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6 August 2021

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Abstract: This study aims to revisit the evidence of co-movement and lead-lag nexus between carbon dioxide emissions and economic growth in G7 countries over a period of two centuries by using the wavelet coherence analysis. The key findings reveal (i) a cyclical relationship between carbon dioxide emissions and GDP per capita, which implies that during the upswing phase of business cycles, economic growth and carbon dioxide emissions both grow, but the latter can be predicted using GDP as an indicator function at the 1- to 2-year scale. (ii) A time-scale bidirectional causality between carbon dioxide emissions and GDP per capita. This implies that carbon dioxide emissions cannot be reduced without adversely affecting economic growth. Further, the finding also implies a rapid adoption of alternative clean energy sources to reduce carbon dioxide emissions without depressing economic growth.
Keywords: Carbon Dioxide Emissions, Economic Growth, G7, Time-Frequency Analysis

1. Introduction

Global warming and anthropogenic climate changes have emerged as the most challenging environmental issues facing the world today. Between 1990 and 2015, global carbon dioxide emissions grew by 60%, with carbon dioxide concentrations forecasted to be doubled by the end of the 21st century (IPCC 2014). The anthropogenic rise in greenhouse gas emissions—for which carbon dioxide emissions is a vital contributor—is expected to cause an increase in global temperatures of between 1.5 and 5.8°C by the end of the 21st century (IPCC 2014). Global efforts are underway to tackle the issues of global warming and climate change as world leaders engage in political negotiations to reduce carbon dioxide and greenhouse gas emissions. For instance, during the recent annual summit held in Paris in June 2015, the leaders of the G7 nations agreed to cut back on greenhouse gas emissions by 40% to 70% by 2050, considering 2010 as a baseline, following the recommendations of the Intergovernmental Panel on Climate Change (IPCC) (The Guardian 2015).

While carbon mitigation policies are critical in combating environmental change, an important consideration in the adoption of these policies is the level of development and the economic growth of a country. The economic development of a country is likely to determine the costs and benefits of adopting such policies and hence directly affecting the CO_2 emissions produced by the country. For instance, the adoption of carbon mitigation efforts, such as reducing reliance on fossil fuels and a shift towards renewable energy sources, requires substantial resources and can only be adopted at later stages of economic development. Thus, as the country progresses on the developmental ladder and experiences sustained economic growth, it can afford to adopt cleaner and green technologies, which helps to improve environmental quality. Another important consideration is reverse causality running from CO_2 emissions to economic growth. Adoption and availability of greener and cleaner technologies can offer countries, especially developing countries, an opportunity to "leapfrog" over developed countries (see, for example, Dasgupta et al. 2002) as the rapid adoption of such technologies may lead to technological progress and eventually sustained long-term economic growth.

Given the complex nature of the relationship between carbon emissions and economic growth, it is pertinent to understand the co-movement and lead-lag nexus between carbon dioxide emissions and economic growth, in order to formulate targeted and effective mitigation policies. Although the economic growth and environmental quality nexus have been extensively explored in both the theoretical and empirical literature, however, there is little consensus on the inter-relationship between CO_2 emissions and economic growth. The results of most existing empirical studies support the existence of the so-called environmental Kuznets curve (EKC) hypothesis. According to the EKC hypothesis, an inverted U-shaped relationship exists between economic growth and environmental degradation. The inverted U-shaped relationship emanates from the assumption that at an early stage of economic development, a country prioritizes economic development at the cost of environmental degradation. However, as the economy grows, the country channels more investment into cleaner technologies, producing environmentally friendly goods and services that improve environmental quality.

One of the major criticisms of the EKC hypothesis is that it only considers unidirectional causality running from income to environmental degradation while ignoring the possibility of a reverse causal relationship between them. Economic growth can be achieved through environmental protection as it increases efficiency and stimulates technical progress (Porter and van der Linde, 1995). Furthermore, a bidirectional causal relationship may exist between economic growth and environmental quality. A number of studies support the bidirectional causal relationship between economic growth and carbon dioxide emissions (see, for example, Coondo and Dinda, 2002; Dinda and Coondo, 2006; Kim et al., 2010).

Even though the existing empirical literature has focused extensively on the income-environmental quality nexus, there still remain several research gaps. First, despite the large proportion of total carbon dioxide emissions (17% of the world) released by the G7 countries, only a handful of studies have examined the causal relationship between income and carbon dioxide emissions in these countries. Several studies have focused on the USA, Canada, and France; however, the G7's remaining four countries have been largely ignored in the existing literature. Second, the majority of the studies suffer from the 'small sample' problem. To truly capture the impact of economic activities on carbon dioxide emissions, we must look at the historical relationship between these two variables going back to the early mid-nineteenth century, particularly when industrialization occurred. Therefore, empirical results from the small time period of 40–50 years may provide misleading results that can be overcome by following Stern et al.'s (1996) proposition that "*a more fruitful approach to the analysis of the relationship between economic growth and environmental impact would be the examination of the historical experience of individual countries, using econometric and qualitative historical analysis"*. Third, many previous studies have tended to overlook structural changes in their analysis, which may be the most crucial problem for time-series data (Granger, 1996). Because GDP per capita and carbon dioxide emissions are macroeconomic variables, structural changes must be considered when analyzing the income–carbon dioxide emissions nexus. Usually, exogenous shocks or regime changes in socioeconomic events—such as political regime shifts, conflicts or war, financial and economic reforms, and globalization—affect macroeconomic series. Fourth, in most of the studies, empirical analysis examining the Granger-causal relationship between economic growth and environmental quality is based on conventional methods that rely on the temporal dimension and neglect time series' frequency domain features. As Andersson and Karpestam (2013) highlight, the nexus for economic growth versus environmental quality may vary across time scales because of business cycle fluctuations in the short term and because of long-term economic growth factors. Moreover, certain policies need time to be implemented, and their result can only be seen after a certain period. Therefore, the assessed characteristics in the frequency dimension can help develop a more in-depth understanding of complex patterns that exist between economic growth and environmental quality.

This study addresses the issues highlighted above and contributes to the existing literature along three dimensions. First, the study explores the link between economic growth and carbon dioxide emissions for all the countries in the G7 group instead of focusing only on a few large economies. Second, the study uses a long-time series covering the period 1820–2015 to explore the growth-carbon dioxide emissions nexus. Third, instead of relying on traditional methods to explore the link between growth and environmental quality, this study utilizes a wavelet coherence (CWT) method. The innovation in this study lies in carrying out the wavelet coherence approach to better evaluate the economic and policy implications and recognize the opportunities of the dynamic association that exists between the carbon dioxide emissions and GDP per capita in the G7 economies. As a point of fact, the use of the wavelet coherence may yield a time-varying nexus between two variables over both the time and frequency simultaneously, as well as underscoring the strength of the dependence structure. However, this enables one to distinguish between the short-term (high frequency dynamics) and the long-term (low frequency dynamics) dependence.

The gains from using this method are twofold. First, the CWT methodology addresses the issue of structural breaks in the data because the methodology is particularly useful when working with non-stationary time series containing various outliers, volatility clustering, many structural breaks, etc. Second, this approach enables us to reveal interactions at various time horizons that can hardly be observed using any other traditional econometric tool. Moreover, the CWT method is non-parametric, implying that the estimation methodology and parameters have no effect on it, making it possible to assess the co-movement between economic growth and environmental quality at a higher level of comprehension. Thus, our analysis provides a deeper understanding of the relationship between economic growth and carbon emissions and results in more informed policymaking which may be utilized to disconnect economic growth from growing carbon dioxide emissions.

Our findings reveal several important results on the interconnection and lead-lag causalities between carbon dioxide emissions and GDP per capita in the G7 countries. First, the results indicate a higher coherency between environmental degradation and economic growth for all G7 countries across different time horizons, and this high interdependence was more pronounced in the short-term horizon. Second, in the majority of time periods and frequency bands, we highlight feedbacks for carbon dioxide emissions versus GDP per capita, confirming the 'feedback hypothesis' across the time scale (bidirectional causality between carbon dioxide emissions and GDP per capita via wavelet scales). These results underscore the need for policy making that considers the various time horizons to form effective policies.

The rest of the paper is structured as follows. Section 2 provides a theoretical underpinning of the CO2 emissions and economic growth. Section 3 provides an overview of related literature. Section 4 outlines the empirical methodology used in the paper. Section 5 presents the data and discussion of the results, and Section 6 concludes the study.

2. CO_2 Emissions and Economic Growth: Theoretical Underpinnings

While the empirical literature on environmental and energy economics is replete with studies on the empirical relationship between CO_2 emissions and economic growth, from a theoretical standpoint, there are several reasons why we should expect a relationship between CO_2 emissions and economic growth. From a purely economic perspective, industrialization and rapid economic growth lead to pollution and environmental degradation. However, Grossman and Krueger (1995) argue that the relationship between CO_2 emissions and economic growth is far from linear. They decomposed the relationship between CO_2 emissions and economic activity into three separate effects: scale effect, composition effect, and technique effect. The scale effect underscores that increased economic activity due to rapid economic growth increases pollution and deteriorates environmental quality if no structural or technological change occurs in the economy. Therefore, economic growth has a detrimental impact on environmental quality via the scale effect. The composition effect, on the other hand, highlights the positive impact of economic growth on environmental quality arising due to the structural changes in the economy.

As the country progresses on the developmental ladder, the structure of the economy changes, transitioning from agriculture to manufacturing, from manufacturing to high-tech manufacturing, and eventually to the service industry. As the economy transitions from agriculture to resource-intensive manufacturing industries in the earlier stages of economic development, it emits a significant amount of carbon dioxide emissions and pollutes the environment. However, in the later stages of economic development, the economy transitions from resource-intensive manufacturing industries to high-tech manufacturing and service industries, resulting in the production of cleaner goods and services, reducing the negative impact of economic growth on the environment. Finally, the technique effect states that when a country enjoys sustained economic growth, it can afford to adopt cleaner and green technologies, which helps to improve environmental quality. Concisely, in the early stages of economic development, pollution is likely to increase because the scale effect is dominant. However, after economic development reaches a certain level, the composition and technique effects overtake the scale effect, and pollution is expected to decrease significantly. This theoretical framework is also the basis for the existence of an inverted U-type relationship between CO_2 emissions and economic growth, often called the Environmental Kuznets Curve (EKC) hypothesis.

3. Review of Related Literature

The relationship between CO_2 emissions and economic growth has been widely explored in the extant literature, especially in the context of EKC. However, the reported empirical evidence remains ambiguous regarding the possibility of its existence. A number of empirical studies have found support for its existence. For instance, Holtz-Eakin and Selden (1995) find an EKC for carbon dioxide emissions per capita using panel data for 130 countries from 1951–1986. In a graphical analysis, using panel data for 12 developed countries from 1950–1992, Unruh and Moomaw (1998) find an EKC for carbon dioxide emissions. De Bruyn et al. (1998) also provide evidence of the existence of the EKC hypothesis for the Netherlands, the UK, the USA, and Western Germany, and Galeotti and Lanza (1999) do so for 110 countries. More recently, several studies used more complex statistical methods to test the EKC hypothesis without finding qualitatively different results (Halkos and Tsionas, 2001; Bertinelli and Strobl, 2004; Martinez-Zarzoso and Bengochea-Morancho, 2004; Bradford et al., 2005; Liu, 2005; Vollebergh et al., 2005; Galeotti et al., 2006; Song et al., 2008; Fodha and Zaghdoud, 2010; Shahbaz et al., 2013; Bassetti et al., 2013; Aeknarajindawat, Suteerachai and Suksod, 2020; Bekun, Agboola and Joshua, 2020; Rana and Sharma, 2019; Rauf et al., 2018; Wasti and Zaidi, 2020 and Zambrano-Monserrate et al., 2016). On the other hand, several studies find limited evidence of the presence of EKC for CO_2 emissions (e.g., Dinda, 2004; Tol et al., 2009; He and Rickard, 2010; Wang et al., 2011; Adedoyin, Awosusi and Adeshola, 2020; Dogan and Inglesi-Lotz, 2020; Koc and Bulus, 2020; Mikayilov, Galeotti and Hasanov, 2018; Sarkodie, 2018 and Wang et al., 2019). In addition, some studies provide evidence of a monotonically increasing or decreasing relationship between income and environmental quality (e.g., Torras and Boyce, 1998; Azomahou et al., 2005; Plassmann and Khanna, 2006; Du et al., 2012; Al-mulali et al., 2015).

As noted earlier, among the G7 countries, most of the studies investigated the relationship between income and the environment in the context of the U.S., France and Canada. De Bryuyn (1998) examined the nexus of economic growth versus three types of emissions—carbon dioxide, nitrogen oxide (NOx) and sulfur dioxide (SO_2) emissions—in four developed nations, namely, the Netherlands, the UK, the USA and Western Germany. The study's results suggest that emissions are positively correlated with economic growth and that emissions reductions may have been achieved because of structural and technological changes in the economy. Millimet et al. (2003) examined the income-emissions nexus focusing on NOx and SO_2 emissions. Using US state-level panel data from 1929–1994, the study confirms the existence of the EKC hypothesis. Similarly, Khanna and Plassmann (2004) investigated the validity of EKC for the U.S. in terms of five air pollutants: SO_2, PM_{10}, CO_2, O_3 and NOx. Employing nationwide household survey data collected in 1990, the study revealed that the demand for better environmental quality that could decrease pollution is missing even for high-income households in the U.S. This finding suggests that household income in the US has not reached the turning point at which more green products and services are demanded. Soytas et al. (2007) explored the impact of output and energy consumption on carbon dioxide emissions in the U.S. from 1960–2004. Using the Granger causality test, the study finds that income does not Granger-cause carbon emissions in the long run.

Day and Grafton (2003), using data for Canada, attempted to examine whether the increase in GDP per capita is related to reduced environmental degradation. Employing a standard reduced-form model, the study reveals that carbon monoxide declines with an increase in real GDP per capita. Additionally, causality tests show a bidirectional causal relationship between income and the environment. Lantz and Feng (2006), using provincial panel data from 1970–2000 for the Canadian economy, evaluated the effect of income, population and technology on carbon dioxide emissions. The study rejected the existence of the EKC hypothesis for Canada because it finds an insignificant relationship between changes in GDP/capita and carbon dioxide emissions. Similar findings were confirmed by He and Richard (2010) from 1948 to 2004. Jaunky (2011), on the other hand, found a positive and significant long-term relationship between economic growth and carbon dioxide emissions in Canada from 1980–2005. In contrast, Hamit-Haggar (2012) reported no significant relationship between GDP per capita and greenhouse gas emissions for Canada from 1990 to 2007. However, a short-term unidirectional relationship runs from GDP per capita to greenhouse gas emissions.

Ang (2007) provides evidence of a dynamic causal relationship between economic growth and pollutant emissions in the long term for France from 1960–2000. The causality tests support the argument that economic growth brings growth in energy use, as well as growth within pollution in the long-term. Iwata et al. (2010) test the existence of the EKC in the context of France by considering the role of nuclear energy in electricity production in relation to the function of carbon emissions. The results confirm the validity of the EKC hypothesis for France. Baek and Pride (2014) contribute to the debate by examining the income–nuclear energy–carbon dioxide emissions nexus in the top six nuclear-generating countries: the U.S., France, Japan, Canada, Spain, and Korea. Their results indicate that in the U.S. and France, income growth has a favorable effect on environmental quality in the long run, whereas in Japan and Spain, the results suggest that income growth leads to environmental degradation in the long run. Furthermore, a statistically insignificant relationship exists between income and the environment in Canada and Korea. Using time-varying Granger causality for G7 countries, Ajmi et al. (2015) re-assessed association of income growth, energy consumption and carbon emissions. The empirical results provide no evidence of the nexus for economic growth-carbon emissions pair for the US, France, Germany and Canada, whereas in Japan and Italy, economic growth brings carbon dioxide emissions. Dogan and Ozturk (2017) confirmed the absence of the EKC hypothesis in the USA by incorporating the role of renewable and non-renewable energy consumption.

In a similar vein, several studies have explored the CO_2 emissions and economic growth nexus using wavelet analysis and other similar approaches in order to understand the short- and long-term interactions between these variables. For instance, Adebayo (2020) studies the causal effect of trade liberalization, energy use, gross capital formation, and real growth on CO_2 emissions in Mexico using ARDL-based bounds and wavelet coherence approaches. The study shows that the EKC hypothesis holds for the case of Mexico and that the impact of economic growth and environmental degradation indicators on CO_2 emissions is positive and significant. Closely related, Kirikkaleli (2020) argues that economic growth is a robust variable for predicting CO_2 emissions in China, the largest carbon emitter. The study finds a significant correlation between economic growth and CO_2 emissions throughout the 2000s, both in the short and medium term.

Adebayo and Akinsola (2021) used time-series data from Thailand to investigate whether economic growth and energy consumption lead to CO_2 emissions. Using the wavelet coherence approach, the study reports that changes in economic growth led to changes in CO_2 emissions. In contrast, using the same techniques, Adebayo and Kalmaz (2021) determines an insignificant link between gross capital formation and CO_2 emissions in Egypt. Their analysis reveals that energy usage and CO_2 emissions are positive and significant correlated while the level of urbanization has no effect on greenhouse gas emissions. Jammazi and Aloui (2015) use the data on six oil-exporting countries from the GCC region to show a two-way causal relationship between EC and EG and no feedback effect between EC and CO_2 emissions. In the region, GHG and CO_2 emissions present a bidirectional causal relationship. In this regard, the authors conclude that the GCC authorities should adopt more sustainable energy policies that include increased investment in energy efficiency measures.

Studying the South African economy, Adebayo and Odugbesan (2021) argue that financial development positively impacts CO2 emissions. Particularly, while urbanization has a negative relationship with CO_2 emissions, real growth leads to positive changes in greenhouse gas emissions. In Turkey, Kalmaz and Kirikkaleli (2019) documented similar results using the wavelet coherence technique and ARDL estimators. Precisely, CO_2 emission is significantly triggered by energy consumption, economic growth and urbanization. In the case of the three most polluting countries in the world, namely the United States, China and India, Khochiani and Nademi (2020) showed that in the US and China, GDP and CO_2 emissions are positively correlated. Yet, for India, although there is a significant positive relationship between GDP and CO_2 emissions, the link between GDP and energy consumption is not well-defined. Likewise, Zhang et al. (2021) suggest that economic growth, gross capital formation, and urbanization positively impact CO_2 emissions. Furthermore, their wavelet coherence test reveals that there is a significant dependence between CO_2 emissions and economic growth, gross capital formation, and urbanization. Furthermore, the authors document a one-way causality from urbanization to CO_2 emissions, a one-way causality from economic growth to CO_2 emissions, as well as for gross capital formation and CO_2 emissions. Table 1 summarizes the findings of the studies used in the literature review.

Based on the literature review, the relationship between income and environmental quality varies substantially across countries, periods or estimation methods. Moreover, most of the existing studies focus on a relatively small data period of 40 to 50 years and ignore the structural breaks in the data series. Looking at such a small data period might not reveal the turning points in the data required to detect the presence of the EKC hypothesis in the long term. The current study aims to meet these limitations, contributing to the advancement of the literature and having some policy implications.

Table-1: Literature Summary

Study	Objectives	Sample*	Variables	Approach/Method(s)	Major Findings
Iwata, Okada & Samreth (2010).	Estimation of EKC by taking role of nuclear energy in electricity production.	Time Series (1960-2003), France [World Bank]	NE, EP, U, EC	ARDL	The impact of NE on CO2 emissions is significantly negative in both in short run and long in France.
Shahbaz, Mutascu & Azim (2013)	To investigate the dynamic relationship between EG, EC and CO2 emission.	Time Series (1980-2010), Romania [World Bank]	EG, EC	ARDL	The authors found evidence of the existence of EKC both in short run and long run in Romania.
Ang (2007)	To examine the dynamic causal relationships between PE, EC, and OP.	Time Series (1960–2000), France [World Bank]	CE, PE, EC & OP	Multivariate Vector Error-Correction Modelling Techniques	The authors found that output growth causes CO2 emissions and energy consumption and the evidence of the existence of EKC in France.
Du, Wei & Cai (2012)	To investigate the DF, ET and RP of China's CE based on a provincial PD set.	Provincial Panel Data (1995–2009), China [?]	TP, ECS, IS, TO, ED & U	Reduced-Form Econometric Model	The authors found that the estimated results not strongly supported EKC in China.
Bruyn, Van den Bergh & Opschoor (1998)	To find the inverted-U relationship between I and EE from PD over time.	Panel Data (4; 1961–1990), Netherlands, UK, USA & Western Germany [IEA, OECD & World Bank]	I, E, EG, ER & TC	Reduced Form Models	The authors found evidence of the existence of EKC in Netherlands, UK, USA & Western Germany.
Fodha & Zaghdoud (2010)	To investigate the relationship between EG and PE for a small developing country.	Time Series (1961–2004), Tunisia [World Bank]	(CO2), (SO2) & GDP	VAR Model & ECM	The authors found an inverted U relationship between SO2 emissions and GDP in Tunisia.
Dogan & Ozturk (2017)	To explore the influence of (GDP), REC &	Time Series (1980–2014), USA [World	GDP, REC, NREC & CE	ARDL	The authors findings suggest that EKC is not

	NREC on CE for (USA) in the (EKC).	Bank]			exist in USA.
Millimet List & Stengos (2003)	To explore the importance of modeling strategies in estimating the emissions-income relationship.	State Level Panel Data (1985–1994), USA [EPA]	E, I, CE & SE	Semiparametric Partially Linear Regression Model	The authors findings suggest that existence of inverted-U shape in USA.
Kim, Lee & Nam (2010)	To Explore the link between CE and EG in Korea with nonlinear evidence.	Time Series (1992–2006), Korea [KEEI & BOK]	CE, EG & IP	STAR models	The findings of the authors indicate that the growth rate CE and IP exhibit a significant nonlinear asymmetric dynamics.
Iwata, Okada & Samreth (2011)	To investigate EKC hypothesis for CE, by using the panel data of 28 countries by taking NE into account.	Panel Data (28; 1960–2003, 1975–2003, 1974–2003), Argentina, Belgium, Brazil, Bulgaria, Canada, China, Czech Republic, Finland, France, Germany, Hungary, India, Japan, Korea, Lithuania, Mexico, Netherlands, Pakistan, Russian Federation, Slovak Republic, Slovenia, South Africa, Spain, Sweden, Switzerland, Ukraine, United Kingdom, United States [World Bank]	CE, GR, I & NE	PMG	The authors findings indicate significantly negative impacts of NE on CE, CE increase monotonically within the sample period in all cases and GR in CE with I is decreasing in OECD countries and increasing in non-OECD countries.
Galeotti, & Lanza (1999)	A study on carbon dioxide emissions in	Panel Data (110; 1960–1996),	EC, CE and ED	Multi-Equation Models	The authors findings suggest that future global

	developing countries	Developing countries[IEA]			emissions will rise.
Lantz & Feng (2006)	To investigate the macroeconomic forces underlying carbon dioxide (CO2) emissions from fossil fuel use in Canada.	Regional Panel Data (1970–2000), Canada [Stats. Can]	CE, GDP_Capita, Pop, TC	More Flexible Model	The authors results show that the technological and population changes are supported over the commonly hypothesized environmental Kuznets curve for affecting CO2 emissions from fossil fuel use in Canada.
Andersson & Karpestam (2013	To analyze the ST and the LT determinants of EI, CI and SE for eight DE and two EE	Panel Data (10; 1973–2007), Denmark, France, Italy, Netherlands, Spain, Sweden, United Kingdom, United States, China, India [CDIAC, World Bank]	EI, CI & SE	Econometrics Model	The authors results show that there is a difference between the ST and the LT results and the climate policy are more likely to affect emission over the LT than over the ST.
Jaunky (2011)	To test the EKC hypothesis for 36 high-income countries	Panel Data (36; 1980–2005), Antigua & Barbuda, Australia, Austria, Bahrain, Belgium, Brunei Darussalam, Canada, Cyprus, Denmark, Estonia, Finland, France, Greece, Hong Kong China, Hungary, Iceland, Ireland, Israel, Italy, Japan, Korea, Luxembourg, Malta, Netherlands, New Zealand, Norway, Oman , Portugal ,	CE & GDP	GMM, VAR Model & VECM	The analysis of the authors provides evidence of an EKC for Greece, Malta, Oman, Portugal and the United Kingdom and it is observed for the whole panel, that a 1% increase in GDP generates an increase of 0.68% in CO2 emissions in the ST and 0.22% in the LR.

		Singapore, Spain, Sweden, Switzerland, Trinidad & Tobago, UAE, UK, US [?]			
Hamilton & Turton (2002)	To analyses the sources of growth in energy-related greenhouse gas emissions for OECD countries	Panel Data (1982–1997), OECD countries [IEA]	Pop, EG, EI, EC, FF & CI	(?)	The authors found that the across the OECD as a whole, growth in emissions has been mainly due to economic growth (both GDP per capita and population growth), as well as an increase in primary energy required for final energy consumption.
Grossman& Krueger (1995)	To examine the reduce form relationship between PCI and various environmental indicators	Panel Data (1982–1997), OECD countries [GEMS]	PCI, UAP, RB, FC & HM	(?)	The authors found no evidence that environmental quality deteriorates steadily with economics growth
Bertinelli & Strobl (2005)	To re-examines the existence of an EKC across the countries	Panel Data (122; 1960–1990), countries [GEMS]	GDP_Capita, SE & CE	SRE	The authors evidence of a bell-shaped link between either SE or CE and GDP/capita. Rather, in contrast to an EKC, the estimate appears to be decidedly linear, environmental pollution increasing with country wealth for low levels of GDP/capita, and becoming flat thereafter.
Coondoo & Dinda (2002)	To examine an inverted U-shaped relationship between the LP & LI	Panel Data (88; 1960–1990), 88 countries [Penn World Table]	CE, LP & LI	GCTRE	The authors observed that for individual country groups well-defined and distinctive patterns of causality prevail.

Halkos& Tsionas (2001)	To test the existence of EKC	Cross sectional data	PCI, PD, GDP, IM	Bayesian Markov chain Monte Carlo methods	There is a monotonic relationship between environmental degradation and income and thus rejects the existence of an EKC.
Liu (2005)	Estimation of a simultaneous equation system in which GDP and CO2 emissions are jointly determined	Panel data (1975-1990), 24 OECD countries	GDP, CO2, E, C, L, T, K, pop,	regression	energy consumption in the regression implies a negative relation between income and CO2 emissions
Hamit-Haggar (2012)	To investigate the long-run and the causal relationship between greenhouse gas emissions, EC and EG	Cross sectional data (1990-2007), 21 Canadian industrial sectors [CIEEDAC]	EC, EG, greenhouse gas emission, output growth	regression	EC has a positive and statistically significant impact on greenhouse gas emissions and a non-linear relationship is found between greenhouse gas emissions and EG.
Dinda & Coondoo (2006)	To investigate of the causality issue of income–emission relationship	Panel data (1960-1990), 88 countries [CDIAC]	PCCO2, PCGDP	Engle–Granger bivariate cointegration analysis framework	There is cointegrating relationship between the variables concerned (PCCO2 and PCGDP) for all the country-groups.
Al-Mulali, Saboori & Ozturk, (2015)	To check for the presence of the EKC hypothesis	Time series data (1981-2011), Vietnam [World Bank]	PCCO2, EC, GDP, L, K	ARDL	The EKC hypothesis does not exist
Shahbaz, Shahzad & Mahalik (2018)	To examine the effects of globalization on CO2 emissions	Time series data (1970-2014), japan[World Bank]	CO2, GDP, EC, G	ARDL	There is a threshold asymmetric cointegration between variables, and a positive and negative shocks arising from globalization increase carbon emissions
Baek & Pride (2014).	To explore the relationship between income,	Time series data, five nuclear states,	PCCO2, NE, PCGDP	CVAR	NE and CO2 emissions have a negative long-run

	nuclear energy and CO2 emission				relationship for all five countries, i.e.; NE tends to reduce CO2 emissions.
Adebayo (2020)	To study the causal effect of trade liberalization, energy use, gross capital formation, and real growth on CO2 emissions	Annual data (1971-2016) in Mexico	CO2, EG, EC, GKF	ARDL, WCA	EKC hypothesis holds in Mexico. Positive effect of economic growth and environmental degradation indicators on CO2 emissions. Bidirectional causality between economic growth and CO2 emissions, unidirectional causality from CO2 emissions to energy use and from CO2 emissions to gross capital formation.
Kirikkaleli (2020)	To document the ability of economic growth to predict CO2 emissions	Annual data (1950-2016) in China	CO2, EG	WCA and causality tests	Significant correlation between economic growth and CO2 emissions throughout the 2000s (in the short and medium term). However, during the 1980s and 1990s the positive correlation was observed only in the short term. Long-term cointegration link between economic growth and CO2 emissions
Adebayo and Akinsola (2021)	To clarify whether economic growth and energy consumption lead to CO2 emissions	Time-series (1971-2018) in Thailand	CO2, EC, EG	WCA and causality tests	Changes in economic growth led to changes in CO2 emissions. Positive correlation between CO2 emissions, GDP growth and energy usage (short and long-run). Bidirectional relationship

					between CO2 and energy consumption.
Adebayo and Kalmaz (2021)	To determine the link between gross capital formation and CO2 emissions	Annual data in Egypt (1971-2014)	GKF, CO2, EC, U	ARDL	Insignificant link between gross capital formation and CO2 emissions. Energy usage and CO2 emissions are positive and significant correlated. The level of urbanization has no effect on greenhouse gas emissions.
Jammazi and Aloui (2015)	To show the causal relationship between EC, EG and CO2 emissions	Six oil-exporting countries from the GCC region (Saudi Arabia, Oman, Bahrain, Kuwait, United Arab Emirates and Qatar)	EC, EG, CO2, GHG	WCA	Two-way causal relationship between EC and EG and no feedback effect between EC and CO2 emissions. Bidirectional causal relationship between GHG and CO2 emissions.
Adebayo and Odugbesan (2021)	To measure the impact of financial development, urbanization and real growth on CO2 emissions	Annual data of South Africa (1971-2016)	EG, CO2, FD	ARDL and WCA	Financial development positively impacts CO2 emissions. Urbanization has a negative relationship with CO2 emissions. Real growth leads to positive changes in greenhouse gas emissions.
Kalmaz and Kirikkaleli (2019)	To explore the relationship between CO2 emissions, energy consumption, economic growth and urbanization	Annual data of Turkey (1960-2015)	EG, CO2, U, EC	ARDL and WCA	CO2 emission is significantly triggered by energy consumption, economic growth and urbanization.
Khochiani and Nademi (2020)	To document the correlation between GDP and CO2 emissions.	Annual data of the United States, China and India (1971-2013)	GDP, CO2	WCA	The results support the pollution haven hypothesis. In the US and China, GDP and CO2 emissions are positively

					correlated. For India, although there is a significant positive relationship between GDP and CO2 emissions, the link between GDP and energy consumption is not well-defined.
Zhang, et al., (2021)	To detail the impact of economic growth, gross capital formation, and urbanization on CO2 emissions	Annual data of Malaysia (1960-2018)	EG, GKF, U, CO2	WCA	Economic growth, gross capital formation, and urbanization positively impact CO2 emissions. One-way causality from urbanization to CO2 emissions, a one-way causality from economic growth to CO2 emissions, as well as for gross capital formation and CO2 emissions.

Notes: * The order of the information contained in this column relates, respectively, to the number of observations/time period covered in the study, countries covered in the study and sources of data.

The abbreviations used in the table are as follows: Autoregressive Distributed Lag (ARDL), Bank of Korea (BOK), Canadian Industrial Energy End-Use Data and Analysis Centre (CIEEDAC), Carbon Dioxide Information Analysis Center (CDIAC), Carbon Intensity (CI), CO2 Emissions (CE), Cointegrated vector autoregression (CVAR), Country-specific dummy (C), Developed Economies (DE), Driving Forces (DF), Economic Development (ED), Economic Growth (EG), Electricity Production (EP), Emerging Economies (EE), Emission Reductions (ER), Emission Trends (ET), Emissions (E), Emissions Estimated (EE), Energy Consumption (EC), Energy Consumption Structure (ECS), Energy Intensity (EI), Environmental Kuznet Curve (EKC), Environmental Protection Agency's (EPA), Error Correction Model (ECM), Fecal Contamination (FC), Fossil Fuels (FF), Generalized Method of Moments (GMM), Global Environmental Monitoring System (GEMS), Globalization (G), Granger Causality Test Regression Equations (GCTRE), Gross Capital Formation (GCF), Gross domestic product (GDP), Gross Domestic Product Per Capita (GDP_Capita), Growth Rate (GR), Heavy Metals (HM), Income (I), industrial CO2 emission (E), Industrial Production (IP), Industry Structure (IS), infant mortality (IM), Korea Energy Economics Institute (KEEI), Level of Income (LI), Level of Pollution (LP), Lobor force (L), Long-Term (LT), Non-Renewable Energy Consumption (NREC), Nuclear Energy (NE), Organization for Economic Cooperation and Development (OECD), Output (OP), Panel Data (PD), Patent applications (a proxy for technology) (T), Per capita CO2 emission (PCCO2), Per capita GDP (PCGDP), Per Capita Income (PCI), Physical capital stock (K), Pollutant Emissions (PE), Pooled Mean Group (PMG), Population (PoP), Population Density (PD), Reduction Potential (RP), Renewable Energy Consumption (REC), River Basins (RB), Scale Effects (SE), Semiparametric Regression Estimator (SRE), Short-Term (ST), SO2 Emissions (SE), Sulfur Dioxide (SO2), Technological Change (TC), Technology Progress (TP), Trade Openness (TO), United States of America (USA), Urban Air Pollution (UAP), Urbanization (U), Vector Autoregression (VAR), Vector Error-Correction Mechanism (VECM), Gross Capital Formation (GKF), Wavelet Coherence approaches (WCA), Greenhouse gas emissions (GHG).

4. Methodology

Wavelet coherency analysis is considered as one of the most effective approaches that furnish novel look into the co-movement and lead-lag connection of real GDP and carbon dioxide emissions. It enables representing the nexus throughout several time length and via frequencies. This econometric technique is helpful for determining the cross-correlation between growth and carbon dioxide emissions in time-frequency space. Let the two time series for GDP and carbon dioxide emissions, the wavelet coherency ($Q_n^2(s)$) is expressed below:

$$Q_n^2(s) = \frac{S(s^{-1}W_n^{GDP,CO2}(s))}{S(s^{-1}|W_n^{GDP}(s)|^2).S(s^{-1}|W_n^{CO2}(s)|^2)} \tag{1}$$

where S refers to smoothing criterion, i.e., it represents the classical correlation coefficient utilized to measure the wavelet coherence by a coefficient of localization for the correlation in both time and frequency. Indeed, equation 1 may be reformulated in polar expression as following:

$$Q_n^2(s) = |Q_n^2(s)|e^{i\varphi_{GDP,CO2}} \tag{2}$$

The wavelet coherency of two time series ($R_n^2(s)$) is denoted by:

$$R_n^2(s) = \frac{\left|S\left(s^{-1}W_n^{GDP,CO2}(s)\right)\right|^2}{S(s^{-1}|W_n^{GDP}(s)|^2).S(s^{-1}|W_n^{CO2}(s)|^2)} \tag{3}$$

We used 1000 replications in the Monte Carlo methods to find the statistical level of significance of the wavelet coherence at the 5% level of significance; therefore, we require to find out the confidence interval of phase difference or the phase relation between two time series. Referring to equation 2, the angle ($\varphi_{GDP,CO2} = \varphi_{GDP} - \varphi_{CO2}$) is nominated the phase difference. The key benefit of the phase difference is that it cannot be influenced by the smoothing choice (Aguiar-Conraria and Soares 2011). It may be written as follows:

$$\varphi_{GDP,CO2} = tan^{-1}\frac{I\{W_n^{GDP,CO2}\}}{R\{W_n^{GDP,CO2}\}}, \quad \varphi_{GDP,CO2} \in [-\pi, \pi] \tag{4}$$

The imaginary and real parts are designated by I and R, respectively, of the smooth power spectrum. The phase connection for the two time series is characterized using path difference, which is considered useful. The time series shifts together with a given frequency if phase-difference values range to zero. The series shift in phase if $\varphi_{GDP,CO2} \in [0, \pi/2]$ when the series GDP is led by carbon dioxide emissions. In contrast, if $\varphi_{GDP,CO2} \in [-\pi/2, 0]$, GDP leads carbon dioxide emissions. Additionally, an anti-phase relation is shown if $\varphi_{GDP,CO2} \in [\pi/2, \pi]$; in that case, GDP causes carbon dioxide emissions, and carbon dioxide emissions cause GDP if $\varphi_{GDP,CO2} \in [-\pi, -\pi/2]$. All over this study, we empirically measure the causality interplays and connection between carbon dioxide emissions and GDP per capita.

5. Empirical analysis and discussion

5.1. The data and summary statistics

We collected annual time series on per capita GDP and per capita CO2 emissions (in metric tons) for the G7 countries during the period covering 1820-2015. The data is sourced from the World Development Indicators (WDI) database. Tables A.1 – A.7 in the Appendix A display the basic descriptive statistics of the per capita GDP and per capita CO2 emissions for US, Canada, France, Germany, Italy, UK, and Japan, respectively. As can be seen from Tables A.1 – A.7, on average, the per capita GDP is high in all the G7 economies, an indication of the high level of economic development. As expected, the standard deviation of the per capita GDP series is too large due to the high level of income in the G7 countries. Further, the mean values of per capita CO2 emissions are very low ranging from 0.595 metric tons in Italy to 2.925 metric tons in US. In addition, it is worth noting that the US still emits the highest mass of CO2 during the whole period under concern.

Following Gencay et al. (2002, 2005), Nason and Silverman (1995), Coifman and Donoho (1995), and Daubechies (1992), the wavelet transforms guarantee that the resulting wavelet series be stationary and thus protects us from the issues caused by non-stationarity. Furthermore, we used annual time series that are much less noisy than monthly, weekly, or daily data. In Figs. A.1 – A.7, we display the evolution of the per capita GDP and per capita CO2 emissions respectively for US, Canada, France, Germany, Italy, UK, and Japan.

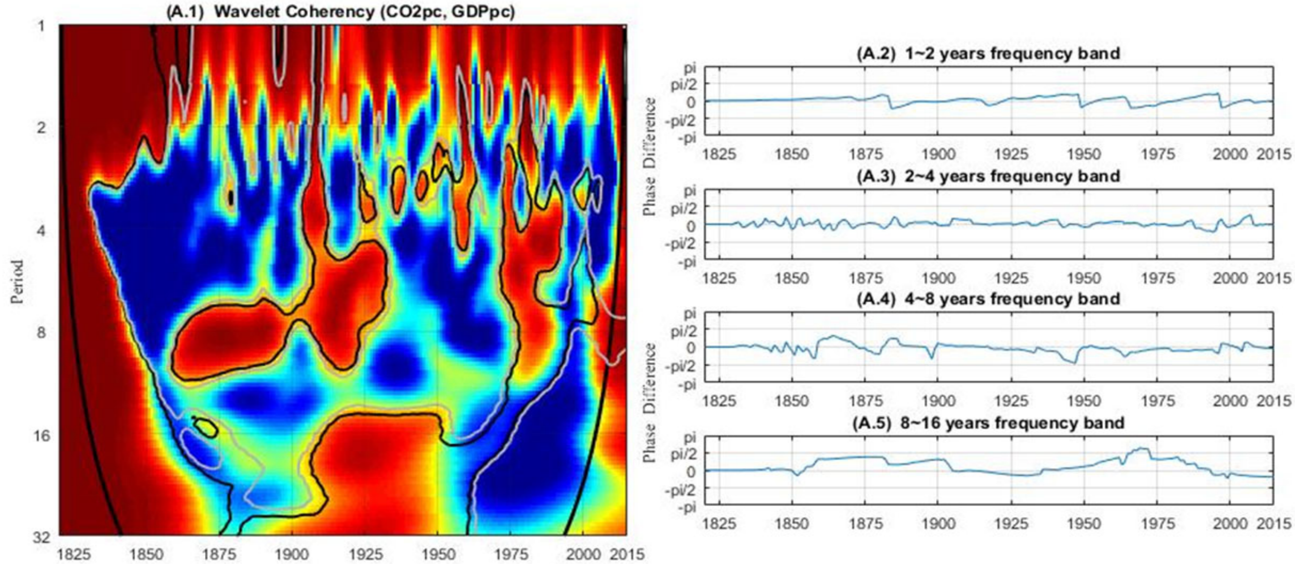
5.2. Discussion of the results

The wavelet coherency framework allows us not only to understand the dynamics of dioxide carbon emissions versus GDP per capita over time but also to see how the carbon dioxide emissions–GDP per capita nexus varies across different frequencies. The wavelet coherency is one of the best tools for dealing with the time-frequency interconnection of dioxide carbon emissions towards GDP per capita.

5.2.1. Evidence from USA

Fig. 1 depicts the wavelet coherency and phase differences for carbon dioxide emissions-GDP per capita pair in the United States. The wavelet coherency analysis quantifies the nexus for carbon dioxide emissions versus GDP per capita in the United States at lower and higher frequencies from 1820–2015. From Fig. 1, it can be seen that dioxide carbon emissions and GDP per capita have some regions of very high coherency (dark red islands) at the lowest frequency band (1–2 years) from 1820–1860. We also reveal a very high coherency at long-term frequencies corresponding to cycles of periodicity between 8 and 16 years and between 16 and 32 years for the period covering 1820 to 1850. Fig. 1 exhibits, as well, that the carbon dioxide emissions–GDP per capita pair, on the other hand, depicted low coherency regions at middle frequencies (2–4 and 4–8 years' frequency bands). In addition, from 1960–2000 and at the highest frequency band (16–32 years' cycle) we observe a region of very low coherency between carbon dioxide emissions and GDP per capita. Additionally, the coherency between these two variables exhibited a high power of coherency at 1–2 years' frequency bands during the entire sample period under study (we observe a deep red island through all of 1820–2015).

Figure-1: The USA Case



Left panel: The wavelet coherence of carbon dioxide - GDP per capita couple. The power of the carbon dioxide–GDP per capita pair coherence is given by the color codification, which ranges between red (high coherency, close to value one) and blue (low coherency, close to value zero). Statistically significant periodicities are displayed with black contours that indicate the 5% significance level obtained through Monte Carlo simulation. The light black dash depicts the edge effect, called the cone of influence. The time is given on the horizontal axis, whereas the vertical axis portrays the period, which is converted to time units (years). Right panel: Phase difference between carbon dioxide and GDP per capita is plotted in blue at four period cycles: 1–2, 2–4, 4–8 and 8–16 years' frequency bands. A phase difference equal to zero implies that carbon dioxide emissions and GDP per capita change simultaneously at a given frequency band; carbon dioxide emissions and GDP per capita move in phase, and carbon dioxide emissions lead GDP per capita if phase-difference values belong to $\left(0, \pi/2\right)$, while GDP per capita leads to phase-difference values included in $\left(-\pi/2, 0\right)$. Conversely, when the phase difference is π or $-\pi$, we say that carbon dioxide emissions and GDP per capita have an anti-phase nexus; if phase-difference values belong to $\left(\pi/2, \pi\right)$, then GDP per capita is leading; carbon dioxide emissions are leading if phase-difference coefficients appertain in $\left(-\pi, -\pi/2\right)$

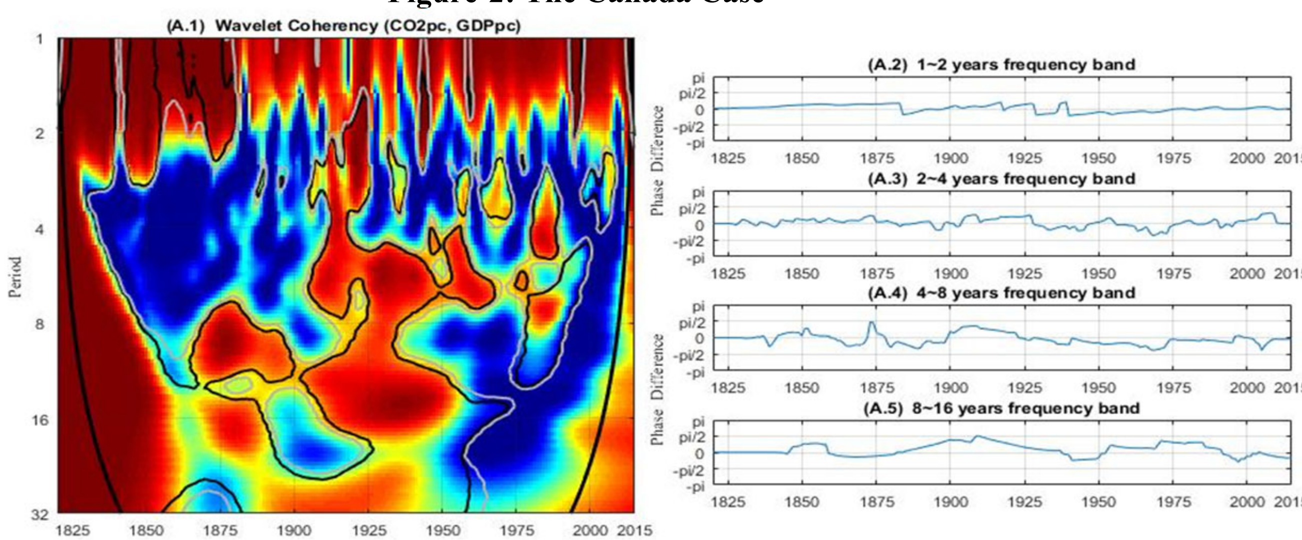
By referring to the coherency map of carbon dioxide emissions and GDP per capita, we revealed that overall, the mid-term behavior of these two variables presented an unstable nexus. However, in some periods and at a given frequency band, we observed high coherencies, and in other periods a low power of coherencies resulted in carbon dioxide emissions-GDP per capita pair. To sum up, the wavelet coherency pattern in the United States showed a relatively high power nexus between carbon dioxide emissions and GDP per capita over different frequency bands and a low (high) coherency registered during a given period was followed by a high (low) coherency in another period. The power of coherency for carbon dioxide emissions-GDP per capita couple moved from one frequency band to another. For instance, from 1925–1950 the low power of coherencies (blue islands) registered at 4–8 and 8–16 years' frequency bands, followed by high intensity of coherencies (red islands) at the 16–32 years' frequency band. Finally, the wavelet coherency analysis between carbon dioxide emissions and GDP per capita evidenced time-varying pockets of the high and low power of interdependency from 1820–2015.

We now turn to the phase-difference analysis of carbon dioxide emissions and GDP per capita pairs plotted in the right panel of Fig. 1. Phase-difference values were close to zero during the first 30 years of our study, indicating that carbon dioxide emissions and GDP per capita move together at the 1–2 years' frequency band (high frequencies) and at the 8–16 years' frequency band (low frequencies). By referring to the phase-difference plot presented at the 8–16 years' cycle, we revealed that carbon dioxide emissions were positively related with GDP per capita, and carbon dioxide emissions were leading from 1850–1910 and 1950–1990. Further, at the majority of 1–2 years' cycles, carbon dioxide emissions led GDP per capita throughout the entire period under study, and the two series move in phase. The exception was for the very short periods where GDP per capita was leading. For instance, carbon dioxide emissions were lagging for the periods approximately 1880, 1950, and 1970 and near 2000. No anti-phase nexus exists for carbon dioxide emissions-GDP per capita couple over the entire time length of study or at the four frequency bands.

5.2.2. Evidence from Canada

Fig. 2 displays the degree of coherence for carbon dioxide emissions-GDP per capita couple in Canada. As shown by red episodes at the 1–2 years' frequency band throughout the entire time length in concern, we highlighted high intensity of co-movement between carbon dioxide emissions and GDP per capita. This demeanor was also registered from 1820–1850 at 4–8, 8–16 and 16–32 year' frequency bands. Fig. 2 also depicted few episodes of low coherence of carbon dioxide emissions versus GDP per capita at the mid- and long-term horizons, observable in dark blue islands throughout the period after 1825. The coherency map shows that carbon dioxide emissions were strongly coherent with GDP per capita from 1900–1925 at frequency bands ranging from 4 to 8 and from 8 to 16 years. Likewise, after 1950 the highest coherence was concentrated at the short term (1–2 years' frequency band), whereas at the medium and long term frequency bands, the coherent pattern between carbon dioxide emissions and GDP per capita was not clear and follows a time-varying structure over a period of 165 years. However, our research findings also reveal few episodes of strong coherences (shown by red areas) and some other episodes of weak coherence for carbon dioxide emissions towards GDP per capita in Canada.

Figure-2: The Canada Case



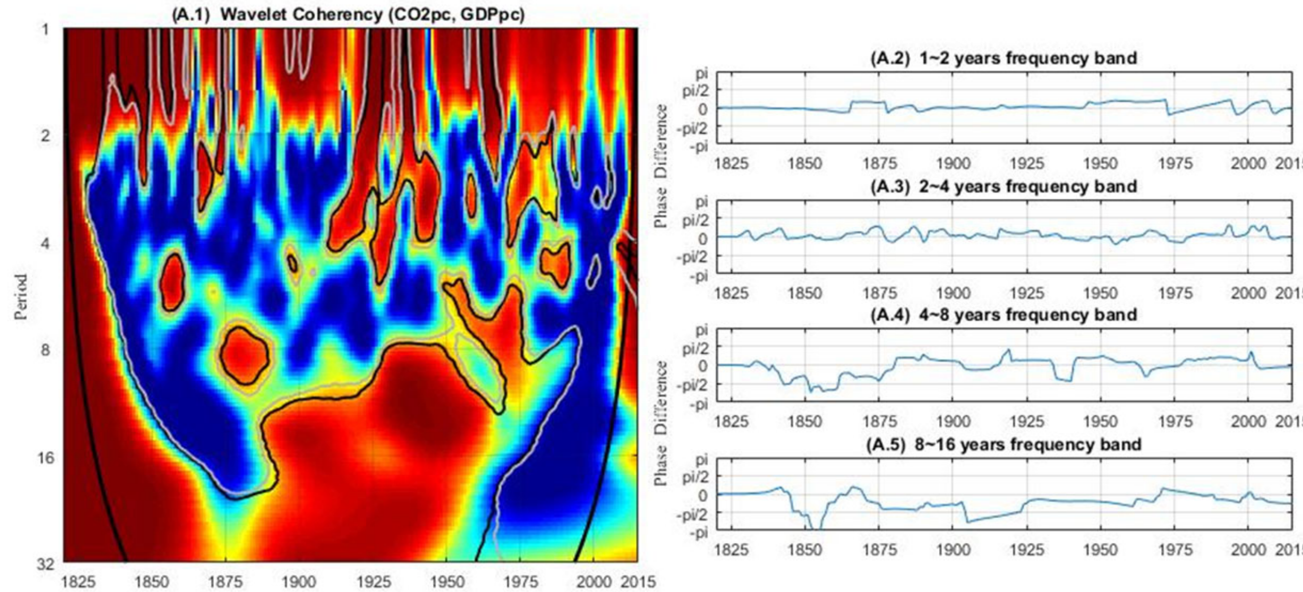
Left panel: The wavelet coherence of carbon dioxide - GDP per capita couple. The power of the carbon dioxide–GDP per capita pair coherence is given by the color codification, which ranges between red (high coherency, close to value one) and blue (low coherency, close to value zero). Statistically significant periodicities are displayed with black contours that indicate the 5% significance level obtained through Monte Carlo simulation. The light black path depicts the edge effect, called the cone of influence. The time is given on the horizontal axis, whereas the vertical axis portrays the period, which is converted to time units (years). Right panel: Phase difference between carbon dioxide and GDP per capita is plotted in blue at four period cycles: 1–2, 2–4, 4–8 and 8–16 years' frequency bands. A phase difference equal to zero implies that carbon dioxide emissions and GDP per capita change simultaneously at a given frequency band; carbon dioxide emissions and GDP per capita move in phase, and carbon dioxide emissions lead GDP per capita if phase-difference values belong to $\left(0, \pi/2\right)$, while GDP per capita leads to phase-difference values included in $\left(-\pi/2, 0\right)$. Conversely, when the phase difference is π or $-\pi$, we say that carbon dioxide emissions and GDP per capita have an anti-phase nexus; if phase-difference values belong to $\left(\pi/2, \pi\right)$, then GDP per capita is leading; carbon dioxide emissions are leading if phase-difference coefficients appertain in $\left(-\pi, -\pi/2\right)$

Our observation of the phase difference between carbon dioxide emissions and GDP per capita, charted in the right panel of Fig. 2, shows that before 1850 the two time series under study move together at 1–2 and 8–16 years' frequency bands (phase-difference values are close to zero before 1850). At the long-term horizon (8–16 year cycle) and from 1880–2000, carbon dioxide emissions and GDP per capita co-move in phase with the leading role of carbon dioxide emissions (phase-difference values belong to $(0, \pi/2)$ indicating that carbon dioxide emissions dominate the nexus pattern. Accordingly, a unidirectional causality occurred at the long-term horizon. According to this finding, we highlight that rising carbon dioxide emissions occurred (more specifically during 1880–1940 and 1950–1990) at longer frequency bands. The phase-difference plot at the 1–2 years' frequency band reveals a prominent finding indicating a bidirectional causality pattern with a strong nexus (shown by dark red regions) between carbon dioxide emissions and GDP per capita after 1950 to the end of the sample period. Accordingly, the rise of carbon dioxide emissions drives the economic growth. A rising emission of carbon dioxide between 1950 and 2015 led to a continuous increase of GDP per capita. Interestingly, Canadian policy makers must pay more attention to the evolution of carbon dioxide emissions in the short-term horizon by finding the most appropriate blueprints and measurements for reducing carbon dioxide emissions and protecting the climate environment.

5.2.3. Evidence from France

Fig. 3 depicts the wavelet coherence map and the lead-lag relationship for carbon dioxide emissions-GDP per capita pair in France. By referring to the coherence map (left panel of Fig. 3), we observe more deep red episodes than blue regions during the entire time length under investigation, revealing strong connection between carbon dioxide emissions and GDP per capita in the short-, mid- and long-term horizons. Likewise, the highest coherences at the 1–2 year's frequency band appeared over the entire time length of our investigation and were registered as a long-term horizon before 1840 (8–16 years' frequency band), during the 1820–1860 (16–32 years' frequency band), 1880–1920 (16–32 years' frequency band), and 1920–1950 (8–16 and 16–32 years' frequency bands). The most important low coherence of carbon dioxide emissions towards GDP per capita was shown at mid- and the long-term horizons from 1960–2010 (we observe a deep blue island during this period). Accordingly, the causality pattern between these two variables was stronger at higher frequencies (1–2 years' frequency band) than at lower frequencies, when the co-movement (causality) was lower.

Figure-3: The French Case



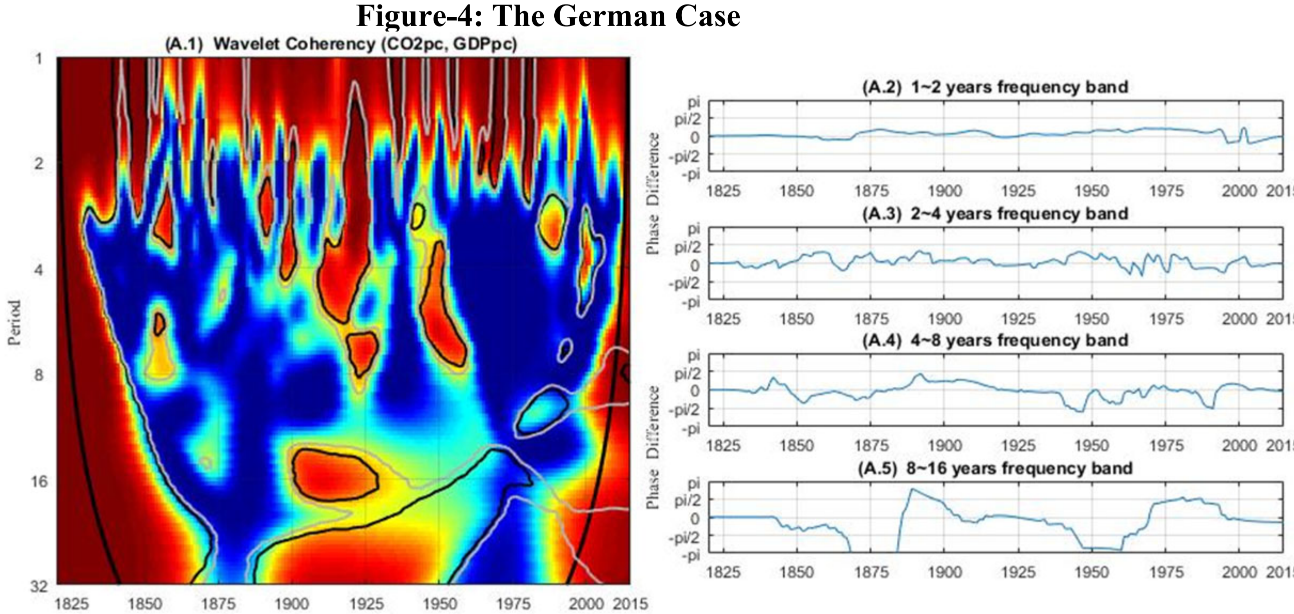
Left panel: The wavelet coherence of carbon dioxide - GDP per capita couple. The power of the carbon dioxide–GDP per capita pair coherence is given by the color codification, which ranges between red (high coherency, close to value one) and blue (low coherency, close to value zero). Statistically significant periodicities are displayed with black contours that indicate the 5% significance level obtained through Monte Carlo simulation. The light black path depicts the edge effect, called the cone of influence. The time is given on the horizontal axis, whereas the vertical axis portrays the period, which is converted to time units (years). Right panel: Phase difference between carbon dioxide and GDP per capita is plotted in blue at four period cycles: 1–2, 2–4, 4–8 and 8–16 years' frequency bands. A phase difference equal to zero implies that carbon dioxide emissions and GDP per capita change simultaneously at a given frequency band; carbon dioxide emissions and GDP per capita move in phase, and carbon dioxide emissions lead GDP per capita if phase-difference values belong to $\left(0, \pi/2\right)$, while GDP per capita leads to phase-difference values included in $\left(-\pi/2, 0\right)$. Conversely, when the phase difference is π or $-\pi$, we say that carbon dioxide emissions and GDP per capita have an anti-phase nexus; if phase-difference values belong to $\left(\pi/2, \pi\right)$, then GDP per capita is leading; carbon dioxide emissions are leading if phase-difference coefficients appertain in $\left(-\pi, -\pi/2\right)$

The lead-lag relationship between carbon dioxide emissions and GDP per capita was displayed in the left panel of Fig. 3. According to phase-difference plots across several frequency bands, the interdependence between carbon dioxide emissions and GDP per capita was not homogeneous over different times and scales. Referring to the first two cycles (1–2 and 2–4 years' frequency bands) the two variables move in phase. More precisely, in the short term (1–2 years' frequency band) carbon dioxide emissions led GDP per capita over the entire time length of study (the majority of phase-difference values belong to $\left(0, \pi/2\right)$. The exception evidenced that GDP per capita was leading approximately 1865, 1875, 1975, 1990 and 2010. Furthermore, phase-difference plots at the 8–16 years' frequency band indicate that GDP per capita dominated carbon dioxide emissions from 1925 to the end of the sample period, suggesting that policy makers in France changed towards the environmental pollution sector. Accordingly, carbon dioxide emissions decreased, and economic development in France had many environmental impacts. Therefore, French policy makers must continue making better policies and advancing more efficient technologies. Lastly, interdependence and causalities between carbon dioxide emissions and GDP per capita exhibited a varying bidirectional behavior across different time and scales.

5.2.4. Evidence from Germany

The wavelet coherence and phases between carbon dioxide emissions and GDP per capita in Germany are mapped in Fig. 4. The map of the coherency given in the left panel of Fig. 4, clearly shows that carbon dioxide emissions were strongly coherent with GDP per capita at the 1–2 years' frequency band during the entire sample period, indicating that throughout the 165 years environmental pollution (carbon dioxide emissions) and economic growth (GDP per capita) in Germany featured a strong short-term interdependency and causality at higher frequencies (lower scales). In particular, from the wavelet coherence map, we observe many statistically significant areas at the 1–2 years' frequency band. We can also infer from the coherency map in Fig. 4 that strong evidence exists for dependence and causalities at lower frequencies (longer scales) from 2000–2015. More precisely, the coherence between carbon dioxide emissions and GDP per capita became strong at the 8–16 and 16–32 years' frequency bands for the last 15 years (shown by the deep red areas).

Figure-4: The German Case



Left panel: The wavelet coherence of carbon dioxide - GDP per capita couple. The power of the carbon dioxide–GDP per capita pair coherence is given by the color codification, which ranges between red (high coherency, close to value one) and blue (low coherency, close to value zero). Statistically significant periodicities are displayed with black contours that indicate the 5% significance level obtained through Monte Carlo simulation. The light black path depicts the edge effect, called the cone of influence. The time is given on the horizontal axis, whereas the vertical axis portrays the period, which is converted to time units (years). Right panel: Phase difference between carbon dioxide and GDP per capita is plotted in blue at four period cycles: 1–2, 2–4, 4–8 and 8–16 years' frequency bands. A phase difference equal to zero implies that carbon dioxide emissions and GDP per capita change simultaneously at a given frequency band; carbon dioxide emissions and GDP per capita move in phase, and carbon dioxide emissions lead GDP per capita if phase-difference values belong to $\left(0, \pi/2\right)$, while GDP per capita leads to phase-difference values included in $\left(-\pi/2, 0\right)$. Conversely, when the phase difference is π or $-\pi$, we say that carbon dioxide emissions and GDP per capita have an anti-phase nexus; if phase-difference values belong to $\left(\pi/2, \pi\right)$, then GDP per capita is leading; carbon dioxide emissions are leading if phase-difference coefficients appertain in $\left(-\pi, -\pi/2\right)$.

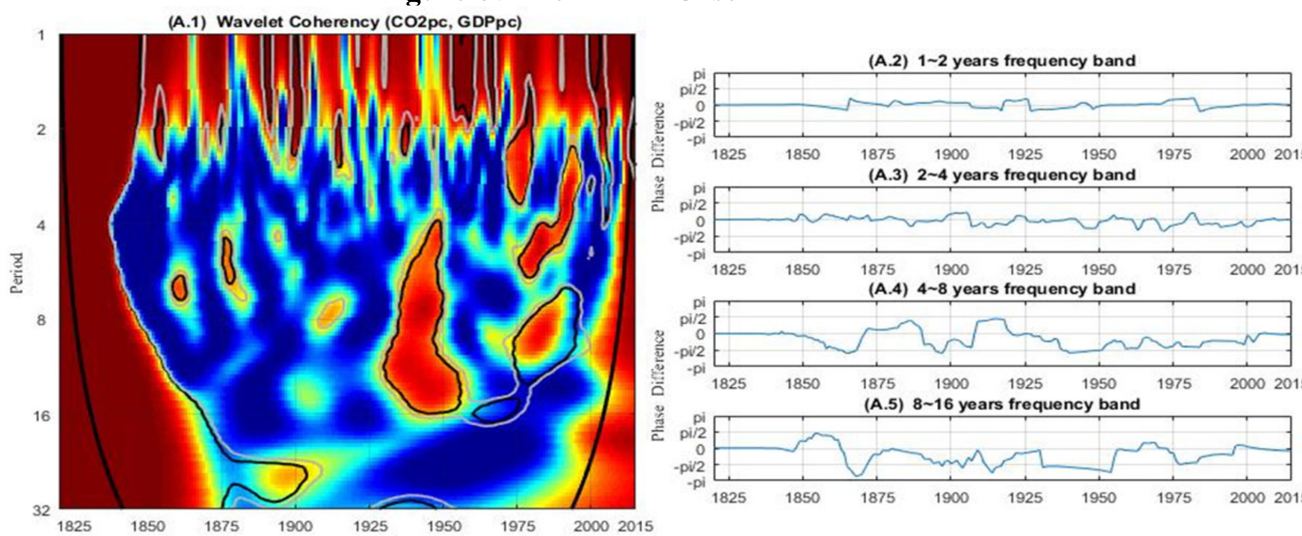
Finally, the coherency map in Fig. 4 shows a weak coherence of carbon dioxide emissions and GDP per capita in mid-term horizon (we observe prominent blue islands at 2–4 and 4–8 years' frequency bands throughout 1840–2010). Exceptions were from 1910–1925 and 1950–1960, with significant red regions at the mid-term horizon. The finding of lower coherence for carbon dioxide emissions-GDP per capita pair registered in mid-term horizon suggests weak interdependences and causalities for these two variables. However, the weak nexus pattern registered at middle frequencies may have been moved to the short- and long-term horizons. The coherency evidenced between environmental pollution (CO_2 emissions) and economic growth (GDP per capita) exhibiting significant strong causalities at higher frequencies (short-term) was followed by weak dependences in the short- or long-term horizons. In connection with the right panel of Fig. 4, the phase difference of the carbon dioxide emissions–GDP per capita pair was plotted in blue lines at the given four frequency bands. For the first three frequency bands, the two series move in phase, with carbon dioxide emissions dominant after 1870 (phase-difference values belong to $\left(0, \pi/2\right)$ at the highest frequencies, 1–2 years' cycles, indicating significant strong positive causalities between environmental pollution and economic growth in Germany with the leading role of carbon dioxide emissions. Furthermore, for the first 50 years of the sample study phase-difference values were zero, which suggests that carbon dioxide emissions and the GDP per capita series move together.

Phase-difference plots, on the other hand, indicate that carbon dioxide emissions were lagging from 2000–2010 in the short-term horizon and from 2000-2015 in the long-term horizon. However, policy makers in Germany used advanced technologies in industrial structure to reduce carbon dioxide emissions. The government must continue applying this policy structure for shorter horizons without changing their current economic development policy. We plotted the phase differences, at 8–16 years' scale, for carbon dioxide emissions-GDP per capita pair in Fig. 4 in the right panel. Based on this period cycle, we found that (i) carbon dioxide emissions and GDP per capita move together over 1820–1840; (ii) carbon dioxide emissions and GDP per capita were positively correlated from 1840–1870, 1925–1940, and 1965–2015; (iii) GDP per capita led carbon dioxide emissions from 1820–1840, 1925–1940, and 1965–1970 and during the last 15 years, while carbon dioxide emissions were leading approximately 1880 and from 1890–1910 and 1970–2000. Accordingly, the lead-lag nexus between the environmental pollution and economic growth in Germany depict a time-varying pattern, and the two time series moved in phase during longer periods, implying the strong dependence and causality for the environment pollution–income pair. Phase analysis at the 8–16 years' frequency band also revealed that carbon dioxide emissions and GDP per capita were out of phase during 1870–1880 and 1940–1960 when GDP per capita was leading. In these periods, we noticed the unidirectional causal interdependence between environmental pollution and economic growth, confirming the strong positive dominance of GDP per capita in the long-term horizon. From 1880–1890, we again observe an out-of-phase situation in which carbon dioxide emissions have a leading causal effect on GDP per capita.

5.2.5. Evidence from Italy

Fig. 5 contains two graphs that display the coherency map (left panel) and phase differences at different frequency bands (right panel) for carbon dioxide emissions and GDP per capita pair in Italy. The coherency map shows that carbon dioxide emissions-GDP per capita pair show a strong and complex connection at different time horizons. However, carbon dioxide emissions were highly correlated with GDP per capita at higher frequencies throughout the sample period under study. Likewise, the carbon dioxide emissions–GDP pair revealed a high nexus pattern in all temporal horizons during the first 30 years (1820–1850). We observe a significant red band of episodes over this period, indicating that the interdependence and the causal structure between environmental pollution and economic growth in Italy from 1820–1850 was at its highest level. The mid- and long-term horizons from 1870–2000 exhibited a weak coherence between carbon dioxide emissions and GDP per capita, indicated by many deep blue islands. After 2010, the highest coherency between the two variables appeared again at lower frequencies (long-term horizon), more precisely, at the 8–16 and 16–32 years' frequency bands.

Figure-5: The Italian Case



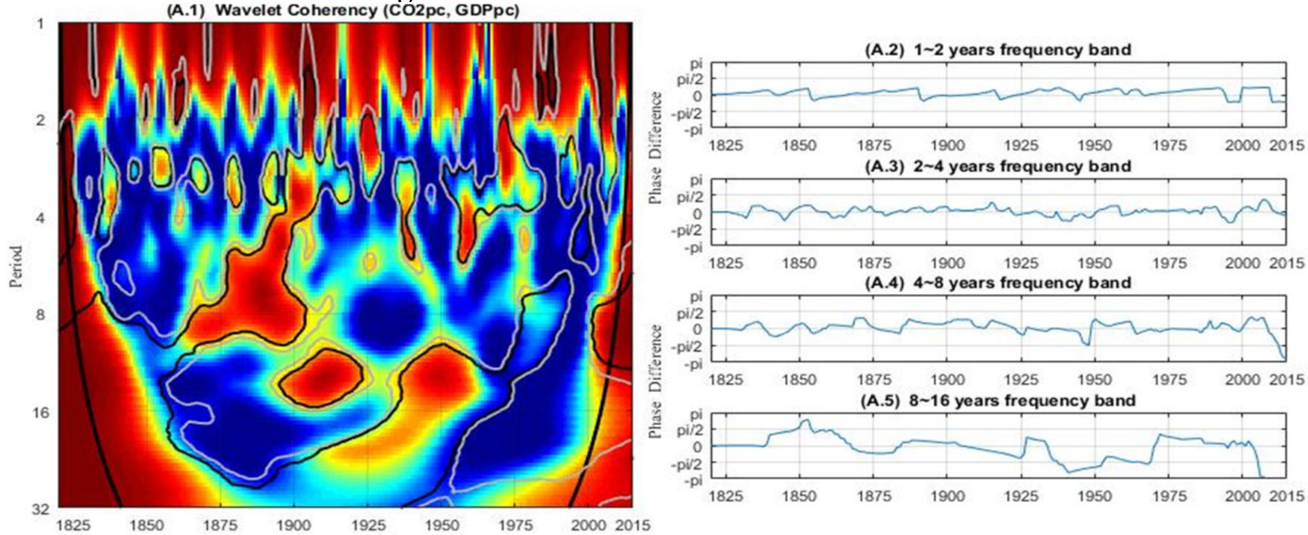
Left panel: The wavelet coherence of carbon dioxide - GDP per capita couple. The power of the carbon dioxide–GDP per capita pair coherence is given by the color codification, which ranges between red (high coherency, close to value one) and blue (low coherency, close to value zero). Statistically significant periodicities are displayed with black contours that indicate the 5% significance level obtained through Monte Carlo simulation. The light black path depicts the edge effect, called the cone of influence. The time is given on the horizontal axis, whereas the vertical axis portrays the period, which is converted to time units (years). Right panel: Phase difference between carbon dioxide and GDP per capita is plotted in blue at four period cycles: 1–2, 2–4, 4–8 and 8–16 years' frequency bands. A phase difference equal to zero implies that carbon dioxide emissions and GDP per capita change simultaneously at a given frequency band; carbon dioxide emissions and GDP per capita move in phase, and carbon dioxide emissions lead GDP per capita if phase-difference values belong to $\left(0,\pi/2\right)$, while GDP per capita leads to phase-difference values included in $\left(-\pi/2,0\right)$. Conversely, when the phase difference is π or $-\pi$, we say that carbon dioxide emissions and GDP per capita have an anti-phase nexus; if phase-difference values belong to $\left(\pi/2,\pi\right)$, then GDP per capita is leading; carbon dioxide emissions are leading if phase-difference coefficients appertain in $\left(-\pi,-\pi/2\right)$.

Lastly, the most prominent finding registered from the coherency map of carbon dioxide emissions–GDP per capita pair was persistence of significant strong causalities in the short-term. The lead-lag nexus for carbon dioxide emissions-GDP per capita couple for Italy was displayed in right panel of Fig. 5. As stated in phase plots, for short and middle frequency bands and during the entire sample period, environmental pollution and economic growth moved in phase with dominance of GDP per capita over the 2–4 years' and 4–8 years' frequency bands. In the short-term (1–2 years' frequency band), phase-difference values were very close to zero during the study's entire sample period, implying that carbon dioxide emissions and GDP per capita moved together for a very long period. Likewise, we observe some exceptions in which the two variables displayed an in-phase situation with the causal influence of carbon dioxide emissions or GDP per capita (with carbon dioxide or GDP leading) but during very short periods. In the long term (8–16 years' frequency band) and after the year 1860, carbon dioxide emissions and GDP per capita clearly moved in an in-phase situation in which GDP per capita led carbon dioxide emissions (phase-difference values belonged to $\left(-\pi/2,0\right)$, suggesting that the economic growth had causal power over environmental pollution in Italy. Finally, the wavelet coherency and phase analysis indicate that the structure of the dependence and causality of carbon dioxide emissions versus GDP per capita in Italy was more complex.

5.2.6. Evidence from the UK

The coherency and phase difference for carbon dioxide emissions and GDP per capita in U.K. are represented in Fig. 6. The coherence map shows the nature of the connection (cointegration) behaves heterogeneously between environmental pollution and economic growth in the U.K. over time-frequency domain. Carbon dioxide emissions and GDP per capita show a high degree of interaction at the highest frequencies (short-term) during the entire time length under investigation (we see red band of regions at the 1–2 years' frequency band, which takes the form of a single highly coherent region). Furthermore, carbon dioxide emissions clearly registered a high degree of co-movement both in the long- and mid-term horizons. For instance, the powerful coherences at middle frequencies were shown from 1870–1890 (at 8-16 years' frequency), 1880–1890 (at 4–8 years' frequency), and 2010–2015 (at 2–4 years' frequency and 4–8 years' frequency). On the other hand, the high level of cointegration at lower frequencies (long-term) appeared throughout the first 30 years (at 8–16 and 16–32 years' frequency) and from 1900–1920 (at 12-16 years' frequency) and 2005–2015 (at 8–16 and 16–32 years' frequency).

Figure-6: The Italian Case



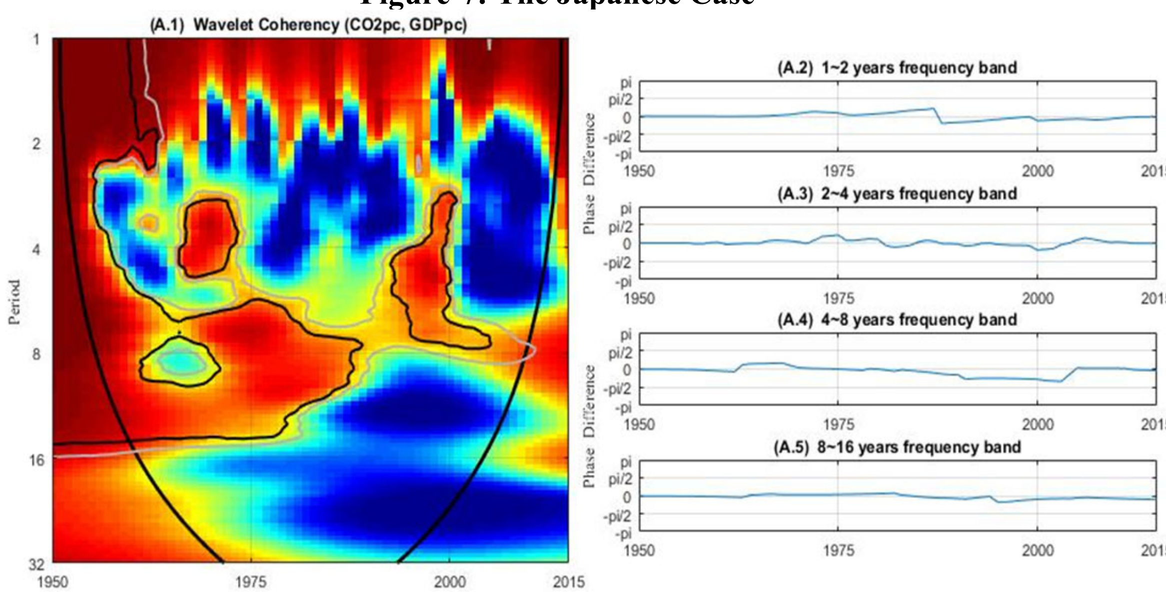
Left panel: The wavelet coherence of carbon dioxide - GDP per capita couple. The power of the carbon dioxide–GDP per capita pair coherence is given by the color codification, which ranges between red (high coherency, close to value one) and blue (low coherency, close to value zero). Statistically significant periodicities are displayed with black contours that indicate the 5% significance level obtained through Monte Carlo simulation. The light black path depicts the edge effect, called the cone of influence. The time is given on the horizontal axis, whereas the vertical axis portrays the period, which is converted to time units (years). Right panel: Phase difference between carbon dioxide and GDP per capita is plotted in blue at four period cycles: 1–2, 2–4, 4–8 and 8–16 years' frequency bands. A phase difference equal to zero implies that carbon dioxide emissions and GDP per capita change simultaneously at a given frequency band; carbon dioxide emissions and GDP per capita move in phase, and carbon dioxide emissions lead GDP per capita if phase-difference values belong to $\left(0, \pi/2\right)$, while GDP per capita leads to phase-difference values included in $\left(-\pi/2, 0\right)$. Conversely, when the phase difference is π or $-\pi$, we say that carbon dioxide emissions and GDP per capita have an anti-phase nexus; if phase-difference values belong to $\left(\pi/2, \pi\right)$, then GDP per capita is leading; carbon dioxide emissions are leading if phase-difference coefficients appertain in $\left(-\pi, -\pi/2\right)$.

The previous findings show a higher degree of interdependence between environmental pollution and economic growth identified at higher frequencies (short-term) becoming less pronounced at lower frequencies (long-term) and vice-versa. This result may be due to the changing structure of U.K. policies toward environmental pollution and economic growth. The lead-lag relationship between carbon dioxide emissions and GDP per capita is depicted in right panel of Fig. 6. The most relevant finding from phase-difference plots is that at all frequency bands, carbon dioxide emissions and GDP per capita moved in phase over the entire sample time length under study (we observe for almost frequency bands that phase-difference values ranged from $-\pi/2$ to $\pi/2$, indicating that the two variables were positively interconnected during the entire periods). The exception is for the long-term (more precisely at the 8–16 years' band) during very short periods when the carbon dioxide emissions and GDP per capita pair uncover an out-of-phase situation with GDP per capita leading carbon dioxide emissions from 1935–1955 and again after 2005 (we see phase-difference values varying from $-\pi$ to π, implying that carbon dioxide emissions and GDP per capita display a negative cause effect). The abovementioned prominent finding (the out-of-phase situation with GDP per capita leading carbon dioxide emissions) indicates that the policy authorities in the U.K. made appropriate environmental policies toward carbon dioxide emissions, and environmental regulations and policy interventions became more important in the long term (also in the short term at the 4–8 years' frequency band from 2010–2015). Furthermore, the last ten years, policymakers in the U.K. restricted the 'pollutant capacities' activity and limited the use of imported 'dirty goods'.

5.2.7. Evidence from Japan

Fig. 7 charts the coherency and phase for the couple carbon dioxide emissions-GDP per capita in Japan. The coherency map and phase-difference plots between carbon dioxide emissions and GDP per capita display some noteworthy differences in their pattern of the interdependence and causal effects compared with the other G7 governments. The coherency map (left panel) in Fig. 7 shows a higher coherency from 1950–1965 (at the 1–2 years' frequency band) throughout the first ten years (approximately) at middle and higher frequencies (at 2–4, 4–8 and 8–16 years' frequency bands). In the very long term, at 16–32 years' frequency, the higher coherency for carbon dioxide emissions and GDP per capita disappeared from beginning of 1975 to the end of the sample study (we see a wide blue area from 1975–2015), implying the weak power of the cause effect between environmental pollution and economic growth in Japan during a long period. Accordingly, the dominance of the blue color both in the mid-term (at 2–4 and 4–8 years' frequency bands from 2000–2015) and in the long-term (at 8–16 and 16–32 years' frequency bands) confirms the lower interdependence and causalities of carbon dioxide emissions over GDP per capita. This finding may indicate that policy authorities in Japan adopted advanced clean technologies in production activities to reduce carbon dioxide emissions. Lastly, the coherency map shows that the cause effect and connection between the studied variables were more persistent in the short-term (at the 1–2 years' frequency band), while this scenario disappears in the mid- and long-term horizons, and the interaction's persistence becomes insubstantial.

Figure-7: The Japanese Case



Left panel: The wavelet coherence of carbon dioxide - GDP per capita couple. The power of the carbon dioxide–GDP per capita pair coherence is given by the color codification, which ranges between red (high coherency, close to value one) and blue (low coherency, close to value zero). Statistically significant periodicities are displayed with black contours that indicate the 5% significance level obtained through Monte Carlo simulation. The light black path depicts the edge effect, called the cone of influence. The time is given on the horizontal axis, whereas the vertical axis portrays the period, which is converted to time units (years). Right panel: Phase difference between carbon dioxide and GDP per capita is plotted in blue at four period cycles: 1–2, 2–4, 4–8 and 8–16 years' frequency bands. A phase difference equal to zero implies that carbon dioxide emissions and GDP per capita change simultaneously at a given frequency band; carbon dioxide emissions and GDP per capita move in phase, and carbon dioxide emissions lead GDP per capita if phase-difference values belong to $\left(0, \pi/2\right)$, while GDP per capita leads to phase-difference values included in $\left(-\pi/2, 0\right)$. Conversely, when the phase difference is π or $-\pi$, we say that carbon dioxide emissions and GDP per capita have an anti-phase nexus; if phase-difference values belong to $\left(\pi/2, \pi\right)$, then GDP per capita is leading; carbon dioxide emissions are leading if phase-difference coefficients appertain in $\left(-\pi, -\pi/2\right)$.

Now we turn to the phase analysis for carbon dioxide emissions-GDP per capita couple displayed in the right panel of Fig. 7. We reveal that the lead-log relationship between environmental pollution and economic growth in Japan exhibited quite similar dynamics at all frequency bands during the entire sample period. We notice that phase differences between carbon dioxide emissions and GDP per capita were very close to zero, which indicates that the two variables under study move together, suggesting that the direction of the interdependence and cause effect connections was almost simultaneous. Accordingly, if anything, the phase-difference values were slightly negative (for instance, at the 4–8 years' frequency band from 1990–2005, when the phase-difference values spanned from $-\pi/2$ to zero), indicating that carbon dioxide emissions were the lagging variable. Hence, the causal nexus went from a GDP per capita to carbon dioxide emissions.

In summary, from the abovementioned findings and discussions for the G7 countries, we can conclude the following prominent results:

i. The coherency maps clearly show that the G7 countries exhibited an approximate similarity in the pattern of nexus causalities between environmental pollution (carbon dioxide emissions) and economic growth (GDP per capita) at all temporal horizons throughout the entire time length under study. The coherency maps display more blue islands in their centers (which corresponds to the mid-term horizon) surrounded by red areas (corresponding to the short- and long-term horizons). Consequently, at middle frequencies, carbon dioxide emissions were weakly connected to GDP per capita. The noteworthy exception is Japan, which yields a different behavior in the relationship dynamics between carbon dioxide emissions and GDP per capita. Accordingly, at coarser scales (in the long term; specifically, at the 16–32 years' frequency band), the carbon dioxide emissions and GDP per capita pair in Japan exhibited lower coherency from 1960 to the ending of the sampling time length, implying the absence of cause-effect relationships between environmental pollution and economic growth.

ii. The first point (i)indicates a slight difference for the carbon dioxide emissions–GDP per capita nexus between Japan and the rest of the G7 countries, suggesting that the long-term carbon dioxide emissions (the rate of environmental degradation) in Japan have been falling more swiftly than for other G7 countries. The reason may be that policy authorities in Japan put more resources at coarser scales (lower frequencies) into attenuating environmental pollution, whereas other G7 countries were focusing more (at the same frequencies) on economic growth (GDP per capita), thereby synchronizing the rate of growth and the cleaning mechanism. Additionally, policymakers in Japan were very cautious and made appropriate decisions towards an environment-economy nexus across different time horizons. Overall, similar (approximately) policy regulations have been adopted in the G7 countries throughout a long period, confirming the so-called ‘concept of policy transfer’.

iii. Based on the phase-difference analysis, carbon dioxide emissions and GDP per capita in G7 economies moved in phase, both in the short term (higher frequencies) and mid term (middle frequencies) during the entire sample period. Also, in the long-term horizon (at the 8–16 years’ frequency band) and for the majority of sample periods the two variables moved in phase. Consequently, the abovementioned finding indicates a time-varying cause effect between environmental pollution and economic growth. For instance, the positive causality from carbon dioxide emissions to GDP per capita registered in one country at higher frequencies (1–2 years’ frequency band) may be due to the swift expansion of the production activities and the use of fossil fuels, such as coal (to generate electricity most of the countries still rely on fossil fuels), which places great pressure on the environment and drives more carbon emissions.

iv. The case of Japan in the phase-difference analysis may lead us to discover that the lead-lag causality between the carbon dioxide emissions and GDP per capita couple exhibited a weak interconnection power, suggesting that policy authorities in Japan employed a clean development mechanism towards environmental degradation by developing green energy sources, such as solar and wind energy.

v. Policymakers must continue following energy policies by increasing renewables consumption. More specifically, at higher frequencies (short-term), they must establish sustainable economic growth along with low carbon emissions.

vi. Wavelet coherency, the phase-difference framework and big data analysis of the interdependence and causality effects between environmental degradation and economic development for the G7 countries support the hypothesis of the so-called ‘neighborhood-effect’. In other words, the disappearance of such interaction and cause effects between environmental pollution and economic growth at a given time horizon (for instance, the short term) and during such period was registered at another time horizon and during a given period, indicating that the persistence of such phenomenon is quite low in the time-frequency domain.

vii. Lastly, we can conclude the existence of a bidirectional causality between environmental degradation and economic growth at several temporal horizons with the dominance of economic growth in Japan (more precisely at coarser scales), implying that the adopted environmental policies in Japan were more appropriate than those used in other G7 countries. Additionally, Japanese policymakers pay more attention to the growth of carbon dioxide emissions.

6. Conclusion and Policy Implications

Over the last few decades, numerous empirical studies have focused on the nexus of and cause-effect interplays between economic growth and the environment to assess climate change globally, with considerable interest paid to the temporal domain framework only. However, the temporal domain approach suffers from a lack of important information about long-term patterns. Therefore, this fundamental loss of information might be very important for energy economists, environmentalists, and climate policymakers globally to design environmental policies well. Very few empirical studies were devoted to an examination of the environment-economy nexus via the time-frequency domain.

To appropriately describe and better understand the nexus between economic growth and environmental pollution (carbon dioxide emissions), we applied a time-scale paradigm (wavelet coherency) to a big data analysis using a large available dataset covering more than 165 years. To the best of our knowledge, this empirical study is the first research focusing on the analysis of the co-movement and causal interplays between environmental degradation and economic growth via a time-frequency space. The findings of our empirical study based on wavelet coherency and phase differences yield many important results about the interconnection and lead-lag causalities between carbon dioxide emissions and GDP per capita in the G7 countries. First, we unveil a higher coherency between environmental degradation and economic growth for all G7 countries across different temporal horizons, and this high interdependence was more pronounced in the short-term horizon. This finding is generally in line with previous results that uncover a significant positive effect from economic growth to environmental degradation in the short term (Shahbaz et al., 2018). However, Shahbaz et al. (2018) noticed that at higher frequencies (in the short term), high levels of economic growth increase environmental pollution. Clootens (2016) showed that an increase in public expenditure has a positive effect on an environmental level of an emerging economy.

The interdependence and cause-effect interplays between environmental degradation and economic growth in the G7 were miscellaneous across different time horizons. In the majority of time periods and frequency bands, we underline feedbacks between carbon dioxide emissions and GDP per capita confirming the ‘feedback hypothesis’ across the time scale (a bidirectional causalities for carbon dioxide emissions and GDP per capita via wavelet scales). In light of the abovementioned finding, this result provides important policy implications for the G7 countries. However, wavelet coherency and phase analysis provide better understanding for climate policymakers and environmentalists. These understandings can help them appropriately intervene (the time horizon of intervention) and design effective policies (the effectiveness of policies and their persistence) incorporating the causal interplay of carbon dioxide emissions and economic growth by not directly determining the environment-economy paradigm but by using suitable environmental policies to influence the direction and content of this paradigm. However, at the short-term horizon it is recommended for policymakers to regulate the activity of “pollutant capacities” and control the use imported “dirty goods” in order to reduce carbon dioxide emissions (Mutasco, 2018).

Based on our findings, we recommend enhancing the environmental pollution–economic growth pair as follows. Policy authorities in G7 countries should strengthen economic inter-cooperation both in the short and long term. In particular, environmentalists and policymakers in the countries under study should pay more attention at higher frequencies (short-term) by better decision-making towards the clean development mechanism (reducing carbon dioxide emissions, developing green energy sources and controlling climate change). Thus, building novel economic systems such as investing in green technologies are the major policy challenges for G7 governments, which is more suitable in the short-term as well as in the long-term. Furthermore, G7 authorities may design efficient policy instruments for instance by imposing more short-term taxation on dioxide carbon consumption.

Acknowledgments

The authors gratefully acknowledge the Editor and the anonymous referees for their useful comments and suggestions which helped us improve this paper. Any shortcomings are our sole responsibility.

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Appendix A.

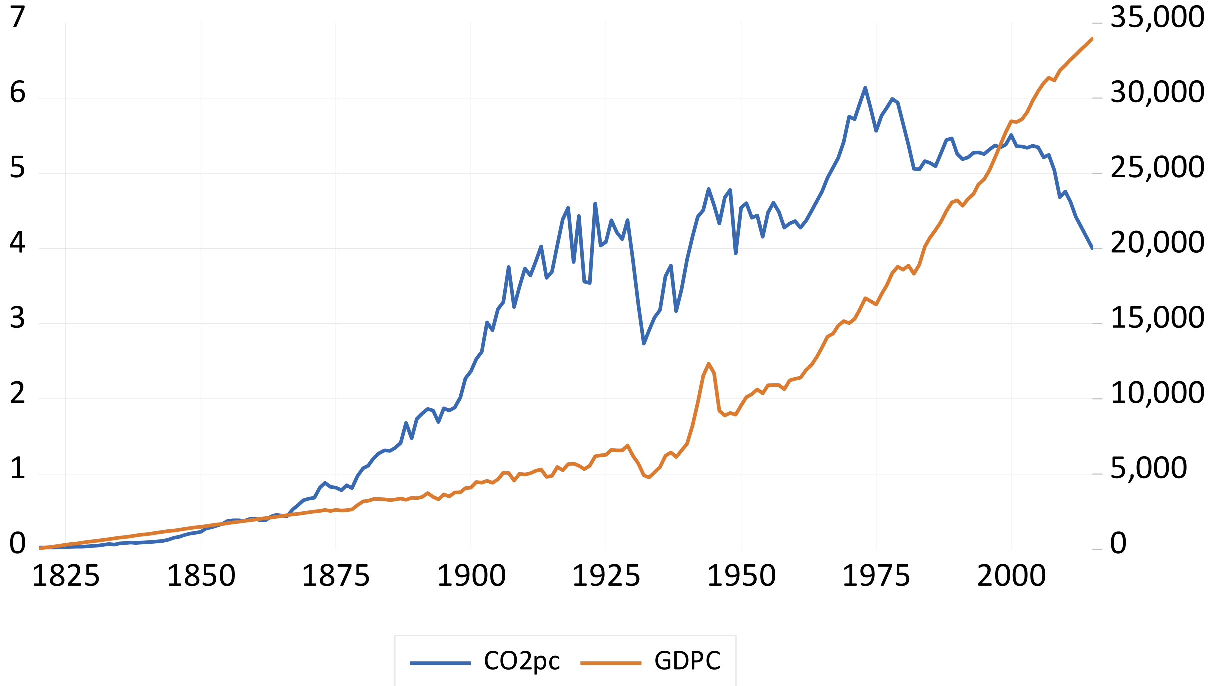

Fig. A.1. Evolution of per capita GDP and per capita CO2 emissions in US.

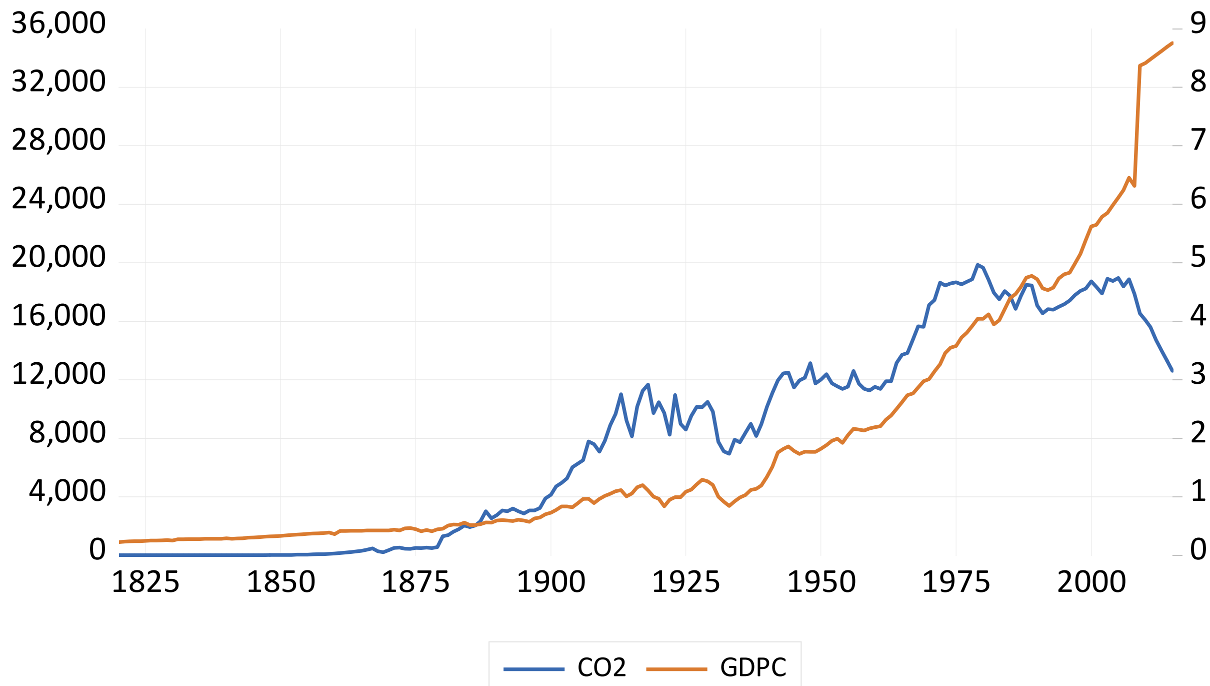

Fig. A.2. Evolution of per capita GDP and per capita CO2 emissions in Canada.

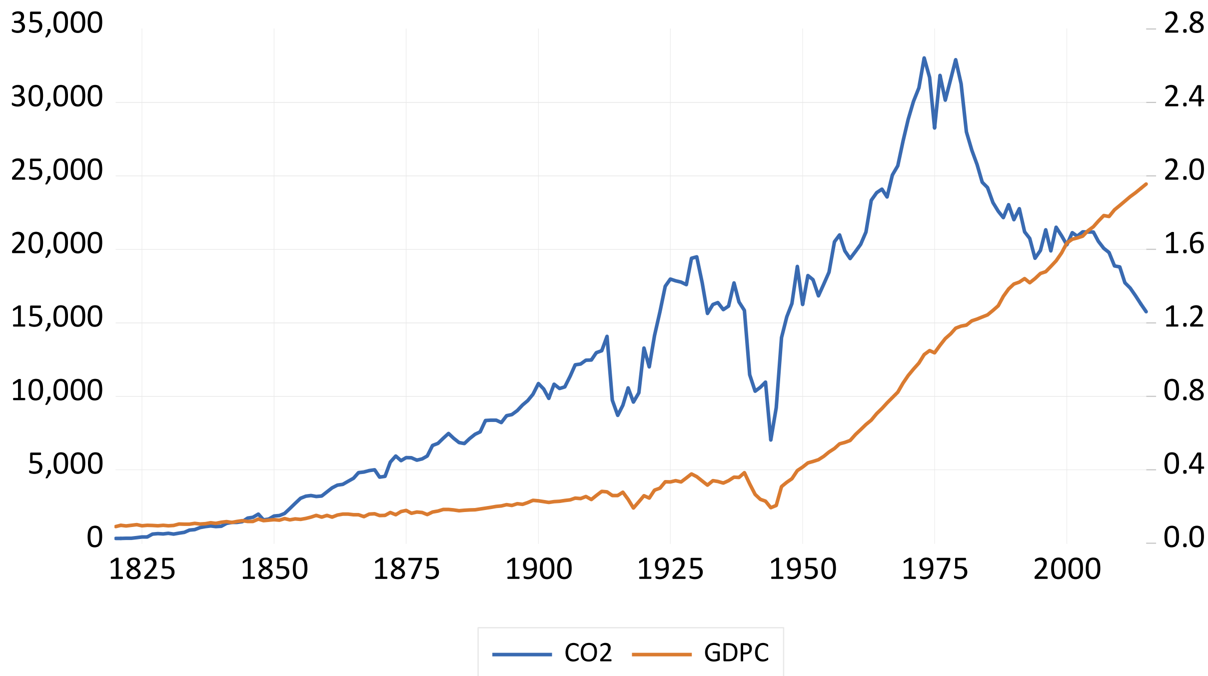

Fig. A.3. Evolution of per capita GDP and per capita CO2 emissions in France.

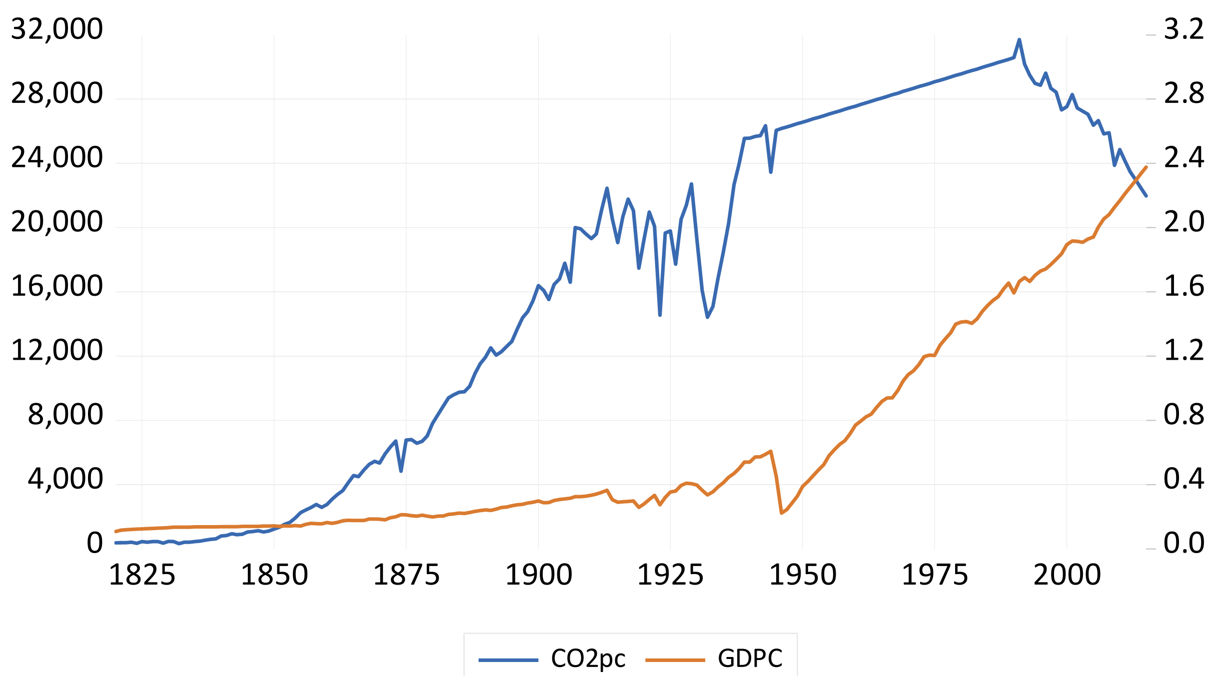

Fig. A.4. Evolution of per capita GDP and per capita CO2 emissions in Germany.

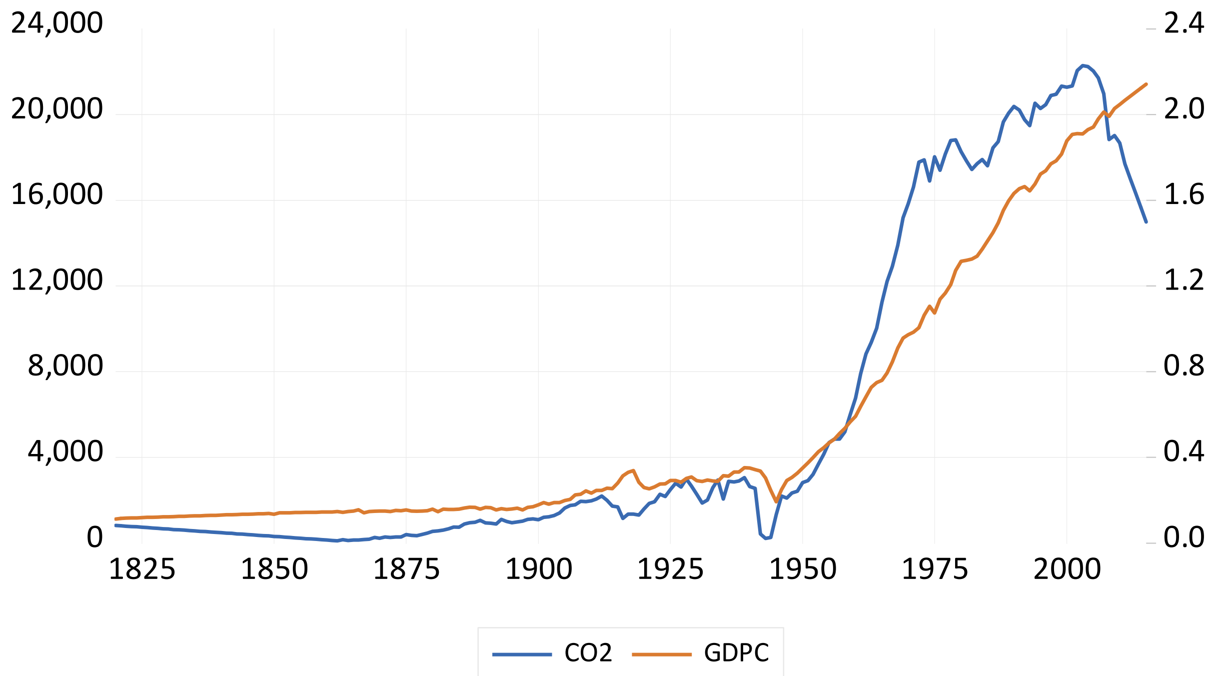

Fig. A.5. Evolution of per capita GDP and per capita CO2 emissions in Italy.

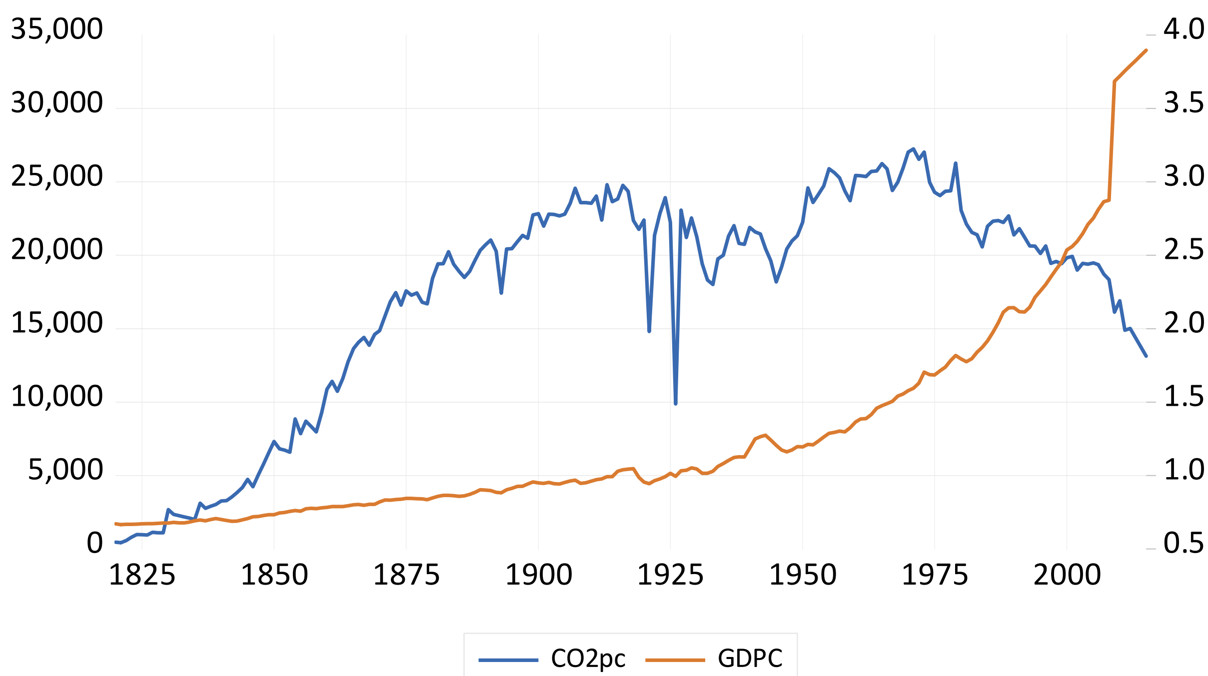

Fig. A.6. Evolution of per capita GDP and per capita CO2 emissions in UK.

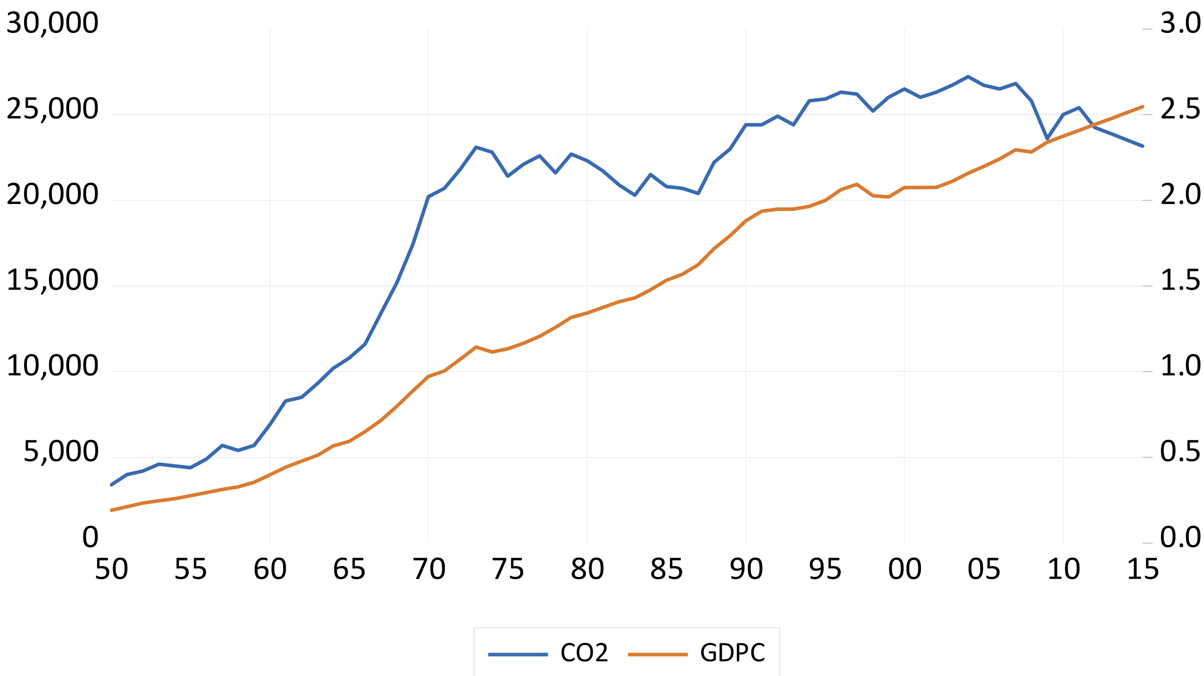

Fig. A.7. Evolution of per capita GDP and per capita CO2 emissions in Japan.

Table A.1. Descriptive statistics of per capita GDP and per capita CO2 emissions for US.

	CO2pc	GDPC
Mean	2.925904	9314.047
Median	3.585203	5224.218
Maximum	6.138692	33960.11
Minimum	0.021642	40.61555
Std. Dev.	2.061441	9392.208
Skewness	-0.188415	1.189138
Kurtosis	1.452807	3.244312
Jarque-Bera	20.70908	46.67976
Probability	0.000032	0.000000
Observations	196	196

Table A.2. Descriptive statistics of per capita GDP and per capita CO2 emissions for Canada.

	CO2pc	GDPC
Mean	2.008542	7678.766
Median	2.050557	3976.489
Maximum	4.965749	35032.20
Minimum	0.000497	904.4118
Std. Dev.	1.735674	8385.689
Skewness	0.198371	1.562648
Kurtosis	1.564592	4.767377
Jarque-Bera	18.11205	105.2773
Probability	0.000117	0.000000
Observations	196	196

Table A.3. Descriptive statistics of per capita GDP and per capita CO2 emissions for France.

	CO2pc	GDPC
Mean	1.016002	6649.436
Median	0.913632	3120.720
Maximum	2.641479	24433.29
Minimum	0.025344	1134.976
Std. Dev.	0.710345	6806.949
Skewness	0.311183	1.281148
Kurtosis	2.095630	3.207031
Jarque-Bera	9.842665	53.96719
Probability	0.007289	0.000000
Observations	196	196

Table A.4. Descriptive statistics of per capita GDP and per capita CO2 emissions for Germany.

	CO2pc	GDPC
Mean	1.652519	6360.635
Median	1.934604	3128.091
Maximum	3.170699	23766.82
Minimum	0.032977	1076.852
Std. Dev.	1.088532	6377.339
Skewness	-0.274177	1.258468
Kurtosis	1.517981	3.192217
Jarque-Bera	20.39276	52.03730
Probability	0.000037	0.000000
Observations	196	196

Table A.5. Descriptive statistics of per capita GDP and per capita CO2 emissions for Italy.

	CO2pc	GDPC
Mean	0.595452	5694.186
Median	0.177367	2553.060
Maximum	2.228563	21425.16
Minimum	0.011053	1116.921
Std. Dev.	0.770509	6242.430
Skewness	1.071639	1.332549
Kurtosis	2.372756	3.256196
Jarque-Bera	40.72781	58.54182
Probability	0.000000	0.000000
Observations	196	196

Table A.6. Descriptive statistics of per capita GDP and per capita CO2 emissions for UK.

	CO2pc	GDPC
Mean	2.227896	7829.018
Median	2.504963	4895.477
Maximum	3.223550	33960.11
Minimum	0.542945	1652.974
Std. Dev.	0.765160	7243.841
Skewness	-0.963573	1.869931
Kurtosis	2.648395	6.261969
Jarque-Bera	31.33974	201.1205
Probability	0.000000	0.000000
Observations	196	196

Table A.7. Descriptive statistics of per capita GDP and per capita CO2 emissions for Japan.

	CO2pc	GDPC
Mean	1.896981	13922.91
Median	2.215000	14192.62
Maximum	2.720000	25454.70
Minimum	0.340000	1920.721
Std. Dev.	0.787260	7539.409
Skewness	-0.894807	-0.180228
Kurtosis	2.225815	1.658089
Jarque-Bera	10.45571	5.309296
Probability	0.005365	0.070324
Observations	66	66