Finance Research Letters 92 (2026) 109598

Contents lists available at ScienceDirect

Finance Research Letters

journal homepage: www.elsevier.com/locate/frl

Climate vulnerability and market volatility: Evidence from European firms

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ARTICLE INFO

Keywords:
Climate vulnerability
climate risk
stock return volatility
financial constraints
equity markets
Europe

ABSTRACT

This study examines the association between country-level climate vulnerability and firm-level stock return volatility in Europe. Using panel data on 490 listed firms across 17 European countries from 2013 to 2022, we find that firms located in more climate-vulnerable countries exhibit significantly higher market volatility. The results are robust across alternative measures, fixed-effects specifications, and endogeneity checks. We further show that this relationship is amplified for financially constrained firms when constraints are measured using the Kaplan–Zingales index. Overall, the findings suggest that climate vulnerability primarily manifests as heightened market uncertainty and that financial frictions play a key role in transmitting macro-level climate risk to firm-level market volatility.

1. Introduction

Climate change[1] has emerged as a systemic source of financial instability, influencing macroeconomic stability, sovereign creditworthiness, and firm-level outcomes (Er et al., 2025; Bolton et al., 2020; Carney, 2015). Empirical evidence shows that climate-related disasters disrupt economic activity, impair infrastructure and long-lived tangible assets, and amplify uncertainty about firms' future cash flows (Ben-Amar et al., 2025; García-Gómez et al., 2025; Addoum et al., 2020; Hong et al., 2019). At the macro level, climate vulnerability is associated with weaker economic resilience, slower growth, and elevated fiscal risk (Huang et al., 2021), all of which amplify market uncertainty. In this sense, financial markets increasingly price environmental risks (Pastor et al., 2022), and central banks such as the European Central Bank (ECB) warn that climate change could destabilize asset markets and increase volatility in equity and credit valuations (Alogoskoufis et al., 2021). However, substantially less is known about how country-level climate vulnerability shapes the second moment of firm-level equity prices, i.e., return volatility. Existing work focuses primarily on expected returns, credit spreads, or default outcomes, whereas volatility captures uncertainty and disagreement about future cash flows and

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[1] Climate change is associated with climate vulnerability, which is defined as a country's exposure, sensitivity, and adaptive capacity to climate shocks (Kahn et al., 2021).

https://doi.org/10.1016/j.frl.2026.109598
Received 29 October 2025; Received in revised form 28 January 2026; Accepted 1 February 2026
Available online 2 February 2026
1544-6123/

financing conditions rather than about average valuation effects, making it a distinct margin of risk that is directly relevant for investors, risk managers, and policymakers.

This paper examines whether and how country-level climate vulnerability is associated with firm-level stock return volatility across European economies. Focusing on volatility is especially important in the context of climate risk for several reasons. First, macro-level climate vulnerability primarily increases uncertainty about firms' operating environments, infrastructure resilience, and policy responses (Chen et al., 2025; Han et al., 2025). Second, volatility is a key input into portfolio allocation, risk management, and regulatory stress testing, making it directly relevant for financial stability analysis (Adrian, 2018). Third, increases in volatility can arise even in the absence of immediate declines in firm performance, reflecting the high sensitivity of equity prices to news and shocks (Fratzscher and Straub, 2013).

Country-level climate vulnerability affects firm-level market volatility through its influence on financial frictions. In financially constrained environments, small variations in perceived risk can lead to disproportionate changes in financing conditions, asset prices, and firm volatility (He and Ren, 2023). Climate vulnerability intensifies such frictions by elevating uncertainty, deteriorating collateral values, and tightening credit supply, all of which increase the sensitivity of equity prices to news and shocks. Within the financial accelerator framework (Bernanke et al., 1999; Kiyotaki & Moore, 1997), external financing costs depend on firms' net worth and perceived credit risk; heightened climate vulnerability increases lenders and investors' required risk premia and induces credit rationing, amplifying fluctuations in investment and firm value (Holmström & Tirole, 1997; Rampini & Viswanathan, 2013). These effects are reinforced through the collateral channel, as climate-related asset destruction and the revaluation of real estate in risk-prone areas reduce the balance-sheet capacity supporting external finance (Chava, 2014; Addoum et al., 2020), further tightening borrowing constraints and magnifying equity price responses (Gilchrist et al., 2014). In parallel, climate-induced fiscal pressures—stemming from adaptation costs and disaster recovery expenditures—can weaken sovereign balance sheets, raise sovereign spreads, and indirectly increase corporate borrowing costs (Longstaff et al., 2011). When sovereign and corporate risk premia are jointly determined (Corsetti et al., 2013), such pressures propagate macro-level climate vulnerability into firm-level valuation risk, increasing the co-movement of equity volatility across firms. Finally, financial intermediaries play a key reinforcing role: as banks and institutional investors incorporate climate risk metrics into credit pricing and portfolio allocation (Krueger et al., 2020; Bolton & Kacperczyk, 2021), high-vulnerability environments become prone to procyclical capital flows, with contractions in credit and equity financing during periods of elevated climate concern. These dynamics intensify liquidity constraints and valuation uncertainty, contributing to higher stock return volatility and greater cross-sectional dispersion in firm performance (Acharya et al., 2024; Pastor et al., 2022).

Guided by these considerations, we develop two testable hypotheses:

H1. Firms headquartered in countries with higher climate vulnerability exhibit higher stock return volatility.

H2. The positive relationship between country-level climate vulnerability and firm-level stock return volatility is stronger for financially constrained firms.

Using a panel of 490 listed firms across 17 European countries from 2013 to 2022, we show that higher country-level climate vulnerability, measured by the ND-GAIN Index (Chen et al., 2024), significantly increases firm-level market volatility. The effect remains robust across alternative measures of climate vulnerability and volatility, diverse model specifications, and endogeneity controls, including instrumental variable regressions using coastline length and population as instruments, which mitigate identification concerns. Importantly, a channel analysis reveals that this relationship is driven by financial frictions: firms facing stronger financial constraints exhibit greater sensitivity of volatility to national climate vulnerability. We test this implication directly by interacting national climate vulnerability with firm-level measures of financial constraints. Overall, our findings highlight that macro-level environmental fragility has a significant and persistent impact on firm-level market stability across Europe.

The study's incremental contribution lies in three specific dimensions. First, we focus on firm-level stock return volatility rather than expected returns or credit spreads because volatility directly reflects uncertainty about future cash flows and financing conditions. Climate vulnerability represents a slow-moving, aggregate source of risk whose primary effect is to increase dispersion in beliefs and sensitivity to shocks, rather than to uniformly reprice assets. As such, its impact is more likely to materialize through higher volatility than through predictable return differentials. Second, we examine country-level climate vulnerability in the European region, as opposed to firm-specific climate exposure or emissions, capturing a systemic source of risk that affects firms through their broader economic and institutional environment. Third, we explicitly examine financial constraints as an amplification channel, testing whether firms facing tighter financing conditions exhibit stronger volatility responses to national climate vulnerability. In doing so, we provide evidence consistent with a macro-financial amplification mechanism linking environmental vulnerability to firm-level market instability.

2. Research design

2.1. Sample selection and variables description

The data selection process is as follows. We focus on all European countries and select listed companies from all TRBC (Thomson Reuters Business Classification) industries (excluding financials) for the period 2013–2022. To construct our sample, we combine several data sources. Firm-level financial data are obtained from Refinitiv Eikon. Country-level variables capturing climate vulnerability are drawn from the ND-Gain Index, the World Bank dataset, and the Yale Center for Environmental Law and Policy Governance Indicators. Additionally, the macroeconomic control variables are collected from the World Bank database. After excluding firms with

Table 1
Distribution of the sample across countries and industries.

Panel A. Countries			
Country	No of obs.	No of firms	%
Austria	54	6	1.22 %
Belgium	101	12	2.45 %
Denmark	169	19	3.88 %
Finland	140	16	3.27 %
France	570	66	13.47 %
Germany	516	62	12.65 %
Ireland	90	10	2.04 %
Italy	196	23	4.69 %
Luxembourg	54	8	1.63 %
Netherlands	226	28	5.71 %
Norway	108	12	2.45 %
Poland	41	5	1.02 %
Portugal	27	3	0,.61 %
Spain	169	19	3.88 %
Sweden	414	48	9.80 %
Switzerland	383	45	9.18 %
United Kingdom	917	108	22.04 %
Total	**4,175**	**490**	**100.00%**
Panel B. Industries			
Industry	**No of obs.**	**No of firms**	**%**
Basic Materials	485	56	11.43 %
Consumer Cyclicals	667	79	16.12 %
Consumer Non-Cyclicals	423	49	10.00 %
Energy	190	23	4.69 %
Healthcare	427	51	10.41 %
Industrials	916	108	22.04 %
Real Estate	262	30	6.12 %
Technology	557	66	13.47 %
Utilities	248	28	5.71 %
Total	**4,175**	**490**	**100.00%**

Note: This table presents the country and industry breakdowns of the sample, consisting of 4,175 firm-year observations from 2013 to 2022. The industry breakdown is established based on the Thomson Reuters Business Classification (TRBC), excluding financial firms.

missing values for key variables used in the empirical analysis, the final dataset comprises 490 unique firms, yielding an unbalanced panel of 4,175 firm-year observations. Table 1 – Panel A displays the distribution of our sample based on countries, while in Panel B, we display the sample breakdown by sector using the TRBC classification.

The relevant **dependent variable** is market volatility. Consistent with previous finance literature (e.g., Chinco et al., 2022; Herskovic et al., 2016), we define the variable *Market_vol* as the standard deviation of a company's daily stock returns for each year.

The relevant **independent variable**, namely a country's climate risk exposure, is the Notre Dame Global Adaptation Initiative (ND-GAIN) Country Index (Chen et al., 2024), which is widely used by the literature (García-Gómez et al., 2025; Alam et al., 2024; Er et al., 2025; Shear et al., 2023). The index measures both how exposed a country is to the impacts of climate change and how prepared it is to strengthen its resilience. The *vulnerability* component reflects the degree to which climate-related disturbances could affect six key areas: food supply, water resources, public health, ecosystem functions, living environments, and infrastructure. The *readiness* component indicates a country's ability to utilize investments for adaptation, based on economic conditions, governance quality, and social factors. Scores range from 0, indicating lower vulnerability, to 100, indicating higher vulnerability. To avoid any reverse causality issues, we use the one-year lagged values of vulnerability ($Vulnerability_{t-1}$) and readiness ($Readiness_{t-1}$).

Alternatively, we use the Environmental Performance Index (*EPI_score*) by the Yale Center for Environmental Law and Policy (Wolf et al., 2022), which ranges from 0 (worse performance and, hence, higher climate vulnerability) to 100 (better performance and, therefore, less climate vulnerability).

We also incorporate various firm and macro-level factors as **controls** in our empirical analysis. At the firm-level, size (*Size*) is expected to be negatively related to volatility, as larger firms benefit from diversification, greater information transparency, and more stable cash flows (Ang et al., 2006; Herskovic et al., 2016; Bekaert, 2025). Financial leverage (*Leverage*) is positively associated with volatility due to the option-like nature of equity and firms' heightened sensitivity to asset and credit shocks (Ericsson et al., 2016). The market-to-book ratio (*MtoB*) is expected to increase volatility, reflecting the greater uncertainty surrounding growth opportunities and intangible assets (Cao et al., 2008). Profitability (*ROA*) is inversely related to volatility, as profitable firms exhibit more stable earnings, stronger internal financing, and lower distress risk (Novy-Marx, 2013; Barinov, 2023). At the macro level, stronger GDP growth (*GDP*) generally dampens volatility by stabilizing demand and financing conditions, although volatility may rise for smaller or more

Table 2
Definitions and data sources of variables.

Variables	Notation	Description	Data source
Dependent variables			
Market risk	Market_vol	Standard deviation of daily returns.	Refinitiv Eikon
Climate Risk Exposure			
Vulnerability	Vulnerability	ND-Gain's vulnerability: propensity or predisposition of human societies to be negatively impacted by climate hazards. The index values range from 0 to 100.	ND-Gain Index
Readiness	Readiness	ND-Gain's readiness: a country's ability to leverage investments to adaptation actions. The index values range from 0 to 100.	
EPI index	EPI	Environmental Performance Index. The index values range from 0 to 100.	Yale Center for Environmental Law & Policy
Firm-level control variables			
Firm Size	Size	Natural logarithm of the book value of assets	Refinitiv Eikon
Leverage	Lev	Ratio of total debt to total assets	
Market to book	MtoB	(Market value of common equity + preferred stock + book value of total liabilities) / Book value of total assets	
Return on Assets	ROA	Return on assets ratio	
Macro-level control variables			
GDP growth	GDP	Real GDP growth rate (Annual %)	World Bank
Inflation	Inflation	Inflation (Annual %)	World Bank
Rule of Law	Rule_law	Perceptions of the extent to which agents have confidence in and abide by the rules of society, and in particular the quality of contract enforcement, property rights, the police, and the courts, as well as the likelihood of crime and violence. It ranges from approximately − 2.5 (weak) to 2.5 (strong).	World Bank
Economic freedom	Ec_freedom	Index that measures the degree of economic freedom in the world's nations. The index values range from 0 to 100.	Heritage Foundation
Firm-level financial constraints			
Kaplan & Zingales Index	KZ_index	$\text{KZ Index}_t = -1.002 \times (\text{Cash Flow}_t/\text{Total Assets}_{t-1}) + 0.283 \times Q_t + 3.139 \times \text{Leverage}_t - 39.368 \times (\text{Dividends}_t / \text{Total Assets}_{t-1}) - 1.315 \times (\text{Cash Holdings}_t / \text{Total Assets}_{t-1})$	Refinitiv Eikon
Hadlock & Pierce Index	HP_index	$\text{HP Index}_t = -0.737 \times \text{Size} + 0.043 \times \text{Size}^2 - 0.040 \times \text{Age}$	

Note: This table displays the variables used in the analysis, their notation, description, and data source.

Table 3
Summary statistics.

	N	Mean	Median	Std. Dev.	Min.	Max.
Market_vol	4,175	0.017	0.016	0.006	0.001	0.038
Vulnerability	4,175	0.302	0.297	0.026	0.249	0.357
Readiness	4,175	0.683	0.694	0.064	0.506	0.801
EPI	4,166	79.192	79.800	6.986	50.400	90.600
Size	4,175	22.771	22.764	1.519	18.593	26.159
Lev	4,175	0.256	0.249	0.150	0.000	0.656
MtoB	4,175	4.371	2.740	5.524	-1.289	37.784
ROA	4,175	0.086	0.075	0.077	-0.129	0.427
GDP	4,175	1.795	2.069	3.667	-11.325	24.37
Inflation	4,175	1.830	1.137	2.240	-1.144	14.429
Rule_law	4,175	1.549	1.600	0.396	0.210	2.120
Ec_freedom	4,175	73.228	74.550	5.964	58.300	84.200
KZ_index	3,772	1.306	1.456	1.575	-5.246	6.342
HP_index	4,121	-4.807	-4.273	1.394	-8.801	-3.032

Note: This table displays the summary statistics for all the variables used in the analysis. See Table 2 for variables' definitions.

leveraged firms during expansions (Di Mauro, 2011; Bartram et al., 2012; Bekaert, 2025). Inflation (*Inflation*) is expected to amplify volatility, as elevated or uncertain inflation strengthens the transmission of macroeconomic shocks to equity returns (Bhamra, 2023; Binder et al., 2025). Institutional quality also plays a stabilizing role: a stronger rule of law (*Rule_law*) is associated with lower market volatility by improving investor protection, contract enforcement, and policy credibility (Pastor and Veronesi, 2013). Similarly, greater economic freedom (*Ec_freedom*) is expected to reduce volatility by fostering competitive markets, efficient capital allocation, and predictable regulatory environments (Blau, 2017).

A summary of the variables description and calculation is recorded in Table 2.

Table 4
Correlation matrix.

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
(1) Market_vol	1.0000										
(2) Vulnerability	0.0741***	1.0000									
(3) Readiness	0.0178	-0.2255***	1.0000								
(4) EPI	-0.0262*	-0.1497***	0.2538***	1.0000							
(5) Size	-0.1331***	0.0247*	-0.1738***	-0.1333***	1.0000						
(6) MtoB	0.0565***	-0.0012	0.0983*	0.0703***	-0.3610***	1.0000					
(7) Lev	-0.0599***	0.0620***	-0.2118***	-0.0397***	0.2699	-0.0410*	1.0000				
(8) ROA	-0.1617***	0.0009	0.1273*	0.0666***	-0.3806	0.4474***	-0.2554***	1.0000			
(9) Inflation	0.2525***	0.1075***	-0.0383*	-0.2447***	0.0780	-0.0342**	0.0303**	0.0035	1.0000		
(10) GDP	-0.2243***	-0.0195	0.0199	-0.0228	-0.0228	0.0147	-0.0509***	0.0995***	0.2577***	1.000	
(11) Rule_law	-0.0752***	-0.2541***	0.9113***	0.2513***	-0.1417***	0.0687***	-0.1758***	0.0741***	-0.1150***	0.0664***	1.000
(12) Ec_freedom	0.0262*	-0.3492***	0.5893***	0.3472***	-0.1466***	0.1246***	-0.1175***	0.0942***	0.0615***	0.0765***	0.6626***
(13) KZ_index	0.0857***	0.1126***	-0.1352***	-0.0589***	0.1919***	0.2182***	0.3696***	-0.3610***	-0.0256*	-0.0540***	-0.1305***
(14) HP_index	0.0791***	0.0482***	-0.2005***	-0.0742***	-0.0981***	0.0374**	0.1193***	-0.0001	-0.0167	-0.0147	-0.1959
Variables	(12)	(13)	(14)								
(12) Ec_freedom	1.0000										
(13) KZ_index	-0.0984***	1.0000									
(14) HP_index	-0.1021***	0.0586***	1.0000								

Note: This table displays the Pearson correlations for all the variables used in the analysis. Statistical significance at 1 %, 5 %, and 10 % are indicated with ***, **, and *, respectively. See Table 2 for variables' definitions.

Table 5
Baseline estimations.

	Dep. Var.: Market_vol		
	(1)	(2)	(3)
$Vulnerability_{t-1}$	**0.0464*** (0.0168)**	**0.0482*** (0.0130)**	**0.0439*** (0.0136)**
Size		-0.0009*** (0.0001)	-0.0010*** (0.0001)
Lev		0.0001*** (0.0000)	0.0001*** (0.0000)
MtoB		-0.0019*** (0.0005)	-0.0019*** (0.0005)
ROA		-0.0224*** (0.0011)	-0.0220*** (0.0011)
Inflation			0.0005*** (0.0001)
GDP			-0.0000 (0.0000)
Rule_law			-0.0080*** (0.0012)
Ec_freedom			0.0002*** (0.0000)
Constant	0.0039 (0.0049)	0.0262*** (0.0040)	0.0287*** (0.0050)
Industry fixed effects	Yes	Yes	Yes
Time fixed effects	Yes	Yes	Yes
Country fixed effects	Yes	Yes	Yes
Observations	4,175	4,175	4,175
R-squared	0.3025	0.4557	0.4672

Note: This table displays the findings from estimating Eq. 1 with OLS. The dependent variable is *Market_vol*. See Table 2 for variables' definitions. We include industry and year fixed effects in all the models. We adjust the error terms for heteroscedasticity at the company level. Standard errors are displayed in parentheses. Statistical significance at 1 %, 5 %, and 10 % are indicated with ***, **, and *, respectively.

Methodology

To assess the relationship between climate vulnerability at the country level and firm-level market volatility, we employ the following baseline model:

$$Market\,volatility_{i,t} = \alpha_0 + \beta Vulnerability_{c,t} + \gamma' X_{i,t} + \theta' Y_{c,t} + n_i + n_t + \mathscr{V}_{itc} \quad (1)$$

In this estimation, X_{it} denotes firm-level and Y_{ct} for macro-level control variables. Moreover, n_i and n_i stand for industry and time-fixed effects, respectively. Finally, νitc stands for the error terms.

We begin our empirical analysis by estimating our baseline model using OLS. For robustness, we apply random-effects estimation (supported by the Hausman test) and the system GMM estimator (Blundell & Bond, 2000; Bond, 2002) to mitigate unobserved heterogeneity and potential endogeneity. The system GMM approach exploits both variable levels and first differences as instruments. Its validity is assessed through the AR(2) test for serial correlation and the Hansen test for over-identifying restrictions. To further address endogeneity, we employ an instrumental variable (IV) strategy using two-stage least squares (2SLS). In the first stage, endogenous regressors are projected on valid instruments and exogenous controls; in the second stage, the fitted values replace the endogenous variables in the structural equation. Instrument validity requires relevance (correlation with the endogenous regressor) and exogeneity (no correlation with the error term). The first-stage F-statistic is used to check for weak instruments, with values below 10 indicating potential bias (Stock and Yogo, 2002).

4. Results and discussion

4.1. Baseline estimations

Before presenting the regression results, we summarize the data characteristics. Table 3 reports the descriptive statistics, and Table 4 displays the Pearson correlation coefficients for the relevant variables in the study.

The multivariate analysis begins with the baseline OLS estimations of eq. 1 examining the impact of country-level climate vulnerability on firm-level market volatility, which results are reported in Table 5. Across all model specifications, the coefficient on *Vulnerability* remains positive and highly significant at the 1 % level, confirming that firms headquartered in more climate-vulnerable countries experience higher stock return volatility. Economically, the estimated coefficients indicate that a one-standard-deviation increase in national climate vulnerability raises firm-level market volatility by approximately 4.4 % to 4.8 %, depending on the specification. This finding aligns with our first hypothesis, i.e., macro-level climate fragility amplifies firm-level risk through

Table 6
Addressing endogeneity. Panel data and GMM.

	Dep. Var.: Market_vol	
	Random effects	GMM
Vulnerability$_{t-1}$	0.0327***	0.0590*
	(0.0114)	(0.0342)
Size	-0.0006***	0.0008
	(0.0001)	(0.0011)
Lev	-0.0000	0.0002**
	(0.0000)	(0.0001)
MtoB	0.0028***	-0.0105*
	(0.0007)	(0.0063)
ROA	-0.0158***	-0.0273***
	(0.0012)	(0.0087)
Inflation	0.0005***	0.0020***
	(0.0001)	(0.0004)
GDP	-0.0000*	-0.0003***
	(0.0000)	(0.0001)
Rule_law	-0.0077***	-0.0259***
	(0.0009)	(0.0047)
Ec_freedom	0.0002***	-0.0000
	(0.0000)	(0.0001)
Constant	0.0218***	-0.0102
	(0.0045)	(0.0834)
Industry fixed effects	Yes	Yes
Time fixed effects	Yes	Yes
Country fixed effects	Yes	Yes
Observations	4,175	4,175
R-squared	0.5271	
Wald test (d.f.)	4,297.5*** (39)	4,119.1*** (39)
m2		-0.50
Hansen test (d.f.)		39.31 (36)

Note: This table displays the findings from estimating Eq. 1 with random effects (column 1) and GMM (column 2). The dependent variable is *Market_vol*. See Table 2 for variables' definitions. We include industry and year fixed effects in all the models. We adjust the error terms for heteroscedasticity at the company level. Standard errors are displayed in parentheses. The Wald test is for the joint significance of the independent variables, the m_2 test is for the lack of second order serial correlation, and the Hansen test is for the validity of the instruments. Statistical significance at 1 %, 5 %, and 10 % are indicated with ***, **, and *, respectively.

heightened uncertainty and capital market distortions. The control variables display expected signs: larger and more profitable firms (*Size, ROA*) exhibit lower volatility, reflecting stronger financial resilience, while leverage (*Leverage*) is positively associated with volatility due to the option-like nature of equity and firms' higher sensitivity to asset and credit shocks. Interestingly, the coefficient on the market-to-book ratio (*MtoB*) is negative and statistically significant. This result, though counterintuitive at first glance, is consistent with the fact that, in European markets, the negative and significant market-to-book coefficient likely reflects that high market valuations proxy for firm quality, stable cash flows, and strong bank monitoring, while low market-to-book firms concentrate distress, cyclical exposure, and downside risk, resulting in higher equity return volatility. The inclusion of macro controls (*GDP, Inflation, Rule_law, and Ec_freedom*) marginally improves explanatory power. Remarkably, the positive and significant coefficient on *Ec_freedom* suggests that greater deregulation and market openness intensify competition, capital reallocation, and firm-level exposure to demand and financing shocks, thereby increasing equity return volatility.

4.2. *Addressing endogeneity*

Table 6 reports the results from the random-effects and dynamic GMM estimations of eq. 1, addressing potential endogeneity concerns in the baseline model. To avoid instrument proliferation, we collapse the instrument matrix and limit lag depth. The positive and significant coefficients of *Vulnerability* across both estimators confirm that country-level climate vulnerability remains a robust determinant of firm-level market volatility, even after accounting for unobserved heterogeneity, dynamic persistence, and possible reverse causality. Economically, the magnitude of the climate vulnerability coefficient in the GMM model (0.0590*) implies that a one-standard-deviation increase in vulnerability raises market volatility by roughly 5.9 %, a magnitude comparable to baseline estimates. Overall, these results indicate that the positive association between climate vulnerability and market volatility is robust to alternative estimators and consistent with a macro-financial amplification mechanism, underscoring the macro-financial relevance of climate risk in shaping firm-level dynamics.

Furthermore, we instrument ND-GAIN vulnerability with each country's coastline length, population, and CO_2 emissions per capita (García-Gómez et al., 2025; Boulton et al., 2021). Coastline length captures physical exposure to coastal hazards, population proxies country scale and adaptive complexity, and CO_2 per capita indexes carbon intensity that helps predict vulnerability. Results are

Table 7
Addressing endogeneity using instrumental variables.

	Inst. Var.: Length_coastline		Inst. Var.: Population		Inst. Var.: CO2_emissions	
	First stage (Dep. var.: Vulnerability)	Second stage Market_vol	First stage (Dep. var.: Vulnerability)	Second stage Market_vol	First stage (Dep. var.: Vulnerability)	Second stage Market_vol
Length_coastline	0.0307*** (0.0009)					
Population			0.1145*** (0.0076)			
CO2_emissions					-0.0007*** (0.0002)	
Vulnerabilityt-1		**0.0778*** (0.0286)**		**0.3210*** (0.0624)**		**1.9305*** (0.7399)**
Size	0.0000 (0.0001)	-0.0009*** (0.0001)	-0.0001 (0.0001)	-0.0009*** (0.0001)	-0.0001 (0.0001)	-0.0008*** (0.0001)
Lev	-0.0000 (0.0000)	0.0001*** (0.0000)	-0.0000* (0.0000)	0.0001*** (0.0000)	-0.0000* (0.0000)	0.0001*** (0.0000)
MtoB	-0.0001 (0.0005)	-0.0030*** (0.0005)	0.0001 (0.0006)	-0.0019*** (0.0005)	-0.0000 (0.0006)	-0.0019 (0.0012)
ROA	0.0002 (0.0011)	-0.0219*** (0.0011)	0.0010 (0.0012)	-0.0224*** (0.0012)	0.0013 (0.0013)	-0.0244*** (0.0028)
Inflation	0.0001 (0.0001)	0.0002 (0.0001)	0.0003** (0.0001)	0.0004*** (0.0001)	0.0002* (0.0001)	-0.0001 (0.0003)
GDP	-0.0003*** (0.0000)	-0.0002*** (0.0000)	-0.0002*** (0.0000)	-0.0000 (0.0000)	-0.0001*** (0.0000)	0.0002 (0.0001)
Rule_law	0.0168*** (0.0013)	-0.0025* (0.0013)	0.0195*** (0.0013)	-0.0118*** (0.0015)	0.0147*** (0.0014)	-0.0337*** (0.0104)
Ec_freedom	0.0010*** (0.0000)	0.0001 (0.0001)	0.0009*** (0.0000)	-0.0001 (0.0001)	0.0010*** (0.0001)	-0.0017** (0.0007)
Constant	0.1861*** (0.0043)	0.0268*** (0.0069)	-1.6419*** (0.1221)	-0.0247* (0.0128)	0.1974*** (0.0051)	-0.3348** (0.1429)
Industry fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Time fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Country fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Observations	4,175	4,175	4,175	4,175	4,175	4,175
Wu-Hausman F test	3.43*		22.78***		36.74***	
First stage F-stat	3,373.15***		2,722.21***		2,580.72***	
R-squared	0.9695	0.4707	0.9625	0.4138	0.9605	0.4642
Wald Test (d.f.)		3,727.09*** (39)		3,344.47*** (39)		653.22*** (39)

Note: This table displays the findings from estimating Eq. 1 with instrumental variables. The dependent variable is *Market_vol*. The independent variable is the IV estimation of the vulnerability index using the variables length of coastline, the natural logarithm of each country's population, and each country CO2 emissions per capita, excluding land use, land-use change, and forestry (LULUCF) emissions. See Table 2 for variables' definitions. We include industry and year fixed effects in all the models. We adjust the error terms for heteroscedasticity at the company level. Standard errors are displayed in parentheses. Statistical significance at 1 %, 5 %, and 10 % are indicated with ***, **, and *, respectively. The Wu-Hausman F test evaluates whether the regressor treated as endogenous actually needs to be instrumented. The First stage F-stat test is for the validity of the first stage estimation, and the Wald test is for the joint significance of the independent variables.

reported in Table 7. The Wu–Hausman tests reject the null hypothesis of exogeneity, suggesting that treating climate vulnerability as endogenous is empirically warranted. First-stage results indicate strong relevance across all instruments, with highly significant coefficients and large F-statistics, well above the conventional threshold of 10 (Staiger & Stock, 1997), alleviating concerns regarding weak instruments. In the second stage, the coefficient of *Vulnerability* remains positive and statistically significant across the three models (0.0778***, 0.3210*** and 1.9305***), consistent with our first hypothesis that greater country-level climate vulnerability is associated with higher market volatility[2].

[2] Additionally, we conduct a set of event-based analyses to assess whether major climate-related policy interventions generate discrete changes in the relationship between climate vulnerability and firm-level market volatility. Specifically, we examine two prominent European climate policy milestones: the adoption of the Paris Agreement in 2015 and the introduction of the Market Stability Reserve (MSR) in 2019. We estimate interaction models between vulnerability and a dummy variable (years 2015 and 2019, respectively) for each policy-specific indicator variables (Vulnerability × Paris Agreement; Vulnerability × MSR). Across specifications, the interaction terms are not statistically significant, which suggests that the relationship between climate vulnerability and firm-level volatility is not driven by short-term regulatory or policy shocks.

Table 8
Robustness analysis.

	Dep. Var.: Market_vol				
	Readiness (1)	EPI_Score (2)	Excluding UK (3)	Alternative firm-level controls (4)	Board variables (5)
Vulnerability$_{t-1}$	**0.0349***		**0.0370*****	**0.0444*****	**0.0399*****
	(0.0185)		**(0.0135)**	**(0.0130)**	**(0.0146)**
Readiness$_{t-1}$	-0.0412***				
	(0.0136)				
Vulnerability*Readiness$_{t-1}$	0.0099				
	(0.0221)				
EPI Score		**-0.0001*****			
		(0.0000)			
Size	-0.0010***	-0.0010***	-0.0010***	-0.0007***	-0.0009***
	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)
Lev	0.0001***	0.0001***	0.0001***	0.0000***	0.0001***
	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)
MtoB	-0.0019***	-0.0019***	-0.0024***	-0.0015***	-0.0021***
	(0.0005)	(0.0005)	(0.0006)	(0.0005)	(0.0005)
ROA	-0.0221***	-0.0222***	-0.0225***	-0.0140***	-0.0223***
	(0.0011)	(0.0011)	(0.0013)	(0.0014)	(0.0012)
Inflation	0.0005***	0.0005***	0.0005***	0.0005***	0.0005***
	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)
GDP	-0.0000	-0.0001**	-0.0000	-0.0000	-0.0000
	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)
Rule_law	-0.0061***	-0.0068***	-0.0095***	-0.0072***	-0.0086***
	(0.0013)	(0.0012)	(0.0015)	(0.0011)	(0.0012)
Ec_freedom	0.0002***	0.0001**	0.0000	0.0002***	0.0002***
	(0.0000)	(0.0000)	(0.0001)	(0.0000)	(0.0000)
Cash				0.0078***	
				(0.0010)	
Dividends				-0.0134***	
				(0.0026)	
Board_size					0.0001*
					(0.0000)
Indep_director					0.0000
					(0.0000)
Women_board					-0.0000***
					(0.0000)
Constant	0.0557***	0.0450***	0.0443***	0.0211***	0.0299***
	(0.0101)	(0.0057)	(0.0066)	(0.0048)	(0.0051)
Industry fixed effects	Yes	Yes	Yes	Yes	Yes
Time fixed effects	Yes	Yes	Yes	Yes	Yes
Country fixed effects	Yes	Yes	Yes	Yes	Yes
Observations	4,175	4,166	3,258	3,772	3,929
R-squared	0.4685	0.4717	0.4585	0.4731	0.4787

Note: This table displays the findings from estimating alternative specifications of Eq. 1 with OLS. The dependent variable is *Market_vol*. See Table 2 for variables' definitions. *Cash* is the ratio of cash and cash equivalents to total assets; *Dividends* is the pay-out ratio; *Board_size* is the number of directors; *Indep_director* is the fraction of independent directors; and *Women_board* is the fraction of female directors. We include industry and year fixed effects in all the models. We adjust the error terms for heteroscedasticity at the company level. Standard errors are displayed in parentheses. Statistical significance at 1 %, 5 %, and 10 % are indicated with ***, **, and *, respectively.

4.3. Robustness analysis

A series of robustness tests designed to assess the stability of our baseline results are reported in Table 8. Across most specifications, the coefficient on climate vulnerability remains positive and significant, reaffirming that firms located in more climate-vulnerable countries experience higher market volatility. In column (1), the inclusion of the readiness index and its interaction with vulnerability shows that, while readiness itself is negatively signed, the interaction term (vulnerability × readiness) is statistically insignificant. This indicates that national adaptive capacity does not yet materially dampen the volatility effects of climate exposure, suggesting that current adaptation efforts may be insufficient to counter systemic financial transmission channels. In column (2), substituting the ND-GAIN measure with the Environmental Performance Index (EPI) yields consistent results, supporting robustness across alternative environmental metrics. Excluding the United Kingdom (column 3) or including additional firm-level controls such as cash holdings and dividend payouts (column 4) leaves the main results virtually unchanged, implying that neither sample composition nor omitted firm-specific heterogeneity drives our findings. Column (5) incorporates board-level variables, showing that larger boards and greater gender diversity are associated with marginally lower volatility, consistent with evidence that strong governance mitigates exposure to systemic shocks (Adams & Ferreira, 2009). Overall, the persistence of the climate-vulnerability effect across multiple robustness checks strengthens our conclusion that macro-level climate fragility remains a structural driver of firm-level market risk, in

Table 9
Moderating role of firm-level financial constraints.

	Dep. Var.: Market_vol			
	KZ Index (1)	KZ Index (2)	HP Index (3)	HP Index (4)
$Vulnerability_{t-1}$	0.0418***	0.0412***	0.0379***	0.0382***
	(0.0131)	(0.0131)	(0.0137)	(0.0137)
KZ_index	0.0002***	0.0001*		
	(0.0001)	(0.0001)		
$Vulnerability_{t-1}$*KZ_index		0.0009***		
		(0.0003)		
HP_index			0.0004***	0.0003***
			(0.0001)	(0.0001)
$Vulnerability_{t-1}$*HP_index				0.0001
				(0.0003)
Size	-0.0008***	-0.0008***	-0.0009***	-0.0009***
	(0.0001)	(0.0001)	(0.0001)	(0.0001)
Lev	0.0000	0.0000	0.0001***	0.0001***
	(0.0000)	(0.0000)	(0.0000)	(0.0000)
MtoB	-0.0027***	-0.0026***	-0.0023***	-0.0023***
	(0.0005)	(0.0005)	(0.0005)	(0.0005)
ROA	-0.0143***	-0.0142***	-0.0225***	-0.0225***
	(0.0013)	(0.0013)	(0.0011)	(0.0011)
Inflation	0.0005***	0.0005***	0.0005***	0.0005***
	(0.0001)	(0.0001)	(0.0001)	(0.0001)
GDP	-0.0000	-0.0000	-0.0000	-0.0000
	(0.0000)	(0.0000)	(0.0000)	(0.0000)
Rule_law	-0.0075***	-0.0075***	-0.0080***	-0.0080***
	(0.0011)	(0.0011)	(0.0012)	(0.0012)
Ec_freedom	0.0002***	0.0002***	0.0002***	0.0002***
	(0.0000)	(0.0000)	(0.0000)	(0.0000)
Constant	0.0237***	0.0240***	0.0318***	0.0317***
	(0.0049)	(0.0049)	(0.0050)	(0.0050)
Industry fixed effects	Yes	Yes	Yes	Yes
Time fixed effects	Yes	Yes	Yes	Yes
Country fixed effects	Yes	Yes	Yes	Yes
Observations	3,772	3,772	4,121	4,121
R-squared	0.4642	0.4652	0.4720	0.4721

Note: This table displays the findings from estimating Eq. 1 including firm-level financial constraints with OLS. The dependent variable is *Market_vol*. See Table 2 for variables' definitions. We include industry and year fixed effects in all the models. We adjust the error terms for heteroscedasticity at the company level. Standard errors are displayed in parentheses. Statistical significance at 1 %, 5 %, and 10 % are indicated with ***, **, and *, respectively.

line with the financial accelerator mechanism (Bernanke et al., 1999; Rampini & Viswanathan, 2013).

4.4. *Channel analysis: firm-level financial constraints*

Table 9 investigates the role of firm-level financial constraints in shaping the relationship between country-level climate vulnerability and stock return volatility. Across all specifications, climate vulnerability remains positively and statistically significant, confirming the robustness of the baseline effect. Both the Kaplan–Zingales (*KZ_index*) and Hadlock–Pierce (*HP_index*) indices enter positively in levels, indicating that more financially constrained firms exhibit higher volatility, consistent with prior evidence linking financing frictions to heightened market sensitivity (Lamont et al., 2001; Whited & Wu, 2006). Importantly, when financial constraints are measured using the KZ index, the interaction between climate vulnerability and financial constraints is positive and highly significant, indicating that the volatility impact of climate vulnerability is amplified for firms with limited access to external finance, in line with financial-frictions and financial-accelerator theories (Bernanke et al., 1999) and supporting Hypothesis 2. This amplification is economically meaningful: Fig. 1 shows that the slope of predicted volatility with respect to climate vulnerability steepens monotonically across the distribution of the KZ index, and moving from the 10th to the 90th percentile of financial constraints increases the marginal effect of climate vulnerability by approximately one-third. In contrast, when financial constraints are proxied by the HP index, the interaction term is statistically insignificant and the marginal effect of climate vulnerability remains essentially flat across the constraint distribution, with confidence bands overlapping zero. This divergence suggests that the amplification mechanism depends on the ability of the constraint proxy to capture firms' sensitivity to external finance rather than reflecting mechanical statistical significance driven by sample size.

5. Conclusions

This study investigates the impact of country-level climate vulnerability on firm-level market volatility across European economies,

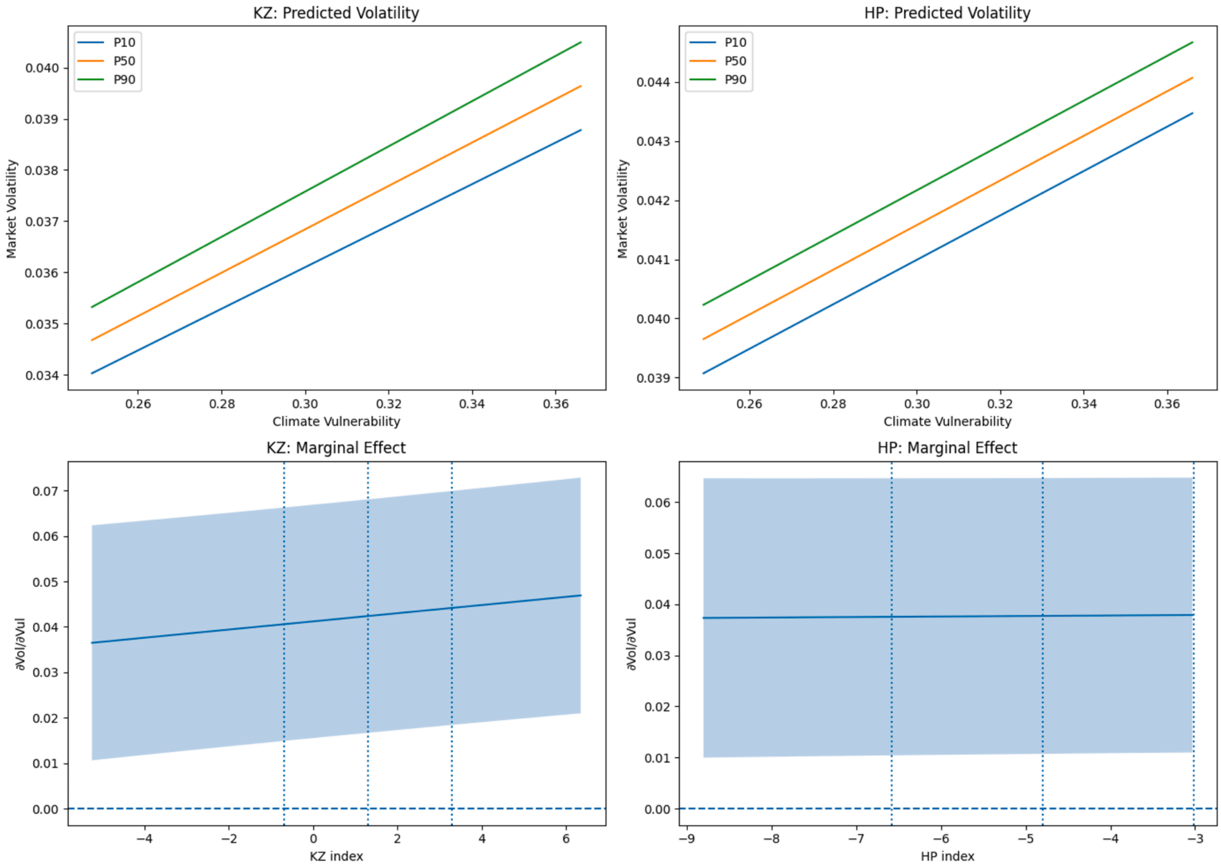

Fig. 1. Financial constraints and the transmission of climate vulnerability to market volatility.
Note: The top panels display predicted market volatility as a function of climate vulnerability at the 10th, 50th, and 90th percentiles of the Kaplan–Zingales (KZ) and Hadlock–Pierce (HP) indices. The predicted values are based on the estimates reported in Table 9. The bottom panels report the marginal effect of climate vulnerability on volatility across the distribution of financial constraints, with 95 % confidence intervals computed using the delta method.

providing new insights into the macro-to-micro transmission of environmental risk. We document that firms headquartered in more climate-vulnerable countries exhibit significantly higher stock return volatility, even after controlling for firm characteristics, macroeconomic conditions, and country fixed effects. Importantly, this effect is robust across alternative measures of climate vulnerability and does not appear to be driven by short-run regulatory or policy shocks, indicating that climate vulnerability acts as a slow-moving, structural source of market uncertainty rather than a transitory risk factor.

Our results highlight financial frictions as a key channel through which climate vulnerability amplifies firm-level risk. The volatility impact of climate vulnerability is significantly stronger for financially constrained firms when constraints are measured using the Kaplan–Zingales index, while no comparable amplification is observed for less sensitive constraint proxies. Graphical and marginal-effects analyses confirm that the economic magnitude of this interaction is substantial: firms in the upper tail of the financial-constraint distribution experience markedly larger volatility responses to climate vulnerability than otherwise similar firms. These findings are consistent with financial-accelerator theories and indicate that climate vulnerability primarily manifests as heightened uncertainty and instability, rather than predictable changes in average valuations.

These results have targeted policy implications. First, because climate vulnerability amplifies volatility through financial constraints, climate-related stress tests that abstract from firms' balance-sheet conditions are likely to underestimate systemic risk. Incorporating firm-level financial resilience into climate stress-testing frameworks would improve their ability to identify vulnerable segments of the corporate sector. Second, policies aimed at strengthening firms' access to liquidity—such as countercyclical credit facilities, climate-contingent loan guarantees, or adaptive investment support in vulnerable regions—may reduce the volatility-amplifying role of financial frictions. Third, the absence of discrete volatility responses to major climate policy events suggests that regulatory risk is not the primary driver of market instability; instead, long-run exposure to climate vulnerability matters more for financial stability. This underscores the importance of sustained adaptation and resilience investments over episodic policy interventions. Finally, since the volatility effects we document arise from country-level vulnerability but affect firm-level outcomes, international coordination on climate adaptation and financial regulation remains essential to limit cross-border transmission of climate-induced market instability.

Funding

The study has been financed by the Spanish Ministry of Science, Innovation and Universities (grants PID2024-155796NB-I00 and PID2023-52671OB-I00). Centro de Economia e Finanças (CEF.UP) is financed by Portuguese public funds through FCT - Fundação para a Ciencia e Tecnologia, I.P., within the framework of project UID/4105/2025. The authors are grateful to the Editor-in-Chief Tony Klein, two anonymous referees, and the First GLOBAFA Conference participants for their valuable comments.

CRediT authorship contribution statement

Sarela Enriquez-Perales: Writing – review & editing, Writing – original draft, Conceptualization. **Conrado Diego García-Gómez:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization, Supervision. **José María Díez-Esteban:** Software, Methodology, Data curation.

Data availability

The authors do not have permission to share data.

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