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Global evidence of time-frequency dependency of temperature and environmental quality from a wavelet coherence approach

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Abstract

The concern that the global emissions or carbon mitigation plans have not yielded the much desired significant improvement in health, air and environmental quality especially since the Conference of Paris has further created some ambiguities. This has further made environmentalists and policymakers wonder if the December 2015 Paris Climate Agreement is "better than no agreement". In advancing the studies of global temperature and carbon emission nexus, the current study rather applied the time-frequency dependency of average global mean temperature anomalies and global carbon dioxide (CO_2) emissions from fossil fuels for the annual data from 1851 to 2017. The present study uses the wavelet coherence technique and the Toda and Yamamoto causality approach that allows the investigation of both the long- and short-term causal relationship between the global average temperature and global CO_2 emissions. The findings of this study indicate that (i) significant vulnerabilities in global average temperature and global CO_2 emissions are observed at different time periods and different frequency levels; (ii) global CO_2 emissions have a strong power for explaining global average temperature at different time periods; (iii) between 1880 and 1910, global average temperature and global CO_2 emissions are positively correlated at medium term; and (iv) the outcome of Toda and Yamamoto causality reveals that global CO_2 emissions cause global average temperature and this outcome is in line with the outcome of wavelet coherence approach.

Keywords Environmental quality · Climate change · Temperature · CO_2 emissions · Wavelet coherence

Introduction

Considering the obvious ambiguities surrounding the climate change debacle, the global action plan and agreement that emanated from the December 2015 Conference of Paris (COP:21) remained elusive. This is because the global warming mitigation plan that targets limiting global temperature to 1.5–2 °C above pre-industrial levels has remained unattainable by the constituting (195) signatory member states of the COP:21 agreement (United Nations Framework Convention on Climate Change 2015a, b) . Giving that the Paris Agreement lacks the blueprint for achieving the aforementioned stabilization objectives, environmentalists and policymakers have wondered if the so-called December 2015 Paris Climate Agreement is better than no agreement (Clémençon 2016; Carfí et al. 2019). In addition to the severe health implications of global warming (Archibald et al. 2018; Pino-Cortes et al. 2020), it has consistently compounded the global economic, social and environmental problems, thus suggesting the lack of commitment of the signatory states to the 21st United Nations Climate Conference (COP21). For instance, the USA's decision to withdraw from the Paris Agreement (Climate Agreement of the United Nations Framework Convention on Climate Change (UNFCCC))[1] is expected to have a serious environmental setback (Alola 2019a, b; Carfí et al. 2019). The implication is that there is a likelihood of an increased share of carbon emissions in the

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[1] The United Nations Framework Convention on Climate Change (UNFCCC) brings all nations into a common cause to undertake ambitious efforts to combat climate change and adapt to its effects (United Nations Framework Convention on Climate Change, 2015).

global emissions by the USA (being the second emitter of carbon after China) and several other emitter states (especially with low commitment to the COP:21).

Given the potential of CO_2 emission to trap the atmospheric heat, the unprecedented increase in the global temperature could not pose a lesser threat to global health and environmental sustainability (Cheng et al. 2008). The global concern for environmental sustainability amidst the revealing evidence of the hazards of climate change is the reason for the obvious intergovernmental collaborations on environment climate and energy transition (López-Santos and Martínez-Santiago 2015; Alola 2019a, c; Alola and Kirikkaleli 2019; Bekun et al. 2019; Adedoyin et al. 2020a, b; Adedoyin and Zakari 2020). However, because of human limitation to regulate or mediate the natural phenomenon such as the global temperature, thus tackling the environmental effects of the cooling and heating degree days remains herculean (Alola et al. 2019). For instance, with the exemption of the year 1998, the world had recorded eighteen (18) warmest years since 2001, thus posing more environmental questions (National Aeronautics and Space Administration (NASA) 2019). Importantly, with the average global temperature of 0.94 °C (1.69 °F) across the ocean and land surfaces, NASA further informed that the world recorded the warmest temperature in 2016.

With the undesirable increase in the average global temperature, the environmental impact of the increasing atmospheric CO_2 especially since the industrial revolution has continued to threaten the ecological system, thus indirectly impeding human sustenance. For instance, the National Oceanic and Administrative Administration (NOAA) 2019) reported that harsh environmental conditions such as the adverse temperature often bleach the coral materials to white, thus reducing its ecological significance. The NOAA further reported that the continuous increase in the average global temperature warm the corals such that it expels the symbiotic algae in the coral tissues. However, other factors such as the economic growth, energy utilization, trade policy, dynamics in the ecological systems, population, immigration and host of other factors have added to the aforementioned environmental consequence of global warming (Alola and Alola 2018; Alola et al. 2019a, b, c; Saint Akadiri et al. 2019a, b; Etokakpan et al. 2020).

In light of the above motivation, the current study examines the time-frequency dependency of the average temperature and carbon emissions. Although previous studies (Ozturk and Acaravci 2010; Saint Akadiri et al. 2019; Usman et al. 2020) have either examined the relationship between carbon emissions and varying factors or the determinants of carbon emissions, the current study make a significant contribution to the extant literature from the perspective of the environmental effects of global temperature. Hence, the current study presents a novel perspective through the following pathways. Foremost, by employing the time-frequency empirical approach, this study provides insight into both the time and frequency of the causative nexus between the average global temperature and environmental degradation for the experimental period from 1851 to 2017. Although studies have examined the environmental impact of temperature change for specific locations, to the best of authors' knowledge, the current investigation presents a rare global perspective of the contextual study. Lastly, in addition to the use of the Toda and Yamamoto causality approach, the current study expands the literature of temperature and environmental degradation nexus.

About the remaining sections of the study, they are outlined as follows. The "Related extant studies" section presents an overview of the previous studies pertaining to the nexus of temperature and carbon emissions. The "Data and method" section covers the variable description and empirical methods employed. The empirical findings and discussion are presented in the "Findings and discussion" section. In the "Conclusion and policy perspectives" section, the concluding remarks, policy implication and the recommendation for future study are outlined.

Related extant studies

Although only a handful of empirical studies illustrate the relationship between temperature and carbon emissions, the study of Kaufmann et al. (2006) is among the rare studies that examined the nexus of CO_2 emissions and other gaseous emissions with the surface temperature in an empirical approach. The aforementioned study examined the likelihood of a bi-directional relationship among the mentioned variables (i.e. the concentration of CO_2, other gaseous emissions and the surface temperature). Importantly, the study of Kaufmann et al. (2006) implied that the increase in the global surface temperature has affected the concentration of CO_2 in the atmosphere, thus causing more hazards since 1870. Similarly, other gaseous emissions such as the atmospheric concentration of CH_4 are arguably been linked with the undesirably rise in the surface temperature, thus implying a more hazardous impact of the GhG emission (De Laat and Maurellis 2004).

Again, by studying the variations of CO_2 and CH_4 emissions, Jacotot et al. (2019) investigated the impact of temperature and biofilm in Rhizophora mangrove forest that has a semi-arid climate. The study found that the production of CO_2 and CH_4 gases within the soil is more during the warmer season, thus causing more fluxes of the gases (CO_2 and CH_4 emissions) during the aforementioned season. In recent times, similar conceptual studies have examined the linkage of temperature dynamics and the GhG vis-à-vis CO_2 emissions (Mansanet-Bataller et al. 2007; Gritsch et al. 2015; Zickfeld et al. 2016; Ekwurzel et al. 2017). Specifically, while acknowledging the proportionality of the global mean surface temperature and the cumulative CO_2 emission, Zickfeld et al. (2016) explored the Earth system model to examine the positive of a significant relationship during periods of net-negative CO_2 emission. As such, the study found that the lagged response of the deep ocean to previously increasing atmospheric CO_2 is responsible for a significant nonlinear relationship between the temperature change and the cumulative CO_2 emissions during periods of net-negative emission.

Furthermore, considering the global desire and commitment toward stabilizing the global warming well below 2 °C above pre-industrial levels, underpinning the determining factors of the variability in the cooling and heating degree days has been prioritized. For instance, Alola et al. (2019b) examined the impact of the energy use, urban population and the ecological footprint on the cooling and heating degree days in the USA. The study employed the autoregressive distributed lag bound testing approach over the period of 1960 to 2015 and found that the ecological footprint has a negative effect on both the heating and the cooling degree days in the USA. However, Yuksel and Michalek (2015) examined the effect of regional ambient temperature difference on battery electric vehicle (BEV) and use-phase power plant CO_2 emissions in the USA. As such, the study found that the spatial and temporal ambient temperature variation is responsible for about 22% of the variation in the BEV emissions. In particular, the efficiency of the BEV is also not speared from the environmental effect especially of the colder climatic regions of the USA. However, in addition to temperature-related factors, environmental quality has consistently been linked to other heat-induced factors such as energy consumption and related factors (Acaravci and Ozturk 2010; Ozturk and Acaravci 2013; Shahbaz et al. 2014; Asongu et al. 2020; Eluwole et al. 2020; Ibrahim and Alola 2020; Joshua and Alola 2020).

Data and method

Data

This section of this study focuses on the data choice and econometrics procedure applied. The data used in the present study are temperature (average global mean temperature anomalies in degrees Celsius relative to a base period) and CO_2 emissions (global CO_2 emissions from fossil fuels) from the Carbon Dioxide Information Analysis Centre, the U.S. Department of Energy. The time series variables used in the empirical tests of this study consist of annual data for the period 1851 to 2017. Figure 1 presents the average global mean temperature anomalies in degrees Celsius relative to a base period and global CO_2 emissions from fossil fuels over the period from 1851 to 2017.

Methodology

To investigate the time-frequency dependence of global temperature anomalies and global CO_2 emissions, the wavelet coherence approach is employed in the present study. The technique roots go back to the novel study of Goupillaud et al. (1984). The key innovation of wavelet coherence is that the technique combines time-domain causality with frequency domain causality (Kondoz et al. 2020). Therefore, this allows us to investigate co-movement between global CO_2 emissions from fossil fuels and average global mean temperature anomalies in the long run and short run, separately. In other words, a multi-scale decomposition method brings out a natural framework to show frequency-dependent behaviour for exploring the relationship between global temperature anomalies and global CO_2 emissions.

The study adopts the wavelet ψ based on the Morlet family of wavelet. The equation is extracted as $\psi(t) = \pi^{-\frac{1}{4}} e^{-i\omega_0 t} e^{-\frac{1}{2}t^2}$, $p(t)$, $t = 1, 2, 3\ldots..,\ T$ (Kirikkaleli 2019).

In Eq. (1), two wavelet parameters namely location (k) as well as and frequency (f) are main components. The core importance of the parameter k is to outline the precise location in time by a fluctuation of the wavelet (Kalmaz and Kirikkaleli 2019). On the other hand, f controls the variations in the frequencies. $\psi_{k,f}$ is constructed initially by the transforming ψ. The transformation equation is presented as:

$$\psi_{k,f}(t) = \frac{1}{\sqrt{h}} \psi\left(\frac{t-k}{f}\right), \quad k, f \in \mathbb{R}, f \neq 0 \tag{1}$$

Furthermore, the continuous wavelet can be constructed from ψ contingent on earlier mentioned wavelet parameter of k and f provided that the time series data set $p(t)$ as follows:

$$W_p(k,f) = \int_{-\infty}^{\infty} p(t) \frac{1}{\sqrt{f}} \psi\left(\overline{\frac{t-k}{f}}\right) dt \tag{2}$$

The aforementioned already generated time series $p(t)$ with its corresponding coefficient ψ is presented in the equation below:

$$p(t) = \frac{1}{C_\psi} \int_0^{\infty} \left[\int_{-\infty}^{\infty} \left|W_p(a,b)\right|^2 da\right] \frac{db}{b^2}. \tag{3}$$

The adoption of the wavelet power spectrum (WPS) is applicable as it characterized with more information and amplitude of the time variables.

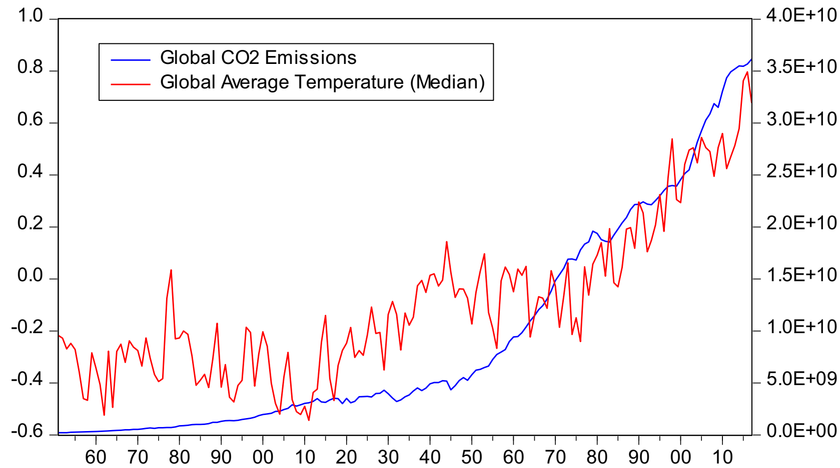
$$\mathrm{WPS}_p(k,f) = \left|W_p(k,f)\right|^2 \tag{4}$$

The present study adopts the wavelet coherence technique. This is premised on the inherent traits of the coherence approach over conventional correlation. The wavelet coherence technique allows for a broader capture of both time domains of the time series $p(t)$ and $q(t)$ in combined time-frequency–based causalities (Orhan et al. 2019).

Furthermore, the cross-wavelet transform of the times series takes the following form:

$$W_{pq}(k,f) = W_p(k,f)\overline{W_q(k,f)} \tag{5}$$

Fig. 1 Global CO_2 emissions and temperature anomalies



where $W_p(k,f)$ and $W_q(k,f)$ denote cross-wavelet transform for $p(t)$ and $q(t)$, respectively as outlined by (Kirikkaleli 2019). In summary, Torrence and Compo (1998) constructed the square version of the wavelet coherence in the equation below:

$$R^2(k,f) = \frac{\left|C\left(f^{-1}W_{pq}(k,f)\right)\right|^2}{C\left(f^{-1}\left|W_p(k,f)\right|^2\right)C\left(f^{-1}\left|W_q(k,f)\right|^2\right)} \tag{6}$$

From Eq. (6), the time and smoothing process over time is captured by C, with values ranging from $0 \leq R^2(k,f) \leq 1$. It is worth mentioning here that when $R^2(k,f)$ gets close to unit (1), this denotes that between the time series, there exists correlation at a particular scale, surrounded by a black line and represented by the colour red. While in the case of the value of $R^2(k,f)$ close to zero (0), it depicts the scenario of no correlation between the time series which is displayed by the colour blue (Kirikkaleli 2020).

In the computation of the values of $R^2(k,f)$, there is no clear distinction for a positive or negative correlation (Umar et al. 2020). Thus, the idea of Torrence and Compo (1998) comes in handy, as it helps to detect the variance in wavelet coherence via the indications of deferrals in the wavering of two-time series (Alola and Kirikkaleli 2019). The equation that provides the differentiation in the wavelet coherence phase is given as:

$$\phi_{pq}(k,f) = \tan^{-1}\left(\frac{\mathrm{L}\left\{C\left(f^{-1}W_{pq}(k,f)\right)\right\}}{O\left\{C\left(f^{-1}W_{pq}(k,f)\right)\right\}}\right) \tag{7}$$

From Eq. (7), the lag operators L and O represent both imaginary operator and real part operator respectively.

As a robustness check, the Toda-Yamamoto causality test is employed to examine the time domain causal nexus of average global mean temperature anomalies in degrees Celsius and global CO_2 emission from fossil fuels for the period from 1851 to 2017. Toda and Yamamoto (1995) develop the causality test through a Wald test statistic that is not affected by the integration order or cointegration properties of the series. Thus, “there is no information loss due to differencing the data series and the procedure is more flexible considering arbitrary levels of integration” (Gokmenoglu et al. 2019).

Findings and discussion

As an initial test, the wavelet power spectrum is employed in this study to explore the significant volatility of average global mean temperature anomalies in degrees Celsius relative to a base period and global CO_2 emissions from fossil fuels over the period from 1851 to 2017. Since the dataset covers the period from 1851 to 2017 (167 observations), a scale of 32 is selected for the wavelet power spectrum and wavelet coherence analyses. Figs. 2 and 3 illustrate the wavelet power spectrum for average global mean temperature anomalies in degrees Celsius relative to a base period and global CO_2 emissions from fossil fuels, respectively. With reference to Figs. 2 and 3, the white curve represents the cone of influence referring to an edge under which the wavelet power is discontinued, while the area surrounded by the black line represents a significant change in the behaviour of the time series variable at 5% significant level that is determined by the means of Monte Carlo simulations. Specifically, in Figs. 2 and 3, the colour indicating the power spectrum varies from blue (weak) to red (strong). Moreover, Fig. 2 clearly reveals that there is significant volatility in the average global mean temperature over the period from 1851 to 2017, but the volatility is temporary since the areas surrounded by black lines are at the 0 to 6 scale periods. As portrayed in Fig. 3, the behaviour of the global CO_2 emissions from fossil fuels changes significantly only between WWI and WWII periods. This clearly shows the dramatic effect of world wars over the global CO_2 emissions. It is worthy to mention that we failed to capture volatility in the global CO_2 emissions of the post-

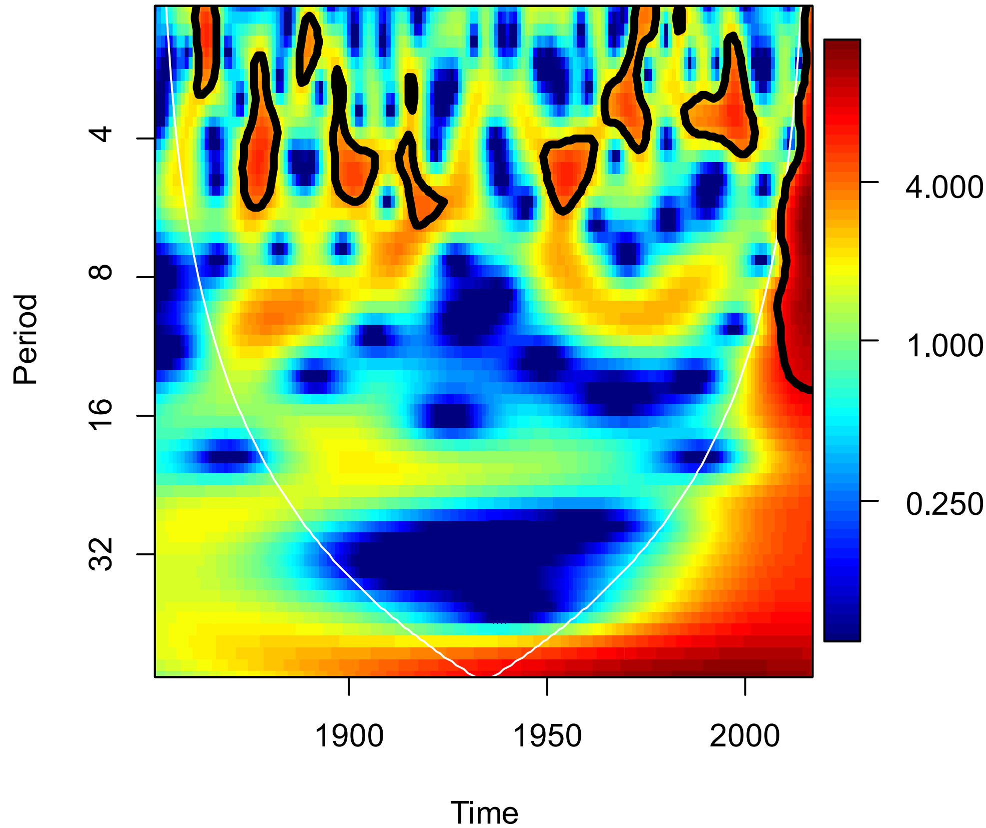


Fig. 2 Wavelet power spectrum for average global mean temperature anomalies

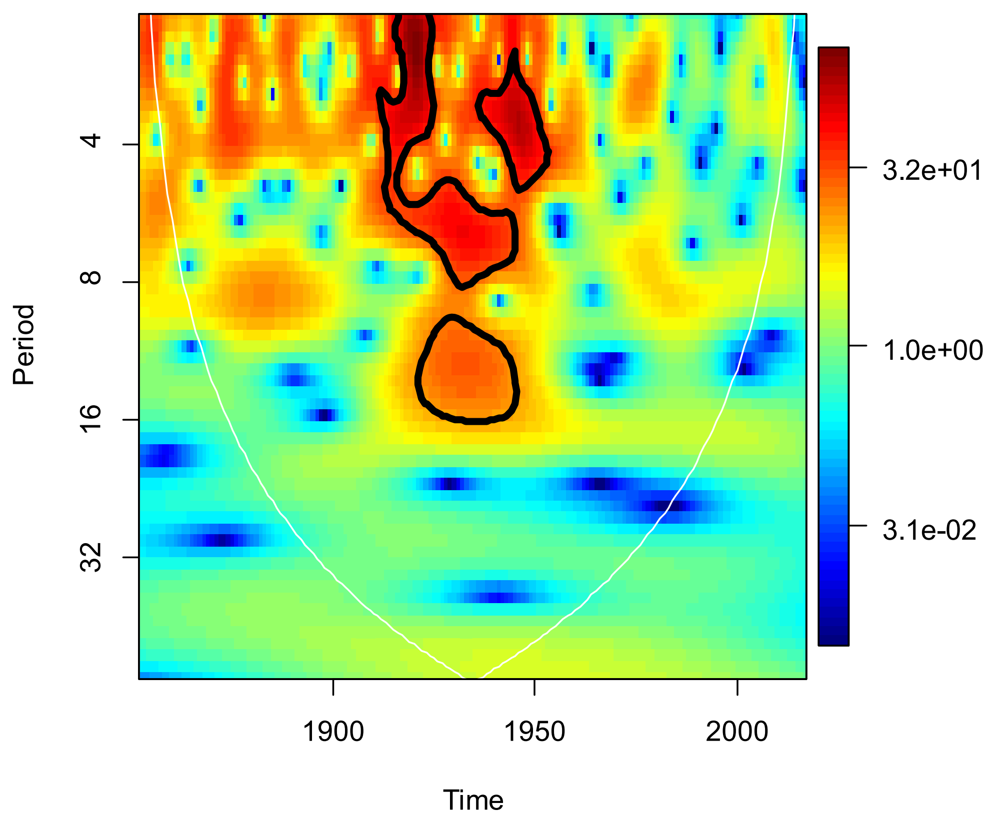


Fig. 3 Wavelet power spectrum for global CO_2 emissions

WWII period due to the continuously upward trend in the CO_2 emissions in the world.

Based on the main aim of the present study, it is interesting to explore whether the volatility of the average global mean temperature anomalies leads to global CO_2 emissions from fossil fuels or merely a coincidence. Therefore, to investigate the co-movement between global CO_2 emissions and average global mean temperature anomalies, the wavelet coherence approach is implemented using "biwavelet" (R software). In Fig. 4, we display the wavelet coherence of average global mean temperature anomalies with global CO_2 emissions from fossil fuels in the joint time-frequency sphere. The wavelet coherence technique measures the local correlation or causality between average global mean temperature anomalies and global CO_2 emissions from fossil fuels in the present study. Indicatively from Fig. 1, there is an upward trend in both the CO_2 emission and the average global mean temperature anomalies in degrees Celsius relative to a base period. In addition to the study of Akadiri et al. (2020) that opined the relationship between ecological footprint and temperature changes, the trend evidence depicted in Fig. 1 further supports the notion of significant cointegration between the indicators as motivated in the study of De Laat and Maurellis (2004) and Zickfeld et al. (2016).

The wavelet coherence will denote the strength of correlation or causality between average global mean temperature anomalies and global CO_2 emissions from fossil fuels, and the brighter the red (hotter) colour, the higher the correlation value with regard to $R^2(k,f)$ as in Eq. (6). The arrows pointed to the left (right) represent that average global mean temperature anomalies and global CO_2 emissions from fossil fuels are negatively correlated (positively correlated). The arrows pointed to the up, right up or left down indicate that global CO_2 emissions from fossil fuels lead to average global mean temperature anomalies while the arrows pointed to the down, right down or left up indicate that average global mean temperature anomalies lead to global CO_2 emissions from fossil fuels.

As clearly seen in Fig. 4, the findings from wavelet coherence revealed a one-way causality running from global CO_2 emissions from fossil fuels to average global mean temperature anomalies at different frequencies between 1910 and 1950 and between 1980 and 1985. This observation is significant because the majority of the arrows point to the up or left down within the cone-shaped white line. The result clearly supports that global CO_2 emissions from fossil fuels are important predictor for average global mean temperature anomalies. In addition to the affirmation of the COP:21 resolution

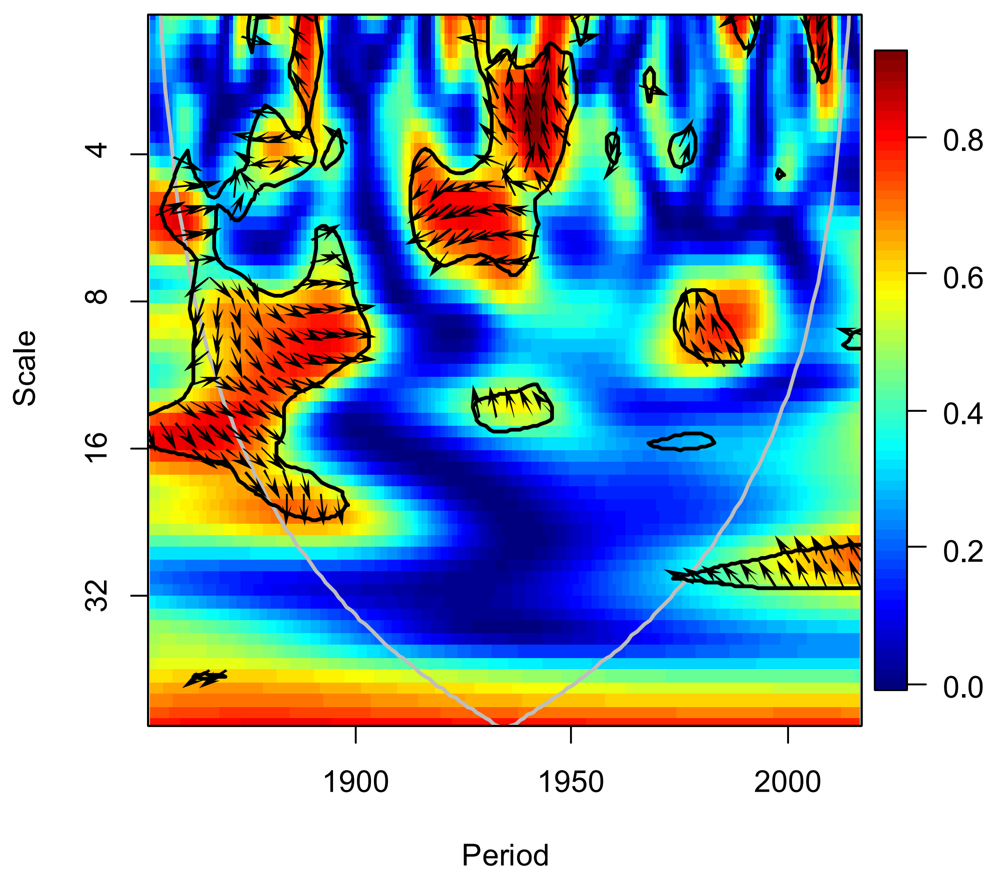


Fig. 4 Wavelet coherence between global average temperature and global CO_2 emissions

Table 1 Toda and Yamamoto causality

	df	M-Wald	Prob.	Decision
GMTA ➔ CO_2	2	0.135907	0.9343	No
CO_2 ➔GMTA	2	6.012554	0.0495	Yes

Note: GMTA denotes global mean temperature anomalies while CO_2 denotes global CO_2 emissions from fossil fuels

➔Denotes direction of causality

of the need for a more deliberate energy transition policy especially by the high-carbon emitter countries (UNFCCC 2015), other studies such as Chen et al. (2014) identified the effects of CO2 emission on temperature changes. In specific, Chen et al. (2014) pointed out that the highest global temperature changes were experienced between 1960 and 2008, and especially the highest in North America and Oceania. Moreover, Table 1 presents the outcome of the Toda and Yamamoto causality test and this result clearly supports the outcome of the wavelet coherence technique since we observed that global CO_2 emissions from fossil fuels cause average global mean temperature anomalies at a 5% significance level. In addition, Fig. 4 also shows that between 1880 and 1910, the average global mean temperature anomalies and global CO_2 emissions are positively correlated in the medium term. The corroborating evidence of the nexus of global temperature or warm climate with emissions (nitrous oxide, chlorofluorocarbons (CFCs), methane, water vapour) especially the carbon dioxide has continued to be been asserted in the last decades (National Aeronautics and Space Administration (NASA) 2020; National Oceanic and Administrative Administration (NOAA) 2020).

Conclusion and policy perspectives

The present study aims to explore the time-frequency dependency of the average global mean temperature anomalies and global CO_2 emissions using the wavelet coherence technique. Since the technique combines both the time and frequency domain causality approaches, the technique allows the present study to identify the short-run and long-run causal relationship between the average global mean temperature anomalies and global CO_2 emissions. In the present study, we used an annual dataset, which covered the period 1851–2017. Like the study of Akadiri et al. (2020), the empirical findings in the current study further revealed the relationship between environmental degradation vis-à-vis and temperature such that (i) significant vulnerabilities in average global mean temperature anomalies and global CO_2 emissions are observed at different time periods and different frequency levels; (ii) changes in global CO_2 emissions lead to changes in average global mean temperature anomalies at different time periods; (iii) between 1880 and 1910, average global mean temperature anomalies and global CO_2 emissions are positively correlated at medium term; and (vi) the outcome of Toda and Yamamoto causality reveals that global CO_2 emissions cause average global mean temperature anomalies and this outcome is in line with the outcome of wavelet coherence approach.

Considering that the current study further reveals the importance of global surface temperature changes to the contextual discussion of the challenges of global warming, certain policy initiatives are provided in this direction. More deliberate and targeted efforts are essential for geographical locations (such as part of Central Europe, Asia, Australia, southern Africa, Madagascar, New Zealand, North America and Eastern South America) that are notable for high annual temperatures over land surfaces. In so doing, greener economic and socio-environmental policies should re-invigorated in these parts of the globe. In addition, emissions such as methane, nitrous oxide, water vapour and others (such as from agricultural practices, wastes decomposition in landfills and manure management of domestic livestock) could be harvested by using the semblance of carbon-capturing technologies.

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