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CO_2 emissions and economic growth: Assessing the heterogeneous effects across climate regimes in Africa

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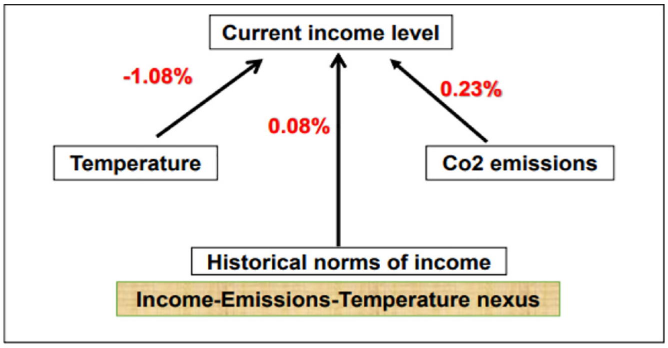
HIGHLIGHTS

- We investigate the effect of Co2 emissions and temperature on growth across climate regimes in Africa.
- The AMG and wavelet methods are used to obtain marginal effects and co-movement between variables.
- We find that an increase in average temperature reduces income in Africa, whereas a rise in emissions spurs income.
- Also, the result suggests that a shift from optimal temperature to extreme patterns deter growth.
- Global climatic policies may not yield success compared to country specific based policies.

GRAPHICAL ABSTRACT



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ABSTRACT

Climate change has occasioned several Earth long-term events, including extreme temperatures. In recent years, Africa was reported as part of the world's regions that experienced extreme temperatures above pre-industrial levels. Despite lower contribution to Green House Gas (GHG) emissions and global warming, Africa remains among the world regions that suffer the most from climate change. However, the impact of climatic factors of temperature and emissions on economic production in Africa has not been broadly investigated, specifically among climate regimes. In this study, we attempt for the first time to understand the heterogeneous impacts of emissions and temperature on income in Africa using panel and time-series techniques on datasets spanning the years 1995-2016. At the global level in Africa, our empirical results reveal that a 1% increase in average temperature reduces income by 1.08%, whereas a 1% rise in CO_2 emissions spurs income by 0.23%. The emissions effect result implies that environmental policies specifically designed to reduce CO_2 emissions in Africa as a whole may significantly impact production in the long run. Also, the result suggests that a shift from optimal temperature levels to extreme patterns deter economic growth. Despite these revelations, our extended analysis based on climate regimes indicates heterogeneous effects across countries. Considering the Paris agreement on climate, this study suggests that policymakers should emphasise country-specific policies than global climatic policies for sustained CO_2 emissions reduction in Africa.

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1. Introduction

Across the globe, and in every aspect of life, it is becoming increasingly difficult to ignore the causes and consequences of climate change. Most notably, climate change is responsible for the decrease in agricultural production and worsening food insecurity (Food and Agriculture Organisation (FAO), 2019), more disease morbidity (World Health Organization (WHO), 2018), and increasing poverty (Hallegatte et al., 2016). Ultimately, climate change is the main impediment to economic growth and development (International Monetary Fund (IMF), 2017, 2019; The Economist Intelligence Unit, 2020). Ironically, the most affected sectors of the economy, particularly agriculture and manufacturing, are the main contributors to climate change. Energy consumption, driven by agriculture and industrial processes, accounts for 73% of greenhouse gas emissions (GHGs) (World Resources Institute, 2020). Thus, the most significant intermediate impact of GHGs is global warming.

The world has been experiencing rising temperatures over the past 40 years. The past six years have been the warmest. 2016 and 2020 are the hottest, recording 1.29 °C (2.33 °F) and 1.27 °C (2.29 °F) higher than the pre-industrial period (1850-1900), respectively (World Meteorological Organization (WMO), 2020a, 2020b). In Africa, the temperature rise has been slightly faster than global average levels (WMO, 2020a, 2020b). The Intergovernmental Panel on Climate Change (IPCC) predicts that Africa will record temperatures 2 °C above the pre-industrial levels by 2080 (IPCC, 2015). Accordingly, Africa is expected to be hit hardest by the effects of global warming. The Economist Intelligence Unit (2020) projects that while the global economy may lose close to 3% of GDP by 2050, Africa may lose up to 4.7%. According to the African Climate Policy Centre (ACPC) (2020), the impact will be heterogenous according to regions, climatic regimes, and temperature projections, as shown in Table 1.

We can see from Table 1 that under the same temperature change projections, the impact on GDP varies according to regions. As a whole, Africa's GDP will shrink by between 2.25% and 12.12% for temperature changes of 1 °C and 4 °C, respectively. The western region is expected to be the hardest hit, with its GDP change forecasted between -4.46% and -22.09% for the same temperature projections. The impact will be mostly negligible in the northern region, which may register -4.11% growth under the worst, yet most unlikely temperature level of 4 °C. This variation reflects the different climatic conditions in the continent. The IPCC (2015) forecasts that the Sahel and Southern Africa regions will be drier, have more frequent heat waves, and experience more frequent drought. Central Africa will experience a reduction in wet spells length. Elsewhere, West Africa will see the number of dry days increasing. The African continent can be classified into six climatic regimes (subtropical moist (STM), subtropical dry (STD), warm temperate moist (WTM), tropical moist (TM), tropical dry (TDR), and tropical desert (TDS)), as shown in Fig. 1. The probable heterogeneous impact of climate change and temperature on economic growth can be seen in Fig. 2.

Table 1
Projected climate change impact on Africa's GDP (annual %) under four temperature regimes.
Source: African Climate Policy Centre (ACPC) (2020) obtained from https://unfccc.int/news/climate-change-is-an-increasing-threat-to-africa. Accessed June 2021.

Sub-region	Annual GDP (%) change			
	1 °C	2 °C	3 °C	4 °C
North (7)	-0.76 ± 0.16	-1.63 ± 0.36	-2.72 ± 0.61	-4.11 ± 0.97
West (15)	-4.46 ± 0.63	-9.79 ± 1.35	-15.62 ± 2.08	-22.09 ± 2.78
Central (9)	-1.17 ± 0.45	-2.82 ± 1.10	-5.53 ± 1.56	-9.13 ± 2.16
East (14)	-2.01 ± 0.20	-4.51 ± 0.34	-7.55 ± 0.63	-11.16 ± 0.85
Southern (10)	-1.18 ± 0.64	-2.68 ± 1.54	-4.40 ± 2.56	-6.49 ± 3.75
Africa (55)	-2.25 ± 1.52	-5.01 ± 3.30	-8.28 ± 5.62	-12.12 ± 7.04

Over the period 1995-2016, the WTM region experienced the most significant increase in temperature (0.22%) and recorded the least growth in GDP per capita (3.17%). However, STM, the region with the slightest temperature increase (0.07%), is not the one with the biggest growth in GDP per capita (4.88%). On the contrary, TM documented the highest growth in GDP per capita (5.86%) despite recording a sizable increase in temperature (0.18%).

The varied impact of climate change can also be noted from the CO_2 emissions and economic development nexus. We observe that the three regions (STM, TDR, and TM) with the biggest increase in CO_2 emissions per capita (1.29%; 3.61%; 5.88%) also have the highest growth rates in GDP per capita (4.88%, 4.95%; 5.86%). For these climatic regimes, economic growth is strongly correlated with CO_2 emissions. This may be due to increasing energy consumption. In the STD region, growth in CO_2 per capita is negative (-1.29%), yet its growth in GDP per capita (3.55%) is higher than that of WTM (3.17%).

Despite the existence of different climate regimes in Africa, existing studies on the nexus between climate change and economic growth (Abid, 2016; Chekouri et al., 2021; Espoir and Sunge, 2021; Olubusoye and Musa, 2020; Omotor, 2016; Yusuf et al., 2020) have ignored the heterogeneous effects of climate regimes and indeed temperature variations. Attempts to account for specific conditions are restricted to the country's levels of development (Olubusoye and Musa, 2020), oil-producing countries (Yusuf et al., 2020), and geographical regions (Demissew Beyene and Kotosz, 2020; Omotor, 2016). These studies implicitly assume the homogeneity of climate regimes and temperature conditions. Elsewhere, evidence has shown that temperature matters. Studies by Akram (2013), Dell et al. (2012), Holtermann and Rische (2020), Kahn et al. (2019), Kalkuhl and Wenz (2018), and Newell et al. (2018) have shown that economic growth tends to be lower for hotter and poorer countries or regions. A few studies (Abidoye and Odusola, 2015; Baarsch et al., 2020; Lanzafame, 2012) have acknowledged the impact of temperature on economic growth in Africa.

While studies enumerated above have provided important evidence, we observe that temperature change effects on the interaction and co-movement between CO_2 emissions and economic growth have not been dealt with clearly. There are conflicting results attributed to differences in data sources, country-specific characteristics, variables selection, and econometric strategies. Moreover, the effect of climate change regime has been sidelined. As a result, such studies turn a blind eye to the reality of the heterogeneous effects of climate variables, particularly temperature changes on the co-movement or absence of, between these variables of interest. Understandably, analysing the interaction effects of variables is difficult to compute and interpret from conventional estimation techniques.

This study investigates the effects of CO_2 emissions and temperature on economic growth across climate regimes using various econometric techniques while considering Africa as a case scenario. The African case is appealing for developing policy alternatives for countries with similar climate-dependent characteristics. To capture the heterogeneous effects based on climate regime criterium, we utilise the wavelet methods. Contrary to several empirical studies in Africa (see, for example, Abid, 2016; Chekouri et al., 2021; Espoir and Sunge, 2021; Olubusoye and Musa, 2020; Omotor, 2016; Yusuf et al., 2020), in this study, we adopt the wavelet coherence transform, multiple wavelets and the partial wavelet analysis for decomposing the time in different time scales. The wavelet method has a consistent set of advantages compared to classical time domains. First, it offers short, medium, and long-run frameworks; second, it details the interaction between variables across different frequencies over time; and third, it displays the lead-lag and cyclical against countercyclical status of the nexus, as reported in Mutascu (2018). For each time scale, both time and frequency causality tests are performed to investigate the direction of interaction between CO_2 emissions and income growth. Our study is important to the discussion of climate change effects and policy in Africa. The continent is projected to be the biggest looser from climate change, with the loss

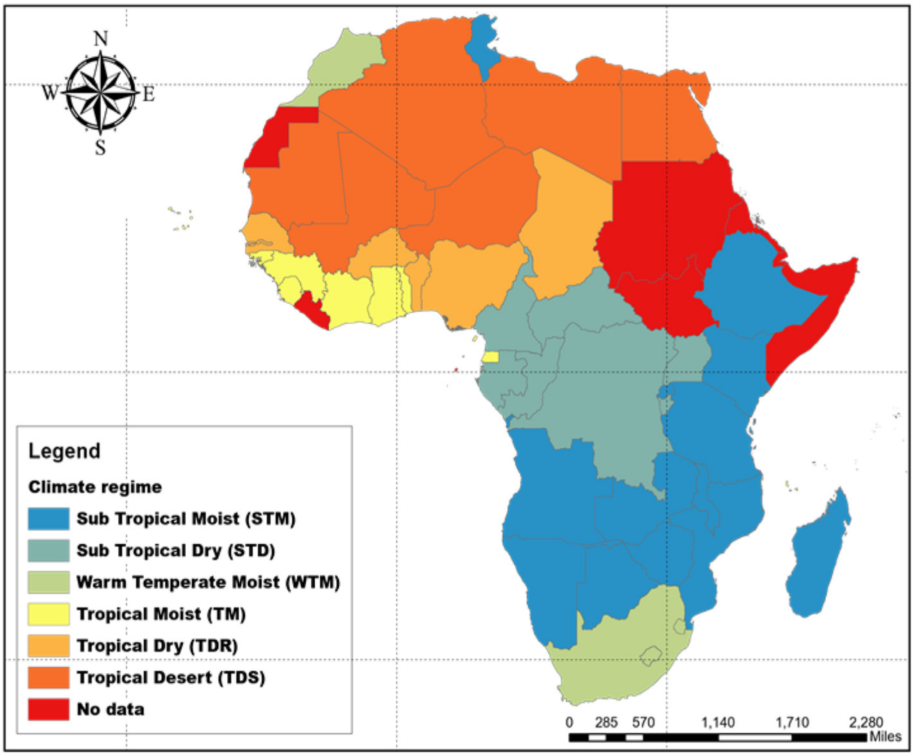

Fig. 1. Map of African countries and their corresponding climate regime.
Source: Authors' self-painting using World Development Indicators online database, World Bank Climate Change Knowledge Portal (2021) and Encyclopaedia Britannica (2021), World Climate Regions online map, accessed in June 2021.

varying according to different climatic regimes. Controlling for heterogeneity emanating from different climate regimes guides policies to accommodate the idiosyncratic nature of African countries.

The scientific contributions of this study are fourfold. First, to the best of our knowledge, this is the first analysis that uses the wavelet methods to explore the interaction between CO_2 emissions and income growth across climate regimes in Africa. The use of these techniques helps identify not only the direction of causality between CO_2 emissions and income growth nexus but also its persistence over time. Second, the results are reinforced by alternative analysis exclusively from the frequency domain. Such an approach allows the examination of the persistence of causal effects over a period of time without sample splitting. The use of the wavelet techniques is appropriate to this study as it allows policy prescription based on whether climate change effects on income levels are short, medium, or long-term. If the effects of temperature and CO_2 emissions on income is short or medium-term, then adaptation kind of policies should be relevant rather than mitigation policies that are appropriate for the long-term (Abidoye and Odusola, 2015). Third, this study novelly applies the Augmented Mean Group panel estimation technique. Unlike classical, traditional panel techniques (fixed and random effects), this approach enables the investigation of heterogeneous effects of CO_2 emissions and temperature on economic growth by taking into account the presence of cross-sectional dependence and slope heterogeneity. These two technical issues are likely to occur in a compact region like Africa due to common financial-economic-pandemic shocks, technological cross-borders spillovers, regional conflicts, and regional economic integration (SADC, ECOWAS, COMESA, and EAC). Fourth, unlike the existing studies, this paper clarifies the effect of climatic factors of temperature and emissions on economic production in Africa at the international policies of climate changes cycle, crucial for policy decisions from both type and time-target perspectives.

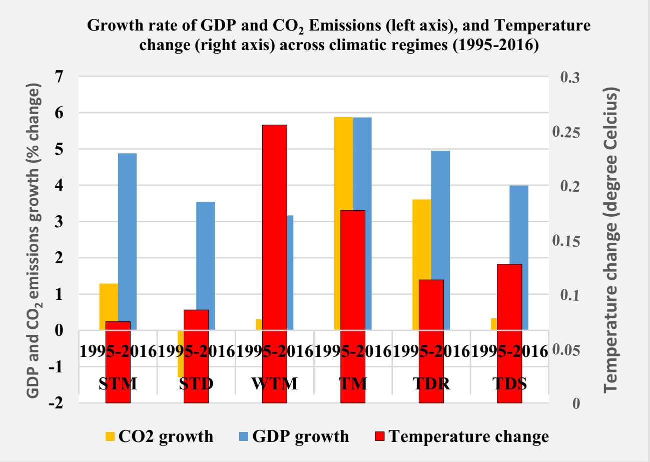

Fig. 2. Average growths rates in GDP per capita, CO_2 emissions, and temperature across climate regimes.
Source: Authors' compilation based on World Bank data.

The rest of the study is structured as follows: Section 2 covers the literature review; Section 3 outlines the materials and methods used. Results are presented and discussed in Section 4, and Section 5 concludes.

2. Literature review

Since the early 1990s, the link between economic growth and environmental deterioration has been a theoretical and empirical topic of study in the discipline of environmental economics (Abid, 2016; Magazzino et al., 2021a, 2021b). The relationship is founded on Kuznets' famous Environmental Kuznets curve (EKC) theory (1955). The EKC implies that environmental deterioration and per-capita income have an inverted-U connection (Grossman and Krueger, 1991). Environmental deterioration would increase during the early stages of economic expansion; but, after a particular threshold of per-capita income is reached, economic growth would result in better environmental outcomes (Abid, 2016; Magazzino, 2017). The EKC has generated a plethora of empirical examinations, with some (Fang et al., 2018; Espoir and Sunge, 2021; Kasperowicz, 2015; Lu, 2017; Zou and Zhang, 2020) confirming it while others (Aye and Edoja, 2017; Munir and Khan, 2014; Omotor, 2016) reject it. Several studies (Magazzino, 2016; Odhiambo, 2017; Omri et al., 2015; Spagnolo, 2012; Zaidi and Ferhi, 2019) have considered testing for causality between the variables. Also, a few studies have investigated the stationarity and convergence of CO_2 emissions in panel data frameworks (Magazzino, 2016, 2019).

These studies have been mixed and inconclusive mainly because of different country/regional samples, time, and econometric approaches. However, one aspect which has been under-researched is whether and how results vary according to climate regimes. At least some studies looked at the effects of temperature variations across countries at different levels of development. Dell et al. (2012) analysed the differential effects of temperature shocks on economic growth between poor and rich countries. Using annual fluctuations in temperature and precipitation across the world from 1950 to 2003, three key findings were documented; (1) higher temperatures cause tremendous and significant negative growth in poor countries only, (2) the effects are on both growth rates and the level of output, and (3) the effects are more profound in reducing agricultural and industrial output and political stability. The study found no significant impact of precipitation. However, we observe that the analysis by Dell et al. (2012) is based on short-run and medium-run fluctuations in temperature. There is every reason that, in the long run, countries may adapt to higher temperatures, thereby neutralizing the effects.

The long-run effects of temperature and climatic conditions on economic growth are also investigated by Kahn et al. (2019). The study used a stochastic growth panel data model of 174 economies over the period 1960 to 2014 in which climate change affects growth through labour productivity. Globally, results suggest that without mitigation strategies, an average annual global temperature change of 0.04 °C will lower global real GDP per capita by at least 7% by 2100. More importantly, the impacts are significantly sensitive across countries, according to the speed of temperature escalations and differences in climate conditions. Unlike the short-run results by Dell et al. (2012), the long-run analysis by Kahn et al. (2019) did not find different effects between poor and rich countries. The latter provided supplementary results of negative effects across USA states and economic sectors state. As in Dell et al. (2012), changes in precipitation do not have a significant impact on growth.

Another study acknowledging the reality that temperature and climate change effects are not universal is Holtermann and Rische (2020). The study registered discomfort in that many studies were based on country-level weather aggregates, ignoring significant country variations. Dynamic spatial econometric approaches were used for analysis to recognize the possibility of spatial dependence through spillovers and heterogeneous effects for divergent spatial regimes. The study found that economic growth across regions responds nonlinearly to increased temperature levels, echoing earlier evidence by Newell et al. (2018). A striking result from this study is that the effects also depend on baseline temperature levels. Hotter temperature changes have adverse effects in warmer regions but foster growth in colder regions. Similar evidence is given by Kalkuhl and Wenz (2018) from their assessment of the effects of climate on Gross Regional Product (GRP) in at least 1500 regions in 77 countries. Findings suggest that yearly temperature shocks decrease GRP in temperate and tropical climate regimes while increasing it in cold regimes.

While several studies (including Abid, 2016; Adzawla et al., 2019; Al-Mulali and Che Sab, 2012; Bouznit and Pablo-Romero, 2016; Gorus and Aydin, 2019; Espoir et al., 2021; Espoir and Sunge, 2021) have looked at the CO_2-economic growth relationship in Africa, very few (Abidoye and Odusola, 2015; Baarsch et al., 2020; Lanzafame, 2012) focused on temperature effects. Using yearly data for 34 African countries for the period 1961-2009, Abidoye and Odusola (2015) find that a 1 °C rise in temperature lowers GDP growth by 0.67 percentage points. However, when 5-year averages of temperature changes and economic growth are used, no relationship could be supported. In a related study, Odusola and Abidoye (2020) employed the Bayesian hierarchical modeling technique to distinguish between country-specific and Africa-wide effects of climate change. A 1% increase in temperature was found to cause a 1.58 percentage point decrease in GDP. The negative impact of temperature was also confirmed by economic growth (Alagidede et al., 2014; Lanzafame, 2012) and income convergence (Baarsch et al., 2020).

While evidence from the studies above is quite important, the effect of temperature changes on the interaction and co-movement between CO_2 and economic growth has not been dealt with clearly. Specifically, the effect of climate change regime has been sidelined. As a result, such studies turn a blind eye to the reality of the heterogeneous effects of climate variables, particularly temperature changes, the relationship between these variables of interest. Understandably, analysing the interaction effects of variables is difficult to compute and interpret (Issartel et al., 2014). This can be done using wavelet estimation, which permits data extraction on how entities change and how long the transition is between states. It also helps to reveal the number of states that can occur in a given period (Issartel et al., 2014). This approach is sparingly used in analysing the CO_2 emission-economic growth relationship with Adebayo and Kirikkaleli (2021), and Magazzino et al. (2021a, 2021b) only used it recently.

Magazzino et al. (2021a, 2021b) recently assessed the climate change effects on economic productivity by paying attention to the heterogeneity of different climate regimes. The study picked six countries[1] in five climatic regions[2] and applied a wavelet estimation technique. The approach allowed setting up sequences of interaction between economic growth and CO_2 emissions with temperature as a control variable. They show that the impact of temperature on the economic growth-CO_2 emissions nexus varies across countries and climate regimes. In the highland regime, temperature extends the perseverance of CO_2 emissions-economic growth effect. In the subtropical regime, temperature supports the growth-emissions nexus, albeit with no short-run effects. It pushes the co-movement of persistence of the variables for the temperate and tropical regimes, only to fall in the long run. Again, CO_2 spurs growth in the temperate regions while the reverse holds for tropical with the desert regime. The study's key finding is that temperature extends the strength of co-movement between growth and CO_2 emissions. Finally, there was no correlation between CO_2 emission and growth in tropical with rainforests and polar with tundra regimes.

3. Empirical model, data, and methodology

3.1. Empirical model

This study's main objective is to investigate the impact of temperature on the CO_2 emissions-economic growth nexus across different climate regimes. The theoretical framework underpinning our econometric model is the famous EKC hypothesis. In principle, the EKC hypothesis asserts that CO_2 emissions increase up to a certain point in the initial stages of economic growth, beyond which they fall (Espoir and Sunge, 2021). Accordingly, there exists an inverted-U-shaped relationship between the two. The existence of the EKC hypothesis is further supported by other theories namely; the Green Solow (Brock and Taylor, 2010), Stokey Alternative (Stokey, 1998; Brock and Taylor, 2010), and the Composition Shifts (Stern, 2004; Brock and Taylor,

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[1] Austria, Israel, Luxembourg, Kuwait, Singapore, and Norway.

[2] Tropical with its rainforest and desert extremes, subtropical, temperate, polar, and highland.

2010). Following Grossman and Krueger (1991), the EKC theory, in panel data form, is expressed as:

$$Co2\ Emissions_{i,t} = \alpha_0 + \alpha_1 Income_{i,t} + \alpha_2 (Income)^2_{i,t} + X_{it} + \varepsilon_{i,t} \tag{1}$$

where CO $_2$ *Emissions* and *Income* are the variables of our key interest and denote per-capita income levels and stock of carbon dioxide emissions, respectively. X is a vector of additional explanatory variables, αs are parameters to be estimated, ε is the conventional error term, i is a country identifier, and t denotes time in years. A positive α_1 and a negative α_2 confirm the EKC hypothesis. Eq. (1) assumes unidirectional causality from economic growth to CO_2 emissions. We agree with Barassi and Spagnolo (2012) that such an imposition is too restrictive. Also, several studies (including Acheampong, 2018; Espoir et al., 2021; Barassi and Spagnolo, 2012; Zaidi and Ferhi, 2019) have confirmed that bi-directional causality exists between the two. Accordingly, we capture the possibility of reverse causality as follows:

$$Income_{i,t} = \alpha_0 + \alpha_1 CO2\ Emissions_{i,t} + X_{it} + \varepsilon_{i,t} \tag{2}$$

Testing the EKC theory is not our priority; hence, we drop $(Income)^2_{i,\ t}$ in Eq. (1). Also, to match the specification by Magazzino et al. (2021a, 2021b), we use temperature as the X variable in Eqs. (1) and (2). We also add the first lagged-dependent variables $Income_{i,\ t-1}$ and $CO2\ Emissions_{i,\ t-1}$. We use them to capture the dynamic, persistent effects of time-series (the historical norms) and minimising bias due to omitted control variables. Accordingly, we express the linear but dynamic income-emission-temperature nexus as:

$$\begin{aligned} Income_{i,t} = {} & \alpha_0 + \alpha_1 Income_{i,t-1} + \alpha_2 Temperature_{i,t} \\ & + \alpha_3 CO2\ Emissions_{i,t} + \varepsilon_{i,t} \end{aligned} \tag{3}$$

$$\begin{aligned} CO2\ Emissions_{i,t} = {} & \alpha_0 + \alpha_1 CO2\ Emissions_{i,t-1} + \alpha_2 Temperature_{i,t} \\ & + \alpha_3 Income_{i,t} + \varepsilon_{i,t} \end{aligned} \tag{4}$$

where $Income_{i,\ t}$ and $Co2\ Emissions_{i,\ t}$ are the variables of our key interest and denote countries' income levels and stock of carbon dioxide emissions, respectively. $Income_{i,\ t-1}$ and $CO_2\ Emissions_{i,\ t-1}$ are the first lagged-dependent variables used to capture the dynamic, persistent effects of time-series (the historical norms) and minimising bias due to omitted control variable bias. α_0 is the constant term, whereas α_1, …, α_3 are the heterogeneous independent variables parameters, and $\varepsilon_{i,\ t}$ is the stochastic error term across countries i a time t.

3.2. Data

The data employed for estimating Eqs. (3) and (4) is a dataset of 47 African countries and six climate regimes,[3] covering the period 1995-2016. Table 2 shows the list of countries included in our sample group and their classification according to their respective climate region. We use the data availability criteria (GDP per-capita and CO_2 emissions) for sample selection. Also, given the diversity of temperature and climate in one land area (in one country), the main criteria behind the grouping of countries into one given climate regime are the dominance of a particular climate in that specific land area and the availability. Concerning climate regime dominance, for example, the Democratic Republic of Congo (DRC) is a country that is dominated by two main climates: the TM and TDR. The subtropical dry covers more than 65% of the country's total land area. Henceforth, the subtropical dry climate regime is selected for the DRC (see online Encyclopaedia Britannica, 2021).

Table 2
African countries and their climate regime classification.
Source: Classification performed based on data collected from World Development Indicators online database, World Bank Climate Change Knowledge Portal (2021) and Encyclopaedia Britannica (2021), World Climate Regions online map, accessed in June 2021.

Climate regime classification					
STM	STD	WTM	TM	TDR	TDS
Angola	DRC	Eswatini	Cape Verde	Benin	Mali
Botswana	Burundi	Lesotho	Côte d'Ivoire	Burkina Faso	Niger
Madagascar	Uganda	South Africa	Ghana	Gambia	Egypt
Malawi	Gabon	Morocco	Guinea	Nigeria	Libya
Mozambique	Cameroon		Guinea-Bissau	Senegal	Algeria
Namibia	Congo		Togo	Chad	Mauritania
Tanzania	CAR		Sierra Leone		
Zambia			Comoros		
Zimbabwe			Mauritius		
Rwanda			Seychelles		
Tunisia			Equatorial Guinea		
Kenya					
Ethiopia					

Note: The classification of African countries into climate regimes as reported in this table corresponds to 47 countries included in our study sample.

Three variables interact to achieve the study's key objectives: CO_2 emissions, temperature, and economic growth. CO_2 emissions represent the total volume/stock of carbon dioxide emissions produced during consumption of solid, liquid, and gas fuels and gas flaring in metric tons per capita. Temperature captures the country-year-average levels of temperature. This variable is expressed as the difference between the highest and lowest temperature in Fahrenheit degrees. The final data employed for this variable is the annual average temperature, which is computed based on monthly average temperatures. Finally, economic growth, which is proxied by GDP per capita. GDP per capita represents the sum of gross value added by all resident producers in the country at a given time, plus any product taxes and minus any subsidies not included in the value of the products.

Temperature, CO_2 emissions, and GDP per capita data are sourced from World Development Indicators online database (World Bank, 2021).[4] The three variables are used in natural logarithm form to minimise white noise due to outliers and obtain elasticities as percentage points. Moreover, the wavelet dataset requires differenced variables to increase the series volatility and remove their trend component (Mutascu, 2018). Therefore, we follow Magazzino et al. (2021a, 2021b) and convert the level variables into first differences for the final wavelet estimations. Table A1 in Appendix 1 presents the descriptive statistics of the variables used in our analysis. The figures in this table show that countries with high GDP per capita also have huge volume of CO_2 emissions.

3.3. Econometric methodology

Nowadays, it has become crucial to employ the appropriate econometric methodology when assessing the impact on economic development originating from the changes in one or multiple determinants. Traditional econometric techniques ignore two technical points: cross-sectional dependence (CD) and slope heterogeneity. Several studies recommend using second-generation econometric methods to minimise bias and inaccurate results if the two issues are present in the data (Bersvendsen and Ditzen, 2021; Espoir and Ngepah, 2021). Testing for CD in panel dataset is now compulsory because the world economies have become more financially and economically integrated. Due to this integration, the econometric literature firmly concludes that panel datasets are likely to present significant CD (Pesaran, 2004).

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[3] See the online Encyclopaedia Britannica (2021) for world climate regions.

[4] For GDP per capita, data are available at: https://data.worldbank.org/indicator/NY.GDP.PCAP.CD, whereas data of CO_2 emissions are available at: https://data.worldbank.org/indicator/EN.ATM.CO2E.PC.

This dependence may happen because of the presence of common shocks, technological cross-country spillovers, integration into common markets, as well as unobserved components that ultimately form part of the error term (Espoir and Ngepah, 2021). Failing to account for CD could lead to spurious results if the errors ($\varepsilon_{i,\ t}$) are not independent across panel units (Herzer and Vollmer, 2012). Concerning slope heterogeneity, panel data methodologies estimate variations in between cross-sectional units by fixed constants (using fixed and random effects techniques). However, some panel datasets exhibit individual variability in the slopes across cross-sectional units. Overlooking this variability may bias the results and cause incorrect inference (Chang et al., 2015; Bersvendsen and Ditzen, 2021). Thus, this study tests the issue of CD and slope heterogeneity before investigating the effect of temperature and CO_2 emissions on economic growth across African countries.

3.3.1. Testing cross-sectional dependence and slope heterogeneity

The Lagrange multiplier (LM hereafter) procedure developed by Breusch and Pagan (1980) is often used to test for CD. It is important to note that the LM test is valid only for relatively small N and sufficiently large T (Chang et al., 2015). Given that our sample unit is sufficiently large than the time series length, using LM test will give invalid results. Thus, we used the residual-based cross-section dependence test recently developed by Pesaran (2004), which is relevant for finite and infinite samples. To test cross-sectional dependence, Pesaran (2004) relied on the following statistic:

$$\text{Pesaran}_{CD} = \sqrt{\frac{2T}{N(N-1)}} \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \widehat{\rho}_{i,j} \tag{5}$$

where $\widehat{\rho}_{i,j}$ is an average parameter denoting the correlation between the errors.

The Pesaran_{CD} indicates the comparison between p-value and significance levels (1, 5 and 10%). This statistic allows us to determine whether CD is present in the panel data. In other words, when the p-value is smaller than the significance level, then there is evidence for the presence of CD, and thus the null hypothesis (i.e., no cross-sectional dependence) is rejected. Otherwise, we do not reject the null hypothesis.

Furthermore, we investigate whether or not the slope coefficients are homogeneous across panel units. We employ the standard delta test ($\widetilde{\Delta}$) proposed by Pesaran and Yamagata (2008). This test is based on a standardised version of Swamy's (1970) test. The Swamy's (1970) test requires panel data models where N is small relative to T, while the Pesaran and Yamagata (2008) test analyses slope homogeneity in large panels where N and T → ∞. For the $\widetilde{\Delta}$ test, Pesaran and Yamagata (2008) proposed two main steps to obtain the test statistic. First, the authors suggested computing the modified version of Swamy's test as:

$$\widetilde{S} = \sum_{i=1}^{N} \left(\left(\widehat{\beta}_i - \widetilde{\beta}_{WFE} \right) \frac{\prime X_i^{\prime} M_\tau X_i}{\widetilde{\sigma}_i^2} \left(\widehat{\beta}_i - \widetilde{\beta}_{WFE} \right) \right) \tag{6}$$

where $\widehat{\beta}_i$ and $\widetilde{\beta}_{WFE}$ are vectors of coefficients from pooled OLS and weighted fixed effect pooled estimator, respectively. $\widetilde{\sigma}_i^2$ is the estimator of σ_i^2 and M_τ is an identity matrix. Using Swamy's statistic from Eq. (6), the standard delta statistic is developed as:

$$\widetilde{\Delta} = \sqrt{N} \left(\frac{N^{-1}\widetilde{S} - K}{\sqrt{2k}} \right) \tag{7}$$

Under the null hypothesis of slope homogeneity with the condition of (N, T)→∞ so long as $\sqrt{N}$/T, the $\widetilde{\Delta}$ test has an asymptotic standard normal distribution ($\varepsilon \sim N(0, \sigma^2)$). Furthermore, for the small sample properties, the $\widetilde{\Delta}$ test can be improved under the same condition of normally distributed errors through a bias-adjusted version as:

$$\widetilde{\Delta}_{adj} = \sqrt{N} \left(\frac{N^{-1}\widetilde{S} - E\left(\widetilde{Z}_{i,t}\right)}{\sqrt{Var\left(\widetilde{Z}_{i,t}\right)}} \right) \tag{8}$$

where the mean $E\left(\widetilde{Z}_{\text{i,t}}\right) = k$ and the variance $Var\left(\widetilde{Z}_{i,t}\right) = \frac{2K(T-k-1)}{T+1}$.

In the presence of cross-sectional dependence and slope heterogeneity, any econometric technique that imposes homogeneity restrictions and ignores spatial dependence effects might produce inaccurate results. Consequently, this study used the Augmented Mean Group (AMG) estimator, which is developed under the two technical issues discussed in this section.

3.3.2. Heterogeneous parameter estimations

3.3.2.1. Augmented Mean Group estimator and convergency analysis. Eberhardt and Teal (2010) introduced the AMG estimator to estimate the long-run effect in heterogeneous panel data, which accounts for cross-sectional dependence and slope heterogeneity. The AMG estimator is deemed a highly robust estimation technique. It provides parameters through two steps. The first step is combining the unobserved common factor with the time dummies in the following equation:

$$\Delta y_{i,t} = \beta_i + \rho_i \Delta x_{i,t} + \varphi g_t + \sum_{i=1}^{N} \vartheta_t D_t + v_{i,t} \tag{9}$$

where $y_{i,\ t}$, and $x_{i,\ t}$ are dependent and independent variables, respectively. Δ denotes the first difference operator; β_i indicates the intercept; ρ_i represents the slope of each unit; φ is the heterogeneous factor loadings, g_t represents the unobserved common factor; D and ϑ are the time dummies and their coefficients respectively, and $v_{i,\ t}$ is the stochastic error term.

The second step is getting the Mean Group (MG) estimator for AMG by averaging the slopes of each unit as:

$$AMG = \frac{1}{N} \sum_{i=1}^{N} \widehat{\rho}_i \tag{10}$$

where $\widehat{\rho}_i$ are the estimates of ρ_i in Eq. (9).

The AMG estimator yields consistent, efficient, and unbiased parameters in finite and large panel datasets (Bond and Eberhardt, 2013).

Furthermore, we examine the proposition of heterogeneous structural effects by testing the hypothesis of CO_2 emissions and temperature convergence across African countries. We do so because the convergence effect is indicated to offset CO_2 emissions and temperature across climate regimes by limiting substantial income disparities (Dell et al., 2009; Magazzino et al., 2021a, 2021b). Specifically, the convergence test helps examine the practicability of either country-specific or common global policies. We apply the methodology developed by Phillips and Sul (2007) to test for full-sample and club convergence and grouping of sampled countries based on similar climatic factors. We begin the procedure by filtering the series to create new trend components. Then, we utilise log-*t*-test using linear regression based on 33.3% discarded data proportion before estimation.

3.3.2.2. Wavelet estimation methods. We finally use a battery of wavelet estimation methods to empirically link––for each climate regime, the economic growth with CO_2 emissions by controlling for temperature diversities. The wavelet methods we employ are the continuous wavelet transformation and wavelet coherency with phase-difference (partial and multiple wavelet coherency).

Regarding the wavelet transform method, it has to be noted that there are two types: continuous and discrete. While the continuous wavelet transform (CWT) works with time series over the entire axis, the discrete wavelet transform (DWT) deals with time series in a limited range. Aguiar-Conraria et al. (2008) show that the CWT is easier to manipulate. Hence, our study uses the CWT. Generally, the CWT function is decomposed in time series by ensuring a zero mean and localised time-frequency space. From this decomposition, it is plausible to get the information from the local area. Moreover, it has to be highlighted that the decomposition of the CWT is achieved through the Morlet function. The general use of the Morlet function is to examine the behaviour of time series in terms of time and frequency domain. The Morlet function is defined as:

$$\varphi^M(t) = \frac{1}{\pi^{1/4}} e^{i\omega_0 t} e^{-t^2/2} \tag{11}$$

where ω_0 is non-dimensional frequency and t is non-dimensional time. When applying wavelets for feature extraction purposes, the Morlet wavelet (with $\omega 0 = 6$) is a good choice, since it makes available a good balance between time and frequency localisation (see Grinsted and Jevrejeva, 2004; Kumar and Foufoula-Georgiou, 1997).

Furthermore, according to Rua and Nunes (2009), with convolution applied to a discrete sequence and a scaled and translated wavelet, the CWT can be defined as:

$$W_s(u,s) = \int_{-\infty}^{\infty} x(t) \frac{1}{\sqrt{s}} \omega\left(\frac{t-u}{s} dt\right) \tag{12}$$

where s, u, and $\frac{1}{\sqrt{s}}$ represent, respectively, the scale dilation parameter, the localisation parameter that provides the wavelet's exact position, and the normalisation factor. The CWT is used to check the co-movement between two series (parameters).

Another powerful wavelet estimation tool widely used in recent literature is the Wavelet Coherence (WC). Torrence and Compo (1998) identify the WC of two-time series x and y as the correlation coefficient localised between the two series in the time and frequency domain. Torrence and Webster (1999) show that the computing of the WC is considered as the squared absolute value of the normalised smoothed cross-wavelet spectra multiplied by the smoothed individual wavelet power spectra of each time series. Therefore, the equation of the wavelet coherence is given by:

$$WC = \frac{|s(s^{-1}W_{xy}(u,s))|}{S\left(s^{-1}|W_x(u,s)|^{1/2}\right) S\left(S^{-1}\left|W_y(\mathrm{u},\mathrm{s})\right|^{1/2}\right)} \tag{13}$$

where x and y describe the phase correlations between the two-time series, and s denotes the smoothing parameter. The WC will be equal to one in the no-smoothing scenario. In contrast, the coefficient of smoothed wavelet coherence satisfies the interval $0 \leq WC \leq 1$. A WC coefficient close to zero designates a weak correlation between x and y, whereas a coefficient close to one indicates a high correlation between x and y. The lateness of the wavering between the two series is quietly provided by the phase difference as a function of frequency and describes the positional relationship between the two-time series.

However, the WC estimation method is divided into two types: the Multiple Wavelet Coherence (MWC) and Partial Wavelet Coherence (PWC). The MWC and PWC were developed by Mihanović et al. (2009) to examine the co-movement between two time-series x and y while controlling for a third determinant, z. Ng and Chan (2012) frames the MWC by stipulating that the relationship of the variables with each other is considered when measuring the phase differences and coherency. They propose that the MWC runs related to the multiple correlations that can capture the coherency of multiple independent variables on a dependent one. The MWC is given by the following expression:

$$RM^2(y,x,z) = \frac{R^2(y,x) + R^2(y,z) - 2R_e[R(y,x)*R(y,z)*R(x,z)]}{1 - R^2(x,z)} \tag{14}$$

where RM^2 designates the multiple wavelet squared correlation between y, x, and z. y is the dependent variable, x is the independent variable, and z is the control variable. Transposing this to our case, y corresponds to economic growth, x is CO_2 emissions, and z is temperature. The MWC method determines the impact of CO_2 emissions on GDP per capita while considering temperature as a control variable. The Monte Carlo simulation is used in the estimation procedure to determine the statistical significance of the MWC method (see Aloui et al., 2018). On the other hand, the PWC method identifies the wavelet coherence between two-time series x and y after eliminating the power of the third series z. The PWC squared after removing the effect of z is given by a similar equation to the partial correlation squared written as:

$$R_p^2(y,x,z) = \frac{|R(y,x) - R(y,z)*R(y,x)^*|^2}{[1 - R(y,z)]^2 [1 - R(z,x)]^2} \tag{15}$$

where * indicates a complex conjugate and R_p^2 denotes the squared partial wavelet. The coefficient of the partial wavelet satisfies the interval $0 \leq R_p^2 \leq 1$. It is recognised as the squared partial correlation between series x and y after controlling for the effect of z in the time and frequency domain.

4. Empirical results and discussion

4.1. Results of slope heterogeneity and cross-sectional dependence

We begin by testing the heterogeneous effects of temperature, CO_2 emissions, and income across different climate regimes in Africa. To this end, we perform two analyses. First, we execute a univariate kernel density estimation of the logarithm of CO_2 emissions and GDP per capita and temperature. The results are presented in Fig. 3. As can be observed from this figure, the results approve the diversity of estimated emissions, income, and temperature across climate regimes in Africa. Therefore, the results indicate the significant degree of heterogeneity within the panel data, underpinning the usefulness of estimating unobserved and structural heterogeneous effects.

Second, we check if slope heterogeneity across climate regimes exists. Together with the CD test, this test helps to decide whether the first- or second-generation econometric methods should be used or not in subsequent analyses. We report the results of slope heterogeneity and that of the CD test in Table 3. For the two regression equations (income and CO_2 emissions equation), the statistic of the two tests ($\widetilde{\Delta}$ and $\widetilde{\Delta}_{adj}$) reject the null hypothesis of slope homogeneity at the 1% level of significance across all the panel units. This signifies that the economic growth regression analysis by assuming slope homogeneity restrictions may provide inaccurate inferences and misleading results.

Thus, our study takes into account countries' specific characteristics in analysing the effect of temperature and CO_2 emissions on growth in Africa. Furthermore, the results of the CD test are also reported in Table 3. The statistic for the income equation is statistically significant at the 1% significance level, while that of the CO_2 emissions equation is insignificant. For the income equation, the significant results indicate that an economic, financial, and pandemic shock originating from one country may produce spatial spillover effects in neighboring countries. Henceforth, the econometric technique to investigate the impact of temperature and CO_2 emissions on growth in Africa should control for this dependence.

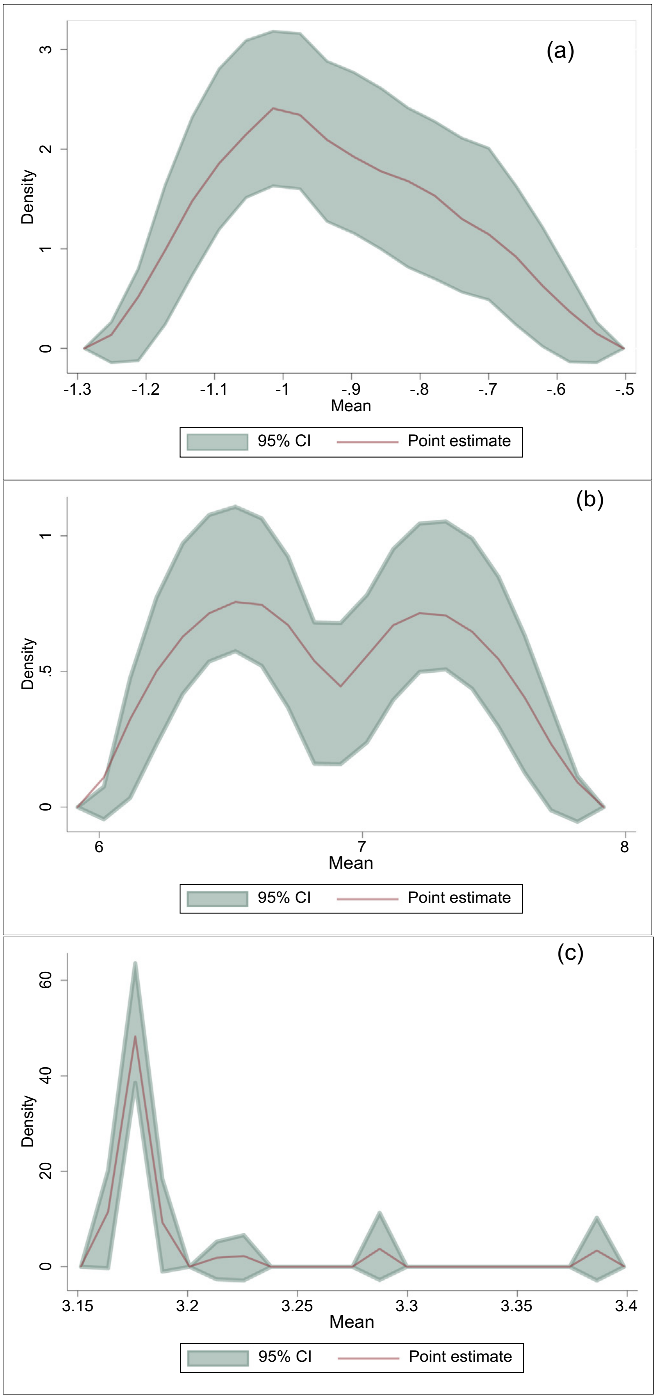


Fig. 3. Heterogenous effects using kernel density estimation: (a) CO2 emissions, (b) GDP per capita, and (c) temperature.

4.2. Results of long-run effects and convergence

Following the presence of cross-sectional and slope heterogeneity in our panel data, we conform to the recent econometric literature and employ the AMG estimator. The estimator considers spillover effects, global financial-economic-pandemic-driven shocks, and unobserved common factors with heterogeneous effects across countries. The results of this analysis are also presented in Table 3. For the income function, the results indicate that the coefficient of the first period lag of income ($Income_{i,\,t-1}$) is positive and statistically significant at the 10% significance level. This finding suggests that the historical records of income level in Africa have a positive long-run impact on the current economic production path among emissions and temperature dynamics. We additionally observe that a 1% increase in temperature declines income by 1.08%, while a 1% rise in CO_2 emission levels boosts income level by 0.23%.

Our findings of the long-run effects of temperature and CO_2 emissions are similar to those in Magazzino et al. (2021a, 2021b), which reports an effect of 0.39% and 0.22%, respectively. Moreover, Dell et al. (2009) present results indicating that a 1% rise in average temperature decreases income by 0.09% across 12 developing and developed countries. Similarly, our results are in line with Abidoye and Odusola (2015), who investigate the relationship between economic growth and climate change in Africa. The authors find that a 1 °C increase in temperature reduces GDP growth by 0.67%.

Concerning the CO_2 emissions equation, we find exciting findings. The regression results indicate that the long-term impact on the current stock of CO_2 emissions from its lagged-emission level ($Co2\ Emissions_{i,\,t-1}$) is positive and statistically significant at the 1% significance level. No significant long-run effect is obtained in the emission-temperature relationship. Meanwhile, the results show that a 1% increase in income level escalates emissions by 0.19%. This finding is similar to that of Espoir and Sunge (2021) that reports a positive effect of about 0.03% from a similar sample group. In sum, Table 3 shows the existence of a causal relationship between CO_2 emission and income levels in Africa. This implies that increasing emissions levels from the agrarian type of production to industrialised economic structures with limited green growth support variations in income levels in Africa. On the other hand, environmental sustainability attributed to the Kuznets curve assumes that expansion of income leads to environmental awareness, reducing pollution in the long term (Sarkodie and Strezov, 2019). Policy-wise, the finding of the causal relationship between CO_2 emissions and income implies that environmental policies specifically designed to reduce CO_2 emissions may significantly impact production. In contrast, growth-accelerating policies may dramatically increase the stock of CO_2 emissions in Africa.

Next, we analyse the hypothesis suggesting that the effect of climate change is assumed to have transboundary or spatial spillover effects across climate regimes due to global common shocks (Magazzino et al., 2021). To test this hypothesis, we use the log-t regression algorithm to estimate the state of convergence of emissions and temperature across climate regimes in Africa. The results of this analysis are reported in Table 4. The estimated results indicate that the *t*-test statistics obtained from the log-t regression algorithm for both emissions and temperature are less than the 5% critical value of -1.65. Consequently, the null hypothesis of convergence across climate regimes in Africa is rejected. However, the lack of convergence at the African level does not cast off the possibility of club clustering or club formation. We, therefore, investigate the possibility of observing club formation or club clustering using Phillips and Sul's (2007) club clustering algorithm, results of which are also presented in Table 4.

From this analysis, we observe that Ghana, Senegal, Togo, Mauritius, Seychelles, South Africa, Rwanda, and Gabon converge in Club 1 emission membership. Benin, Cape Verde, Côte d'Ivoire, Nigeria, Angola, DRC, Eswatini, Malawi, Mozambique, Namibia, Tanzania, Zambia, Zimbabwe, Chad, Tunisia, Algeria, Morocco, Uganda, Kenya, and Ethiopia converge in Club 2 emission membership. Gambia and Guinea converge in Club 3 emission membership; Burkina Faso, Guinea-Bissau, Mali, and Botswana converge in Club 4 emission membership; whereas Sierra Leone, Lesotho and Mauritania converge in Club 5 emission membership. Madagascar, Burundi, and Libya converge in Club 6 emission membership, while Comoros, Cameroon, and Egypt converge in Club 7 emission membership. Niger, Equatorial Guinea, Congo, the Republic of, and the Central African Republic are the countries that form the non-convergent Club (8th Club).

In contrast, Burkina Faso, Mali, Niger, Senegal, and Namibia converge in Club 1 temperature membership; Benin and Morocco converge in

Table 3
Heterogeneous estimation of emissions, temperature, and income.

Estimation	Income	Emissions
CO_2 Emissions$_{t-1}$	–	0.357*** (0.128) [0.106; 0.608]
Income$_{t-1}$	0.081* (0.049) [-0.178; 0.014]	–
Temperature	-1.078*** (0.439) [-1.940; -0.215]	0.725** (0.837) [-0.916; 2.367]
CO_2 Emissions	0.231*** (0.095) [0.043; 0.419]	–
Income	–	0.192*** (0.087) [0.020; 0.364]
C-d-p	0.911*** (0.055) [0.803; 1.019]	0.710 (0.494) [-0.257; 1.679]
Trend	0.001 (0.007) [-0.014; 0.015]	0.0001 (0.005) [-0.010; 0.011]
Constant	4.747*** (1.504) [1.798; 7.696]	1.062 (2.127) [-3.106; 5.232]
Pesaran$_{CD}$	11.427*** {0.000}	-0.321 {1.2519}
$\widetilde{\Delta}$	6.277*** {0.000}	2.060*** {0.039}
$\widetilde{\Delta}_{adj}$	6.940*** {0.000}	2.360*** {0.018}

Notes: (…) is the generated standard errors, […] is the 95% confidence interval, whereas {…} is the calculated p-value. Variable C-d-p refers to the common dynamic process, while the variable Trend refers to the group-specific linear trend terms.
*** Statistical significance at p-value < 0.01.
** Statistical significance at p-value < 0.05.
* Statistical significance at p-value < 0.1.

Club 2 temperature membership; whereas Gambia and Ghana form Club 3 temperature membership. Guinea-Bissau, Nigeria, and Libya are part of Club 4 temperature membership; Côte d'Ivoire and Sierra Leone converge in Club 5 temperature membership. Malawi, Uganda, Kenya, and Cameroon form Club 6 temperature membership; Ethiopia and Gabon are in Club 7 temperature membership; Botswana, Comoros, Mauritius, and Zimbabwe constitute Club 8 temperature membership. Cape Verde, Lesotho, Tunisia, Mauritania, and Equatorial Guinea constitute Club 9 temperature membership. Also, Angola, South Africa, and Rwanda are part of Club 10 temperature membership; Togo, DRC, Madagascar, Mozambique, Tanzania, Zambia, and Chad converge in Club 11 temperature membership, whereas Seychelles, Burundi, and Algeria from Club 12 temperature membership. Finally, Guinea, Eswatini, Egypt, Congo Republic, and the Central African Republic constitute Club 13, where the temperature does not converge. Fig. A1 in Appendix 2 presents the club relative transition path for both CO_2 emissions and temperature. However, the club convergence findings further strengthen the argument of heterogeneous structural impacts by suggesting that the common global climatic policies may not yield the expected outcome compared to country-specific based policies.

Furthermore, we conduct two additional regressions to confirm the convergence results of emissions and temperature. First, we employ the conditional panel inter-and intra- group trend estimator to examine group regression trends in a bivariate specification. We perform four different regressions across climate regimes. In all the four regressions, we control for additional covariate and omitted-variable bias. The results are presented in Fig. 4. In the emission-temperature model, we account for historical temperature variations and income levels depicted in Fig. 4(a). The inter-and intra- functions reveal that increasing emission levels escalate extreme temperatures TDS and STM––owing to unobserved confounders within countries. In the emission-income regression, we observe that increased emissions spur income growth in WTS, TDS, TM, and TDR while decreasing emissions in STD and STM (Fig. 4(b)).

Concerning the income-emission gradient, the result shows that increasing income levels raise emissions in WTM, STM, and TDS, while decreasing emissions in TM (Fig. 4(c)). Finally, in the temperature-income regression, the results suggest that an increase in average temperature produces a favorable effect on income level in WTM, TDS, STM, and

Table 4
Emissions and temperature final club convergence/divergence results.

	Country name	$\widehat{\beta}Coef$	$t-stat$
Results for CO_2 emissions			
Full-sample		-1.4984***	-90.794
Final club classification			
1st Club	|Ghana|Senegal|Togo|Mauritius|Seychelles|South Africa|Rwanda|Gabon|	3.892	25.104
2nd Club	|Benin|Cape Verde|Côte d'Ivoire|Nigeria|Angola|DRC|Eswatini|Malawi|Mozambique|Namibia|Tanzania|Zambia|Zimbabwe|Chad|Tunisia|Algeria|Morocco|Uganda|Kenya|Ethiopia|	-1.447***	-59.846
3rd Club	|Gambia|Guinea|	-0.361	-0.875
4th Club	|Burkina Faso|Guinea-Bissau|Mali|Botswana|	-1.292***	-44.472
5th Club	|Sierra Leone|Lesotho|Mauritania|	-1.493***	-70.602
6th Club	|Madagascar|Burundi|Libya|	-1.004***	-49.960
7th Club	|Comoros|Egypt|Cameroon|	-1.602***	-160.176
Non-convergent group (8th Club)	|Niger|Equatorial Guinea|Congo, Republic of|Central African Republic|	-2.076***	-34.794
Results for temperature			
Full-sample		-0.7359***	-17.8241
Final club classification			
1st Club	|Burkina Faso|Mali|Niger|Senegal|Namibia|	-0.666***	-12.603
2nd Club	|Benin|Morocco|	-0.687***	-14.622
3rd Club	|Gambia|Ghana|	1.005	1.868
4th Club	|Guinea-Bissau|Nigeria|Libya|	-0.865***	-8.349
5th Club	|Côte d'Ivoire|Sierra Leone|	-1.795	-1.203
6th Club	|Malawi|Uganda|Kenya|Cameroon|	-1.097***	-7.016
7th Club	|Ethiopia|Gabon|	-0.590***	-4.301
8th Club	|Botswana|Comoros|Mauritius|Zimbabwe|	- 1.124***	-4.879
9th Club	|Cape Verde|Lesotho|Tunisia|Mauritania|Equatorial Guinea|	-0.679***	-12.616
10th Club	|Angola|South Africa|Rwanda|	-0.392***	-3.815
11th Club	|Togo|DRC|Madagascar|Mozambique|Tanzania|Zambia|Chad|	-0.873***	-14.382
12th Club	|Seychelles|Burundi|Algeria|	-1.017***	-21.778
Non-convergent group (13th Club)	|Guinea|Eswatini|Egypt|Congo, Republic of|Central African Republic|	-0.519***	-6.170

Note: Estimation uses truncation parameter: $z = 0.33$ and asymptotic critical value: $c = 0.3$. The t-statistic at the 5% significance level: -1.645.
** and *** denote rejection of the null hypothesis (H0) of convergence as well as clubconvergence merging at the 5 and 10% level.

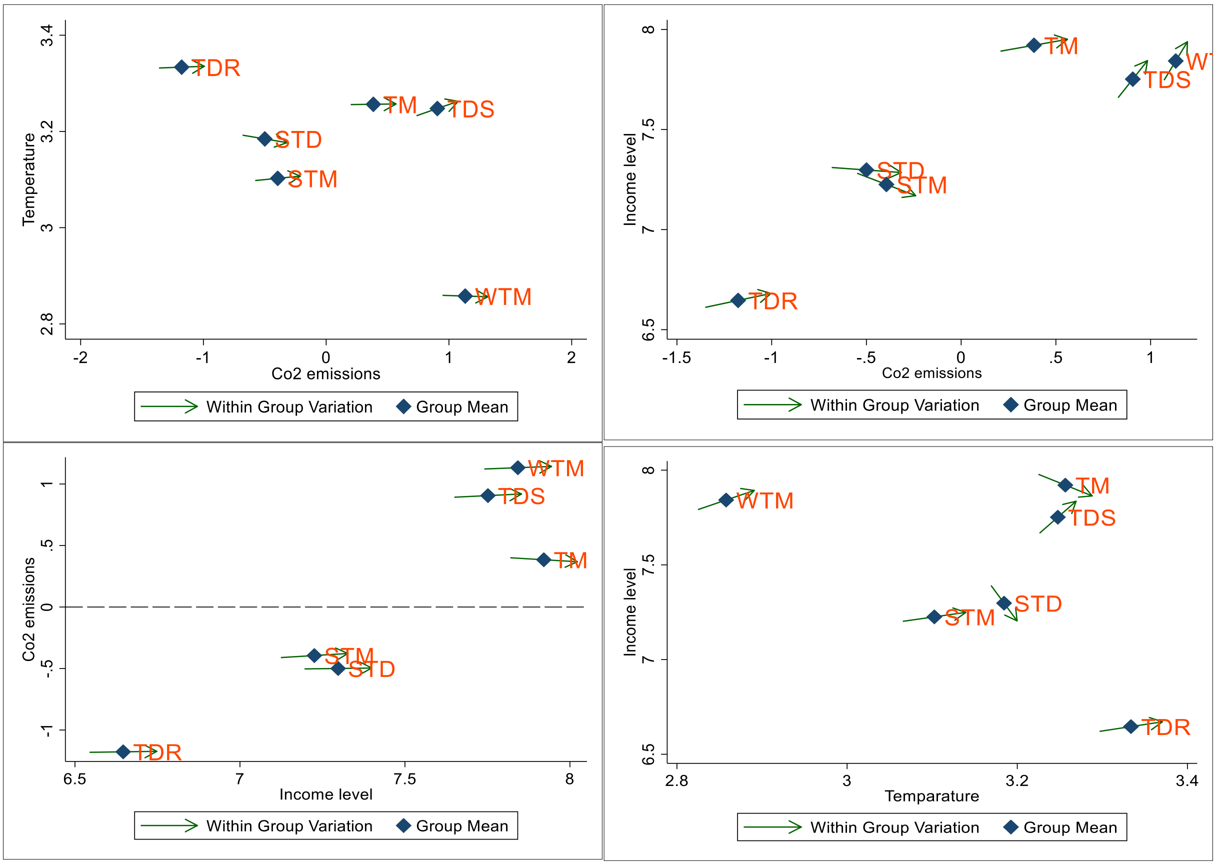


Fig. 4. Heterogenous impact between (a) CO_2 and temperature; (b) CO_2 and income; (c) income and CO_2; and (d) temperature and income. The blue diamond symbol (♦) denotes group means (between-country means) of climate regimes, whereas the green slope arrow (⟶) indicates the within-group variation of the estimated country-specific relationship gradient while controlling for lagged-dependent variable and additional covariate bias. In (a), we include the first lag of temperature and income level. In (b), we control for the first lag of income and temperature, in (c), we account for the first lag of emissions and temperature, and finally, in (d), we account for lagged-income and emissions. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

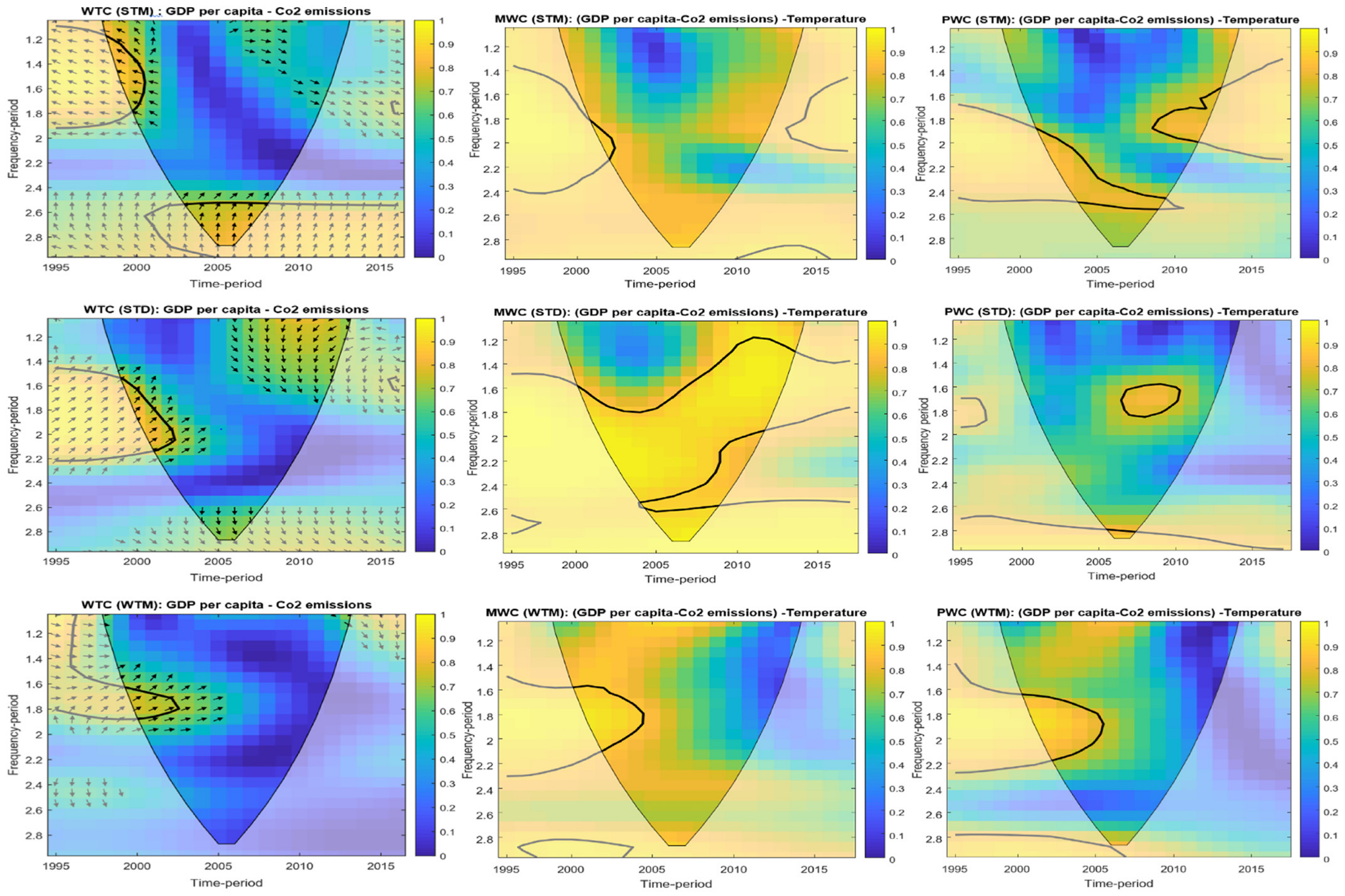
TDS, whereas decreasing income level in STD and TM (Fig. 4(d)). This specific finding is not surprising since it is shown that a shift from cold temperature to warmer temperature improves economic production in colder territories. In contrast, a shift from optimal warmer temperatures to extreme temperatures leads to economic losses. Similarly, warming declines economic productivity in low-altitude countries while expanding economic development in high-altitude countries (Diffenbaugh and Burke, 2019; Magazzino et al., 2021).

Second, we fit the Swamy (1970) random-coefficients linear regression for the income model, which does not impose the assumption of constant parameters across panels to obtain group-specific coefficients. The results of these regressions are reported in Table A2 of Appendix 1. They corroborate the finding of the convergence test and those of the conditional panel inter-and intra- group trend. Consequently, our finding validates the argument of structural heterogeneous impacts by suggesting that the common global climatic policies may not yield the expected outcome compared to country-specific based policies.

4.3. Country-specific climate regime

We further investigate country-specific regimes using wavelet regression methods. As indicated earlier, we regroup African countries into six different climate regimes: STM, STD, WTM, TM, TDR, and TDS. In each regime, we try to find the interaction effect between income and CO_2 emissions by considering temperature as a controlled variable. We maintain three frequency band scales (see Table 5). Figs. 5–7 exhibit the estimated results of the first, second, and third climate regime. From WTC (Fig. 5(a)) plot, two key episodes appear for STM. The first episode is observed at high frequency (up to 1 and half-year band of scale, i.e., short-term) covering 1998–2001. As the arrows point to the left and upward, CO_2 emissions positively influence income growth. The second episode is revealed at high frequency (2.8 to 3 years band of scale, i.e., long-term), over the period 2003-2008. The direction of the arrows is upright, suggesting that income growth positively drives CO_2 emissions in the long run. By including temperature in MWC (Fig. 5(b)), we observe that temperature reduces the intensity of co-movement between income and CO_2 emissions. In other words, this regression indicates that the registered co-movement in WTC is reduced for the long-term episode according to the intense yellow area in MWC, which appears at high frequency (up to 2 years band of scale), over the period 2000-2003. Moreover, fascinating results are observed by removing the temperature in PWC (Fig. 5(c)). We detect two episodes. The first episode is observed at high frequency (from 1.9 to 2.5 years band of scale, i.e., medium-term) covering the period 2000–2009. The second episode is detected at high frequency (from 1.5 to 1.9 years band of scale, i.e., medium-term) covering the period 2008–2012. Overall, we discern that temperature is not a critical factor driving co-movement between CO_2 emissions and income levels in countries parting to STM climate regime.

The results of the STD climate regime are presented in Fig. 6. We observe only one significant effect between CO_2 emissions and income reported in WTC plots (Fig. 6(a)). In this plot, at high frequency (from


WTC (STM) : GDP per capita - Co2 emissions

MWC (STM): (GDP per capita-Co2 emissions) -Temperature

PWC (STM): (GDP per capita-Co2 emissions) -Temperature

WTC (STD): GDP per capita - Co2 emissions

MWC (STD): (GDP per capita-Co2 emissions) -Temperature

PWC (STD): (GDP per capita-Co2 emissions) -Temperature

WTC (WTM): GDP per capita - Co2 emissions

MWC (WTM): (GDP per capita-Co2 emissions) -Temperature

PWC (WTM): (GDP per capita-Co2 emissions) -Temperature

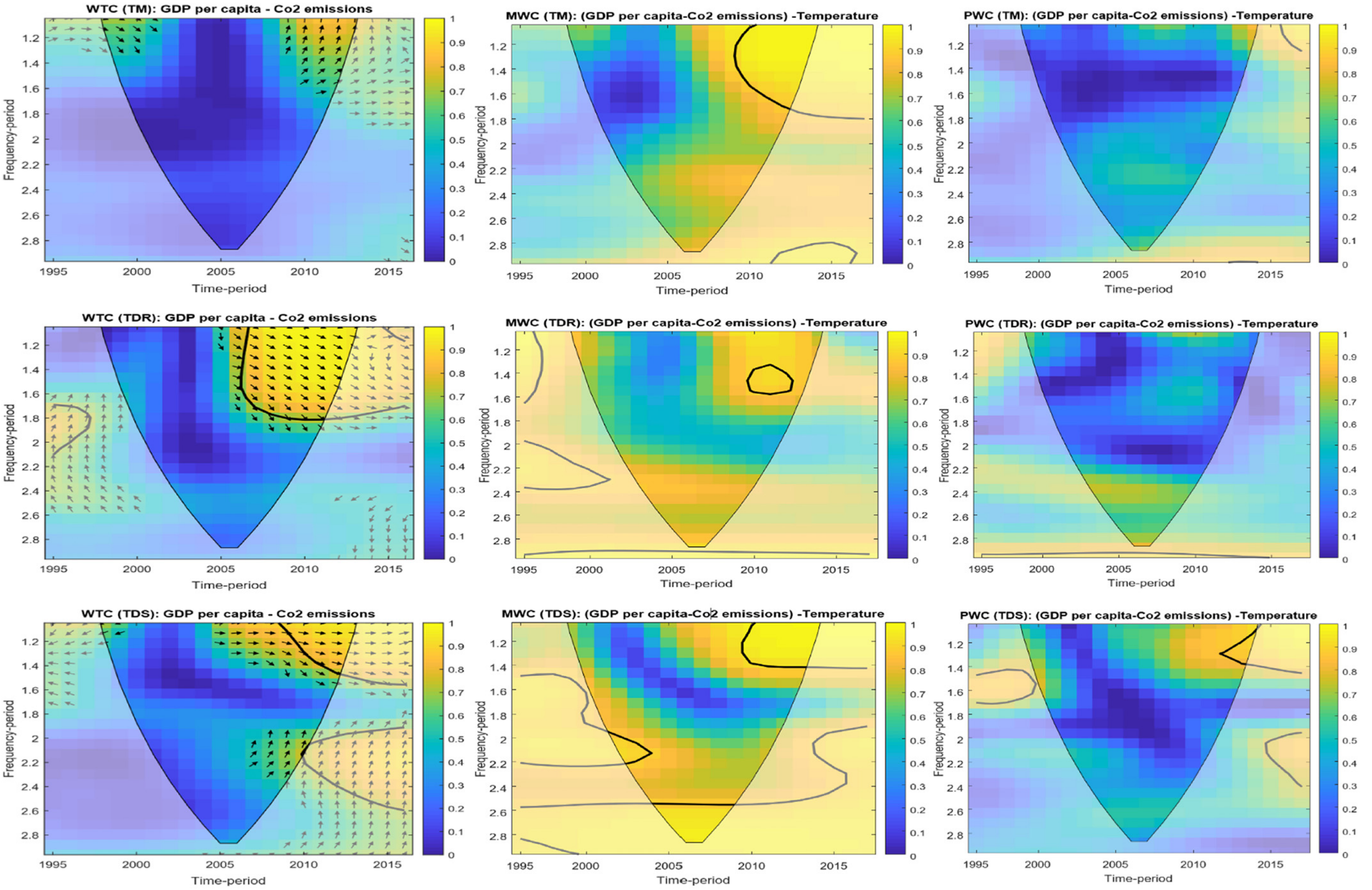
Figs. 5–7. The set WTC-MWC-PWC of 'GDP per capita - CO_2 emissions' pair with temperature as a control variable in MWC and PWC. The first raw is STM, the second raw is WTC, and the third raw is WTM. Legend: (1) The thick black contour indicates the 5% significance level. The lighted shadow shows the cone of influence (COI) where the edge effects might distort the picture. (2) The color code for power ranges goes from blue (low power) to yellow color (high power), suggesting the intensity of co-movement. (3) The phase difference between the two series is indicated by arrows position: the variables are in a phase when the arrows point to the right (positively linked) and out of phase when the arrows point to the left (negatively linked). In the phase scenario, growth drives emissions when the arrows are oriented to the right and up. CO_2 emissions drive growth when the arrows are pointed to the right and downward. In the out-of-phase scenario, growth explains emissions when the arrows are oriented to the left and downward. CO_2 emissions predict growth when the arrows point to the left and up. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

5 to 2.2 years band of scale, i.e., medium-term), over 1999–2002, the arrows are oriented to the right and up, suggesting that income growth positively influences CO_2 emissions in the medium period. In MWC (Fig. 6(b)) we consider the intermediating effect of temperature. The result indicates a shift from medium to long-term co-movement. Specifically, we see that temperature extends the intensity of co-movement between income and CO_2 emissions. The intensity appears at high frequency (from 2 to 2.6 years band of scale), over the period 2004-2011. When we remove temperature in PWC (Fig. 6(c)), two distinct co-movements appear. First, we see a co-movement at high frequency (from 1.6 to 1.9 years band of scale, i.e., short-term) covering the period 2006–2009. Second, we witness a co-movement at high frequency (from 2.8 and up the band of scale, i.e., long-term). This suggests that the temperature serves as a ground for income and CO_2 emissions connection in the long-term in the STD climate regime.

For the WTM climate regime in Fig. 7, income growth positively influences CO_2 emissions at medium frequency, as the arrows point to the right and upward in related WTC (Fig. 7(a)). The medium frequency refers to the period 2000–2004 (from 1.6 to 1.8 years band of scale, i.e., medium-term). When we included the temperature as a control variable in MWC (Fig. 7(b)) and when we remove it in PWC (Fig. 7 (c)), we observe the persistence of co-movement between CO_2 and income growth. This co-movement is seen at high frequency (from 1.5 to 2.2 years band of scale, i.e., medium-term), throughout 2000–2004. These findings imply that temperature is not a significant factor driving co-evolution between CO_2 emissions and income levels in countries that belong to the WTM climate regime.

The findings of TM are presented in Fig. 8. Growth positively drives CO_2 emissions over 2009–2012, at the medium frequency (from 1.2 to 1.6 years band of scale, i.e., short-term) with arrows oriented to the right and up, WTC (Fig. 8(a)). However, the positive influence of income growth is not statistically significant. Next, we include temperature as a control variable in the CO_2 emissions and income growth co-evolution. As can be seen in MWC (Fig. 8(b)), income growth positively determines CO_2 emissions over 2009–2012, at high frequency (from 1.2 to 1.6 years band of scale, i.e., short-term). When we remove temperature in PWC regression (Fig. 8 (c)), we see no significant effect in the co-movement between CO_2 emissions and income growth. Hence, the MWC regression's inclusion highlights the significant role that temperature plays in driving the effect of income growth on CO_2 emissions in the TM climate regime.

The case of TDR is displayed in Fig. 9. CO_2 emissions positively run income growth at high frequency, as the arrows are pointed to the right and downward in related WTC (Fig. 9(a)). In this figure, the high frequency refers to the period between 2006 and 2012 (from 1.2 to 1.7 years band of scale, i.e., short and medium-term). We perform



Figs. 8–10. The set WTC-MWC-PWC of 'GDP per capita - CO_2 emissions' pair with temperature as control variable in MWC and PWC. The first raw is TM, the second raw is TDR, and the third raw is TDS. Legend: (1) The thick black contour indicates the 5% significance level. The lighted shadow shows the cone of influence (COI) where the edge effects might distort the picture. (2) The color code for power ranges goes from blue (low power) to yellow color (high power), suggesting the intensity of co-movement. (3) The phase difference between the two series is indicated by arrows position: the variables are in a phase when the arrows point to the right (positively linked) and out of phase when the arrows point to the left (negatively linked). In the phase scenario, growth drives emissions when the arrows are oriented to the right and up, while CO_2 emissions drive growth when the arrows are pointed to the right and downward. In the out-of-phase scenario, growth explains emissions when the arrows are oriented to the left and downward. CO_2 emissions predict growth when the arrows point to the left and up. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

additional regression to test the robustness of the WTC result for the TDR climate regime. As for the other climate regime, we execute the MWC and PWC regression (Fig. 9(b) and (c)). Fig. 9(b) includes the temperature as a control variable that helps depict the exact co-movement between CO_2 emissions and income growth. The temperature insertion in MWC (Fig. 9(b)) confirms the significant effect of co-movement between CO_2 emissions and income growth nexus at the 5% significant level. As intense yellow color proves for the period between 2009 and 2011 (from 1.2 to 1.4 years band of scale, i.e., short-term), the result confirms that CO_2 emissions positively influences income growth. On the other hand, in Fig. 9(c), we remove the temperature variable to test the CO_2 emissions and income growth co-movement with the PWC regression (Fig. 9(c)). The result shows that no significant effect is depicted between the two variables. Therefore, we conclude that temperature plays a significant role in explaining the interaction between CO_2 emissions and income growth in countries grouped into the TDR climate regime.

Table 5
Frequency interpretation of time scales for yearly data.
Source: Authors' own elaboration.

Time scale	Yearly frequency
d1	1.2–1.79 years
d2	1.8–2.59 years
d3	2.6 years and up

Finally, the findings of TDS are displayed in Fig. 10. As can be observed in WTC (Fig. 10(a)), the arrows are pointing to the right, suggesting that the CO_2 emissions and income growth are in a phase (i.e., positively correlated). Further, we execute additional regressions to validate the WTC result for the TDS climate regime. We run the MWC and PWC regression (Fig. 10(b) and (c)). Fig. 10(b) includes the temperature as a control variable to depict the co-movement between CO_2 emissions and income growth. The results we obtain with the temperature insertion in MWC (Fig. 10(b)) show three episodes. The first episode is observed at high frequency (from 1.2 to 1.4 years band of scale, i.e., short-term) covering the period 2009–2013. The second episode is detected at high frequency (from 1.9 to 2.2 years band of scale, i.e., medium-term) covering the period 2001–2004. The third episode is also detected at high frequency (from 2.6 and up years band of scale, i.e., long-term) covering the period 2004–208. Finally, we remove temperature in the PWC regression (Fig. 10(c)). The result shows a co-movement only at high frequency (from 1.2 to 1.4 years band of scale, i.e., short-term). Thus, we conclude that there is a persistent co-evolution between CO_2 emissions and income growth in the short term for countries that form the TDS climate regime.

In sum, in the STM climate regime, we conclude that temperature extends the co-movement between CO_2 emissions and income growth in the medium-term. However, it is not a critical factor driving co-movement between the two variables in the long term. In the STD climate regime, the temperature serves as a ground for income and CO_2 emissions connection in the long term. For the WTM, we find that temperature is not a significant factor neither in the short and medium-term nor in the long-term in driving co-movement between CO_2 emissions and income levels. Moreover, an exciting result for TM highlights the significant role that temperature plays in driving the effect of income growth on CO_2 emissions in the short term. For the TDR climate regime, we conclude that temperature plays a significant role in explaining the interaction between CO_2 emissions and income growth only in the short term. Finally, the TDS climate regime results indicate no significant role of temperature in the interaction between CO_2 emissions and income growth. This conclusion is taken since there is a persistent co-evolution between CO_2 emissions and income growth in the short-term.

The impact of temperature in CO_2 emissions and growth nexus differs from climate-to-climate regime. Country-specific geographical and economic contexts firmly particularise this difference. This conclusion is drawn regardless of whether the evidence occurs in the short, medium, or long term.

5. Conclusion and policy implications

In recent times, the necessity to examine the impact of climate change on various human activities has grown in importance. This is because, although rising global population and industrialisation accelerate energy demand and consumption, a variety of human activities have also resulted in the usage of inputs that raise global greenhouse gas (GHG) emissions. In 2018, carbon dioxide (CO_2) emissions, which account for more than 65% of total GHG emissions, hit new highs of 36.4 million tons. Given the foregoing, it is more likely that the achievement of the Paris climate agenda at the horizon of 2050 will fall short of the objective.

This study investigates the heterogeneous effects of CO_2 emissions and temperature on economic growth across climate regimes in Africa. First, we test the heterogeneous effects of temperature, CO_2 emissions, and income across different climate regimes. We perform two analyses in this stage. We execute a univariate kernel density estimation of the logarithm of CO_2 emissions and GDP per capita and temperature and check if slope heterogeneity across climate regimes exists. Our kernel density results show diversity in emissions, income, and temperature across climate regimes in Africa. This underpins the fact that a significant degree of heterogeneity exists within our panel data, thereby justifying the need to estimate unobserved and structural heterogeneous effects as opposed to similar studies. Contrary to existing studies that impose country homogeneity on the relationship between temperature, CO_2 emissions, and growth, our results of slope heterogeneity reject this hypothesis across all the panel units. We conclude that by assuming slope homogeneity, studies on economic growth may provide unreliable and spurious results.

The second unique feature of our study is that we adopt the augmented mean group estimator (AMG) to estimate the long-run relationship between CO_2, temperature, and income. The AMG estimator takes into account spillover effects, global financial-economic-pandemic-driven shocks, and unobserved common factors with heterogeneous effects across countries. Regarding the income function, our results for income are significant and positive. We conclude that on the trajectory of economic production, income levels have a positive long-run effect amidst CO_2 emission and temperature dynamics in Africa. More so, we observe that increase in temperature reduces income while a rise in CO_2 emission levels raises income. For the CO_2 emissions function, we find a positive and significant long-term effect of the lagged-emission level on the current stock of CO_2 emissions. At the same time, our results show that an increase in income causes CO_2 emissions to rise in Africa. The strong and significant relationship between CO_2 emissions and income means that a country's emissions will rise in lockstep with per capita income, given that fossil fuels support wealth creation. However, no significant long-run effect is obtained in the emission-temperature relationship.

Subsequently, we assess the state of convergence in CO_2 emissions and temperature across climate regimes in Africa. Our study identifies 8 club convergence membership for CO_2 emission. Club 1 entails Ghana, Senegal, Togo, Mauritius, Seychelles, South Africa, Rwanda, and Gabon. Club 2 comprises Benin, Cape Verde, Côte d'Ivoire, Nigeria, Angola, DRC, Eswatini, Malawi, Mozambique, Namibia, Tanzania, Zambia, Zimbabwe, Chad, Tunisia, Algeria, Morocco, Uganda, Kenya, and Ethiopia. In club 3 are Gambia and Guinea, and club 4 entails Burkina Faso, Guinea-Bissau, Mali, and Botswana. Sierra Leone, Lesotho, and Mauritania are in Club 5. Madagascar, Burundi, and Libya form Club 6; Comoros, Cameroon, and Egypt make up Club 7; whereas Niger, Equatorial Guinea, Congo, Republic of, and Central African Republic (CAR) are the countries that form the non-convergent Club (8th Club). Contrarily, 12 club convergence membership is identified for temperature.

Club 1 consists of Burkina Faso, Mali, Niger, Senegal, and Namibia; club 2 entails Benin and Morocco; club 3 comprise Gambia and Ghana. Guinea-Bissau, Nigeria, and Libya form club 4; Côte d'Ivoire and Sierra Leone make up club 5. Club 6 comprises Malawi, Uganda, Kenya, and Cameroon. Ethiopia and Gabon form club 7; Botswana, Comoros, Mauritius, and Zimbabwe constitute Club 8, while Cape Verde, Lesotho, Tunisia, Mauritania, and Equatorial Guinea make up club 9. In club 10 are Angola, South Africa, and Rwanda. Togo, DRC, Madagascar, Mozambique, Tanzania, Zambia, and Chad make club 11, whereas Seychelles, Burundi, and Algeria form club 12. Lastly, Guinea, Eswatini, Egypt, Congo Republic, and the Central African Republic constitute the non-convergent Club (club 13). These findings have important policy implications. In reducing CO_2 emissions blow pre-industrial levels, African Countries, in particular, must embrace innovative methods that substantially contribute to a long-term growth process while maintaining high environmental standards. Due to heterogeneity among the countries under examination, a single-level policy for all countries may not be particularly effective. However, the club convergence membership implies that emission-based strategies can be replicated across countries found within a particular club.

In the inter-and intra-function emission-temperature path, we find that increased emission levels lead to extreme temperatures in Tropical Desert (TDS) and Sub Tropical Moist (STM) climatic zones. This is primarily due to unobserved confounders within countries. In the emission-income path, we observe that growth in emission increase income levels in Warm Temperate Moist (WTM), TDS, Tropical Moist (TM), and Tropical Dry (TDR) while decreasing income in Sub Tropical Dry (STD) and STM. The strong positive effect between emission and income reaffirms the need for countries to embark on energy transition. On the income-emission path, we show that increasing income levels raise emissions in WTM, STM, and TDS while decreasing emissions in TM. More so, in the temperature-income path, we observe an increase in average temperature leads to a positive impact on income levels in WTM, TDS, STM, and TDS while decreasing income levels in STD and TM. This shows that while a change in temperature from cold to warm improves economic production in colder climatic territories, switching from optimal warmer temperatures to extreme temperatures may yield economic losses. This implies that variations in temperature from optimal levels may reduce economic production in the DRC, Burundi, Uganda, Gabon, Cameroon, Congo, Central African Republic, Cape Verde, Côte d'Ivoire, Ghana, Guinea, Guinea-Bissau, Togo, Sierra Leone, Comoros, Mauritius, Seychelles, and Equatorial Guinea.

The findings of this research have major policy implications and should be considered when developing and implementing future environmental, and economic policies for African countries. Given that our results are mixed, policies aimed at reducing the effects of climate change on growth should be heterogenous. On one hand, we recommend that adaptation policies should be prioritised in countries where the effect of CO_2 emissions on income is observed in the short and medium-term. In particular, policy reforms to build ecological resilience as well as enhancing research and development are needed in Africa. On the other hand, mitigation policies are highly encouraged for countries where CO_2 emissions impacts growth in the long-term. In view of the foregoing, our study prescribes that emissions reduction policies be streamlined based on emission convergence routes that are specific to country clusters. Policies to enhance energy efficiency are required because they can boost energy security and reduce CO_2 emissions while without compromising economic growth. Additionally, given the prevalence of spillover effects, country-specific structures must be taken into account when creating and executing policies to reduce emissions, so that other countries are not harmed as a result of the influence and actions of others. Also, while admitting the difficulty in minimising energy demand amidst increasing population growth in Africa, there is a need for individuals and policymakers to become more environmentally conscious. However, this cannot be achieved without good and effective institutions. Therefore, there is the need to strengthen and empower African institutions to increase environmental advocacy. Furthermore, in order to ensure that economic growth and environmental sustainability is achieved in African countries, international organisations and private investors should boost their investments in renewable energy development projects. In terms of research agenda, future studies are recommended to extend this analysis to sub-regional country levels. This may help to improve our understanding of the heterogeneous short, medium, and long-term impact of CO_2 emissions and temperature on growth in Africa.

CRediT authorship contribution statement

Delphin Kamanda Espoir conceived the key ideas for this research paper. He collected and analysed the data. He also worked on the introduction, methodology, and discussion of the results. Benjamin Mudiangombe worked on the methodology, data analysis, and discussion of the results. Frank Bannor worked on data compilation and analysis and wrote the conclusion of the paper. Regret Sunge and Jean-Luc Mubenga worked on the introduction and literature review of this research paper. Softwares: DK. Espoir and B. Mudiangombe. All authors have read and approved the final version of this manuscript.

Declaration of competing interest

The authors declare no conflict of interest. The School of the University of Johannesburg and the Department of Economics, Munhumutapa School of Commerce, Great Zimbabwe University had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

Appendix 1

Table A1
Descriptive statistics.

Climate regime	GDP per capita		CO_2 per capita		Temperature	
	Mean	Std. dev	Mean	Std. dev	Mean	Std. dev
STD	1491.451	599.939	0.679	0.089	22.254	0.184
STM	1587.958	605.288	0.611	0.079	24.155	0.192
TDR	2709.073	937.240	3.108	0.181	17.426	0.341
TDS	3092.495	1423.71	1.569	0.508	25.958	0.233
TM	846.918	359.204	0.316	0.071	28.041	0.213
WTM	2473.464	893.531	2.479	0.162	25.731	0.238

Table A2
Heterogeneous estimation of emissions, temperature, and income (group-specific coefficients).

Estimation	Income equation					
	STM	STD	WTM	TM	TDR	TDS
Income_{t-1}	0.978*** (0.059)	0.881*** (0.053)	0.771*** (0.067)	0.876*** (0.043)	0.881*** (0.046)	0.791*** (0.085)
	[0.862; 1.094]	[0.776; 0.986]	[0.638; 0.904]	[0.790; 0.962]	[0.790; 0.972]	[0.624; 0.959]
Temperature	-1.143 (1.229)	1.065 (1.491)	1.656* (0.959)	-0.349 (1.107)	-0.872 (1.051)	-0.128 (1.214)
	[-3.553; 1.266]	[-1.856; 3.987]	[-3.536; 0.223]	[-2.519; 1.820]	[-2.933; 1.188]	[-2.508; 2.250]
Co2 Emissions	-0.152 (0.193)	-0.349*** (0.197)	1.104*** (0.394)	0.192*** (0.077)	0.176* (0.099)	0.566 (0.375)
	[-0.531; 0.227]	[-0.736; 0.037]	[0.330; 1.878]	[0.041; 0.343]	[-0.019; 0.372]	[-0.168; 1.302]
Constant	-3.409 (4.062)	4.110** (4.881)	-4.174 (2.861)	-0.193 (3.636)	-1.875 (3.429)	0.704 (4.100)
	[-11.372; 4.553]	[-5.457; 13.678]	[-9.782; 1.433]	[-7.321; 6.933]	[-8.596; 4.845]	[-7.332; 8.741]

Notes: (…) is the generated standard errors whereas […] is the 95% confidence interval.
*** Statistical significance at p-value < 0.01.
** Statistical significance at p-value < 0.05.
* Statistical significance at p-value < 0.1.

Appendix 2

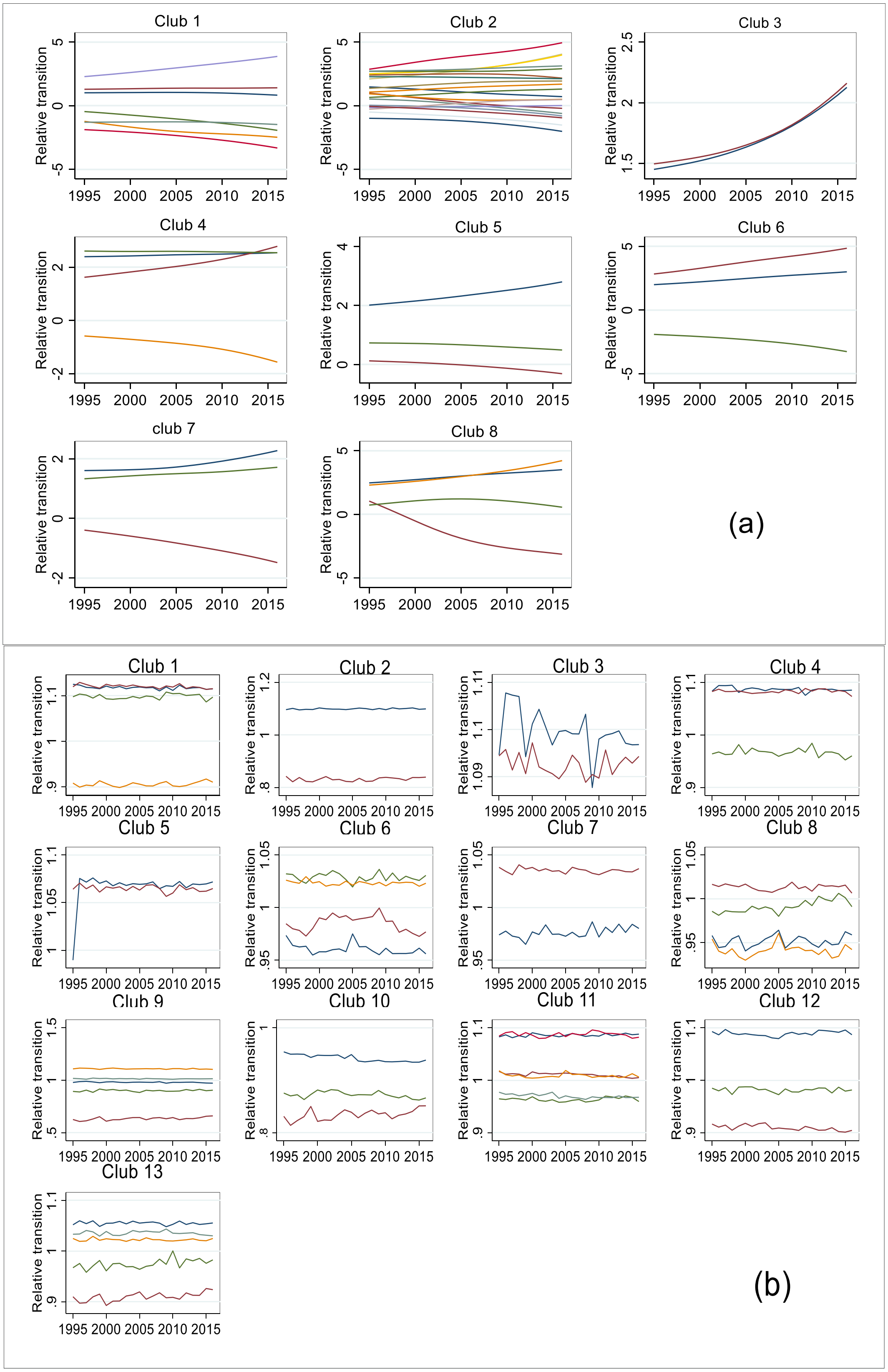


Fig. A1. Relative transition path by Club during 1995-2016. (a) Co2 emissions and (b) temperature.

References

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

Abidoye, B.O., Odusola, A.F., 2015. Climate change and economic growth in Africa: an econometric analysis. J. Afr. Econ. 24 (2), 277–301. https://doi.org/10.1093/jae/eju033.

Adebayo, T.S., Kirikkaleli, D., 2021. Impact of renewable energy consumption, globalization, and technological innovation on environmental degradation in Japan: application of wavelet tools. Environ. Dev. Sustain. https://doi.org/10.1007/s10668-021-01322-2.

Acheampong, A.O., 2018. Economic growth, CO 2 emissions and energy consumption: what causes what and where. Energy Econ. 74. https://doi.org/10.1016/j.eneco.2018.07.022.

ACPC, 2020. Climate Change Is an Increasing Threat to Africa. https://unfccc.int/news/climate-change-is-an-increasing-threat-to-africa. (Accessed 24 June 2021).

Adzawla, W., Sawaneh, M., Yusuf, A.M., 2019. Greenhouse gasses emission and economic growth nexus of Sub-Saharan Africa. Sci. Afr. 3. https://doi.org/10.1016/j.sciaf.2019.e00065.

Aguiar-Conraria, L., Azevedo, N., Soares, M.J., 2008. Using wavelets to decompose the time–frequency effects of monetary policy. Physica A 387, 2863–2878.

Akram, N., 2013. Is climate change hindering economic growth of Asian economies? Asia-Pac. Develop. J. 19 (2), 1–18. https://doi.org/10.18356/e7cfd1ec-en.

Alagidede, P., Adu, G., Frimpong, P.B., 2014. WIDER Working Paper 2014/017 The Effect of Climate Change on Economic Growth Evidence From Sub-Saharan Africa.

Al-Mulali, U., Che Sab, C.N., 2012. The impact of energy consumption and CO2 emission on the economic growth and financial development in the sub-Saharan African countries. Energy 39, 180–186.

Aloui, C., Hkiri, B., Hammoudeh, S., Shahbaz, M., 2018. A multiple and partial wavelet analysis of the oil Price, inflation, exchange rate, and economic growth nexus in Saudi Arabia. Emerg. Mark. Financ. Trade 54 (4), 935–956.

Aye, G.C., Edoja, P.E., 2017. Effect of economic growth on CO2 emission in developing countries: evidence from a dynamic panel threshold model. Cogent Econ. Finance 5 (1). https://doi.org/10.1080/23322039.2017.1379239.

Baarsch, F., Granadillos, J.R., Hare, W., Knaus, M., Krapp, M., Schaeffer, M., Lotze-Campen, H., 2020. The impact of climate change on incomes and convergence in Africa. World Dev. 126, 104699. https://doi.org/10.1016/j.worlddev.2019.104699.

Barassi, M.R., Spagnolo, N., 2012. Linear and non-linear causality between CO2 emissions and economic growth. Energy J. 33 (3).

Bersvendsen, T., Ditzen, J., 2021. Testing for slope heterogeneity in stata. Stata J. 21 (1), 51–80.

Bond, S., Eberhardt, M., 2013. Accounting for unobserved heterogeneity in panel time series models. Working Paper. University of Oxford, Nuffield College.

Bouznit, M., Pablo-Romero, M.d., 2016. CO2 emission and economic growth in Algeria. Energy Policy 96, 93–104.

Breusch, T.S., Pagan, A., 1980. The Lagrange multiplier test and its applications to model specification in econometrics. Rev. Econ. Stud. 47 (1), 239–253.

Brock, W.A., Taylor, S., 2010. The Green Solow model. J. Econ. Growth 15 (2), 127–153.

Chang, T., Gupta, R., Inglesi-Lotz, R., Simo-Kengne, B., Smithers, D., Trembling, Amy, 2015. Renewable energy and growth: evidence from heterogeneous panel of G7 countries using Granger causality. Renew. Sust. Energ. Rev. 52 (C), 1405–1412 Elsevier.

Chekouri, S.M., Chibi, A., Benbouziane, M., 2021. Economic growth, carbon dioxide emissions and energy consumption in Algeria: a wavelet coherence approach. World J. Sci. Technol. Sustain. Develop. 18 (2), 172–189. https://doi.org/10.1108/wjstsd-12-2020-0097.

Dell, M., Jones, B.F., Olken, B.A., 2009. Temperature and income: reconciling new crosssectional and panel estimates. Am. Econ. Rev. 99 (2), 198–204.

Dell, M., Jones, B.F., Olken, B.A., 2012. Temperature shocks and economic growth: evidence from the last half century. Am. Econ. J. Macroecon. 4 (3), 66–95. https://doi.org/10.1257/mac.4.3.66.

Demissew Beyene, S., Kotosz, B., 2020. Testing the environmental kuznets curve hypothesis: an empirical study for east african countries. Int. J. Environ. Stud. 77 (4), 636–654. https://doi.org/10.1080/00207233.2019.1695445.

Diffenbaugh, N.S., Burke, M., 2019. Global warming has increased global economic inequality. Proc. Natl. Acad. Sci. 116 (20), 9808–9813.

Eberhardt, M., Teal, F., 2010. Productivity analysis in global manufacturing production. Discussion Paper 515. University of Oxford, Department of Economics . http://www.economics.ox.ac.uk/research/WP/pdf/paper515.pdf.

Encyclopaedia Britannica, 2021. World Climate Regions Online Map.

Espoir, D.K., Ngepah, N., 2021. Income distribution and total factor productivity: a cross-country panel cointegration analysis. IEEP https://doi.org/10.1007/s10368-021-00494-6.

Espoir, K., Sunge, R., 2021. CO2 emissions and economic development in Africa: evidence from a dynamic spatial panel model CO2. Econstor (Issue May) https://doi.org/10.13140/RG.2.2.24275.09764.

Espoir, K., Sunge, R., Bannor, F., 2021. Economic growth and CO2 emissions: evidence from heterogeneous panel of African countries using bootstrap Granger causality. Econstor, ZBW - Leibniz Information Centre for Economics https://doi.org/10.13140/RG.2.2.35499.77606 (Issue June).

Fang, Z., Huang, B., Yang, Z., 2018. Environmental Kuznets Curve: Evidence from Cities in the People's Republic of. Asian Development Bank Institute (Issue 882).

FAO, 2019. FAO's Work on Climate change. United Nations Climate Change Conference 2019 , pp. 1–40.. http://www.fao.org/3/ca7126en/ca7126en.pdf.

Grinsted, Moore, Jevrejeva, C., 2004. Application of the cross wavelet transform and wavelet coherence to geophysical time series. Nonlinear Processes in Geophysics, European Geosciences Union (EGU). 11, pp. 561–566 5/6.

Gorus, M.S., Aydin, M., 2019. The relationship between energy consumption, economic growth, and CO2 emission in MENA countries: causality analysis in the frequency domain. Energy 168, 815–822.

Grossman, G.M., Krueger, A.B., 1991. Environmental impacts of a North American free trade agreement. Working Paper 3914. https://doi.org/10.3386/w3914

Kumar, P., Foufoula-Georgiou, E., 1997. Wavelet analysis for geographical applications. Rev. Geogr. 35 (4), 385–412.

Hallegatte, S., Bangalore, M., Bonzanigo, L., Fay, M., Kane, T., Narloch, U., Rozenberg, J., David Treguer, A.V.-S., 2016. Shock waves: managing the impacts of climate change on poverty. 59 (1). http://www.journals.cambridge.org/abstract_S0022112081001535.

Herzer, D., Vollmer, S., 2012. Inequality and growth: evidence from panel cointegration. J. Econ. Inequal. 10, 489–503. https://doi.org/10.1007/s10888-011-9171-6.

Holtermann, L., Rische, M.-C., 2020. The Subnational Effect of Temperature on Economic Production: A Disaggregated Analysis in European Regions. MPRA Working Paper, 104606. https://mpra.ub.uni-muenchen.de/104606/MPRA.

IMF, 2017. The effects of weather shocks on economic activity: how can low-income countries cope? World Economic Outlook: October 2017, pp. 117–183

IMF, 2019. The economics of climate. Financ. Develop. 4 (54), 65.. https://www.imf.org/external/pubs/ft/fandd/2019/12/pdf/fd1219.pdf.

IPCC, 2015. Summary for policymakers. In: Core Writing Team, Pachauri, R.K., Meyer, L.A. (Eds.), Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva, Switzerland https://doi.org/10.1017/CBO9781139177245.003.

Issartel, J., Bardainne, T., Gaillot, P., Marin, L., 2014. The relevance of the cross-wavelet transform in the analysis of human interaction - a tutorial. Front. Psychol. 5 (OCT), 1–18. https://doi.org/10.3389/fpsyg.2014.01566.

Kahn, M., Mohaddes, K., Ng, R., Pesaran, M., Raissi, M., Yang, J.-C., 2019. Long-term macroeconomic effects of climate change. IMF Working Papers 19 (19). https://doi.org/10.5089/9781513514598.001.

Kalkuhl, M., Wenz, L., 2018. The Impact of Climate Conditions on Economic Production. Evidence from a Global Panel of Regions. Econstor, ZBW - Leibniz Information Centre for Economics. http://hdl.handle.net/10419/178288%0AStandard-Nutzungsbedingungen.

Kasperowicz, R., 2015. Economic growth and CO2 emissions: the ECM analysis. J. Int. Stud. 8 (3), 91–98. https://doi.org/10.14254/2071-8330.2015/8-3/7.

Lanzafame, M., 2012. Temperature, rainfall and economic growth in Africa. Empir. Econ. 46 (1), 1–18. https://doi.org/10.1007/s00181-012-0664-3.

Lu, W.-C., 2017. Greenhouse gas emissions, energy consumption and economic growth: a panel cointegration analysis for 16 Asian countries. Int. J. Environ. Res. Public Health 14 (1436), 1–15. https://doi.org/10.3390/ijerph14111436.

Magazzino, C., 2016. Economic growth, CO2 emissions and energy use in the south caucasus and Turkey: a PVAR analyses. Int. Energy J. 16 (4), 153–162.

Magazzino, C., 2017. The relationship among economic growth, CO2 emissions, and energy use in the APEC countries: a panel VAR approach. Environment Systems and Decisions 37 (3), 353–366. https://doi.org/10.1007/s10669-017-9626-9.

Magazzino, C., 2019. Testing the stationarity and convergence of CO2 emissions series in MENA countries. International Journal of Energy Sector Management 13 (4), 977–990. https://doi.org/10.1108/IJESM-09-2018-0008.

Magazzino, C., Mele, M., Schneider, N., 2021. A machine learning approach on the relationship among solar and wind energy production, coal consumption, GDP, and CO2 emissions. Renew. Energy 167, 99–115. https://doi.org/10.1016/j.renene.2020.11.050.

Magazzino, C., Mutascu, M., Sarkodie, S.A., Adedoyin, F.F., Owusu, P.A., 2021. Heterogeneous effects of temperature and emissions on economic productivity across climate regimes. Sci. Total Environ. 775 (February), 145893. https://doi.org/10.1016/j.scitotenv.2021.145893.

Mihanović, H., Orlić, M., Pasrić, Z., 2009. Diurnal thermocline oscillations driven by tidal flow around an island in the Middle Adriatic. J. Mar. Syst. 78, S157–S168.

Munir, S., Khan, A., 2014. Impact of fossil fuel energy consumption on CO2 emissions: evidence from Pakistan (1980–2010). Pak. Dev. Rev. 53 (4), 327–346.. https://www.jstor.org/stable/24398722.

Mutascu, M., 2018. A time-frequency analysis of trade openness and CO2 emissions in France. Energy Policy 115, 443–455.

Newell, R.G., Prest, B.C., Sexton, S.E., 2018. The GDP-Temperature Relationship: Implications for Climate Change Damages Climate Change Damages. In Resources for the Future (No. 18-17 REV; Issue November). https://media.rff.org/archive/files/document/file/RFF_WP-18-17-rev.pdf.

Ng, E.K., Chan, J.C., 2012. Geophysical applications of partial wavelet coherence and multiple wavelet coherence. J. Atmos. Ocean. 29, 1845–1853.

Odhiambo, N.M., 2017. CO2 emissions and economic growth in sub-saharan african countries: a panel data analysis. International Area Studies Review 20 (3), 264–272. https://doi.org/10.1177/2233865917715943.

Odusola, A., Abidoye, B., 2020. Effects of temperature shocks on economic growth and welfare in Africa. Resour. Environ. Econ. 2 (2), 158–171. https://doi.org/10.25082/ree.2020.02.002.

Olubusoye, O.E., Musa, D., 2020. Carbon emissions and economic growth in Africa: are they related? Cogent Econ. Finance 8 (1). https://doi.org/10.1080/23322039.2020.1850400.

Omotor, D.G., 2016. Economic Growth and Emissions: Testing the Environmental Kuznets Curve Hypothesis for Ecowas.

Omri, A., Daly, S., Rault, C., Chaibi, A., 2015. Financial development, environmental quality, trade and economic growth: what causes what in MENA countries. Energy Econ. 48 (8868). https://doi.org/10.1016/j.eneco.2015.01.008.

Pesaran, M.H., 2004. General Diagnostic Tests for Cross Section Dependence in Panels.

Pesaran, M.H., Yamagata, T., 2008. Testing slope homogeneity in large panels. J. Econ. 142 (1), 50–93.

Phillips, P.C., Sul, D., 2007. Transition modeling and econometric convergence tests. Econometrica 75 (6), 1771–1855.

Rua, A., Nunes, L.C., 2009. International comovement of stock market returns: a wavelet analysis. J. Empir. Financ. 16, 632–639.

Sarkodie, S.A., Strezov, V., 2019. A review on environmental Kuznets curve hypothesis using bibliometric and meta-analysis. Sci. Total Environ. 649, 128–145. https://doi.org/10.1016/j.scitotenv.2018.08.276.

Spagnolo, M.R.B.N., 2012. Linear and non-linear causality between CO2 emissions and economic growth published by: International Association for Energy Economics Stable. Energy J. 33 (3), 23–38.. https://www.jstor.org/stable/23268093.

Stern, D.I., 2004. The rise and fall of the Environmental Kuznets Curve. World Dev. 32 (8), 1419–1439.

Stokey, N.L., 1998. Are there limits to growth? Int. Econ. Rev. 39 (1), 1–31.

Swamy, P.A.V.B., 1970. Efficient inference in a random coefficient regression model. Econometrica 38 (2), 311–323.

The Economist Intelligence Unit, 2020. Resilience to climate change? A new index shows why developing countries will be most affected by 2050. The Economist. https://www.eiu.com/public/topical_report.aspx?campaignid=climatechange2019.

Torrence, C., Compo, G.P., 1998. A practical guide to wavelet analysis. Bull. Am. Meteorol. Soc. 79, 61–78.

Torrence, C., Webster, P.J., 1999. Interdecadal changes in the ENSO–Monsoon system. J. Clim. 12, 2679–2690.

WHO-World Health Organization, 2018. Climate change and health. https://www.who.int/news-room/fact-sheets/detail/climate-change-and-health. (Accessed 25 June 2021).

WMO-World Meteorological Organization, 2020a. Global Climate Report - August 2020| State of the Climate. https://www.ncdc.noaa.gov/sotc/global/202008.

World Bank, 2021. World Development Indicators. Retrieved June, 2021, from http://data.worldbank.org/country.

World Bank Climate Change Knowledge Portal, 2021. https://climateknowledgeportal.worldbank.org/download-data.

World Meteorological Organization, 2020b. State of the Climate in Africa-2019 (Issue WMO-No. 1253). World Meteorological Organization.

WRI, 2020. Climate. 4 Charts Explain Greenhouse Gas Emissions by Countries and Sectors. https://www.wri.org/insights/4-charts-explain-greenhouse-gas-emissions-countries-and-sectors. (Accessed 25 June 2021).

Yusuf, A.M., Abubakar, A.B., Mamman, S.O., 2020. Relationship between greenhouse gas emission, energy consumption, and economic growth: evidence from some selected oil-producing African countries. Environ. Sci. Pollut. Res. 27 (13), 15815–15823. https://doi.org/10.1007/s11356-020-08065-z.

Zaidi, S., Ferhi, S., 2019. Causal relationships between energy consumption, economic growth and CO2 emission in Sub-Saharan: evidence from dynamic simultaneous-equations models. Mod. Econ. 10 (09), 2157–2173. https://doi.org/10.4236/me.2019.109136.

Zou, S., Zhang, T., 2020. CO2 emissions, energy consumption, and economic growth nexus: evidence from 30 provinces in China. Math. Probl. Eng. 2020. https://doi.org/10.1155/2020/8842770.