline of emissions in a few countries, most countries in the continent exhibit a rapid rise in emissions. Electricity generation has a significant impact on the growth of the economy of a nation (Lean and Smyth 2010). However, the use of oil, natural gas, and coal for electricity generation will have an adverse effect on CO_2 emissions (Ehigiamusoe 2020). Electricity generation is the primary cause of high CO_2 emissions

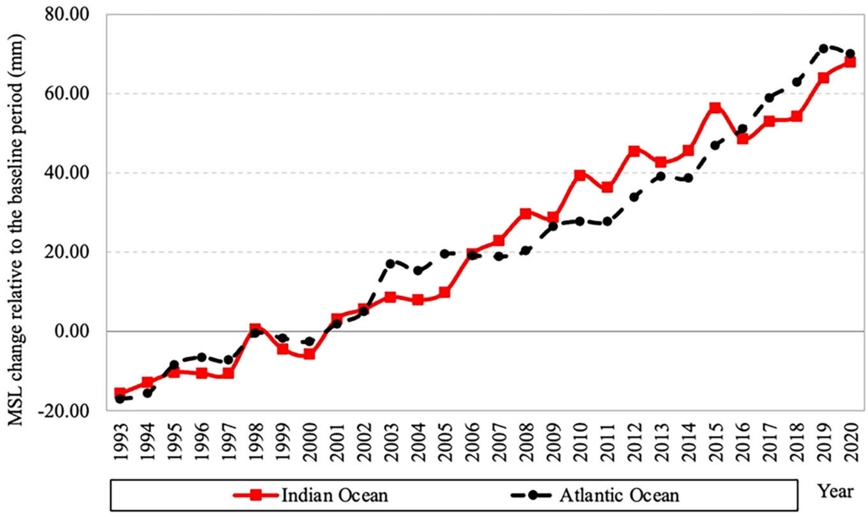

Fig. 1 Ocean-wise Comparison of Annual MSL Change Source: Authors' Illustration based on IMF Dashboard Data.

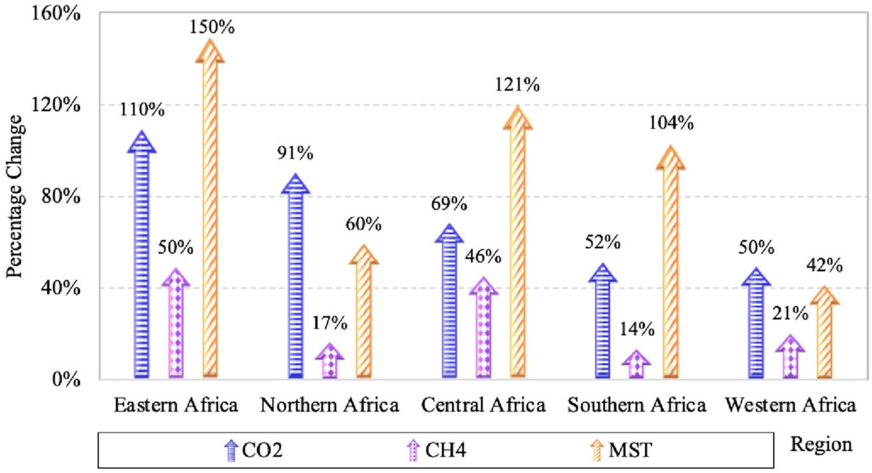

Fig. 2 Region-wise Comparison of Decadal CO_2, CH_4, and MST Levels (1993 to 2002 and 2011 to 2020) *Source:* Authors' Illustration based on WB Indicators and IMF Dashboard data.

in most top emitters of Africa. Accordingly, South Africa has the highest average CO_2 emissions for both decades and experienced a 51% increase in CO_2 emissions between the two decades. The country is one of the top twenty CO_2 emitters globally, and its high emissions can be attributed to heavy reliance on coal for electricity generation (IEA 2021j). Egypt ranks second highest for CO_2 emissions in both decades studied and shows a 107% increase in emissions between the two decades. The use of natural gas and increasing demand in the electricity and heat generation sector make Egypt a significant emitter in the African continent (IEA 2021e). Furthermore, the electricity and heat generation sectors, along with the heavy use of oil as an energy source, have made Morocco and Libya in NA among the main emitters in the region for the considered decades (IEA 2021g, 2021h). CO_2 emissions in Morocco and Libya have increased by 99% and 25% between these two decades.

Similarly, Algeria, a top emitter in NA, relies on natural gas for energy production. The electricity and heat generation sector, followed by the transport sector, are the highest emitting sectors in the country, showing a 97% increase in CO_2 emissions between the two decades (IEA 2021a). Nigeria's economy, one of the largest in Africa and the highest in WA, heavily relies on oil mining and related exports, making it one of the top emitters in the region. It is among the top five emitters in both decades and shows an 18% increase in CO_2 emissions.

CO_2 emissions from the transportation sector primarily originate from the combustion of fossil fuels for personal and commercial transportation through road, rail, air, and marine transport. Although CO_2 emissions are relatively low in both decades, the most significant percentage increase in emissions is in Benin, situated in WA, with a 457% increase between the two decades considered. Being a least developed country, the economy heavily relies on transportation and trade with bordering countries. Hence, the transportation sector is the highest contributing sector to CO_2 emissions in Benin (UNFCCC 2015). This increase in emissions is further aggravated due to the increasing use of biofuels and waste for energy generation (IEA 2021c). Increased oil combustion in the transportation sector has been the primary driver for CO_2 emissions in Angola, a top emitter in CA (IEA 2021b).

Similarly, countries like Burkina Faso in WA, Mozambique in EA, Ethiopia in EA, and Uganda in EA have experienced a dramatic increase of over 300% in CO_2 emissions over the considered decades. This rise can also be attributed to the growing use of oil and the resulting increase in emissions from these countries' transportation sectors (IEA 2021d, 2021f, 2021i).

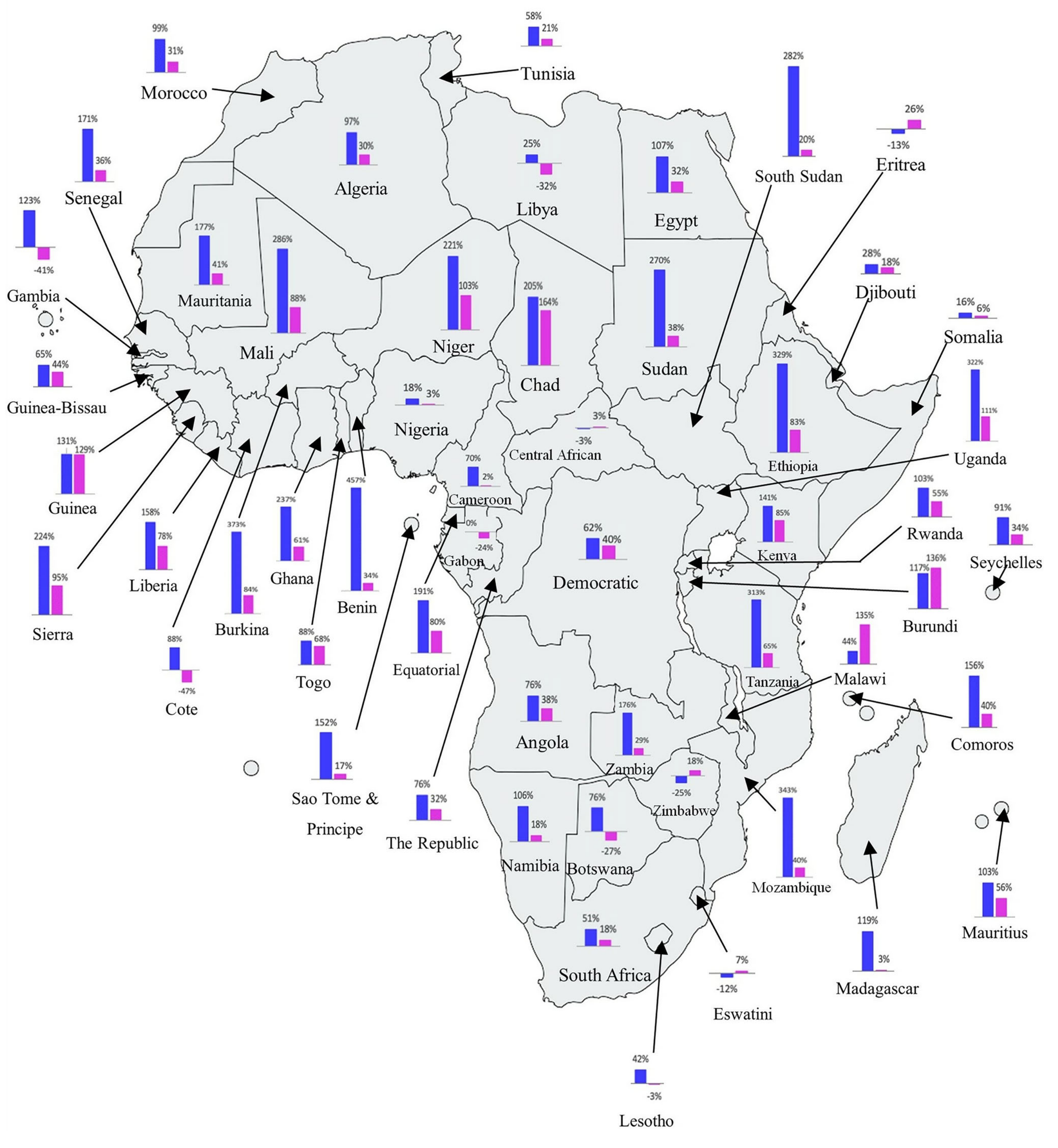

Fig. 3 Bar Map on Country-wise Percentage Change of Decadal CO_2 and CH_4 Emissions (1993 to 2002 and 2011 to 2020) Source: Authors' Illustration based on WB Indicators Data.

Hence, the transportation sector for many African countries is a significant and mounting contributor to CO_2 emissions.

A positive trend can be seen in the CO_2 emissions of Eswatini, Eritrea, and Zimbabwe, with a reduction in emissions over the last decade compared to the initial decade. This is primarily due to these countries lacking large-scale manufacturing (UNFCCC 2018). Additionally, as mainly agrarian countries, their CO_2 emissions have declined compared to other industrialised countries over the decades, contrasting with their respective CH_4 emissions.

CH_4 emissions within the African continent predominantly stem from agricultural practices, the extraction and combustion of fossil fuels, and waste disposal methods such as landfills and open dumping. In the agricultural industry, particularly within livestock farming, ruminants contribute significantly to CH_4 emissions through enteric fermentation during digestion. Additionally, anaerobic emissions resulting from rice cultivation are a significant source of CH_4 emissions on the continent (Hook et al. 2010; Magazzino et al. 2024).

Nigeria in WA has the highest average CH_4 emissions over the decades, with a 3% increase in CH_4 emissions. Primary factors influencing the rising CH_4 emissions in Nigeria are the intensity of GHG emissions from agriculture and the increase in per capita agricultural output (Okorie and Lin 2022). Ethiopia in EA, another primary emitter of CH_4 in both decades, shows a dramatic increase of 83% in CH_4 emissions over the two decades. This rapid rise in emissions can be attributed to the growing population and increased demand for meat-based products. The expanding population of livestock feeding on low-quality nutrition and high-fibre-based feed leads to high CH_4 emissions in the country (Berhanu et al. 2019).

Similarly, South Africa in SA shows an increase of 18% in CH_4 emissions over the two decades due to the growing cattle population (Toit et al. 2014). Egypt in NA has experienced a 32% rise in CH_4 emissions over the two decades, mainly due to rice and sugar cane cultivation using flooding practices. The country's elevated temperatures exacerbate the emissions from these agricultural activities (Western et al. 2021).

The countries of Chad, Burundi, Malawi, Guinea, and Uganda have all experienced a CH_4 emission increase of over 100% over the considered two decades. Population growth across these countries has further intensified the demand for agriculture, resulting in elevated CH_4 emissions. In Chad, significant contributors to CH_4 emissions include livestock farming and enteric fermentation. The subsistence farming sector incorporating livestock in Burundi has led to increased CH_4 levels (UNFCCC 2022). Expanding agricultural land and reducing forest areas in Malawi, Guinea, and Uganda are the primary factors driving the increase in CH_4 emissions (UNFCCC 2021d, 2021 2022). The rising trend of CH_4 emissions in many African countries underscores the pressing need for sustainable agricultural practices and effective emissions management strategies to mitigate future increases in CH_4 emissions across the continent.

A comparison of the change in MST levels of African countries between the two decades of 1993–2002(A) and 2011–2020(B) is presented in Fig. 4. MST percentage change values for respective countries are presented in Supplementary Table S6. Uganda in EA shows the highest percentage change, with a 276% increase in MST change over the two decades. Similarly, there is a significant increase of over 200% in MST change over the considered decades in the countries of Rwanda, Zimbabwe, and Eritrea in EA. Countries such as Mauritania, Cabo Verde in WA and Tunisia, Morocco, and Algeria in NA show a relatively, minor percentage increase in MST over the two decades; however, they exhibit a relatively high average MST in the latter decade. The growing population and the increasing emissions in the region are expected to worsen, given that the African region is experiencing the fastest rate of urbanisation worldwide and is expected to become predominantly urban by the 2030 s, with developed megacities (UN 2018). Consequently, the warming trends in the region are likely to intensify. Therefore, it is essential to understand the impact of escalating GHG emissions in the region, the associated variations in MST, and the consequent variations in MSL. This understanding is crucial for devising effective climate adaptation and mitigation strategies.

Panel regressions results. Individual LLC tests conducted for the panels of $LogCO_2$, $LogCH_4$, and MST rejected the null hypothesis at a 5% significance level, indicating that the panels were stationary. However, MSL failed to reject the null hypothesis at a 5% level of significance hence the first difference was obtained. The stability test for the model's equations using PVAR showed that all eigenvalues were less than one and lie within the unit circle, as shown in Supplementary Fig. S7.

The results of the sensitivity tests carried out for the three equations in the model are presented in Table 2. Equations (1), (2) and (3) rejected the null hypothesis of the F-Test and the Lagrange Multiplier test at a 5% significance level indicating that POLS estimation is not appropriate for the model. The results of the Hausman test rejected the null hypothesis for all three equations indicating that the FE estimation is more accurate than the RE estimation. Hence, FE estimation was employed for all three equations in the model.

The FE estimation results of the model are summarised in Table 3. As per the results of Eq. (1), $LogCO_2$ shows a positive significant impact on MST_1 at a 1% level of significance, indicating that a 1% rise in CO_2 emissions would result in a 0.43°C rise in MST. Analogous results were observed for CH_4, where $LogCH_4$ exhibited a positive significant relationship at a 1% significance level with MST_2. However, in contrast to CO_2 emissions, CH_4 indicated a higher warming potential, where a 1% increase in CH_4 emissions would result in a 0.58°C rise in MST.

$\widehat{MST}$ derived from the average of the predicted MST_1 and MST_2 in Eqs. (1) and (2) show a positive significant impact on MSL. Specifically, the model results suggest that a 1°C increase in $\widehat{MST}$, the rise in MSL from one year to the next is expected to increase by approximately 3.05 mm. Statistically significant at a 5% significance level, the results indicate an acceleration of MSL each year with the rise of $\widehat{MST}$. The panel results highlight the need for urgent climate action, as this is an indication of a compounded MSL rise, suggesting worsened impacts over time. A dynamic panel estimation was conducted to reinforce the findings of the static panel estimation, and the results are presented in Supplementary Note S8.

The result of the study suggests that rising levels of MST due to increasing CO_2 and CH_4 emissions in the region are strongly associated with increasing MSL. There is a notable increase in MST in Africa (Collins 2011). IPCC (2023d), elaborates that the increasing MST levels in Africa are evident due to human-induced climate change. Climate projections indicate that heightened GHG emissions will continue to cause MST to rise across the continent with more frequent temperature extremes. With over 1°C warming occurring across Africa, the region's temperature will rise by 2.7 °C by 2040 if current emission trends continue (Bedair et al. 2023). Surging GHG emissions lead to rising MST levels. Ocean's act as reservoirs of heat, elevated MST levels will result in absorbing substantial amounts of heat. The rising temperatures of oceans have significant environmental and climatic impacts, including rising MSLs and intensified hurricanes and storms (Venegas et al. 2023). A strong correlation exists between rising MSLs and increasing MST in the Indian Ocean, resulting in more frequent coastal flooding and heightened vulnerability for the coastal regions in Africa (Carvalho and Wang 2019). The western tropical Indian Ocean has been experiencing a significant warming trend (Mohan et al. 2021). In the last few decades, the Indian Ocean warmed by 0.7 °C, while the Western Indian Ocean experienced a 1.2°C temperature increase (Koll et al. 2014). 35% of Africa's 26,000 km coastline is vulnerable to increasing sea levels. 40% of African coasts are exposed to moderate to high risks, and 75% are moderate to highly sensitive to increasing sea levels. Tailored adoption and mitigation strategies focusing on protecting, accommodating, and retreating should be considered at regional levels to address vulnerabilities (El-Shahat et al. 2021). By 2100, MSL around South Africa are expected to rise by about 0.5 m under a low-emission scenario, and around 0.85 m under a high-emission scenario, relative to 1986-2005 levels (Allison et al. 2022).

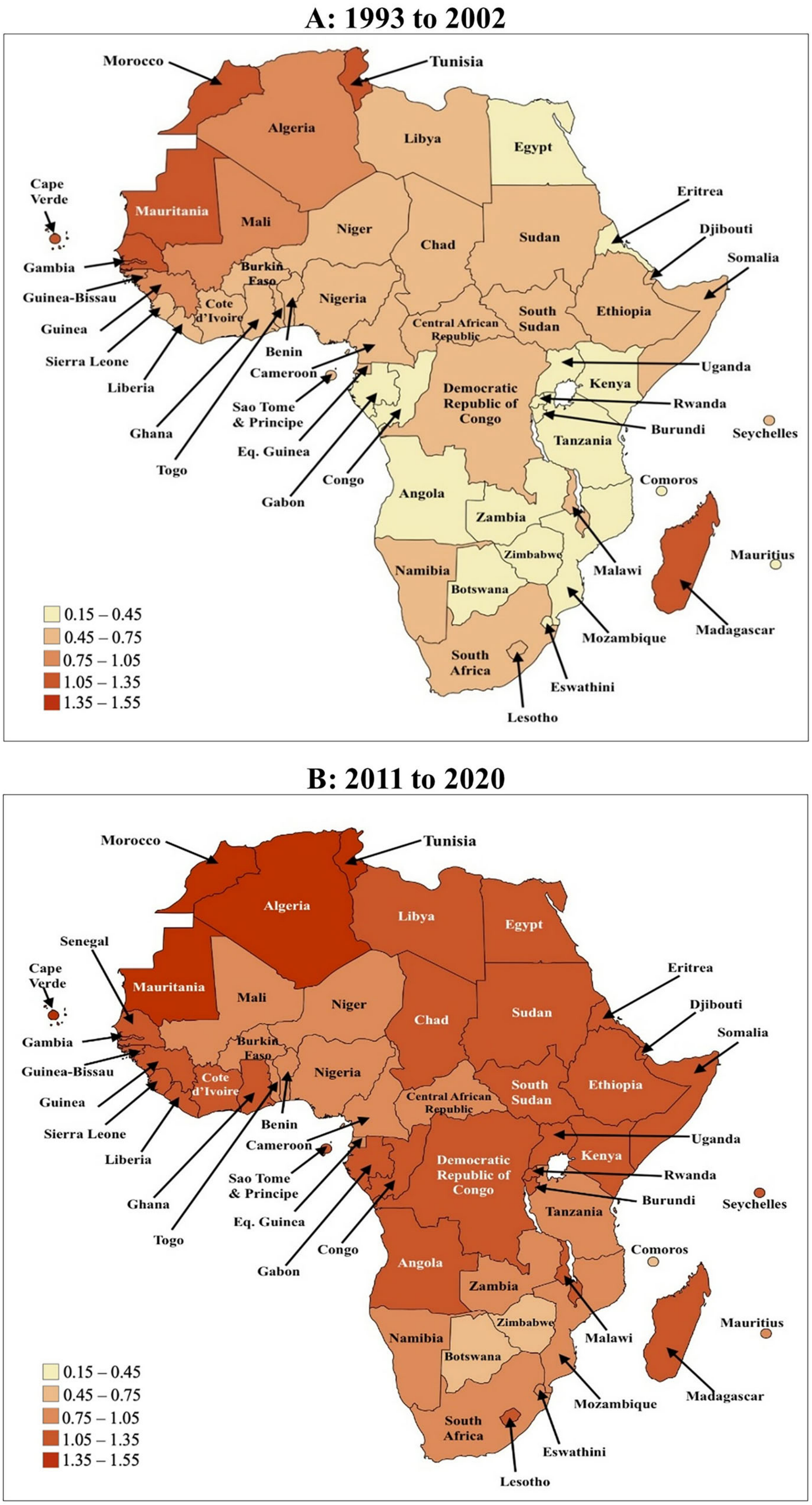

Fig. 4 The average change in MST across African countries over two different decades. A illustrates the average MST changes observed during the period 1993–2002, while **B** illustrates the average MST changes during 2011–2020. The color gradient represents the magnitude of temperature change, with darker shades indicating higher increases.

Table 2 Sensitivity tests results.

Sensitivity tests	Equation 1	Equation 2	Equation 3
F test	19.20***	14.03***	0.28***
Hausman test	312.94***	203.05***	14.39***
Bruesch Pagan test	984.04***	886.95***	0.00***

Source: Authors' Calculations Based on WB Indicators and IMF Dashboard Data.
Note: * Significant at 10%, ** Significant at 5%, *** Significant at 1%.

Table 3 Panel regressions results for the African Continent.

Equation 1 – FE		Equation 2 – FE		Equation 3 – FE	
Variable	MST_1	Variable	MST_2	Variable	MSL
$LogCO_2$	0.4364*** (0.0381)	$LogCH_4$	0.5888*** (0.1190)	$\widehat{MST}$	3.0521** (0.3179)
Constant	-2.5780*** (0.3015)	Constant	-4.2354*** (1.0362)	Constant	0.5002** 0.2790
Overall R^2	0.0133	Overall R^2	0.0004	Overall R^2	0.0003

Source: Authors' Calculations Based on WB Indicators and IMF Dashboard Data.
Note: ** Significant at 5%, *** Significant at 1%. FE denotes the Fixed Effect model. Parenthesis indicates the Robust standard error.

Table 4 Regression Results for Selected Highly Vulnerable Countries in the Continent.

Coefficients			
Country	Equation 1	Equation 2	Equation 3
Somalia	2.53	5.04	140.74
Guinea-Bissau	0.48	0.65	233.62
Liberia	0.55	0.91	102.65
DR of the Congo	0.76	2.34	90.76
Sierra Leone	0.40	0.71	109.91
Mauritania	0.35	1.03	154.55
Madagascar	0.69	1.76	161.25
Benin	0.19	1.22	133.50
Guinea	0.50	0.50	133.26
The Republic of the Congo	0.96	1.64	76.67

Source: Authors' Calculations Based on WB Indicators and IMF Dashboard Data.
Note: All coefficients are positive and statistically significant at a significance level below 10% except Eq. (2) of Madagascar.

Practical mitigation efforts to reduce GHG emissions could significantly benefit Africa by limiting MST rise and consequently hindering the MSL rise.

The results of a country-wise SLR analysis conducted on highly vulnerable African countries with coastlines, based on the Notre Dame Global Adaptation Initiative (ND-GAIN) index score, are summarised in Table 4 (ND-GAIN 2021b). Country-wise regressions analysis results for all the African countries are presented in the Supplementary Table S9.

Somalia is one of the most vulnerable countries to climate change in Africa (ND-GAIN 2021c). The economy of the country, one of the poorest in Africa, relies primarily on the agriculture and livestock sectors. Even though the country's emissions are low, with the growing population in the country, GHG emissions are bound to increase (UNFCCC 2021a). The model estimates a significantly high regional MST increase for the increase of CO_2 and CH_4 emissions. The country is already experiencing changes in rainfall patterns, causing an increased frequency of droughts and floods due to variations in local MST levels (Omer 2024). With a coastline of 3,025 km, the projections indicate a 0.1 m MSL rise under low-emission scenarios by 2030, which aligns with the model estimation results (NASA 2024b).

Bound by the Atlantic Ocean, Guinea-Bissau is a coastal country that is also highly vulnerable to climate change (ND-GAIN 2021a). The country's primary source of income is agriculture, with a specific focus on exporting cashew nuts. The model predicts a 1 °C rise in MST would result in a 0.23 mm rise in MSL for Guinea-Bissau. The country's coastal region is home to the majority of the country's population (UNFCCC 2021f). Hence, the increase in MSL could endanger most human settlements and livelihoods in the country.

Similarly, the majority population of Liberia lives in the country's coastal cities (UNFCCC 2021b). Since most livelihoods in the country are based on the sectors of rubber, rice, cassava cultivation, and animal husbandry, the increasing agricultural output due to population rise would significantly increase CH_4 emissions (UNFCCC 2021b). The model predicts a local MST rise of 0.55 °C for a 1% increase in CO_2 emission and a 0.91 °C MST rise for a 1% rise in CH_4 emissions. Considering the estimated impact of CH_4 emissions on local MST levels, rising CH_4 emissions in the country may cause high variations in the local MST levels, consequently causing regional MSL to rise.

Sierra Leone has a coastline of 506 km, bordered by Liberia and the Atlantic Ocean. The rising MSL is affecting most of the country's settlements, tourism, and fisheries sectors. The country's CO_2 emissions stem from the use of personal domestic generators for electricity generation, and CH_4 emissions are dominated by improper waste disposal (UNFCCC 2021e).

Madagascar, an Island nation, is sparsely industrialised with limited infrastructure. Agriculture is the main livelihood, followed by fisheries and tourism, relying on natural ecosystems and biodiversity. Agriculture, forest cover loss, and land use change account for most regional emissions (UNFCCC 2024). The regression results indicate a 0.16 mm rise in MSL from one year to the next for every 1°C MST rise. Changes in local climate patterns can negatively impact the country's vital economic sectors, posing a significant risk of submerging certain regions due to rising MSL.

Countries such as Guinea and the Republic of Congo, which have significant mining reserves, will experience an increase in energy demand as the mining sector expands. However, this growth, coupled with population increase, may lead to higher CO_2 and CH_4 emissions as mining processes are energy-intensive (UNFCCC 2021c). MSL in the coastal region of Guinea and the Republic of Congo is projected to increase by 0.11 m and 0.12 m, respectively by 2030 under low GHG emission scenarios (NASA 2024c).

The Democratic Republic of Congo, bordering the Atlantic Ocean, is highly susceptible to MST variations as 70% of the country's active population is employed in the agriculture and rural sectors. Practices followed by the country such as slash-and-burn cropping, reduce carbon sinks due to deforestation, and contribute to CO_2 emissions. Alongside this, rice cultivation and livestock produce CH_4 emissions (NDC 2022). As agriculture expands to meet the growing demand, the emissions will increase. The coefficients suggest that the local MST is highly sensitive to local emissions. Similarly, Mauritania is also heavily susceptible to MST changes given that rainfed agriculture is predominant in Mauritania and livestock rearing is a major economic activity in the country's western region. Being bordered by the Sahara Desert, the country has been affected by unpredictable rainfall and increased drought frequency (Ahmedou et al. 2008; Thiam 2003).

For all the selected countries, CO_2 emissions have a positive impact on local MST rise, and CH_4 emissions also have a significant positive impact on local MST rise (except Madagascar). Further, MST has a consequent positive considerable impact on MSL. The results of this estimation on local emissions, MST levels, and MSL suggest that local emissions play a critical role in local climate variations. Thus, local mitigation efforts may yield not only favourable global outcomes but also may result in favourable local outcomes.

Effective mitigation is necessary for all the highly vulnerable countries on the continent, as most economies are primarily based on Agricultural output. Therefore, changes in local climate dynamics will severely affect livelihoods. Furthermore, most countries on the continent belong to the low- and lower-middle-income groups (ND-GAIN, 2021b). Hence, most countries have limited adaptive capacity. Moreover, with the population growth in the continent, as MSL continues to rise, the vulnerability of Africa's coastal infrastructure, groundwater resources, and economies is expected to increase.

Conclusion

In conclusion, the African continent has continuously growing emissions across the countries, resulting in increasing MST and MSL levels. This study investigated the impact of CO_2 and CH_4 emissions on MST and the resulting impact of MST on the MSL. The study contributes to existing literature by examining the distinct impact of CO_2 and CH_4 emissions on MST for the African continent and its countries, highlighting the subsequent impact of MST on MSL rise through Panel Regression and SLR.

According to the study results, the EA region has the highest growth of CO_2 emissions for the two decades 1993–2002 and 2011–2020. The WA region has the lowest growth of CO_2 emissions. A country-wise decadal comparison shows that forty nine out of the fifty-four countries have increased CO_2 emissions. Similarly, the EA region has had the highest growth of CH_4 emissions for the last two decades. In contrast, the SA region shows the lowest growth in CH_4 emissions. A country-wise decadal comparison of CH_4 emissions reveals forty-eight countries out of fifty-four indicate an increase in CH_4 emissions. EA region showcases the highest MST rise, and the WA region showcases the lowest increase in MST. Alarmingly, all fifty-four countries show a surge in MST between the two decades 1993–2002 and 2011–2020.

Through the Panel Regression and the SLR analysis, it was discovered that anthropogenic CO_2 emissions have a significant positive impact on MST for the overall continent and a significant positive impact on MST at a country level for forty-five countries (thirty-one countries at 1% significance level, eleven countries at 5% significance level, three countries at 10% significance level). Anthropogenic CH_4 emissions also significantly positively impact MST for the African continent and at the country level for forty-five countries (thirty-six countries at a 1% significance level, seven countries at a 5% significance level, two countries at a 10% significance level). Finally, average MST has a significant positive impact on MSL for the African continent and a significant positive impact on MSL for fifty-two countries (fifty-two countries at 1% significance level). Key contributors to CO_2 emissions include electricity generation, coal and oil mining, transportation, economic development, population growth, and industrialisation. Whereas CH_4 emissions stem primarily from agricultural activities, land use, livestock management, and waste disposal (landfills, open dumps). The observed emissions are associated with MST increases, which may contribute to ocean thermal expansion, glacial melt, and rising sea levels, consistent with broader climate science literature.

While these findings highlight the importance of implementing emission mitigation strategies in Africa, the study has certain limitations. The study relies exclusively on secondary data and does not account for real-time observational variability or region-specific data gaps, especially in less developed countries where reporting systems may be weak. It only focuses on regional GHG emissions without considering additional factors, such as emission concentrations or respective forcing, which could offer deeper insights into the regional climate dynamics. Although the model remained statistically stable over the period analysed, climate systems are inherently non-linear and complex, suggesting that further interdisciplinary studies combining econometrics with physical climate models would be beneficial for future research. Additionally, econometric models may exhibit several limitations when compared to climate simulations. Omitted variable bias is a notable drawback, as econometric approaches may not fully account for external climate-influencing factors such as aerosols, ocean currents, and feedback loops, potentially leading to biased estimates. Also, while panel regression offers valuable insights into general trends, it does not account for possible spatial autocorrelation or interactions among neighbouring countries, which may influence regional climate dynamics. Forecasting accuracy can also be a concern, as econometric models assume past trends will persist, which may not be held under evolving climatic conditions or policy shifts.

Despite these limitations, this study underscores the growing impact of anthropogenic emissions in the African continent and their long-term consequences of rising MST and MSL. Addressing these challenges requires collective efforts among the African countries to implement emission reduction policies and align with the global climate targets.

Policy implication

Based on the above analysis results, African countries can employ different policies and measures to mitigate CO_2 and CH_4 emissions. To reduce the CO_2 emissions from using coal for electricity generation, South Africa can invest in renewable energy such as solar and wind power as the country has significant solar resources and shoreline wind potential. Nigeria can invest in off-grid solutions to support the decentralised renewable energy solutions. Kenya should focus more on developing geothermal energies, which the country holds immense potential. Egypt can develop solar and wind power generating projects in the country's deserts utilising unlimited renewable sources. Further, African countries can focus on strengthening policies for high-emission practices, supporting industries to adapt to cleaner technologies, diversifying the continent's energy mix, and investing more in energy storage solutions.

Nigeria, a country that struggled with gas flaring, should implement rules and regulations to reduce the flaring by reinjection, utilising it in power production, or converting it to liquified natural gas for trade. Similarly, Angola, Ghana, Mozambique, Egypt, and Algeria should focus on utilising associated gas from oil extraction for domestic consumption or exports, investing in infrastructure to capture the associated gas, and ensuring that liquified natural gas projects adhere to best practices in emissions management.

South Africa, Nigeria, Kenya, Ethiopia, and Egypt have the highest GHG emissions occurring from transportation in the African continent. Mitigating these emissions requires tailormade strategies and actions for each country according to their economy, social structures, and infrastructure. Nigeria should improve public transportation by expanding and reforming public transportation methods such as buses and trains. The country can develop and improve its Bus Rapid Transit systems for more efficient public transportation options South Africa can focus more on shifting towards cleaner fuels or alternative energy sources and implementing a better traffic management system to reduce congestion and long commutes. Kenya should boost the use of electric motorcycles and vehicles, which are popular in the country. Similarly, countries with lower transport emissions till the year 2024 should also focus on implementing strategies such as improving public transport, use of electric vehicles, traffic management, a system to eliminate older, less efficient vehicles, proper urban planning, implementing emissions standards, and use of cleaner fuels to maintain low transportations emissions in the future.

The African continent can be regarded as the fastest-growing continent in the world. The ever-increasing emissions accompany rapid development. Most countries in the continent are facing the complex challenge of balancing economic growth and increasing emissions. Hence, these countries need to make a collective effort and coordinated action to address the shared environmental challenges of the entire continent and achieve global climate targets. The African continent should focus on altering the energy consumption sector, shifting to renewable energy sources such as solar and wind, improving energy efficiency in sectors such as energy, agriculture, and mining, developing clean technologies, and sharing emissions mitigation technologies among all the countries in the continent.

Agriculture, livestock management, and land use are substantial contributors to GHGs on the African continent. Top rice cultivation countries like Nigeria, Egypt, Madagascar, Burkina Faso, Ghana, Kenya, Mali, Ethiopia, Niger, Tanzania, Uganda, and Zambia should employ necessary actions to regional CH_4 emissions occurring from microbial sources. African countries should implement alternative wetting and drying water management systems for rice paddies instead of continuously flooding the rice fields. Additionally, these countries can use precision farming techniques, integrated nutrient management techniques, conservation tillage practices, cover cropping practices, and crop rotation practices to reduce soil disturbance and enhance soil health to reduce emissions. Also, the countries in the region can focus on agroforestry and sustainable grazing practices to prevent excess emissions. African countries should also focus on waste-to-energy projects and recycling practices to reduce emissions occurring from waste management.

Countries in the African continent should implement policies to protect the existing forest area from illegal logging and conversion of forests to agricultural lands. As a collective effort, the continent should invest in reforestation. Further, to mitigate the emissions from livestock management, countries such as Ethiopia, Chad, Sudan, Tanzania, and Kenya, which hold the most considerable livestock in the African continent, should improve feed efficiency to reduce CH_4 emissions, implement proper manure management, and integrate livestock management.

Further, as suggested, African countries can adopt various policies to mitigate GHG emissions in the continent. However, robust funding mechanisms and strong regional cooperation play a vital role in successfully implementing those strategies. African nations can explore a number of innovative funding mechanisms. These countries can actively engage with international financial institutions focused on climate change, such as the Green Climate Fund, and seek its support for their renewable energy projects and energy efficiency projects. They can also seek funds from bilateral and multilateral donors. Governments should partner with the private sector and encourage private sector investments in clean energy projects. Public-private partnerships can be critical in developing renewable energy infrastructure and effective energy storage solutions. Further, African nations must implement carbon pricing mechanisms such as carbon taxes, and cap and trade systems to mitigate the emissions. Additionally, engaging with the carbon credit markets, and voluntary carbon markets can help to generate additional funding for emission reduction efforts. African countries can consider issuing green bonds to finance large renewable energy infrastructure projects.

The African continent's shared environmental challenges necessitate collaborative effort and regional cooperation among the countries to mitigate GHG emissions. Hence, African countries should work together to build integrated regional energy markets which allow countries to share renewable energy sources, making energy access cost-effective and more reliable. Further, Africa's diverse climate conditions and resource availability call for a tailor-made solution in emission reduction. Given that, regional cooperation in climate research and new technology development will enable countries to mitigate emissions and transition to clean energy more effectively. Moreover, African countries should match their climate policies, emission reduction targets and renewable energy standards to ensure consistency in regulatory frameworks. Regional cooperation on cross-border infrastructure projects such as cross-border electricity lines, electricity grids and shared resources management can help the countries to achieve their mitigation targets. Regional cooperation should focus on building capacity and sharing knowledge among the African countries.

Data availability

All the data utilised in the analysis is attached as a supplementary material Supplementary Table S1.

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References

Abid M (2016) Impact of economic, financial, and institutional factors on CO2 emissions: Evidence from Sub-Saharan Africa economies. Uti Policy 41:85–94. https://doi.org/10.1016/j.jup.2016.06.009

Acheampong AO, Dzator J, Savage DA (2021) Renewable energy, CO2 emissions and economic growth in sub-Saharan Africa: Does institutional quality matter? J Policy Model 43(5):1070–1093. https://doi.org/10.1016/j.jpolmod.2021.03.011

Adebayo T, Odugbesan T (2021) Modeling CO2 emissions in South Africa: empirical evidence from ARDL based bounds and wavelet coherence techniques. Environ Sci Pollut Res 28:1–13. https://link.springer.com/article/10.1007/s11356-020-11442-3

Ahmedou OCA, Nagasawa R, Osman AE, Hattori K (2008) Rainfall variability and vegetation dynamics in the Mauritanian Sahel. Clim Res 38(1):75–81. https://doi.org/10.3354/cr00776

Allison L, Palmer M, Haigh I (2022) Projections of 21st century sea level rise for the coast of South Africa. Environ Res Commun 4:025001. https://doi.org/10.1088/2515-7620/ac4a90

Bamisile O, Obiora S, Huang Q, Yimen N, Abdelkhalikh Idriss I, Cai D, Dagbasi M (2021) Impact of economic development on CO2 emission in Africa; the role of BEVs and hydrogen production in renewable energy integration. Int J Hydrog Energy 46(2):2755–2773. https://doi.org/10.1016/j.ijhydene.2020.10.134

Bedair H, Alghariani M, Omar E, Anibaba Q, Remon M, Bornman C, Alzain H (2023) Global warming status in the African Continent: Sources, Challenges, policies, and future direction. Int J Environ Res 17(3):45. https://doi.org/10.1007/s41742-023-00534-w

Berhanu Y, Olav, L, Nurfeta A, Angassa A, Aune JB (2019) Methane emissions from ruminant livestock in ethiopia: Promising forage species to reduce CH4 emissions. Agriculture 9(6). https://doi.org/10.3390/agriculture9060130

Bernardino JN, Olusegun AD, Franck EKG (2023) Sea Level Rise and Climate Change - Impacts on African Coastal Systems and Cities. *Sea Level Rise and Climate Change - Impacts on Coastal Systems and Cities*, Ch. 7. https://doi.org/10.5772/intechopen.113083

Camberlin P (2018) Climate of Eastern Africa In *Oxford Research Encyclopedias*

Canadell JG, Raupach MR, Houghton RA (2009) Anthropogenic CO2 emissions in Africa. Biogeosciences 6(3):463–468. https://doi.org/10.5194/bg-6-463-2009

Carvalho KS, Wang S (2019) Characterizing the Indian Ocean sea level changes and potential coastal flooding impacts under global warming. J Hydrol 569:373–386. https://doi.org/10.1016/j.jhydrol.2018.11.072

Chakamera C, Alagidede P (2018) Electricity crisis and the effect of CO2 emissions on infrastructure-growth nexus in Sub Saharan Africa. Renew Sustain Energy Rev 94:945–958. https://doi.org/10.1016/j.rser.2018.06.062

Collins JM (2011) Temperature Variability over Africa. J Clim 24(14):3649–3666. https://doi.org/10.1175/2011JCLI3753.1

Dao NB, Dogan B, Ghosh S, Kazemzadeh E, Radulescu M (2024) Toward sustainable ecology: how do environmental technologies, green financial policies, energy uncertainties, and natural resources rents matter? Clean Technol Environ Policy. https://doi.org/10.1007/s10098-024-02887-y

Dharmapriya N, Edirisinghe S, Gunawardena V, Methmini D, Jayathilaka R, Dharmasena T, Rathnayake N (2024) Towards a greener future: examining carbon emission dynamics in Asia amid gross domestic product, energy consumption, and trade openness. Environ Sci Pollut Res 31(14):21488–21508. https://doi.org/10.1007/s11356-024-32475-y

Dickson KB, Middleton JFM, Clarke JI, Gardiner RKA, Kröner A, Mabogunje AL, … Steel RW (2024) Africa continent. In *Britannica*

Djoumessi D, Any F (2021) Relationship between methane emissions and economic growth in Central Africa countries: Evidence from panel data. Glob Transit 3:126–134. https://doi.org/10.1016/j.glt.2022.02.001

Dube K, Nhamo G, Chikodzi D (2021) Rising sea level and its implications on coastal tourism development in Cape Town, South Africa. J Outdoor Recreat Tour 33:100346. https://doi.org/10.1016/j.jort.2020.100346

Ehigiamusoe KU (2020) A disaggregated approach to analyzing the effect of electricity on carbon emissions: Evidence from African countries. Energy Rep. 6:1286–1296. https://doi.org/10.1016/j.egyr.2020.04.039

El-Shahat S, El-Zafarany AM, El Seoud TA, Ghoniem SA (2021) Vulnerability assessment of African coasts to sea level rise using GIS and remote sensing. Environ, Dev Sustainability 23(2):2827–2845. https://doi.org/10.1007/s10668-020-00639-8

Elshall A, Ye M, Kranz SA, Harrington J, Yang X, Wan Y, Maltrud M (2022) Application-specific optimal model weighting of global climate models: A red tide example. Clim Serv 28:100334. https://doi.org/10.1016/j.cliser.2022.100334

Engelbrecht F, Adegoke J, Bopape M-J, Naidoo M, Garland R, Thatcher M, … Gatebe C (2015a) Projections of rapidly rising surface temperatures over Africa under low mitigation. Environ Res Lett 10(8). https://doi.org/10.1088/1748-9326/10/8/085004

Engelbrecht F, Adegoke J, Bopape M-J, Naidoo M, Garland R, Thatcher M, … Gatebe C (2015b) Projections of rapidly rising surface temperatures over Africa under low mitigation. Environ Res Lett 10. https://doi.org/10.1088/1748-9326/10/8/085004

Espoir DK, Mudiangombe Mudiangombe B, Bannor F, Sunge R, Tshitaka J-LM (2022) CO2 emissions and economic growth: Assessing the heterogeneous effects across climate regimes in Africa. Sci Total Environ 804:150089. https://doi.org/10.1016/j.scitotenv.2021.150089

Fomby TB, Vogelsang TJ (2003) Tests of common deterministic trend slopes applied to quarterly global temperature data. Maximum Likelihood Estimation Misspecified Models: Twenty Years Later 17:29–43. https://doi.org/10.1016/S0731-9053(03)17002-8

Fontaine B, Janicot S, Monerie P-A (2013) Recent changes in air temperature, heat waves occurrences, and atmospheric circulation in Northern Africa. J Geophys Res: Atmospheres 118(15):8536–8552. https://doi.org/10.1002/jgrd.50667

Griggs G, Reguero BG (2021) Coastal adaptation to climate change and sea-level rise. Water, 13(16). https://doi.org/10.3390/w13162151

Hamdan A, Al-Salaymeh A, AlHamad IM, Ikemba S, Ewim DRE (2023) Predicting future global temperature and greenhouse gas emissions via LSTM model. Sustain Energy Res 10(1):21. https://doi.org/10.1186/s40807-023-00092-x

Harde H (2017) Scrutinizing the carbon cycle and CO2 residence time in the atmosphere. Glob Planet Change 152:19–26. https://doi.org/10.1016/j.gloplacha.2017.02.009

Hickman JE, Scholes RJ, Rosenstock TS, Pérez García-Pando C, Nyamangara J (2014) Assessing non-CO2 climate-forcing emissions and mitigation in sub-Saharan Africa. Curr Opin Environ Sustainability 9-10:65–72. https://doi.org/10.1016/j.cosust.2014.07.010

Hinkel J, Brown S, Exner L, Nicholls RJ, Vafeidis AT, Kebede AS (2012) Sea-level rise impacts on Africa and the effects of mitigation and adaptation: an application of DIVA. Regional Environ Change 12(1):207–224. https://doi.org/10.1007/s10113-011-0249-2

Hook SE, Wright A-DG, McBride BW (2010) Methanogens: Methane Producers of the Rumen and Mitigation Strategies. Archaea 2010(1):945785. https://doi.org/10.1155/2010/945785

Hsiao C (2014) Analysis of Panel Data (3 ed.). Cambridge: Cambridge University Press

Humlum O, Stordahl K, Solheim J-E (2013) The phase relation between atmospheric carbon dioxide and global temperature. Glob Planet Change 100:51–69. https://doi.org/10.1016/j.gloplacha.2012.08.008

IEA (2021a) Energy system of Algeria. Retrieved from https://www.iea.org/countries/algeria

IEA (2021b) Energy system of Angola. Retrieved from https://www.iea.org/countries/angola

IEA (2021c) Energy system of Benin. Retrieved from https://www.iea.org/countries/benin

IEA (2021d) Energy system of Burkina Faso. Retrieved from https://www.iea.org/countries/burkina-faso

IEA (2021e) Energy system of Egypt Retrieved from https://www.iea.org/countries/egypt

IEA (2021f) Energy system of Ethiopia. Retrieved from https://www.iea.org/countries/ethiopia

IEA (2021g) Energy system of Libya. Retrieved from https://www.iea.org/countries/libya

IEA (2021h) Energy system of Morocco. Retrieved from https://www.iea.org/countries/morocco

IEA (2021i) Energy system of Mozambique. Retrieved from https://www.iea.org/countries/mozambique

IEA (2021j) Energy system of South Africa. Retrieved from https://www.iea.org/countries/south-africa

IPCC (2021) Climate Change 2021 – The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Retrieved from Cambridge: https://www.cambridge.org/core/product/415F29233B8BD19FB55F65E3DC67272B

IPCC (2023a) Annex VII: Glossary (9781009157889). Retrieved from Cambridge: https://www.cambridge.org/core/product/058768DADC00B52E2ED3381D0259B4E0

IPCC (2023b) Atlas. In C. Intergovernmental Panel on Climate (Ed.), Climate Change 2021 – The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (pp. 1927-2058). Cambridge: Cambridge University Press

IPCC (2023c) Climate Change 2022 – Impacts, Adaptation and Vulnerability: Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press

IPCC (2023d) Climate Change Information for Regional Impact and for Risk Assessment. In C. Intergovernmental Panel on Climate (Ed.), Climate Change 2021 – The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (pp. 1767-1926). Cambridge: Cambridge University Press

Jabir A-A, Hasan GMJ, Anam MM (2021) Correlation between temperature, sea level rise and land loss: An assessment along the Sundarbans coast. J King Saud Univ - Eng Sci https://doi.org/10.1016/j.jksues.2021.07.012

James R, Washington R (2013) Changes in African temperature and precipitation associated with degrees of global warming. Clim Change 117(4):859–872. https://doi.org/10.1007/s10584-012-0581-7

Joos F, Spahni R (2008) Rates of change in natural and anthropogenic radiative forcing over the past 20,000 years. Proc Natl Acad Sci 105(5):1425–1430. https://doi.org/10.1073/pnas.0707386105

Kaufmann R (2002) Correction to "Cointegration analysis of hemispheric temperature relations" by Robert K. Kaufmann and David I. Stern. J Geophys Res 107. https://doi.org/10.1029/2002JD002080

Kazemzadeh E, Fuinhas JA, Radulescu M, Koengkan M, Silva N (2023) The heterogeneous impact of the environmental policy stringency on premature indoor and outdoor deaths from air pollution in the G7 countries: Do economic complexity and green innovation matter? Atmos Pollut Res 14(2):101664. https://doi.org/10.1016/j.apr.2023.101664

Kim S-K, Shin J, An S-I, Kim H-J, Im N, Xie S-P, Yeh S-W (2022) Widespread irreversible changes in surface temperature and precipitation in response to CO2 forcing. Nat Clim Change 12(9):834–840. https://doi.org/10.1038/s41558-022-01452-z

Koengkan M, Kazemzadeh E, Fuinhas JA, Tash MNS (2023) Heterogeneous impact of eco-innovation on premature deaths resulting from indoor and outdoor air pollution: empirical evidence from EU29 countries. Environ Sci Pollut Res 30(1):2298–2314. https://doi.org/10.1007/s11356-022-22423-z

Koll R, Ritika K, Terray P, Masson S (2014) The Curious Case of Indian Ocean Warming. J Clim 27:8501–8509. https://doi.org/10.1175/JCLI-D-14-00471.1

Lean HH, Smyth R (2010) CO2 emissions, electricity consumption and output in ASEAN. Appl Energy 87(6):1858–1864. https://doi.org/10.1016/j.apenergy.2010.02.003

Levin A, Lin C-F, James Chu C-S (2002) Unit root tests in panel data: asymptotic and finite-sample properties. J Econ 108(1):1–24. https://doi.org/10.1016/S0304-4076(01)00098-7

Lindsey R (2024) Climate Change: Atmospheric Carbon Dioxide Retrieved from NOAA website: https://www.climate.gov/news-features/understanding-climate/climate-change-atmospheric-carbon-dioxide

MacDougall AH, Friedlingstein P (2015) The Origin and Limits of the Near Proportionality between Climate Warming and Cumulative CO2 Emissions. J Clim 28(10):4217–4230. https://doi.org/10.1175/JCLI-D-14-00036.1

Magazzino C, Madaleno M, Waqas M, Leogrande A (2024) Exploring the determinants of methane emissions from a worldwide perspective using panel data and machine learning analyses. Environ Pollut 348:123807. https://doi.org/10.1016/j.envpol.2024.123807
Maji IK (2019) Impact of clean energy and inclusive development on CO2 emissions in sub-Saharan Africa. J Clean Prod 240:118186. https://doi.org/10.1016/j.jclepro.2019.118186
Mar KA, Unger C, Walderdorff L, Butler T (2022) Beyond CO2 equivalence: The impacts of methane on climate, ecosystems, and health. Environ Sci Policy 134:127–136. https://doi.org/10.1016/j.envsci.2022.03.027
Mimura N (2013) Sea-level rise caused by climate change and its implications for society. Proc Jpn Acad, Ser B 89(7):281–301. https://doi.org/10.2183/pjab.89.281
Mohan S, Mishra SK, Sahany S, Behera S (2021) Long-term variability of Sea Surface Temperature in the Tropical Indian Ocean in relation to climate change and variability. Global and Planetary Change *199*, 103436. https://doi.org/10.1016/j.gloplacha.2021.103436
NASA (2024a) Global Mean Sea Level Retrieved from https://sealevel.nasa.gov/understanding-sea-level/key-indicators/global-mean-sea-level/
NASA (2024b) IPCC 6th Assessment Report Sea Level Projections Retrieved from https://sealevel.nasa.gov/ipcc-ar6-sea-level-projection-tool
NASA (2024c) Sea Level Evaluation & Assessment Tool Retrieved from https://sealevel.nasa.gov/data_tools/16/
ND-GAIN (2021a) Guinea-Bissau. Retrieved from https://gain-new.crc.nd.edu/country/guinea-bissau
ND-GAIN (2021b) Rank countries by ND-GAIN Country Index, Vulnerability and Readiness. Retrieved from https://gain-new.crc.nd.edu/ranking/vulnerability
ND-GAIN (2021c) Somalia. Retrieved from https://gain-new.crc.nd.edu/country/somalia
NDC (2022) Democratic Republic of the Congo Retrieved from https://ndcpartnership.org/country/cod#:~:text=The%20Democratic%20Republic%20of%20the,%2C%20energy%2C%20and%20waste%20sectors
Neumann B, Vafeidis AT, Zimmermann J, Nicholls RJ (2015) Future coastal population growth and exposure to sea-level rise and coastal flooding-a global assessment. PLoS One 10(3):e0118571. https://doi.org/10.1371/journal.pone.0118571
Nyadzi E, Bessah E, Kranjac-Berisavljevic G (2020) Taking Stock of Climate Change Induced Sea Level Rise across the West African Coast. Environ Claims J 33(1):77–90. https://doi.org/10.1080/10406026.2020.1847873
Nyasulu M, Haque MM, Kumar KR, Banda N, Ayugi B, Uddin MJ (2021) Temporal patterns of remote-sensed tropospheric carbon dioxide and methane over an urban site in Malawi, Southeast Africa: Implications for climate effects. Atmos Pollut Res 12(3):125–135. https://doi.org/10.1016/j.apr.2021.02.005
Okorie DI, Lin B (2022) Emissions in agricultural-based developing economies: A case of Nigeria. J Clean Prod 337:130570. https://doi.org/10.1016/j.jclepro.2022.130570
Omer MA (2024) Climate variability and livelihood in Somaliland: a review of the impacts, gaps, and ways forward. Cogent Soc Sci 10(1):2299108. https://doi.org/10.1080/23311886.2023.2299108
Rafique R, Kumar S, Luo Y, Xu X, Li D, Zhang W, Asam Z-u-Z (2014) Estimation of greenhouse gases (N2O, CH4 and CO2) from no-till cropland under increased temperature and altered precipitation regime: a DAYCENT model approach. Glob Planet Change 118:106–114. https://doi.org/10.1016/j.gloplacha.2014.05.001
Silva N, Fuinhas JA, Koengkan M, Kazemzadeh E (2024) What are the causal conditions that lead to high or low environmental performance? A worldwide assessment. Environ Impact Assess Rev 104:107342. https://doi.org/10.1016/j.eiar.2023.107342
Sims CA (1980) Macroeconomics and Reality. Econometrica 48(1):1–48. https://doi.org/10.2307/1912017
Stips A, Macias D, Coughlan C, Garcia-Gorriz E, Liang XS (2016) On the causal structure between CO2 and global temperature. Sci Rep. 6(1):21691. https://doi.org/10.1038/srep21691
Thiam AK (2003) The causes and spatial pattern of land degradation risk in southern Mauritania using multitemporal AVHRR-NDVI imagery and field data. Land Degrad Dev 14(1):133–142. https://doi.org/10.1002/ldr.533
Toit CD, Meissner H, Niekerk WV (2014) Direct methane and nitrous oxide emissions of South African dairy and beef cattle. South Afr J Anim Sci 43:320–339. https://doi.org/10.4314/sajas.v43i3.7
UN (2018) News [Press release]. Retrieved from https://www.un.org/development/desa/en/news/population/2018-revision-of-world-urbanization-prospects.html
UNFCCC (2015) Benin's First Nationally Determined Contribution Under Paris Aagreement Retrieved from https://unfccc.int/sites/default/files/NDC/2022-06/CDN_BENIN_VERSION_ANGLAISE.pdf
UNFCCC (2018) Nationally Determined Contributions (NDCs) Report to UNFCCC Retrieved from https://unfccc.int/sites/default/files/NDC/2022-06/NRC%20Eritrea.pdf
UNFCCC (2021a) The Federal Republic of Somalia Updated Nationally Determined Contribution (Ndc) Retrieved from https://unfccc.int/sites/default/files/NDC/2022-06/Final%20Updated%20NDC%20for%20Somalia%202021.pdf
UNFCCC (2021b) Liberia's Revised Nationally Determined Contribution (NDC). Retrieved from https://unfccc.int/sites/default/files/NDC/2022-06/Liberia%27s%20Updated%20NDC_RL_FINAL%20%28002%29.pdf
UNFCCC (2021c) Nationally determined contributions (NDCs). Retrieved from https://unfccc.int/documents/497517
UNFCCC (2021d) Republic of Malawi Upadated Nationally Determined Contributions Retrieved from https://unfccc.int/sites/default/files/NDC/2022-06/Malawi%20Updated%20NDC%20July%202021%20submitted.pdf
UNFCCC (2021e) Updated Nationally Determined Contribution (NDC) Retrieved from https://unfccc.int/sites/default/files/NDC/2022-06/210804%202125%20SL%20NDC%20%281%29.pdf
UNFCCC (2021f) Updated Nationally Determined Contribution in The Framework of The Paris Climate Agreement. Retrieved from https://unfccc.int/sites/default/files/NDC/2022-06/NDC-Guinea%20Bissau-12102021.Final.pdf
UNFCCC (2021) Guinea Nationally determined contributions (NDCs). Retrieved from https://unfccc.int/documents/497517
UNFCCC (2022) Chad. National communication (NC) 3. Retrieved from https://unfccc.int/documents/461041
UNFCCC (2022) The Republic of Uganda Updated Nationally Determined Contribution (NDC). Retrieved from https://unfccc.int/sites/default/files/NDC/2022-09/Updated%20NDC%20_Uganda_2022%20Final.pdf
UNFCCC (2024) Nationally determined contributions (NDCs). Retrieved from https://unfccc.int/sites/default/files/NDC/2024-01/NDC%202%20MADAGASCAR.pdf
Venegas RM, Acevedo J, Treml EA (2023) Three decades of ocean warming impacts on marine ecosystems: A review and perspective. Deep Sea Res Part II: Topical Stud Oceanogr 212:105318. https://doi.org/10.1016/j.dsr2.2023.105318
Vermeer M, Rahmstorf S (2009) Global sea level linked to global temperature. Proc Natl Acad Sci 106(51):21527–21532. https://doi.org/10.1073/pnas.0907765106
Vizy EK, Cook KH (2017) Seasonality of the Observed Amplified Sahara Warming Trend and Implications for Sahel Rainfall. J Clim 30(9):3073–3094. https://doi.org/10.1175/JCLI-D-16-0687.1
Vogelsang TJ, Franses PH (2005) Are winters getting warmer? Environ Model Softw 20(11):1449–1455. https://doi.org/10.1016/j.envsoft.2004.09.016
Vousdoukas MI, Clarke J, Ranasinghe R, Reimann L, Khalaf N, Duong TM, Simpson NP (2022) African heritage sites threatened as sea-level rise accelerates. Nat Clim Change 12(3):256–262. https://doi.org/10.1038/s41558-022-01280-1
Wang G, Eltahir EAB (2002) Impact of CO2 concentration changes on the biosphere-atmosphere system of West Africa. Glob Change Biol 8(12):1169–1182. https://doi.org/10.1046/j.1365-2486.2002.00542.x
Western LM, Ramsden AE, Ganesan AL, Boesch H, Parker RJ, Scarpelli TR, Rigby M (2021) Estimates of North African Methane Emissions from 2010 to 2017 Using GOSAT Observations. Environ Sci Technol Lett 8(8):626–632. https://doi.org/10.1021/acs.estlett.1c00327
WMO (2023) News [Press release]. Retrieved from https://wmo.int/news/media-centre/africa-suffers-disproportionately-from-climate-change
Zickfeld K, Solomon S, Gilford DM (2017) Centuries of thermal sea-level rise due to anthropogenic emissions of short-lived greenhouse gases. Proc Natl Acad Sci 114(4):657–662. https://doi.org/10.1073/pnas.1612066114

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TG: writing original draft, conceptualisation, formal analysis, investigation, data analysis, validation, methodology, and writing (review/editing). SL: writing original draft, conceptualisation, formal analysis, investigation, data analysis, validation, methodology, and writing (review/editing). CP: writing original draft, conceptualisation, formal analysis, data analysis, methodology, and writing (review/editing). SB: writing original draft, conceptualisation, formal analysis, data analysis, methodology, and writing (review/editing). RJ: conceptualisation, formal analysis, methodology, supervision, validation, writing (review/editing).

Competing interests

The authors declare no competing interests.

Ethics approval

This study did not involve any experiments with human participants or animals performed by any of the authors. The research was based exclusively on publicly available secondary data obtained from institutional repositories, including the World Bank and International Monetary Fund. Therefore, ethical approval was not required. The study complied with the ethical standards outlined in the Declaration of Helsinki and its later amendments.

Informed consent

This study did not involve human participants, and thus, no informed consent was required.

Additional information

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