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RESEARCH ARTICLE

Modelling the globalization-CO_2 emission nexus in Australia: evidence from quantile-on-quantile approach

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Abstract
Sustainable development policies for achieving net-zero emissions require understanding the factors that influence carbon emissions. Capitalizing on the limitations of the existing literature, this study applies the quantile-on-quantile approach to investigate economic globalization's impact on carbon emissions in Australia for 1970–2018. The results from the quantile-on-quantile revealed a positive feedback linkage between globalization and carbon emissions at all quantiles. The results further indicated that while there is a positive feedback linkage between economic growth and carbon emissions at most quantiles, a positive feedback interconnection exists between carbon emissions and coal consumption at all quantiles. As a robustness check, we employed the quantile regression test, and the results from quantile regression are consistent with the findings from the quantile-on-quantile approach. The consistency of the results suggests that these study findings are reliable and suitable for informing policies that seek to address carbon emissions in Australia. The policy implications for Australia are discussed.

Keywords Australia · Globalization · CO_2 emissions · Quantile-on-quantile approach

Introduction

The Paris Agreement on climate change and the sustainable development goal (SDG)13 prioritize countries to take urgent measures to combat climate change and its impact. Tackling climate change requires implementing strategies for mitigating carbon emissions, the chief greenhouse gas responsible for climate change. The Australian government remains committed to achieving the Paris Agreement on climate change and SDG 13. For instance, the Australian government has implemented carbon emissions reduction initiatives such as improving the efficiency of vehicles, developing strategies to enhance the utilization of solar power, developing a low emissions technology roadmap, phasing down hydrofluorocarbons, and having a national energy productivity plan[1] to contribute to combating climate change. Despite implementing these innovative strategies, carbon emissions continue to soar in Australia due to robust economic growth and the consumption of fossil fuels.

Undoubtedly, economic development in advanced economies improves living standards and comes with environmental costs (Acheampong 2019; Khan et al. 2021a; Shahbaz et al. 2016a). Most developed economies recognize the dangers of economic growth and have implemented several environmentally sustainable strategies to mitigate the adverse effects of economic growth and development on the environment (Adebayo et al. 2021; Alola et al. 2019). Such interventions have achieved promising outcomes, but not at the pace of global environmental concerns. The twenty-first century has been dubbed the "jet age," in which the whole world has been reduced to a tiny village due to technological advancements.

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[1] https://www.environment.gov.au/system/files/resources/f52d7587-8103-49a3-aeb6-651885fa6095/files/summary-australias-2030-emissions-reduction-target.pdf

The advantages of this transition from localized individualized states to an internationally integrated society are numerous (Sarkodie et al. 2020). Thus, integrating distant economies through capital flows, trade, foreign direct investment, and technological opportunities contributes significantly to economic growth and development (Shahbaz et al. 2017b).

While economic globalization promotes economic development, it also impacts the environment (Hipolito Leal and Cardoso Marques 2019; Rahman 2020; Shahbaz et al. 2017b). Theoretically, the impact of globalization on CO_2 emissions is priori uncertain. Thus, there is a conflicting theoretical debate on economic globalization-CO_2 emissions relationships. For instance, the proponents of the pollution-haven hypothesis opine that developing countries have been the host of environmental polluting industries from the developed economies due to the stringent environmental regulatory policies in advanced economies. The strict environmental regulatory policies in the advanced economies impose a high cost on degrading environmental industries. To remain competitive, these environmental degrading industries relocate to developing countries with weak environmental regulatory policies (Wheeler 2001). Contrarily, the proponents of the pollution-halo hypothesis argue that globalization reduces CO_2 emissions as it ensures the transfer and spread of environmentally efficient technologies, knowledge, and standard environmental management practices in the host countries (Acheampong et al. 2019a, 2019b; Doytch and Uctum 2016; Pao and Tsai 2011). Similarly, Krugman et al. (2017) argue that globalization can retard CO_2 emissions by stimulating countries to change their production and consumption mix as they become wealthier. With the conflicting theoretical debates, the empirical findings remain inconsistent and inconclusive. For instance, some of the studies have reported a positive effect of globalization on CO_2 emissions (Abdouli et al. 2018; Meng et al. 2018; Shahbaz et al. 2018), while others have reported a negative effect of globalization on CO_2 emissions (Liu et al. 2017; Lv and Xu 2018; Shujah Ur et al. 2019). The last group of empirical studies has also reported a neutral effect of globalization on CO_2 emissions (Dogan and Turkekul 2016; Haseeb et al. 2018; Xu et al. 2018).

While recent studies have attempted to probe the environmental impact of globalization on globalization on CO_2 emissions, You and Lv (2018) argue that the environmental effect of globalization requires further scrutiny due to the limitations of the existing studies. For instance, prior empirical studies have either used trade openness or foreign direct investment as a proxy for economic globalization to examine their respective effect on CO_2 emissions (Acheampong 2018; Acheampong et al. 2019a, 2019b; Ning and Wang 2018; Sarkodie and Strezov 2019; Shahbaz et al. 2017a). However, neither trade openness nor foreign direct investment is an adequate measure of economic globalization since they fail to capture other economic globalization dimensions such as the spread of technology, capital controls, and knowledge beyond borders (Lv and Xu 2018). It is argued that overlooking these dimensions of economic globalization can seriously underestimate economic globalization's effect on CO_2 emissions (Lv and Xu 2018; You and Lv 2018).

Also, the prior empirical studies on the relationship between globalization and CO_2 emissions are restricted to the traditional parametric econometric approaches (Shariff et al. 2020; Shahbaz et al. 2020; Adebayo and Kirikkaleli 2021; Rjoub et al. 2021; Kihombo et al. 2021). However, parametric estimators are not robust to outliers and sometimes fail to account for slope heterogeneity (Dzator and Acheampong 2020). Therefore, understating the effect of economic globalization on CO_2 emissions requires an advanced novel econometric approach robust to outliers and could account for slope heterogeneity. However, using a non-parametric econometric estimator such as the quantile-on-quantile (QQ) approach to examine the impact of economic globalization on CO_2 emissions remains rare in the literature. Therefore, this study seeks to fill these knowledge gaps by applying the QQ approach to investigate economic globalization's effect on CO_2 emissions in Australia for 1970–2018 while controlling economic growth and coal consumption.

Investigating the impact of globalization on CO_2 emissions in Australia while controlling for economic growth, coal consumption is crucial since Australia is a prosperous nation with natural resources with an enormous territory area. For a century, open immigration policies are critical for sustainable growth and a liberalized economic and trade environment. Australia has gained in the last four decades due to the emergence of globalization due to reducing trade barriers, smooth flows of capital, technological diffusion, labor mobility, and better use of resources. This research focuses on Australia, which has unique features which make the nation particularly fascinating to study. Australia is ranked 15th position globally in terms of greenhouse gas (GHG) pollution. Besides, Australia is the second biggest coal exporter and the world's leading liquefied natural gas exporter (LNG) (Crabonbrief 2021).

Despite the increased use of gas and renewables, mainly rooftop solar, the electricity system heavily depends on coal. It is also highly susceptible, including excessive temperatures, droughts, bushfires, and agriculture damage, to the effects of climate change. Australia is off-track to reducing emissions by 26–28% by 2030 compared to the 2005 pace. Also, Australia rendered its climate commitment to the Paris climate talks in August 2015 (Crabonbrief 2021). By 2030, Australia pledged to reduce emissions by 26–28% relative to the 2005 level. Also, Australian energy consumption increased by 0.6% between 2018 and 2019 to achieve 6196 petajoules. Fossil fuels (oil, gas, and coal) contributed to 94% of the primary energy mix in Australia between 2018 and 2019, with oil (39%), coal (29%), natural gas (26%), and renewable energy (6%).

Furthermore, Figures 1 and 2 present the total energy supply (TES) by source and low-carbon electricity generation in Australia from 1990 to 2019.

Finally, Australia is firmly integrated with the rest of the world and pursuing some trade agreements, including the Comprehensive and Progressive Agreement for Trans-Pacific, Peru-Australia Free Trade Agreement, the Indonesia-Australia Comprehensive Economic Partnership, and Hong Kong-Australia Free Trade Agreement. When these trade agreements are finalized, they will cover 88% of Australia's trade (Department of Foreign Affairs and Trade 2019). For these reasons, focusing on Australia will contribute significantly to the literature and further inform policies for achieving the net zero by 2050 in Australia.

This study contributes to the literature in the following ways: To the authors' knowledge, this paper extends the literature on the globalization-carbon emissions relationship by being the first empirical study to employ Sim and Zhou's (2015) QQ technique to examine the impact of economic globalization on CO_2 emissions in Australia. Bekun et al. (2021) and Sharif et al. (2020) argue that econometric approaches are crucial in achieving unbiased research outcomes and recommend using effective advanced novel econometric methods. The QQ method is advantageous because it can combine the concepts of quantile regressions (QR) and non-parametric estimation analysis distinguishes it. The QQ approach is robust to outliers and could account for slope heterogeneity. Secondly, we used the non-parametric causality-in-quantiles test to capture causality between CO_2 emissions and the regressors (globalization, economic growth, and coal consumption). Since causation in the conditional mean may not exist during some periods, but higher-order interdependencies may be substantial, such an assessment is critical. The mean and variance causality link between CO_2 emissions and the regressors (globalization, economic growth, and coal consumption) can be tested using this technique. Third, the literature review suggests that most empirical studies are based on panel data modeling techniques. Although estimates from panel data techniques are efficient, their conclusions and policy implications may not apply to individual countries due to their heterogeneities (Acheampong 2018; Coggin 2019). With this argument, this study further adds to the body of knowledge by utilizing a time-series approach to analyze the effect of globalization on CO_2 emissions to provide policy guidelines to Australia. Finally, this study relies on the KOF economic globalization index to provide a broader perspective than the existing studies that either uses trade openness or foreign direct as a proxy for globalization. The Konjunkturforschungsstelle (KOF) economic globalization index is multidimensional, capturing trade in goods and services, trade partner diversity, foreign direct investment, portfolio investment, international debt, international reserves, and international income payments (Gygli et al. 2019). Finally, this study is relevant for policy since the outcome will contribute to Australia's formulation and implementation of future climate change policies.

The remaining section of this paper is outlined as follows: Literature review is presented in the "Review of related literature" section. The "Methodology and data" section presents methodology and data, while the "Empirical results" section presents empirical findings and discussions. Conclusion and policy implications are presented in the "Conclusion and policy implications" section.

Review of related literature

The pollution-haven and pollution-halo hypotheses are the main theoretical framework for studying the relationship between globalization and CO_2 emissions. The proponents of the pollution-haven hypothesis opine that developing countries have been the host of environmental polluting industries

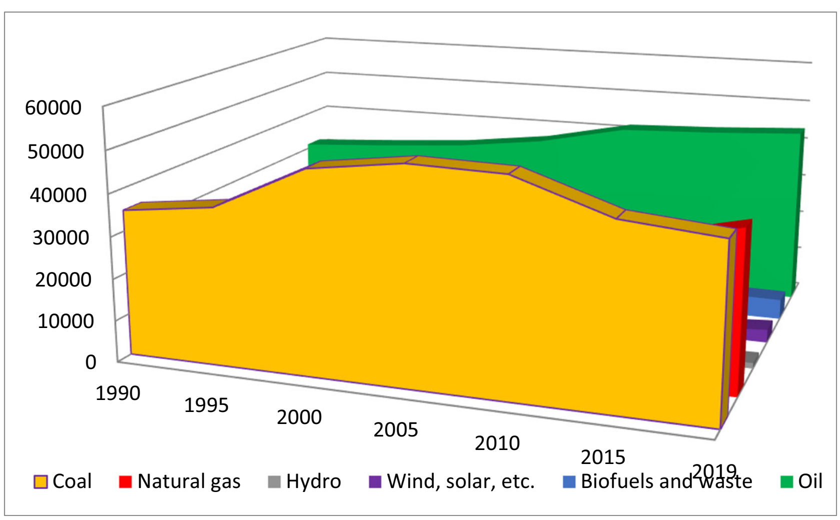


Fig. 1 Total energy supply (TES) by source, Australia 1990–2019 (Ktoe)

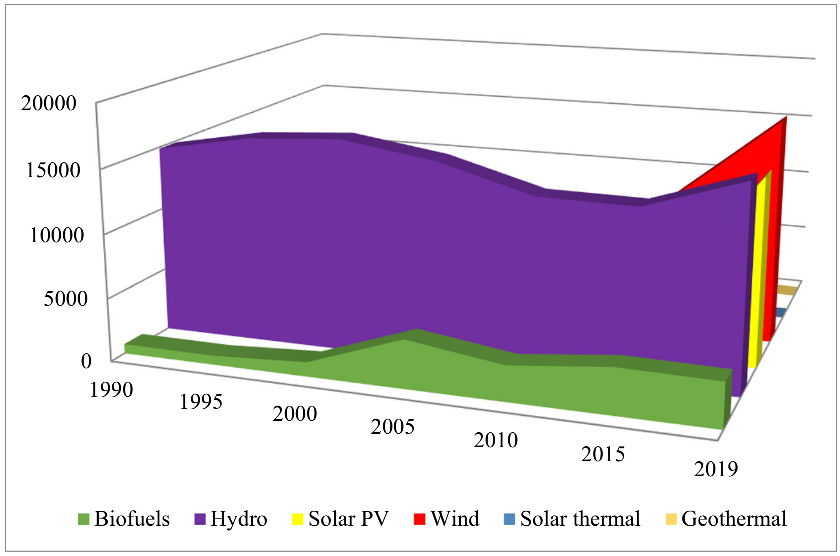


Fig. 2 Low-carbon electricity generation by source, Australia 1990–2019 (GWh)

from the developed economies due to the stringent environmental regulatory policies in advanced economies. The strict environmental regulatory policies in the advanced economies impose a high cost on degrading environmental industries. To remain competitive, these environmental degrading industries relocate to developing countries with weak environmental regulatory policies (Wheeler 2001). The pollution-haven hypothesis implies that globalization reduces environmental pollution, such as mitigating CO_2 emissions in developed economies while it increases CO_2 emissions in developing countries. Some existing empirical results have collaborated with the pollution-haven hypothesis using either a time series or panel data approach. For instance, Akadiri et al. (2019b) revealed that globalization worsens CO_2 emissions. Shahbaz et al. (2017b) also found that globalization induces higher CO_2 emissions in Japan.

For BRICTS countries, Abdouli et al. (2018) found that globalization proxied by FDI increases CO_2 emissions. Further, in Pakistan, Khan and Ullah (2019) found that economic, political, and social globalizations contribute to higher CO_2 emissions. For the case of 25 developed countries, Shahbaz et al. (2017b) indicated that globalization contributes to CO_2 emissions. For 83 countries, You and Lv (2018) showed that economic globalization contributes to CO_2 emissions. Using panel data for 101 countries, Meng et al. (2018) also revealed that globalization measured by trade openness worsens CO_2 emissions. Akadiri et al. (2019a) also showed that globalization worsens CO_2 emissions in Italy. For South Africa, Kohler (2013) also found that trade openness worsens CO_2 emissions. Further, the study of Acheampong et al. (2019a, 2019b) found that while FDI reduces CO_2 emissions, trade openness increases CO_2 emissions in 46 sub-Saharan African countries. Also, Shahbaz et al. (2018) found that FDI contributes to CO_2 emissions in France. Shahbaz et al. (2015) further observed that globalization increases CO_2 emissions in India.

Contrarily, the proponents of the pollution-halo hypothesis argue that globalization reduces CO_2 emissions as it ensures the transfer and spread of environmentally efficient technologies, knowledge, and standard environmental management practices in the host countries (Acheampong et al. 2019a, 2019b; Doytch and Uctum 2016; Pao and Tsai 2011). Similarly, Krugman et al. (2017) argue that globalization can retard CO_2 emissions as it could stimulate countries to change the mix of their production and consumption as they become wealthier. Some of the existing empirical findings have confirmed the pollution-halo hypothesis using time series or panel data approaches. For instance, Lee and Min (2014) found that globalization curbs CO_2 emissions in a panel of 225 countries. For 112 Chinese cities, Liu et al. (2017) found that globalization measured by FDI reduces CO_2 emissions. Also, for 15 emerging economies, Lv and Xu et al. (2018) found that globalization measured by FDI mitigates CO_2 emissions. Rahman (2020) also observed that globalization reduces CO_2 emissions. Also, Shahbaz et al. (2016b) indicated that globalization improves CO_2 emissions in a panel of 19 Africa countries.

Similarly, Shujah Ur et al. (2019) revealed that globalization reduces carbon emissions in 16 Central and Eastern Africa countries. Focusing on the Asia Pacific Economic Cooperation countries, Zaidi et al. (2019) indicated that globalization reduces carbon emissions. For the case of 5 Southeast Asian countries, Zhu et al. (2016) suggested that FDI lowers carbon emissions. Similarly, Acheampong (2018), using the system GMM-PVAR approach, found that trade openness reduces carbon emissions in Asia-Pacific, MENA, sub-Saharan Africa, and globally. In another study, Shahbaz et al. (2013) found that globalization measured by trade openness improves CO_2 emissions in South Africa. Similarly, Zhang and Zhou (2016) found that FDI lowers carbon emissions from western, eastern, and central regions in China.

Inconsistent with both the pollution-haven and pollution-halo hypothesis, another empirical study revealed that globalization has a neutral effect on CO_2 emissions. For instance, Haseeb et al. (2018) utilized the dynamic seemingly unrelated regression and Dumitrescu-Hurlin Causality approach and found that globalization does not affect carbon emissions in BRICS countries. Also, Boutabba (2014) revealed that trade openness exerts no effect on carbon emissions in India. Dogan and Turkekul (2016), using ARDL, also found that trade has no significant relationship with carbon emissions in the USA. Xu et al. (2018) found that globalization has an insignificant effect on carbon emissions in Saudi Arabia. Le and Ozturk (2020a, 2020b) study on the globalization-emission association unveils that globalization impacts emissions positively.

Also, several studies have explored other determinants of environmental degradation. For instance, Khan et al. (2021) assessed the CO_2-GDP interrelationship in the top ten manufacturing countries and found a positive linkage between GDP and CO_2. Likewise, Khan and Hou (2021) used thirty IEA countries to support the positive GDP-CO_2 interrelationship. The positive connection between GDP and emissions is also validated by the studies of Yuping et al. (2021) for Argentina, Shan et al. (2021) for decentralized economies, Khan et al. (2021c), Ahmad et al. (2021) for G7 economies, Khan et al. (2021d), Lawal et al. (2020), and Murshed and Dao (2020) for South Asian countries. Furthermore, using South Asian economies as a case study, the study of Usman et al. (2021) disclosed that an increase in economic growth contributes to environmental degradation. The study of Gyamfi et al. (2021) using E-7 economies unveiled that energy consumption and economic growth contribute to environmental degradation. Moreover, Qin et al. (2021) research on the influence of financial inclusion on environmental degradation reveals that financial development and economic growth contribute to the degradation of the environment. Murshed (2021) demonstrated that an upsurge in economic growth and LPG consumption triggers environmental degradation using South Asian economies as a case study and recent econometric approaches. In their analysis, Khan et al. (2021b) reported that an increase in natural resources, economic growth, and population enhances environmental degradation in the USA. Similarly, the study of Murshed (2020) unveiled that trade openness and ICT increase environmental degradation. Recently, the study of Rehman et al. (2021) in China on the asymmetric linkage between CO_2 emissions and urbanization and energy utilization found that an increase (decrease) in GDP and urbanization increases (decreases) CO_2 emissions.

Given these conflicting theoretical and empirical findings, further studies are needed to reconcile the inconsistency in the literature. Existing studies have employed different econometric approaches and different globalization measures to examine the effect of globalization on CO_2 emissions. The empirical literature survey reveals that the existing studies' results are conflicting and still inconclusive as some studies report either globalization increase, reduce, or have a negligible effect on CO_2 emissions. Also, the empirical studies on the relationship between globalization and CO_2 emissions are restricted to the traditional parametric econometric approaches (Shariff et al. 2020; Shahbaz et al. 2020; Adebayo and Kirikkaleli et al. 2021; Rjoub et al. 2021; Kihombo et al. 2021). However, parametric estimators are not robust to outliers and sometimes fail to account for slope heterogeneity (Dzator and Acheampong 2020). Therefore, understating the effect of economic globalization on CO_2 emissions requires an advanced novel econometric approach robust to outliers and could account for slope heterogeneity. In addition, Australia is highly integrated with the rest of the world and plays a significant role in global carbon emissions. However, there is limited literature on the relationship between globalization and CO_2 emissions in Australia. Therefore, this study contributes to the literature by applying the QQ approach to investigate economic globalization's impact on CO_2 emissions in Australia for 1970–2018 while controlling economic growth and coal consumption.

Methodology and data

Unit root tests

To identify the order of integration of the variables, the two traditional unit root tests, the Augmented Dickey-Fuller (ADF) (Dickey and Fuller 1979) and the Phillips-Perron (PP) (Phillips and Perron 1988), are used. Additionally, the quantile unit root tests established by Koenker and Xiao (2004) and Galvao (2009) are used in the study. The quantile autoregressive (QAR) unit root test is used to ensure that all variables are stationary. By integrating a linear temporal trend and variables into the QAR model, Galvao (2009) broadened the technique.

Quantile-on-quantile regression approach

In this current study, we utilized the novel quantile-on-quantile (QQ) technique initiated by Sim and Zhou (2015) to assess the broad interrelationship between CO_2 emissions and globalization use, economic growth, and coal consumption in Australia. This model is a refinement of traditional quantile regression, which emphasizes the influence of a single independent variable's quantiles on the distinct quantiles of the dependent variable. The use of non-parametric estimations and quantiles is fundamental to this technique. To begin, traditional quantile regression is utilized to explore the impact of

Table 1 Variable measurements and source

Symbol	Variables	Unit	Source
CO_2	Environmental degradation	Metric tonnes per capita	BP
GDP	Economic growth	GDP per capita	WDI
COAL	Coal consumption	Exajoule	BP
GLO	Globalization	Index based on FDI, trade, and portfolio investment	Gygli et al. (2019): revised KOF globalization index

an independent variable on the dependent variable's various quantiles. The traditional quantile regression technique is utilized as an enhancement to the conventional least square approach. Unlike the linear regression model, quantile regression investigates the impact of a variable on the conditional mean of the dependent variable and distinct quantiles. In this sense, the quantile regression model gives a more comprehensive relationship than the least square method.

Moreover, Cleveland (1979) and Stone (1977) propose using standard linear regression to explore the effect of the independent variable's exact quantile on the dependent variable. Investigators can study the impact of different dependent variable quantiles on different dependent variable quantiles by combining these two techniques, namely conventional quantile regression and classic linear regression. Consequently, rather than using standard techniques like OLS and simple quantile regression, combining these two approaches can assist in understanding the fundamental connection. Additionally, we use Sim and Zhou's (2015) quantile-on-quantile estimate to explore the effect of different X quantiles on the various Y quantiles using the following non-parametric quantile regression model.

$$Y_t = Y^{\sigma}(X_t) + \mu_t^{\sigma} \quad (1)$$

where Y_t illustrates dependent variable in period t and X_t illustrates independent variable in time t. σ is the σ^{th} quantile on the distribution of X. Additionally, μ_t^{σ} depicts quantile error term, where estimated σ^{th} quantile is equal to zero. Furthermore, $\propto^{\sigma}(.)$ is unknown since no information is available on the relationship between X and Y. Moreover, understanding bandwidth selection is essential when utilizing non-parametric analysis. Finally, it is vital to understand bandwidth selection when doing non-parametric analysis. This bandwidth assists in the simplicity of the target point, the size of the quarter backgrounds, and, as a result, bandwidth gear-shifts the pace of the conclusion. A large bandwidth, h, decreases variance while raising estimate deviation and vice versa. We use a bandwidth value of $h = 0.05$ in this investigation, as Sim and Zhou (2015) advised.

Data

This study examines the interconnection between CO_2 and globalization, GDP, and coal consumption. The dataset for this empirical analysis covers between 1970 and 2018 (49 observations). The description, source, and measurement of the dataset are depicted in Table 1. Furthermore, a summary of the variables utilized in this empirical analysis is presented in Table 2. The outcomes from Table 2 disclosed that economic growth scores better on average due to its higher mean. The standard deviation is a gauge of the amount of variation or dispersion of a set of values. Thus, the standard deviation is utilized to check the variable which had more consistent scores. CO_2 has the lowest standard deviation, which indicates that the scores are less spread out from the mean. Thus, CO_2

Table 2 Descriptive statistics

	CO_2	COAL	GDP	GLO
Mean	7.871503	459.7481	39,791.02	70.95093
Median	7.687916	468.2643	37,133.04	72.21075
Maximum	9.594431	677.2213	56,832.05	81.64704
Minimum	6.736522	231.6946	26,120.62	56.84417
Std. Dev.	0.745371	135.3737	10,208.50	8.387600
Skewness	0.564470	−0.158214	0.259098	−0.112517
Kurtosis	2.649423	1.752200	1.595745	1.428413
Jarque-Bera	2.853049	3.383311	4.574272	5.146074
Probability	0.240142	0.184214	0.101557	0.076303
Observations	49	49	49	49

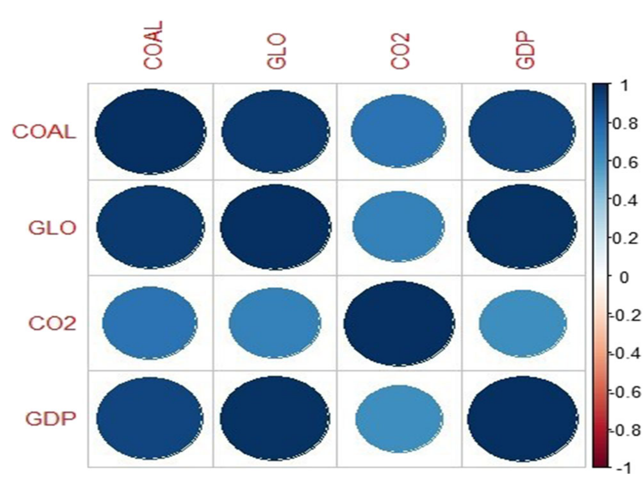


Fig. 3 Correlation box

Table 3 BDS test

	$M = 2$	$M = 3$	$M = 4$	$M = 5$	$M = 6$
CO_2	13.063*	13.751*	13.807*	13.519*	13.349*
GDP	30.367*	31.335*	33.245*	36.306*	40.634*
COAL	32.413*	34.234*	36.255*	39.208*	43.220*
GLO	31.148*	32.649*	34.768*	38.262*	42.963*

*Signifies $P < 0.01$

has a more consistent score. Skewness results reveal that CO_2 emissions and GDP are positively skewed while coal use and globalization are negatively skewed. The value of the kurtosis disclosed that all the variables are platykurtic. The Jaque-Bera statistics unveil that the series are normally distributed. The correlation between the indicators is depicted in Figure 3 (correlation box), which ranges from blue (positive correlation) to red (negative correlation). The outcomes of the correlation box disclosed that GDP, globalization, and coal consumption positively correlate with CO_2 emissions, which infer that an increase in coal consumption, globalization, and GDP is associated with an increase in CO_2 emissions.

Empirical results

Pre-estimation tests

It is essential to conduct a linearity test to ascertain the variables' linearity feature. Centered on this, this study utilized the Brock, Dechert and Scheinkman (BDS) test to examine the nonlinearity of the variables. The outcomes of the BDS test are illustrated in Table 3. Centered on these outcomes, utilizing the normal linear techniques will produce disingenuous outcomes. Thus, we employed a non-linear method to assess the influence of GDP, GLO, and COAL on CO_2 emissions in Australia. Moreover, we verify the stationarity characteristics of the variables by employing the traditional ADF and PP unit root tests. The outcomes of the ADF ad PP unit root tests are presented in Table 4, and the results disclosed that all the series are non-stationary at level. Nevertheless, all the variables are found to be stationary at first difference. Furthermore, the outcomes of the quantile unit root test are depicted in Table 5. Since the *t*-statistic is numerically smaller than the critical value, then the null hypothesis of $\beta(\pi) = 1$ is rejected at the 5% level.

Table 4 Unit root tests

Variables	ADF		PP	
	At level	First difference	At level	First difference
CO_2	−2.1891	−8.2146*	−2.1384	−8.3632*
GDP	−2.1840	−5.5587*	−2.1840	−5.5170*
COAL	−0.1498	−4.2946*	0.2973	−4.2679*
GLO	−0.3155	−5.4783*	−0.6732	−5.4837*

*Signifies $P < 0.01$correspondingly

QQ approach results

This part of the research reveals the main empirical outcomes of the QQ analysis of the impact of trade openness, GDP, and renewable energy consumption on CO_2 emissions in Australia. Figures 4a–f reveal the slope coefficient estimate, $\beta_1(\theta, \tau)$, which catch the influence of the τth quantile of X on the θth quantile of Y, at various values of θ and τ for Australia. The QQ outcomes are illustrated in Figures 4a–f.

Figure 4a discloses the effect of GDP on CO_2 emissions in Australia. The slope coefficient ranges from −1.5 to 0.5. The impact of GDP on CO_2 is negative at lower quantiles of GDP (0.1–0.3) and higher quantiles of CO_2 emissions (0.7–0.95). Furthermore, the value of the slope coefficient is positive and weak in middle and higher (0.35–0.95) quantiles of GDP and lower and middle (0.1–0.75) quantiles of CO_2 emissions. These outcomes indicate that both negative and positive effects exist between CO_2 emissions and GDP in Australia; nevertheless, there is evidence of weak effects. Thus, economic growth is not a significant driver of Australia's carbon emissions. This finding contradicts existing studies such as Acheampong et al. (2021b), Apergis and Payne (2009), and Sehrawat et al. (2015), which suggest that economic growth is a significant determinant of carbon emissions.

The influence of CO_2 on GDP in Australia is depicted in Figure 4b. The scale of the slope coefficient ranges from 0 to 10. The impact of CO_2 on GDP is positive at most combinations of quantiles of GDP and CO_2 emissions; however, the effect of CO_2 on GDP is positive and strong in the higher quantiles (0.80–0.95) quantiles of CO_2 and lower quantiles of GDP (0.1–0.35) as revealed by the scale of the slope coefficient. This result suggests implementation of stringent carbon abatement policies could impede Australia's economic growth. This evidence concurs with the findings of Awosusi et al. (2021) for Brazil, Bekun et al. (2021) for Indonesia, Udemba et al. (2021) for India, Zhang et al. (2021) for Malaysia, and Adebayo et al. (2021) for South Korea, who established a positive linkage between CO_2 emissions and GDP.

Figure 4c reveals the influence of COAL on CO_2 in Australia. The coefficient of the slope ranges from −0.2 to 1.4. The impact of COAL on CO_2 is positive and weak at most of the combination of quantiles of COAL and quantiles of CO_2 emissions; however, there is evidence of a strong positive effect of COAL on CO_2 in the high quantiles (0.8–0.95) of COAL and low quantiles (0.1-0.3) of CO_2 emissions.

Table 5 Quantile unit root test

Quantiles	CO_2 emissions (CO_2)			Economic growth (GDP)			Globalization (GLO)			Coal consumption (COAL)		
	$\alpha(\tau)$	T-stats	CV	$\alpha(\tau)$	T-stats	CV	$\alpha(\tau)$	T-stats	CV	$\alpha(\tau)$	T-stats	CV
0.05	1.0403	1.3190	−2.1558	1.0078	1.2821	−2.2909	0.9923	−1.4015	−2.1827	0.9937	−1.2792	−2.1200
0.1	1.0083	0.2641	−2.5546	1.0038	1.5817	−2.4699	0.9941	−1.3277	−2.1200	0.9926	−1.4504	−2.3515
0.15	0.9740	−1.1990	−2.4934	1.0028	1.1356	−2.5154	0.9949	−1.5347	−2.3093	0.9927	−1.4966	−2.5349
0.2	0.9901	−0.5721	−2.7356	1.0006	0.3712	−2.5343	0.9972	−1.9595	−2.2726	0.9944	−1.4022	−2.7327
0.25	0.9889	−0.7866	−2.8254	1.0002	0.1699	−2.6145	0.9971	−2.2857	−2.4950	0.9957	−1.8868	−2.7490
0.3	0.9882	−1.1147	−2.8271	0.9999	−0.0966	−2.5510	0.9980	−1.7120	−2.5753	0.9972	−1.4472	−2.7727
0.35	0.9903	−0.9310	−2.8514	0.9871	−0.3968	−2.5783	0.9989	−1.0077	−2.6188	0.9987	−0.8144	−2.6950
0.4	0.9865	−1.5598	−2.629 1	0.9996	−0.5505	−2.5771	0.9991	−1.0166	−2.7091	0.9997	−0.8550	−2.6527
0.45	0.9865	−1.6510	−2.5613	0.9995	−0.6737	−2.6422	0.9997	−0.3661	−2.7366	0.9997	−0.8201	−2.6357
0.5	0.9845	−1.9084	−2.5182	0.9995	−1.1469	−2.6405	1.0001	0.1094	−2.7931	0.9999	−0.7084	−2.6553
0.55	0.9842	−1.9340	−2.5723	0.9992	−1.4305	−2.6009	1.0002	0.1851	−2.7664	1.0000	−0.0296	−2.6993
0.6	0.9832	−1.9966	−2.6357	0.9992	−1.2884	−2.5640	1.0001	0.1283	−2.7665	1.0003	0.0414	−2.6410
0.65	0.9820	−1.8941	−2.7833	0.9988	−1.6365	−2.6027	1.0003	0.2240	−2.8093	0.9997	−0.3503	−2.7599
0.7	0.9839	−1.5647	−2.8269	0.9988	−2.0473	−2.4500	1.0009	0.5642	−2.8117	0.9995	0.0434	−2.6697
0.75	0.9783	−1.5561	−2.7497	0.9984	−1.9079	−2.5227	1.0009	0.5387	−2.6925	1.0001	−0.2077	−2.6111
0.8	0.9732	−1.4901	−2.7012	0.9977	−1.8873	−2.5682	1.0007	0.3406	−2.7230	0.9996	0.2467	−2.5203
0.85	0.9691	−1.1409	−2.6957	0.9974	−1.1644	−2.1381	1.0004	0.1696	−2.4813	0.9979	−0.6094	−2.4077
0.9	0.9543	−1.0772	−2.1200	0.9957	−1.8103	−2.1200	1.0034	1.1953	−2.3511	1.0051	1.4464	−2.2149
0.95	0.9619	−1.0452	−2.1300	0.9810	−1.8108	−2.1300	1.0052	1.0813	−2.1200	1.0010	1.2310	−2.2018

The table presents point estimates-statistics and critical values for the 5% level of significance. If the t-statistic value is less than the critical value, then the null hypothesis of $\beta(\pi) = 1$ is rejected at the 5% level

On the other hand, Figure 4d presents the influence of CO_2 on COAL. In all quantiles of CO_2 and COAL (0.1–0.95), the effect of CO_2 on COAL is positive; nevertheless, the effect of CO_2 o COAL is positive and stronger in the middle quantiles of both CO_2 and COAL. In summary, there is a positive feedback effect between CO_2 and COAL in Australia. These outcomes are not surprising since coal consumption (29.1%) constitutes a big chunk of Australia's energy mix. This outcome is consistent with the findings of Oluwajana et al. (2021) for South Africa, Pata (2018) for Turkey, and Lin et al. (2018) for China.

Figure 4e shows the effect of globalization on CO_2 in Australia. The coefficient of the slope ranges from 0.2 to 0.7. In all quantiles (0.1–0.95) of GLO and CO_2, the influence of GLO on CO_2 is positive. Nonetheless, in the middle and higher quantiles (0.4–0.95) of GLO and CO_2, the positive effect of GLO on CO_2 is more pronounced. Also, the impact of CO_2 on GLO is depicted in Figure 4f. The coefficient of the slope ranges from 0 to 2.5. The effect of CO_2 on GLO is positive at all quantiles of CO_2 and GLO; however, in the higher quantiles (0.75–0.95) of CO_2 and lower quantiles (0.1–0.3), the positive effect of CO_2 on GLO is stronger. The possible explanation for globalization's positive impact on CO_2 is that it increased trade increases overall factor productivity due to globalization. Foreign direct investment (FDI) and the transition of advanced technologies between industrialized and developing economies fuel economic growth. Furthermore, the globalization trend creates investment prospects via FDI and strengthens capital markets via financial liberalization. Undoubtedly, this mechanism boosts capital markets, commerce, and economic development, resulting in increased energy demand and, as a result, environmental deterioration. According to Kirikkaleli et al. (2021), globalization triggers a gradual increase in CO_2 due to the intensive use of resources to manufacture and use goods and services in industrialized and developing economies. This outcome complies with the findings of Kirikkaleli et al. (2021) for Turkey, Saint Akadiri et al. (2019) for South Africa, Adebayo and Kirikkaleli (2021) for Japan, and Le and Ozturk (2020a, 2020b) for seven (7) emerging nations who established a positive connection between globalization and CO_2 emissions.

Robustness check for QQ approach

The QQ methodology can be conceived as a decomposition procedure for the traditional QR model's estimates, allowing for precise estimates for various quantiles of the dependent variable. The QR model used in this analysis is focused on regressing the θth quantile of Y on X, so the quantile regression

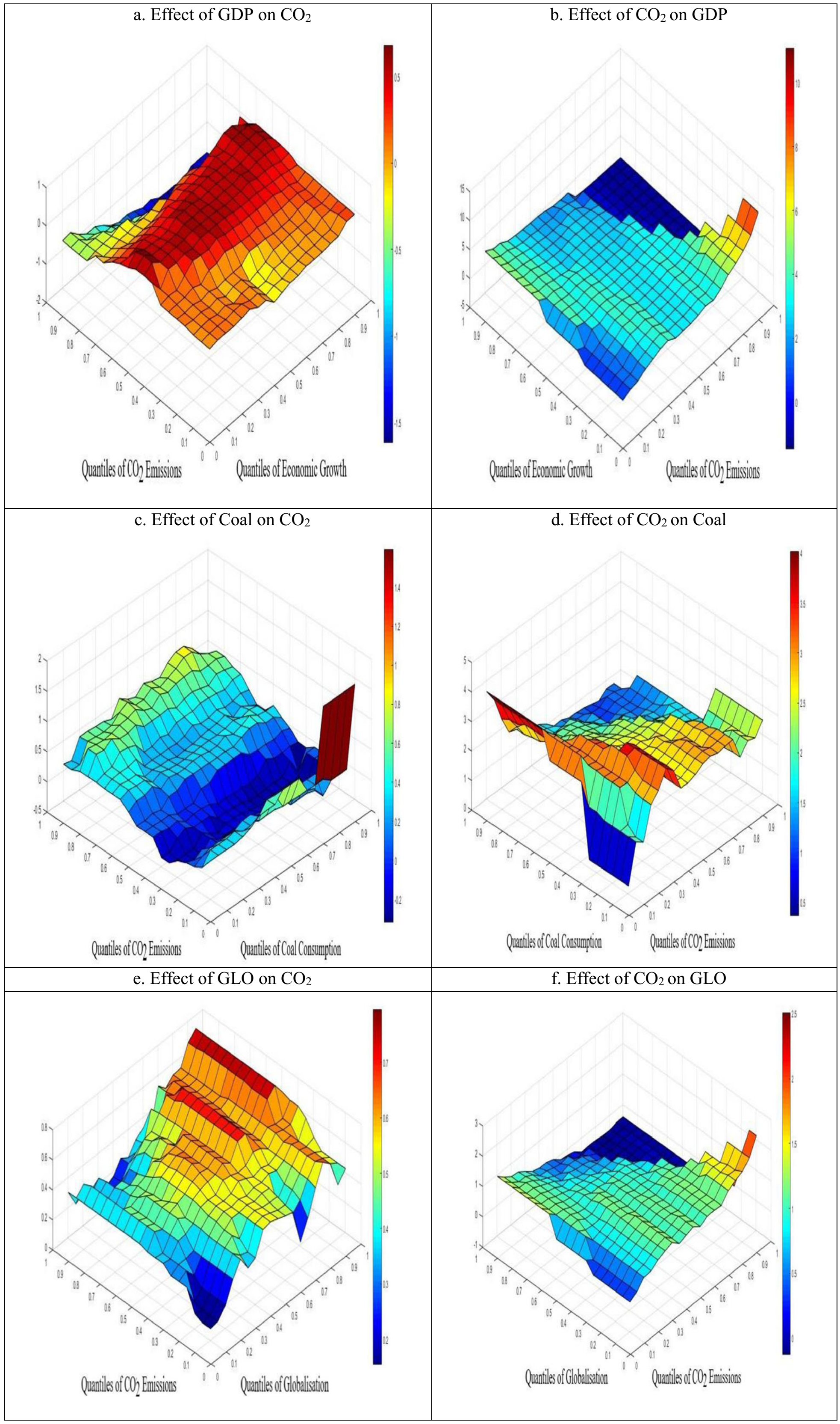
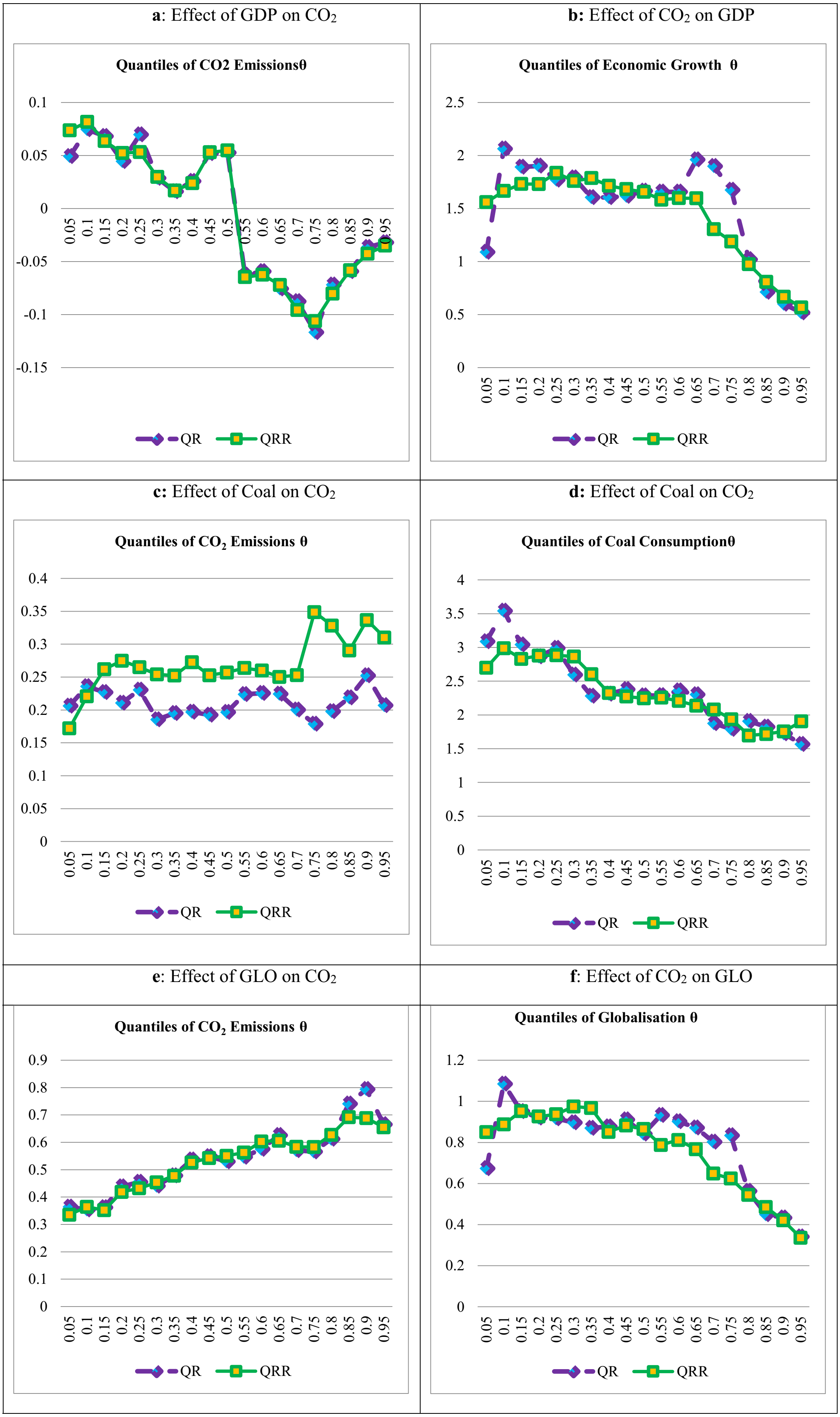


Fig. 4 Quantile-on-quantile (QQ) estimates of the slope coefficient. **a** Effect of GDP on CO_2. **b** Effect of CO_2 on GDP. **c** Effect of coal on CO_2. **d** Effect of CO_2 on coal. **e** Effect of GLO on CO_2. **f** Effect of CO_2 on GLO


a: Effect of GDP on CO2
Quantiles of CO2 Emissionsθ
QR
QRR
b: Effect of CO2 on GDP
Quantiles of Economic Growth θ
QR
QRR
c: Effect of Coal on CO2
Quantiles of CO2 Emissions θ
QR
QRR
d: Effect of Coal on CO2
Quantiles of Coal Consumptionθ
QR
QRR
e: Effect of GLO on CO2
Quantiles of CO2 Emissions θ
QR
QRR
f: Effect of CO2 on GLO
Quantiles of Globalisation θ
QR
QRR

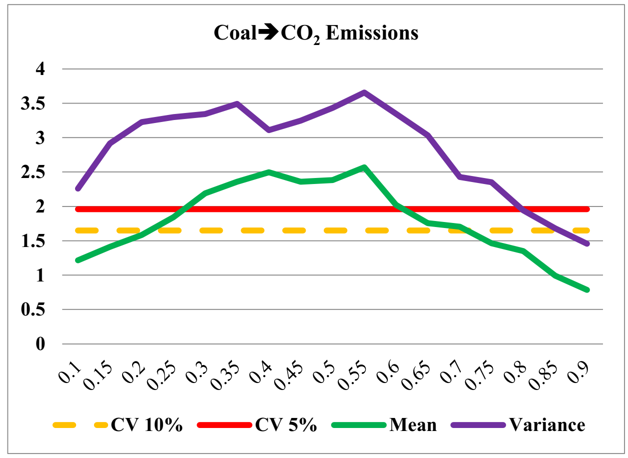
◀ **Fig. 5** Comparison of quantile regression and quantile-on-quantile estimate. **a** Effect of GDP on CO_2. **b** Effect of CO_2 on GDP. **c** Effect of coal on CO_2. **d** Effect of CO_2 on coal. **e** Effect of GLO on CO_2. **f** Effect of CO_2 on GLO

parameters are only indexed by θ. That being said, since the QQ analysis regresses the θth quantile of Y on the quantile of X, the variables will be defined by both θ and τ, as previously mentioned. As a result, the QQ method provides more disaggregated details about the X–Y connection than the quantile regression model since the QQ method considers this relationship to be inherently heterogeneous through X quantiles. Given the QQ approach's inherent decomposition property, the QQ estimates can be used to retrieve the traditional quantile regression estimates. The QQ parameters around τ can produce the QR parameters that are only indexed by θ. For instance, the coefficient of the QR model slope, which is denoted by $\gamma_1(\theta)$, is utilized to calculate the influence of X on Y, as follows:

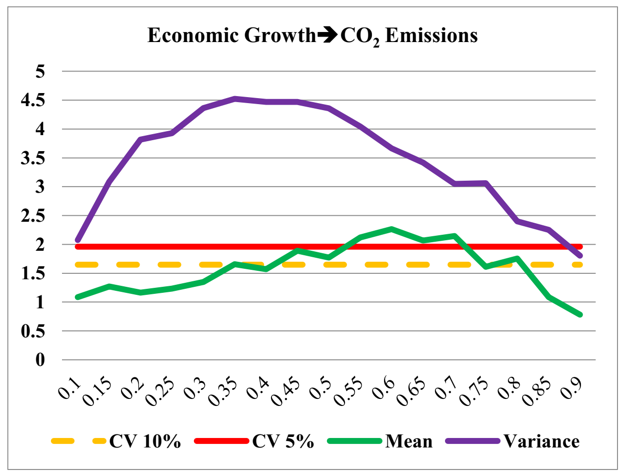
$$\gamma_1 \equiv \overline{\widehat{\beta}_1(\theta)} = \frac{1}{S}\sum_\tau \widehat{\beta}_1(\theta, \tau) \tag{2}$$

where S = 19 is the quantiles number and τ = [0.05, 0.10, …., 0.95] is considered.

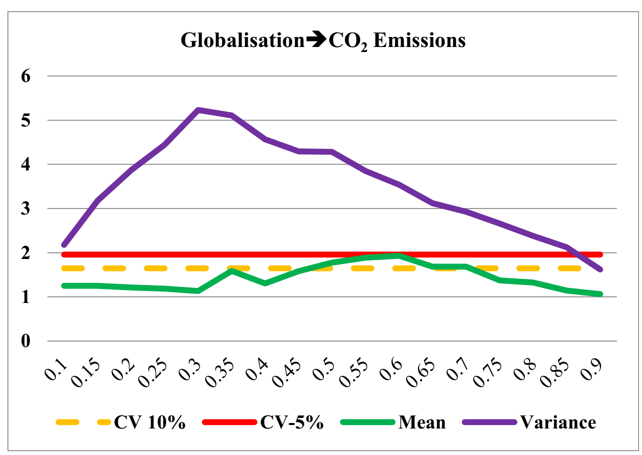
The graphs in Figures 5a–f show that irrespective of the quantile chosen, the averaged QQ estimates of the slope coefficient are comparable to the QR estimates for Australia. This graphical proof revealed that the main characteristics of the QR model could be retrieved by illustrating the more extensive details found in the QQ estimates, including a clear justification of the QQ approach. Thus, Figure 5a affirms the outcomes of the QQ analysis reported above. The outcomes of the QR disclosed that at all quantiles, the impact of GDP on CO_2pollution is positive, which is consistent with the QQ regression outcome. On the flip side, Figure 5b illustrates that the QR results are consistent with the QQ results, demonstrating that CO_2 emissions positively influence economic growth. Furthermore, in Figure 5c, the outcomes of the QR disclosed that COAL influences CO_2 positively at all quantiles, which are consistent with the findings of the QQ. On the other side, in Figure 5d, the influence of CO_2 on COAL is positive at all quantiles, as revealed by both QR and QQ outcomes. This result illustrates that the QR and QQ outcomes validate each other. Also, in Figure 5e, the influence of globalization on CO_2 emissions is positive at all quantiles, as revealed by the results from QR and QQ estimators. In Figure 5f, the effect of CO_2 emissions on globalization is positive at all quantiles, as shown by QR. These results are consistent with QQ results reported earlier. In summary, the results of the QR validate the results of QQ as indicated in Figures 5a–f.



a: Causality -in-mean and variance from Coal to CO_2



b: Causality -in-mean and variance from GDP to CO_2



c: Causality -in-mean and variance from GLO to CO_2

Fig. 6 **a** Causality-in-mean and variance from coal to CO_2. **b** Causality-in-mean and variance from GDP to CO_2. **c** Causality-in-mean and variance from GLO to CO_2

Table 6 Causality-in-mean and variance outcomes

Quantile	CV 10%	CV 5%	Causality-in-mean			Causality-in-variance		
			COAL	GDP	GLO	COAL	GDP	GLO
0.10	1.65	1.96	1.2168	1.0855	1.2492	2.2559*	2.0741*	2.1775*
0.15	1.65	1.96	1.4120	1.2723	1.2499	2.9117*	3.083*	3.1775*
0.20	1.65	1.96	1.5841	1.1660	1.2113	3.2273*	3.8166*	3.8724*
0.25	1.65	1.96	1.8439	1.2347	1.1886	3.2979*	3.9239*	4.4446*
0.30	1.65	1.96	2.1914*	1.3494	1.1351	3.3445*	4.3615*	5.2075*
0.35	1.65	1.96	2.3586*	1.6587	1.5908	3.4896*	4.5249*	5.1184*
0.40	1.65	1.96	2.4979*	1.5706	1.3065	3.1104*	4.4707*	4.5669*
0.45	1.65	1.96	2.3602*	1.8897**	1.5809	3.2471*	4.4707*	4.2948*
0.50	1.65	1.96	2.3826*	1.7712**	1.7751**	3.4313*	4.3581*	4.2897*
0.55	1.65	1.96	2.5699*	2.1211*	1.8905**	3.6564*	4.0436*	3.8508*
0.60	1.65	1.96	2.0197*	2.2629*	1.9393**	3.3477*	3.6644*	3.5376*
0.65	1.65	1.96	1.7558**	2.0689*	1.6877**	3.0325*	3.4189*	3.1285*
0.70	1.65	1.96	1.7049**	2.1479*	1.6927**	2.4259*	3.0475*	2.9272*
0.75	1.65	1.96	1.4633	1.6123	1.3722	2.3511*	3.0606*	2.6677*
0.80	1.65	1.96	1.3485	1.7540**	1.3240	1.9405*	2.4015*	2.3814*
0.85	1.65	1.96	0.9934	1.0873	1.14467	1.6794*	2.2514*	2.1249*
0.90	1.65	1.96	0.7850	0.7832	1.0635	1.4561	1.8038*	1.6216

* and ** represent $P < 0.05$ and $P < 10\%$, respectively. The null hypothesis for the quantile causality test statistic is environmental variable (globalization, economic growth, and coal consumption) does not Granger CO_2 emissions

Non-parametric causality-in-quantile outcomes

Figures 6a–c and Table 6 present the causal impact of globalization, economic growth, and coal consumption on CO_2 emissions in all quantiles (0.10-0.90). Figure 6a shows the causal impact of coal on CO_2. The causal effect of coal on CO_2 is strong in the lower and middle quantiles (0.25–0.65) of the provisional distribution of the emissions. The effect becomes stronger and more significant in the middle quantiles, as shown by the *t*-statistic value of approximately 2.56. Furthermore, the volatility of coal can also be observed in Figure 6a. In addition, the causal influence on volatility is asymmetric since it is significant for the lower, middle, and upper quantiles of the conditional distribution, respectively. Figure 6b presents the causal effect of economic growth (GDP) on CO_2. The causal effect of GDP on CO_2 is strong in the middle quantile (0.45–0.70) of the emissions' provisional distribution, as shown by a *t*-statistic value of approximately 2.25. Furthermore, the volatility of GDP can also be observed in Figure 6b. In addition, the causal influence on volatility is asymmetric since it is significant for the lower, middle, and upper quantiles of the conditional distribution, respectively. Figure 6c presents the causal effect of globalization (GLO) on CO_2. The causal effect of GLO on CO_2 is strong in the middle quantile (0.45–0.70) of the provisional distribution of the emissions, as shown by a *t*-statistic value of approximately 1.94. Furthermore, the volatility of GLO can also be observed in Figure 6c. In addition, the causal influence on volatility is asymmetric since it is significant for the lower, middle, and upper quantiles of the conditional distribution, respectively.

Conclusion and policy implications

The current paper applied newly developed econometrics techniques to explore the interconnection between CO_2 emissions, coal consumption, globalization, and GDP in Australia using data spanning from 1970 to 2018. Utilizing the novel QQ method, the current paper contributes to the ongoing literature and policy discussions on the relationships between carbon emissions, globalization, coal consumption, and economic growth. Unlike conventional techniques, including OLS or quantile regression, the QQ approach helps one approximate how the quantiles of independent variables impact the quantiles of the dependent variable, thereby offering a more detailed explanation of the overall dependency structure between CO_2 emission and the regressors. To the authors' understanding, no prior study has examined these associations utilizing the novel QQ method. As an initial test, the study examines the linearity of the variables under investigation by employing the BDS test. The results from the BDS suggested that using the linear techniques will yield a misleading result, making the application of non-linear or non-parametric techniques such as the QQ approach crucial for this study. Furthermore, the outcomes of the QQ regression illustrated: (i) a positive feedback linkage between GDP and CO_2 emissions at most of the quantiles, (ii) a positive feedback linkage between globalization and CO_2 emissions at all quantiles, and (ii) a positive feedback interconnection between CO_2 pollution and coal consumption at all quantiles. As a robustness check, we employed the quantile regression (QR) test, and the results from QR are consistent with the findings from QQ.

These findings have significant implications for Australia's carbon abatement policies. Existing studies claim that economic globalization lowers carbon emissions in developed countries because of the associated benefits of economic globalization, such as the spread of green technologies and standard environmental management practices as well as the enforcement of strict environmental regulation in developed countries (Doytch and Uctum 2016; Pao and Tsai 2011). However, our study has indicated that economic globalization worsens carbon emissions in Australia. The evidence suggests that Australia's policymakers need to consider economic globalization in designing and implementing climate change policies for achieving the net-zero emissions target. Thus, given that economic globalization worsens carbon emissions at all quantiles, policymakers in Australia should not underestimate economic globalization on climate change and should be incorporated in designing and implementing an environmental sustainability policy framework. Failure to integrate economic globalization in carbon emissions forecasting models and environmental policies could impede Australia's efforts for achieving the net-zero emissions target. The study also suggests that coal consumption has been driving Australia's carbon emissions. Australia uses coal to drive its economic growth but comes at the expense of deteriorating environmental quality. Australia's total energy mix has been dominated by fossil energy; therefore, mitigating the negative environmental effect of coal consumption requires policymakers to fast-track Australia's transition towards renewable energy use. In doing so, it is recommended that the Australian government should subsidize and increase its budget allocation for financing renewable energy technologies. Finally, the study revealed that there is a positive feedback relationship between economic growth and carbon emissions. Thus, increasing economic growth induces higher carbon emissions while mitigating carbon emissions can cause a decline in the country's economic growth. Therefore, it is recommended that policymakers in Australia be cautious in designing and implementing its climate change policies without causing closed form relationships that can cause a decline in the country's economic growth.

Future research is needed because of the following limitations. First, this study examines the effect of economic globalization on carbon emissions without considering other the political and social aspects of globalization; however, a recent study has documented that economic, political, and social globalizations have a disparate effect on economic growth and energy consumption (Acheampong et al. 2021a, 2021b). Because of this, future studies can extend this study by comparing the impact of economic, political, and social globalizations on the environment. Second, given that this study focused on carbon emissions, future studies can also extend this study by exploring the economic, political, and social globalizations on ecological footprint, a compressive measure of environmental degradation. Lastly, given that Australia has a robust and well-established financial system, future studies can adapt our methodology to explore the environmental cost of Australia's financial development.

Author contribution Tomiwa Sunday Adebayo: Conceptualization, Methodology, Formal analysis, Data Curation, Writing original draft. Alex O. Acheampong: Conceptualization, Methodology, Writing original draft, Writing — review and editing

Data availability The data used in this study are openly available in World Bank (2019), World Development Indicators Database at https://databank.worldbank.org/source/world-development-indicators.

Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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