Heterogeneous multi-scale quantile effects of climate policy uncertainty on green bond returns

İklim politikası belirsizliğinin yeşil tahvil getirileri üzerindeki heterojen çok ölçekli kantil etkileri

Aslan Aydoğdu[1]

[1] Dr. Lecturer, Sivas University of Science and Technology, Sivas, Türkiye, aydogduaslan34@gmail.com

ORCID: 0000-0001-9732-0614

Abstract

This study examines the impact of climate policy uncertainty (CPU) on green bond returns (GB) under different time horizons and market conditions. For this purpose, monthly data from the news-based CPU index developed by Gavriilidis (2021) and the S&P Green Bond Index for the period from June 2015 to June 2025 are employed. The analysis is conducted using wavelet-based quantile-on-quantile regression (WQQR) and wavelet-based quantile-on-quantile Granger causality (WQQGC), which capture non-linear, asymmetric, and distribution-dependent dynamics. The findings reveal that the impact of CPU on green bond returns varies across time horizons and quantile levels. In the short term, increases in CPU are found to suppress green bond returns in low-return regimes, while exerting a positive effect in high-return regimes. In the medium term, this relationship reverses, and the CPU effect gradually evolves from negative to positive. In the long term, CPU is found to exert a statistically significant and positive effect on green bond returns across all quantile levels. Furthermore, the causality analysis indicates that the effects of CPU on the green bond market exhibit a heterogeneous, market-condition-dependent structure across both time-frequency and quantile dimensions.

Keywords: Green Finance, Quantile-on-Quantile Regression, Green Bond, Wavelet Analysis, Quantile-on-Quantile Causality

Jel Codes: C21, C22, G15, G32, D53

Öz

Bu çalışma, iklim politikası belirsizliğinin (CPU) yeşil tahvil getirileri (GB) üzerindeki etkisini farklı zaman ufukları ve piyasa koşulları altında incelemektir. Bu kapsamda, Gavriilidis (2021) tarafından geliştirilen haber temelli CPU endeksi ile S&P Green Bond Index'e ait Haziran 2015-Haziran 2025 dönemine ilişkin aylık veriler kullanılmıştır. Analiz, doğrusal olmayan, asimetrik ve dağılıma bağlı dinamikleri yakalayabilen wavelet quantile-on-quantile regression (WQQR) ve wavelet quantile-on-quantile Granger causality (WQQGC) yöntemleriyle gerçekleştirilmiştir. Elde edilen bulgular, CPU'nun yeşil tahvil getirileri üzerindeki etkisinin hem zaman ufkuna hem de kantil düzeylerine bağlı olarak farklılaştığını ortaya koymaktadır. Kısa vadede CPU artışlarının, düşük getiri rejimlerinde yeşil tahvil getirilerini baskıladığı, buna karşılık yüksek getiri rejimlerinde pozitif etki yarattığı tespit edilmiştir. Orta vadede bu ilişkinin yön değiştirdiği ve CPU etkisinin negatiften pozitife doğru evrildiği görülmektedir. Uzun vadede ise CPU'nun tüm kantil düzeylerinde yeşil tahvil getirileri üzerinde istatistiksel olarak anlamlı ve pozitif bir etki oluşturduğu belirlenmiştir. Nedensellik analizi sonuçları, CPU'nun yeşil tahvil piyasası üzerindeki etkilerinin zaman-frekans ve kantil boyutlarında heterojen ve piyasa koşullarına bağlı bir yapı sergilediğini göstermektedir.

Anahtar Kelimeler: Yeşil Finans, Kantil-Kantil Regresyon, Yeşil Tahvil, Wavelet Analizi, Kantil-Kantil Nedensellik

Jel Kodları: C21, C22, G15, G32, D53

Introduction

In recent years, the nexus between climate policy uncertainty and financial market dynamics has become a prominent theme in the green, sustainable, and environmental finance literature (Liu et al., 2022; Tian et al., 2022). As economies transition toward low-carbon and sustainability-oriented growth paths, assessing the implications of CPU for green, clean, and socially responsible investment assets has become increasingly critical. This relevance is further amplified by the intensification of regulatory interventions to address climate change. The heightened sensitivity of financial markets to climate-related policy shocks underscores the need for rigorous empirical analyses that inform investors, policymakers, and other market participants in evolving regulatory environments (Naifir, 2024). As governments worldwide design and implement climate mitigation and transition policies, the associated uncertainty can substantially influence capital allocation, asset pricing, and risk-taking behaviour, particularly in green and sustainable energy markets.

Green bonds are fixed-income securities specifically issued to finance environmentally sustainable projects and climate-aligned investments (Gulal et al., 2025). They channel capital toward activities such as renewable energy development, climate change mitigation and adaptation, and carbon-emission reduction, thereby supporting the global transition to a low-carbon economy (Menteşe, 2021; Gulal et al., 2025). In this context, CPU, as developed by Gavriilidis (2021), captures the degree of unpredictability surrounding government policies, regulatory frameworks, and strategic commitments to climate change mitigation. The CPU index reflects the informational frictions and regulatory risks faced by market participants, particularly regarding the scope, credibility, timing, and political consistency of environmental policies. Fluctuations in climate policy therefore have the potential to materially affect investors' and policymakers' expectations, risk perceptions, and portfolio allocation decisions. While an elevated CPU may discourage investment in green financial instruments by increasing perceived regulatory and transition risks, a transparent, credible, and stable climate policy framework can facilitate capital inflows into green bond markets by enhancing market confidence and reducing uncertainty premiums.

Climate policy uncertainty can impede the development of green financial markets by eroding investor confidence due to regulatory volatility, inconsistent implementation, and shifting policy commitments. Elevated uncertainty increases perceived regulatory and transition risks, thereby constraining green financing channels and dampening capital flows toward sustainable investment projects. By contrast, a stable, transparent, and credible climate policy framework can enhance the appeal of green bonds, deepen market liquidity, and promote broader capital mobilisation for environmental investments. Within this context, understanding how climate policy uncertainty affects green bond returns and market efficiency is essential for policymakers seeking to align financial markets with the low-carbon transition. Moreover, this nexus offers important theoretical and methodological insights for the sustainable, green, and environmental finance literature, as well as for risk management, portfolio allocation, and investment strategy design. A rigorous examination of the interaction between climate policy uncertainty and the green bond market is therefore of strategic importance, as it influences not only short-term market dynamics but also the pace and effectiveness of medium- and long-term climate transition objectives.

A growing body of literature has examined the effects of climate policy uncertainty on green assets as well as on energy- and carbon-intensive equity and bond markets (Engle et al., 2020; Diaz-Rainey et al., 2021; Yang et al., 2021; Shabir et al., 2021; Schlenker and Taylor, 2021; Husain et al., 2022; Liang et al., 2022; Wang et al., 2022; Bouri et al., 2022; Tian et al., 2022; Syed et al., 2023; Barnett, 2023; Siddique et al., 2023; Yu et al., 2023; Ren et al., 2023; Huo et al., 2023; Gulal et al., 2025). However, empirical evidence on the response of green bond markets to climate policy uncertainty across different investment horizons and state-dependent return regimes remains scarce. Consequently, a time-frequency- and quantile-based investigation of the green bond market under climate policy uncertainty is essential for uncovering new insights into its risk-return dynamics. Such a framework enables investors to better assess the diversification, hedging, and downside-risk properties of green bonds under climate-related policy shocks, thereby improving portfolio resilience and strategic asset allocation.

This study examines the relationship between climate policy uncertainty and green bond returns across different time horizons, thereby addressing an important gap in the existing literature. It makes two primary contributions to the fields of green finance, sustainable finance, and environmental economics. First, while prior studies have examined the causal link between CPU and green bond markets, they have mainly overlooked whether and how this uncertainty propagates across different investment horizons and state-dependent return distributions. High green bond returns may signal to policymakers and market participants that climate-related initiatives are both economically viable and

environmentally effective, thereby reinforcing policy credibility and reducing regulatory uncertainty. By explicitly modelling this mechanism, the present study provides new insights into the role of the CPU in shaping green bond market dynamics. Second, the relationship between CPU and green bond (GB) returns is inherently time-varying rather than static. Ongoing changes in climate policy frameworks, the growing maturity of green bond markets, shifting macroeconomic and political conditions, and evolving investor risk preferences jointly induce dynamic and regime-dependent interactions between uncertainty and asset valuation. Accordingly, analysing the impact of CPU on GB returns across different time horizons yields valuable insights for investors with heterogeneous risk profiles and for policymakers seeking to stabilise and deepen green financial markets.

This study advances the existing literature by examining the impact of climate policy uncertainty on green bond returns across short-, medium-, and long-term investment horizons. To this end, we employ the wavelet quantile-on-quantile regression (WQQR) framework recently developed by Özkan et al. (2024), which enables a multidimensional assessment of distributional and time-frequency dynamics by jointly modelling conditional quantiles (0.10-0.90) across different horizons. Traditional econometric approaches—such as ordinary least squares (OLS), vector autoregression (VAR), traditional quantile regression (QR), and standard quantile-on-quantile regression (QQR)—are inherently limited in their ability to capture horizon-dependent and scale-specific interactions. The WQQR methodology overcomes these limitations by integrating wavelet decomposition with the QQR framework, thereby allowing the systematic identification of non-linear, asymmetric, and horizon-dependent relationships. By decomposing time series into short-, medium-, and long-term components, wavelet analysis provides a multi-scale representation of market dynamics, particularly well suited to capturing the evolving nature of financial and policy-driven shocks (Aydoğdu and Meder Çakır, 2025; Aydoğdu and Uyar, 2025). Moreover, WQQR isolates regime-specific dependencies across quantiles and horizons, enhancing the precision and robustness of the estimated relationships and yielding a more accurate characterisation of the transmission of climate policy uncertainty to green bond markets.

This study further employs the WQQGC framework recently proposed by Adebayo and Olanrewaju (2025) to examine causal linkages between climate policy uncertainty and green bond returns across different quantiles and time horizons. WQQGC identifies directional predictability by exploiting interactions between the conditional distributions of the dependent and independent variables within the time-frequency domain (Ying et al., 2025). By integrating quantile-based causality with wavelet decomposition, this approach offers several methodological advantages over conventional linear causality tests. First, it captures non-linear and asymmetric causal relationships that are typically obscured by mean-based frameworks. Second, it accommodates key features of financial time series, including volatility clustering, heteroskedasticity, and structural instability (Adebayo and Olanrewaju, 2025). Third, by allowing causality to vary across quantiles, WQQGC explicitly reveals how extreme market conditions—such as tail risks and stress regimes—propagate across variables, which is particularly relevant for financial risk management. Fourth, the wavelet component enables the simultaneous identification of short-, medium-, and long-run causal channels. Finally, WQQGC provides a robust characterisation of heterogeneous dependence structures by reducing sensitivity to outliers and avoiding the restrictive assumption of homogeneous average effects embedded in traditional Granger causality tests.

The remainder of the paper is organised as follows. The next section reviews the relevant literature and outlines the data, variable definitions, and econometric methodology. Section 3 presents and discusses the empirical findings. The final section concludes by summarising the main results and outlining policy implications for policymakers and market participants.

Literature review

This section reviews the existing literature on green bonds and climate policy uncertainty, which constitutes the core focus of the present study. Prior research indicates that green bonds have attracted rapidly growing attention, as they represent an innovative fixed-income instrument relative to conventional bonds, align corporate financing with environmental (E), social (S), and governance (G) objectives, and offer investors a long-term, sustainability-oriented investment vehicle. The rising global urgency of climate change and the increasing frequency of climate-related extreme events have further strengthened investor demand for green bonds. In parallel, a substantial body of literature has documented the effects of climate policy uncertainty on a wide range of financial markets (Ilhan et al., 2020; Lasisi et al., 2022; Bouri et al., 2022; Shang et al., 2022; He and Zhang, 2022; Khalfaoui et al., 2022; Husain et al., 2022; Hoque et al., 2022; Lv and Li, 2023; Treepongkaruna et al., 2023; Chen et al., 2023; Wang et al., 2023a; Siddique et al., 2023). However, empirical evidence on the transmission of climate

policy uncertainty to green bond markets remains relatively scarce, highlighting a critical gap that this study seeks to address.

For instance, Yu et al. (2023) document that climate policy uncertainty exerts time-varying effects on green bond market volatility in China, with distinct dynamics across short-, medium-, and long-term horizons. Similarly, Ren et al. (2023) investigate the short- and long-run linkages between the green bond market and climate policy uncertainty and report no significant association in the short run but a positive long-run relationship. Using evidence from Taiwan, Wang et al. (2022) show that firms' perceived exposure to climate-related risks increases following green bond issuance, indicating that green bonds function not only as financing instruments but also as mechanisms that enhance corporate environmental awareness and risk recognition. Tian et al. (2022) further demonstrate that the Chinese green bond market responds asymmetrically to climate policy uncertainty, primarily in the short run. In contrast, the European green bond market exhibits long-run asymmetries similar to those observed in the United States. Collectively, these findings highlight that the transmission of climate policy uncertainty to green bond markets is highly heterogeneous across time horizons, regions, and market structures.

Bouri et al. (2023) report that climate policy uncertainty arising from transition risks can, under certain periods and heightened market volatility, reduce green bond market volatility, suggesting that CPU does not uniformly act as a risk-amplifying factor but may instead serve a stabilising role in specific market environments. Wang et al. (2023b) further show that climate policy uncertainty consistently exhibits a risk-absorbing and risk-transmitting function by passively incorporating shocks originating from the green bond market, indicating that CPU is not merely an exogenous source of disturbances but also an endogenous indicator reflecting evolving market conditions. In a related vein, Aharon et al. (2025) demonstrate that the influence of climate policy uncertainty is inherently time-varying. While static models imply that green investments are insulated mainly from CPU fluctuations, dynamic frameworks reveal that CPU frequently acts as a net shock transmitter.

In a recent contribution, Özkan et al. (2024) examine the effects of climate policy uncertainty on green bonds, clean energy assets, and broader sustainable finance indicators, documenting statistically significant and positive CPU effects across all markets. Their findings suggest that the CPU can serve as a key transmission channel, shaping investor expectations and capital allocation in sustainability-oriented financial markets. Similarly, Raza et al. (2024) analyse the relationship between climate policy uncertainty and green bonds, clean energy, and sustainable market indices, showing that increases in CPU are associated with heightened volatility across these asset classes. This evidence indicates that the CPU plays an important role not only in green bond markets but also in the broader sustainable finance ecosystem, shaping risk dynamics. In a related study, Wang et al. (2024) investigate the interaction between climate policy uncertainty and multiple policy uncertainty indices using five green finance indicators, including the S&P Green Bond Index. Their results reveal that economic policy uncertainty (EPU) and monetary policy uncertainty (MPU) exert statistically significant effects on green financial assets, whereas the impact of CPU is comparatively weaker. Taken together, these findings highlight the heterogeneous effects of different forms of policy-related uncertainty on green finance markets.

Zhu et al. (2023) show that Chinese green bonds can function as a long-term haven against risks stemming from climate policy uncertainty, implying that green bonds serve not only environmental objectives but also provide hedging benefits during periods of elevated policy-related uncertainty. Dong et al. (2024) similarly document that climate policy uncertainty exerts both positive and negative effects on the green bond index—used as a proxy for the green finance market—across different subperiods. In a related study, Köycü (2025) examines the impact of economic and climate policy uncertainty on green bond returns and finds that CPU significantly depresses green bond performance. Gulal et al. (2025) further demonstrate that the relationship between climate policy uncertainty and the green bond market is non-stationary and highly sensitive to episodic shocks and structural changes. Taken together, these studies indicate that the effects of CPU on green bond markets are time-varying, asymmetric, and regime-dependent, with both the direction and magnitude of the relationship shaped by evolving macroeconomic and policy conditions.

As evidenced by the empirical literature reviewed above, a growing number of studies have employed green bond indices as proxies for green finance markets. However, most of this work has examined the relationship between CPU and green bond returns at an aggregate level, without accounting for heterogeneity across investment horizons or state-dependent return distributions. Consequently, the joint role of time-scale dynamics and quantile-specific behaviour in shaping the CPU-green bond nexus remains largely unexplored. A framework that simultaneously incorporates different time horizons and different regions of the return distribution enables a more comprehensive and robust assessment of the

magnitude and direction of the relationship, as well as its causal structure. Against this backdrop, the present study addresses a critical methodological gap by analysing the dynamic interaction between CPU and green bond returns across short-, medium-, and long-term horizons and across the full range of conditional quantiles. In doing so, it provides a novel contribution to the literature by jointly capturing horizon dependence and distributional asymmetry. The mixed and sometimes conflicting findings reported in previous studies are likely attributable to differences in sample periods, market proxies, uncertainty measures, and econometric methodologies. These inconsistencies underscore the absence of a unified conclusion in the literature and highlight the need for more refined, multidimensional empirical approaches—such as the one adopted in this study.

Data and methods

Data

This study uses monthly time series data on green bond returns and the Climate Policy Uncertainty (CPU) Index for the period June 2015-June 2025. The S&P Green Bond Index (GB) is used to analyse green bond returns. This index represents the global green bond market and reflects its performance and trends. To analyse climate policy uncertainty, we use the widely known CPU index data developed by Gavriilidis (2021). This index is a new indicator proposed to quantify global climate policy uncertainty. It should be noted that Gavriilidis (2021) follows the methodology introduced by Baker et al. (2016), who pioneered the development of the EPU index. The dataset was obtained from the Refinitiv Eikon Database and the web address https://www.policyuncertainty.com. Within the scope of the analysis, CPU data were converted to natural logarithms, while GB data were calculated as natural logarithmic returns (log-returns) using first differences.

Figure 1 reports the descriptive statistics of the CPU and GB series. CPU exhibits the highest mean, whereas GB displays the lowest. The standard deviations -0.470 for CPU and 2.148 for GB—indicate substantial variability, reflecting the sensitivity of climate-related policy uncertainty and green bond markets to global macro-financial and regulatory developments. The negative skewness values suggest that both series are left-skewed, while kurtosis values below three indicate platykurtic distributions. The Jarque-Bera test (1980) statistics further reject the null of normality for both variables, indicating that non-Gaussian features, such as asymmetry and excess tail behaviour, characterise the data, justifying the use of quantile-based and non-linear econometric techniques.
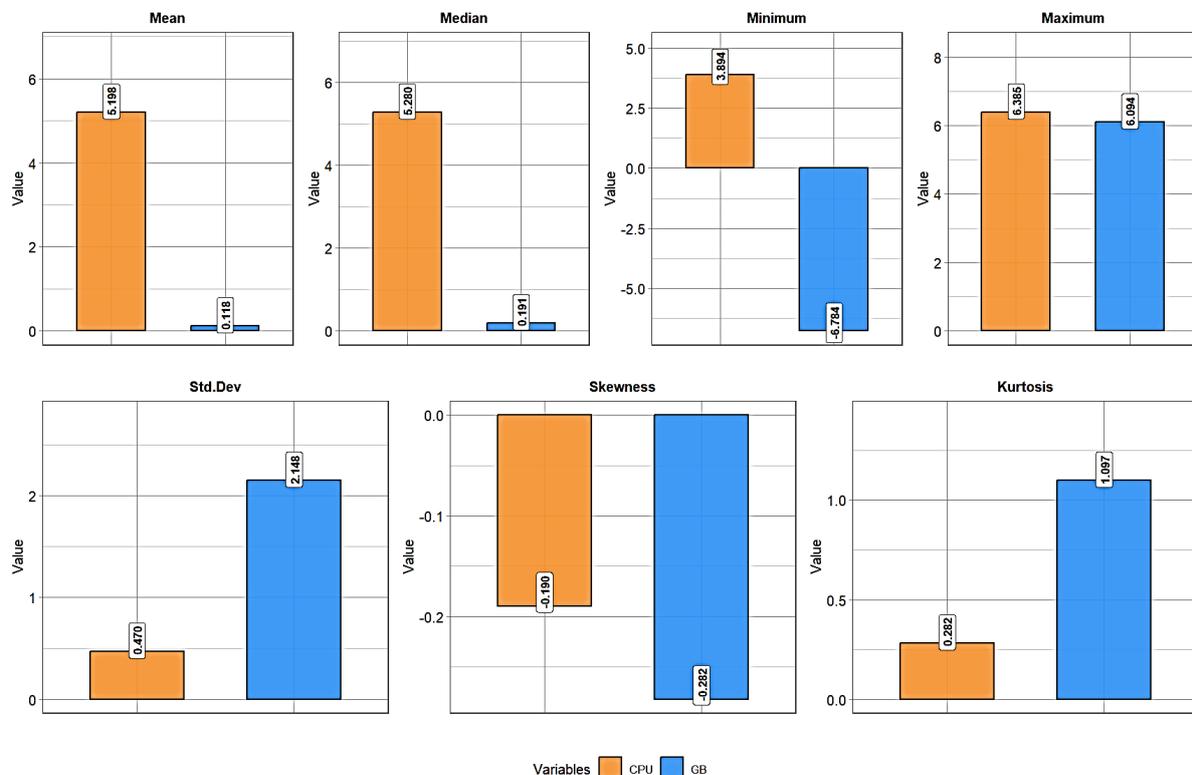
Source: Author's computation.

Methods

Wavelet quantile-on-quantile regression

Because most time series exhibit non-linear properties, using a linear method is likely to yield misleading results. The study begins by using quantile-based unit root tests proposed by Adebayo et al. (2025). These methods offer several advantages over traditional ADF and PP unit root testing methods. First, by examining different quantile levels, quantile unit root tests comprehensively examine the time series across its entire distribution. These methods can clarify differences in shock persistence across different distribution regions, making them particularly valuable for time series data in the economic and financial sectors, which exhibit distinct structures.

Quantile-on-quantile regression (QQR), developed by Sim and Zhou (2015), is a more advanced analysis method than traditional quantile regression (QR). This method considers the quantiles of both independent and dependent variables to capture their influence or relationship. According to Sim and Zhou (2015), QQR is represented as follows:

$$y_t = \underbrace{\beta_0(\delta,\phi) + \beta_1(\delta,\phi)\big(x_{i,t} - x_i^{\phi}\big)}_{*} + e_t^{\delta} \tag{1}$$

Here, $x_{i,t}$ and y_t, represent the independent and dependent variables, respectively. Furthermore, $\beta_1(\delta,\phi)$ and $\beta_0(\delta,\phi)$ represent the slope coefficient and the constant term, respectively. Furthermore, e_t^{δ} represents the error term in the quantile δ. However, the QQR technique does not account for relationships across different time horizons. To overcome this methodological limitation, Özkan et al. (2024) developed the Wavelet Quantile on Quantile Regression (WQQR) method. WQQR offers significant methodological advantages by integrating wavelet analysis into the QQR framework. Wavelet analysis allows the examination of relationships between variables at short-, medium-, and long-term time scales and, in this respect, provides a multi-scale perspective. This multi-scale method offers a significant advantage for analysing the dynamic structure of time series, enabling the simultaneous evaluation of variable interactions across different periods.

WQQR enables a better understanding of underlying relationships by isolating specific correlations across different time scales, thereby improving the accuracy and reliability of regression analysis. This methodological advantage makes WQQR a highly effective tool for identifying complex, non-linear relationships frequently observed in time-series data. Furthermore, the WQQR method allows for examining how the conditional quantiles of the independent variable $x_{i,t}$ affect the conditional quantiles of the dependent variable y_t at different time horizons. This method offers important insights, particularly in fields characterised by heterogeneous, time-dependent dynamics, such as financial markets. Finally, the WQQR approach at a specific level of decomposition (J) is shown in Equation (2) (Adebayo et al., 2025).

$$d_j[y_t] = \underbrace{\beta_0(\delta,\phi) + \beta_1(\delta,\phi)\big(d_j[x_{i,t}] - d_j[x_i^{\phi}]\big)}_{*} + e_t^{\delta} \tag{2}$$

Here, $x_{i,t}$ and y_t represent the independent and dependent variables, respectively. $\beta_1(\delta,\phi)$ and $\beta_0(\delta,\phi)$ represent the slope coefficient and the constant term, respectively. Furthermore, e_t^{δ}, δ represents the error term in the quantile.

To apply WQQR, the MODWT approach proposed by Percival and Walden (2000) was used to decompose the data series considered in the study. Following Özkan and Eweade et al. (2024), three wavelet pairs were obtained based on the J-level maximum decomposition calculated with the formula $J = \text{round}(\log2(\text{sample size}) - 3)$. Accordingly, the first decomposition (D1: 2-4 months) was classified as short-term, the second decomposition (D2: 4-8 months) as medium-term, and the third decomposition (D3: 8-16 months) as long-term.

Wavelet quantile-on quantile-granger causality

The traditional causality method developed by Granger (1969) reveals that variable X can predict variable Y, and this is shown in Equation (3) as follows:

$$Y_t = \gamma_0 + \sum_{i=1}^{p} \gamma_i Y_{t-i} + \sum_{i=1}^{p} \beta_i X_{t-i} + \varepsilon_t \tag{3}$$

Here, γ_0 represents the constant term, p represents the degree of lag, t represents time, γ_i represents the coefficients of the lagged values of Y, Y_{t-i}, represents the lagged values of the Y variable at different times $(t-1, t-2, \dots, t-p)$, β_i represents the coefficients of the lagged values of X, X_{t-i} represents the

lagged values of the X variable at different periods $(t-1, t-2, \dots, t-p)$, and ε_t represents the error term at time t.

Granger causality determines whether one time series can predict another in a linear framework. Still, it ignores the nonlinearity of the series and the quantiles of the independent and dependent variables. To address this gap, Adebayo and Özkan (2024) developed the quantile-on-quantile Granger causality (QQGC) approach, which examines how the quantiles of the independent variable can predict the quantiles of the dependent variable. According to Adebayo and Özkan's (2024) study, QQGC is expressed in Equation (4) as follows:

$$QY_{\tau,t} = \gamma_{\tau,\theta,0} + \sum_{i=1}^{p} \gamma_i QY_{\tau,t-i} + \sum_{i=1}^{p} \beta_i QX_{\theta,t-i} + \varepsilon_{\tau,\theta,t} \tag{4}$$

Here, $Q_{Y(\tau,t)}$ represents the quantile of the dependent variable Y at time t; $Q_{X(\theta,t-i)}$ represents the quantile θ of the independent variable X at time $t-i$. In addition, $\gamma_{(\tau,\theta,0)}$ is the constant term specific to τ and θ quantiles, γ_i measures the effect of past values of Y on the τ quantile; β_i measures the effect of past values of X on the θ quantile. $\varepsilon_{(\tau,\theta,t)}$ represents the error term at time t. However, QQGC only assesses whether the quantiles of the independent variable predict the quantiles of the dependent variable; it does not account for short-, medium-, and long-term time horizons. Based on this shortcoming, the WQQGC approach is used in this study. WQQGC allows us to examine how different quantiles of the independent variable predict corresponding quantiles of the dependent variable across short-, medium-, and long-term time horizons. The WQQGC approach is illustrated in Equation (5):

$$Q[d_j Y_t]_\tau = \gamma_{(d_j,\tau,\theta,0)} + \sum_{i=1}^{p} \gamma_{i,d_j} Q[d_j Y_{t-i}]_\tau + \sum_{i=1}^{p} \beta_{i,d_j} Q[d_j X_{t-i}]_\theta + \varepsilon_{(d_j,\tau,\theta,t)} \tag{5}$$

Here, $Q_{d_j}[Y_t]^\tau$ and $Q_{d_j}[X_t]^\theta$ represent the τ and θ quantiles of the wavelet transformed series at time t and scale d_j. In addition, the coefficients $\gamma_{(d_j,\tau,\theta,0)}$, γ_{i,d_j} and β_{i,d_j} reflect the dependencies and lagged terms at scale d_j.. $\varepsilon_{(d_j,\tau,\theta,t)}$ show the error terms at the relevant scale, quantile levels and increment (Adebayo and Olanrewaju, 2024).

To apply WQQGC, the MODWT method proposed by Percival and Walden (2000) was used to decompose the data series considered in the study. Following Özkan and Eweade et al. (2024), three wavelet pairs were obtained based on the J-level maximum decomposition calculated with the formula $J = \text{round}(\log2(N) - 3)$. Accordingly, the first decomposition (D1: 2-4 months) was classified as short-term, the second decomposition (D2: 4-8 months) as medium-term, and the third decomposition (D3: 8-16 months) as long-term. Secondly, following the study by Li et al. (2015), the quantile series of the dependent and independent variables at the levels of 0.05, 0.10, …, 0.90, and 0.95 were estimated. Then, the analysis was performed using the Granger test function after determining the most appropriate lag length for each pair of quantile series using the AIC criterion.

Empirical results

Diagnostic test results

This section reports a set of preliminary diagnostic tests designed to characterise the statistical properties of the underlying time series. To assess the presence of non-linear dependence, we employ the Brock-Dechert-Scheinkman (BDS) test of independence (Brock et al., 1996), which is widely used to detect departures from independence and identically distributed $(i.i.d.)$ behaviour in financial data. Although earlier results indicate that both series deviate from normality, testing for non-linear dynamics is essential for selecting an appropriate econometric framework. The BDS z-statistics reported in Table 1 reject the null hypothesis of $(i.i.d.)$ for both the CPU and GB series across embedding dimensions M2 through M6, providing robust evidence of non-linear dependence and justifying the use of non-linear and distribution-sensitive modelling approaches.

Table 1: BDS Test Results

Dimension	CPU	*p*-value	GB	*p*-value
M2	11.959***	0.000	0.950	0.342
M3	11.922***	0.000	2.305**	0.021
M4	11.722***	0.000	2.580***	0.009
M5	11.613***	0.000	2.463**	0.013
M6	11.821***	0.000	2.676***	0.007

Note: ***$P < 0.01$ ve **$P < 0.05$. **Source:** Author's computation.

Figure 2 shows the Quantile-Quantile (Q-Q) plots for the CPU and GB series, which are commonly used to assess whether the data follow a normal distribution. In each panel, the empirical quantiles of the observed data are plotted against the corresponding theoretical quantiles of a standard normal distribution, with the 45-degree reference line indicating perfect normality. The pronounced departures of the plotted points from this benchmark—particularly in the lower and upper tails—provide strong visual evidence of non-Gaussian behaviour in both series. These deviations imply excess tail risk and distributional asymmetry, suggesting that extreme observations occur more frequently than expected under normality. Consequently, econometric approaches that explicitly account for distributional heterogeneity and tail behaviour—such as quantile-based and non-linear models—are more appropriate than conventional parametric techniques. These graphical results are entirely consistent with the statistical evidence obtained from the Jarque-Bera test (1980) and BDS tests.
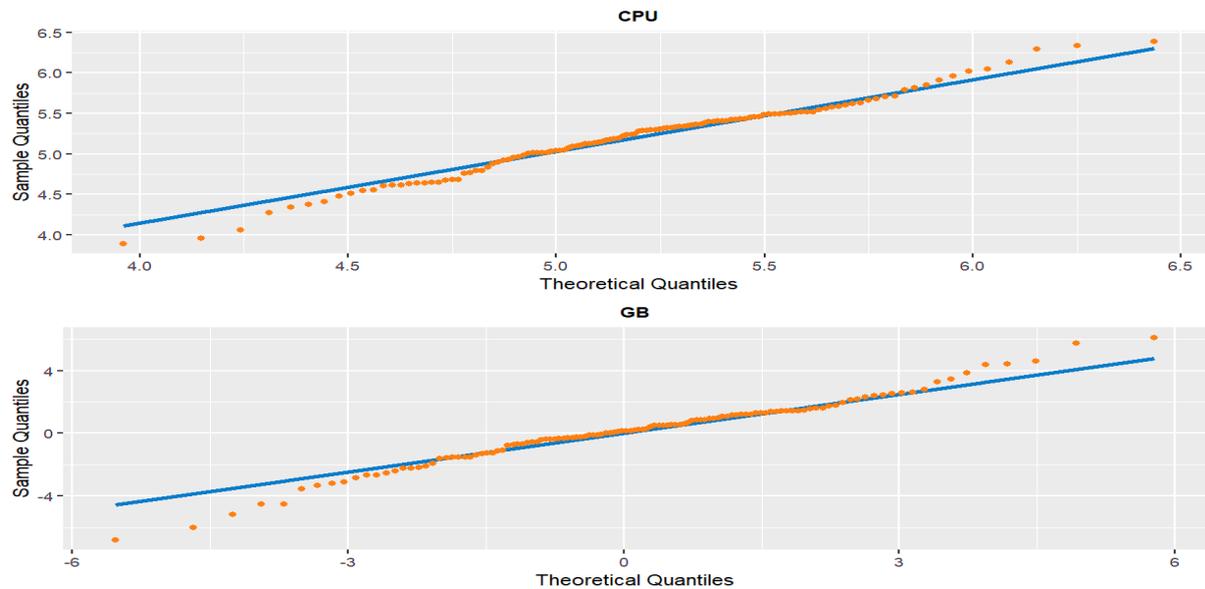
Figure 2: Q-Q Plots

Source: Author's computation.

QADF and QPP unit roots results

As widely recognised in the time-series econometrics literature, conventional unit root tests such as the Augmented Dickey-Fuller (ADF; Dickey and Fuller, 1979) and Phillips-Perron (PP; Phillips and Perron, 1988) procedures are based on mean dynamics and therefore fail to capture distributional heterogeneity across different states of the data. To address this limitation, this study applies the quantile-based ADF (QADF) and Phillips-Perron (QPP) tests developed by Adebayo and Özkan (2024), which allow for stationarity testing across the full conditional distribution. By testing the null hypothesis of a unit root at different quantiles, these methods provide a more comprehensive characterisation of persistence and stochastic trends. The QADF and QPP results reported in Figure 3 indicate that both the CPU and GB series are stationary across all quantiles, confirming that the underlying processes are stable over time and suitable for distribution-sensitive and time-frequency-based econometric analysis. Figure 4 shows the results of the Wavelet Quantile Zivot-Andrews (WQZA) test (Sunday Adebayo vd. 2025). In both series, the test statistics are generally below the 10% critical value. This indicates that the unit root null hypothesis is rejected for all periods and quantile levels. Furthermore, it has been determined that the break dates for the CPU and GB variables are concentrated in certain periods.
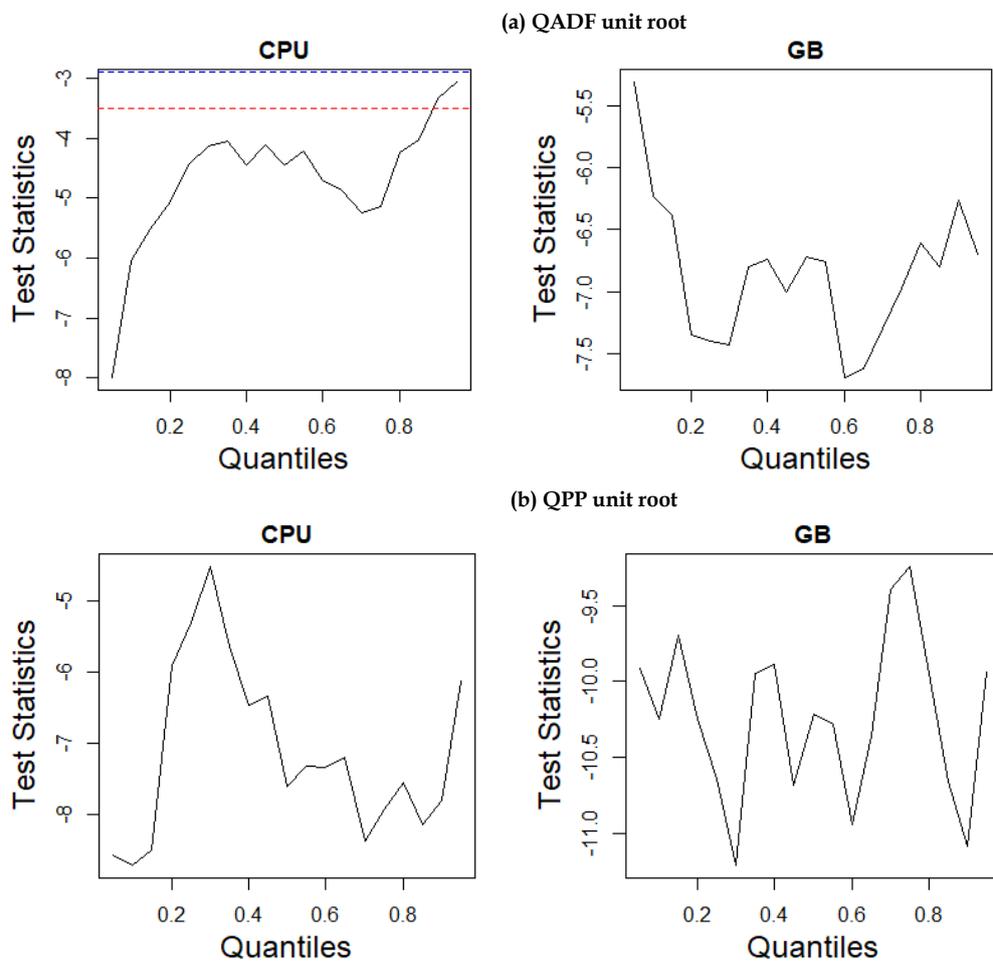
(a) QADF unit root

(b) QPP unit root

Figure 3: (a) QADF and (b) QPP Unit Root Results

Note: The test statistics correspond to critical values of -2.58, -2.89, and -3.49, with significance levels of 10%, 5%, and 1%, respectively.
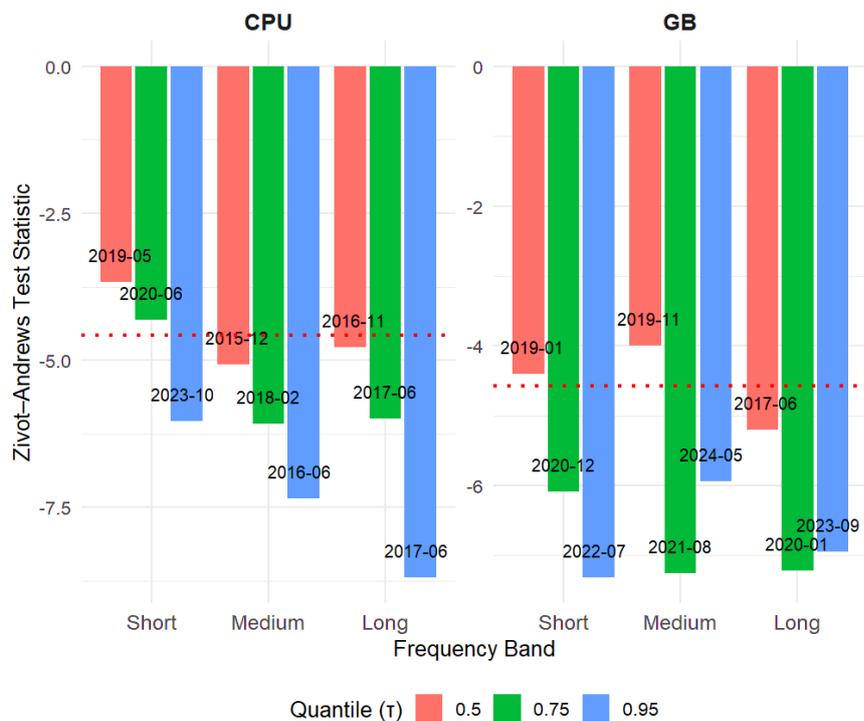
Source: Author's computation.

**Figure 4:** WQZA Unit Root Test Results

Source: Author's computation.

Wavelet quantile-on-quantile regression

Figure 5 presents three-dimensional response surfaces illustrating the effect of climate policy uncertainty on green bond returns across conditional quantiles and different time-frequency horizons (short-, medium-, and long-term). The short-run results reported in Figure 5a reveal a pronounced quantile-dependent response of green bond returns to climate policy uncertainty. At low CPU quantiles (0.10-0.30), particularly when green bond returns are also in their lower quantiles (0.10-0.30), CPU exerts a statistically significant negative effect, indicating that green bond markets are adversely affected during periods of subdued climate policy uncertainty. As CPU moves toward its middle quantiles (0.40-0.60), this negative effect weakens, and the relationship begins to reverse. At high CPU quantiles (0.80-0.90), the effect becomes positive and increasingly strong, especially for green bonds located in the lower tail of the return distribution. This pattern implies that elevated climate policy uncertainty can enhance green bond returns under adverse market conditions, revealing a pronounced asymmetric and quantile-dependent transmission mechanism in the short run.

The medium-run results displayed in Figure 5b further confirm the heterogeneous nature of the CPU-GB relationship across quantiles. At low to moderate CPU levels (0.20-0.60), the effect on green bond returns is mixed and relatively weak, suggesting that moderate climate policy uncertainty exerts only limited downward pressure on market performance. However, once the CPU reaches its upper quantiles (0.80-0.90), its impact becomes uniformly positive and statistically significant across green bond return quantiles, indicating that heightened policy uncertainty is associated with improved bond performance in the medium term. This regime shift suggests that, as uncertainty intensifies, investors increasingly perceive green bonds as resilient and strategically valuable assets. The emergence of a positive, stabilising effect at higher CPU levels implies that market participants internalise climate policy signals more effectively over the medium term and adjust their portfolios toward sustainability-oriented instruments.

The long-run results presented in Figure 5c indicate that the impact of climate policy uncertainty on green bond returns converges toward a more homogeneous, stable, and predominantly positive distribution. CPU exerts a statistically significant positive effect on green bond returns at nearly all quantile combinations (0.10-0.90), with the strongest responses observed at the middle and upper quantiles of CPU. This pattern suggests that, over longer horizons, climate policy uncertainty does not erode green bond performance but instead becomes associated with higher returns across market states. Such dynamics imply that investors gradually internalise climate-related policy risks and increasingly view green bonds as resilient assets in the transition toward a low-carbon economy.

Moreover, the results indicate that when the CPU is at its lowest levels—reflecting periods of high policy clarity and regulatory stability—green bond returns are most strongly linked to the upper tail of the return distribution. This cross-quantile dependence is more pronounced than the relationships observed when both CPU and green bond returns lie in similar low or high quantile states, suggesting that policy certainty enhances investor confidence and demand for green bonds. Overall, these findings support the interpretation that green bonds increasingly acquire safe-haven and performance-enhancing characteristics as climate policy frameworks become more credible and predictable over the long run.

(a) Short-term

**(b) Medium-term**
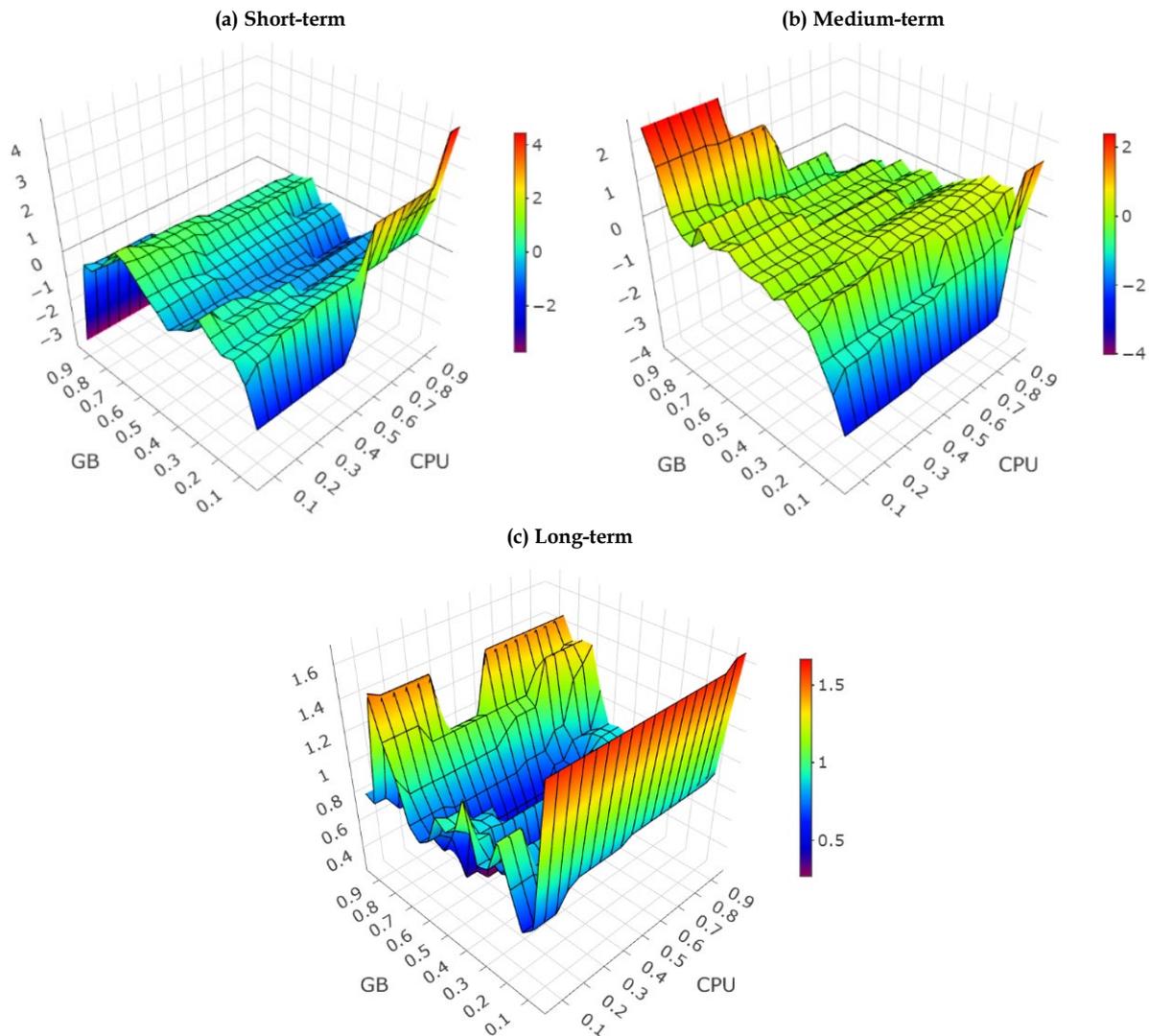
(c) Long-term

Figure 5: WQQR Plots between CPU and GB

The results obtained across short-, medium-, and long-term horizons demonstrate that the impact of climate policy uncertainty on green bond returns is both time- and quantile-dependent. These findings are broadly consistent with recent empirical evidence. In particular, Yu et al. (2023), Ren et al. (2023), Tian et al. (2022), Aharon et al. (2025), and Zhu et al. (2023) similarly report that the effects of CPU vary across market conditions and may shift in sign and magnitude over time. By contrast, other studies, such as Wang et al. (2024) and Köycü (2025), document predominantly negative and more limited effects of CPU on green bond markets. While these findings partially align with our short- and medium-term results, they diverge from our long-run evidence, which shows a statistically significant, positive association between climate policy uncertainty and green bond returns. This discrepancy underscores the importance of explicitly accounting for horizon- and regime-dependent dynamics when assessing the financial implications of climate-related policy uncertainty.

Robustness check (average WQQR and WQR)

The robustness of the WQQR framework is evaluated using two complementary approaches. Figure 6 presents comparative estimates of the impact of climate policy uncertainty on green bond returns obtained from wavelet quantile regression (WQR) and average wavelet quantile-on-quantile regression (AWQQR). In the short run (Figure 6a), CPU negatively affects green bond returns, whereas in the medium and long runs (Figure 6b, 6c), the relationship becomes positive. The consistency of these patterns across alternative estimation techniques supports the stability of the results. It confirms the reliability of the WQQR methodology for capturing the dynamic, regime-dependent effects of climate policy uncertainty on green bond markets.
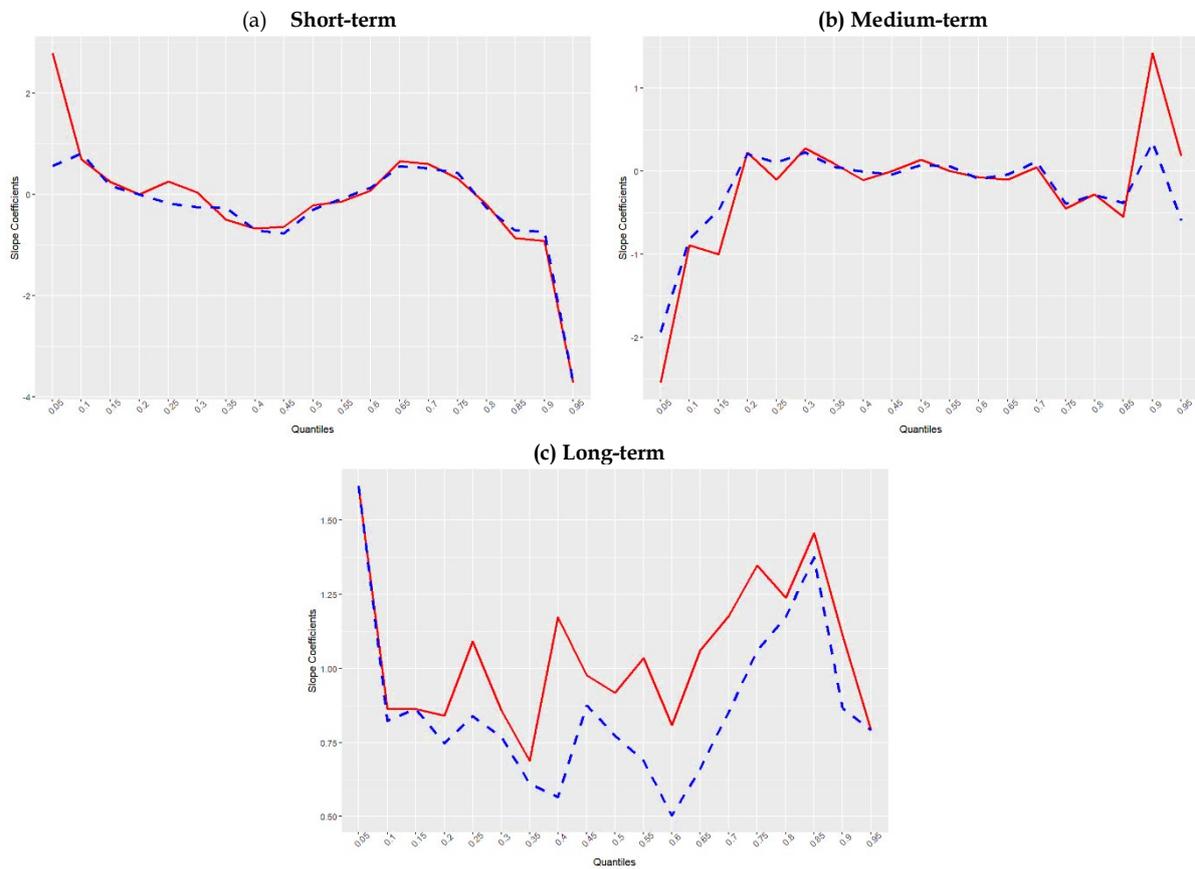
Figure 6: The Impact of CPU on GB

Note: The blue and red lines show the slope coefficient comparing wqr and awqqr across all periods and quantiles.

Wavelet quantile-on-quantile Granger causality

The QQGC frameworks are unable to identify causal transmission mechanisms across different time horizons. To address this limitation, this study employs the WQQGC approach, which jointly evaluates the conditional quantiles of the explanatory and dependent variables across different time-frequency scales. By integrating quantile causality with wavelet decomposition, WQQGC provides a multi-scale characterisation of heterogeneous and time-varying causal dynamics. Figure 6 depicts the causal effects of climate policy uncertainty on green bond returns.

In the short run (Figure 7a), the causal structure from CPU to GB returns exhibits pronounced quantile heterogeneity. Statistically significant causality is detected at the lower quantiles of CPU (0.05-0.35) and at both the lower (0.10-0.25) and upper (0.70-0.95) quantiles of GB returns, indicating that variations in CPU have predictive power for green bond performance across both downside and upside market conditions. Moreover, the re-emergence of significant causality from the upper tail of CPU (0.90-0.95) to the lower tail of GB returns suggests that extreme uncertainty shocks are rapidly transmitted to adverse market outcomes in the short term. Overall, these results point to a highly non-linear and asymmetric short-run transmission mechanism.

In the medium run (Figure 7b), significant causal linkages are primarily concentrated in the upper quantiles of CPU (0.75-0.95) and the mid-to-high quantiles of GB returns (0.55-0.75), indicating that elevated levels of climate policy uncertainty are effectively priced in high-return regimes over intermediate horizons. By contrast, causality is weaker and more localised at lower and middle CPU quantiles, suggesting the presence of adjustment frictions whereby moderate changes in uncertainty exert limited predictive power over green bond returns in the medium term.

In the long run (Figure 7c), the causal linkage between climate policy uncertainty and green bond returns becomes both more substantial and more pervasive across the distribution. Statistically significant Granger causality is observed from the lower quantiles of CPU (0.05-0.25) to the lower and middle quantiles of green bond returns (0.05-0.45), indicating that subdued levels of policy uncertainty systematically predict downside and moderate market outcomes. At the same time, robust causal transmission from the upper quantiles of CPU (0.80-0.95) to the upper quantiles of GB returns (0.70-0.95) suggests that elevated uncertainty is also priced into high-return regimes. These results imply that, over long horizons, financial markets internalise climate policy uncertainty as both a source of risk and

a driver of return opportunities, reflecting an increasingly sophisticated information-processing mechanism in green bond markets.

From a policy perspective, these findings underscore the importance of a stable and credible climate policy framework in shaping long-term investment behaviour. By reducing unnecessary policy volatility and enhancing regulatory predictability, policymakers can strengthen investor confidence and support sustained capital inflows into green finance instruments. For investors, climate policy uncertainty emerges not merely as a risk indicator but also as a forward-looking pricing signal that can be exploited in portfolio diversification and hedging strategies. Consequently, incorporating CPU into long-term asset allocation decisions is essential for improving the resilience and effectiveness of sustainable investment portfolios and for facilitating the broader transition toward a low-carbon economy.
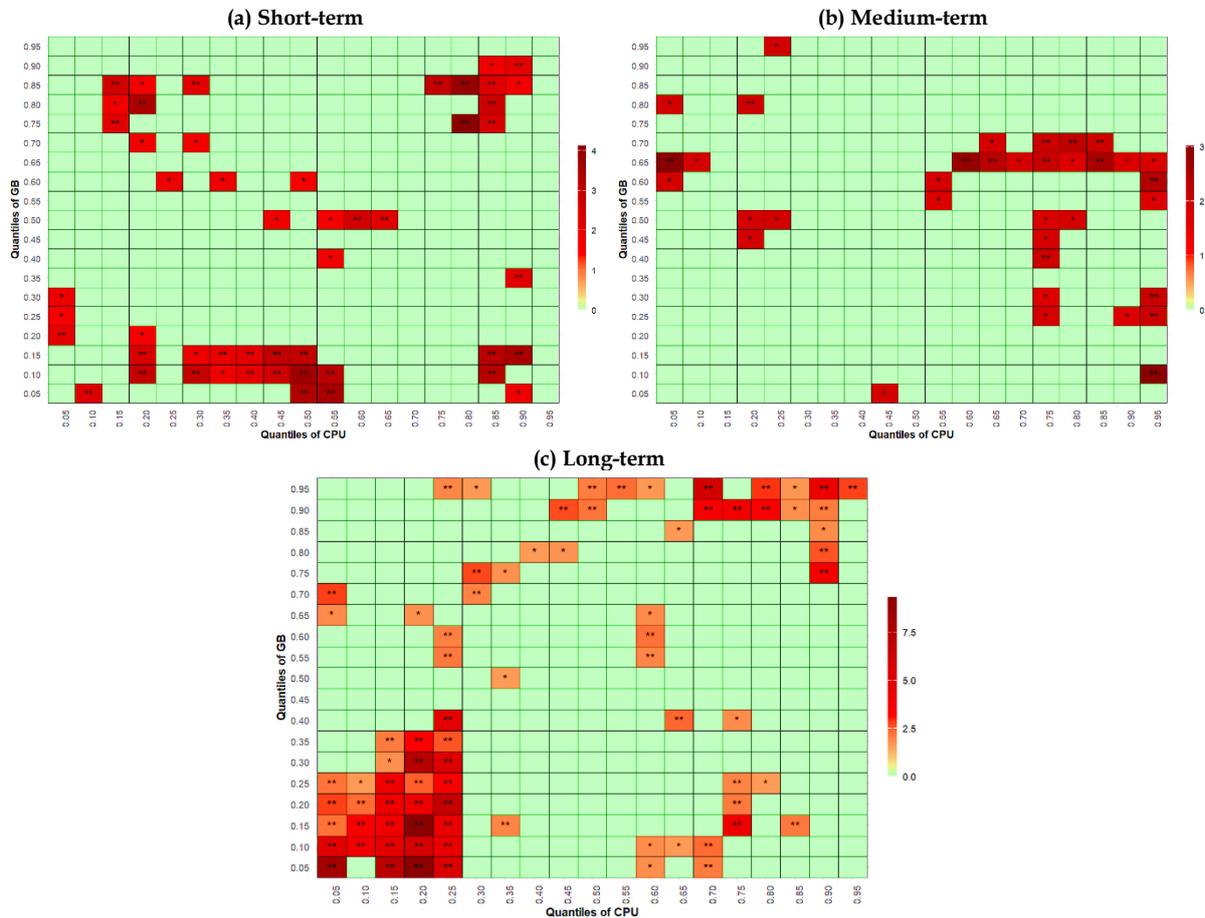

Figure 7: WQQGC from CPU to GB

Note: This graph shows the estimated test statistics for each pair of quantile series across different time horizons (short-term, medium-term, and long-term). The colour gradient ranges from dark green to red, indicating increasing values of the test statistic. * and ** indicate statistical significance at the 10% ,and 5% levels, respectively.

Conclusions and policy recommendations

This study examines the effects of climate policy uncertainty on green bond returns across short-, medium-, and long-term horizons and across different regions of the state-dependent return distribution. Employing the recently developed wavelet quantile-on-quantile regression and wavelet quantile-on-quantile Granger causality frameworks, we identify how climate policy uncertainty is transmitted to green bond markets through non-linear, asymmetric, and scale-dependent channels. The results show that the impact of CPU on green bond returns varies markedly across both time horizons and quantile levels, confirming that this relationship is neither uniform nor stable but instead exhibits pronounced heterogeneity, nonlinearity, and time-varying behaviour.

The WQQR results indicate that the effect of climate policy uncertainty on green bond returns is highly heterogeneous across both time horizons and conditional quantiles. In the short run, CPU exerts a statistically significant negative impact on the lower tail of the return distribution. At the same time, positive effects dominate in the upper quantiles, reflecting strong state-dependent asymmetry. In the medium run, this relationship undergoes a regime shift, with CPU exerting a predominantly positive, statistically significant influence in the mid-to-upper quantiles. In the long run, CPU shows a uniformly

positive and robust effect across all quantiles, indicating that heightened climate policy uncertainty is systematically associated with higher green bond returns over longer investment horizons. These findings confirm that the transmission of CPU to financial markets is neither homogeneous nor time-invariant but instead governed by dynamic, quantile- and horizon-specific mechanisms. The persistent positive long-run effect further suggests that green bonds increasingly serve as resilience-enhancing or safe-haven assets amid climate-related policy uncertainty, reflecting their intrinsic environmental value and favourable market perception.

The WQQGC results support the WQQR findings by demonstrating that the causal transmission from climate policy uncertainty to green bond returns is both horizon- and quantile-dependent. In the short run, statistically significant causality is observed from the lower quantiles of CPU to both the lower and upper quantiles of green bond returns, together with a re-emergence of causal effects from the upper tail of CPU to the lower tail of GB returns. In the medium run, causal linkages are primarily concentrated in the upper quantiles of CPU and the mid-to-high quantiles of GB returns, with only limited and localised effects at lower and middle CPU levels. In the long run, strong and persistent causal relationships emerge between the lower and upper quantiles of CPU and the corresponding regions of the green bond return distribution. Collectively, these results indicate that the causal structure between CPU and green bond markets is inherently non-linear, regime-dependent, and shaped by both time-scale dynamics and distributional interactions.

These results indicate that the impact of climate policy uncertainty on green bond returns is particularly pronounced in the upper regions of the return distribution. In particular, low-uncertainty regimes are associated with elevated investor confidence and stronger performance in the green bond market, as evidenced by the stronger effects observed when CPU is in its lower quantiles and green bond returns are in their upper quantiles. This cross-quantile dependence is more pronounced than in states where both CPU and GB returns lie in lower quantiles, suggesting that policy clarity amplifies upside market conditions. At the same time, the positive response of green bond returns to increases in CPU at higher quantiles implies that markets may interpret rising climate policy uncertainty as a signal of forthcoming regulatory action or policy tightening that could ultimately benefit climate-aligned assets. Such dynamics reflect prevailing market sentiment and forward-looking expectations regarding the evolution of climate policy frameworks. Moreover, they suggest that investors increasingly perceive green bonds as resilient investment vehicles, supported by their intrinsic environmental value and their relative insulation from conventional policy-driven risks relative to other asset classes.

The observed causal linkages between climate policy uncertainty and the upper quantiles of green bond returns suggest that green bonds tend to outperform when policy-related uncertainty diminishes and investor confidence strengthens. These results indicate that CPU functions not only as a risk metric but also as a market signalling device that conveys information about the credibility and future direction of climate policy. When climate policy frameworks are perceived as stable and predictable, investors increasingly allocate capital toward environmentally aligned financial instruments, thereby driving up demand and prices in the green bond market. From a policy standpoint, the findings highlight the importance of clear, consistent, and forward-looking climate strategies in promoting both environmental objectives and financial market stability. Policy regimes that foster transparency and long-term commitment to sustainability are therefore likely to enhance investor confidence, deepen market liquidity, and support the continued growth of sustainable finance.

In conclusion, this study makes a substantive contribution to the green and sustainable finance literature by combining a novel methodological framework with a distributional and time-frequency perspective. The empirical findings carry important implications for investors, financial analysts, and policymakers. By revealing how green bond markets respond heterogeneously to climate policy uncertainty across different horizons and market conditions, the analysis enables investors to design more informed portfolio allocation and risk management strategies. Financial analysts can further exploit the insights generated by the wavelet quantile-on-quantile regression and wavelet quantile-on-quantile Granger causality frameworks to better assess downside risk, tail dependence, and return dynamics in sustainable financial assets. From a policy perspective, the results underscore the critical role of clear, credible, and forward-looking climate policies in reducing market uncertainty, strengthening investor confidence, and supporting the long-term development of green financial markets. Stable and transparent regulatory frameworks not only facilitate the mobilisation of capital toward environmentally sustainable projects but also contribute to broader financial stability.

This study has some limitations. First, the empirical analysis is limited to climate policy uncertainty and the green bond market. It does not fully reflect other transmission channels and financial instruments that may affect sustainable finance markets. Second, while monthly data is suitable for capturing

medium- and long-term dynamics, it may miss high-frequency market adjustments and short-term volatility shocks. Third, although the WQQR and WQQGC approaches offer a flexible analytical framework in the time-frequency-quantile domain, analyses using alternative econometric methods that address the issue from different perspectives could provide additional contributions to the literature. Future studies examining different performance regimes, various asset classes, higher-frequency data, and regional financial markets may contribute to a more comprehensive understanding of the dynamic and heterogeneous nature of green and sustainable finance under climate policy risks.

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