



CO₂ emissions persistence: Evidence using fractional integration

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ABSTRACT

The main cause of climate change are carbon dioxide emissions. In the context of the COVID-19 pandemic, the number of emissions has been significantly reduced for the first time in many years. Now it is necessary to answer the question of whether CO₂ emissions are stationary or not, because the results will let us know whether environmental policies have to be strengthened rather than relaxed in intensity. To this end, this paper investigates the persistence in CO₂ emissions in a group of countries to determine if shocks in the series have permanent or transitory effects. The results, based on fractional integration indicate evidence of mean reversion, with values of the differencing parameter constrained between 0 and 1 in all cases, independently of the assumption made about the error term (white noise or autocorrelation). Focusing on the areas under examination, it is obtained that the EU27+UK, Japan and the US present the lowest degrees of integration, while Russia, China and India display the highest values. Decreasing time trends are only observed for the EU27+UK and US.

1. Introduction

Environmental pollution has been increasing over the last few decades and it poses a continuing risk to human lives. CO₂ emissions constitute the main cause of climate change and global warming [1–3] and are among the most used indicators of environmental degradation [4–9]. The COVID-19 pandemic has caused an unprecedented cessation of human activities; at least 186 countries established restrictions on movement by COVID-19 pandemic and 82 of them were affected by lockdown by September 2020 [10]. It has affected global energy use and CO₂ emissions that fell by 6.4% in 2020 [11] after rising steadily for decades. A decrease in global annual emissions of this magnitude had not been observed before [12,13].

The COVID-19 pandemic exposes the world to the possibilities of a protracted decarbonized environment [14] and may mark a turning point in the world's energy and economic structure, which may influence the trajectory of CO₂ emissions [15]. This pandemic may help us to better prepare for the future and offers us the opportunity to discuss the existing sustainability constraints and investigate opportunities for change [16–18].

We can use the data and existing evidence to model and forecast the socio-economic and environmental impacts and its implications on future climate change policies. While some studies indicate a fast

recovery in most countries when the pandemic finishes [19,20], others have identified changes in energy consumption associated with a massive increase in telecommuting [21]) or have suggested that the longer-term effects on CO₂ emissions are unknown [12].

But as far as we know, there are no studies that use the methodology based on the concept of fractional integration to analyse the impact of the COVID-19 pandemic on the CO₂ emissions. To know whether, in these uncertain times, environmental policies need to be strengthened rather than relaxed in intensity, it is necessary to examine if the impact of the COVID-19 pandemic on the carbon dioxide emissions will have a transitory or permanent impact. This is the objective of this study that aims to provide an empirical investigation on the persistence of CO₂ emissions to analyse if these effects are transitory or permanent. We implement techniques based on fractional integration and focus on the US, the UE27+UK, Japan, China, India and Russia which are some of the countries most affected by the COVID-19 pandemic and are the five largest emitters of carbon dioxide (US Carbon Monitor). We use the estimates of daily country-level CO₂ emissions from January 1st, 2019 to December 31st, 2020, constructed primarily from near-real-time activity data, results of the international research initiative Carbon Monitor.¹

The rest of the paper is structured as follows. Section 2 presents a literature review on the impact of the COVID-10 pandemic on carbon emissions along with a description of the fractional integration approach

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¹ <https://carbonmonitor.org/>.

used in the paper. Section 3 presents the dataset. Section 4 is devoted to the results, while Section 5 contains the discussion and Section 6 the conclusions of the reported results.

2. Literature review

Over the last 100 years the temperature on the Earth's surface has raised significantly [22–24]. The literature shows a clear relationship between CO₂ emissions and climate change and global warming [1–3].

Since the early days in the COVID-19 pandemic, the WHO has been advocating for isolation and physical distancing in order to mitigate the transmission of the virus. One of the impacts of COVID-19 is on global climate, which will improve to some extent due to the drop in consumption of energy [25]. There is evidence showing that the COVID-19 pandemic has affected CO₂ emissions, which have decreased for the first time in decades [11–13].

There is an increasing number of papers that focus on the environmental and climate effects of the COVID-19 pandemic [26]. The studies have not yet quantified either the depth or how long the cut in global carbon dioxide emissions will last, despite the relevance of CO₂ emissions for estimating the global climate change [27]. Many studies have estimated the change in emissions using different approaches. Le Quéré [28] combined government policies and activity data to forecast the annual CO₂ emissions drop. Some study used activity data from industry, transport, power generation and residential energy consumption to estimate a CO₂ emissions change for China, Europe, and the United States [21]. Other studies use fossil fuel energy demand to estimate the decline in CO₂ emissions [29], the GDP changes and inventory data for China [30], or the coal consumption and economic activity rates in China [31]. The impact of restricted human activity due to the COVID-19 pandemic on air quality in different countries or groups of countries has been analysed, for example in India [32–34], China [35–38], Europe [39–44] the United States [45,46] or Brazil [47,48]. All of them conclude that the air quality has improved by the COVID-19 pandemic.

So, the COVID-19 pandemic offers the chance to mark a turning point in the world's energy and economic structure, which may influence the trajectory of CO₂ emissions. We find several works that propose policies for managing future climate change with urgency in these times of uncertainty [19,49,50]. Climate Action Tracker [51] affirms that it is necessary to incorporate policies for low-carbon development into the economic measures designed to foster recovery from the COVID-19 pandemic. Rosenbloom et al. [52] show that policymakers should set in motion new types of economic measures associated with low-carbon pathways. The COVID-19 pandemic offers the chance to incorporate broader changes in consumption and production with regard to sustainability [52,53] and coordinated action that can create low-carbon models for business [49,54]. Other papers analyse the environmental effects of the COVID-19 pandemic and propose strategies as future guidelines for environmental sustainability such as the use of green and public transport to reduce emissions [19].

But the policies needed will be different depending on the persistence of CO₂ emissions. Recent literature before the COVID-19 pandemic addressed, using a variety of approaches, the question of whether CO₂ emissions are stationary or not. The results are contradictory and some of these studies detected that CO₂ emissions are stationary [55–57] and others affirm they are nonstationary [58–60]. There are a variety of approaches, and we can find analysis of long samples such as the 18 OECD countries [61], the study of components of the CO₂ emissions, the techniques based on conventional univariate unit-root tests [57–59,62] or the Dickey Fuller-GLS test [63]. However, these unit root tests have very low power if the true data displays a long memory pattern that is very often found in environmental series [64,65]. In fact, in this paper we use a methodology based on fractional integration that implies that the number of differences required in a series to render it stationary $I(0)$ may not be 1 (as in the unit root tests) but a fractional value.

Other papers have used a similar approach to ours. For example, Barassi et al. [61] found evidence of fractional integration and mean reversion in a long sample of 18 OECD countries, except for five of the highest polluters in per capita terms. Barros et al. [66] examined the various components of the CO₂ emissions employing also fractional integration. In another recent paper, Gil-Alana and Trani [67] analysed the evolution across time of CO₂ emissions in the European Union using a methodology based once more on the concept of fractional integration, while Gil-Alana et al. [68] studied the differences between emerging economies and G7 countries using the same methodology. In this context, it might be claimed that two years of data as is the period examined in this work is not sufficient to guaranty the validity of long memory model (see e.g., the critics in [69,70], which claim in the context of unit root models that what matters is the time span and not the number of observations). This is a point to be taken into account and thus our results should be taken with caution.

Thus, the literature offers us numerous studies about the impact of COVID-19 pandemic on CO₂ emissions, estimating the emissions change using different approaches. Other studies analyse the effect of restricted human activity due to the COVID-19 pandemic in air quality. There also are several works that propose policies for managing future climate change and finally there are many studies that analyse the stationarity of CO₂ emissions before the pandemic. But as far as we know, there are no studies looking at the persistence in CO₂ emissions after the pandemic.

Our contribution is important because there are no studies that use the methodology based on the concept of fractional integration to analyse the impact of the COVID-19 pandemic on the CO₂ emissions. Furthermore, we focus on the world's largest emitters of CO₂ and in those countries most affected by the pandemic. It is important to examine if the impact of the COVID-19 pandemic on the large emitters of carbon dioxide will have a transitory or permanent impact. These results are necessary to know whether, in these times of uncertainty, environmental policies have to be strengthened rather than relaxed in intensity.

3. Data

We use daily data of CO₂ emissions (MtCO₂ per day) from the world's largest emitters, these being the EU27+UK, the US, Japan, Russia, China and India. The number of observations reaches 730 from January 1, 2019 to December 31, 2020 to assess CO₂ emissions before and during COVID-19. The data source is Carbon Monitor² that is a near-real-time daily CO₂ emission dataset to monitor the variations in CO₂ emissions at the national level, with global coverage on a daily basis and the potential to be frequently updated. We consider the total emissions that result from the sum of the emissions of the sectors considered by Carbon Monitor (Power, Ground transport, Industry, Residential, Domestic aviation). This Carbon Monitor dataset is very appropriate for our study because it manifests the dynamic nature of CO₂ emissions through daily variations as influenced by the unfolding impacts of the COVID-19

Table 1
Descriptive statistics.

Series	Mean	St. Deviation	Max. Value	Min. Value
CHINA	33.685	4.163	36.62	30.742
INDIA	8.265	0.508	8.624	7.905
JAPAN	2.962	0.256	3.144	2.781
RUSSIA	4.664	0.323	4.893	4.436
EU27 + UK	7.961	1.383	8.939	6.983
US	12.982	0.295	13.195	12.776
WORLD	99.769	9.424	106.433	93.105

² data available at <https://carbonmonitor.org/>.

pandemic [21].

Table 1 displays some descriptive statistics. We observe that the country with the highest mean CO₂ emissions is China (33.686), while the economies with the lowest mean CO₂ emissions are Japan (2.963) and Russia (4.665). China is also the highest volatile country within this group with the highest standard deviation (4.163), while Japan with the lowest standard deviation (0.257) is the least volatile.

4. Results

Our results are based on the following regression model,

$$y_t = \alpha + \beta t + x_t, \quad (1 - B)^d x_t = u_t, \quad t = 1, 2, \dots, \quad (1)$$

where y_t is the time series we observe (CO₂ emissions), α and β are unknown coefficients referring respectively to a constant and the coefficient for a linear time trend, and the regression errors, x_t are integrated of order d or $I(d)$ where d is a real value and B refers to the backshift operator, i.e., $Bx_t = x_{t-1}$, so that u_t is an $I(0)$ process. Note that the fact that d may be any real value to be estimated allows us to consider a higher degree of flexibility in the specification of the model, including, for instance, stationary long memory models (if $0 < d < 0.5$) and nonstationary though mean reverting processes (if $0.5 \leq d < 1$).³

Tables 2 and 3 refer to the case of white noise errors, while in Tables 4 and 5 weak autocorrelation is allowed by means of the exponential model of Bloomfield (1973) [68].⁴

We see across Tables 2 and 3 that the time trend coefficient is insignificant in all cases, while the intercept is required; the estimates of d are all in the range (0.5, 1) displaying nonstationarity with mean reversion, the values ranging from 0.62 (EU27 + UK) to 0.89 (India).

Allowing autocorrelation (Tables 4 and 5) the time trend is required for the EU27 + the UK and the US, displaying in both cases a negative time trend. The estimated values of d are once more lower than 1 (and thus displaying mean reversion) though they are now slightly smaller, moving from 0.26 (EU27 + UK) to 0.76 (India). Using logs, the same conclusions hold and the results are reported in the four tables in the

Table 2
Estimates of the differencing parameter. White noise errors.

Series	No terms	With a constant	With a constant and a linear time trend
CHINA	0.97 (0.91, 1.03)	0.86 (0.79, 0.93)	0.86 (0.79, 0.93)
INDIA	0.97 (0.92, 1.03)	0.89 (0.83, 0.96)	0.89 (0.83, 0.96)
JAPAN	0.84 (0.78, 0.91)	0.69 (0.62, 0.79)	0.69 (0.62, 0.79)
RUSSIA	0.91 (0.87, 0.96)	0.76 (0.72, 0.82)	0.76 (0.72, 0.82)
EU27 + UK	0.79 (0.71, 0.89)	0.62 (0.53, 0.75)	0.62 (0.53, 0.75)
US	0.92 (0.86, 1.00)	0.73 (0.66, 0.83)	0.73 (0.66, 0.83)
WORLD	0.96 (0.90, 1.03)	0.70 (0.64, 0.79)	0.70 (0.64, 0.79)

NB. We report the estimates of d along with their associated 95% confidence bands. Values in bold correspond to the selected specification for the deterministic terms, i.e., the selected models depending on the inclusion of a constant or a constant with a linear trend.

³ Note that reversion to the mean occurs as long as d is smaller than 1, and lower the value of d is, faster is the process of reversion.

⁴ The model of Bloomfield [71] reproduces the autocorrelation structure of autoregressive (AR) models without imposing a parametric explicit model. It has the advantage that it accommodates very well in the context of fractional integration. (See, e.g. [72]).

Table 3
Estimated coefficients of the selected models in Table 2.

Series	No terms	With a constant	With a constant and a linear time trend
CHINA	0.86 (0.79, 0.93)	30.867 (29.06)	–
INDIA	0.89 (0.83, 0.96)	7.892 (30.86)	–
JAPAN	0.69 (0.62, 0.79)	2.950 (15.51)	–
RUSSIA	0.76 (0.72, 0.82)	4.458 (35.55)	–
EU27 + UK	0.62 (0.53, 0.75)	8.440 (11.04)	–
US	0.73 (0.66, 0.83)	13.443 (21.85)	–
WORLD	0.70 (0.64, 0.79)	95.990 (32.24)	–

Values in parenthesis in column 3 are the corresponding t-values.

Table 4
Estimates of the differencing parameter. Autocorrelated errors.

Series	No terms	With a constant	With a constant and a linear time trend
CHINA	0.84 (0.78, 0.93)	0.66 (0.59, 0.73)	0.65 (0.59, 0.73)
INDIA	0.93 (0.85, 1.01)	0.76 (0.69, 0.82)	0.76 (0.69, 0.82)
JAPAN	0.65 (0.60, 0.70)	0.43 (0.37, 0.48)	0.42 (0.38, 0.48)
RUSSIA	0.89 (0.84, 0.97)	0.66 (0.62, 0.72)	0.66 (0.62, 0.71)
EU27 + UK	0.48 (0.41, 0.53)	0.27 (0.23, 0.32)	0.26 (0.23, 0.32)
US	0.71 (0.66, 0.77)	0.44 (0.39, 0.49)	0.43 (0.39, 0.50)
WORLD	0.82 (0.76, 0.88)	0.48 (0.44, 0.53)	0.49 (0.44, 0.53)

NB. We report the estimates of d along with their associated 95% confidence bands. Values in bold correspond to the selected specification for the deterministic terms, i.e., the selected models depending on the inclusion of a constant or a constant with a linear trend.

Table 5
Estimated coefficients of the selected models in Table 3.

Series	No terms	With a constant	With a constant and a linear time trend
CHINA	0.66 (0.59, 0.73)	30.584 (35.17)	–
INDIA	0.76 (0.69, 0.82)	7.838 (32.86)	–
JAPAN	0.43 (0.37, 0.48)	3.035 (35.64)	–
RUSSIA	0.66 (0.62, 0.72)	4.465 (40.17)	–
EU27 + UK	0.26 (0.23, 0.32)	8.883 (37.64)	–0.00163 (–3.02)
US	0.43 (0.39, 0.50)	14.009 (42.64)	–0.00233 (–2.69)
WORLD	0.48 (0.44, 0.53)	95.790 (54.29)	–

Values in parenthesis in column 3 are the corresponding t-values.

Appendix.

5. Discussion

To examine the CO₂ emissions persistence after the COVID-19 pandemic is essential because, on the one hand, these emissions are

the main cause of climate change and, on the other hand, the pandemic has pushed down the CO₂ emissions for the first time in many years. However, even though there are many studies about the environmental and climate effects of the COVID-19 pandemic (e.g. [25,27]), it is also necessary to look at the persistence of CO₂ emissions after the COVID-19 using updated time series methods like fractional integration.

This work shows evidence of fractional integration in all cases, with values of the differencing parameter constrained between 0 and 1 in all the series investigated, independently of the assumption made about the error term (white noise or autocorrelation). Focusing on the areas under examination, the EU27+ the UK, Japan and the US present the lowest degrees of integration, while Russia, China and India display the highest values. On the other hand, decreasing time trends are only observed for the EU27+ the UK and US.

These findings suggest that although the COVID-19 pandemic may prepare us better for the future and offers us the opportunity to discuss the existing sustainability constraints and investigate opportunities for change [16–18], it is necessary to act quickly and with intensive policies because the shock is transitory, especially in the EU27+UK, Japan and the US. Our work points to climate change advantages after COVID-10 pandemic, but only if governments take advantage of the drop in CO₂ emissions and implement low-carbon development strategies.

For all the analysed countries, but especially for the EU27+UK, Japan and the US, there is evidence that it is necessary to take advantage of the changes brought about by COVID-19 to intensify the policy reforms. The empirical analysis conducted in this study shows that if the policymakers do not take reforms, CO₂ emissions might rebound or grow quickly in the future and we will have lost an opportunity to improve the future environment.

Our results are consistent with other studies that show that COVID-19 pandemic can have important implications on future climate change policies [50], and it can be a chance for the implementation of structural changes towards net-zero emissions [69] and for the development of policies against global climate change [70]. Our results are also consistent with many works that propose policies for managing future climate change with urgency in these times [19,48,49].

6. Conclusions

This paper examines the persistence of CO₂ emissions using a methodology based on fractional integration. Our objective was to find evidence of whether the impact of the COVID-19 pandemic on CO₂ emissions will be transitory or permanent to know whether it is appropriate to adopt strong policies or not to curb climate change.

Focusing on the world's largest CO₂ emitters and those most affected by the pandemic, our results show low levels of persistence. We have found the lowest degrees of integration for the EU27+UK, Japan and the US, while Russia, China and India display the highest values. Decreasing time trends are only observed for the EU27+ the UK and US.

These results show that in all the world's largest emitters of CO₂ emissions, the effects of COVID-19 will be transitory, especially in the

EU27+UK, Japan and the US where the degrees of integration are lower. If governments and policymakers do not adopt strong policy measures, we will lose the opportunity to incorporate broader changes in terms of sustainability.

Our results show that the CO₂ emissions will grow quickly in the future if policymakers and governments do not adopt strong policy measures. This historic moment in which the CO₂ emissions has pushed down for the first time in many years should serve to incorporate broader changes in terms of sustainability and to coordinate action that creates low-carbon models. We propose to incorporate policies for low-carbon development into the economic measures designed to recover from the COVID-19 pandemic and set in motion new types of economic measures associated with low-carbon pathways [50,51].

As a final comment, the paper can be extended in several directions. From a methodological viewpoint, longer time series should be examined, and nonlinear structures can be incorporated in the model, including non-linear deterministic trends like those propose in [73] and based on Chebyshev polynomials in time or even other more complex structures based on Fourier functions [74] or neural networks [75]. Work in these directions is now in progress.

Consent for publication

Not applicable.

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Credit author statement

Dr. Gloria Claudio proposed the original idea. She conducted the introduction, literature review, interpreted the empirical results and conclusions. Prof. Luis A. Gil-Alana conducted the empirical results, interpretation of the results and discussion along with the general overview of the manuscript.

Declaration of competing interest

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

APPENDIX. Results in logarithm form

Table A1

Estimates of the differencing parameter. White noise errors

Series in logs	No terms	With a constant	With a constant and a linear time trend
CHINA	1.00 (0.94, 1.06)	0.87 (0.81, 0.95)	0.87 (0.81, 0.95)
INDIA	0.98 (0.93, 1.04)	0.87 (0.82, 0.93)	0.87 (0.82, 0.93)
JAPAN	0.83 (0.77, 0.90)	0.68 (0.61, 0.77)	0.68 (0.61, 0.77)
RUSSIA	0.93 (0.89, 0.99)	0.73 (0.69, 0.79)	0.73 (0.69, 0.79)
EU27 + UK	0.86 (0.80, 0.95)	0.57 (0.49, 0.69)	0.57 (0.49, 0.69)
US	0.98 (0.83, 1.05)	0.71 (0.65, 0.80)	0.71 (0.65, 0.80)
WORLD	1.00 (0.95, 1.06)	0.69 (0.63, 0.77)	0.69 (0.63, 0.77)

NB. We report the estimates of d along with their associated 95% confidence bands. Values in bold correspond to the selected specification for the deterministic terms, i.e., the selected models depending on the inclusion of a constant or a constant with a linear trend.

Table A2
Estimated coefficients of the selected models in Table A1

Series	No terms	With a constant	With a constant and a linear time trend
CHINA	0.87 (0.81, 0.95)	3.429 (88.89)	–
INDIA	0.87 (0.82, 0.93)	2.065 (50.12)	–
JAPAN	0.68 (0.61, 0.77)	1.079 (15.88)	–
RUSSIA	0.73 (0.69, 0.79)	1.494 (47.13)	–
EU27 + UK	0.57 (0.49, 0.69)	2.131 (23.47)	–
US	0.71 (0.65, 0.80)	2.598 (55.07)	–
WORLD	0.69 (0.63, 0.77)	4.563 (136.54)	–

Values in parenthesis in column 3 are the corresponding t-values.

Table A3
Estimates of the differencing parameter. Autocorrelated errors

Series in logs	No terms	With a constant	With a constant and a linear time trend
CHINA	0.95 (0.88, 1.05)	0.65 (0.59, 0.73)	0.66 (0.59, 0.73)
INDIA	0.96 (0.89, 1.06)	0.78 (0.72, 0.86)	0.78 (0.72, 0.86)
JAPAN	0.65 (0.60, 0.71)	0.42 (0.37, 0.48)	0.42 (0.37, 0.48)
RUSSIA	0.92 (0.85, 0.99)	0.64 (0.60, 0.69)	0.64 (0.60, 0.69)
EU27 + UK	0.64 (0.58, 0.70)	0.26 (0.22, 0.31)	0.26 (0.21, 0.30)
US	0.89 (0.82, 0.94)	0.45 (0.40, 0.51)	0.45 (0.40, 0.51)
WORLD	0.97 (0.90, 1.07)	0.47 (0.43, 0.53)	0.47 (0.43, 0.53)

NB. We report the estimates of d along with their associated 95% confidence bands. Values in bold correspond to the selected specification for the deterministic terms, i.e., the selected models depending on the inclusion of a constant or a constant with a linear trend.

Table A4
Estimated coefficients of the selected models in Table A3

Series	No terms	With a constant	With a constant and a linear time trend
CHINA	0.65 (0.59, 0.73)	3.419 (107.19)	–
INDIA	0.78 (0.72, 0.86)	2.060 (52.23)	–
JAPAN	0.42 (0.37, 0.48)	1.098 (35.59)	–
RUSSIA	0.64 (0.60, 0.69)	1.494 (53.50)	–
EU27 + UK	0.26 (0.21, 0.30)	2.164 (68.23)	–0.00191 (–2.69)
US	0.45 (0.40, 0.51)	2.634 (95.29)	–0.00017 (–2.28)
WORLD	0.47 (0.43, 0.53)	4.552 (245.31)	–

Values in parenthesis in column 3 are the corresponding t-values.

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