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Climate Change and Corporate Operating Risk: Evidence from China

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Abstract: Climate change undermines progress toward sustainable development goals. This paper uses a two-way fixed-effects model to examine whether and how climate change affects firms' operating risk from the perspective of heat exposure. The sample comprises 29,128 firm-year observations of Chinese listed firms for the period 2010 to 2021. The main results are as follows: (1) Increased heat exposure leads to higher corporate operating risk. (2) The impact of heat exposure on operating risk varies on firm characteristics. Specifically, manufacturing firms, small firms, and firms located in less developed cities are more susceptible to heat exposure. (3) The mechanism analysis shows that heat exposure exacerbates operating risk by affecting operating income and inventory management. This paper contributes to prior research on the economic impacts of climate change. In the context of climate change, these findings are of significant value in raising corporate awareness of climate change and motivating corporate involvement in low-carbon initiatives that contribute to climate adaptation and mitigation efforts.

Keywords: climate change; heat exposure; operating risk; sustainable development

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1. Introduction

With the increased frequency of climate change events, such as extreme temperatures, heat waves, heavy precipitation, droughts, and other climatic events, there is an increase in the uncertainty of enterprise development which poses a severe threat to the sustainable development of society. The Sixth Assessment Report (AR6) of the IPCC points out that the global surface temperature was 1.09 °C higher in 2011–2020 than in 1850–1900, and the 1.5 °C global warming threshold is very likely to be reached or exceeded in the near future. Given the frequent occurrence of extreme temperature events and their serious consequences on humanity and society, such as productivity, firm performance, and economic growth [1–5], it is therefore crucial to comprehend their effects on businesses as they play a major role in society.

There is an increasing focus on the impact of climate change on businesses due to growing concern about environmental and climate issues. Existing research demonstrates that climate change negatively affects labor and capital productivity, leading to higher labor costs and exacerbating capital depreciation [1,2]. As a result, both total factor productivity (TFP) and output are negatively affected [3]. Climate change also affects business operations, resulting in higher overhead costs, lower revenues, lower operating income, and poorer financial performance [4,5]. As climate risk increases, firms increase their cash holdings out of precautionary concerns [6,7]. Further, the heightened awareness of climate

change risks among financial market participants has led to a rise in the cost of capital [8,9]. Climate change results in a loss of firm value and greater operational uncertainty. The impact of climate change on business may further affect operating risk. According to the existing literature, the influencing factors of operating risk can be categorized into internal and external factors. From the internal perspective, governance levels, ownership structures, equity concentration, and managerial experience have an impact on operating risk [10,11]. From the external perspective, the corporate tax system, the carbon emissions trading market, and bank regulation affect operating risk [12–14]. However, the relationship between environmental issues and operating risk is complex. On the one hand, environmental issues, such as air pollution and daily temperature fluctuations, lead to heightened negative emotions and business uncertainty. This, in turn, may prompt firms to adopt more conservative strategies and reduce risk-taking [15,16]. Conversely, environmental issues may also drive firms to engage in risky behaviors in order to mitigate the value destruction caused by environmental issues [17,18]. Ultimately, these shifts in risk preferences will lead to changes in corporate operating risk.

In summary, the impact of environmental issues on operating risk remains unclear. To test the two opposing views of the impact of environmental problems on business, this paper examines the impact of climate change on operating risk. This paper measures climate change using the number of high-temperature days per year at the company's registered city to measure heat exposure and using the Zscore proposed by Altman [19] to measure operating risk. Based on data from China A-share non-financial listed firms from 2010 to 2021, this paper finds that heat exposure led to higher operating risks. Moreover, our research demonstrates that the extent of this impact varies with firm size, temperature sensitivity, and local economic development.

The main contributions of this paper are as follows. First, this paper examines the economic impacts of climate change on business operation from the perspective of operating risk, which plays a vital role in business sustainable development. Previous studies mainly focus on the effects of climate change on corporate production and operation, such as labor productivity and capital depreciation [1,20,21], TFP and output [3], inventory management [22], firm performance [5,23], regulatory risk [8], and investor awareness [5,9]. Thus, as the negative impacts of climate change are not easily hedged, our findings can help firms and market participants to better understand the relevant risks and make better decisions.

Second, this study enriches the research on the influencing factors of operating risk from a climate perspective, contributing to a more comprehensive understanding of the operational environment. Previous studies have analyzed internal factors that influence operating risk from various aspects, including director experience [11], large shareholder diversification [10], and governance reform [24], while overlooking exogenous climatic stressors. The results show that increased heat exposure increases firms' operating risk, which extends the research on the external factors influencing operating risk and helps bridge the gap between climate science and business operations. Third, this paper investigates the mechanism of the impact of climate change on operating risk and finds that heat exposure affects operating risk by impacting firms' revenue and inventory management. As climate change has long-term and multifaceted impacts on firm development, it is important to enhance climate change resilience to achieve sustainable development. The results of the mechanism analysis provide practical solutions for firms to better cope with climate change.

The remaining sections proceed as follows: Section 2 overviews the literature and hypothesis development. Section 3 describes the data and methodology used. The main results are reported in Section 4. Section 5 presents robustness tests, and Section 6 concludes the study.

2. Literature Review and Hypothesis Development

2.1. Theoretical Background

Stakeholder theory suggests that companies not only need to be accountable to shareholders but also need to balance the claims of multiple stakeholders, such as employees, customers, suppliers, and government. The claims or changes of any of these stakeholders may lead to operating risks.

From the perspective of investors, the significant impact of climate change on business performance has raised increased awareness of climate risk among investors [5,9,23]. As a result, investors are demonstrating greater sensitivity to firm-level climate risk, which may prompt them to sell shares in companies with a high climate risk. At the same time, companies are facing increased disclosure requirements in terms of climate risk.

From the perspective of consumers, climate change may lead to increased awareness of environmental, prompting consumers to purchase low-carbon products or products from environmentally friendly companies, thereby affecting the market environment. In addition, due to the heightened awareness of environmental protection, companies that do not take proactive climate action may also face a higher reputational risk.

From the perspective of employees, climate change poses challenges to employee health and safety, such as reduced cognitive ability and productivity due to high temperatures [2], as well as brain drain due to extreme environments, all of which could impact firm operation.

From the perspective of governments, as climate change intensifies, there is an urgent need to take various measures to mitigate climate change, such as strengthening environmental regulations, promoting energy structural transformation, establishing a national carbon emissions market [14], and enhancing corporate climate information disclosure, which will increase the regulatory risk of enterprises and put greater pressure on the legitimacy of corporate operations [8].

In general, climate change affects business operations through multi-dimensional impacts on critical stakeholders. As these stakeholders play a vital role in business, climate-induced changes in their behaviors will further translate into operating risk.

2.2. Influencing Factors of Operating Risk

Existing research on the influencing factors of operating risk can be divided into internal and external dimensions. From the internal perspective, the characteristics of governance and management affect its operating risk. When directors underestimate the cost of distress after experiencing bankruptcy, they tend to take more risky activities, leading to increased operating risk [11]. Moreover, firms with diversified large shareholders have a greater willingness to pursue risky investments, thus resulting in a higher operating risk [10].

Regarding the external factors, banking deregulation has significantly reduced operating risk by easing firms' credit constraints [12]. Some studies investigate the impact of environmental factors on operating risk. Wang et al. [15] find that negative emotions induced by air pollution increase managers' risk aversion and lead to lower risk. Similarly, the decreased production certainty and operational flexibility caused by daily temperature fluctuations significantly impede a firm's risk behavior [16]. On the contrary, Xu et al. [18] provide evidence that managers tend to take more risks to increase profits when climate

risk reduces firm value. Further, the experience of scorching weather encourages firms to adjust their risk toward optimal thresholds [17].

2.3. Climate Change and Operating Risk

Climate change affects production and operation activities. Prior research suggests that increased high temperatures negatively affect labor productivity and working hours, exacerbate capital depreciation [1,20,21], and further negatively affect TFP and output [3,25]. Meanwhile, the emotional and cognitive differences caused by high temperatures may lead to inefficient managerial decisions. Climate policy uncertainty negatively impacts corporate financialization [26]. Heyes and Saberian [27] found that high temperatures lead to more conservative and less rational decisions. Furthermore, climate change risk also impacts firm value and the volatility of stock price, which in turn affects its performance in capital markets [28,29]. To mitigate the adverse shocks from climate change, companies may resort to opportunistic behavior to increase their cash flow, such as tax avoidance practices [30]. Research has shown that an additional day with temperatures above 90 °F led to a 0.097% decrease in the effective tax rate.

Climate change resulted in higher operating and financing costs. High temperatures not only increase a firm's selling and administrative expenses but also negatively affect revenue and firm performance [5,23]. For companies that installed air conditioning to reduce the negative effects of high temperatures on employees, the cooling and production expenses increased accordingly [31]. Dafermos [20] finds that climate change destroys firms' capital and reduces their profitability, which further adversely affects liquidity and increases the probability of default. Griffin [32] examines the impact of high temperatures on the stock market and finds that the stock market reacts negatively to high-temperature events. With the rising climate risk increasing the likelihood of defaulting on loans and share price, capital markets have become increasingly aware of the importance of pricing climate risk. Therefore, firms with environmental problems or climate change risks are subject to higher interest rates from lenders compared to others [8,9], resulting in an elevation of the cost of capital [9,33].

Climate change impacts investors' risk appetite and decision-making. As climate change makes the business environment more complex and volatile, investors pay more attention to climate risk. Retail investors become more aware of climate change after experiencing abnormally high temperatures, so they choose to sell shares of carbon emission-intensive firms, leading to lower stock returns for these firms [34]. Meanwhile, weather conditions have a significant impact on people's moods [35]. As high temperatures rise investor apathy and risk aversion, Cao and Wei [36] find that high temperatures negatively affect stock returns. Specifically, an additional degree increase in temperature leads to a significant decline in stock returns when temperatures are below 15 °F or above 85 °F [37].

As local governments increase environmental regulations and penalties for environmental issues, the regulatory risk also increases [8,38]. Therefore, enterprises tend to increase their investment in environmental protection to participate in environmental governance, leading to decreased production and operational funds [39]. Furthermore, Birindelli and Chiappini [40] find that climate change policies are more likely to have negative impacts on firms than positive ones.

In summary, climate change affects enterprises' production and operation activities, leading to a decline in operational efficiency and an increase in operational uncertainty. The theoretical framework is shown in Figure 1. Based on the above analysis, we propose Hypothesis 1 as follows:

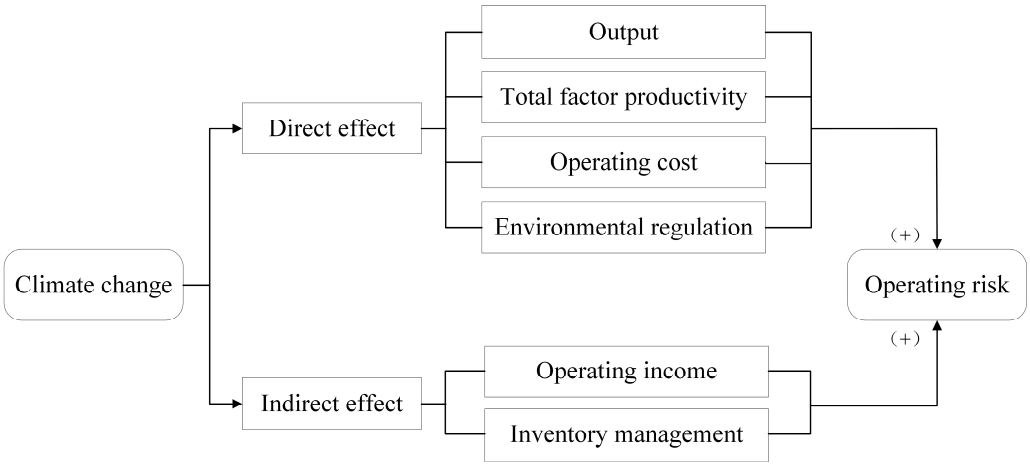


Figure 1. Theoretical framework.

H1. *Firms in areas with a high climate change risk face higher operating risks.*

2.4. Climate Change, Operating Income, and Operating Risk

From the supply side, high temperatures affect both worker efficiency and working time, which in turn affects output [41–44]. As temperature increases, workers' attention, memory, and information process ability are affected, negatively impacting physical and mental work [45]. Seppanen et al. [2] found that work performance peaks at an ambient temperature of 22 °C and declines as the temperature increases, which is in line with the findings of Pilcher et al. [43]. In addition, hot weather hurts salesman's working hours and efficiency, which in turn hurts sales.

From the demand side, high temperatures affect people's psychological perceptions and emotions, impacting their climate change perceptions and economic decisions [34,46]. Furthermore, heightened climate change awareness and environmental consciousness prompt consumers to pay more attention to a firm's environmental performance and purchase products from environmentally friendly companies [47,48]. Hence, companies that do not actively participate in climate change mitigation activities face a heightened risk to their reputation, negatively impacting brand value and consumer loyalty [49].

In general, high temperatures not only affect firms' ability to produce and sell but also affect consumers' purchasing decisions, affecting revenue and operating income. Based on the above analysis, we propose Hypothesis 2 as follows:

H2. *Climate change impacts operating risk by affecting firms' operating income.*

2.5. Climate Change, Inventory Management, and Operating Risk

The operational uncertainty resulting from climate change has led companies to increase investment in inventory to ensure operational stability. As climate change affects regional transportation conditions, the increase in transportation costs may adversely affect production and sales. Li and Li [50] and Shirley and Winston [51] propose that external risks, such as air pollution and rising transportation expenses, encourage firms to increase non-product inventories to secure assets for future requirements. He et al. [22] investigate the impacts of climate risks on firm inventory management using Chinese manufacturing data, and they report that a 1% increase in climate disaster losses leads to a 0.0044% increase in total inventory. Furthermore, the rise in inventory requires extensive financial resources, augmented warehousing costs, and management costs, which ultimately influence the firm's liquidity and operations.

Based on the above analysis, we propose Hypothesis 3 as follows:

H3. *Climate change affects operating risk by influencing inventory management.*

3. Data and Methodology

3.1. Data and Sample Selection

Given that the financial crisis of 2007–2009 had significant effects on both consumer demand and financial markets, this study chose Chinese A-share listed companies from 2010 to 2021 as our research sample to exclude the influence of the financial crisis. The data have been processed as follows:

(1) Excluding financial firms. It is recognized that the primary business of financial firms is capital operations, and their accounting standards differ from those of other industries, which may make the data of financial firms incomparable.

(2) Excluding firms registered in Xinjiang and Tibet. There are significant climate variations in Xinjiang and Tibet due to the complexity of the terrain and the huge area, so meteorological stations may fail to accurately capture the climate conditions exactly.

(3) Excluding ST and *ST firms. The prefixes "ST" (special treatment) and "ST*" (delisting risk warnings) indicate that these firms have operational anomalies and financial stress, and these factors may distort our results.

(4) Excluding firms with an asset–liability ratio greater than 1. An asset–liability ratio greater than 1 indicates that the firm's total liabilities are greater than its total assets, and that the firm's operating condition is not very good, with a high degree of financial risk. Thus, these samples may be masking the real impact of climate-related risks on operating risk for its pre-existing financial instability.

(5) Winsorizing all continuous variables at the 1% and 99% quantile points to exclude the interference of outliers. This study finally obtained 29,128 sets of observations from 4021 listed companies. The company data come from the CSMAR database, the temperature data from the Global Surface Summary of the Day (GSOD), and the regional data from the *Regional Statistical Yearbook*.

3.2. Research Design

To investigate the effect of heat exposure on operating risk, this paper constructs the regression model as Equation (1). $Zscore_{i,t}$ represents the operating risk of firm i in year t. $Temp_{i,t}$ refers to the number of heat exposure days. $Control_{i,t}$ denotes the control variables. In addition, this study includes firm fixed effects $Firm_i$ and year fixed effects $Year_t$ in the model to capture firm- and time-specific factors that may affect the results. Standard errors are all clustered at the firm level.

$$Zscore_{i,t} = \beta_1 + \beta_2\, Temp_{i,t} + \beta_3\, Control_{i,t} + Firm_i + Year_t + \varepsilon_{i,t} \quad (1)$$

3.3. Variables

3.3.1. Dependent Variable

The main measures of operating risk are as follows. (1) Zscore. Altman proposed the Zscore to measure the probability of a company falling into financial crisis [19]. The higher the value of the Zscore, the lower the operating risk and the more stable the business, while lower values indicate a higher level of operating risk. Specifically, Zscore = 1.2 × working capital/total assets + 1.4 × retained earnings/total assets + 3.3 × EBIT/total assets + 0.6 × total owners' equity/total liabilities + 0.999 × revenues/total assets. (2) The volatility of corporate earnings. Some scholars use the standard deviation or range of a certain rolling period to present operating risk, and higher earnings volatility indicates a higher operating risk [52–54]. (3) Cash flow volatility. Researchers use the variance or standard

deviation of net cash flow over a given period to represent the volatility of cash flow, and a higher cash flow volatility indicates a higher operating risk [55]. (4) The probability of enterprise survival in a given period [10]. (5) The market β coefficient, which is an objective measure of the risk a firm faces during the year from an investor's point of view [56].

Specifically, the volatility of corporate earnings is mainly measured based on the earnings in the past three to five years and therefore cannot effectively reflect the level of operating risk of the enterprise in the current year. Cash flow volatility is only measured from the single dimension of cash flow and cannot comprehensively assess the business condition of the firm. The probability of survival is more concerned with the likelihood of delisting than the level of operating risk. The market β coefficient is based on stock market indices and reflects the investor's perceptions rather than actual operating conditions. Thus, after a comprehensive comparison, we believe that Zscore can comprehensively assess the financial situation from the perspectives of asset structure, profitability, and operational capacity. Therefore, referring to previous research [57–60], we choose Zscore to measure operating risk. In addition, to enhance the credibility of the findings, we also use the market β as a proxy measurement for operating risk in the robustness tests. The definitions of the variables are shown in Table 1.

Table 1. Definitions of variables.

Type	Variable Name	Symbol	Definition	Relevant Research
Dependent variables	Operating risk	*Zscore*	The operating risk measured by Zscore	[38,57–60]
Independent variables	Heat exposure	*Temp*	The number of days above the temperature threshold (30 °C)	[5,23,61]
		Temp2	The number of days above the temperature threshold (90%)	
		Temp3	The number of days above the temperature threshold (32 °C)	
Control variables	Leverage	*Lev*	Total liabilities/total assets	[9,23,58,59]
	Ownership concentration	*Own*	Shares held by the top 10 shareholders	
	Return on total assets	*ROA*	Net profits/total assets	
	Board independence	*Ind*	The ration of independent directors	
	Firm age	*Age*	Current year-listing year	
	Firm size	*Size*	Natural logarithm of total assets	
	Book to market	*MB*	Book value/market value	
	Managerial ownership	*Manshare*	The percentage of shares owned by the managers	
	Dual role	*Dual*	Combined title of board chair and CEO, Dual = 1; otherwise, Dual = 0	

3.3.2. Independent Variable

To measure firm-specific heat exposure, we count the number of high-temperature days that exceed the temperature threshold per year in the firm's registration city. Specifically, prior research has proved that productivity peaks at a temperature of 22 °C [2]. Furthermore, the task performance of workers drops at an increasing rate when the ambient temperature exceeds 30 °C [43]. As labor plays an important role in business production and operation, the negative effect on work performance will be further reflected in firm performance. Thus, referring to previous studies, we choose 30 °C as the temperature threshold and count the days when the maximum temperature exceeds this threshold.

In addition, to enhance the robustness of the results, we have replaced the temperature threshold in robustness tests. First, given that individuals and organizations may be

adaptable to regional climatic conditions, the impact of heat exposure may differ according to historical temperature conditions. Referring to the study of Pankratz et al. [5], we first derive the historical temperature distributions from 1970 to 2000 by day of the year and city, and choose the 90th percentile of each day as the temperature threshold. Second, we consider that in recent years, with the intensification of climate change and the increase in the frequency intensity of extreme weather events, the occurrence of high temperatures has become more frequent and intense. As a result, people's adaptation to hot environments may have intensified as their temperature tolerance has increased, with a possible consequent rise in the thresholds for judging high temperatures. Therefore, we choose 32 °C as the threshold for defining high-temperature days.

3.3.3. Control Variables

This study controls for firm characteristics that may affect operating risk from the following aspects. From the perspective of financial performance, climate change has been shown to affect firm performance, which is closely related to operating risk. Hence, we include the rate of net profit on total assets (*ROA*), asset–liability ratio (*Lev*), and book-to-market ratio (*MB*) as control variables. From a governance perspective, since operating risk has been shown to be associated with firm governance, we then select ownership concentration (*Own*), board independence (*Ind*), managerial ownership (*Manshare*), and dual role (*Dual*) as control variables. In addition, firm size and age are closely related to operations and risk management, which may bias the results. Therefore, firm age (*Age*) and firm size (*Size*) are also included as control variables. Table 2 reports the summary statistics of the main variables. The mean *Zscore* is 2.962, which is higher than the safety threshold of *Zscore* (2.675).

Table 2. Descriptive statistics.

Variables	Obs	Mean	Std.Dev.	Min	Max
Zscore	29,128	2.962	2.296	−0.574	13.484
Size	29,128	22.138	1.278	19.930	26.160
Lev	29,128	0.409	0.205	0.049	0.870
ROA	29,128	0.041	0.059	−0.230	0.196
MB	29,128	0.612	0.243	0.116	1.155
Dual	29,128	0.293	0.455	0.000	1.000
Ind	29,128	0.375	0.053	0.333	0.571
Manshare	29,128	0.147	0.203	0.000	0.686
Own	29,128	0.592	0.152	0.235	0.903
Age	29,128	9.427	7.540	0.000	27.000

Notes: (1) T-statistics clustered at the firm level are reported in parentheses; (2) The estimate results for the control variables are omitted due to space limitations.

4. Main Results

4.1. Baseline Regression

Table 3 reports the results of Equation (1). Column (1) present the results of the baseline regression controlling for firm and year fixed effects, and the coefficient of Temp is significantly negative. Column (2) reports the result after controlling for firm characteristic variables and firm and year fixed effects. The results show that the coefficient of *Temp* is −0.002 and significant at the 1% level.

Table 3. Heat exposure and operating risk.

Variables	(1)	(2)	(3)	(4)	(5)
	Zscore	*Zscore*	*Zscore*	*Zscore*	*Zscore*
Temp	−0.003 ***	−0.002 ***	−0.002 ***	−0.002 ***	−0.002 ***
	(−3.618)	(−3.452)	(−3.447)	(−3.450)	(−3.445)
Control	No	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes
Industry FE	No	No	Yes	No	Yes
Province FE	No	No	No	Yes	Yes
Observations	28,674	28,674	28,674	28,674	28,674
R-squared	0.700	0.843	0.843	0.843	0.843

Notes: (1) T-statistics clustered at the firm level are reported in parentheses. (2) Significance at the 1% levels is indicated by ***, (3) The estimate results for the control variables are omitted due to space limitations.

Since a lower Zscore represents a higher operating risk, the result is consistent with Hypothesis 1 that increased heat exposure leads to a higher operating risk. To exclude the bias in the conclusions due to the fluctuation of industry and province characteristics, column (3) further controls industry fixed effects and column (4) controls province fixed effects. The estimation results after controlling firm, year, industry, and province fixed effects are shown in column (5). All results show a significant effect of heat exposure on operating risk.

4.2. Heterogeneity Analysis

4.2.1. Size Heterogeneity

Prior research suggests that the operations of large firms tend to be more stable than those of small firms [52], and firms' life-cycle stages and financing constraints vary significantly by size. Therefore, firm size may moderate the effect of heat exposure on operating risk. We re-estimate Equation (1) by grouping the sample by the median firm size to examine differences in the estimates by firm size. The results are presented in columns (1)–(2) of Table 4. For small firms, the coefficient of *Temp* is −0.003 and significant at the 5% level, while heat exposure has a negligible effect on the operating risk of large firms. A possible explanation is that large firms can cope with heat exposure more effectively due to their mature operational systems and well-developed management systems.

Table 4. Heterogeneity analysis.

Variables	Size		Industry		Location			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Large	Small	Manufacturing	Other	High	Low	High	Low
Temp	−0.000	−0.003 **	−0.002 ***	−0.001 *	−0.001	−0.002 **	−0.001	−0.003 ***
	(−0.994)	(−2.471)	(−3.097)	(−1.652)	(−1.488)	(−2.497)	(−0.971)	(−3.254)
Control	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	14,244	14,021	18,255	10,419	12,814	12,773	12,602	12,852
R-squared	0.906	0.848	0.853	0.819	0.862	0.856	0.875	0.862

Notes: (1) T-statistics clustered at the firm level are reported in parentheses. (2) Significance at the 10%, 5%, and 1% levels is indicated by *, **, and ***, respectively. (3) The estimate results for the control variables are omitted due to space limitations.

4.2.2. Industry Heterogeneity

The negative impact of heat exposure on operating risk may vary across industries. Existing studies pointed out that high temperatures not only affect workers' emotions and performance, but also increase capital depreciation [1,34,42,43,58]. As manufacturing is characterized by high labor demand and significant investments in fixed assets, the effect of heat exposure on operating risk should be more significant for manufacturing firms. We grouped the sample according to whether it belongs to the manufacturing sector and re-estimated Equation (1). The results are shown in columns (3)–(4) of Table 4. We find that the effect of heat exposure on operating risk is significant at the 1% level for manufacturing firms but less significant and weaker in other firms.

4.2.3. Geographic Heterogeneity

Differences in regional development due to infrastructure, institutional policies, and economic conditions may affect a firm's resilience to extreme weather. Based on a sample of firms from 93 countries, Pankratz et al. [5] found that exposure to heat led to a decrease in revenue and operating income [5]. However, Addoum et al. [61] found no significant effect of extreme heat on sales and productivity for US firms. Therefore, the impact of heat exposure on operating risk may vary depending on the city's economic structure or development level where the firm is registered. We grouped the samples according to the median of TIPGDP (Third Industry GDP) and GDP per capital.

The results are shown in columns (5)–(8) of Table 4. It is significant that the impact of heat exposure on operating risk is more pronounced and significant for firms registered in less developed cities, which is in line with the findings of Pankratz et al. [5]. This means that regional differences, such as infrastructure, resources, and transport, help to moderate the impacts of climate change.

4.3. Mechanism Analysis

The results of the baseline regressions indicate that one additional high-temperature day leads to an increase in operating risk. In this section, we further analyze the mechanism of how heat exposure affects operating risk from the perspective of operating income and inventory management. Previous studies suggest that the increase in high temperature exposure negatively affects revenue and operating income [5], and a firm's total inventory is also significantly affected by climate risk [22]. Therefore, we choose the natural logarithm of operating income and net inventory as the mediating variable to explore the impact mechanism. The results are presented in Table 5.

Table 5. Mechanism analysis.

Variables	Operating Income		Total Inventory	
	(1)	(2)	(3)	(4)
	Op	*Zscore*	*Ti*	*Zscore*
Temp	−0.000 *	−0.002 ***	0.001 *	−0.002 ***
	(−1.960)	(−3.350)	(1.808)	(−2.939)
Op		0.168 ***		
		(3.445)		
Ti				−0.368 ***
				(−12.644)

Table 5. *Cont.*

Variables	Operating Income		Total Inventory	
	(1)	(2)	(3)	(4)
	Op	*Zscore*	*Ti*	*Zscore*
Control	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Observations	28,674	28,674	28,305	28,305
R-squared	0.958	0.843	0.874	0.718

Notes: (1) T-statistics clustered at the firm level are reported in parentheses. (2) Significance at the 10%, and 1% levels is indicated by *, and ***, respectively. (3) The estimate results for the control variables are omitted due to space limitations.

Columns (1) and (3) show the results when we examine the effect of heat exposure on the mediating variables. As heat exposure increases, operating income is negatively affected and total inventory also increases. Furthermore, the results shown in columns (2) and (4) indicate that the negative effect of heat exposure on operating income and inventory management further leads to a higher operating risk.

4.4. Further Analysis

4.4.1. The Persistent Effect of Heat Exposure

Since lagged high temperatures significantly affect a firm's production and operation in the current year [5,25], we further examine whether the effect of heat exposure on operating risk is long-lasting. We re-estimate Equation (1) after including the heat exposure variables with one- and two-year lags, and the results are presented in Figure 2. Figure 2a shows the results of including heat exposure in both the preceding year ($t-1$) and the current year (t), while Figure 2b extends the temporal score to a three-year window from year $t-2$ to t. The small bars indicate 95% confidence intervals.

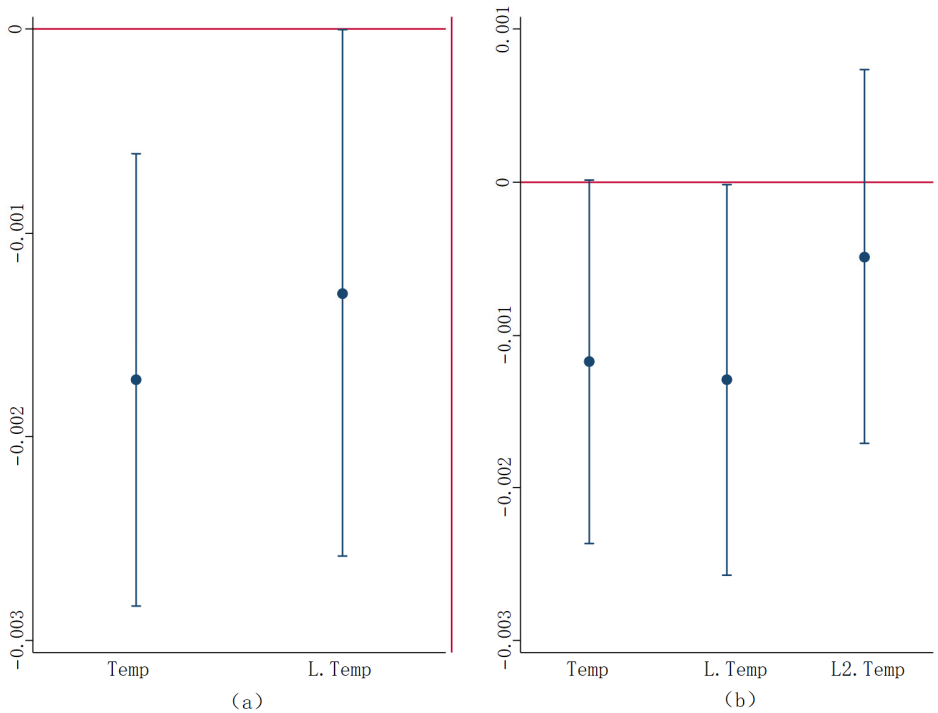


Figure 2. The persistent effect of heat exposure: (**a**) The impact of heat exposure from $t-1$ to t; (**b**) The impact of heat exposure from $t-2$ to t.

Consistent with the baseline regression, the estimated coefficient of *Temp* is significantly negative in Figure 2a; the coefficient of *L.Temp* is −0.001 and significant at the 5% level, indicating that operating risk in the current year is affected by one-year lagged heat exposure. As the estimated results in Figure 2b show, the coefficients of *Temp* and *L.Temp* are both significantly negative. The coefficient of *L2.Temp* is negative but insignificant, indicating that heat exposure in the previous two years before has no significant effect on the operating risk in the current year.

A possible explanation is that after encountering severe heat exposure, firms tend to adopt climate change adaptation behaviors such as improving the working environment and actively fulfilling social responsibility [62,63] to gain the trust and support from stakeholders to mitigate the negative effects of heat exposure. However, as the implementation of climate change adaptation is a long process, the mitigation of operating risk caused by heat exposure takes longer. As a result, the negative effects of heat exposure persist for some time.

4.4.2. Seasonal Temperature

This paper further examines the effect of seasonal temperature on operating risk and plots the estimation results in Figure 3. Consistent with the baseline results that heat exposure negatively affects operating risk, the results show a negative and significant effect of average summer temperature on operating risk. In winter, the estimated coefficient of *Temp* is close to zero and insignificant. A possible explanation is that firms tend to shelter from the negative effect of low temperatures by reducing the extent of outdoor activities and operations.

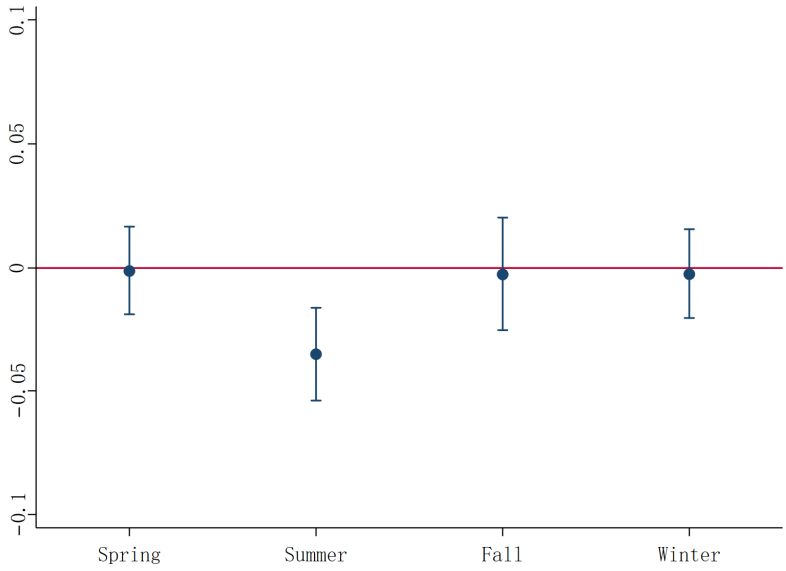


Figure 3. The impact of seasonal temperature on operating risk.

5. Robustness Tests

This paper employs the following methods to test robustness: (1) Change the measurement of the independent variable. (2) Change the measurement of the dependent variable. (3) Use one-period lagged control variables. (4) Use propensity score matching. (5) Exclude samples with many affiliates. (6) Include city-level control variables. (7) Exclude the effect of low temperature. (8) Use instrumental variables. (9) Permutation test. The results are presented as follows, and all are consistent with the baseline results, which confirms the association between climate change and heat exposure.

5.1. Alternative Measures of Heat Exposure

This paper uses alternative measures of the independent variable. In the robustness tests, this study first chooses the 90th percentile of daily temperature from 1970 to 2000 as the threshold, and *Temp2* refers to the number of days when the daily maximum temperature exceeds the threshold. Second, *Temp3* refers to the number of days when the daily maximum temperature exceeds 32 °C. The results obtained after using an alternative independent variable are reported in columns (1) and (2) of Table 6, verifying the negative effect of heat exposure on operating risk.

Table 6. Robustness test 1.

Variables	(1)	(2)	(3)	(4)	(5)	(6)
	Zscore	***Zscore***	***Beta***	***Zscore***	***Zscore***	***Zscore***
Temp			0.000 ***	−0.002 ***	−0.002 ***	−0.002 ***
			(2.697)	(−2.782)	(−3.461)	(−2.830)
Temp2	−0.002 ***					
	(−2.912)					
Temp3		−0.001 **				
		(−2.095)				
Control	Yes	Yes	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	28,674	28,674	28,642	23,669	28,670	20,428
R-squared	0.843	0.843	0.458	0.766	0.843	0.852

Notes: (1) T-statistics clustered at the firm level are reported in parentheses. (2) Significance at the 5%, and 1% levels is indicated by **, and ***, respectively. (3) The estimate results for the control variables are omitted due to space limitations.

5.2. Alternative Measures of Operating Risk

This paper also employs the market beta as a proxy for measuring operating risk. Specifically, beta is calculated based on daily returns of firm i in year t, and a higher beta value is indicative of a higher operating risk. The results after using an alternative dependent variable are reported in column (3) of Table 6. The estimated coefficient of *Temp* is positive and statistically significant at the 1% level, indicating that exposure to heat contributes to an elevated operating risk.

5.3. Lagged Control Variables

Considering that there may be some correlation between the firm variables in the same period, further leading to reverse causation, this paper lags the control variables by one year, and the results are shown in column (4) of Table 6. The estimated coefficient of Temp is significantly negative, consistent with the baseline results.

5.4. Propensity Score Matching (PSM)

PSM is used to avoid the endogeneity problem caused by systematic differences between firms exposed to different heat levels. This study chooses the 80th percentile of heat exposure as the threshold to generate a dummy variable that equals 1 if the firm is exposed to heat temperatures above the threshold and 0 otherwise. The samples that meets the common support assumption are used and the regression results of the PSM with nearest neighbor matching are shown in column (5) of Table 6. The coefficient of *Temp* is still significantly negative at the 1% level, consistent with the baseline results.

5.5. Exclude Special Samples

As listed firms have several affiliates that may be geographically dispersed, matching firm-level data with weather data based on their registration city may lead to an incomplete assessment of the heat exposure that firms have experienced. To mitigate the resulting bias, this study excludes firms with a number of affiliates above the first quartile and re-estimates the coefficient. The results are shown in column (6) of Table 6. The estimated coefficient of *Temp* remains negative and significant at the 1% level, consistent with our baseline results.

5.6. Add Control Variables

This study further includes regional characteristics as control variables in the robustness test to minimize omitted variable bias in the results. Given that the level of regional development may affect firms' operating risk, this study includes additional control variables in the regression. Column (1) of Table 7 presents the results of further controlling for the population and the GDP of the firm's registration city. The coefficient of *Temp* is significantly negative at the 1% level, consistent with the baseline results.

Table 7. Robustness test 2.

Variables	(1)	(2)	(3)	(4)
	Zscore	***Zscore***	***Zscore***	***Zscore***
Temp	−0.002 ***	−0.002 ***		−0.002 ***
	(−2.695)	(−3.442)		(−3.299)
Pro_Ave_Temp			0.998 ***	
			(286.48)	
Cold day controls	No	Yes	No	No
Control	Yes	Yes	Yes	Yes
Control2	Yes	No	No	No
Firm FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
K-P rk LM statistic			2060.943	
Observations	22,106	28,674	28,674	28,674
R-squared	0.836	0.843	0.870	0.524

Notes: (1) T-statistics clustered at the firm level are reported in parentheses. (2) Significance at the 1% levels is indicated by ***. (3) The estimate results for the control variables are omitted due to space limitations.

5.7. Exclude the Effect of Low Temperature

To ensure that extremely low temperatures do not affect operating risk, this study further controls for the number of days below −12 °C, between −12 °C and −6 °C, and between −6 °C and 0 °C. As the results in column (2) of Table 7 show, after controlling for the effect of cold days, the operating risk still increases significantly with the increase in heat exposure.

5.8. Two-Stage Instrumental Variable Regressions

Although temperature, as an important part of weather conditions, is highly exogenous and randomly distributed, there is no significant correlation between heat exposure and the error term. However, as the agglomeration of firms may increase regional carbon emission intensity and further influence regional temperature, this study chooses the average number of high temperature days in year t in the province where the firm is registered (*Pro_Ave_Temp*) as the IV. On the one hand, since climatic conditions do not vary much from city to city in the same province, the average heat exposure of a province is related to the heat exposure of an individual firm. On the other hand, it is also strictly exogenous to the

firm's operating risk, as the production and operational activities are mainly concentrated in the city where the firm is registered. The results of the two-stage IV regression are reported in columns (3)–(4) of Table 7. Column (3) reports the results of first-stage regression; the results show that the regression coefficient of *Pro_Ave_Temp* is positive and significant at the 1% level, indicating the high correlation between the explanatory variable and the instrumental variable. The results of the second-stage regression are reported in column (4) and the coefficient of *Temp* is −0.002 and significant at the 1% level, consistent with the baseline results.

5.9. Permutation Test

To exclude the possibility that the results are due to research design errors or a result of chance, this study further conducts the permutation test as follows. Specifically, following previous research [5,64], this study reassigns heat exposure in two ways: (1) reassigning heat exposure across firms while preserving year order, and (2) reassigning heat exposure across time and within firms. This paper re-estimates Equation (1) 2000 times and the results are shown in Figure 4. The distribution of the coefficients of heat exposure shows that they are all close to zero, which is far from the actual coefficient estimates shown by the dotted gray line.

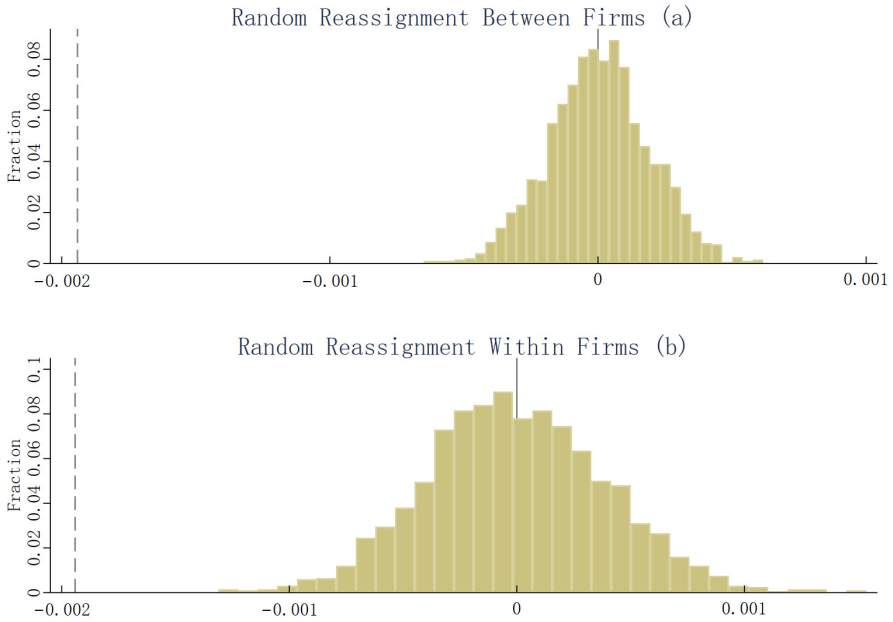


Figure 4. The results of permutation test: (**a**) The results of the random reassignment between firms; (**b**) The results of the random reassignment within firms.

6. Discussion and Conclusions

Climate change has become an increasingly important issue for the international community. In this context, raising enterprises' awareness of climate change and deepening research on the economic consequences of climate change will not only help prompt enterprises to actively participate in climate change response actions, but also provide some empirical references for the whole society's climate response.

This article investigates the impact of climate change on operating risk and its mechanism based on a sample of Chinese non-financial listed companies. The main findings of this paper are as follows.

(1) Heightened heat exposure leads to a higher operating risk. This finding contributes to the evolving literature on the economic impacts of climate change by shifting the focus beyond conventional emphases on output and performance [3,5].

(2) The impact of heat exposure on operating risk varies depending on firm characteristics. Large firms, which exhibit greater stability than small firms [52], are less sensitive to heat exposure. In addition, high temperatures not only affect workers' emotions and performance, but also increase capital depreciation [1,34,42,43,59]. Given that manufacturing firms are highly dependent on both labor and capital, they are more susceptible to heat exposure. Furthermore, firms in less developed regions often face more fragile infrastructure and resource constraints [5], making them more vulnerable to heat exposure.

(3) The mechanism analysis shows that heat exposure increases operating risk by negatively affecting operating income and inventory management. This helps to complement existing research on the channel through which climate change affects business, providing empirical evidence for developing effective climate change responses.

(4) Further analysis shows that the effect of heat exposure on operating risk persists longer than the heat exposure actually does. In addition, rising summer temperatures are positively associated with operating risk, which further confirms the correlation between rising temperatures and operating risk. The policy implications are as follows. (1) As small firms, manufacturing firms, and firms registered in less developed cities are more sensitive to heat exposure, it is crucial to enhance their awareness of climate change and take adaptation measures to strengthen climate resilience, such as enhancing innovation and CSR practices [65,66]. (2) In addition, we have demonstrated the mechanism of how heat exposure affects operating risk; more attention should be paid to process management, such as effectively adjusting inventory management or accelerating product upgrading to better meet market needs. (3) For policy makers, as the market's attention to climate change continues to grow, climate risk information should be added to the relevant provisions of corporate information disclosure so as to force enterprises to strengthen their awareness of climate change through mandatory means and market forces.

The limitations and future directions are as follows. First, this paper examines the impact of climate change on operating risk mainly from the perspective of temperature, which plays an important role in assessing climate change. However, as extreme climate events have become more frequent and intense, future research should try to enrich the relationship between climate factors, such as heavy precipitation, floods, and droughts, and business operations. Second, based on a comprehensive understanding of the impacts of climate change, it is crucial to explore potential solutions to enhance climate resilience, such as innovation, governance, or strategy alignment. Third, when assessing climate risk at the firm level, a comprehensive assessment model should be formulated in terms of physical risk, transition risk, and a firm's climate response; green innovation, CSR strategies, and a low-carbon transition should be considered to achieve a comprehensive assessment.

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