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Article

Global Dynamics of Environmental Kuznets Curve: A Cross-Correlation Analysis of Income and CO_2 Emissions

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Abstract: The environmental Kuznets curve (EKC) hypothesis posits an inverted U-shaped relationship between economic growth and environmental degradation. However, there is no consensus regarding the EKC hypothesis among countries and regions of different income groups. In this study, we analyze the EKC hypothesis for 158 countries and 44 regions from 1990 to 2020, categorizing them into different income groups based on the World Bank's income classification (low, lower-middle, upper-middle, and high-income countries). Our findings reveal mixed patterns in the EKC across different income levels, highlighting the heterogeneous relationship between economic growth and carbon emissions and showing differentiated patterns among different income levels. While a rise in income for high-income countries should be reflected in a shift toward fewer carbon emissions, for lower-income countries, growth is still associated with rising emissions. This underscores the urgent need for policy interventions that decouple economic development from environmental degradation. A balanced approach to economic growth, which prioritizes carbon neutrality across all stages of development, by tailoring environmental and economic strategies to address CO_2 emissions effectively, should be adopted, recognizing the different developmental stages and income levels of countries and regions.

Keywords: Environmental Kuznets curve; CO_2 emissions; Economic growth; Cross-correlation analysis; Income levels; Sustainable development

1. Introduction

For human survival and development, the Earth's climate must be suitable and stable [1,2]. However, according to the Berkeley Earth press release [3], 2023 was the warmest year, with global surface temperatures having accelerated by ~1.5 °C since the pre-industrial period. Human activities and anthropogenic greenhouse gas emissions have been "unequivocally" identified as the main causes of global warming [4]. Considering the identified causality, one issue requires academic and governmental attention: how to change the existing paradigm of development to bring into line with the principles of climate mitigation [5–9].

In the environmental economics literature, the environmental Kuznets curve (EKC) is widely discussed. The EKC is a re-interpretation, from the economics field, of the nonlinear relationship between per capita income and income inequality, proposed by Kuznets [10]. In the 1990s, Grossman and Krueger [11] proposed the EKC concept to describe the inverted U-shaped relationship between economic growth and environmental degradation. The EKC links economic development with environmental quality and posits that at the early stages of economic development, due to the higher

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priority given to income over environment, both economic growth and environmental pollution would increase. However, after a certain point of economic development, as a greater proportion of the population is willing to pay for a clean environment, and due to more effective environmental policies, this scenario would be reverted, and pollution would start declining. This means that in the early stages of development, there exists a positive relationship between environmental degradation and per capita income (a positive slope), but after a certain level of growth, pollution decreases with an increase in per capita income, i.e., a negative slope [12–14].

Given the above, it was expected that most developed countries would display an inverted U-shaped relationship between economic growth and environmental degradation. However, several recent studies point out that some developed countries are ecologically deficient (see, for example, [15,16]); there are also other countries (such as Germany, the Netherlands and Austria), which are once again turning to coal for electricity and heating, as they struggle with a European energy crisis triggered by the Russia–Ukraine conflict beginning in 2022 [17,18]. Furthermore, it is important to test the relationship between environmental quality and economic growth as it allows policymakers to judge the response by the environment to economic growth; this is crucial since the objective function of any economy is to maximize economic growth. Moreover, it is crucial to consider the targets for global carbon neutrality and net zero carbon emissions by 2050, which are central to international climate policies. Many high-income countries have committed to achieving net zero emissions by mid-century, implying significant changes in energy production and consumption. These targets underscore the necessity for sustainable development where economic growth is decoupled from carbon emissions. Integrating these targets into EKC analyses can provide relevant insights into the alignment of economic and environmental policies and identify gaps and opportunities for improvement in climate mitigation strategies. Thus, we revisit the EKC by considering recent data (from 1990–2020) and a broad set of countries, grouped by their income levels, to identify for which exists (or does not exist) evidence of an inverted U-shaped relationship between income level (measured by the GDP per capita) and environmental degradation [measured by carbon dioxide (CO_2) emissions per capita]. The study also aims to identify if there are differences in how GDP and CO_2 are related in different groups of countries. To perform this assessment, providing an empirical contribution, we test the EKC hypothesis by applying the cross-correlation coefficient (CCC) approach of Narayan et al. [19].

Our findings reveal that low-income countries display the highest percentage of countries aligned with the EKC hypothesis, while high-income countries display the lowest. However, there are countries whose behavior is partially aligned with the EKC hypothesis, i.e., countries for whom it is expected that CO_2 emissions will reduce in the future with increased GDP. In this case, high-income countries display the highest percentage of alignment, while none of the lower-income countries reveals a trend of CO_2 reduction in the future with an increase in GDP. Across the world, there are significant variations in the alignment with the EKC hypothesis. Generally, Europe and Asia are the world regions whose behavior best fits the EKC hypothesis. Our results also reveal that 11.36% of the world regions are on a carbon neutrality path where economic growth is decoupled from carbon emissions.

This article is organized as follows: Section 1, which presents the motivation for this study and the main results; Section 2, which provides a brief literature review of the studies related to the EKC hypothesis; Section 3, which provides an overview of the analyzed data and the applied methods; Section 4, which discusses the results, and Section 5, which offers some concluding remarks.

2. Brief Literature Review

Climate change and its consequences for the global economy have been discussed in the economic literature since the 1980s [20]. In recent years, one of the major concerns of nations has become global warming, particularly its adverse effects on the Earth, and implicitly, on the quality of life. The start of the Industrial Revolution contributed to significant changes at the global level (both economically and socially) with subsequent effects on the environment. Thus, reducing emissions of greenhouse gases (GHG), such as CO_2, methane (CH_4), nitrous oxide (N_2O), and a set of fluorinated gases [hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulfur hexafluoride (SF_6), and nitrogen trifluoride (NF_3)] is the key to mitigating climate change.

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The EKC, which emerged in the early 1990s [11], is one hypothesis linking economy and environmental quality. Grossman and Krueger [21] identified evidence of a nonlinear relationship between income and environmental quality and proposed an inverted U-shaped relationship between both variables. According to their theory, the GDP per capita initially leads to greater environmental deterioration at low-income levels, but other factors may eventually cause an improvement in environmental quality with further economic development.

The EKC theory, which suggests an inverted U-shaped relationship between environmental degradation and income, has been the subject of much debate (see, for example, [22–26] for extensive and systematic literature reviews in this regard, which are not covered by this research since we do not aim to review or cite all the rapidly growing number of studies).

For example, Ekins [27] examined the evidence for an EKC relationship between environmental quality and income. They found that important indicators show a monotonically increasing (rather than inverted-U) relationship between environmental quality and income. Furthermore, they concluded that the income-environment relationship is still very problematic from the environmental sustainability perspective and determined that environmental policies will be required to make income growth compatible with sustainable development. Cole [22] provided a comprehensive analysis of the relationship between economic growth and environmental degradation, reviewing historical debates and examining recent statistical studies on the topic. The authors found that the EKC studies suggest that some environmental indicators appear to improve with growth, while others deteriorate, indicating a need to interpret EKCs carefully.

The EKC hypothesis suggests that economic growth improves environmental quality [23], but research findings are mixed. More studies are needed to understand the relationship between economic growth and sustainability. Policy measures are necessary to promote sustainability, and economic models should incorporate better the physical and ecological aspects of economic activity and the interaction between the economy and the environment.

Following the same line of thinking, Ekis [27] and Aslanidis [28] also questioned the existence of a clear EKC and provided a critical review of the literature on the EKC for carbon emissions. The author found no clear-cut evidence supporting or rejecting the existence of the EKC for carbon emissions despite using more sophisticated econometric techniques. The assumption of homogeneous income effects across countries is rejected, with the EKC holding true only for some developed countries. Carbon emissions and GDP per capita are integrated variables, although not always co-integrated, which casts doubt on the validity of the EKC [14].

Mbatu and Otiso [29] examined the environmental, ecological, and sociopolitical impacts of Chinese economic expansionism in Africa, particularly in the Cameroonian forest sector, and concluded that this engagement is detrimental to African peoples and their environment. They argue that the EKC hypothesis can be misleading or dangerous, as it requires a very high threshold of economic development before environmental quality begins to improve. Chen et al. [30] argue that the EKC pattern may not be valid for situations of more damaging pollution, given human-bounded rationality and societal uncertainties. Conversely, Purcel [24], in a literature review of the EKC hypothesis found that recent empirical studies indicate a consensus on the pollution-growth nexus and EKC validity in developing and transition economies. Several other studies also found a long-term relationship between pollution and growth, supporting the EKC hypothesis.

Although the EKC knowledge domain has developed substantially since its inception, no consensus exists on the existence, shape, and turning points of the EKC among researchers [26]. While several studies validated the existence of the EKC while dealing with a wide sample of economies, other multi-country studies failed to validate this theory, and some others found mixed evidence (see, for example, [31], for an extensive state-of-the-art review). Moreover, only a few studies explore the cross-correlation between per capita GDP and environmental degradation indicators over the lags and leads, i.e., past and future, by reinforcing the concept of the ECK hypothesis. However, there are several exceptions cited in literature [19,32–35]. Using the EKC hypothesis, these studies have explored the relationship between economic growth, CO_2 emissions, globalization and environmental degradation. Some studies found evidence supporting the EKC hypothesis in countries with different income levels, suggesting that income growth can reduce CO_2 emissions and environmental degradation. However, the impact of factors such as financial development and tourism revenues varies depending on the country's income level. Additionally, the role of exports and imports in sustainable development in developing countries was also examined, with exports showing positive effects and imports

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having negative impacts. Overall, the results provide insights into how different factors influence environmental outcomes in various countries.

Despite the huge number of studies that test the EKC hypothesis by considering panel data analysis, and although some use larger groups of countries, most of them investigate the EKC validity by considering almost exclusively developing and transition economy samples. Alternatively, they use specific groups of countries, justifying revisiting the EKC hypothesis by considering a broad set of countries and world regions, as well as also using more recent data. Furthermore, studies on the relationship between GDP per capita and CO_2 emissions, using the cross-correlation approach, and considering the lag and lead relationship, still need to be more extensive, leaving a gap in research and highlighting the need for more. This approach represents an important inquiry in this research stream, to determine how the GDP per capita might lead to a reduction in CO_2 emissions.

3. Data and Methods

3.1. Data

To test the EKC hypothesis, data on GDP per capita (current US$) and CO_2 emissions (metric tons per capita) were retrieved from the World Bank (https://data.worldbank.org/). Carbon dioxide emissions are a leading indicator of environmental pollution and are used in several studies that test the EKC hypothesis (see, for example, [24] for a survey of studies that use this indicator in this regard). The data covers 193 countries and 46 world regions.

To analyze a similar period for all the countries and regions, and due to data availability for both variables selected (GDP and CO_2 emissions), the analysis covers 158 countries. As for the world regions South Asia and South Asia (IDA and IBRD), and for Sub-Saharan Africa and Sub-Saharan Africa (IDA and& IBRD countries), the values of GDP per capita and CO_2 emissions are the same, the world regions South Asia (IDA & IBRD) and Sub-Saharan Africa (IDA & IBRD countries) were not considered. The IDA countries include those countries that receive concessional loans (low or zero interest) from the International Development Association (IDA). On the other hand, the IBRD countries include both middle-income and creditworthy low-income countries that receive loans from the International Bank for Reconstruction and Development (IBRD) for development projects. Thus, 44 world regions were considered. The data ranges from 1990 (the first year for which there are available data on CO_2 emissions) to 2020 (the last year with data on CO_2 emissions).

To compare the results, the countries were then grouped into categories based on their income level (which evolves over time). For this classification, the last year of available data (2020) was considered, as detailed in Table 1. These categories follow the World Bank Group assignments, which are widely used and recognized in economic literature. Specifically, the countries were grouped into low, lower-middle, upper-middle, and high-income levels. This classification is based on the Gross National Income (GNI) per capita (in US$, converted from the local currency using the Atlas method). This classification provides a standardized and reliable framework for comparing economic and environmental data across different income levels.

Table 1. Classification of countries by income level.

Country categories (Panels)	Acronym	GNI (US$)	Number of countries by category
High income	H	> 12.695	47
Upper-middle income	UM	4.096–12.695	44
Lower-middle income	LM	1.046–4.095	49
Low income	L	≤ 1.045	18

As countries are at different stages of development, their incomes per capita are different. Thus, and as hypothesized by the EKC hypothesis, this has direct implications for the magnitude of carbon emissions, meaning it is relevant to their classification by income level.

3.2. Methods

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The EKC hypothesis is tested using the cross-correlation coefficient (CCC) proposed by Narayan et al. [19], which states that a reduction in CO_2 emissions with an increase in income over time will be observed if: (i) there is a negative cross-correlation between the current level of income and the future level of CO_2 emissions, and (ii) there is a positive cross-correlation between the current level of income and the past level of CO_2 emissions. This cross-correlation coefficient is estimated according to equation (1):

$$CCC = \frac{\sum_{t=1}^{n}(GDP_t-\overline{GDP})(CO2_{t+k}-\overline{CO2})}{\sum_{t=1}^{n}(GDP_t-\overline{GDP})^2(CO2_{t+k}-\overline{CO2})^2} \quad (1)$$

where $\overline{GDP}$ and $\overline{CO2}$ are, respectively the mean GDP and CO_2 emissions per capita, and t ranges from 1 to 31 (since we have yearly observations for the 31 years from 1990 to 2020).

To avoid spurious correlations between the analyzed variables, both time series are detrended with the Hodrick–Prescott (HP) filter, which uses a mathematical equation that minimizes the sum of the squared differences between the original time series (cyclical component) and the trend component (which represents the long-term underlying growth or decline in the series), subject to a constraint on the smoothness of the trend component. This filter is, among the data-smoothing techniques, one of the most commonly used in the literature [36,37], and uses a lambda (λ) parameter to control the trade-off between smoothing the trend and preserving the data fluctuations.

Considering the annual frequency of the data used, the λ parameter was set as λ=100. After detrending the series, the CCC was estimated for the lags $-20 \leq k \leq 20$, which are sufficient to gauge the behavior of CO_2 emissions in response to changes in income [19]. Where $k > 0$ we obtain the CCC between GDP_t and k lead or future values of CO_2 ($CO2_{t+k}$); where $k = 1$, we obtain the CCC between GDP_t and the one-period lead or future value of CO_2 ($CO2_{t+1}$). Where $k = 0$ the CCC between GDP_t and $CO2_t$ is obtained which is the contemporaneous correlation between both variables. On the other hand, where $k < 0$, we obtain the CCC between GDP_t and the k period lag values of CO_2.

The EKC hypothesis is considered correct if there exists: (i) a negative cross-correlation between the current level of GDP (GDP_t) and future levels (leads) of CO_2 emissions ($CO2_{t+k}, \forall\, 0 < k \leq 20$), and (ii) a positive cross-correlation between the current level of GDP (GDP_t) and past levels (lags) of CO_2 emissions ($CO2_{t+k}, \forall -20 \leq k < 0$); CO_2 emissions will decline with the progression of GDP over time after a certain point.

4. Results and Discussion

4.1. Preliminary Results

Tables 2–6 present some descriptive statistics, namely the mean and standard deviation (Std.Dev.) for both time series. Tables 2–5 report the results for the countries (which are grouped according to the categories in Table 1), and Table 6 reports the results for the world regions. The penultimate column of each table shows the values of the unconditional correlation between GDP and CO_2 emissions per capita. The null hypothesis of unconditional correlation equal to zero was tested (with a t-test using the t-statistics), and the results are displayed in the last column.

Table 2. Summary and descriptive statistics for the panel of high-income (H) countries.

Country	Code	GDP		CO_2 emissions		Corr.	t-statistic	
		Mean	Std.Dev.	Mean	Std.Dev.			
Andorra	AND	33513.756	12730.017	6.991	0.490	−0.458	−2.773	***
Antigua and Barbuda	ATG	12606.951	3440.824	4.598	0.810	0.955	17.249	***
Australia	AUS	37398.457	17743.386	16.917	1.153	0.003	0.018	
Austria	AUT	37669.077	11201.962	7.948	0.671	−0.160	−0.872	
Bahamas, The	BHS	23617.698	7225.189	6.170	0.647	−0.491	−3.039	***
Bahrain	BHR	16955.385	6683.277	22.059	0.870	−0.034	−0.184	
Barbados	BRB	13513.067	3910.232	4.526	0.676	0.681	5.003	***
Belgium	BEL	35184.785	10319.811	10.040	1.391	−0.875	−9.748	***
Brunei Darussalam	BRN	25144.941	10539.514	16.086	2.534	0.685	5.067	***

Canada	CAN	34749.151	12273.542	15.834	0.826	0.058	0.313	
Chile	CHL	8897.364	4712.158	3.641	0.845	0.945	15.542	***
Czechia	CZE	13257.629	7453.118	11.342	1.448	−0.814	−7.558	***
Denmark	DNK	45961.280	13673.947	9.186	2.439	−0.786	−6.842	***
Finland	FIN	36981.853	11611.069	10.455	1.791	−0.514	−3.223	***
France	FRA	32848.105	8406.669	5.564	0.675	−0.755	−6.203	***
Germany	DEU	35496.418	9128.758	9.855	1.029	−0.838	−8.275	***
Greece	GRC	18240.602	6296.672	7.683	1.214	0.187	1.023	
Hong Kong SAR, China	HKG	30551.181	9719.464	5.233	0.582	−0.822	−7.767	***
Iceland	ISL	44024.655	15999.350	6.845	1.212	−0.708	−5.400	***
Ireland	IRL	43305.016	21700.216	9.292	1.401	−0.437	−2.619	**
Italy	ITA	28779.928	6980.172	6.865	1.001	−0.344	−1.973	*
Japan	JPN	37999.932	4955.627	9.187	0.396	0.204	1.120	
Korea, Rep.	KOR	19019.393	8642.434	9.940	1.841	0.913	12.061	***
Kuwait	KWT	28096.194	13518.981	23.522	5.081	0.584	3.873	***
Luxembourg	LUX	80509.712	33061.083	21.268	4.711	−0.587	−3.902	***
Malta	MLT	17272.450	8152.843	5.696	1.282	−0.724	−5.647	***
Monaco	MCO	135307.698	45555.805	3.585	1.829	−0.433	−2.590	**
Netherlands	NLD	39411.272	12443.167	9.900	0.788	−0.675	−4.920	***
New Zealand	NZL	26995.219	11864.834	7.232	0.605	−0.171	−0.932	
Norway	NOR	61278.249	26302.374	7.710	0.516	0.045	0.243	
Oman	OMN	13526.097	6821.440	12.861	3.694	0.920	12.600	***
Poland	POL	8593.375	4888.651	8.191	0.543	−0.607	−4.111	***
Portugal	PRT	16996.778	5512.428	5.089	0.670	−0.102	−0.552	
Qatar	QAT	47103.477	28177.851	38.361	5.684	−0.177	−0.968	
Saudi Arabia	SAU	14270.104	6556.716	13.351	2.091	0.937	14.440	***
Seychelles	SYC	10653.678	3435.597	4.314	1.172	0.906	11.512	***
Singapore	SGP	36894.723	17488.764	9.076	1.038	−0.806	−7.337	***
Slovak Republic	SVK	11405.345	6464.644	7.034	1.124	−0.868	−9.392	***
Spain	ESP	23038.405	7321.656	6.241	0.974	−0.042	−0.225	
St. Kitts and Nevis	KNA	13298.978	5711.927	4.223	0.804	0.917	12.393	***
Sweden	SWE	42712.338	12272.594	5.342	1.162	−0.859	−9.033	***
Switzerland	CHE	61599.929	19686.175	5.694	0.730	−0.866	−9.306	***
Trinidad and Tobago	TTO	11092.989	6105.806	11.292	3.038	0.886	10.303	***
United Arab Emirates	ARE	35667.627	7996.840	24.926	4.130	−0.796	−7.086	***
United Kingdom	GBR	34866.662	9954.021	8.046	1.554	−0.658	−4.712	***
United States	USA	43131.007	12689.830	17.986	2.094	−0.855	−8.884	***
Uruguay	URY	9796.516	5645.954	1.782	0.326	0.671	4.876	***

Note: (i) "***", "**" and "*" correspond to the statistical significance at 1%, 5% and 10% significance levels, respectively; (ii) "Std.Dev." corresponds to the standard deviation; (iii) "Corr." corresponds to the unconditional correlation between both variables.

Table 3. Summary and descriptive statistics for the panel of upper middle-income (UM) countries.

Country	Code	GDP		CO_2 emissions		Corr.	t-statistic	
		Mean	Std.Dev.	Mean	Std.Dev.			
Albania	ALB	2665.109	1800.928	1.298	0.444	0.804	7.282	***
Argentina	ARG	8518.593	3227.707	3.715	0.411	0.786	6.852	***
Armenia	ARM	2123.591	1619.682	1.812	1.141	0.054	0.291	
Azerbaijan	AZE	2930.402	2657.006	3.901	1.439	−0.433	−2.590	**

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Botswana	BWA	4690.513	1590.257	2.280	0.423	0.430	2.567	**
Brazil	BRA	6549.213	3415.845	1.837	0.328	0.857	8.942	***
Bulgaria	BGR	4718.178	3114.510	6.182	0.642	−0.306	−1.730	*
China	CHN	3620.801	3476.529	4.655	2.182	0.945	15.529	***
Colombia	COL	4277.592	2226.098	1.543	0.125	0.198	1.089	
Costa Rica	CRI	6470.315	3710.129	1.419	0.200	0.737	5.870	***
Dominica	DMA	5740.121	1653.786	1.895	0.612	0.928	13.457	***
Dominican Republic	DOM	4227.287	2222.225	1.961	0.376	0.724	5.645	***
Ecuador	ECU	3632.565	1851.646	2.060	0.340	0.874	9.678	***
Equatorial Guinea	GNQ	7175.954	6775.226	3.837	1.786	0.708	5.405	***
Fiji	FJI	3441.352	1376.748	1.144	0.204	0.731	5.770	***
Gabon	GAB	6318.011	2019.434	3.803	0.892	−0.785	−6.820	***
Georgia	GEO	2342.236	1625.935	2.097	1.365	0.117	0.634	
Grenada	GRD	5909.886	2169.873	2.021	0.462	0.922	12.842	***
Guatemala	GTM	2490.587	1210.400	0.805	0.195	0.856	8.910	***
Guyana	GUY	2956.967	2353.561	2.331	0.569	0.837	8.226	***
Iraq	IRQ	3077.271	2547.821	3.702	0.681	−0.099	−0.536	
Jamaica	JAM	3971.723	1238.576	3.310	0.616	−0.371	−2.153	**
Jordan	JOR	2696.632	1223.568	2.946	0.354	−0.429	−2.558	**
Kazakhstan	KAZ	5512.682	4348.579	11.822	2.339	0.459	2.785	***
Libya	LBY	8345.772	2814.005	8.323	1.018	0.313	1.772	*
Malaysia	MYS	6631.129	3043.872	5.963	1.403	0.896	10.872	***
Maldives	MDV	5069.865	3375.597	2.132	0.954	0.970	21.379	***
Marshall Islands	MHL	2915.601	1028.386	2.206	0.773	0.773	6.566	***
Mauritius	MUS	6343.081	3021.857	2.328	0.752	0.940	14.778	***
Mexico	MEX	8056.363	2420.964	3.809	0.303	0.653	4.646	***
North Macedonia	MKD	3519.998	1618.463	4.119	0.412	−0.633	−4.408	***
Panama	PAN	7398.370	4574.470	2.075	0.521	0.848	8.625	***
Paraguay	PRY	3421.072	1963.058	0.835	0.207	0.779	6.680	***
Peru	PER	3746.250	2082.419	1.281	0.319	0.969	21.244	***
Romania	ROU	5752.380	4257.793	4.486	0.868	−0.634	−4.414	***
Russian Federation	RUS	6902.982	4683.833	11.461	1.068	0.018	0.099	
South Africa	ZAF	5226.971	1825.468	7.108	0.890	0.853	8.791	***
St. Lucia	LCA	7379.675	2389.200	2.430	0.496	0.905	11.485	***
St. Vincent and the Grenadines	VCT	5227.806	2141.860	1.781	0.558	0.915	12.199	***
Suriname	SUR	4408.957	2894.728	3.911	0.901	−0.132	−0.715	
Thailand	THA	3857.679	1909.120	3.103	0.658	0.833	8.109	***
Turkiye	TUR	6980.295	3622.281	3.695	0.814	0.889	10.438	***
Turkmenistan	TKM	3117.179	2706.998	9.776	1.692	0.664	4.786	***
Tuvalu	TUV	2481.515	1242.141	0.859	0.148	−0.149	−0.814	

Note: (i) "***", "**" and "*" correspond to the statistical significance at 1%, 5% and 10% significance levels, respectively; (ii) "Std.Dev." corresponds to the standard deviation; (iii) "Corr." corresponds to the unconditional correlation between both variables.

Table 4. Summary and descriptive statistics for the panel of lower middle-income (LM) countries.

Country	Code	GDP		CO_2 emissions				
		Mean	Std.Dev.	Mean	Std.Dev.	Corr.	t-statistic	
Algeria	DZA	3136.814	1432.914	3.061	0.542	0.817	7.616	***
Angola	AGO	1982.430	1586.901	0.888	0.169	0.226	1.251	

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Bangladesh	BGD	774.193	588.449	0.281	0.154	0.944	15.452	***
Belize	BLZ	4962.751	929.042	1.742	0.228	−0.615	−4.201	***
Benin	BEN	775.224	344.346	0.340	0.198	0.951	16.531	***
Bolivia	BOL	1679.277	990.356	1.359	0.328	0.842	8.390	***
Cabo Verde	CPV	2337.745	1192.087	0.803	0.227	0.868	9.416	***
Cameroon	CMR	1173.040	320.181	0.361	0.068	0.040	0.214	
Comoros	COM	1136.511	327.103	0.232	0.076	0.653	4.638	***
Congo, Rep.	COG	1838.393	998.058	1.135	0.148	−0.005	−0.026	
Cote d'Ivoire	CIV	1432.329	506.953	0.326	0.069	0.703	5.325	***
Djibouti	DJI	1321.574	779.032	0.486	0.055	−0.690	−5.132	***
Egypt, Arab Rep.	EGY	1814.874	960.204	1.934	0.350	0.812	7.494	***
El Salvador	SLV	2564.978	1034.958	0.983	0.200	0.776	6.625	***
Eswatini	SWZ	2666.611	1105.311	1.015	0.190	−0.702	−5.304	***
Ghana	GHA	990.185	732.772	0.340	0.138	0.930	13.615	***
Haiti	HTI	881.238	425.613	0.206	0.071	0.921	12.689	***
Honduras	HND	1522.123	590.852	0.867	0.212	0.765	6.400	***
India	IND	944.063	604.968	1.133	0.380	0.986	31.738	***
Indonesia	IDN	1990.622	1323.478	1.519	0.390	0.909	11.776	***
Kenya	KEN	860.717	562.280	0.290	0.061	0.927	13.351	***
Kiribati	KIR	1104.692	386.045	0.476	0.104	0.754	6.184	***
Kyrgyz Republic	KGZ	735.667	393.812	1.624	0.976	0.079	0.425	
Lao PDR	LAO	988.265	866.027	0.676	0.897	0.902	11.226	***
Lesotho	LSO	762.700	309.704	0.970	0.155	0.859	9.035	***
Mauritania	MRT	1223.134	459.310	0.547	0.153	0.830	7.999	***
Micronesia, Fed. Sts.	FSM	2445.629	614.171	1.292	0.421	0.018	0.099	
Mongolia	MNG	1946.519	1588.169	5.102	1.162	0.802	7.225	***
Morocco	MAR	2345.155	867.836	1.396	0.317	0.967	20.350	***
Myanmar	MMR	582.229	527.164	0.254	0.164	0.763	6.358	***
Nepal	NPL	490.987	347.138	0.183	0.143	0.933	13.921	***
Nicaragua	NIC	1261.086	549.009	0.715	0.125	0.737	5.873	***
Nigeria	NGA	1601.920	829.271	0.686	0.122	−0.695	−5.211	***
Pakistan	PAK	873.978	417.101	0.694	0.102	0.915	12.222	***
Papua New Guinea	PNG	1493.388	791.845	0.615	0.097	0.551	3.553	***
Philippines	PHL	1812.246	892.837	0.925	0.174	0.758	6.253	***
Samoa	WSM	2537.854	1294.011	0.898	0.199	0.892	10.602	***
Senegal	SEN	1059.197	308.972	0.491	0.134	0.825	7.849	***
Solomon Islands	SLB	1465.966	579.793	0.546	0.076	−0.146	−0.795	
Sri Lanka	LKA	1981.855	1442.738	0.635	0.252	0.889	10.473	***
Tajikistan	TJK	525.295	317.412	0.617	0.432	0.102	0.550	
Tanzania	TZA	564.769	319.562	0.137	0.058	0.961	18.803	***
Tunisia	TUN	2998.875	992.619	2.250	0.316	0.931	13.781	***
Ukraine	UKR	2115.424	1183.604	6.610	2.278	−0.396	−2.322	**
Uzbekistan	UZB	1175.693	790.401	4.412	0.726	−0.823	−7.798	***
Vanuatu	VUT	2063.623	716.584	0.451	0.079	0.483	2.968	***
Viet Nam	VNM	1257.278	1157.203	1.322	0.959	0.973	22.813	***
Zambia	ZMB	900.692	521.524	0.261	0.084	0.226	1.252	
Zimbabwe	ZWE	876.170	442.966	1.024	0.357	−0.337	−1.930	*

Note: (i) "***", "**" and "*" correspond to the statistical significance at 1%, 5% and 10% significance levels, respectively; (ii) "Std.Dev." corresponds to the standard deviation; (iii) "Corr." corresponds to the unconditional correlation between both variables.

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Table 5. Summary and descriptive statistics for the panel of low-income (L) countries.

Country	Code	GDP		CO_2 emissions		Corr.	t-statistic	
		Mean	Std.Dev.	Mean	Std.Dev.			
Burkina Faso	BFA	483.356	211.656	0.123	0.065	0.873	9.628	***
Burundi	BDI	189.134	46.069	0.036	0.010	0.376	2.182	**
Central African Republic	CAF	372.932	87.692	0.049	0.010	−0.574	−3.779	***
Chad	TCD	538.884	305.413	0.081	0.017	0.882	10.068	***
Ethiopia	ETH	334.374	249.384	0.080	0.039	0.945	15.608	***
Gambia, The	GMB	620.288	122.167	0.209	0.030	0.417	2.469	**
Guinea	GIN	587.920	207.676	0.207	0.052	0.834	8.146	***
Guinea-Bissau	GNB	438.391	194.574	0.155	0.015	0.002	0.012	
Madagascar	MDG	386.385	99.034	0.099	0.020	0.576	3.793	***
Malawi	MWI	425.618	157.423	0.077	0.008	−0.477	−2.921	***
Mali	MLI	518.234	231.972	0.120	0.049	0.935	14.198	***
Niger	NER	380.385	132.584	0.071	0.019	0.813	7.528	***
Rwanda	RWA	446.082	227.983	0.079	0.015	0.615	4.204	***
Sierra Leone	SLE	340.939	170.745	0.098	0.033	0.894	10.773	***
Sudan	SDN	1122.105	782.028	0.351	0.133	0.741	5.942	***
Togo	TGO	548.882	234.301	0.273	0.064	0.326	1.854	*
Uganda	UGA	483.754	278.287	0.082	0.035	0.937	14.498	***
Yemen, Rep.	YEM	931.176	398.789	0.735	0.246	0.105	0.570	

Note: (i) "***", "**" and "*" correspond to the statistical significance at 1%, 5% and 10% significance levels, respectively; (ii) "Std.Dev." corresponds to the standard deviation; (iii) "Corr." corresponds to the unconditional correlation between both variables.

Table 6. Summary and descriptive statistics for the world regions.

World region	Code	GDP		CO_2 emissions		Corr.	t-statistic	
		Mean	Std. Dev.	Mean	Std.Dev.			
Arab World	ARB	4409.764	1994.329	3.687	0.551	0.958	18.087	***
Caribbean small states	CSS	7079.385	2907.295	4.930	0.592	0.797	7.101	***
Central Europe and the Baltics	CEB	8716.471	5125.355	6.933	0.641	−0.677	−4.953	***
Early-demographic dividend	EAR	2145.871	997.383	1.758	0.324	0.983	29.132	***
East Asia & Pacific	EAS	6277.222	2971.174	4.279	1.426	0.965	19.857	***
East Asia & Pacific (excluding high-income)	EAP	3102.089	2735.300	3.707	1.582	0.953	17.009	***
East Asia & Pacific (IDA & IBRD countries)	TEA	3137.219	2765.625	3.719	1.614	0.953	16.953	***
Euro area	EMU	30041.323	8329.311	7.521	0.813	−0.701	−5.290	***
Europe & Central Asia	ECS	18426.500	6185.380	7.558	0.741	−0.664	−4.787	***
Europe & Central Asia (excluding high-income)	ECA	5074.851	3165.363	7.606	0.940	−0.156	−0.850	
Europe & Central Asia (IDA & IBRD countries)	TEC	5449.408	3331.387	7.473	0.857	−0.220	−1.213	

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European Union	EUU	26145.894	7939.703	7.460	0.770	−0.752	−6.151	***
Fragile and conflict-affected situations	FCS	1426.060	602.529	1.282	0.335	−0.645	−4.540	***
Heavily indebted poor countries (HIPC)	HPC	632.022	278.419	0.205	0.046	0.973	22.850	***
High income	HIC	32361.412	8926.937	10.915	0.730	−0.660	−4.728	***
IBRD only	IBD	3222.182	2068.898	3.339	0.791	0.987	33.038	***
IDA & IBRD total	IBT	2652.901	1627.332	2.667	0.556	0.985	31.048	***
IDA blend	IDB	1183.662	567.481	0.897	0.067	−0.901	−11.179	***
IDA only	IDX	744.650	324.124	0.289	0.060	0.968	20.673	***
IDA total	IDA	890.843	399.954	0.491	0.025	0.747	6.049	***
Late-demographic dividend	LTE	4487.925	3304.814	4.735	1.390	0.982	27.865	***
Latin America & Caribbean	LCN	6267.761	2639.431	2.443	0.260	0.897	10.935	***
Latin America & Caribbean (excluding high-income)	LAC	5966.245	2463.491	2.258	0.238	0.912	11.967	***
Latin America & the Caribbean (IDA & IBRD countries)	TLA	6169.196	2624.209	2.459	0.265	0.897	10.910	***
Least developed countries: UN classification	LDC	620.251	326.348	0.218	0.074	0.957	17.747	***
Low & middle income	LMY	2540.821	1573.965	2.599	0.568	0.985	30.271	***
Low income	LIC	649.790	214.273	0.394	0.094	−0.386	−2.252	**
Lower middle income	LMC	1210.648	676.003	1.283	0.222	0.980	26.532	***
Middle East & North Africa	MEA	5109.302	2336.851	4.648	0.749	0.956	17.448	***
Middle East & North Africa (excluding high-income)	MNA	2817.581	1229.723	3.156	0.442	0.914	12.099	***
Middle East & North Africa (IDA & IBRD countries)	TMN	2825.307	1235.171	3.190	0.449	0.913	12.054	***
Middle income	MIC	2730.098	1733.156	2.807	0.654	0.986	31.420	***
North America	NAC	42300.725	12518.295	17.770	1.927	−0.837	−8.239	***
OECD members	OED	29249.160	7759.829	9.912	0.773	−0.725	−5.669	***
Other small states	OSS	8366.543	4673.966	5.300	0.742	0.972	22.326	***
Pacific island small states	PSS	2619.201	952.894	1.020	0.112	0.505	3.152	***
Post-demographic dividend	PST	33151.302	9035.017	11.068	0.906	−0.755	−6.203	***
Pre-demographic dividend	PRE	1009.993	490.465	0.474	0.040	0.065	0.353	
Small states	SST	7761.159	4095.455	4.950	0.666	0.968	20.902	***
South Asia	SAS	916.023	574.025	0.968	0.313	0.988	33.776	***

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		1177.86				−0.03	−0.16	
Sub-Saharan Africa	SSF	1	470.510	0.768	0.029	0	2	
		1176.86				−0.03	−0.17	
Sub-Saharan Africa (excluding high income)	SSA	0	470.380	0.768	0.029	2	1	
	UM	4323.45					27.08	**
Upper middle income	C	3	2930.511	4.360	1.210	0.981	2	*
	WL	7700.69					15.61	**
World	D	9	2545.740	4.263	0.322	0.945	1	*

Notes: (i) "***", "**" and "*" correspond to the statistical significance at 1%, 5% and 10% significance levels, respectively; (ii) "Std.Dev." corresponds to the standard deviation; (iii) "Corr." corresponds to the unconditional correlation between both variables.

As was expected, high-income countries report higher mean GDP (and standard deviation) values, and generally higher mean CO_2 emissions. However, it is curious to observe that the Principality of Monaco reports the highest mean GDP value but does not report one of the highest values of mean CO_2 emissions. Monaco's highest mean value of GDP per capita can be explained by its robust financial sector, luxury tourism, and the presence of wealthy residents. Unlike countries with high industrial output, Monaco's economy does not rely on heavy manufacturing or large-scale industrial activities that typically result in significant CO_2 emissions. Thus, despite its high economic wealth, Monaco has a low carbon footprint, which may reflect Monaco's implementation of stringent environmental regulations and sustainable practices. This combination of a service-oriented economy and proactive environmental policies could explain why Monaco enjoys a high GDP per capita without correspondingly high CO_2 emissions.

On the other hand, Qatar is the country that reports the highest mean value of CO_2 emissions, which can be explained by the extensive oil and gas industry, which is a major contributor to the country's economy. Despite the significant revenues from hydrocarbons, Qatar's wealth distribution, population size and economic structure result in a lower GDP per capita compared to other countries with diversified and technologically advanced economies. Qatar's economic model, which is heavily reliant on fossil fuels, could explain its high CO_2 emissions but without a corresponding high GDP per capita.

The countries with the highest levels of CO_2 emissions are Bahrain, Kuwait, Qatar and the United Arab Emirates, all of which are countries with large reserves of oil and natural gas (the exploitation of these natural resources being fundamental pillars of their economies) and economies that are heavily dependent on the production and export of hydrocarbons, which can explain their higher values of mean CO_2 emissions.

Considering the values of estimated unconditional correlation (between the mean GDP per capita and the mean CO_2 emissions per capita), the relationship between GDP and CO_2 emissions per capita varies significantly between the different groups of countries, according to their stage of economic development. Except for the high-income countries, most of the correlations are positive and statistically significant, meaning that, on average, incomes have led to increased emissions over the 1990–2020 period; this is in line, for example, with the findings of Narayan et al. [19].

For the high-income countries, 24 unconditional correlations (of the 47 possible) are negative and statistically significant, which could mean these countries passed the inflection point of the EKC. These results seem to be not only in agreement with the EKC hypothesis but also with the energetic transition theory, which suggests that as countries develop, they pass from traditional energy sources to renewable and clean energy sources. From high-income countries to low-income countries (as the income levels decline), the percentage of positive and statistically significant correlations increases. This preliminary evidence seems to agree with the EKC hypothesis, i.e., countries of high-income levels seem to have reached a point where their economic growth is not strongly associated with an increase in CO_2 emissions.

The evidence found for the upper-middle and lower middle-income countries could be a sign that these countries are still in the ascending phase of the EKC, where economic growth results in higher levels of CO_2 emissions.

Concerning low-income countries, although this category has the smallest number of countries, 77.78% of these countries display positive and statistically significant unconditional correlations,

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suggesting that even in the early stages of development, there exists a clear relationship between economic growth and CO_2 emissions.

Considering the world regions, North America, post-demographic dividend regions (mostly high-income countries where fertility has transitioned below replacement levels), and high-income regions, are the ones that report the highest level of mean GDP per capita and simultaneously the highest mean values of CO_2 emissions. The Euro area follows these regions in terms of mean GDP per capita but not in terms of mean CO_2 emissions, which the OECD members follow. This could mean that countries outside the Euro area are the major ones responsible for CO_2 emissions among the OECD members (as only 19 of the 38 OECD members are from the Euro area). This could also be a sign that the Euro area could have implemented more effective policies and technologies in terms of the reduction of CO_2 emissions than other members of the OECD. Thus, the Euro area could be viewed as an example of how high levels of development can coexist with lower levels of emissions through strict environmental policies. Regarding the OECD countries, our results do not seem to agree with the EKC hypothesis, which contradicts the findings of Galeotti et al. [38], who found evidence for the EKC. This could be a sign that OECD countries may need to address the global nature of environmental issues.

The relationship between GDP and CO_2 emissions per capita also varies between the different world regions, with most of the correlations being positive and statistically significant, meaning that, on average, incomes have led to increased emissions over the 1990–2020 period. The world, as a whole, displays a positive and statistically significant correlation between the analyzed variables, meaning that global economic growth and CO_2 emissions are still strongly associated, which could mean that the world as a whole is still at an early or intermediate stage on the EKC.

Globally, 40 out of the 158 countries (25.3%) and 11 of the 44 world regions (25%) display a negative and statistically significant unconditional correlation between GDP and CO_2 emissions per capita. This percentage is higher than the one found by Narayan et al. [19], which, considering the period 1960–2008, found 20 countries (of 181 analyzed) with this pattern. These results indicate that, as GDP per capita increases, CO_2 emissions decrease, reflecting a significant change in the traditional relationship between economic growth and CO_2 emissions, which could mean that economic growth is no longer necessarily associated with higher CO_2 emissions in many countries. At the same time, and considering the perspective of the EKC, this could mean that more countries have reached the inflection point or are in the process of reaching it. However, this transition is not yet universal, which is confirmed by the different results for the world regions.

4.2. Cross-Correlation Coefficient Analysis

The correlations obtained in the previous sub-section are static and do not allow us any insight into how these relationships will behave in the future. Thus, to get some insights in this respect and evaluate how GDP per capita is negatively or positively correlated with CO_2 emissions over the past (lags), and in the future (leads), the CCC proposed by Narayan et al. [19] was estimated, and the results are displayed in Tables 7–10 for countries (which are grouped according to the categories in Table 1) and in Table 11 for world regions.

Table 7. Cross-correlation coefficient results for the panel of high-income (H) countries.

Country	Code	Lags		Leads		(Aver. CCC lags)/(Aver. CCC leads)			
		Σ of CCC	Aver. CCC	Σ of CCC	Aver. CCC	(+)/(-)	(-)/(-)	(-)/(+)	(+)/(+)
Andorra	AND	−7.042	−0.352	3.093	0.155			X	
Antigua and Barbuda	ATG	1.640	0.082	3.098	0.155				X
Australia	AUS	−6.409	−0.320	6.783	0.339			X	
Austria	AUT	−7.123	−0.356	5.411	0.271			X	
Bahamas, The	BHS	1.416	0.071	−3.417	−0.171	X			
Bahrain	BHR	−5.458	−0.273	6.009	0.300			X	
Barbados	BRB	−2.998	−0.150	4.982	0.249			X	

Belgium	BEL	−4.467	−0.223	0.149	0.007			X	
Brunei Darussalam	BRN	1.482	0.074	1.873	0.094				X
Canada	CAN	−6.774	−0.339	6.410	0.320			X	
Chile	CHL	1.603	0.080	3.273	0.164				X
Czechia	CZE	−3.458	−0.173	−1.595	−0.080		X		
Denmark	DNK	−4.665	−0.233	0.072	0.004			X	
Finland	FIN	−6.599	−0.330	2.805	0.140			X	
France	FRA	−5.332	−0.267	0.943	0.047			X	
Germany	DEU	−2.401	−0.120	−2.587	−0.129		X		
Greece	GRC	−8.195	−0.410	4.505	0.225			X	
Hong Kong SAR, China	HKG	−1.112	−0.056	−3.821	−0.191		X		
Iceland	ISL	−5.115	−0.256	0.536	0.027			X	
Ireland	IRL	−5.985	−0.299	3.257	0.163			X	
Italy	ITA	−7.367	−0.368	3.658	0.183			X	
Japan	JPN	−6.023	−0.301	4.230	0.211			X	
Korea, Rep.	KOR	0.578	0.029	4.455	0.223				X
Kuwait	KWT	−4.113	−0.206	4.203	0.210			X	
Luxembourg	LUX	−3.479	−0.174	−1.592	−0.080		X		
Malta	MLT	−4.985	−0.249	0.753	0.038			X	
Monaco	MCO	2.582	0.129	−6.264	−0.313	X			
Netherlands	NLD	−6.040	−0.302	1.540	0.077			X	
New Zealand	NZL	−6.196	−0.310	6.340	0.317			X	
Norway	NOR	−6.793	−0.340	5.898	0.295			X	
Oman	OMN	1.103	0.055	2.717	0.136				X
Poland	POL	0.528	0.026	−5.257	−0.263	X			
Portugal	PRT	−6.901	−0.345	5.672	0.284			X	
Qatar	QAT	−6.852	−0.343	5.832	0.292			X	
Saudi Arabia	SAU	1.557	0.078	2.515	0.126				X
Seychelles	SYC	2.038	0.102	3.242	0.162				X
Singapore	SGP	−1.033	−0.052	−3.481	−0.174		X		
Slovak Republic	SVK	−1.767	−0.088	−3.144	−0.157		X		
Spain	ESP	−7.544	−0.377	5.409	0.270			X	
St. Kitts and Nevis	KNA	0.452	0.023	4.513	0.226				X
Sweden	SWE	−3.878	−0.194	−0.355	−0.018		X		
Switzerland	CHE	−3.793	−0.190	−0.711	−0.036		X		
Trinidad and Tobago	TTO	0.151	0.008	2.131	0.107				X
United Arab Emirates	ARE	−3.084	−0.154	−1.219	−0.061		X		
United Kingdom	GBR	−6.325	−0.316	1.431	0.072			X	
United States	USA	−4.803	−0.240	0.309	0.015			X	
Uruguay	URY	−1.334	−0.067	5.689	0.284			X	

Notes: (i) “CCC” corresponds to the cross-correlation coefficient estimated according to the method proposed by Narayan et al. (2016); (ii) “Aver.” corresponds to the mean of the CCC.

Table 8. Cross-correlation coefficient results for the panel of upper middle-income UM) countries.

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Country	Code	Lags		Leads		(Aver. CCC lags)/(Aver. CCC leads)			
		Σ of CCC	Aver. CCC	Σ of CCC	Aver. CCC	(+)/(-)	(-)/(-)	(-)/(+)	(+)/(+)
Albania	ALB	2.572	0.129	1.421	0.071				X
Argentina	ARG	−1.809	−0.090	5.497	0.275			X	
Armenia	ARM	3.980	0.199	−6.273	−0.314	X			
Azerbaijan	AZE	2.142	0.107	−5.760	−0.288	X			
Botswana	BWA	5.719	0.286	−1.355	−0.068	X			
Brazil	BRA	1.226	0.061	2.794	0.140				X
Bulgaria	BGR	−0.522	−0.026	−4.344	−0.217		X		
China	CHN	0.601	0.030	3.943	0.197				X
Colombia	COL	6.090	0.304	−5.558	−0.278	X			
Costa Rica	CRI	−1.143	−0.057	5.850	0.292			X	
Dominica	DMA	0.782	0.039	3.851	0.193				X
Dominican Republic	DOM	−0.984	−0.049	5.961	0.298			X	
Ecuador	ECU	−0.369	−0.018	4.789	0.239			X	
Equatorial Guinea	GNQ	−3.124	−0.156	3.915	0.196			X	
Fiji	FJI	1.171	0.059	4.052	0.203				X
Gabon	GAB	−3.635	−0.182	0.720	0.036			X	
Georgia	GEO	4.636	0.232	−7.120	−0.356	X			
Grenada	GRD	1.276	0.064	3.933	0.197				X
Guatemala	GTM	0.667	0.033	4.708	0.235				X
Guyana	GUY	2.944	0.147	1.842	0.092				X
Iraq	IRQ	5.283	0.264	−6.099	−0.305	X			
Jamaica	JAM	−6.906	−0.345	3.431	0.172			X	
Jordan	JOR	−6.571	−0.329	3.835	0.192			X	
Kazakhstan	KAZ	1.546	0.077	−2.976	−0.149	X			
Libya	LBY	−4.513	−0.226	6.170	0.309			X	
Malaysia	MYS	0.258	0.013	4.560	0.228				X
Maldives	MDV	1.493	0.075	3.479	0.174				X
Marshall Islands	MHL	−0.372	−0.019	5.549	0.277			X	
Mauritius	MUS	0.781	0.039	4.087	0.204				X
Mexico	MEX	−4.029	−0.201	4.495	0.225			X	
North Macedonia	MKD	−4.714	−0.236	1.115	0.056			X	
Panama	PAN	−0.258	−0.013	5.076	0.254			X	
Paraguay	PRY	3.121	0.156	1.264	0.063				X
Peru	PER	1.919	0.096	2.436	0.122				X
Romania	ROU	0.232	0.012	−5.237	−0.262	X			
Russian Federation	RUS	2.822	0.141	−6.041	−0.302	X			
South Africa	ZAF	−0.629	−0.031	3.504	0.175			X	
St. Lucia	LCA	0.297	0.015	4.700	0.235				X
St. Vincent and the Grenadines	VCT	0.318	0.016	4.420	0.221				X
Suriname	SUR	5.648	0.282	−6.308	−0.315	X			

Thailand	THA	−0.578	−0.029	5.583	0.279			X	
Turkiye	TUR	3.570	0.179	0.906	0.045				X
Turkmenistan	TKM	−0.722	−0.036	3.844	0.192			X	
Tuvalu	TUV	−6.195	−0.310	5.766	0.288			X	

Notes: (i) "CCC" corresponds to the cross-correlation coefficient estimated according to the method proposed by Narayan et al. (2016); (ii) "Aver." corresponds to the mean of the CCC.

Table 9. Cross-correlation coefficient results for lower middle-income (LM) countries.

Country	Code	Lags		Leads		(Aver. CCC lags)/(Aver. CCC leads)			
		Σ of CCC	Aver. CCC	Σ of CCC	Aver. CCC	(+)/(-)	(-)/(-)	(-)/(+)	(+)/(+)
Algeria	DZA	4.102	0.205	−0.346	−0.017	X			
Angola	AGO	−4.264	−0.213	5.273	0.264			X	
Bangladesh	BGD	0.686	0.034	3.729	0.186				X
Belize	BLZ	1.398	0.070	−4.353	−0.218	X			
Benin	BEN	2.272	0.114	2.525	0.126				X
Bolivia	BOL	3.386	0.169	−1.245	−0.062	X			
Cabo Verde	CPV	0.743	0.037	3.582	0.179				X
Cameroon	CMR	4.937	0.247	−7.669	−0.383	X			
Comoros	COM	2.943	0.147	1.325	0.066				X
Congo, Rep.	COG	4.618	0.231	−5.458	−0.273	X			
Cote d'Ivoire	CIV	1.507	0.075	3.856	0.193				X
Djibouti	DJI	−3.880	−0.194	2.471	0.124			X	
Egypt, Arab Rep.	EGY	−0.120	−0.006	4.455	0.223			X	
El Salvador	SLV	−1.105	−0.055	5.670	0.283			X	
Eswatini	SWZ	0.549	0.027	−3.841	−0.192	X			
Ghana	GHA	1.088	0.054	3.561	0.178				X
Haiti	HTI	2.643	0.132	2.221	0.111				X
Honduras	HND	−1.539	−0.077	6.070	0.303			X	
India	IND	1.776	0.089	2.878	0.144				X
Indonesia	IDN	0.794	0.040	4.129	0.206				X
Kenya	KEN	2.843	0.142	0.968	0.048				X
Kiribati	KIR	−0.374	−0.019	4.338	0.217			X	
Kyrgyz Republic	KGZ	3.337	0.167	−7.047	−0.352	X			
Lao PDR	LAO	3.118	0.156	0.419	0.021				X
Lesotho	LSO	0.641	0.032	3.001	0.150				X
Mauritania	MRT	2.926	0.146	0.907	0.045				X
Micronesia, Fed. Sts.	FSM	−2.482	−0.124	4.009	0.200			X	
Mongolia	MNG	3.658	0.183	−2.346	−0.117	X			
Morocco	MAR	2.354	0.118	2.396	0.120				X
Myanmar	MMR	3.740	0.187	0.539	0.027				X
Nepal	NPL	2.907	0.145	1.167	0.058				X
Nicaragua	NIC	−1.402	−0.070	5.709	0.285			X	
Nigeria	NGA	−1.219	−0.061	−2.816	−0.141		X		

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Pakistan	PAK	1.766	0.088	3.367	0.168				X
Papua New Guinea	PNG	−1.266	−0.063	5.309	0.265			X	
Philippines	PHL	2.785	0.139	1.786	0.089				X
Samoa	WSM	1.870	0.094	3.248	0.162				X
Senegal	SEN	0.628	0.031	3.601	0.180				X
Solomon Islands	SLB	−5.705	−0.285	5.866	0.293			X	
Sri Lanka	LKA	1.283	0.064	3.779	0.189				X
Tajikistan	TJK	4.742	0.237	−7.472	−0.374	X			
Tanzania	TZA	2.741	0.137	2.177	0.109				X
Tunisia	TUN	2.682	0.134	1.322	0.066				X
Ukraine	UKR	−0.118	−0.006	−4.406	−0.220		X		
Uzbekistan	UZB	−1.843	−0.092	−2.292	−0.115		X		
Vanuatu	VUT	4.250	0.212	−0.697	−0.035	X			
Viet Nam	VNM	2.030	0.102	2.504	0.125				X
Zambia	ZMB	7.000	0.350	−5.704	−0.285	X			
Zimbabwe	ZWE	2.766	0.138	−7.409	−0.370	X			

Notes: (i) “CCC” corresponds to the cross-correlation coefficient estimated according to the method proposed by Narayan et al. (2016); (ii) “Aver.” corresponds to the mean of the CCC.

Table 10. Cross-correlation coefficient results for the panel of low-income (L) countries.

		Lags		Leads		(Aver. CCC lags)/(Aver. CCC leads)			
Country	**Code**	**Σ of CCC**	**Aver. CCC**	**Σ of CCC**	**Aver. CCC**	**(+)/(-)**	**(-)/(-)**	**(-)/(+)**	**(+)/(+)**
Burkina Faso	BFA	3.388	0.169	0.836	0.042				X
Burundi	BDI	4.111	0.206	−3.874	−0.194	X			
Central African Republic	CAF	2.653	0.133	−1.602	−0.080	X			
Chad	TCD	3.009	0.150	0.231	0.012				X
Ethiopia	ETH	0.550	0.027	3.212	0.161				X
Gambia, The	GMB	1.928	0.096	1.590	0.079				X
Guinea	GIN	0.931	0.047	3.144	0.157				X
Guinea-Bissau	GNB	5.180	0.259	−6.979	−0.349	X			
Madagascar	MDG	3.746	0.187	0.645	0.032				X
Malawi	MWI	3.356	0.168	−4.334	−0.217	X			
Mali	MLI	1.907	0.095	2.875	0.144				X
Niger	NER	1.254	0.063	1.030	0.051				X
Rwanda	RWA	3.432	0.172	0.806	0.040				X
Sierra Leone	SLE	3.057	0.153	1.047	0.052				X
Sudan	SDN	0.858	0.043	1.852	0.093				X
Togo	TGO	−3.624	−0.181	7.107	0.355			X	
Uganda	UGA	2.133	0.107	2.301	0.115				X
Yemen, Rep.	YEM	−3.368	−0.168	3.962	0.198			X	

Notes: (i) “CCC” corresponds to the cross-correlation coefficient estimated according to the method proposed by Narayan et al. (2016); (ii) “Aver.” corresponds to the mean of the CCC.

Table 11. Cross-correlation coefficient results for the world regions.

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World region	Code	Lags		Leads		(Aver. CCC lags)/(Aver. CCC leads)			
		Σ of CCC	Aver. CCC	Σ of CCC	Aver. CCC	(+)/(-)	(-)/(-)	(-)/(+)	(+)/(+)
Arab World	ARB	1.4163	0.0708	2.7020	0.1351				X
Caribbean small states	CSS	−0.7673	−0.0384	3.3647	0.1682			X	
Central Europe and the Baltics	CEB	−0.7807	−0.0390	−4.2701	−0.2135		X		
Early-demographic dividend	EAR	1.7162	0.0858	2.9637	0.1482				X
East Asia & Pacific	EAS	0.9762	0.0488	3.6751	0.1838				X
East Asia & Pacific (excluding high-income)	EAP	0.6940	0.0347	3.8910	0.1945				X
East Asia & Pacific (IDA & IBRD countries)	TEA	0.6817	0.0341	3.9099	0.1955				X
Euro area	EMU	−5.7828	−0.2891	1.4026	0.0701			X	
Europe & Central Asia	ECS	−2.8028	−0.1401	−2.1610	−0.1081		X		
Europe & Central Asia (excluding high-income)	ECA	1.8913	0.0946	−5.7348	−0.2867	X			
Europe & Central Asia (IDA & IBRD countries)	TEC	1.7816	0.0891	−5.7382	−0.2869	X			
European Union	EUU	−5.1135	−0.2557	0.4929	0.0246			X	
Fragile and conflict-affected situations	FCS	−0.8084	−0.0404	−3.5588	−0.1779		X		
Heavily indebted poor countries (HIPC)	HPC	2.3229	0.1161	1.8006	0.0900				X
High income	HIC	−6.3282	−0.3164	2.5069	0.1253			X	
IBRD only	IBD	1.6665	0.0833	2.6546	0.1327				X
IDA & IBRD total	IBT	1.6870	0.0843	2.5757	0.1288				X
IDA blend	IDB	−0.8144	−0.0407	−3.8206	−0.1910		X		
IDA only	IDX	2.6625	0.1331	1.9562	0.0978				X

IDA total	IDA	4.0536	0.2027	0.1180	0.0059				X
Late-demographic dividend	LTE	1.4871	0.0744	2.8646	0.1432				X
Latin America & Caribbean	LCN	−0.4408	−0.0220	4.1896	0.2095			X	
Latin America & Caribbean (excluding high-income)	LAC	−0.0048	−0.0002	3.9480	0.1974			X	
Latin America & the Caribbean (IDA & IBRD countries)	TLA	−0.4764	−0.0238	4.2045	0.2102			X	
Least developed countries: UN classification	LDC	1.9338	0.0967	2.6043	0.1302				X
Low & middle income	LMY	1.6198	0.0810	2.6587	0.1329				X
Low income	LIC	−3.5011	−0.1751	−0.2927	−0.0146		X		
Lower middle income	LMC	2.8035	0.1402	1.4232	0.0712				X
Middle East & North Africa	MEA	1.0904	0.0545	3.0532	0.1527				X
Middle East & North Africa (excluding high-income)	MNA	1.1766	0.0588	2.4594	0.1230				X
Middle East & North Africa (IDA & IBRD countries)	TMN	1.2038	0.0602	2.4229	0.1211				X
Middle income	MIC	1.6087	0.0804	2.7081	0.1354				X
North America	NAC	−5.0336	−0.2517	0.6449	0.0322			X	
OECD members	OED	−6.0581	−0.3029	1.9011	0.0951			X	
Other small states	OSS	1.7261	0.0863	2.2628	0.1131				X
Pacific island small states	PSS	−1.9978	−0.0999	6.6179	0.3309			X	
Post-demographic dividend	PST	−5.8276	−0.2914	1.5317	0.0766			X	
Pre-demographic dividend	PRE	5.8432	0.2922	−4.6393	−0.2320	X			
Small states	SST	1.4265	0.0713	2.5121	0.1256				X
South Asia	SAS	1.7308	0.0865	2.9572	0.1479				X

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		−6.58	−0.32	4.220	0.211				
Sub-Saharan Africa	SSF	06	90	5	0			X	
		−6.57	−0.32	4.199	0.210				
Sub-Saharan Africa (excluding high income)	SSA	58	88	1	0			X	
	UM	1.374	0.068	3.003	0.150				
Upper middle income	C	3	7	0	2				X
	WL	1.240	0.062	2.837	0.141				
World	D	5	0	4	9				X

Notes: (i) "CCC" corresponds to the cross-correlation coefficient estimated according to the method proposed by Narayan et al. [19]; (ii) "Aver." corresponds to the mean of the CCC; (iii) "X" represents the world regions for which the relationship between the average of the CCC for the lags/leads displayed in the top of each column is verified.

The third and fifth columns of each table report the sum of the cross-correlation coefficients over the past 20 lags and the future 20 leads of CO_2 emissions, respectively. The fourth and sixth columns report the mean values of the same lags and leads, respectively. If past/future values of CO_2 emissions per capita, i.e., lags/leads, are positively/negatively correlated with the current values of GDP per capita, there is evidence of an inverted U-shaped relationship (identified with an "X" in the seventh column of Tables 7–11). This means that the CO_2 emissions increased with GDP in the past, but will decline in the future, supporting the EKC hypothesis. However, in addition to this scenario, another three can be observed: (i) negative cross-correlation between both past and future values of CO_2 emissions (lags and leads) and the current level of GDP per capita (identified with an "X" in the eighth column of Tables 7–11), meaning in this case, increasing GDP per capita has led in the past, and could lead in the future, to a reduction in carbon emissions, which partially supports the EKC hypothesis; (ii) past/future values of CO_2 emissions per capita, i.e., lags/leads, could be negatively/positively correlated with the current values of GDP per capita, meaning that, although in the past an increase in the GDP level led to a reduction of CO_2 emissions per capita, in the future it will not happen (identified with an "X" in the ninth column of Tables 7–11); (iii) positive cross-correlation between both past and future values of CO_2 emissions (lags and leads) and the current level of GDP per capita, meaning in this case, increasing GDP per capita has led in the past, and will probably lead in the future, to an increase in carbon emissions (identified with an "X" in the tenth column of Tables 7–11).

To verify whether our results are consistent, we begin our analysis by verifying whether the sign of the sum of the CCC for the lags and leads and their averages are similar, i.e., whether they are both (sum and average) negative or positive. As displayed in Tables 7–11, they are. Thus, we can consider as valid the values of the averages of the CCC in our analysis.

Considering the results of the average CCC (that can soften outliers and provide a clearer view of the general pattern), displayed in Table 7, for the 47 countries categorized as high-income countries, only three (namely, The Bahamas, Monaco, and Poland) show signs of an inverted U-shaped relationship between the current levels of GDP per capita and past and future values of CO_2 emissions. On the other hand, Czechia, Germany, Hong Kong, Luxembourg, Singapore, the Slovak Republic, Sweden, Switzerland, and the United Arab Emirates (a total of nine countries), reveal negative mean values of the CCC over the lags and leads, which may be a sign that for these countries the CO_2 decreased in the past and will continue to decrease in the future, with the increase in GDP per capita. These results partially agree with the EKC hypothesis and corroborate the results of Narayan et al. [19] in the cases of Czechia, Luxembourg, the Slovak Republic, Sweden and Switzerland. For the majority of high-income countries (26 countries), we find a negative cross-correlation for the lags and a positive for the leads, which could mean that although, in the past, an increase in GDP level led to a reduction of CO_2 emissions per capita, it will not happen in the future. The remaining countries of this panel (precisely, nine countries) display positive cross-correlation for the lags and leads, meaning that increasing GDP per capita has led in the past, and will probably lead in the future, to an increase in carbon emissions.

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Considering the 44 upper middle-income countries, the results suggest that 10 countries (namely, Armenia, Azerbaijan, Botswana, Colombia, Iraq, Kazakhstan, Romania, the Russian Federation and Suriname) agree with the EKC hypothesis, although Bulgaria is only in partial agreement. For the remaining countries in this panel, 17 reveal negative/positive cross-correlations for the lags/leads and 16 positive cross-correlations for the lags and leads.

For the lower middle-income countries, 12 (namely, Algeria, Belize, Bolivia, Cameron, the Congo Republic, Eswatini, the Kyrgyz Republic, Mongolia, Tanzania, Vanuatu, Zambia and Zimbabwe) show evidence of an inverted U-shaped relationship, and three (Nigeria, Ukraine and Uzbekistan) are only in partial agreement with the EKC hypothesis, displaying negative average CCC for the leads. For the remaining countries (34), the results do not provide any support for the EKC hypothesis.

For the panel of 18 lower-income countries, four (namely, Burundi, the Central African Republic, Guinea-Bissau, and Malawi) show an inverted U-shaped relationship. For the remaining 14 countries, two (Togo and the Yemen Republic) reveal negative/positive cross-correlations for the lags/leads and 12 positive cross-correlations for the lags/leads.

If we compare our results with those of Shahbaz et al. [32], who explored the nexus between globalization and energy demand for 86 high, middle, and low-income countries over the period 1970–2015, we can highlight that: (i) some countries have changed, in relation to the income level criteria, their category/classification; (ii) several countries of different income levels (but mostly from high-income levels) have maintained or improved the relationship between the mean GDP per capita and the mean CO_2 emissions for the lags, but have displayed a similar pattern for the leads. However, there are four countries, namely Denmark, the United States, Gabon and the Philippines, which, although revealing a similar pattern for the lags, display a positive (sum and average) CCC for the leads [while in the study of Shahbaz et al. [32] they displayed a negative CCC (sum and average), indicating an undesirable inversion on their pathway to sustainable development; (iii) on the other hand, Botswana, Algeria, Bolivia and the Congo Republic, although revealing a similar pattern for the lags, display a negative (sum and average) CCC for the leads (while in the study of Shahbaz et al. [32] they displayed a positive CCC (sum and average)), also indicating an inversion on their pathway to sustainable development. However, for these countries, it is a desirable one, since a reduction in CO_2 emissions is expected with increasing GDP; (iv) for Albania, Ghana and Sudan, increasing GDP has led in the past, and will lead in the future, to rising CO_2 emissions, entirely contradicting the findings of Shahbaz et al. [32]; (v) on the other hand, for Sweden and Nigeria, increasing GDP has led in the past, and will lead in the future, to decreasing CO_2 emissions, also entirely contradicting the findings of Shahbaz et al. [32].

Considering the results of the average CCC displayed in Table 11, for the 44 regions, only three (namely, Europe & Central Asia (excluding high-income), Europe & Central Asia (IDA & IBRD countries) and Pre-demographic dividend) show signs of an inverted U-shaped relationship between the current levels of GDP per capita and past and future values of CO_2 emissions. This evidence suggests that these regions are managing to balance economic growth with effective environmental policies. On the other hand, Central Europe and the Baltics, Europe & Central Asia, fragile and conflict-affected situations, IDA blends, and low-income regions, reveal negative mean values of the CCC over the lags and leads, partially supporting the EKC hypothesis. For fragile and low-income regions, it may be a positive sign that economic growth is not being achieved at the expense of increasing carbon emissions, but these results may also reflect economic challenges that limit growth. For 13 regions, the results reveal negative cross-correlation for the lags and positive ones for the leads, which could mean that although in the past an increase in GDP level has led to a reduction in CO_2 emissions per capita, in the future, this will not happen. These results may indicate that these regions may face the risk of reversing the environmental gains they have achieved in the past, which may be due to a possible lack of continuity in environmental policies or new economic challenges. Thus, for these regions, there is an urgent need to implement or reinforce environmental policies that ensure that future economic growth does not increase CO_2 emissions. Finally, the majority of regions (23) display positive cross-correlation for the lags and leads, meaning that increasing GDP per capita has led in the past, and probably will lead in the future, to an increase in carbon emissions. In these regions, the growth of per capita GDP has historically led, and will probably continue to lead, to a rise in CO_2 emissions, which may indicate that these economies are at an early stage of the EKC. It is,

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therefore, essential that these regions adopt strict environmental policies and promote clean technologies to reverse this trend.

Table 12 summarizes all the above results for a brief and easier analysis. The first column ((+)/(-)) identifies the number and percentage of countries and regions that, considering the average CCC for the 20 lags and 20 leads, reveal a pattern in agreement with the EKC hypothesis. The second column identifies the number and percentage of countries and regions that reveal a pattern in partial agreement with the EKC hypothesis. The last two columns show the number and percentage of countries and regions for which it is expected that, in the future, there will be an increase in CO_2 emissions with GDP per capita. It is interesting to note that high-income countries are the ones that are in least agreement with the EKC hypothesis. It was expected that these countries, being economically well-established and having the necessary infrastructure and resources to maintain and promote a cleaner environment, would be in greater agreement with the EKC hypothesis, but this is not verified.

Table 12. Summary of the average CCC of the lags and leads for each panel of countries and world regions.

	(Average CCC lags)/(Average CCC leads)				***Total***
	(+)/(-)	**(-)/(-)**	**(-)/(+)**	**(+)/(+)**	
Panel A: High-income (H) countries					
Number of countries	*3*	*9*	*26*	*9*	*47*
Percentage of countries	*6.38%*	*19.15%*	*55.32%*	*19.15%*	*100%*
Panel B: Upper middle-income (UM) countries					
Number of countries	*10*	*1*	*17*	*16*	*44*
Percentage of countries	*22.73%*	*2.27%*	*38.64%*	*36.36%*	*100%*
Panel C: Lower middle-income (LM) countries					
Number of countries	*12*	*3*	*10*	*24*	*49*
Percentage of countries	*24.49%*	*6.12%*	*20.41%*	*48.98%*	*100%*
Panel D: Lower-income (L) countries					
Number of countries	*4*	*0*	*2*	*12*	*18*
Percentage of countries	*22.22%*	*0.00%*	*11.11%*	*66.67%*	*100%*
World regions					
Number of regions	*3*	*5*	*13*	*23*	*44*
Percentage of regions	*6.82%*	*11.36%*	*29.55%*	*52.27%*	*100%*

Generally, the results suggest that 18.35% of the countries (29 out of 158) and 6.82% of the world regions (three out of 44) support the EKC hypothesis. Comparing our results with the ones of Narayan et al. [19], which found 12% with clear evidence supporting the EKC hypothesis), the percentage of countries in agreement with this hypothesis has increased. Considering the countries/regions that are in partial agreement, i.e., the ones in which it is expected that an increase in the GDP will be accompanied by a reduction in CO_2 emissions in the future, our results reveal that only 8.23% of countries, and 11.36% of world regions, seem to be aligned with this pattern. If we compare this result with the one of Narayan et al. [19], which found that 27% of the countries partially agree with the EKC hypothesis, our results are not very encouraging regarding CO_2 reductions in the future. According to our results, it is expected that 73.42% of countries and 81.82% of world regions will see an increase in CO_2 emissions with an increase in GDP.

For a more accurate analysis of which countries and regions agree with the EKC hypothesis using the CCC proposed by Narayan et al. [19], it is crucial to consider both the average values of the lags and leads as well as the detailed graphical representation of these coefficients over the 20 lags and 20 leads. Although the average values of the lags and leads provide a simplified and aggregated view of the relationship between GDP and CO_2 emissions, we must not forget some possible limitations related to this analysis. Using averages can mask significant variations and trends within

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the individual lag and lead periods. Furthermore, a graphical presentation of the CCC for each of the 20 lags and leads allows a more nuanced and detailed analysis. The graphs will enable us to highlight the specific periods where the relationship changes, providing relevant information about the temporal dynamics that the average values cannot capture. For instance, a graph might show that the correlation is positive for the initial few lags/leads but starts to decline and eventually turns negative as we approach the 20th lag/lead. This transition is critical in understanding how economic activities can influence environmental outcomes over time and supports a more robust interpretation of whether a country/region agrees with the EKC hypothesis. Moreover, graphical analysis can help us identify any anomalies or outliers that could significantly affect the average values. Visualizing the CCC over time can also illustrate the consistency or volatility of the relationship between the analyzed variables, providing context essential for interpreting the results accurately. This dual approach ensures that we capture the full complexity of the relationship between the analyzed variables, allowing more accurate conclusions about agreement of countries/regions with the EKC hypothesis. For these reasons, Figure 1 displays the plots for the countries/regions whose behavior seems to agree with the EKC hypothesis (with reference to the positive sign (+) for the average CCC for the lags, and the negative (-) one for the average CCC for the leads), and Figure 2 displays the graphs for the countries/regions which seem to be in partial agreement with the EKC hypothesis, i.e., the ones that display negative sign (-) for the average CCC for the leads. We plotted the graphs for the 20 lags and leads for all the countries and regions (a total of 202 graphs). However, due to space constraints, it is not possible to present all of them here, but they are all available upon request.

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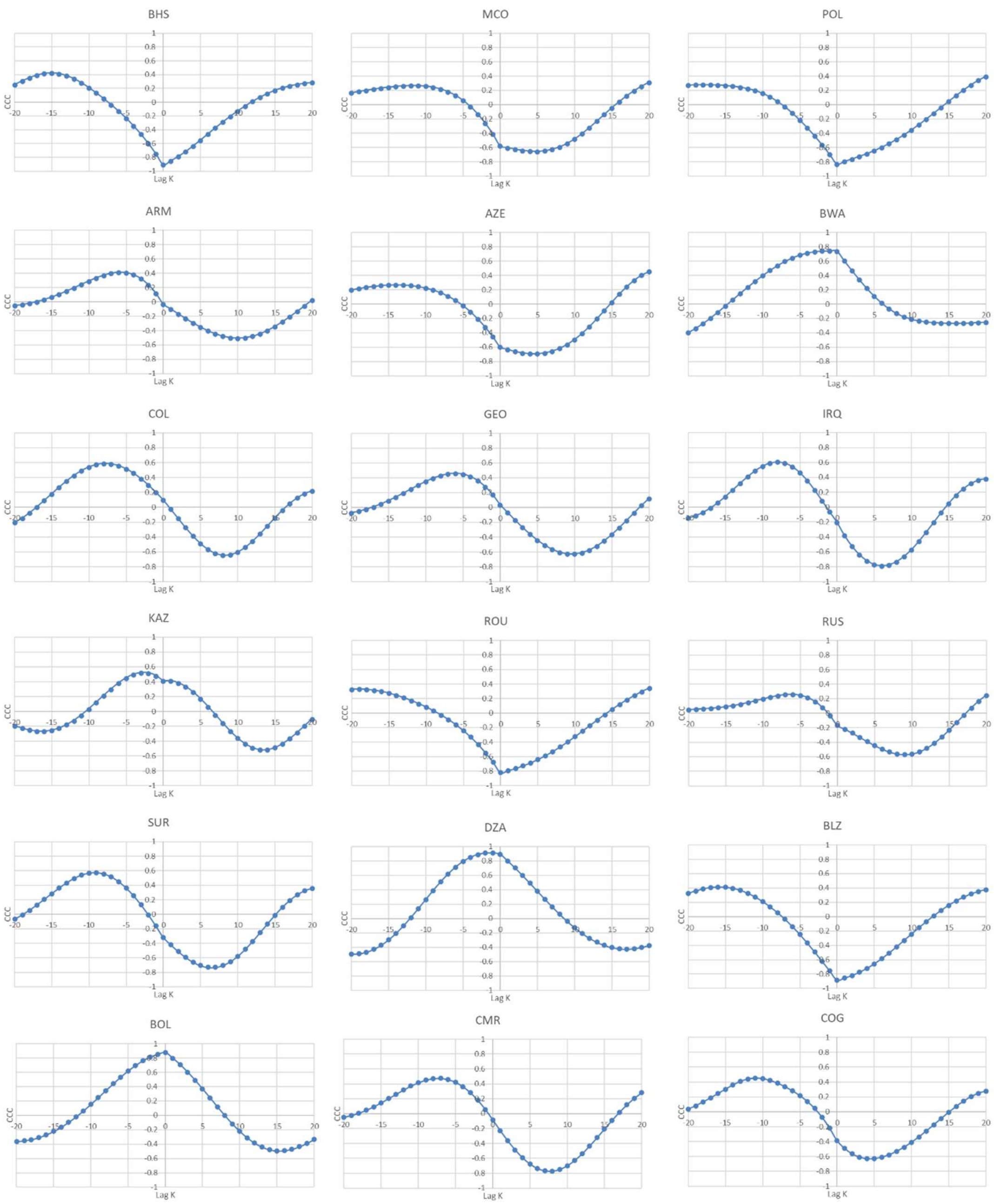

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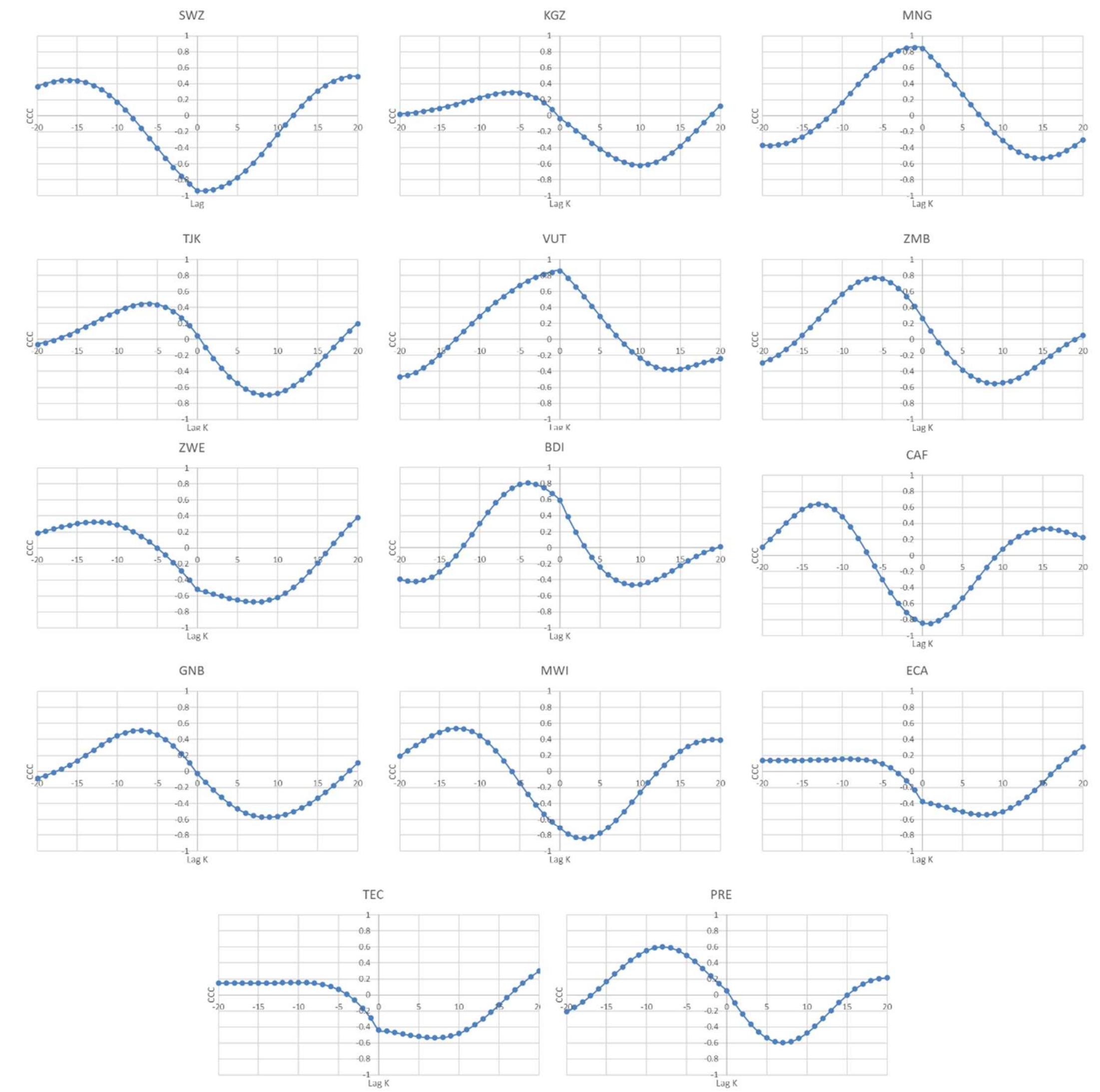

Figure 1. Plots of the cross-correlation coefficient (CCC) for countries/regions in agreement with the EKC hypothesis. Note: k negative/positive values correspond, respectively, to the lags (past)/leads(future).

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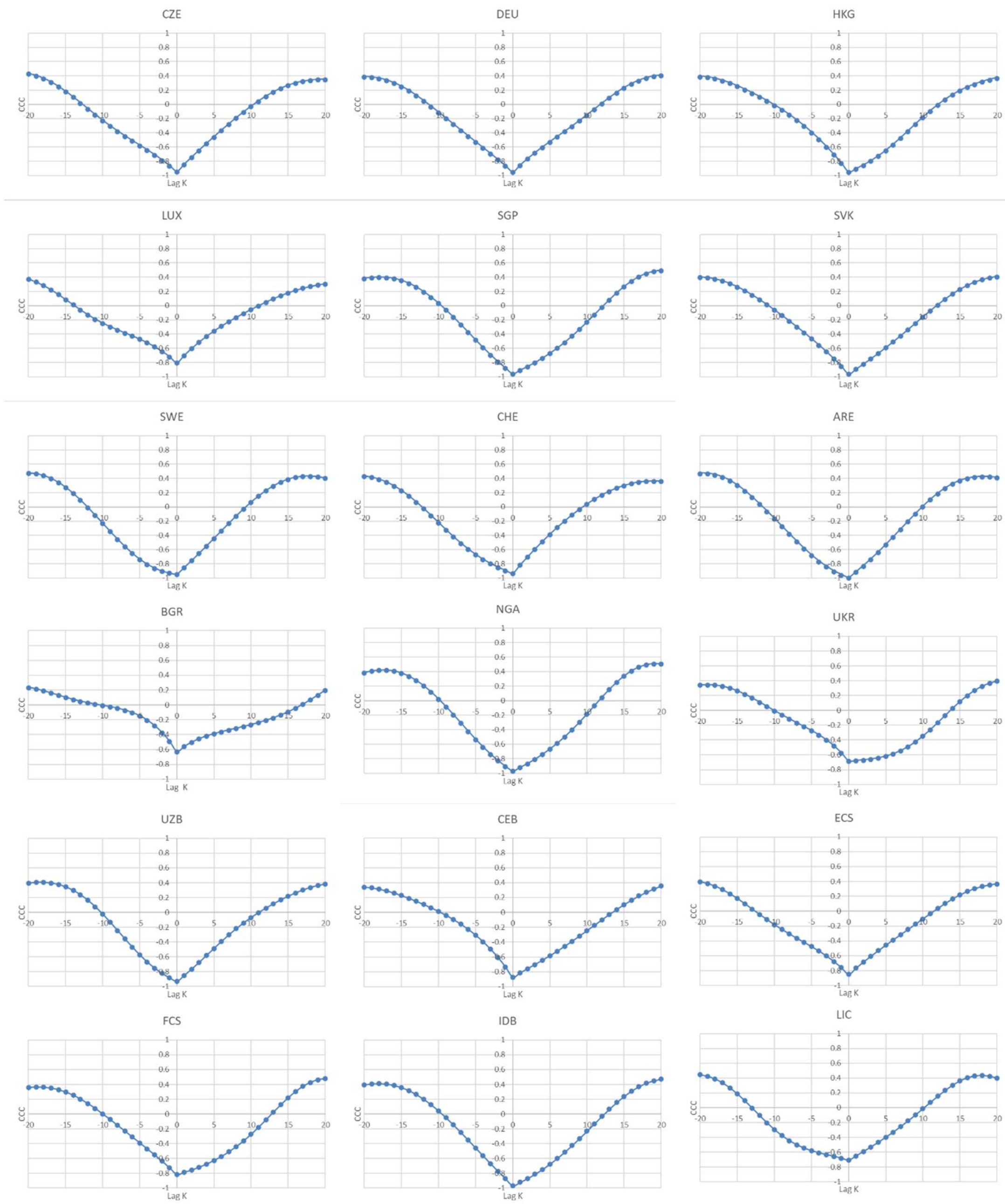

Figure 2. Plots of the cross-correlation coefficient (CCC) for countries/regions which are in partial agreement with the EKC hypothesis. Note: (i) *k* negative/positive values correspond, respectively, to the lags (past)/leads(future); (ii) were countries/regions in partial agreement with the EKC hypothesis, the ones that display negative sign (-) for the average CCC for the leads are those where an increase in income will reduce (expectantly) CO_2 emissions in the future.

5. Conclusions

Due to concerns about global climate change, the number of studies related to CO_2 emissions has increased in recent decades. Although most studies empirically identify a relationship between economic growth and environmental negative indicators in the context of the EKC, the results do not always agree, highlighting the need for deeper analysis.

This study looked at GDP and CO_2 emissions per capita from 1990 to 2020 in 158 countries and 44 world regions. Countries were grouped into income levels, with high-income countries showing the lowest alignment with the EKC hypothesis (CO_2 reduction with GDP increase), while lower-income countries showed the highest alignment. For high-income countries, there was a higher percentage of countries partially aligned with the EKC

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hypothesis. It was found that CO_2 emissions may be reduced in the future with increased GDP for high-income countries but not for lower-income countries. High-income and upper middle-income countries may not see a reduction in CO_2 emissions with GDP increase in the future, indicating a need for reinforcement of environmental policies and investment in green technologies. Upper middle-income countries should transition to more sustainable practices like renewable energy adoption and energy efficiency improvements.

In lower-middle and lower-income countries, a high percentage of nations have shown a positive correlation between economic growth and CO_2 emissions (in the past and in the future). This indicates that as GDP increases, carbon emissions also rise, which is a concerning trend. To address this issue, policymakers in these regions should prioritize sustainable development by incorporating environmental considerations into economic planning. This can be achieved through measures such as promoting renewable energy, improving energy efficiency, and implementing stricter environmental regulations to limit CO_2 emissions. Future research should focus on identifying barriers that prevent these countries from decoupling economic growth from carbon emissions, including examining socio-economic, political, and technological factors. Understanding these obstacles can help develop targeted interventions and policies to overcome the unique challenges faced by lower-middle and lower-income countries in reducing their carbon footprint.

Regarding world regions, it is possible to conclude that there are significant variations in the agreement with the EKC hypothesis. Regions such as Europe & Central Asia (excluding high income countries), Europe & Central Asia (IDA & IBRD countries), and Pre-demographic dividend, i.e., 6.82% of the analyzed regions, reveal a pattern that is aligned with the EKC hypothesis, suggesting that these regions have reached the turning point of the EKC, where economic growth starts contributing to environmental improvement. 11.36% of world regions are in partial agreement with the EKC hypothesis, suggesting they are on a sustainable development path where economic growth is decoupled from carbon emissions. For 29.55% of world regions, CO_2 levels have decreased with GDP growth in the past, but are projected to increase with future GDP growth, meaning emerging challenges exist. This shift implies potential backsliding in environmental gains and indicates the need for stronger policy interventions to obtain decoupling. For the majority of world regions, 52.27%, both past and future GDP growth are accompanied by increases in CO_2 emissions, meaning there remains a situation where economic growth is highly carbon-intensive. This reveals significant challenges in transitioning towards sustainable growth and underscores the need for urgent and robust environmental policies.

In the literature, there are contradictory results regarding EKC. The different findings depend on many criteria (e.g., the pollutants considered, the data set, the selection of variables, and the choice of methodology). In this regard, our analyses should be perceived as empirical, and they do not disprove the validity of the EKC. Although our results support the EKC hypothesis for some countries (in the different panels) and regions, this could also be considered problematic, i.e., the EKC hypothesis posits that economic growth could be a way to reduce environmental degradation, which could mean that the exploration of natural resources or the sake of economic growth may be acceptable until reaching the turning point of the curve. This means that the irreversibility of ecological damage, and the ecosystem's capacity for resilience, are apparently overlooked. Thus, actions to slow down the release of CO_2 emissions should not wait until reaching high income, i.e., independently from the income level, global, regional, and local policies are needed now to combat climate change, or at least to adapt to climate change.

Based on our research, we propose that investments be directed towards advancing energy efficiency and renewable energy in countries that do not align with the EKC hypothesis. Additionally, we advise policymakers to enhance environmental regulations, particularly for industries that are energy-intensive and contribute to pollution. These measures can thereby stimulate economic growth and lead to a critical juncture where the correlation between GDP and CO_2 emissions shifts to a negative trajectory.

Our findings in this paper are not without limitations. First, although 'carbon emissions' have great significance in theory and practice, they may not fully capture environmental degradation or environmental sustainability as a whole. The second limitation is related to obtaining data for analysis. In this regard, the series for analyzing all countries and variables was only available up to 2020.

Future research may explore other response variables such as ecological footprints, air pollution, and negative environmental sustainability-related indicators. Second, future research should explore positive environmental, sustainability-related, indicators to reinvestigate with macroeconomic indicators other than economic growth, to test our findings' reliability and resilience, which will enhance generalizability. Lastly, CCC results show association or correlation, but not causation. To

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address this, future research should explore the causal relationship between economic growth and environmental sustainability or degradation indicators. Using panel Granger causality can contribute to this line of research and enhance the generalizability of our findings.

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