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Heterogeneous effects of temperature and emissions on economic productivity across climate regimes

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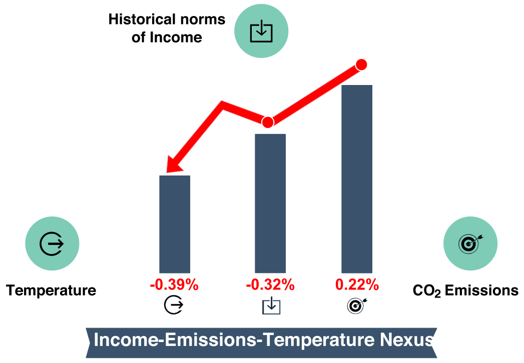
HIGHLIGHTS

- We assess the effect of climate-driven temperature variation across country-specific climate regimes.
- Both wavelet and heterogenous estimation techniques are used in emissions and income function.
- Israel, Luxembourg, and Kuwait converge in income club 1 whereas Austria, Singapore, and Norway in income club 2.
- Emission levels escalate extreme temperatures in Israel, Luxembourg, Singapore, Kuwait, and Norway.
- Global common climatic policies may not yield success compared to country-specific based policies.

GRAPHICAL ABSTRACT



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ABSTRACT

The impact of climate change has resulted in several long-term events including extreme temperatures. Besides, the occurrence of climate events impedes economic progress––affecting economic readiness of climate mitigation. However, the effect of climatic factors on economic productivity has not been extensively covered in existing literature, especially among climate regimes. Here, we use sophisticated panel and time series techniques to examine the heterogeneous effects of temperature and emissions on income from 1960 to 2014. Our empirical results indicate a 1% rise in temperature declines income by 0.39% whereas 1% increase in emission levels stimulates income by 0.22%. This implies a mutual relationship between income and emissions––where environmental pollution supports wealth creation and vice versa. We find that a shift from optimal temperature levels to extreme patterns hamper economic productivity. Extreme temperatures affect heating and cooling degree days due to increased energy requirements, hence, escalating energy demand and emissions. With the agenda towards emission reduction, this study emphasizes economic structural change through transition from brown to green growth.

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1. Introduction

The need to examine the effect of climate change on several aspects of human activities has become increasingly important in the last decade. This is because while an increase in global population and industrialization creates a need for increased energy requirement and consumption, several human activities have led to the use of sources that triggers an increase in greenhouse gas emissions (Sarkodie and Strezov, 2019). Such continual increase in emissions results in high rates of emissions which may become double its preindustrial level in 2035 (Stern et al., 2006). Empirical evidence has shown that a condition in the climate has an intense way of impacting the functionality of contemporary human societies (Burke et al., 2015). Therefore, the increase in world temperature resultant from high atmospheric concentration of GHG has led to extreme weather conditions evidenced in the events of droughts, floods, cold and heat waves, and natural disasters. These occurrences are increasingly damaging than the previous––affecting both developed and developing economies alike (Sánchez-Rodríguez et al., 2019; Kahn et al., 2019).

Given the foregoing, this study examines the effect of emissions on economic productivity, while accounting for differences in climate regions. Previous attempts in the literature to address this narrative has been to assess the role of alternative sources of energy (renewable energy [RE]), with a potential argument for a positive effect of RE in reducing GHG emissions (Charfeddine and Kahia, 2019). Several studies have attempted to explore the relationship between emissions, temperature, and economic productivity using various methods and models which account for both minor and/or significant differences and limitations in research findings. For instance, while a changing relationship between economic growth and temperature with damage function remain static (Moore and Diaz, 2015), a non-linear relationship between natural gas consumption and economic growth may also exist––such that when natural gas consumption increases, economic growth is expected to increase as well (Galadima and Aminu, 2020). In agreement with the feedback hypothesis, the nonlinear causality test showed that bidirectional causality exists between the positive impact of consumption of natural gas and growth in the economy while a unidirectional causality exists between growth in the economy and negative impact of consumption in natural gas.

Another argument for the connection between climate change and economic productivity is that a cointegrated relationship exists between nitrous oxide (N_2O) emissions and growth in the economy while the consideration of other variables such as agricultural landmass has a significant positive effect on the emissions of N_2O (Haider et al., 2020). This may, however, not hold when a country's stage of development is considered (Apergis, 2016). Besides, economic growth and N_2O emissions have also shown a long run quadratic connection (Zambrano-Monserrate and Fernandez, 2017). Similarly, income growth is linked to methane emissions embodied in higher consumption patterns, however, the effect is severe on CO_2 emissions (Fernández-Amador et al., 2018).

Put succinctly, most studies adopting one form of causality analysis or the other reveal how growth in the economy, as well as other variables, have an intense impact on emissions in the long and short-run––while emissions increase in the short run, a reduction is arguably observed in the long run (Malik et al., 2020). This also extends to establishing an inversely shaped U relationship between consumption of energy and level of income–––indicating a decarbonized and services economy, thus, showing improved energy efficiency (Sarkodie et al., 2019).

While past literature suggests inconsistent evidence on the effect of temperature on economic growth in developed and developing countries, submitting a negative impact result for hot and/or poor countries and a limited one for cold and/or rich countries. A continuous climate change in the long term is argued to negatively impact growth in the economy (Kahn et al., 2019). Thus, a deviation of temperature from its historical norm implies a lower long term income growth per year, and such negative long-run effects are universal, affecting all countries, rich or poor, and hot or cold, alike.

Besides, when the climate debate is clustered across climatic regions at global and/or regional levels, growth in the economy does not necessarily influence the consumption of energy. Specifically, excluding the global cluster and Caribbean-Latin American countries, growth in the economy has no causal influence on emissions of CO_2 (Acheampong, 2018). Moreover, growth in the economy was found to negatively impact global emissions levels and Caribbean-Latin America. Emissions of CO_2 positively impact growth in the economy, and consumption of energy has a positive impact on growth in the economy in sub-Saharan Africa while it causes negative growth in the economy at the global level, the MENA, Asia-Pacific, and Caribbean-Latin America (Acheampong, 2018). In perspective, consumption of energy positively causes emissions of CO_2 in MENA but causes negative emissions of CO_2 in sub-Saharan Africa and Caribbean-Latin America.

A sum of the extant literature suggests several variations in terms of the impact of climatic factors on economic productivity. Some of these variations are due to differences in methodology, measurement of variables used as well as data structure. A consensus, however, is that in the long run, global GHG emission levels have a significant impact on economic productivity. Thus, since the impact of climate change results in several long-term events including extreme temperatures, an examination of climate events and their economic impacts is vital. The novelty of this study is three folds: first, this study carries out an extensive assessment of how climatic factors impede economic productivity; second, this study utilizes advanced empirical tools on a rich dataset; and third, this study considers analysis across several climatic regimes. One of the key findings from this study suggests that a shift from optimal temperature levels to extreme patterns hamper economic productivity. Besides, extreme temperatures affect heating and cooling degree days due to increased energy requirements, hence, escalating energy demand and emissions. With the agenda towards emission reduction, this study emphasizes economic structural change through transition from brown to green growth.

The next session highlights the data and methodology used while section three presents the discussion of findings. This study concludes in section four with important policy implications of the findings.

2. Methods

2.1. Data

The ground for panel and wavelet analyses is a dataset with six countries (i.e., Austria, Israel, Luxembourg, Kuwait, Singapore, and Norway), covering the period 1960–2014. Given temperature implications, the sample is carefully constructed to ensure better statistical significance. The main criteria behind the selected countries are world ranking attributed carbon dioxide (CO_2) emissions (per capita),[1] climate regime (i.e., tropical with its rainforest and desert extremes, subtropical, temperate, polar, and highland one[2]), and land area. Considering the severe restrictions in data availability, one country from each climate regime is selected by fitting the highest world position in respect to CO_2 emissions per capita and relative reduced territory. This land area "size' approach allows to avoid the higher heterogeneity in terms of temperatures across the land area (i.e., the country average temperature becomes irrelevant for extended territory). Table 1 shows the selected countries according to the aforementioned criteria.

Three variables outline the content of sampled data: economic growth, CO_2 emissions, and temperature.

Economic growth is captured via GDP per capita. The variable denotes the sum of gross value added by all resident producers in the economy

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[1] The rank was constructed based on CO_2 emissions (metric tons per capita) variable, offered by World Development Indicators online database, World Bank (2020).

[2] Refer to online Encyclopaedia Britannica (2020) for world climate regions.

plus any product taxes and minus any subsidies not included in the value of the products, expressed per capita, in current US$ (data availability).

CO_2 emissions denote the volume of carbon dioxide emissions produced during consumption of solid, liquid, and gas fuels and gas flaring in metric tons per capita.

Temperature captures the level of country-year-average temperature, expressed as a difference between the highest and lowest temperature, in Fahrenheit degree. The annual average temperature is calculated based on daily and monthly average temperatures by considering the main country's meteorological stations and their geographical positions (i.e., latitude, longitude, and elevation).

GDP per capita and CO_2 emissions are derived from World Development Indicators online database, World Bank (2020), while temperature comes from Global Climate Change Data from Data Society (2020). All variables are treated in their natural logarithm form. Additionally, to deal with wavelet dataset requirements (Mutascu, 2018), the first difference is considered in the final estimations to increase the series volatility and remove their trend component.

2.2. Empirical procedure

The empirical procedure presented in this study encompasses several strategies presented in Scheme 1. Both panel and time series estimation methods are utilized for robust, consistent, and unbiased analysis. For the panel estimation strategy, we first examine the stationarity properties of sampled series using first-generational panel-based unit root tests. We subsequently examine the variables for potential cross-section dependence due to global recurrent shocks and transboundary effects (Pesaran, 2004). Next, we test the null hypothesis of slope homogeneity––owing to the differences in both geographical and economic structure (Pesaran and Yamagata, 2008). In confirming the presence of cross-section dependence and heterogeneous effects across sampled countries, we re-estimate the stationarity properties of the data series using the second-generational panel-based unit root tests (Pesaran et al., 2003). These panel-based tests account for both stationarity amidst heterogeneity and cross-section dependence. We further apply the novel augmented mean group estimation approach that (Bond and Eberhardt, 2013; Destek and Sarkodie, 2019): first, estimates cross-country extension of unobserved "*common dynamic process*" from 1960 to 2014 via first-differenced pooled regression with year-specific dummies. Second, impose country-specific "common dynamic process" through climate regime regression with time-invariant fixed-effects captured by the intercept. Third, averaging climate regime-specific regression parameters across countries with or without cointegration. To validate the estimated model, we assess the robustness of the parameter estimates using residual cross-section dependence, Wald test, and error metrics. The generic panel model specifying the linear but dynamic income-emission-temperature relationship can be expressed as:

$$Income_{i,t} = \beta_0 + \beta_1 Income_{i,t-1} + \beta_2 CO_2\ Emissions_{i,t} + \beta_3 Temperature_{i,t} + \varepsilon_{i,t} \tag{1}$$

$$CO_2\ Emissions_{i,t} = \beta_0 + \beta_1 CO_2\ Emissions_{i,t-1} + \beta_2 Income_{i,t} + \beta_3 Temperature_{i,t} + \varepsilon_{i,t} \tag{2}$$

Here, $Income_{i,\ t}$ and $CO_2\ Emissions_{i,\ t}$ are the target variables denoting income level and CO_2 emissions. β_0 represents the constant whereas, $Income_{i,\ t-1}$ and, $CO_2\ Emissions_{i,\ t-1}$ are the lagged-dependent series to capture historical norms, unobserved factors, and control for omitted-variable bias. β_1, …, β_3 are the heterogeneous parameters while, $\varepsilon_{i,\ t}$ is the multifactor white noise across sampled countries i and period t.

In the second part of the panel modeling, we test the hypothesis of temperature and emission convergence across heterogeneous countries. The effect of convergence is reported to offset emissions and temperature across climate regimes by limiting sustained income disparities (Dell et al., 2009). Importantly, convergence test is essential to ascertain the viability of either global common policies or country-specific policies. We begin by filtering the series to create new trend components. Second, we apply log-*t*-test using linear regression based on 33.3% discarded data proportion prior to estimation. Third, we test for club convergence and clustering of sampled countries based on similar climatic factors (Phillips and Sul, 2007).

A battery of wavelet methods empirically connects––for each country, the economic growth with gas emissions by controlling for surface temperature. This set includes the continuous wavelet transformation, wavelet coherency with phase-difference, multiple wavelet coherency, and partial wavelet coherency, respectively.

The continuous wavelet transformation (CWT) decomposes the series in both time and frequency having as main element the Morlet function $\psi_0(\eta)$, with this shape (Grinsted et al., 2004):

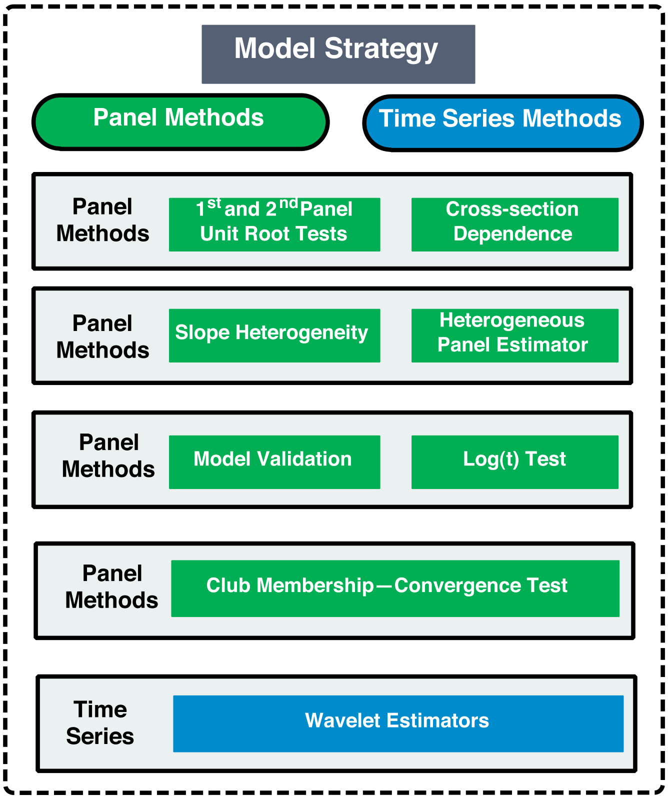
$$\psi_0(\eta) = \pi^{-\frac{1}{4}} e^{i\omega\eta} e^{-\frac{1}{2}\eta^2} \tag{3}$$

where η is the non-dimensional 'time' parameter, ω denotes the non-dimensional frequency set at the level of 6 (Farge, 1992), i representing,

Table 1
Selected countries and their corresponding climate regime.

Country	Climate regime
Austria	Highland (varies with altitude)
Israel	Subtropical
Luxembourg	Temperate
Kuwait	Tropical with desert
Singapore	Tropical with rainforest
Norway	Polar with tundra

Source: performed based on World Development Indicators online database, World Bank (2020) and Encyclopaedia Britannica (2020), World Climate Regions online map, accessed in May 2020.



Scheme 1. Model estimation procedure.

$\sqrt{-1}$. Supposing a time-series $\{x_n\}$, with $n = 0 \ldots N\text{-}1$, the CWT has this form:

$$w_n^x(s) = \frac{\delta t}{\sqrt{s}} \sum_{n\prime=0}^{N-1} x_{n\prime} \psi^* \left((n\prime - m) \frac{\delta t}{s} \right) \tag{4}$$

where s is the scale by time-step δt, and $m = 0, 1, \ldots, N-1$.

According to Torrence and Webster (1999), for two time-series $x = \{x_n\}$ and $y = \{y_n\}$, the wavelet coherency (WTC) tool can be performed based on their wavelet transformed W_n^x and W_n^y forms, as follows:

$$R_n(s) = \frac{\left| S\left(s^{-1} W_n^{xy}(s)\right) \right|}{S\left(s^{-1} \left|W_n^x\right|\right)^{\frac{1}{2}} S\left(s^{-1} \left|W_n^y\right|\right)^{\frac{1}{2}}} \tag{5}$$

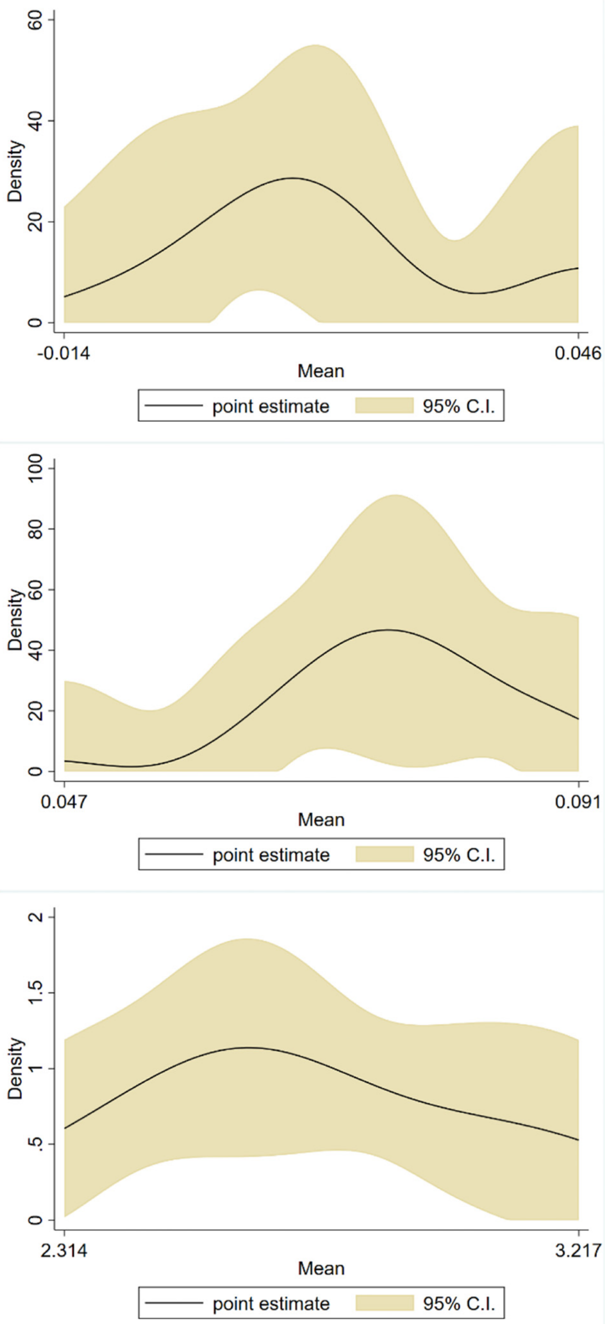


Fig. 1. Heterogenous effects using kernel density estimation (a) CO_2 (b) GDP (c) Temperature.

where, $|W_n^{xy}|$ is the cross-wavelet power having the smoothing operator in both time and scale S. Aguiar-Conraria et al., 2008 define the WTC as" the ratio of the cross-spectrum to the product of the spectrum of each series, and can be thought of as the local correlation, both in time and frequency, between two time series". Based on WTC, the phase difference status of transformed series is employed showing the position in the pseudo-cycle of the series in respect to sign, directions, and lead-lag status. For each estimation, the interpretation of phase difference is presented in the Results section.

Finally, multiple wavelet coherency (MWC) and partial wavelet coherency (PWC) developed by Mihanović et al. (2009) are also considered to control for a third determinant z.

The MWC offers details about the interaction of more than two independent variables on a dependent one. Transposed to our case, the MWC allows investigating the impact of x (economic growth) and z (temperature) on y (CO_2 emissions), variable z serving as control determinant. Hence, the MWC is as follows:

$$\left(RM_n^{yxz}\right)^2 = \frac{\left(RM_n^{yx}\right)^2 + \left(RM_n^{yz}\right)^2 - 2\,Re\left(RM_n^{yx} RM_n^{yz*} RM_n^{yx*}\right)}{1 - \left(RM_n^{xz}\right)^2} \tag{6}$$

The PWC shows the interaction between two time series x and y, after removing the influence of the third one z (i.e., control determinant). The PWC is calculated as squared of partial wavelet coherence after removal of the z's effect:

$$\left(RP_n^{yxz}\right)^2 = \frac{\left| RP_n^{yx} - RP_n^{yz} RP_n^{yx*} \right|^2}{\left[1 - \left(RP_n^{yz}\right)\right]^2 \left[1 - \left(RP_n^{xz}\right)\right]^2} \tag{7}$$

The empirical strategy supposes running the set of wavelet tools for each country's objects of analysis.

3. Results & discussion

The validation of heterogeneous effects in Fig. 1 confirms the diversity of estimated income, temperature, and emissions across climate regimes. We find a substantial degree of heterogeneity within the

Table 2
Heterogeneous estimation of income, temperature, and emissions.

Estimation	Income	Emissions
CO_2 Emissions$_{t-1}$	–	−0.175 [0.131] (−0.433; 0.082)
Income$_{t-1}$	−0.316*** [0.069] (−0.451; −0.181)	–
Temperature	−0.391*** [0.116] (−0.619; −0.163)	0.728 [0.645] (−0.536; 1.992)
CO_2 Emissions	0.224*** [0.082] (0.063; 0.384)	–
Income	–	0.341*** [0.073] (0.198; 0.485)
Constant	1.048*** [0.343] (0.376; 1.720)	−2.204 [1.840] (−5.811; 1.402)
RMSE	0.089	0.177
Obs	313	314
Wald chi^2	32.02	23.65
Prob > chi^2	0.000***	0.000***
CD-test	−1.56	−0.81
p-Value	0.119	0.416
	CO_2 Emissions	Temperature
Log(t)	−5.498**	−5.245**
Club 1 - Log(t)	5.882 ISR | LUX | KWT	2.088 AUT | ISR | LUX | SGP | NOR
Club 2- Log(t)	8.658 AUT | SGP | NOR	– –
Not convergent Group 2	–	KWT

Notes: ***signifies statistical significance at *p-value* < *0.01*; ** means the rejection of the null hypothesis of convergence at *T-stat* < *−1.65*. […] is the generated standard errors whereas (…) is the 95% confidence interval.

sampled data series, underscoring the significance of estimating unobserved and structural heterogeneous effects. Following this revelation, we employ the augmented mean group estimation technique that controls for spillover effects, global economic-pandemic-driven shocks, and unobserved common factors with heterogeneous effects across countries. By enforcing the implementation of common dynamic process, our model produces robust estimates presented in Table 2. To validate residual independence of the estimated parameters, we assess the generated residuals using residual-based cross-section dependence. The *p-values* of the estimated CD-tests are 12% and 42%––respectively for models in income function and emission function. This implies that the residuals of the estimated model and its error structure exhibit cross-section independence. The income function model reveals that lagged-income ($\text{Income}_{t\text{-}1}$) is negative and statistically significant at 1%. This implies that the historical norm of income level has negative long-term effect on wealth amidst temperature and emission dynamics. We further observe that 1% rise in temperature declines income by 0.39% whereas 1% increase in emission levels spurs income by 0.22%. Similarly, 1% increase in average temperature is reported to decrease income by 0.09% across 12 developing and developed nations (Dell et al., 2009). In contrast, we find that permanent changes in emissions from its lagged-emission level (CO_2 $\text{Emissions}_{t\text{-}1}$) have no long-term escalation effects in the emission function model. No significant evidence is demonstrated in emission-temperature nexus, however, 1% growth in

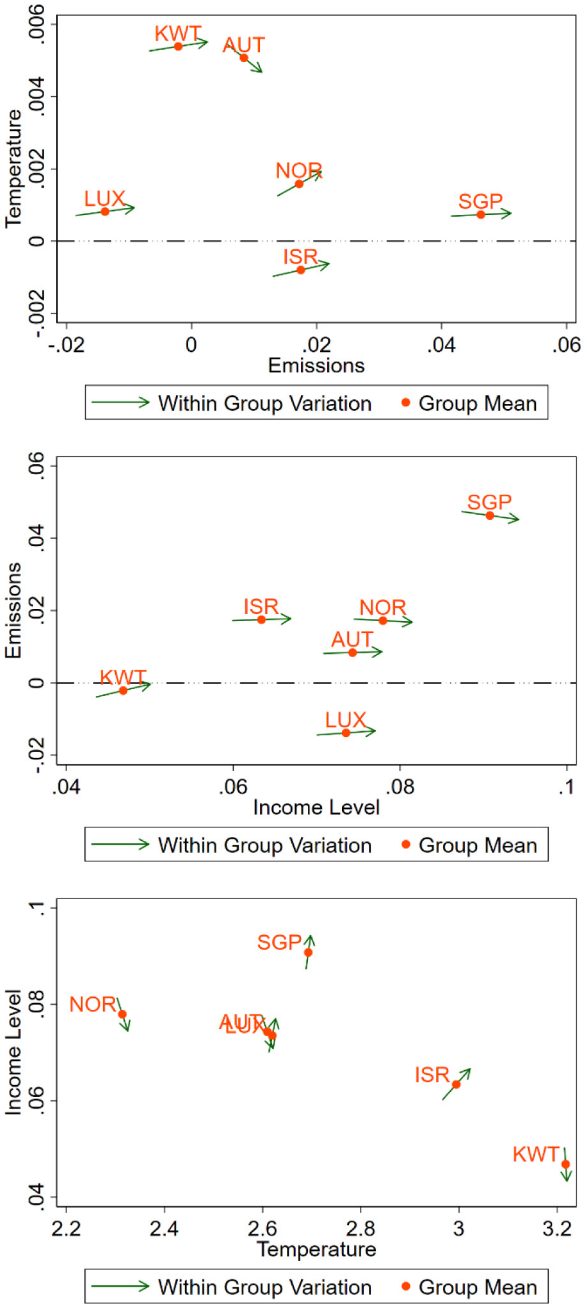


Fig. 2. Heterogenous nexus between (a) Temperature and CO_2 (b) CO_2 and Income (c) Income and Temperature. The dot (●) denotes group mean (between-country means) of climate regimes whereas the slope arrow (→) signifies the within-group variation of the estimated country-specific relationship gradient while controlling for lagged-dependent variable and additional covariate bias. In Fig. 2(a), we account for lagged-temperature and income level. In Fig. 2(b), we control for lagged-emissions and temperature. In Fig. 2(c), we account for lagged-income and emissions.

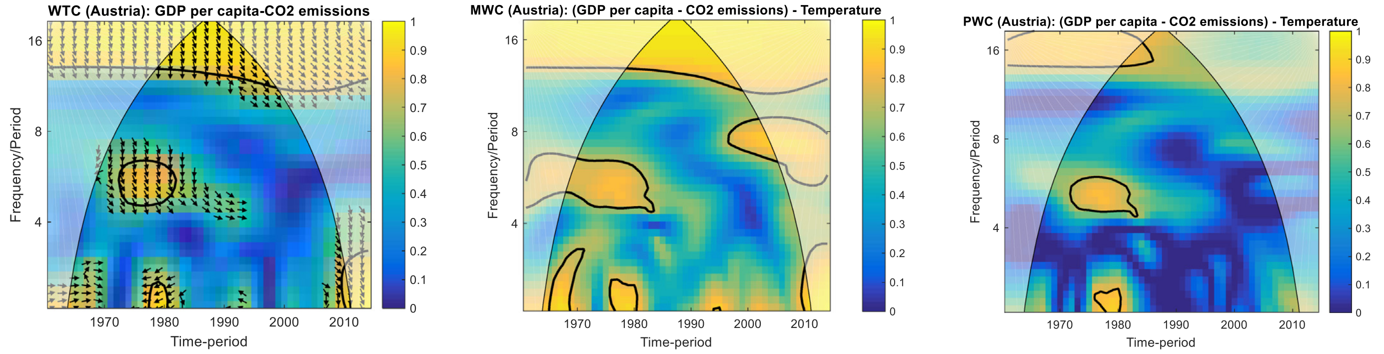


Fig. 3. The set WTC-MWC-PWC of 'GDP per capita - CO_2 emissions' pair with temperature as control variable in MWC and PWC – Austria. Legend: (1) The thick black contour indicates the 5% significance level. The lighted shadow shows the cone of influence (COI) where the edge effects might distort the picture. (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, while CO_2 emissions predict growth when the arrows point to the left and up.

income escalates emissions by 0.34%. The effects of temperature and emissions on long-term income productivity are compensated by the effect of convergence across countries of similar economic structure. Economic development is driven by energy intensity and dependence on fossils––especially in industrialized economies. This in effect exacerbates anthropogenic emissions due to economic productivity, hence, increasing levels of emissions from agrarian to industrialized economies with limited green growth underpin changes in income level (Sarkodie, 2021). In contrast, environmental sustainability attributed Kuznets curve assumes that expansion of income triggers environmental awareness, thus, decline pollution in the long-term (Sarkodie et al., 2019). Hence, the existence of mutualistic relationship between income and emission levels is evidential in Table 2 and not farfetched.

The impact of climate change is assumed to have transboundary effects across climate regimes due to global common shocks. To verify such assertion, we estimate the state of convergence of emissions and temperature across climate regimes using the log-t-based regression. We find that the estimated *t*-test statistics from the log-t regression for both emissions and temperature are below the optimal −1.65, hence, rejects the null hypothesis of convergence across climate regimes. Next, we examine club membership of climate regimes and observe that Israel, Luxembourg, and Kuwait converge in Club 1 emission membership whereas Austria, Singapore, and Norway converge in Club 2 emission membership. In contrast, Israel, Luxembourg, Austria, Singapore, and Norway converge in Club 1 temperature membership whereas Kuwait exhibits divergence in temperature. This further strengthens the proposition of structural heterogeneous effects––implying that common global climatic policies may not yield the required success compared to country-specific based policies. To validate the convergence test, we used the novel panel inter- and intra- group trend estimator to assess group regression trends in a bivariate model while controlling for omitted-variable and additional covariate bias. The resultant variations of trend estimate from the conditional panel regression are presented in Fig. 2. In the temperature-emission model, we account for historical temperature changes and economic development depicted in Fig. 2(a). The inter- and intra- functions reveal that growth in emission levels escalates extreme temperatures in Israel, Luxembourg, Singapore, Kuwait, and Norway excluding Austria––owing to unobserved confounders within countries. In the emission-income gradient, we observe that an increase in income level spurs emissions in Israel, Luxembourg, Kuwait, and Austria while decreasing emissions in Norway and Singapore [Fig. 2(b)]. The income-temperature gradient reveals that rising mean temperatures decline income level in Norway, Luxembourg, and Kuwait whereas expansion of income is evident in Singapore, Austria, and Israel [Fig. 2(c)]. It is reported that a shift from cold temperature to warmer temperature improves economic productivity in colder countries whereas a shift from optimal-warmer temperature to extreme temperatures leads to

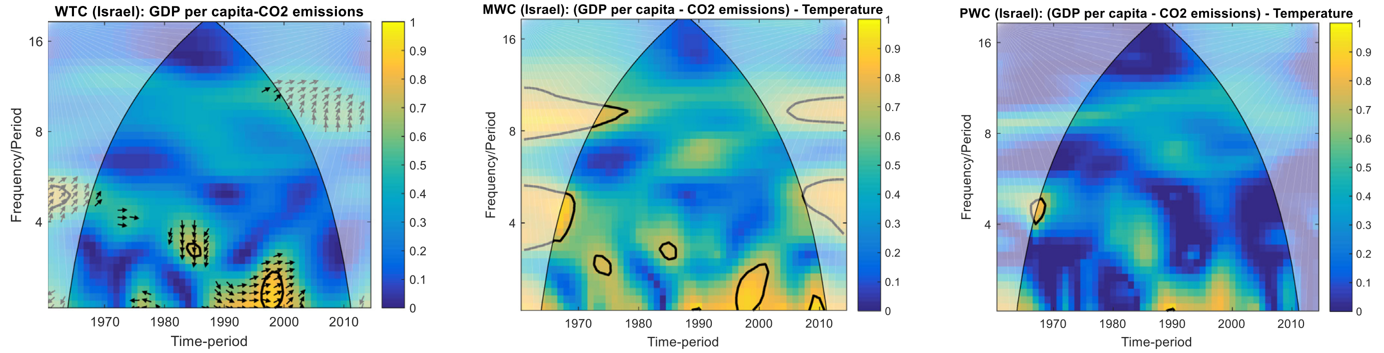


Fig. 4. The set WTC-MWC-PWC of 'GDP per capita - CO_2 emissions' pair with temperature as control variable in MWC and PWC – Israel. Legend: (1) The thick black contour indicates the 5% significance level. The lighted shadow shows the cone of influence (COI) where the edge effects might distort the picture. (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, while CO_2 emissions predict growth when the arrows point to the left and up.

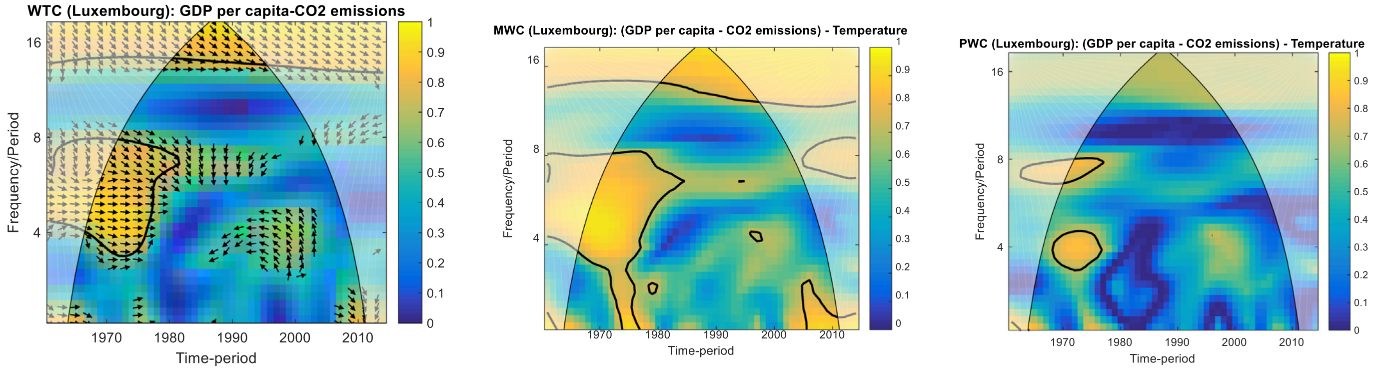


Fig. 5. The set WTC-MWC-PWC of 'GDP per capita - CO_2 emissions' pair with temperature as control variable in MWC and PWC – Luxembourg. Legend: (1) The thick black contour indicates the 5% significance level. The lighted shadow shows the cone of influence (COI) where the edge effects might distort the 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, while CO_2 emissions predict growth when the arrows point to the left and up.

economic losses. Similarly, warming declines economic productivity in low-altitude countries while expanding economic development in high-altitude countries (Diffenbaugh and Burke, 2019).

3.1. Country-specific climate regime

We examine country-specific climate regimes using wavelet estimation approach. For each country, the wavelet set routines of interaction between economic growth and CO_2 emissions having temperature as control are presented in Figs. 3–8. The first set of plots presents the case of Austria (Fig. 3). From WTC [Fig. 3(a)] plot, three episodes arise. The first episode is registered at high frequency (up to 1-year band of scale, i.e., short-term) covering the period 1978–1980. As arrows are oriented to the left and downward, growth negatively drives CO_2 emissions. The second episode is revealed at medium frequency (5–7 years band of scale, i.e., medium-term), over the period 1970–1980. The arrows are pointed to the right and downward, indicating that CO_2 emissions positively explain growth. Finally, important co-movements are evidenced at low frequency, for 1975–2005 (more than 13 years band of scale, i.e., long-term). CO_2 emission leads growth with a positive sign, as arrows are also pointed to the right and downward. The plot shows that the variables have countercyclical effect (i.e., opposite signs) in the first episode, while the cyclical effect (i.e., same signs) is registered otherwise. By incorporating temperature in MWC [Fig. 3(b)], it is clear that temperature extends the intensity of co-movement between growth and CO_2 emissions. Herein, all registered co-movements in WTC are maintained for all episodes according to intense yellow areas in MWC, as follows: 1978–1980 (up to 1-year band of scale), 1970–1980 (5–7 years band of scale), and 1975–2005 (more than 13 years band of scale). Further, interesting outputs arise by removing the temperature in PWC [Fig. 3(c)]. Unlike the MWC plot, the co-movements between growth and CO_2emissions drastically reduce in the long-term, under highland climatic regime. This highlights the 'enhancer' role of temperature for 'growth and CO_2 emissions' nexus but in the long-term.

The results of Israel are presented in Fig. 4. There is only one significant interaction between growth-CO_2 emissions reported in WTC plots [Fig. 4(a)]. Herein, at high frequency (up to 1-year band of scale, i.e., short-term), over 1995–2000, growth positively leads CO_2 emissions, the arrows being oriented to the right and up. In this case, the variables have cyclical effects (i.e., same signs). MWC [Fig. 4(b)] evidences the persistence of the interaction 'growth-CO_2 emissions' under temperature influence. More precisely, the intense yellow color registered over 1995–2000, for up to 1-year band of scale, indicates a strong co-movement between growth and CO_2 emissions under temperature presence. When temperature is removed in PWC [Fig. 4(c)], the link

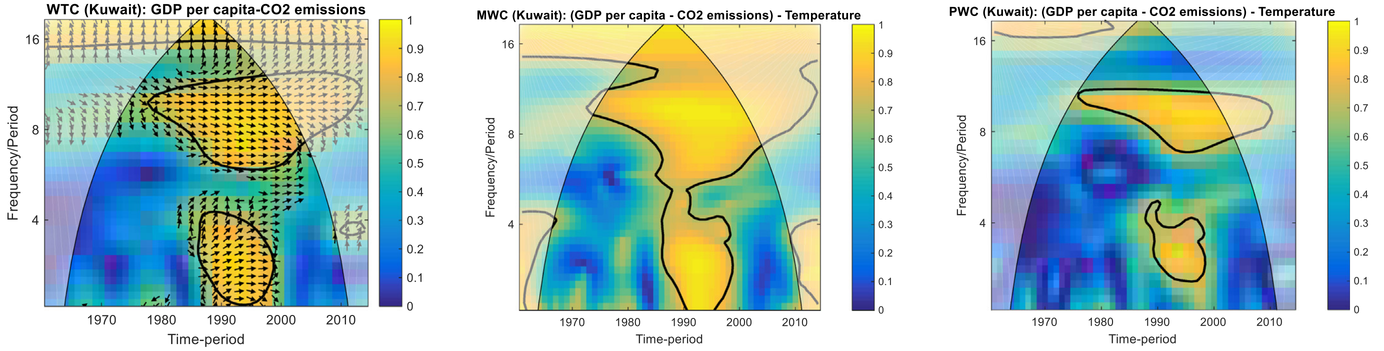


Fig. 6. The set WTC-MWC-PWC of 'GDP per capita - CO_2 emissions' pair with temperature as control variable in MWC and PWC – Kuwait. Legend: (1) The thick black contour indicates the 5% significance level. The lighted shadow shows the cone of influence (COI) where the edge effects might distort the picture. (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, while CO_2 emissions predict growth when the arrows point to the left and up.

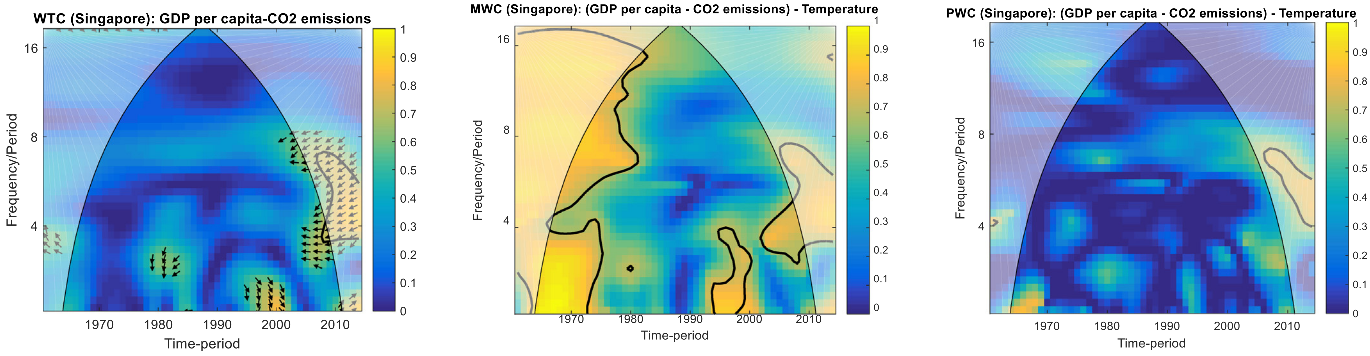


Fig. 7. The set WTC-MWC-PWC of ‘GDP per capita - CO_2 emissions’ pair with temperature as control variable in MWC and PWC – Singapore. Legend: (1) The thick black contour indicates the 5% significance level. The lighted shadow shows the cone of influence (COI) where the edge effects might distort the 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, while CO_2 emissions predict growth when the arrows point to the left and up.

disappears. This suggests that the temperature serves as a ground for ‘growth-CO_2 emissions’ connection in the short-term in subtropical climate regime.

The case of Luxembourg is shown in Fig. 5. CO_2 emissions positively run growth at medium and low frequency, as the arrows are pointed to the right and downward in related WTC [Fig. 5(a)]. The medium frequency refers to the period 1960–1980 (3–8 years band of scale, i.e., medium-term), while low frequency to 1980–2000 (more than 13 years band of scale, i.e., long-term). In both episodes, the variables have cyclical effects (i.e., same signs). The temperature insertion in MWC (Fig. 5(b)) extends the zones of co-movement of ‘growth-CO_2 emissions’ nexus as intense yellow color proves for both 1960–1980 (3–8 years band of scale) and 1960–1980 (more than 13 years band of scale) periods, respectively. Noteworthy is that the co-movement completely falls in the long-term by removing the temperature influence in PWC [Fig. 5(c)] under temperate climate status. Hence, temperature seems to play a crucial role as enhancer for ‘growth-CO_2 emissions’ nexus in the long-term.

The findings of Kuwait are depicted in Fig. 6. Growth positively drives CO_2 emissions over 1988–2000, at high frequency (up to 4 years band of scale, i.e., short-term) with arrows oriented to the right and up. The same interaction is also registered over 1980–1995, but at low frequency (more than 15 years band of scale, i.e., long-term). CO_2 emissions positively run growth over 1975–2005, at medium frequency (7–13 years band of scale, i.e., medium-term), as the arrows are pointed to the right and downward. In all cases, the variables have cyclical effects, registering the same signs. The temperature extends the co-movement area of interest variables [MWC, Fig. 5(b)]. As the intense yellow color areas indicate, the interaction between growth and CO_2 emissions is reinforced across all WTC episodes: 1988–2000 (up to 4 years band of scale), 1980–1995 (more than 15 years band of scale) and 1975–2005 (7–13 years band of scale), respectively. By removing its influence in PWC [Fig. 6(c)], the link completely disappears in the long-term under tropical desert climate regime. This also is an important sign showing that temperature plays the role of enhancer for ‘growth-CO_2 emissions’ interactions.

No significant interactions of ‘growth-CO_2 emissions’ are observed in Singapore at WTC scenario [Fig. 7(a)]. Although some evidence is registered with temperature influence in the MWC [Fig. 7(b)], but disappears for all investigated periods and frequencies, as PWC reveals [Fig. 7(c)]. The intense yellow areas in MWC plot indicate that temperature supports the ‘growth-CO_2 emissions’ link but probably has other drivers not considered here. This suggests that the ‘growth-CO_2 emissions’ link is very sensitive under temperature influence in tropical with rainforest climate regime. Herein, the temperature seems to be strong support of co-movements between growth and CO_2 emissions but in a mix with other factors.

The case of Norway is presented in Fig. 8. Similar to Singapore's model, no notable connection of ‘growth-CO_2 emissions’ is found

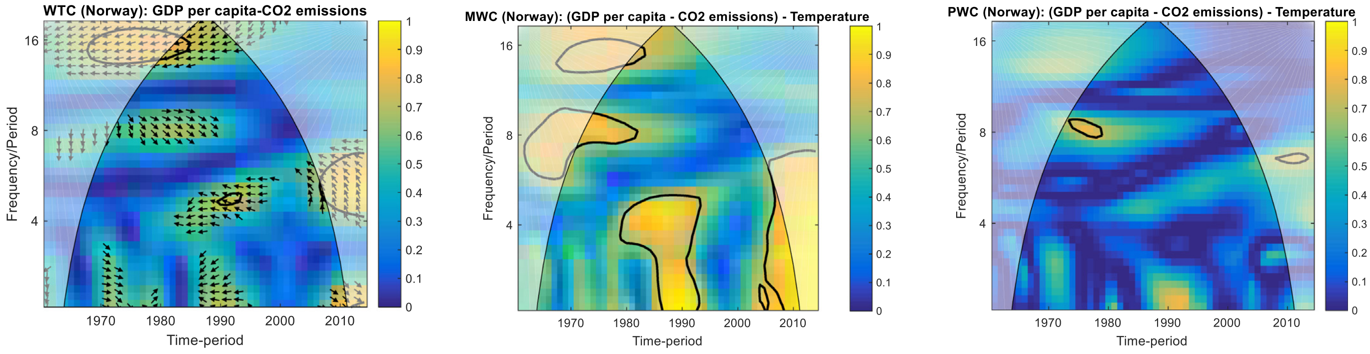


Fig. 8. The set WTC-MWC-PWC of ‘GDP per capita - CO_2 emissions’ pair with temperature as control variable in MWC and PWC – Norway. Legend: (1) The thick black contour indicates the 5% significance level. The lighted shadow shows the cone of influence (COI) where the edge effects might distort the picture. (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, while CO_2 emissions predict growth when the arrows point to the left and up.

[WTC, Fig. 8(a)]. Although two 'short' episodes are observed over 1990–1992 (5–6 years band of scale, i.e., medium-term) and 1975–1980 (14–16 years band of scale, i.e., long-term), their actions are rather negligible. By introducing temperature, it seems to play an important role in stimulating the link, possibly in a mixed action with other drivers [MWC, Fig. 8(b)]. Further, by removing its effect, the co-movements disappear [PWC, Fig. 8(c)]. Like the case of Singapore, a strong sensitivity of connection under temperature influence is evidenced, but in a mix action with other drivers for polar with tundra climate regime.

Concretely, in the highland climate regime varying with altitude, temperature extends the persistence of CO_2 emission-growth effect. The control of CO_2 emissions in the long-term can partially be the result of temperature effects. In the subtropical climate regime, temperature supports the 'growth-CO_2 emissions' link but has no stimulating effect in the short-term. In temperate and tropical with desert climate regimes, temperature extends the co-movement persistence of interest variables but falls in the long-term. CO_2 emissions spur growth in the temperate regime whereas growth drives CO_2 emissions in tropical with desert regime. Interesting results of no co-movement between 'CO_2 emission-growth' are reported for tropical with rainforest and polar with tundra climate regimes. Moreover, temperature has a huge potential to activate the link, thus, very sensitive under its influence. The influence of temperature on growth-CO_2 emissions interaction differs from country-to-country, strictly particularized by its specific economic contexts. Whatever, some pieces of evidence are registered especially in short- and long-terms. No rule is proved regarding the lead-lag status of variables, however, both directions of co-movement are registered irrespective of considered climate regimes.

4. Conclusion

This study examines heterogeneous effects of CO_2 emissions and temperature changes on income. Subsequently, we assess the long-term impact of growth in income and temperature variability on CO_2 emissions. We observe that historical fluctuations in income due to changes in temperature and emissions are temporal, hence, corrected overtime. Similarly, uncertainty in emission levels across countries––owing to temperature variability and growth in income is time-bound, hence, has mitigation effects. Our study shows that temperature, income, and emissions are somewhat affected by heterogeneous effects, global shocks, and possibly, transboundary effects. This then implies that studies that fail to consider such parametric and initial conditions may result in misspecification bias, and erroneous inferences. While the sampled countries may exhibit income convergence, our study identifies two-club memberships for emission convergence––Club 1 entails Israel, Luxembourg, and Kuwait, whereas––Club 2 captures Austria, Singapore, and Norway. This infers that common emission-based policies or successful environmental sustainability strategies can be mimicked across club memberships. The strong positive relationship between income and emissions indicates that carbon intensity through fossils underpins wealth creation and vice versa. This underscores the state of mutualism between income and emissions, validating the scale effect hypothesis. Second, the strong negative effect of temperature on income productivity across countries has policy implications. Variabilities in temperature leading to extreme patterns from optimal levels hamper economic activities. While a swing in temperature from extreme cold to temperate may favor wealth creation in Norway, the opposite may occur in temperate and tropical regions like Luxembourg, Kuwait, and Singapore. Such scenario of extreme temperature levels affects energy requirements through heating and cooling degree days––thus, escalating energy consumption cum emissions. Decarbonization of economic productivity is obviously the vehicle towards emission reduction and climate change mitigation. However, such strict conservation strategies will require structural changes with green growth.

Future research could benefit from both short and long-run income effects of temperature and emission across extensive climate regions with several and varying income groups.

CRediT authorship contribution statement

Cosimo Magazzino: Conceptualization, Data curation, Writing – original draft. **Mihai Mutascu:** Formal analysis, Software, Validation, Writing – original draft. **Samuel Asumadu Sarkodie:** Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Festus Fatai Adedoyin:** Writing – original draft. **Phebe Asantewaa Owusu:** Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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