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Temperature fluctuations, climate uncertainty, and financing hindrance

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Abstract

Undesirable temperature fluctuations pose significant financial risks for enterprises. By merging fine-grained meteorological data with a panel of publicly listed firms, we delve into the relationship between temperature volatility and financing constraints. Our analysis reveals a positive correlation between temperature fluctuations and increasingly stringent financing limitations. State-owned or large-scale enterprises endowed with greater resources and risk diversification mechanisms are more likely to counteract the adverse effects of temperature volatility. Furthermore, we furnish evidence indicating that temperature fluctuations exert a substantial influence on corporate labor productivity. In response, companies tend to expand their workforce and elevate wages during the fiscal year. Faced with dwindling income and escalating operational costs, enterprises significantly amplify their insurance expenditures. The pronounced escalation in default risk and borrowing costs could undermine investors' sanguine profit expectations, subsequently prompting declines in firms' price-to-earnings and price-to-book ratios. Our study underscores the imperative for executive management teams to prudently account for climate change-induced financing constraints when devising investment and production strategies.

KEYWORDS

financing constraints, firm behavior, investor confidence, temperature fluctuations

1 | INTRODUCTION

Climate change has engendered unparalleled repercussions on a global scale (Findlay & Wake, 2021; Sanders, 2022). The ramifications encompass escalated global warming, rising sea levels, ocean acidification, and a surge in more frequent and severe weather anomalies, all of which have enfeebled pivotal assets and infrastructure (Melvin et al., 2017). These transformations have cast a profound impact on human productivity and well-being (Meierrieks, 2021; Somanathan et al., 2021; Yu et al., 2019), imperiled food security (Randell et al., 2021), and cast an alarming shadow on sectors vital to economies such as forestry, fisheries, and tourism (Burke et al., 2015; Kalkuhl & Wenz, 2020; Moore & Diaz, 2015). In the summer of 2023, a record-shattering surge in temperatures traversed the Northern Hemisphere, spanning North America, Europe, and Asia. This unprecedented heatwave inflicted its scorching influence upon numerous cities, subjecting hundreds of millions to its extreme thermal embrace. Presently, the progression of climate-driven meteorological extremities continues its inexorable rise in both frequency and intensity (Dellink et al., 2019).

One of the primary physical risks associated with climate change resides in the escalation of temperatures. Extensive research has been dedicated to assessing how elevated temperatures impact the production processes within the agricultural and manufacturing sectors. Agriculture is intrinsically intertwined with atmospheric conditions, thus its susceptibility to heightened temperatures has become a focal point in evaluating the ramifications of climate change (Buggle and Durante, 2021; Trinh, 2018). Mendelsohn et al. (1994) conducted early research across 3000 counties in the United States, demonstrating that elevated temperatures engender a decrease on average farm values. Schlenker and Roberts (2009) identified a nonlinear and asymmetric relationship between temperature and efficiency, prognosticating a reduction of 63%–82% in the growth of crops like corn, soybeans, and cotton under the swiftest warming scenarios. Climate-induced crop substitution is considered a potential stimulus for agricultural expansion (Cui, 2020).

Recognizing that prior literature fell short of fully elucidating the gross domestic product (GDP) losses, primarily due to the relatively smaller share of agriculture compared to industry, recent research by Zhang et al. (2018) delineated an inverted U-shaped relationship between temperature and total factor productivity (TFP) within China's manufacturing enterprises. Chen and Yang (2019) further established the existence of an optimal temperature range, specifically 21°C–24°C, for industrial production by firms. Notably, findings underscore an economic return linked to elevated temperatures in developing countries, corresponding to an approximate 2% decrease in industrial output per Celsius degree reduction (Somanathan et al., 2021). In contrast, Colmer (2021) discerned that as temperatures rise in India, there emerges a heightened demand for agricultural labor, and the reconfiguration of labor resources can mitigate the impact of temperature elevation—an analogous scenario was observed in the American Midwest (Xie et al., 2019).

As the frequency and intensity of extreme weather events continue to escalate, central banks and international financial institutions are progressively incorporating climate risk analysis into their decision-making processes (European Central Bank, 2021; International Monetary Fund, 2021; Mieg, 2022). The Green Finance Network of Central Banks and Supervisors asserted, in its inaugural comprehensive report of 2019, that "climate-related risks are a source of financial risk," a declaration that reverberates as a clarion call to the financial industry. The collective admonitions issued by over 40 central banks and regulatory bodies worldwide demand the unwavering attention of all financial investors. Research has posited that companies experiencing hurricanes tend to augment their cash holdings postdisaster (Brown et al., 2021; Dessaint & Matray, 2017), indicating that extreme cold can impact corporate cash holdings. Moreover, Pankratz et al. (2023) evaluated how elevated temperatures affect the profitability of publicly traded firms, determining that heightened exposure to high temperatures adversely affects both revenues and operating profits. Capital market participants, however, remain incapable of entirely foreseeing the economic repercussions of heightened temperatures.

Echoing the emphasis of numerous studies, the financial sector must take proactive measures to alleviate climate change-related risks (Taylor, 2014). Nonetheless, the scale and severity of climate change's impact on the financial sector remain uncertain. Most of its effects are yet to be concretely manifested, and there exists an ongoing lack of consensus on measurement methodologies and the extent of these effects, as well as the contentious question of whether these impacts are adequately priced in market valuations. Consequently, significant endeavors are still required to ensure the financial sector's robust response to the challenges posed by climate change.

Financial constraints are a comprehensive reflection of a firm's overall financial condition and operating environment and should be central to financial sector regulation in the context of climate change (Campello et al., 2010). Financial constraints arise from the interaction of various conditions within firms, encompassing fundamental factors, such as profitability, cash flow stability, asset-to-liability ratio, return on assets, balance sheet, and investment opportunities, as well as external conditions, including industry prospects, market competitive dynamics, and macroeconomic environments (Guariglia, 2008). Due to the multidimensional impact of climate change on factors such as revenue, costs, and asset values, the degree of financial constraint may more accurately reflect the funding pressures faced by firms due to climate shocks than ex post indicators such as market valuations and cost of capital (Balvers et al., 2017; Javadi & Masum, 2021). This provides regulators with early warnings and a basis for forward-looking regulatory measures. Moreover, the asymmetric effects of climate change across firms often manifest in different financial constraints. Small and medium-sized enterprises with weak financial foundations are particularly vulnerable to financing difficulties due to climate pressures, while large enterprises are less affected due to their own resources or policy support. This underscores the importance for regulatory authorities to balance efficiency and fairness in policy making, thereby avoiding exacerbating capital allocation distortions (Beck & Demirguc-Kunt, 2006). Finally, when firms globally face worsening financial constraints stemming from climate change, financial institutions such as banks, as suppliers of capital, are also under pressure. To control their exposure to credit risks, they need to proactively assess the climate risks of the borrowing firms, optimize the credit resource allocation, and guide the firms to strengthen climate governance through pricing mechanisms and other means. This process fosters a virtuous interaction between the financial sector and the real economy in responding to climate change (Paravisini, 2008).

Furthermore, while one of the primary physical risks of climate change is the rise in temperatures, temperature volatility can induce more immediate and pressing effects in the short term. Temperature elevation leads to alterations of the long-term temperature trends, subsequently influencing factors such as atmospheric circulation and ocean heat distribution. This, in turn, triggers more frequent and intense temperature fluctuations, encompassing heatwaves, cold snaps, and extreme weather events. Consequently, these fluctuations swiftly propagate far-reaching impacts across economic and societal systems (Bartusek et al., 2022; Drouet et al., 2021). Prior research has often approached the understanding of climate change impacts from the perspectives of mean temperature or frequency of high-temperature days. This has spurred our contemplation of the profound repercussions of altered climate patterns through an exploration of second-order temperature changes.

Within this study, we investigate over 2200 publicly listed companies in China from 2011 to 2019 to comprehend how climate change affects corporate financing constraints in the context of temperature volatility. Grasping this issue is of paramount importance, as corporate financing capacity directly influences growth, innovation, competitiveness, and risk management (Giuzio et al., 2019). Pertinently, according to research and predictions from various institutions, the future holds an escalation in temperature volatility and extreme weather events. Notably, driven by the El Niño phenomenon, the year 2023 has witnessed widespread climate fluctuations and meteorological disasters globally. Unprecedented floods have struck regions including Slovenia and northern China, resulting in dozens of casualties. Simultaneously, as firefighting teams battle forest fires in Canada and Portugal, Alaska in the United States declared a state of emergency following a glacier rupture. These occurrences serve as indicators that the topic of temperature volatility will assume greater gravity in the future.

To address the inquiry of whether temperature volatility influences the performance of corporate financing constraints, we causally establish the net effect of temperature volatility using the variance of annual average temperatures. This variation can be deemed exogenous and randomly distributed. On the one hand, in the short term, temperature volatility might be more influenced by stochastic weather events rather than long-term climate trends. Additionally, short-term natural factors (such as ocean currents, volcanic activity, etc.) as opposed to anthropogenic factors (like greenhouse gas emissions) drive the variation, making it more likely to be exogenous. On the other hand, in geographically heterogeneous areas, which encompass diverse terrains and ocean influences, temperature volatility may manifest distinct patterns at different locations due to various natural factors. Consequently, it could be seen as spatially randomly distributed. If the study accounts for seasonal and yearly (i.e., time-fixed) effects, the model might eliminate temperature changes caused by seasons and long-term trends, rendering the residual temperature changes rather exogenous and random. Therefore, temperature variation can be regarded as an ongoing natural experiment (Auffhammer, 2018, 2022; Auffhammer et al., 2013; Dell et al., 2014). We find that elevated temperatures have a negative impact on various measures of corporate financing constraints. Subsequently, our channel analysis tests alterations in relevant firm-specific indicators and investor confidence within the capital market.

On average, our findings reveal that a 1% increase in temperature volatility leads to an average decrease of approximately 3.5% in daily revenue (operating profit) due to heightened financing constraints. These estimated outcomes hold significant economic implications and reject our null hypothesis. Notably, an observed annual growth of 1.05% in temperature fluctuation compared to the previous year implies a temperature-induced contribution to a financing constraint deterioration of at least 29% by the year 2030. This constitutes 8.7% of the sales revenue of the listed companies (Caggese et al., 2019).

Diverse companies and industries may exhibit significant variations in sensitivity to temperature volatility and their ability to respond. Enterprises with stronger adaptive capabilities typically possess greater resources and risk diversification mechanisms (Ramezani & Camarinha-Matos, 2020). We look into whether the adverse impacts of temperature volatility are also discernible at the individual level of publicly listed companies based on these characteristics. We differentiate based on corporate ownership, scale, technological profile, and the specific industry they operate in. State-owned or large corporations usually possess more resources and risk-diversification mechanisms, enabling them to cope more effectively with these adverse effects. Simultaneously, high-tech firms, by employing advanced adaptive technologies, may mitigate the negative consequences of high-temperature fluctuations. Conversely, when temperature volatility emerges as an exogenous shock, financing constraints for private and small enterprises deteriorate significantly. Furthermore, across all economic sectors, industries like mining, manufacturing, transportation, warehousing, postal services, and real estate, which predominantly conduct their operations outdoors, are more susceptible to the detrimental impacts of temperature volatility. Traditional labor-intensive sectors are particularly vulnerable to the effects of temperature fluctuations.

Adaptation plays a pivotal role in addressing climate change. While an extensive body of literature underscores the role of adaptation in fostering climate-resilient socioeconomic structures (Deschenes, 2014; Kahn, 2016; Pankratz and Schiller, 2022; Quiroga et al., 2020; Vale, 2016), few discussions dig into how companies adapt to climate change through economic, financial, and innovative measures. In the economic realm, for instance, extreme heat's impact on mortality rates is significantly lower in states accustomed to such conditions (Barreca et al., 2015). In regions prone to elevated temperatures, like parts of India, losses due to high temperatures are considerably diminished (Taraz, 2018). Jagnani et al. (2021) highlight that farmers, in response to intraseasonal temperature variations, shift investments from productivity-enhancing technologies towards more adaptive and defensive strategies. Additionally, adaptation measures such as indoor/outdoor time reallocation, household-level architectural adjustments, warning systems, and community health outreach have garnered substantial research attention (Zivin & Neidell, 2014). In terms of financial and innovation-related adaptation, studies like Miao and Popp (2014) investigate how drought leads to increased investments in drought-resistant crops. Millner and Dietz (2015) highlight investors' perceptions of profitability in adaptive sectors. Adaptive investments mitigate losses, thus affording the economy additional gains (Zemel, 2015). Moreover, Catalano et al. (2020) demonstrate that adaptation can alleviate climate change's impact on capital depreciation and GDP growth. Crucially, companies can tailor their capital and labor inputs to manage and minimize risk (Balvers et al., 2017). Our study employs the

"Huai River–Qin Mountains boundary" as a natural geographic divide between northern and southern China to account for varying levels of temperature fluctuation, which are more pronounced in the south. Additionally, it incorporates "above-median Nino days" as an indicator of heightened climate variation, linking it to increased potential for temperature instability. Our empirical findings corroborate the notion that companies exhibit stronger adaptive capacities in environments characterized by greater climate variability. These adaptations encompass advanced technologies, flexible business models, robust risk management strategies, as well as hedging and insurance mechanisms. These measures assist companies in mitigating the risks posed by weather events and temperature variations without undergoing extreme shocks.

To gain a more comprehensive understanding of the underlying economic channels at play, we conducted a series of additional tests. First, we examined the significant impact of temperature volatility on labor productivity within enterprises. This effect can be attributed to extreme temperature fluctuations potentially causing variations in employee work efficiency and performance. Extreme high or low temperatures might negatively affect employee comfort and health, consequently reducing their work effectiveness, motivation, as well as job satisfaction and focus (Seppänen et al., 2006). Furthermore, temperature volatility could disrupt work environments and the production processes of specific industries. This diminished productivity might drive firms to hire more workers within a fiscal year to counterbalance the drop in output (Somanathan et al., 2021). Subsequently, firms must accommodate the increased labor costs (Pankratz et al., 2023). Additionally, if a region experiences widespread productivity decline, it can result in heightened labor demand and consequently drive up wages (Émilien Gouin-Bonenfant, 2022), as observed in our empirical analysis—wages tend to increase with exacerbated temperature volatility. This complex web of productivity, labor demand, and wages highlights the multifaceted impacts of temperature volatility on various aspects of business operations and economic performance.

Second, we observed that substantial temperature volatility significantly leads to a decline in company revenues, aligning with the observation of decreased labor productivity. Moreover, the pronounced fluctuations in temperatures also influence the consumer purchasing behavior, supply chain operations, and market demand, collectively resulting in a direct decline in corporate revenues—this is in line with the findings of Sheth (2020) and Davis et al. (2021). Consequently, firms significantly increase their spending on insurance to mitigate the risks associated with temperature volatility. However, when experiencing more intense temperature volatility, firms' cost of goods sold (GS) and expenses for sales, administration, and finance (SAF) show significant increases after a fiscal year, rather than in the current period. This pattern mirrors the dynamics we observed in terms of wage fluctuations. This interplay of various economic variables underscores the intricate web of causality linking temperature volatility to multiple dimensions of corporate performance and risk management strategies.

In the face of declining labor productivity and corporate revenue, investors might increasingly focus on climate-sensitive industries or companies. We discovered that temperature volatility significantly raises a company's average borrowing cost, a phenomenon that remains significant even in lagged periods—consistent with the observations of Klusak et al. (2023). The instability in production, supply chain disruptions, or sales downturns due to temperature fluctuations can heighten a firm's default risk. For higher-risk borrowers, banks and other financial institutions might demand higher risk premiums, thereby elevating the company's borrowing costs (Javadi & Masum, 2021). Additionally, the ratio of unsecured debt to total debt declines after the fiscal year-end. This might be due to climate-induced scrutiny of the company's financial condition, potentially making it more challenging to secure collateralized financing from financial institutions, similar to the analysis of Kling et al. (2021). Our empirical findings further suggest that in regions typically influenced by temperature fluctuations, a company's price-to-earnings and price-to-book ratios typically decrease. On the one hand, the increased temperature uncertainty and risk a company faces may dampen investors' optimism regarding its future profit expectations (Bolton & Kacperczyk, 2021). On the other hand, temperature volatility might result in impairment or devaluation of a company's fixed assets, inventory, or other crucial assets, leading to a deterioration of the balance sheet (Fiedler et al., 2021). However, considering the efficient market hypothesis and the significance and magnitude of estimated coefficients, we contend that investors might not possess sufficient information to comprehend the effects of temperature volatility on companies, in line with the findings of Pankratz et al. (2023).

The contribution of this paper lies in providing a comprehensive analysis of the impact of temperature volatility within climate change on corporate financing constraints and economic performance. First, our study adds an incremental contribution to the literature on climate change risk assessment. Previous research primarily focused on the long-term temperature trends of climate change (Schlenker & Roberts, 2009; Somanathan et al., 2021; Zhang et al., 2018); our study focuses on short-term temperature fluctuations, revealing the immediate effects of temperature volatility on corporate financing constraints and economic performance. Second, existing research lacks a climate perspective in microlevel corporate behavior within the financial sector. While some studies have assessed corporate finance and other environmental risks (Brown et al., 2021; Dessaint & Matray, 2017; Pankratz et al., 2023), our paper specifically examines financing constraints. Indeed, the recent pandemic, geopolitical instability, and the high demand for capital due to new technologies have collectively exacerbated the issue of financing constraints, making it more pertinent and urgent. Moreover, the paper further investigates the disparities in sensitivity and adaptability to temperature volatility across different industries and companies. By contrasting data from different industries, company sizes, and technological profiles, we reveal that certain types of enterprises may exhibit greater adaptability and risk mitigation capabilities when facing climate change. Third, we conduct an in-depth exploration of the impact of temperature volatility on various economic channels, including labor productivity, corporate revenue, investor sentiment, and capital market valuation. Analyzing these channels helps elucidate how temperature volatility affects corporate performance and market reactions through different pathways. We also present evidence that challenges the efficient market hypothesis in the context of climate change, suggesting that investors might lack sufficient information to fully comprehend the effects of temperature volatility on companies.

The rest of the paper proceeds as follows. Section 2 outlines the data sources and our empirical strategy. Section 3 presents the benchmark results, heterogeneity analysis, and preadaptation effects. In Section 4, we delve into potential underlying mechanisms. Finally, Section 5 presents our conclusions and policy implications.

2 | DATA AND IDENTIFICATION

2.1 | Weather data

The weather data used in this study are mainly from the National Climate Data Center (NCDC) of the National Oceanic and Atmospheric Administration (NOAA), based on collection from meteorological stations around the world. We have selected only those continuous and valid weather records as Zhang et al. (2018). Around China, hundreds of weather observations are recorded automatically each day. This paper uses the most common processing steps turning daily weather data at station level into annual climate data at city level. More specifically, a city's daily temperature is calculated by averaging the maximum and minimum temperatures in a day; a city's annual temperature fluctuation is given by the standard deviation of all daily temperatures in a year.

2.2 | Firm data

With regard to the economic and financial indicators required for our dependent variable and controls (see details in Sections 2.3 and 2.4), we have used firm-level data since 2011 from the Shanghai and Shenzhen Stock Exchange, the China Stock Market & Accounting Research Database (CSMAR), and the Wind Info China A-share Quantitative Factor Database (see http://www.gtarsc.com/ and https://www.wind.com.cn/).

Data cleansing was carried out as follows. First, companies listed for less than a year, with large equity financing and fewer financial constraints, were excluded. Second, companies marked *ST* (Special Treatment), that is, whose stocks suffered losses for 2 consecutive years and warned of investment risks, and *ST**, that is, that are likely to face a great risk of delisting for their deficit in 3 years, were all removed. Then, companies with missing indicators were removed. Finally, the quantiles below 1% and above 99% for all continuous variables were winsorized. This exercise led to a total of 2286 listed companies and 16,420 samples obtained.

2.3 | Measuring financing constraints

Our main dependent variable is the financing constraints of the companies. Following Whited and Wu (2006), we use an index that captures multiple facets of companies' financial status. This is based on the following estimated Euler equation of structural model of the production function:

$$WW = b_1 \times CFA + b_2 \times DIV + b_3 \times LD + b_4 \times Size + b_5 \times ISG + b_6 \times CH, \tag{1}$$

where *CFA* is the ratio of operating cash flow to total assets, *DIV* takes value 1 if the firm pays cash dividends and 0 otherwise, *LD* is the ratio of long-term debt to total assets, *Size* is the natural logarithm of total assets, *ISG* corresponds to the firm's three-digit industry sales growth, *SG* to the firm's sales growth itself, and *CH* is the ratio of liquid to total assets. The coefficient vector ***b*** is provided by Whited and Wu (2006); the larger the value, the higher the degree of financing constraints for the company.

In addition, for robustness we formulate an alternative financial-constraints index *KZ* (Kaplan & Zingales, 1997) based on a different calculation method. Let OCF, C, Lev and A be the operating cash flow, cash, leverage and firm assets, respectively. For each year t, we classify the sample by OCF_{it}/A_{it-1}, DIV_{it}/A_{it-1}, C_{it}/A_{it-1}, Lev_{it} and Tobin's Q which, when above the median, result in associated indicators kz_1, kz_2, kz_3, kz_4, and kz_5 taking value 1. We then calculate $KZ = kz_1 + kz_2 + kz_3 + kz_4 + kz_5$ and run an Ordered Logistic Regression of KZ on OCF_{it}/A_{it-1}, DIV_{it}/A_{it-1}, C_{it}/A_{it-1}, Lev_{it} and Q, collecting the estimated coefficients. Finally, we take the fitted value as the *KZ* index of each listed company's financing constraints. Aiming to verify our conclusion across the board, we employ the *WW* index as the leading dependent variable and the *KZ* index as secondary since they are both positively associated with the degree of financing constraints faced by companies.

It is important to note that almost all firms face financing challenges, albeit to varying degrees. We utilize continuous variables such as the *KZ* and the *WW* index to measure financial constraints, as these reflect the declining status of firms in terms of availability of external financing. Additionally, the impact of temperature fluctuations on financial constraints is ubiquitous and gradual and not limited to high-risk businesses (Beladi et al., 2021). Long-term climate stress continues to build, eroding the financial resilience of enterprises, exacerbating their funding gaps, and, ultimately, deteriorating the financial constraint indicators. This negative effect can affect firms placed at different ends of the spectrum of financial constraints (Behr et al., 2013). For firms with relatively superior financial conditions, temperature changes may only slightly worsen their position; however, for financially strained firms, an equivalent degree of climate shock can aggravate their challenges and financial status (Hartzmark & Shue, 2023). Therefore, our sample covers enterprises with diverse financial conditions, facilitating a comprehensive assessment of climate change risks.

2.4 | Identification strategy

For company i in city j in year t, we use the following specification to examine whether temperature fluctuations influence financing constraints:

$$Y_{ijt} = \alpha + \beta \times Temp_{jt} + \mathbf{X}_{it}\vartheta + \mu_t + \mu_i + \mu_c + \epsilon_{it}, \tag{2}$$

where the dependent variable Y_{ijt} refers to company i's financing constraints in city j in year t; the variable of interest is $Temp_{jt}$ measured by the standard deviation of the annual temperature of city j in year t. We control for the characteristics at the company-year level via the vector $\mathbf{X}_{it}$, including the natural logarithm of total assets (*Size*), leverage (*Lev*), return-on-assets (*Roa*), book-to-market ratio (*B/Mratio*), growth of operating revenue (*Growth*), net property, plant, and equipment (*PPE*), operating cash flow (*OCF*), the log-number of directors (*Board*), whether the chairman and president coincide (*Dual*), and the proportion of managerial ownership (*Hold*). The vector $\mu_{ict} = (\mu_i, \mu_c, \mu_t)$ encompasses semiparametric controls, that is, firms' fixed effects, years' fixed effects, and two-digit industries, respectively, to control for the unobserved factors that are homologous to the above. Besides, we cluster standard errors within cities in all regressions to settle possible spatial and serial correlations in the residuals ϵ_{it} (Cameron et al., 2011; Santos & Cincera, 2022).

In addition, we employ the following approach to discern the channels through which temperature fluctuations more profoundly affect financing constraints:

$$Mediators_{it} = \alpha_1 + \beta_1 \times Temp_{jt} + \mathbf{X}_{it}\vartheta + \mu_t + \mu_i + \mu_c + \epsilon_{it}, \tag{3}$$

where $Mediators_{it}$ correspond to mediate variables which we introduce later in Section 4. Finally, we convert the nominal economic variables into real ones by applying the price deflator base on the year 2010. The Pearson correlations between temperature fluctuations, financing constraints and our controls range between 0.1 and 0.3 with a variance inflation factor (VIF) of less than 10, implying no serious multicollinearity issue. Further descriptive statistics for the main variables are shown in Table 1.

3 | EMPIRICAL ANALYSIS

3.1 | Main results

We kick off our analysis by presenting the estimation outcome for the benchmark model specified by Equation (2) in Table 2. More specifically, column (1) refers to the pure regression of companies' financing constraints on temperature fluctuations. In columns (2)–(5), we add firm-level control variables, while in columns (3)–(5) we introduce common shocks across firms, years, and two-digit industries, respectively. In column (6), we replace the dependent variable by *KZ*.

Without exceptions, we find that the coefficient of temperature fluctuations, that is, the main variable of interest, is persistently positive at least at the 10% level, manifesting that higher temperature fluctuations are significantly associated with companies' worse financing constraints. As indicated in column (5), each 1% increase in the mean annual temperature standard deviation can worsen the financing constraints of companies by 3.456%. Adopting a long-term view of climate change and extrapolating from our sample reveals a trend of 1.048% average increment of temperature fluctuation compared to the previous year, hence a temperature-driven contribution to the deterioration of the financing constraints of at least 28.975% by the year 2030 ($(2030 - 2022) \times 1.048\% \times 3.456\% \approx 28.975\%$), which is 8.693% of the sales revenue of listed companies (Caggese et al., 2019).

The parameter estimates of the control variables are discrepant but support essential information. More specifically, the *B/M ratio*, *OCF*, *Roa*, *Lev*, *Growth* are identified as potential alleviators of financial constraints, while a consistent positive relationship between *Size* and *WW* is noted. The suggestion of a nonlinear relationship encourages a deeper exploration of the intricate connections between these variables.

TABLE 1 Descriptive statistics.

Variable	No. of obs.	Mean	SD	Min	Max	Skew.	Kurt.
WW	16,420	−0.626	7.184	−156.007	177.517	22.222	590.128
KZ	14,320	1.021	1.738	−5.669	5.645	−0.977	5.502
Temp	16,420	2.155	0.258	0.889	2.827	−0.613	3.094
Typhoon	16,420	0.034	0.181	0	1	5.149	27.514
Intensities	16,420	0.122	0.7	0	6	6.188	41.888
Size	16,419	22.328	1.395	15.715	28.636	0.714	3.898
Lev	12,839	20.793	33.411	0	1884	15.204	779.027
Roa	16,419	0.034	0.126	−6.776	8.441	9.677	1891.164
B/M ratio	15,946	0.648	0.249	0.006	1.43	−0.076	2.299
Growth	16,020	0.198	0.523	−0.64	3.894	4.386	28.879
PPE	16,419	0.923	0.097	0.076	1	−2.85	13.564
OCF	16,419	0.041	0.085	−4.27	0.876	−9.698	450.988
Board	16,420	1.24	1.11	0	2.944	−0.199	1.084
Dual	16,420	0.204	0.403	0	1	1.47	3.161
Hold	16,420	9.831	18.62	0	89.725	1.785	4.894

3.2 | Heterogeneity analysis

In theory, the roles played by company ownership, scale, and technological profile are pivotal in assessing the impact of elevated temperature volatility on corporate financing constraints. Enterprises of a private or smaller nature might find themselves more susceptible to the repercussions of financing constraints due to information asymmetry and market frictions, particularly when amplified by the emergence of elevated temperature volatility as an exogenous shock. In contrast, state-owned or larger enterprises commonly possess augmented resources and risk-diversification mechanisms, potentially rendering them more adept at countering such adversities. The technological dimension also assumes a critical role. For instance, high-tech enterprises could potentially ameliorate the adverse effects of elevated temperature volatility through the utilization of sophisticated adaptive technologies. Lastly, divergences across industries (such as agriculture, manufacturing, or services) in their sensitivities and adaptability to temperature fluctuations further mediate their respective financing constraints (Wu, 2023). These heterogeneous impacts afford a refined perspective, enabling a deeper comprehension of how to more effectively manage and alleviate the financing constraint issues stemming from temperature volatility across distinct corporate and industrial contexts.

On the one hand, Table 3 presents the heterogeneity results across companies' ownership, scale, and technological types. We first divide the sample by shareholder ownership as shown in columns (1) and (2). The effects of financing constraints are found to be persistently significant on private rather than state-owned companies. Intuitively, state-owned firms can avoid losing out due to climate change through state aid and compensation, as well as low-interest loans and guarantees from state-owned banks. This semimandated and market-driven pattern helps companies hedge for catastrophe risk. Relatively speaking, private enterprises might need to rely on market financing, which could be even more challenging under unstable climate conditions.

TABLE 2 Effects of temperature fluctuations on financing constraints.

Dependent variable	WW (1)	(2)	(3)	(4)	(5)	KZ (6)
Temp	0.3870*	0.5998**	4.5462**	3.4562***	3.4562***	0.3693***
	(0.2070)	(0.2496)	(1.8321)	(0.9506)	(0.9506)	(0.0869)
Size		0.3496***	0.7933***	0.4420*	0.4420*	−0.1079*
		(0.1019)	(0.2422)	(0.2496)	(0.2496)	(0.0630)
Lev		−0.0051***	−0.0029	−0.0043	−0.0043	0.0016*
		(0.0019)	(0.0022)	(0.0028)	(0.0028)	(0.0009)
Roa		−0.433	−0.2995	−0.3075	−0.3075	−1.6663**
		(0.4937)	(0.5489)	(0.5012)	(0.5012)	(0.7212)
B/M ratio		−2.2688***	−3.0005***	−1.5077**	−1.5077**	−1.8831***
		(0.5882)	(0.7901)	(0.6388)	(0.6388)	(0.1358)
Growth		−0.3424	−0.4981	−0.5151	−0.5151	−0.5223***
		(0.3883)	(0.4438)	(0.4492)	(0.4492)	(0.0483)
PPE		0.1491	−0.4998	−0.2875	−0.2875	−1.0138***
		(0.5281)	(1.0126)	(1.0352)	(1.0352)	(0.3282)
OCF		−2.9155***	−0.9543	−1.2855	−1.2855	−8.6218***
		(1.0227)	(1.1769)	(1.1965)	(1.1965)	(0.3003)
Board		−0.129	0.3278	0.464	0.464	−0.2439
		(0.0800)	(1.3609)	(1.3307)	(1.3307)	(0.1880)
Dual		−0.0899	−0.065	−0.1075	−0.1075	−0.1237
		(0.1371)	(0.0789)	(0.0855)	(0.0855)	(0.0822)
Hold		0.0001	0.0151	0.0147	0.0147	−0.0085***
		(0.0028)	(0.0092)	(0.0094)	(0.0094)	(0.0026)
Firm FE	No	No	Yes	Yes	Yes	Yes
Year FE	No	No	No	Yes	Yes	Yes
Industry FE	No	No	No	No	Yes	Yes
Observations	16420	12160	11883	11883	11883	11045
Goodness of fit	0.000	0.005	0.155	0.168	0.168	0.733

Note: Standard errors shown in parentheses are clustered within cities in all regressions. *FE* refers to the "Fixed Effect." The dependent variables *WW* and *KZ* stand for the indicators of companies' financing constraints proposed by Whited and Wu (2006) and Kaplan and Zingales (1997), correspondingly.

**p* < 0.10; ***p* < 0.05; ****p* < 0.01.

We also delve into potential heterogeneity of temperature fluctuations' impacts across firms, focusing on their varying scales, as measured by sales revenue. To discern such discrepancies, we segregate our sample based on whether a firm surpasses the median sales value, thus assembling a "Large Scale" group and a "Small Scale" group. The results in columns (3) and (4) show that large companies have much greater market power and can withstand

TABLE 3 Heterogeneity across companies' ownership, scale, and technology types.

Dependent variable	*WW*					
	(1)	(2)	(3)	(4)	(5)	(6)
Categories	SOE	Non-SOE	Large Scale	Small Scale	High-tech	Low-tech
Temp	2.4957	3.5336***	−2.4417	3.6539***	−0.5331***	3.9078***
	(2.2076)	(1.0702)	(2.2421)	(1.0205)	(0.1502)	(1.1976)
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Industry FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	546	11,309	723	11,134	890	10,993
Goodness of fit	0.346	0.170	0.149	0.171	0.827	0.170

Note: Standard errors shown in parentheses are clustered within cities in all regressions. The dependent variable *WW* stands for the indicators of companies' financing constraints proposed by Whited and Wu (2006). *FE* refers to the "Fixed Effect." "SOE" and "Non-SOE" refer to state-owned and non-state-owned enterprises, respectively. "Large Scale" refers to companies having above-median assets. "High-tech" involves medicine, aviation and aerospace, information chemicals, and information and communications technology sectors following China's NBS documents. The full results with control variable estimations are available upon request.

*p < 0.10; **p < 0.05; ***p < 0.01.

the shock of temperature fluctuations. This can be attributed to their adeptness in judicious distribution of commodity stockpiles across numerous machines and the seamless operation of their in-stock equipment. Furthermore, it is noteworthy that companies of significant size usually have a wider range of financial instruments and strategic avenues at their disposal, including the issuance of bonds or equity, which allows them to mitigate financing constraints. In stark contrast, diminutive establishments often struggle with inadequacies in their financial reserves to cope with such volatility. As a result, they can find themselves reliant on conventional bank loans or other relatively limited means of financing, which can be even more challenging amid heightened uncertainties arising from temperature fluctuations.

Columns (5) and (6) compare subsets of different technological types whose classification criteria are derived from documents of the National Bureau of Statistics of China. The results indicate that the financing constraints of low-tech companies are significantly exacerbated, while high-tech companies not only internally absorb the impact but also convert it, consistently with the findings of Zhang et al. (2018). A possible explanation is that companies with advanced and high technology can make better use of the opportunities behind the crisis. In other words, temperature fluctuations reshape market structures and squeeze out the market share of low-tech companies. As the old saying goes, "fortune favors prepared minds." High-tech companies could seize the chance and capture more market share.

On the other hand, due to the large variability of temperature exposures and the sensitivity and resilience of the equipment to temperature, the impact of temperature fluctuations on companies' financing constraints and adaptability can vary considerably in different sectors. Thus, we investigate which sectors are most affected by temperature fluctuations, by jointly defining Equation (2) for the main sectors.

Figure 1 shows the point estimates and the corresponding 95% confidence intervals of the estimated coefficients for the different sectors, insinuating significant heterogeneity in the effects of temperature fluctuations on financing constraints. Notably, our findings underscore significant climatic sensitivity primarily within the mining, manufacturing, transportation, storage, postal services and real estate sectors. These sectors' predominant operational activities transpire outdoors, as evidenced by the extraction of mineral resources through subterranean or

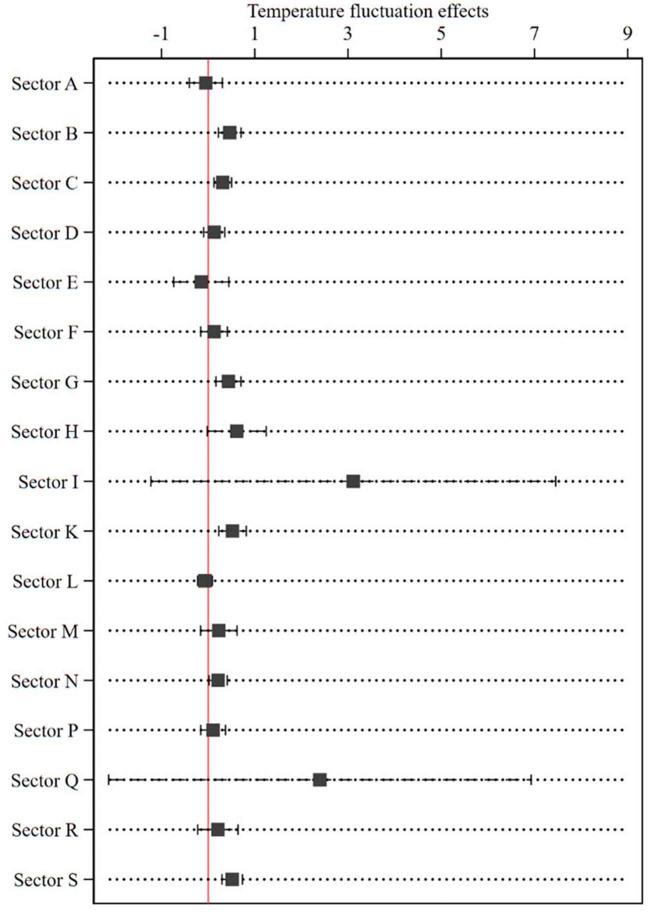

FIGURE 1 Distribution of estimated effect of companies' financing constraints for main economic sectors. The above illustration reveals the cumulative effect of temperature fluctuations on companies' financing constraints. The dashed lines correspond to 95% confidence intervals of the estimated coefficients for the different sectors labeled A–S: Agriculture, forestry, animal husbandry, and fishery (A); Mining (B); Manufacturing (C); Electricity, heat, gas and water production and supply (D); Construction (E); Wholesale and retail (F); Transportation, storage and postal services (G); Accommodation and catering (H); Information transmission, software and information technology services (I); Real estate (K); Leasing and business services (L); Scientific research and technology services (M); Water conservancy, environment and public facilities management (N); Education (P); Health and social work (Q); Culture, sports and entertainment (R); Comprehensive (S). [Color figure can be viewed at wileyonlinelibrary.com]

open-cast methods, rendering them directly responsive to climatic adversities. Temperature fluctuations can potentially disrupt mining efforts.

Manufacturing processes, marked by intensive mechanical and equipment operations, exhibit increased sensitivity to temperature shifts. Rapid temperature changes may precipitate equipment malfunctions, production interruptions, and quality issues, thereby inflating production costs and jeopardizing market competitiveness. Warehousing requires maintaining optimal temperature and humidity conditions to protect stored goods from deterioration. Temperature oscillations can disrupt warehousing environments, affecting both product quality and storage duration.

The real estate sector is still subject to climatic influences, which mainly affect the property construction and maintenance. Extreme temperatures can trigger construction delays, material deterioration, and housing infrastructure failures. These contingencies can escalate project costs and delay sales or leasing transactions. In contrast, the transportation sector seems more resilient to temperature volatility. Plausible explication lies in the sector's ability to bolster infrastructural resilience against climatic adversities. This may include repairing and fortifying transportation facilities such as roads and bridges, rendering them more impervious to natural calamities. Such proactive measures serve to mitigate the risk of transportation disruption, uphold supply chain stability, and curtail the deleterious effects on enterprises from transportation disruptions (Chen & Yang, 2019). In summary, the results in Table 3 highlight that traditional labor-intensive economic sectors are more prone to adverse effects from temperature fluctuations.

3.3 | Regional ex ante adaptation

We have verified that higher temperature fluctuations are associated with a higher level of financing constraints, everything else remaining constant. In this section, we investigate whether ex-ante adaptation has been undertaken to cancel out the negative effects of rising temperature fluctuations. For this, we focus on regions with different levels of intense climatic fluctuations. It is speculated that companies in regions exposed to high temperature fluctuations for an indefinite period may take steps to prepare for the changes that could occur in the coming years and decades. For example, their risk management could call for allocation of supply chains, avoiding those suppliers who are highly exposed to abnormal temperature fluctuations; they may introduce assistance of specialized climate modelers, who could highlight what parts of the business are vulnerable and what types of outbreaks are most likely to occur in different temperature, humidity, or rainfall patterns; they should also buy more durable equipment of higher quality, while the manpower could operate flexibly by allocating time in unpredictable weather conditions (Kahn, 2016; McLaren & Markusson, 2020).

In practice, we construct sets of weather variables through interacting *Temp* and dummies for geographic indicators in accordance with the "Huai River–Qin Mountains boundary" and whether they have "above-median Nino days." Specifically, the southern part of China is considered to have rapid temperature fluctuations and frequent cooling and heating alternations, and the Huai River–Qin Mountains boundary is exactly the natural line between the northern and southern parts of China. Besides, the more days with the Nino phenomenon in a year, the more pronounced the climate variation.

The columns of Table 4 collectively suggest a consistent trend: the interaction term involving the geographic dummy and *Temp* has a statistically significant negative coefficient at least at the 5% level. At the same time, the coefficients pertaining to *Temp* itself remain positive. This implies that enterprises situated in regions characterized by strong temperature fluctuations have proactively embraced measures to address the climate change challenge and offset its deleterious ramifications. This is particular contrast to their counterparts in regions marked by inherently lower temperature variability. A plausible explanation for this phenomenon unfolds. Foremost, the protracted exposure to elevated temperature oscillations endows these enterprises with the capacity to anticipate and internalize latent operational impacts. This catalyzes the uptake of preventive measures, exemplified by strategic supply chain adjustments to steer clear of collaborations with suppliers prone to climatic oscillations. Furthermore, the integration of sound risk management practices becomes a pivotal facet of their modus operandi. Second, the adept engagement of specialized climatic expertise enhances the understanding of climatic dynamics. Collaborative endeavors with climate modelers furnish these enterprises with a deep understanding of intricate vulnerabilities and latent disruptions induced by temperature, humidity, and precipitation patterns. Finally, the enterprises' commitment to invest in better-quality, enduring equipment signals recognition of the criticality of fortifying against temperature fluctuations. This strategic investment enhances operational continuity, thereby minimizing the sensitivity of their production processes to unforeseen climatic shifts (Sautner et al., 2023).

TABLE 4 Effect of temperature fluctuations on financing constraints in regions of high-temperature fluctuations.

Dependent variable	*WW*			
High-temperature fluctuation regions	Huai River–Qin Mountains boundary		Above-median Nino days	
Temp		2.6895***		3.3335***
		(0.6931)		(0.9905)
Effect in high - temperature fluctuation regions	1.1113	4.3756	0.311	0.0419
	(3.1954)	(3.4673)	(0.3015)	(0.2766)
Temp × *"high - temperature fluctuations" region dummy*	0.7989	−0.9592	−0.3530**	−0.3161**
	(0.8909)	(1.0276)	(0.1617)	(0.1513)
Firm FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Industry FE	Yes	Yes	Yes	Yes
Observations	11,883	11,883	10,508	10,508
Goodness of fit	0.168	0.168	0.183	0.183

Note: Standard errors shown in parentheses are clustered within cities in all regressions. The dependent variable *WW* stands for the indicators of companies' financing constraints proposed by Whited and Wu (2006). *FE* refers to the "Fixed Effect." *Huai River–Qin Mountains boundary* is the natural line between the northern and southern parts of China. *Nino days* are defined as the number of days of sudden climate change in a given year. The full results with control variable estimations are available upon request. Also,
*p < 0.10; **p < 0.05; ***p < 0.01.

4 | ECONOMIC CHANNELS

4.1 | Labor impairment

The findings reveal that temperature fluctuations bring into play adverse effects on corporate financing constraints. To achieve a deeper understanding of corporate responses, we investigate whether temperature volatility also impacts labor productivity and causes labor impairment (Krueger et al., 2020; Park et al., 2021). Rising temperatures can directly affect the operational performance and labor productivity, particularly in sectors that require outdoor work or lack adequate air conditioning infrastructure. Given a decline in productivity, firms may find it imperative to increase their workforce to compensate for the output reduction (Somanathan et al., 2021). At the same time, companies are forced to remunerate the expanded workforce with wages and benefits (Pankratz et al., 2023). Moreover, decline in labor productivity in a specific region can cause the labor demand to soar, consequently driving up wages (Émilien Gouin-Bonenfant, 2022). Our observations are directed at three distinct variables closely related to these considerations: a firm's labor productivity, wage levels, and employment figures. Labor productivity is linked to a measure of output per worker, signifying the value created by each worker for the firm.

Table 5 presents the outcomes of the effect of temperature on labor productivity and labor input. Columns (1) and (2) reveal that as temperature volatility rises, a statistically significant decline of at least 1% in firms' labor productivity is observed. In addition, considering the $Temp_{t-1}$ coefficient, the lagged temperature variability also has a significant effect on future labor productivity. This highlights that the intensification of temperature fluctuations can hinder workers' efficiency, increasing the risk of labor impairment and, consequently, reducing productivity (Somanathan et al., 2021). This, in turn, can affect a firm's revenues and profits, thereby reducing its ability to

TABLE 5 Potential transmission to labor impairment.

Dependent variable	ln(Revenues/Employment$_{-1}$) (1)	(2)	ln(Employment) (3)	(4)	ln(Wages) (5)	(6)
$Temp_t$	−0.2317***		0.024		−0.0928	
	(0.0713)		(0.0415)		(0.0972)	
$Temp_{t-1}$		−0.2478***		0.0965**		0.2453**
		(0.089)		(0.0473)		(0.1104)
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Industry FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	9361	8562	9368	8565	9358	8555
Goodness of fit	0.836	0.854	0.905	0.918	0.742	0.758

Note: Reports of channel tests of temperature fluctuation on (log-scaled) unit labor output (*Revenues/Employment*$_{-1}$, columns (1)–(2)), the number of employees (columns (3)–(4)), and labor wage (columns (5)–(6)). Standard errors shown in parentheses are clustered within cities in all regressions. *FE* refers to the "Fixed Effect." The full results with control variable estimations are available upon request.

*$p < 0.10$; **$p < 0.05$; ***$p < 0.01$.

service its debt obligations. The results in columns (3) and (4) suggest that the increase in employment figures becomes evident after a fiscal year has passed rather than immediately. Based on production inventory or turnover time, the gap resulting from reduced productivity may only become apparent in the later stages of the fiscal year, delaying corporate response, as observed in Barrot and Sauvagnat (2016).

In light of the aforementioned findings, we argue that to compensate for the decline in productivity, firms may choose to hire additional employees later or work overtime to fulfill the same workload. However, increased labor inflow can lead to more labor costs. If companies are unable to adjust the prices of their products or services in a timely manner, their profitability can be at risk. This also weakens the financing and repayment capacity of the business. Climate-induced temperature fluctuations could cause wage increases, such as due to the need to provide high-temperature allowances or employees demanding higher compensation due to increasingly discomforting working environments (LoPalo, 2023). This claim is validated in columns (5) and (6), where temperature volatility is associated with wage hikes at the statistically significant 5% level. On average, a 1% increase in temperature variability corresponds to a 0.2453% rise in the wages paid by the companies. However, increased wages squeeze the companies' profit margins, reducing both its financing and repayment capability. At the regional level, a general decline in labor productivity can cause an upsurge in labor demand for the entire region, thereby driving up wages. This indirectly exacerbates the firm's financing constraints, as illustrated by the interconnected results.

Contrary to previous research, our findings do not support the notion of declining labor demand accompanied by increased capital investment. However, discussions around this disparity contribute to a deeper understanding of the specific contexts of emerging economies and developing countries. First, China, as one of the most populous countries boasts a very large labor market. Faced with declining labor efficiency due to climate change, enterprises find it relatively feasible to offset production losses by increasing the amount of labor. Despite potentially increased labor costs, in labor-abundant environments this strategy remains practical and more feasible than an immediate shift towards costly automation or technological solutions. Even in economically developed eastern provinces, companies can readily tap into migrant workers from less developed regions (Li et al., 2012). Second, a significant portion of the Chinese economy still comprises labor-intensive industries, particularly within manufacturing and agriculture. These exhibit high sensitivity to climate change while heavily relying on human labor for production tasks; therefore, increasing labor to sustain or enhance production serves as a direct and pragmatic strategy (Chen & Yang, 2019). Furthermore, the Chinese government sees employment as key to maintaining social stability by strengthening the social security system and protecting labor right via safeguarding low-income and vulnerable groups and preventing social injustice due to wage cuts. Measures to this end include adjusting minimum wage standards and improving work injury benefits and unemployment insurance, particularly in the face of economic recessionary pressures or external shocks such as climate fluctuations (Yu et al., 2023). In such cases, the government alleviates the negative effects impacts of climate variations by supporting business operations and creating employment opportunities. Responding to climate-related adverse working conditions for outdoor laborers, businesses are addressing the need for employment stability by providing higher wages, more benefits and protection to motivate workers who endure arduous conditions (Zhao et al., 2016). Finally, when climate fluctuations affect production, the prices of basic goods, including food, rise, increasing also the cost of living. To sustain livelihood, labor unions within companies demand wage increases, which are supported by both the companies and the government in the context of maintaining social stability and harmony (Nam, 2021).

4.2 | Revenue instability

Despite firms adopting strategies such as increased labor force and wages to mitigate temperature fluctuations, they prove insufficient to offset the impact of productivity decline. Additionally, temperature volatility disrupts the regularity of consumer demand patterns. For example, excessive heat during winter can lead to reduced demand for certain heating equipment, resulting in shrinking income and decreased corporate cash flow. This, in turn, affects the company's debt servicing capability, subsequently increasing the financing costs or limiting the access to available funding.

Table 6 presents the connection between temperature fluctuations and corporate revenue instability. As shown in columns (1) and (2), for every 1% increase in temperature volatility, there is a 0.0778% reduction in

TABLE 6 Potential transmission to revenue instability.

Dependent variable	$ln(Revenues/Assets_{-1})$		$ln(Insurance\ Liability/Assets_{-1})$		$ln(SAF)$		$ln(GS)$	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
$Temp_t$	−0.0778***		0.0015**		0.0275		0.1096	
	(0.0293)		(0.0007)		(0.0458)		(0.1296)	
$Temp_{t-1}$		−0.1301***		0.0017**		0.0674*		0.2281**
		(0.0484)		(0.0008)		(0.0379)		(0.0972)
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Industry FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	15,616	14,053	10,770	9210	15,462	13,904	15,470	13,912
Goodness of fit	0.791	0.805	0.2	0.233	0.96	0.962	0.886	0.893

Note: Reports of channel tests of temperature fluctuation on (log-scaled) revenues as a share of assets ($Revenues/Assets_{-1}$, columns (1)–(2)), net amount of insurance liability reserve withdrawn as a share of assets ($Insurance\ Liability/Assets_{-1}$, columns (3)–(4)), expenses for sales, administration, and finance (*SAF*, columns (5)–(6)), and cost of goods sold (*GS*, columns (7)–(8)). Standard errors shown in parentheses are clustered within cities in all regressions. *FE* refers to the "Fixed Effect." The full results with control variable estimations are available upon request.

*p < 0.10; **p < 0.05; ***p < 0.01.

revenue per unit of assets, and this significance persists in the lagged term. Previous research suggests that temperature volatility increases certain production input costs, such as cooling or maintenance expenses (Pankratz et al., 2023). And, with an upswing in climate-related damages, companies may end up making more frequent insurance claims, consequently thus leading to a significant increase in premiums, as noted in columns (3) and (4).

Columns (5)–(8) provide clarity on specific costs. Temperature fluctuations lead to a positive change in sales, general expenses, administrative costs, and cost of goods sold, although the overall coefficients may not be very significant. Intuitively, due to the influence of climate change on the pre-existing market, companies may need to redesign or adjust their product lines, seek out or develop new markets, and allocate capital for novel marketing strategies, advertising campaigns, and promotional activities (Indaco & Ortega, 2020). In addition, sustained temperature volatility prompts firms to upgrade their old cooling or heating systems, or introduce more advanced and energy-efficient alternatives. Constant temperature variations lead to the need for specialized training of employees; companies must also acquire additional emergency supplies and equipment, as well as train staff to handle unforeseen health events. Furthermore, the conclusions drawn from Schlenker and Roberts (2009) align with the estimation results from GS, suggesting that extreme weather events may lead to shortages of essential resources (such as water, specific crops, or minerals) or reduced production efficiency in upstream factories, thus increasing the prices of intermediate products. If local access to necessary raw materials is impeded, companies may have to import from other regions or countries with potentially higher transportation and tariff costs. Considering these increased costs alongside reduced revenue, companies may experience cash flow challenges, resulting in tightening financing constraints.

4.3 | Weaken investor confidence

With temperature volatility and accompanying extreme weather events, both the productivity and operational performance of companies face varying degrees of challenges. Investors might become more attentive to industries

TABLE 7 Potential transmission to investor confidence.

Dependent variable	ln(*Interest Expenses/Debt*) (1)	(2)	ln(*Unsecured Debt/Debt*) (3)	(4)	*P/E ratio* (5)	(6)	*P/B ratio* (7)	(8)
Temp	0.0014**		0.0199		−0.1143		−0.0564	
	(0.0007)		(0.024)		(0.0919)		(0.0491)	
$Temp_{t-1}$		0.0019**		0.0422***		−0.1993**		−0.0398
		(0.0009)		(0.0148)		(0.0939)		(0.0527)
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Industry FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	8586	7439	13,726	12,322	8298	7558	9323	8533
Goodness of fit	0.461	0.483	0.66	0.674	0.799	0.809	0.86	0.873

Note: Reports of channel tests of temperature fluctuation on interest expenses as a share of debt (*Interest Expenses/Debt*, columns (1)–(2)), ratio of unsecured debt to total (*Unsecured Debt/Debt*, columns (3)–(4)), price-to-earnings ratio (*P/E ratio*, columns (5)–(6)), and price-to-book ratio (*P/B ratio*, columns (7)–(8)). Standard errors shown in parentheses are clustered within cities in all regressions. *FE* refers to the “Fixed Effect.” The full results with control variable estimations are available upon request.

**p* < 0.10; ***p* < 0.05; ****p* < 0.01.

or companies sensitive to climate change, thereby affecting the companies' future profit projections and market valuations (Krueger et al., 2020).

Table 7 illustrates the link between temperature fluctuations and corporate revenue instability. Columns (1) and (2) show that temperature fluctuations have a significant impact on increasing a company's average borrowing cost, which remains pronounced in the lagged term. Increased default risk for businesses due to temperature-induced production instability, supply chain disruptions, or sales downturns could be caused. For higher-risk borrowers, banks and other financial institutions may demand higher risk premiums, thereby raising the borrowing costs for the company (Javadi & Masum, 2021).

In columns (3) and (4), it is evident that the ratio of unsecured debt to total debt experiences a decline after the passage of a fiscal year. As climate change places the company's financial standing under scrutiny, it may find it more challenging to secure financing from financial institutions. Consequently, it may increasingly turn to unsecured financing, which could result in higher financing costs (Krueger et al., 2020).

Finally, columns (5) through (8) suggest that in regions generally affected by temperature fluctuations, both the price-to-earnings ratio (*P/E ratio*) and price-to-book ratio (*P/B ratio*) of companies commonly fall. Possible explanations are as follows. First, increased temperature uncertainty and risk faced by companies may reduce investors' optimism about future profit expectations (Bolton & Kacperczyk, 2021). Second, companies may be forced to revise downwards their profit projections to account for potential business losses arising from climate change. A third explanation is reduced long-term investments, which do not favor the health of their balance sheets. Furthermore, temperature volatility can lead to impairment or devaluation of a company's fixed assets, inventory, or other critical assets, resulting in balance sheet deterioration (Fiedler et al., 2021). However, given the efficient market hypothesis, based on the significance and magnitude of the estimated coefficients in Table 7, we believe that investors do not possess sufficient information to fully comprehend the impact of temperature fluctuations on the company.

In conclusion, deteriorating investor and lender confidence in companies could lead to higher rates or discounts when issuing bonds or stocks. The decrease in P/E and P/B ratios implies a reduction in the market value of these stocks, limiting the amount companies can borrow and their ability to secure financing based on collateral.

5 | CONCLUDING DISCUSSION AND POLICY

This paper contributes to the evolving literature on the impact of climate change on financial risk. It constitutes a key study of estimated causal effects of temperature fluctuations on corporate financing constraints. Our research underscores the imperative for senior management teams within firms to prudently factor in the financing constraints arising from climate change and temperature fluctuations when formulating investment and production strategies.

First, we empirically establish a positive correlation between temperature fluctuations and the severity of corporate financing constraints. Specifically, we observe that each 1% increase in the annual temperature standard deviation corresponds to a 3.5% worsening of financing constraints. By 2030, the losses for publicly listed companies due to temperature fluctuations are expected to contribute to 29% exacerbation of financing constraints, equivalent to about 8.7% of their annual sales revenue. Second, there exist significant variations in the sensitivity and adaptive capacity to temperature fluctuations across different enterprises and industries. State-owned or large-scale enterprises typically have more resources and risk diversification mechanisms, giving them greater resilience against these adverse effects. At the same time, high-tech enterprises may leverage advanced adaptive technologies to potentially mitigate the negative repercussions of high-temperature fluctuations. In cases where these fluctuations emerge as exogenous shocks, the financing constraints of private and small-scale enterprises demonstrably deteriorate. Moreover, across the spectrum of economic sectors, industries characterized by outdoor operations or labor-intensive processes, such as mining, manufacturing, transportation, and so on, are notably susceptible to such adverse effects. Nevertheless, companies with enhanced adaptive capacities in environments with increased climate fluctuation can effectively mitigate the risks associated with weather events and temperature variations, thus overcoming the extremities of these shocks.

To gain deeper insights into the economic pathways underpinning this impact, we conducted a series of supplementary analyses. Temperature fluctuations exhibit significant adverse influence on firms' labor productivity. In response, companies tend to expand their workforce and raise wages within a fiscal year, aiming to offset the detrimental effects. Moreover, temperature volatility markedly triggers a decline in companies' revenue, in line with the observed decrease in labor productivity. Companies exhibit noticeable conduct by significantly increasing their insurance expenditures, possibly as a way to mitigate the risks arising from temperature fluctuations. Concurrently, this phenomenon causes noteworthy increases in companies' sales costs, as well as financial, managerial, and administrative expenses within the fiscal year. Faced with declining labor productivity and dwindling revenue, the default risk for enterprises substantially escalates, thereby elevating their current and future borrowing costs. Ultimately, increased temperature uncertainty and associated risks companies encounter can dampen investors' sanguine expectations of their future profits. This, in turn, accelerates the decline of P/E and P/B ratios. Nonetheless, we posit that investors lack sufficient information to comprehend the full extent of companies' susceptibility to temperature fluctuations.

The conclusions of our study offer important insights for policymakers. First, there is a compelling need to establish a mechanism for financing support aimed at mitigating the risks associated with fluctuations in temperature. Given the empirical evidence pointing to a positive correlation between temperature oscillations and the deteriorating financial health of enterprises, it is imperative that a dedicated financing mechanism be instituted jointly by governmental bodies and financial institutions. The primary goal of this would be to ameliorate the negative effects of climate-related risks on enterprise funding. On the one hand, the provision of concessional loans entails extending loans at reduced interest rates to companies particularly susceptible to the impacts of climate shifts. On the other hand, the development of risk guarantees involves crafting financial instruments capable of serving as safeguards, guaranteeing a predetermined percentage of the loans.

Second, the government should actively foster research and training initiatives focused on enhancing industry adaptability. Recognizing the divergent sensitivities and capacities of various sectors and businesses in responding to temperature fluctuations, it is imperative that the government allocates resources to promote industry-specific research and disseminate best practices. Targeted assistance measures can be outlined as follows: first, establishment of tailored training programs with emphasis on equipping small and private businesses, which tend to be more vulnerable to climate perturbations, with the necessary skills to face such challenges; second, provision of subsidies to bolster the capacity of these businesses to adapt to temperature shifts; third, provision of specialized technical support, particularly for labor-intensive or outdoor sectors including mining, manufacturing, transportation, warehousing, postal services, and real estate.

Moreover, it is imperative to cultivate an environment conducive to green finance policies as a means of mitigating the impacts of climate volatility on businesses. In this context, envisaged policies may include initiatives such as facilitating low-interest loans and implementing incentive measures to induce financial institutions to extend more favorable financing terms to companies that demonstrate exemplary performance in mitigating climate-related risks. The are several potential advantages of such policies. On the one hand, enterprises will benefit from lower borrowing costs, enhancing their competitiveness and long-term viability. On the other hand, such a framework will incentivize businesses to adopt green technologies and sustainable operational practices. In addition, the carbon emissions trading policy is seen as assisting enterprises in finding a balance between addressing climate risks and achieving their own sustainable operations (Wu, 2022; Wu & Wang, 2022).

In closing, we underscore the importance of enhancing the disclosure of climate risk information. Empirical studies have highlighted the limited information available to investors to gauge the ramifications of temperature fluctuations on corporate entities. To address this gap, proactive measures are essential. Such could entail the promulgation of legislation mandating companies to incorporate climate change-related risks and their potential impacts within their annual or quarterly reports. Formulating standardized metrics and frameworks for climate risk disclosure is also vital to ensure transparency and comparability across diverse industries. We also note that our study focuses on investigating the effect of temperature volatility on corporate financing constraints. However, climate change risks may affect firms' financial conditions also through other channels, such as capital costs (e.g., see Lee et al., 2021). Our future research will explore how climate change affects firms' financing conditions and capital allocation via influencing their risk perception and profit expectations, thus contributing to a fuller understanding of multidimensional climate risk effects. Finally, due to data limitations, the current study does not discern to what extent climate factors affect financing constraints due to changes in firms' credit risks. Clarifying this requires further refinement of the transmission mechanisms of climate change impacts on both borrowers and lenders.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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