Climate Change-Stock Return Volatility Nexus in Advanced Economies: The Role of Technology Shocks

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Abstract

Design\Methodology\Approach:
We use a GARCH-MIDAS model to examine the relationship between climate change and stock return volatility since it enables data analysis at various frequencies within the same framework. We employ a novel dataset to trach technological shocks, and the study spans decades of data from 1880 to 2018.

Purpose:
Given the systemic nature of climate change, there are many interdependencies between its primary components and feedback loops, emphasising the need to simultaneously consider the stock market implications of physical and transitional climate-related risks. More importantly, carbon emissions are expected to be reduced through various transition pathways. However, transitional climate risks have been validated as capable of predicting stock market behaviour, hence the motivation for the role of technological shocks.

Finding:
We find that the relationship between climate change and stock return volatility is episodic and varies with different degrees of intensity of high-temperature anomalies and technology shocks. Our results suggest that policy actions should include investing in climate technologies to reduce greenhouse gas emissions and encouraging investment in eco-friendly assets.

Originality\Value:
There has been little or no consideration for the probable complementary effects of physical and transition climate-related risks on stock markets. Hence, the novelty in the context of this study is the hypothesis that transitional risks, if explored from the point of view of technological innovations, can moderate the stock market's vulnerability to physical climate risks.

Keywords: Climate change; Stock return volatility; Technology shocks; Advanced economies
JEL Codes: C53; G10; Q54; Q55

1. Introduction

Climate change is affecting ecosystems in various ways. It has reduced water availability and agricultural outputs and caused extreme weather events that affect human health and welfare (Montgomery, 2017). In addition to these effects, the changing climate is also becoming a significant risk factor to consider when it comes to ensuring environmental sustainability for investment in stocks to thrive. In other words, recent research focusing on investors' concerns regarding climate change risks has documented that climate change risks are an essential ingredient in investment decision-making and the pricing of financial assets (see Krueger et al., 2019; Ilhan et al., 2020; Monasterolo & De Angelis, 2020; Bolton & Kacperczyk, 2021). That said, it is now suggested that investors with innovative ideas for utilising emerging technologies are more likely to sustain the environment and, by extension, maximise returns from their investment in financial assets. While acknowledging the possibility of utilising technologies to mitigate the impact of climate change has been recently validated in the context of real estate prices (see Salisu et al., 2023), the extent to which it matters in the volatility of conventional stocks has been largely unexplored. As a result, the innovation in this study is to revisit the systematic risk of climate change in stock returns with an extended analysis of the role of technological innovations in the nexus. Thus, the following highlights the contribution of this study to the literature:

To begin, while risk associated with the changing climate is widely categorised into physical and transitional risks (see Carney, 2015; Jung and Song, 2023), the dominant practice in the literature has been to separate the effect of physical risk on stock market performance from the effect of transition risk on stock market performance. As a result, there has been little or no consideration for the probable complementary effects of these alternative climate-related risks on stock markets. Meanwhile, in addition to being a derived risk amid the global goal of transitioning to a low-carbon economy (Curtin et al., 2019), the transition climate-related risk has the potential to mitigate the vulnerability of the stock market to physical climate-related risk. This implies that a timely and smooth transition may contribute to lower physical risk exposure and, by extension, a reduction in the extent to which the stock market may be vulnerable to acute or chronic physical risks.

Given the foregoing, the first contribution of this study is to experiment with the probable complementary effects of physical and transitional climate-related risks on stock returns (see Adediran et al., 2023). Premising on the view that the transition risks can also manifest in terms of firm reputations and technological changes (see Semieniuk et al., (2021), we hypothesize that the transitional risks, if explored from the point of view of technological innovations, can moderate the stock market's vulnerability to physical climate risk. Generally, carbon emissions are expected to be reduced through various transition pathways, but we consider a measure of transitional climate risk that has been validated as capable of predicting stock market behaviour (Hsu and Huang, 2010; Papanikolaou, 2011; Kogan and Papanikolaou, 2014; Sharma and Narayan, 2022) while also having the potential to moderate the stock market's vulnerability to physical climate risk. Essentially, we favour the technological channel of transitioning to a low-carbon economy using the novel global historical, technological shocks developed by Sharma and Narayan (2022). Indeed, the transition risks are shaped not only by technological innovations but also by policies and consumer market sentiment (or a firm's reputation), among others. However, we believe that technological innovation is the best measure of transition risk in this study because it has been shown to directly impact stock market performance while also being capable of mitigating the impact of physical climate risks on stock markets.

Secondly, while climate change is a global phenomenon, the physical and transitional risks associated with it cannot be expected to manifest exactly across different economies. Therefore, the potential vulnerability of the stock market to physical and transitional climate risks and the extent to which the latter may act as a moderator of the former is dependent on factors such as the sophistication of the financial market and the level of technological advancement, among others (see Drechsler et al., 2020). To avoid making sweeping generalizations about our hypothesis, we used the cases of a group of economies, in this case, the G7, with relatively similar economic and financial market structures to arrive at a just and robust comparison regarding the validity of our hypothesis. More importantly, the G7 are responsible for 25% of the world's energy-related carbon emissions, thus making them disproportionately liable for climate change.

Third, the historical nature of our dataset, which dates to 1889 for some of the G7 countries under consideration, fuels the concern that the stock returns –climate nexus may be episodic. One of the historical events that shaped the dynamics of the global economy was the 1930s Great Depression/Recession. Considering the widespread evidence of a correlation between booming episodes and increasing climate change, we hypothesize that the volatility effect of climate change in stock returns is relatively higher in the Great Depression period. As a result, we categorized our historical sample into full-sample and Great-Depression-sample, with the latter in particular enabling us to validate or refute the hypothesis that the stock returns volatility consequence of climate change is higher aftermath of the 1930s Great Depression. The use of historical data enables us to understand the empirical relationship over a long period, and therefore, we can exploit the large historical variations in the data for countries that have transformed from being financially underdeveloped in the 19th century into being quite developed in the beginning of the 20th century, and for financial systems that experienced increasing repression from the start of

WWI to the end of WWII but enjoyed more liberalized and open regimes in the post-WWII period (Madsen and Ang (2016)); Sharma and Narayan (2022)).

Finally, and from the methodological point of view, we employ the Generalized Autoregressive Conditional Heteroscedasticity – Mixed Data Sampling (GARCH-MIDAS) modelling framework to enable us to explore the variables of interest in their natural frequencies and then, consequently, overcome the loss of information associated with the data-splicing technique of aggregating variables of different frequencies into a uniform frequency. With the GARCH-MIDAS, our dependent variable, for instance, the stock returns of the individual G7 economies, has a higher (monthly) frequency, while the exogenous factor, particularly the measure for the transitional climate risks, has a lower (annual) frequency. The GARCH-MIDAS has been empirically validated to be effective in dealing with both returns and volatility dynamics of financial instruments such as stock prices (see Wang et al., 2020; Salisu & Gupta, 2021; Salisu et al., 2022a, 2022b). Our finding of preliminary evidence of conditional heteroscedasticity and serial correlation also supports the use of GARCH-MIDAS in this study.

Our evidence validates the episodic behaviour of the connection between climate change and stock return volatility as hypothesized, and this behaviour depends on the events characterizing the different episodes. While we also hypothesize that climate change can have disruptive effects on stock markets, we find that the aftermath of the Great Depression witnessed a relatively less disruptive effect of climate change on the stock markets of the advanced economies compared to the full sample period. Also, the degree of intensity of temperature anomalies impacts somewhat differently on stock return. We find that the disruptive role of climate change in the stock markets heightens with the rising intensity of temperature anomalies. Meanwhile, technology shocks help moderate the disruptions regardless of the sample period. Overall, investment in climate technologies and eco-friendly assets can help us reduce the disruptive role of climate change in the stock markets of advanced economies.

2. Brief Literature Review

There is no denying that the topic of "climate change" has been at the forefront of international debate for decades (see Guyatt, 2011; Clapp et al., 2017; Hunt & Weber, 2019; Bender et al., 2019; Venturini, 2022, among others). This may not be unconnected to the fact that climate change not only affects our health but also poses a significant risk to the different spheres of our economic activity (Matthews et al., 2017; He & Liu, 2018; Teng & He, 2020; Litterman et al., 2020; Alsaifi et al., 2020). The direction of the impact on stock market performance has been made abundantly obvious by the literature on climate risk and the stock market. Salisu and Oloko (2015) claim that flow or stock channels can be used to express the relationship between stock returns and climate change. Through the flow channel, climate change is predicted to have a negative impact on stock returns by decreasing the firm's cash inflows due to higher costs associated with mitigation and adaptation to the changing climate. On the other hand, the stock channel depends on the principle of portfolio balance or diversification.

Additionally, this channel points to a negative correlation between stock returns and climate change since the former raises demand for investments connected to climate change while the latter decreases demand for traditional equities. As a result, stock prices will drop, ultimately lowering conventional stock returns. It is reasonable to anticipate that climate change will increase the volatility of traditional equities since lower market returns indicate that investing is riskier. According to Wu et al. (2022), increased risks associated with climate change portend an unpredictable future for the market, which will cause stock prices to fluctuate.

Considering the aforementioned, among other things, there is growing evidence in the literature (Krueger et al., 2019; Monasterolo & De Angelis, 2020; Ilhan et al., 2020; Giglio et al., 2021; Bolton & Kacperczyk, 2021; Gimeno & González, 2021; Antoniuk & Leirvik, 2021; Reboredo & Ugolini, 2022) suggesting that climate change exposes firms to new risks and has significant financial implications for underlying stocks. However, these extant studies not only predominantly focus on climate-related stocks, such as clean energy stocks, among others, but the notable few on the association between climate change and conventional stocks mostly concern themselves with prices and the return dynamics of the stocks (Salisu and Oloko, 2015). Thus, the effect of climate risk on stock market volatility remains understudied. More importantly, climate change-related risks are commonly classified into two categories: physical risk and transition risk (Carney, 2015; IMF, 2022; Jung and Song, 2023). The former, which usually manifests in the form of extreme fluctuations in precipitation patterns, extreme temperature anomalies, and rising sea levels, among others, has been predicted to be capable of causing higher production costs, lower profitability, and a declining value of a company's equity (Tankov and Tanter, 2019; Hong et al., 2020; Kruttli et al., 2021; Schlenker and Taylor, 2021). The latter, which, on the other hand, refers to risks resulting from policy, technology, legal, and market changes that occur during the move to a low-carbon economy, is expected to indirectly expose a company's equity to shocks and disruptions (see Venturini, 2022).

Given that both physical and transitional risks associated with climate change are capable of heightening the volatility of stock returns, the existing studies on the systematic risk impact of climate change on stock returns have continued to favour the traditional approach of regressing stock returns separately on physical climate-related risks (Vlady, 2015; Bansal et al., 2016; Oloko et al., 2022) and on transition climate-related risks (Antoniuk & Leirvik, 2021; Reboredo & Ugolini, 2022). However, there are many interdependencies between the primary components of the changing climate and its feedback loops, which emphasises our motivation to consider further the stock return implications of physical and transition climate-related risks concurrently. We contribute to this literature gap by exploring whether a timely and smooth transition may contribute to lower physical risk exposure and, by extension, reduce the extent to which the stock return is vulnerable to acute or chronic physical risks. Motivated by the possibility of utilising technologies to mitigate the impact of the systematic risk of climate change on the volatility of stock returns, we rest on the technological channel of transitioning to a low-carbon economy to hypothesise that the transitional risks, if explored from the point of view of technological innovations, can moderate the stock market's vulnerability to physical climate risks.

3. Data and Preliminary Results[6]

Our data scope covers several decades from 1880 (although some start from 1915) to 2018. The availability of data for technology shocks governs the end period. Specifically, our variables of interest are stock returns (SR), climate change (CC), and technological shock (TS). The SR measured as log-return of monthly stock prices (SP) is obtained from the Global Financial Database, while the two alternative measures of CC considered are the average of temperature (TMP) anomalies and mean-precipitation (PRCP). The former is obtained from the National Aeronautics and Space Administration (NASA) Goddard Institute for Space Studies (GISS), and

[6] The presentation and discussion of the preliminary results are available in the online appendix of this paper.

the latter is obtained from the World Bank Climate Change Knowledge Portal database (https://climateknowledgeportal.worldbank.org/). The technology shock (TS) data used in this study is obtained from Sharma and Narayan (2022), whose approach to constructing the TS is consistent with the idea proposed by Hsu (2009), where TS is computed in terms of the number of patents granted to residents. More importantly, the TS is considered both in terms of local technology shock (TS) and global technology shock (GTS), such as the aggregation of patent rights of the OECD economies (GTS_OECD) and 164 global economies (GTS_164).

Given that the performance of a stock market may be sensitive to the macroeconomic environment, we also account for the role of inflation (INFL) as a measure of macroeconomic instability. The data herein are a mix of historical monthly and annual frequencies with varying start dates for each of the G7 member countries under consideration. For example, while the end date (i.e. 2018) is uniform for all the countries, the start date is 1880 for France, Germany, the UK, and the US; 1906 for Italy; and 1915 for Canada and Japan, respectively. The start also depends on whether the indicator of climate change under consideration is TMP or PRCP and whether the estimated model is with or without a control variable.

4. Methodology

The Arbitrage Pricing Theory (APT) underpins the theoretical relationship between climate change and stock returns and the impact of technological shocks on that relationship. This theory assumes that an asset's expected return (and thus its volatility) may be forecasted using a variety of macroeconomic parameters that account for systematic risk. Climate risk and technological shock are examples of systematic risks because they affect more than just the environment or sector from whence they arise. As a result, the APT is ideally adapted to explain the theoretical relationship between climate change and stock return volatility. That said, the differing nature of the scope of our data influences the choice of estimation technique for this study. As evident in our preliminary results, the variables of interest are characterised by mixed frequencies of monthly and annual series, resulting in our preference for a mixed data sampling (MIDAS) technique as the most appropriate for preserving the uniqueness of the variables of interest. However, it is instructive that, just like the stock return variable, which is sourced on a monthly basis, the two alternative measures of climate change, namely, TMP and PRCP, as well as the control variable, are also available on a monthly basis. Therefore, in addition to the MIDAS approach, which enables us to accommodate our key variable of interest, for instance, the technological shock in its original annual frequency, we begin our estimation framework with a modelling approach that enables us to estimate the effect of the two alternative measures of climate change on stock returns using a uniform monthly frequency. However, since the intuition here is mainly to determine the robustness of the alternative climate change measures in the models with and without control variables, then the non-MIDAS framework and the estimates obtained from it for this purpose are reported in the online appendix of this paper.

Having confirmed the robustness of the alternative measures of climate change (see Table A1 in the online appendix), irrespective of whether the estimated model includes or does not include a control variable, we herein proceed to employ a GARCH-MIDAS model that allows for the analysis of data at different frequencies within the same framework. One of the main advantages of this approach, particularly in the context of this study, is that it has a feature that allows us to link the higher frequency (monthly) stock returns) with a lower frequency (annual) technology variable and a climate change proxy. More importantly, the GARCH-MIDAS has the potential to help guide against information loss usually associated with the use of splicing techniques to aggregate or disaggregate data. In other words, the GARCH-MIDAS is a framework where all the variables are concurrently captured irrespective of their varying frequencies, thereby ensuring that information inherent in the original data is fully preserved for better estimation outcomes. On the whole, our preference for the GARCH-MIDAS model and its superiority over other competing alternatives find support in a number of the extant studies (Asgharian et al., 2013; Salisu and Gupta, 2021; among others) that have also favoured the same when modelling with series of mixed frequencies. Following the procedure in studies like Engle et al. (2013), Asgharian et al. (2013), and Salisu and Gupta (2021), among others, our GARCH-MIDAS is specified as.

$$r_{i,t} = \nu + \sqrt{\mu_t \circ \tau_{i,t} \circ \varepsilon_{i,t}}, \qquad \forall i = 1, 2..., N_t \tag{1}$$

$$\varepsilon_{i,t} \mid \varsigma_{i-1,t} : \; N(0,1) \tag{2}$$

Equation (1) defines our monthly stock returns process with subscripts (i,t) used to denote monthly and annual frequencies, respectively, while N_t representing the number of months in a year t. The term ν on the right-hand-side (R.H.S) of the equation measures the unconditional mean of the stock returns while $\sqrt{\mu_t \circ \tau_{i,t}}$ expressing the conditional variance into a short-term component defined by $(\tau_{i,t})$, and a long-term component defined by μ_t. The error term in equation (2), for instance ($\varepsilon_{i,t}$), follows a Gaussian distribution and $\varsigma_{i-1,t}$ is the information set up $(i-1)^{th}$ month of year *t*. The conditional variance dynamics of the short-run component, $\tau_{i,t}$, is as given below.

$$\tau_{i,t} = (1-\lambda-\gamma 0) + \lambda \frac{(r_{i-1,t} - v)^2}{\mu} + \gamma \tau_{i-1,t} \tag{3}$$

where λ and γ represents ARCH and GARCH terms, respectively; conditioned to be positive and/or at least zero $(\lambda > 0 \text{ and } \gamma \geq 0)$ and summing to less than a unit $(\lambda + \gamma < 1)$. Our low-frequency series (CC and TS) are changed into a monthly frequency without losing generality (for technical details, see Engle et al. (2013)). As a result, the months in year *t* are rolled back without being recorded. Hence, equations (4) and (5) are, therefore, the monthly long-term component (μ_i) for the realized volatility and exogenous factors:

$$\mu_i = m + \varphi \sum_{k=1}^{K} \theta_k(\omega_1, \omega_2) RV_{i-k} \tag{4}$$

$$\mu_i = m + \varphi \sum_{k=1}^{K} \theta_k(\omega_1, \omega_2) X_{i-k} \tag{5}$$

where *m* represents the long-run component intercept; φ is the coefficient of the predictor (realized volatility or the exogenous factor). Also of interest in equations (4) and (5) are the beta polynomial weights, wh $\theta_k(\omega_1, \omega_2) \geq 0, k = 1, ..., K,$ ich is the weighting scheme that must sum to one for the parameters of the model to be identified.

5. Results and Discussion

The main goal of this study is to unravel the dynamics of climate change as a potential predictor of stock return volatility while controlling for the moderating role of technology, focusing on the G7 member nations responsible for 25% of the world's energy-related carbon emissions. That said, and for the sake of robustness, we begin our empirical analysis to determine the consistency of the alternative climate change measures under consideration in the model with and without control variables. The empirical estimates obtained in this regard are documented in Table B1 in the online appendix of the paper. The table shows that our finding is robust to the alternative measures of climate change, irrespective of whether the model is with or without control variables. Therefore, our preference for TMP as a measure of climate change in the main analysis based on our second modelling framework (GARCH-MIDAS) is motivated by the anomalies feature of the TMP and the quest to test the moderating role of the technological shock across different temperature percentiles.

Given the above, notable innovations in the study include the hypothesis that technological shocks can moderate the stock market's vulnerability to climate change and that the climate change stock return volatility nexus is episodic. Thus, in the quest for a comprehensive analysis of our data, result presentation and discussion of findings are explored across five different but related sub-headings. In Section 5.1, we use our full historical data sample to investigate the climate change-stock return volatility nexus in a restrictive form without controlling for the role of technological shock. In Section 5.2, we adjust the start date of our data set to 1950 to define the post-Great Depression (PGD) sample. The motive in this regard is to determine whether the volatility effect of climate change on stock returns is episodic, particularly whether the increased technological advances during the economic recovery process moderate or heighten the effect of climate change on stock return volatility. In Section 5.3, we control for the role of technology shock for the full-sample and the post-Great Depression samples, respectively. Additional results are presented in the online appendix of the paper (see Table B2, B3, B4, and B5), where we experiment with 25%, 50%, and 75% percentiles in high-temperature anomalies.[7] to test whether stock returns react differently to varying degrees of climate change with or without the role of technology.

5.1 Climate change –stock return volatility based on full-sample

Using our full-sample data set, the parameter μ in Table 1 measures the unconditional mean stock returns, and the values appear positive for virtually all the G7 member countries. Regarding the ARCH (α) and GARCH (β) terms, we find their respective impacts on stock return volatility to be statistically significant, irrespective of the variant of the GARCH-MIDAS models considered.

[7] The high temperature is derived as the positive values of temperature anomalies. Thus, the 25^{th}, 50^{th}, and 75^{th} percentiles are of the high temperature to test whether varying degrees of intensity of high-temperature matter in the climate change-stock return volatility nexus

That said, the persistence of the shock associated with the ARCH and GARCH terms in the volatility of stock returns appears to be relatively higher in the GARCH-MIDAS-X models, where the sum of the terms $(\alpha+\beta)$ is close to one (1) irrespective of whether the X-factor is captured as temperature or high temperature. The persistence of the ARCH and GARCH effects is equally evident in the realized volatility except for Canada. Regarding the slope coefficient, we find the term (θ) to be statistically significant for both the realized volatility and the exogenous regressor(s). This indicates that the climate change information is relevant to the volatility dynamics of stock returns, as it offers insights beyond what is readily contained in the realized volatility of the stock markets. Not only do our findings in this regard lend support to Rameli et al. (2021), which conclude that climate change has a significant influence on stock returns and volatility (see also Oloko et al., 2022), but we also reveal, within the context of this study, the potential dual role of climate change in the volatility of stock returns. For instance, climate change is a systematic risk. According to the Arbitrage Pricing Theory (APT), it is expected to increase stock market volatility. Still, while this position holds for France, Italy, and the UK, we find evidence of the declining volatility effect of climate change in Canadian, German, and Japanese stock returns. Such a declining volatility effect of climate change on stock returns may be due to the likelihood that the affected G7 countries have benefited from low-carbon transition initiatives such as adopting new energy technologies, among others. Similar to this position is the study by Salisu et al. (2013), whose findings report the moderating role of technological shock in climate change volatility in real estate prices. In the context of this present study, however, we find the potential of climate change to cause declining volatility in stock returns to be relatively larger for high temperatures.

Table 1: Climate change-Stock return volatility nexus based on the full-sample

		μ	α	β	θ	w	m
Canada	RV	0.0056***	0.1118***	0.1470***	0.0681***	20.785***	0.0004***
		(0.0011)	(0.0300)	(0.1992)	(0.0052)	(6.1644)	(0.0000)
	TEMP	0.0052***	0.1010***	0.8654***	-0.5149***	1.7270**	0.0028***
		(0.0011)	(0.0125)	(0.0142)	(0.1347)	(0.7541)	(0.0003)
	h-TEMP	0.0052***	0.1016***	0.8656***	-0.6169***	1.7761**	0.0033***
		(0.0011)	(0.0125)	(0.0141)	(0.1618)	(0.6941)	(0.0005)
France	RV	-0.0015***	0.1606***	0.7537***	0.1234***	1.0031***	-5.68e-06***
		(0.0002)	(0.0159)	(0.0235)	(0.0111)	(0.0454)	(7.12e-07)
	TEMP	0.0010**	0.0368***	0.9631***	0.0970***	5.6835***	5.37e-05***
		(0.0005)	(0.0037)	(0.0036)	(0.0245)	(0.1090)	(0.0076)
	h-TEMP	0.0008	0.0566***	0.9387***	1.0116***	3.4070***	-0.0002***
		(0.0005)	(0.0055)	(0.0050)	(0.3110)	(0.3682)	(8.35e-05)
Germany	RV	0.0041*	0.1484***	0.6768***	-0.0081***	1.0010***	0.0061***
		(0.0023)	(0.0201)	(0.0414)	(0.0019)	(0.1931)	(0.0004)
	TEMP	0.0030	0.1513***	0.6117***	-0.8921***	12.984	0.0058***
		(0.0021)	(0.0209)	(0.0397)	(0.1502)	(13.659)	(0.0002)
	h-TEMP	0.0030	0.1508***	0.6128***	-1.0508***	15.855	0.0070***
		(0.0022)	(0.0208)	(0.0397)	(0.1870)	(17.789)	(0.0004)
Italy	RV	0.0029**	0.1286***	0.0003	0.0723***	30.874***	0.0008***
		(0.0015)	(0.0304)	(0.1591)	(0.0050)	(10.943)	(0.0001)
	TEMP	0.0033**	0.1133***	0.8534***	1.4465***	1.0960*	0.0029***
		(0.0015)	(0.0130)	(0.0166)	(0.3702)	(0.5862)	(0.0004)
	h-TEMP	0.0033**	0.1135***	0.8478***	0.2765***	1.0738***	0.0001
		(0.0016)	(0.0139)	(0.0180)	(0.3790)	(0.3004)	(0.0003)
Japan	RV	0.0042***	0.2132***	0.5479***	0.0590***	12.628*	0.0012***
		(0.0013)	(0.0280)	(0.0874)	(0.0078)	(7.2990)	(0.0002)
	TEMP	0.0044***	0.1632***	0.7986***	-1.0345***	1.0010***	0.0054***
		(0.0011)	(0.0209)	(0.0236)	(0.3778)	(0.1865)	(0.0011)
	h-TEMP	0.0044***	0.1629***	0.7980***	-1.3250***	1.0010***	0.0067***
		(0.0011)	(0.0209)	(0.0209)	(0.4696)	(0.1516)	(0.0014)
UK	RV	0.0022***	0.2214***	0.5140***	0.0957***	7.7190***	0.0001***
		(0.0006)	(0.0323)	(0.0754)	(0.0064)	(2.1264)	(2.98e-05)
	TEMP	0.0016***	0.1404****	0.8524***	0.5619***	1.0010***	0.0018*
		(0.0006)	(0.0139)	(0.0139)	(0.3409)	(0.2224)	(0.0010)
	h-TEMP	0.0019***	0.1516***	0.8437***	2.3235	1.0999	1.87e-05
		(0.0006)	(0.0147)	(0.0142)	(2.1028)	(0.8585)	(4.88e-05)
USA	RV	0.0068***	0.1671***	0.7641***	0.0343***	1.0283***	0.0010***
		(0.0009)	(0.0152)	(0.0262)	(0.0125)	(0.3232)	(0.0002)
	TEMP	0.0064***	0.1542***	0.8104***	-0.0536	15.0590	0.0021***
		(0.0008)	(0.0121)	(0.0144)	(0.1407)	(227.59)	(0.0003)
	h-TEMP	0.0064***	0.1548***	0.8010***	0.0387***	25.679	0.0018***
		(0.0008)	(0.0121)	(0.0147)	(0.1897)	(1690.6)	(0.00003)

Note: TEMP denoting temperature anomalies measures climate change, while h-TEMP is high temperature derived as the positive values of temperature anomalies. ***, ** & * represents significant at 1%, 5% and 10% levels of significance.

5.2 Climate change–stock return volatility based on PGD sample

Our finding of mixed evidence of positive and negative coefficients of climate change, as reported in the preceding section, may not be unconnected to the fact that both episodes of boom and Depression characterize our historical sample. On the one hand, the significant positive effect of climate change on the long-term stock return volatility of three of the G7 countries in Table 1 is an indication that climate change tends to cause higher volatility (see Antoniuk & Leirvik, 2021; Oloko et al., 2022). The fact that we also reveal climate change as capable of reducing volatility in the stock returns of other G7 countries further suggests that investment demand and stock returns may increase amid climate change. This, among others, informed our earlier submission of the dual role of climate change in the volatility dynamics of the G7's stock returns. However, unlike Oloko et al. (2022) and other previous studies (Vlady, 2015; Bansal et al., 2016; Reboredo & Ugolini, 2022), the historical sample utilized in this study includes some events that may have shaped the business cycle of the global economy. One such economic event that lasted more than a decade was the Great Depression, which began in 1929 and lasted until 1941. Characterized by an episode of record dwindling economic activity, the period of the Great Depression covered in our historical sample might have been overwhelmed by reductions in energy consumption and, thus, carbon emissions and, by extension, declining climate change. On the likelihood that such an episode of unprecedented declines in the activity of the global economy would have constituted an outlier in our dataset and possibly influenced our findings thus far, we adjust our data sample to exclude the period of the Great Depression. However, a cursory look at the GARCH-MIDAS estimates obtained from the PGD sample (see Table 2) reveals that the coefficients of exogenous regressors are negative for all the G7 member countries, with Japan the only notable exception. This indicates that the rapid technological advancement on the pathway to the global goal of low-carbon emissions in the aftermath of the Great Depression may have moderated the disruptive role of climate change on the stock markets of the advanced economies. We further assess the role of technology in the nexus in the following immediate section.

Table 2: Climate change-Stock return volatility nexus based on PGD-sample

		μ	α	β	θ	w	m
Canada	RV	0.0048***	0.1372***	0.8329***	-0.0377**	6.6753*	0.0033***
		(0.0015)	(0.0225)	(0.0302)	(0.0158)	(3.8600)	(0.0009)
	TEMP	0.0051***	0.1302***	0.7972***	-0.3019*	49.941	0.0031***
		(0.0016)	(0.0266)	(0.0472)	(0.1620)	(366.89)	(0.0006)
	h-TEMP	0.0051***	0.1300***	0.7974***	-0.3237*	48.980	0.0032***
		(0.0016)	(0.0266)	(0.0473)	(0.1842)	(363.98)	(0.0007)
France	RV	0.0049***	0.1138***	0.8473***	-0.0331**	2.4139	0.0040***
		(0.0019)	(0.0324)	(0.0423)	(0.0170)	(1.6651)	(0.0010)
	TEMP	0.0053***	0.1267***	0.7515***	-0.7034*	3.1579	0.0052***
		(0.0020)	(0.0457)	(0.0976)	(0.4192)	(3.4039)	(0.0014)
	h-TEMP	0.0056***	0.1286***	0.7471***	-0.8132*	3.1800	0.0057***
		(0.0020)	(0.0465)	(0.0994)	(0.4893)	(3.0466)	(0.0017)
Germany	RV	0.0037**	0.1062***	0.8747***	-0.0429***	1.1449***	0.0039***
		(0.0016)	(0.0182)	(0.0179)	(0.0157)	(0.2285)	(0.0012)
	TEMP	0.0032*	0.1262***	0.8179***	-0.7277**	6.3287	0.0052***
		(0.0017)	(0.0260)	(0.0317)	(0.3747)	(8.9623)	(0.0014)
	h-TEMP	0.0030*	0.1262***	0.8178***	-0.7470**	6.5494	0.0053***
		(0.0017)	(0.0260)	(0.0317)	(0.3859)	(9.3452)	(0.0015)
Italy	RV	0.0058***	0.1895***	0.5881***	0.0693***	2.1196*	0.0005*
		(0.0020)	(0.0402)	(0.0887)	(0.0138)	(1.2457)	(0.0003)
	TEMP	0.0060***	0.1157***	0.8637***	-1.5867**	9.3399	0.0095**
		(0.0020)	(0.0194)	(0.0220)	(0.8199)	(20.297)	(0.0044)
	h-TEMP	0.0060***	0.1157***	0.8637***	-1.6848*	9.0504	0.0100**
		(0.0020)	(0.0194)	(0.0220)	(0.8908)	(19.447)	(0.0046)
Japan	RV	0.0061***	0.1694***	0.5904***	0.0648***	2.1708*	0.0007**
		(0.0019)	(0.0353)	(0.0927)	(0.0130)	(1.1494)	(0.0003)
	TEMP	0.0057***	0.0947***	0.8827***	0.2922	9.0606	0.0021
		(0.0018)	(0.0158)	(0.0201)	(0.8244)	(69.337)	(0.0029)
	h-TEMP	0.0057***	0.0947***	0.8827***	0.2942	9.0732	0.0020
		(0.0018)	(0.0158)	(0.0201)	(0.8487)	(72.397)	(0.0031)
UK	RV	0.0051***	0.1773***	0.6784***	0.0569***	5.4611	0.0011**
		(0.0017)	(0.0512)	(0.1100)	(0.0150)	(3.9968)	(0.0004)
	TEMP	0.0048***	0.1434***	0.8330***	-0.8799*	7.2755	0.00064***
		(0.0015)	(0.0264)	(0.0264)	(0.4697)	(9.2015)	(0.0024)
	h-TEMP	0.0048***	0.1434***	0.8329***	-0.9096***	7.4076	0.0066***
		(0.0015)	(0.0264)	(0.0306)	(0.4742)	(9.0068)	(0.0025)
USA	RV	0.0076***	0.1600***	0.7990***	-0.0385***	2.8169***	0.0020***
		(0.0011)	(0.0229)	(0.0313)	(0.0092)	(0.5908)	(0.0004)
	TEMP	0.0071**	0.1620***	0.7638***	-0.2650***	49.912	0.0023***
		(0.0012)	(0.0307)	(0.0546)	(0.1002)	(154.41)	(0.0004)
	h-TEMP	0.0073***	0.1804***	0.7489***	-0.2955***	43.435	0.0025***
		(0.0012)	(0.0328)	(0.0544)	(0.1055)	(341.67)	(0.0005)

Note: TEMP denoting temperature anomalies measures climate change, while h-TEMP is high temperature derived as the positive values of TEMP. ***, ** & * represents significant at 1%, 5% and 10% levels of significance.

5.3 The role of technology shock (TS) in the Climate change–stock return volatility nexus

Motivated by the probable reducing effect of climate change on the volatility of stock returns being sensitive to a rapid improvement in technology, particularly in the aftermath of the Great Depression, we hypothesize that technology matters in the climate change–stock return volatility nexus. Essentially, we control for the role of technological shock as a moderator of the volatility effect of climate change on stock returns both for the full sample and the PGD sample and across the alternative proxies of technological shocks.

5.3.1 The role of TS [full-sample]

Using a full sample of our historical data, the GARCH-MIDAS-X estimates presented in Table 3a are largely robust to those earlier presented in Table 1. We show that for the G7 countries where climate change earlier exhibits the potential of reducing volatility, the magnitude of the reduction seems larger when the technological shock is controlled for in the nexus. Notable in this regard are Canada, Germany, and Japan, where the role of technological shock in the climate change–stock return volatility nexus also seems sensitive to the scope of the technological shock under consideration. In other words, the extent to which technological shock aids climate change by reducing volatility appears relatively more pronounced magnitude-wise when the measure of technological shock is GTS-164. Even when the inclusion of the technological shock in the nexus reveals climate change as likely to raise the return volatility in some of the G7 countries, quite an interesting finding is that for most of these countries, the magnitude of the increasing effect of the climate change on the volatility of stock returns is relatively lower compared to what is earlier reported from the model without the role of the technology shock. On the whole, we find, on the one hand, the significance of technological shock in strengthening the reducing effect of climate change on the volatility of stock returns or moderating its increasing effects on the other hand.

5.3.2 The role of TS [PGD-sample]

Here, we further investigate the effect of technological shock on the climate change-stock return volatility nexus by limiting our sample to primarily represent the post-Great Depression era to maintain consistency and a fair comparison as previously done for the same sample, albeit without accounting for the role of technology shocks. Thus, the empirical estimates produced from the GARCH-MIDAS-X model that accounts for the role of technology shocks are provided in Table 3b, with 1950 as the start date of our adjusted sample. However, in contrast to our previous submission in this regard, where climate change tends to reduce volatility in stock returns of almost all the G7 countries, a look at Table 3b reveals that the results are mixed with introducing technological shock into the nexus. This may not be unconnected to the fact that, for some countries, adopting technology at the point of recovery from the Great Depression was not directly targeted at mitigating climate change but at boosting economic activity. One of the proven vices likely to have emanated from such increasing economic activity in the aftermath of the Great Depression is increasing climate change, thus validating the usual few pieces of evidence of technological shock inducing climate change to cause increased volatility in the stock returns of G7 countries such as France and Germany. This result supports the work by Tao et al. (2023), whose finding stresses the significance of technological innovation in alleviating the restraining effect of coal-based energy structures on pollution emissions.

Overall, the significance and the magnitude at which climate change reduces volatility in the stock return aftermath of the Great Depression appears to be relatively more pronounced in the model that does not include technological shock. This, again, may be sensitive to the fact that at the early part of the recovery from the Great Depression, the rapid adoption of technologies is not primarily targeted at transitioning to low-carbon emissions but to enhance economic activity. This is a possible explanation for the decline rate at which climate change reduces volatility in stock returns when technology is introduced into the nexus post-Great Depression period.

Table 3a: The role of TS in the Climate change-Stock return volatility nexus based on full-sample

		μ	α	β	θ	w	m
Canada	h-TEMP-TS	0.0053***	0.1054***	0.8639***	-1.4152***	2.0120***	0.0031***
		(0.0011)	(0.0132)	(0.4441)	(0.4441)	(0.5815)	(0.0005)
	h-TEMP-GTS-OECD	0.0052***	0.1021***	0.8681***	-0.5003***	3.7065**	0.0021***
		(0.0011)	(0.0124)	(0.0137)	(0.1821)	(1.7228)	(0.0002)
	h-TEMP-GTS-164	0.0054***	0.1026***	0.8581***	-1.2649***	2.9651***	0.0018***
		(0.0011)	(0.0134)	(0.0152)	(0.1933)	(0.2340)	(0.0001)
France	h-TEMP-TS	0.0034***	0.0515***	0.9421***	2.1137***	2.4082***	0.0025***
		(0.0007)	(0.0059)	(0.0058)	(0.4980)	(0.1950)	(0.0006)
	h-TEMP-GTS-OECD	-0.0016	0.0509***	0.9462***	0.0106***	7.6878***	5.17e-05***
		(0.0001)	(0.0033)	(0.0031)	(0.0036)	(1.4635)	(1.76e-05)
	h-TEMP-GTS-164	0.0041***	0.0532**	0.9400***	0.8252*	1.0020***	0.0020***
		(0.0009)	(0.0062)	(0.00611)	(0.0061)	(0.2713)	(0.0005)
Germany	h-TEMP-TS	0.0034	0.1488***	0.6196***	2.9805***	3.8722	0.0056***
		(0.0024)	(0.0203)	(0.0391)	(0.6449)	(1.8982)	(0.0002)
	h-TEMP-GTS-OECD	0.0039**	0.1206***	0.6802***	-1.4337***	5.0211***	0.0051***
		(0.0016)	(0.0152)	(0.0328)	(0.0767)	(0.1475)	(0.0002)
	h-TEMP-GTS-164	0.0033	0.1557***	0.5956***	-7.0196***	1.5229***	0.0039***
		(0.0021)	(0.0217)	(0.0406)	(0.3783)	(0.0347)	(0.0001)
Italy	h-TEMP-TS	0.0020	0.1061***	0.8542***	1.296***	1.2495***	0.0062***
		(0.0014)	(0.0125)	(0.0168)	(0.1432)	(0.2468)	(0.0007)
	h-TEMP-GTS-OECD	0.0023	0.1071***	0.8513***	2.0263***	1.7003**	0.0040***
		(0.0015)	(0.0130)	(0.0178)	(0.4486)	(0.7859)	(0.0004)
	h-TEMP-GTS-164	0.0037**	0.1092***	0.8524***	1.8095**	3.5766	0.0050***
		(0.0016)	(0.0135)	(0.0182)	(0.7552)	(2.5322)	(0.0006)
Japan	h-TEMP-TS	0.0044***	0.1431***	0.8179***	2.9616***	1.2219***	0.0045***
		(0.0011)	(0.0192)	(0.0225)	(0.8823)	(0.2617)	(0.0008)
	h-TEMP-GTS-OECD	0.0044***	0.1394***	0.8235***	-1.0106***	1.5265***	0.0040***
		(0.0011)	(0.0194)	(0.0227)	(1.0721)	(0.1544)	(0.0007)
	h-TEMP-GTS-164	0.0046***	0.1400***	0.8226***	-3.4352***	1.8126***	0.0027***
		(0.0011)	(0.0194)	(0.0226)	(0.9856)	(0.2827)	(0.0005)
UK	h-TEMP-TS	0.0016***	0.1341***	0.8548***	0.1531***	13.056	0.0014***
		(0.0005)	(0.0128)	(0.0128)	(0.0594)	(18.508)	(0.0004)
	h-TEMP-GTS-OECD	0.0018***	0.1385***	0.8506***	0.2935**	2.0164*	0.0012***
		(0.0005)	(0.0132)	(0.0131)	(0.1331)	(1.2173)	(0.0004)
	h-TEMP-GTS-164	0.0017***	0.1349**	0.8541***	0.1399**	19.519	0.0012***
		(0.0005	(0.0129)	(0.0129)	(0.0545)	(28.394)	(0.0004)
USA	h-TEMP-TS	0.0066***	0.1501***	0.8097***	0.1808	3.2139	0.0017***
		(0.0008)	(0.0117)	(0.0144)	(0.6602)	(13.024)	(0.0004)
	h-TEMP-GTS-OECD	0.0064***	0.1553***	0.8013***	0.3071	1.0036***	0.0018***
		(0.0008)	(0.0121)	(0.0146)	(0.2515)	(0.2554)	(0.0002)
	h-TEMP-GTS-164	0.0066***	0.1507***	0.8097***	0.2530	3.5825	0.0019***
		(0.0008)	(0.0117)	(0.0144)	(0.5511)	(8.8350)	(0.0003)

Note: TEMP denoting temperature anomalies measures climate change, while h-TEMP is high temperature derived as the positive values of TEMP. The interactive terms h-TEMP-TS, h-TEMP-GTS-OECD, and h-TEMP-GTS-164 are derived as the interaction of the high-temperature dummy (where one is assigned to positive values of TEMP and zero otherwise) with the respective technology shock proxies. ***, ** & * represent significance at 1%, 5% and 10% levels, respectively.

Table 3b: The role of TS in the Climate change-Stock return volatility nexus based on PGD-sample

		μ	α	β	θ	w	m
Canada	h-TEMP-TS	0.0052***	0.1302***	0.8013***	-0.2663*	31.164	0.0026***
		(0.0016)	(0.0263)	(0.0456)	(0.1398)	(52.392)	(0.0004)
	h-TEMP-GTS-OECD	0.0051***	0.1314***	0.7970***	-0.4414	5.2421	0.0025***
		(0.0016)	(0.0269)	(0.0473)	(0.3026)	(6.4457)	(0.0004)
	h-TEMP-GTS-164	0.0051***	0.1313***	0.7958***	-0.1773**	46.940	0.0022***
		(0.0016)	(0.0268)	(0.0474)	(0.0880)	(221.80)	(0.0002)
France	h-TEMP-TS	0.0054***	0.1334***	0.7500***	-0.5958	47.530	0.0030***
		(0.0019)	(0.0459)	(0.0923)	(0.7162)	(330.61)	(0.0003)
	h-TEMP-GTS-OECD	0.0047**	0.1259***	0.7716***	-0.1709	48.567	0.0029***
		(0.0019)	(0.0421)	(0.0814)	(0.2468)	(933.91)	(0.0003)
	h-TEMP-GTS-164	0.0053***	0.1346***	0.7491***	-0.3242	27.655	0.0030***
		(0.0019)	(0.0467)	(0.0934)	(0.2149)	(108.88)	(0.0003)
Germany	h-TEMP-TS	0.0040**	0.1293***	0.8116***	-0.5003***	49.873	0.0024***
		(0.0018)	(0.0264)	(0.0322)	(0.1646)	(184.67)	(0.0004)
	h-TEMP-GTS-OECD	0.0036**	0.1229***	0.8221***	-0.5665**	1.3456**	0.0032***
		(0.0017)	(0.0249)	(0.0305)	(0.2749)	(0.6464)	(0.0005)
	h-TEMP-GTS-164	0.0043***	0.1463***	0.8505***	4.3853*	5.0975***	0.0193*
		(0.0016)	(0.0205)	(0.0205)	(2.5793)	(0.2258)	(0.0114)
Italy	h-TEMP-TS	0.0053***	0.1439***	0.8379***	4.6466*	2.7759*	0.0123**
		(0.0019)	(0.0227)	(0.0250)	(2.4219)	(1.4703)	(0.0051)
	h-TEMP-GTS-OECD	0.0056***	0.1129***	0.8648***	2.4139	24.557	0.0009
		(0.0019)	(0.0188)	(0.0219)	(2.7739)	(24.917)	(0.0027)
	h-TEMP-GTS-164	0.0055***	0.1157***	0.8653***	0.2950	49.906	0.0035**
		(0.00200	(0.0195)	(0.0220)	(0.4924)	(1378.9)	(0.0015)
Japan	h-TEMP-TS	0.0056***	0.0944***	0.8830***	-0.8756	47.159	0.0020
		(0.0018)	(0.0157)	(0.0200)	(1.2931)	(270.81)	(0.0016)
	h-TEMP-GTS-OECD	0.0056***	0.0967***	0.8832***	-0.3092	49.849	0.0036***
		(0.0018)	(0.0162)	(0.0200)	(0.4844)	(376.92)	(0.0012)
	h-TEMP-GTS-164	0.0057***	0.0953***	0.8828***	0.1470	5.7275	0.0031***
		(0.0018)	(0.0159)	(0.0201)	(0.4801)	(33.397)	(0.0009)
UK	h-TEMP-TS	0.0049***	0.1552***	0.8219***	-0.3697**	49.947	0.0029***
		(0.0015)	(0.0275)	(0.0310)	(0.1871)	(378.73)	(0.0010)
	h-TEMP-GTS-OECD	0.0052***	0.1444***	0.8289***	-0.4609**	6.1418	0.0037***
		(0.0015)	(0.0266)	(0.0313)	(0.1855)	(5.1315)	(0.0009)
	h-TEMP-GTS-164	0.0041***	0.1529***	0.8207***	-0.6794***	5.9391***	0.0037***
		(0.0015)	(0.0276)	(0.0321)	(0.2102)	(1.3551)	(0.0011)
USA	h-TEMP-TS	0.0073***	0.1713***	0.7566***	-0.1671**	49.678	0.0016***
		(0.0012)	(0.0319)	(0.0543)	(0.0771)	(276.00)	(0.0002)
	h-TEMP-GTS-OECD	0.0075***	0.1717***	0.7550***	-0.3049**	2.1415	0.0017***
		(0.0012)	(0.0319)	(0.0548)	(0.1415)	(1.3267)	(0.0002)
	h-TEMP-GTS-164	0.0073***	0.1790***	0.7547***	-0.1617***	47.698	0.0016***
		(0.0012)	(0.0323)	(0.0530)	(0.0556)	(363.25)	(0.0002

Note: TEMP denoting temperature anomalies measures climate change, while h-TEMP is high temperature derived as the positive values of TEMP. The interactive terms h-TEMP-TS, h-TEMP-GTS-OECD, and h-TEMP-GTS-164 are derived as the interaction of the high-temperature dummy (where one is assigned to positive values of TEMP and zero otherwise) with the respective technology shock proxies. ***, ** & * represent significance at 1%, 5% and 10% levels, respectively.

6. Conclusions

This study offers a comprehensive long-term perspective on the issue of climate change and stock return volatility by considering several plausible ways these two variables connect, particularly for the advanced economies from 1880 to 2018. Consequently, we test the following hypotheses: (i) we test whether the climate change-stock return volatility nexus is episodic by considering the entire data sample and a sub-sample that is restricted to the post-Great Depression period, which begins from 2018; (ii) we also assess how climate change effect of stock return volatility responds to varying degrees of intensity of high temperature; and (iii) we test whether technology matters in the nexus within the context of (i) and (ii). We employ the GARCH-MIDAS framework since the stock return series are of a higher frequency while the technology and climate change proxies are utilized at a lower frequency. The technology proxies are obtained from the Sharma and Narayan (2022) new datasets, which involve patents of residents in the selected advanced countries, and they note that these patents help to track the technology prospects for an economy over a long period. We also measure climate change using temperature anomalies, while the high temperature used in the empirical exercise is obtained as positive values of the temperature anomalies. Three additional (varying) degrees of high temperature derived as 25th, 50th, and 75th percentiles of high temperature are also used to test whether varying degrees of intensity of high-temperature matter in the climate change-stock return volatility nexus.

We show evidence that lends credence to the episodic behaviour of the climate change-stock return volatility nexus as hypothesized. Although some specifics are highlighted for a number of the advanced economies, we can document that climate change can have disruptive effects on their stock markets. However, the evidence obtained for the post-Great Depression shows a relatively less disruptive effect of climate change on the stock markets of the advanced economies compared to the full sample period. Also, when we consider varying degrees of intensity of temperature anomalies from the 25th percentile to the 75th percentile, we find that climate change impacts somewhat differently on stock return volatility. We demonstrate that the potential of climate change to cause disruptions in the stock markets of advanced economies heightens with the rising intensity of temperature anomalies. We further note that technology shocks can help moderate the disruptions regardless of the sample period.

Some useful policy implications of these findings necessarily revolve around the role practitioners and policymakers have to play in climate issues as they relate to the subject of focus. First, investors in the stock market must consider climate change challenges as well as the level of investment in technology that has occurred in the stock market when making investment decisions. For example, boosting investments in environmentally friendly assets can help us limit the disruptive impact of climate change on industrialised economies' capital markets. Second, while rapid climate change may threaten stock market investment, technological innovation can simply be employed to offset the negative consequences of climate change's systemic risk on stock returns. Finally, investing in climate solutions that help prevent environmental degradation connected with economic activities that may impact stock pricing can effectively mitigate the disruptive effects of climate change.

Notwithstanding the above, among other things, it is not clear if the moderating role of technological innovations in the climate change-stock return volatility nexus, as demonstrated herein in the context of technologically advanced economies, can be replicated for less developed economies. To this end, we suggest future investigations of our findings in the context of emerging and developing economies.

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