

The effect of climate change on firms' debt financing costs: Evidence from China

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ABSTRACT

This paper matched the data for all non-financial listed firms in China from 1990 to 2017 with weather data and used temperature and precipitation to represent climate change. Using daily temperature and daily precipitation data, we constructed temperature bins and precipitation bins. This study presents a potential first empirical analysis that applies the risk perception theory to comprehensively examine the impacts of daily temperature and daily precipitation on firms' debt financing costs. Compared to a day with a suitable temperature, a day with temperatures above 30 °C increases firms' debt financing costs by 0.2411%. Compared to a sunny day, a day with torrential rain increases firms' financing costs by 0.2697%. Approximately \$122.13 million and \$20.49 million in extra costs were incurred across all firms in 2017. We conducted a series of heterogeneity tests. We found that the negative impacts of climate change on debt financing costs are greater for firms that investor considers more vulnerable. Finally, we found two possible mechanisms. First, from the firm's subjective initiative perspective, firms that respond proactively during seasons of high temperatures and heavy rains can reduce the negative impacts. Second, adverse weather caused by climate change may also increase firms' debt financing costs by blocking travel. These results enrich the literature on firms' debt financing costs and contribute to the understanding of climate change's impact on firms.

1. Introduction

Climate change's disruption of economic activities is one of the greatest concerns of this century (Han et al., 2023; Monge and McDonald, 2023; Zhao et al., 2023). It disrupts economic activities primarily by causing extreme weather, most commonly high temperatures and extreme rainstorms (Frame et al., 2020). Extreme heat and frequent heavy rains can disrupt agricultural production activities, for example, persistent hot weather can lead to crop failure, including wilting and death (Vogel et al., 2019). Frequent extreme rainfall not only increases crop exposure to pests and diseases but also affects soil quality and reduces the useability of agricultural machinery (Skendzić et al., 2021).

In the context of industrial production, high temperatures negatively affect firms' labor productivity. High temperatures can induce physical discomfort among employees and even result in cognitive impairments,

leading to potential mistakes in their work. (Zhang et al., 2018; Somanathan et al., 2021). These negative effects on human beings in their work are also observed on days of torrential rain due to the terrible weather conditions and moist environment (Coviello et al., 2014). On days of high temperatures or heavy rain, machines are more likely to be damaged by excessively high temperatures or humid environments (Zhang et al., 2018). Furthermore, during days of high temperatures and heavy rains, adverse weather conditions amplify the challenges associated with employee commute, including increasing commuting difficulty and longer commuting times. These factors not only impact the workforce but also hinder the ability of responsible individuals within firms to secure financing due to higher risks of accidents and traffic congestion. (Koetse and Rietveld, 2009). Extreme rainstorms not only hinder traffic, reduce employee working hours, and increase the difficulty of transporting products (Wu et al., 2023), but they also lead to a

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series of geological disasters, causing damage to the fixed assets of firms (Liu and Song, 2019).

The business activities of the tertiary sector are also being disrupted by climate change. For example, climate change alters the preferences of tourists when selecting their destinations (Dubois et al., 2016) and increases the operating costs of firms in the tourism industry (Sibitane et al., 2022). The hotel and restaurant sectors have experienced a decline in profitability attributable to climate change, characterized by a reduction in customer numbers, increased operational expenses, and closures due to extreme weather (He et al., 2019; Ngin et al., 2020).

Based on the perceived risk theory, these negative impacts caused by climate change on firms have become one of the important factors that investors and borrowers consider when firms are being financed and evaluated (Cotter and Najah, 2012). Firms' debt financing costs affect their survival and sustainable management. Therefore, firm managers and owners must be aware of this phenomenon.

This article presents the first empirical study that uses both high temperatures and torrential rain to represent climate change and to provide empirical evidence that climate change increases firms' debt financing costs. This study constructed temperature bins and precipitation bins to measure the negative impact of the annual distribution of daily temperature and daily precipitation on a firm's debt financing costs. Days with temperatures above 30 °C (86 °F) and precipitation above 50 mm are regarded as high temperature days and torrential rain days, respectively.

First, in our baseline regression section, this study utilized data from 1990 to 2017 from A-share listed firms in China and found that both high temperatures and torrential rain increase firms' debt financing costs. A series of robustness tests verified the results.

Second, this study conducted a series of heterogeneity tests to study whether climate change has a larger impact on firms that investors consider more vulnerable. The tests show that labor-intensive industries are slightly more affected than capital-intensive industries. Because the effect of negative environmental events tends to be more damaging for physical workers, who usually work in more hostile conditions (Zhang et al., 2018). Meanwhile, regarding different ownership situations, as expected, state-owned firms are generally less negatively affected by climate change than private firms. We also find that firms with high labor productivity and low risk levels are less negatively affected by climate change. The extensive heterogeneity analysis in the study provides a comprehensive understanding of the mechanism by which climate change affects firms' debt financing costs under various characteristics.

Last, this paper proposes the possible mechanisms of influence from the firms' subjective initiative perspective. On the one hand, we expect that firms that actively respond to climate change tend to be favored by investors and receive lower financing costs. This tendency was observed when the firm's subjective initiative during seasons of intense high temperatures and torrential rains was analyzed. For example, in seasons with frequent high temperatures and torrential rains, providing a better working environment, adequate material security, and even higher financial subsidies may increase employees' enthusiasm for work and thus weaken this negative influence. On the other hand, the degree of close financial concentration around firms influences this relationship between climate change and financing as severe weather conditions, such as extreme heat and torrential rain, may make it harder for people to travel long distances to receive financing. Firms cannot usually obtain the optimal financing scheme that represents the lowest cost within a certain range.

In this paper, Section 2 is the literature review and hypotheses. Section 3 describes and details the conceptual model, data sample sources, and the conditions of the variables. Section 4 presents the empirical results, discusses the heterogeneity analyses, and analyzes the potential influencing mechanisms. Finally, section 5 draws conclusions and outlines policy implications.

2. Literature review and hypotheses

Searching through the literature, we identified empirical studies relevant to climate change and firms' financing. We argue that the literature mainly has deficiencies in the following aspects, and our marginal contribution aims to solve the following issues:

First, the sample in most studies only included firms in a particular industry. For example, firms in the mining industry (Chu and Sui, 2023), heavy pollution industries (Chang and Nie, 2021), the fossil fuel industry (Delis et al., 2019), and the banking industry (Javadi and Masum, 2021). Small sample studies limited to specific industries are prone to possible sample selection bias as the most significant effects tend to occur in the most susceptible samples (Chang et al., 2019). This study selected all non-financial listed firms in the world's largest developing country for around 30 years, thereby excluding sample selection issues.

Second, existing research mainly focuses on firms' equity capital costs (Balvers et al., 2017; Noh, 2018; Kling et al., 2021; Chu and Xu, 2022). Although both equity financing and debt financing are important methods for firms to obtain financing in financial markets, only small firms and start-ups tend to opt for equity financing (Yazdanfar and Öhman, 2015; Coleman et al., 2016). After going public, few companies raise a significant amount of equity financing (Carpenter and Petersen, 2002). The pecking order theory also points out that, especially for listed companies, equity financing is the last choice for them to obtain financing (Myers, 1984; Alkhatib, 2012) as equity financing usually brings serious agency costs (Jensen and Meckling, 1976; Harris and Raviv, 1991). Hence, we argue that using debt financing costs can better measure the impact of climate change on firms' financing activities, especially for the sample of listed firms.

Third, climate change not only brings rising temperatures but also more frequent and irregular precipitation (Trenberth, 2011; Fischer and Knutti, 2015). Several papers have studied how precipitation impacts economic activities (Hendrix and Salehyan, 2012; Damanian et al., 2020; Kotz et al., 2022). However, the effects of precipitation on firms' debt financing costs have not been systematically assessed in previous studies. Meanwhile, regarding temperature, especially high temperatures, most studies focus on how the annual temperature impacts firms' financing activities (Chang and Nie, 2021; Kling et al., 2021; Chu and Sui, 2023), while there is a lack of literature specifically assessing the impact of daily temperature on firms' debt financing costs.

Hence, we attempt to provide what is possibly the first empirical paper that comprehensively uses high temperatures and torrential rains as proxies for climate change to study the impact of daily high temperatures and daily precipitation on firms' debt financing costs.

Based on the risk perception theory, when investors perceive a firm is under threat from climate change, investors in the financial market will treat this signal with caution and incorporate it into the assessment of firms (Goldstein et al., 2019). In particular, financial institutions and investors usually play the role of experts in the financial market. Their rich experience and keen observation make them more adept to perceive and observe the risks of climate change that firms face. (Bush et al., 2001; Noel et al., 2021). Based on the risks posed by climate change, investors will demand higher-risk compensation (Wang et al., 2016; Bolton and Kacperczyk, 2021; Shi et al., 2022), reflected in financing activities through an increase in firms' financing costs. Meanwhile, we argue that climate change, as a negative factor, will magnify the existing problems of firms and intensify the concerns of borrowers. As a result, firms that already have operational problems and risks will be more affected by climate change.

Hence, we put forward our hypothesis H1 and H2:

H1. Climate change increases firms' debt financing costs.

H2. Climate change has a greater impact on firms that investor considers more vulnerable.

In this article, we also focus on the firm's subjective initiative to

respond to climate change (Slawinski and Bansal, 2012). We point out that as one of the most important and active participants in the market (Gruetter and Lalive, 2009), firms will not passively bear the damage caused by climate change without responding (Galbreath, 2011). If the risks posed by climate change serve as a clear signal in financial markets that increases investor concern (Ardia et al., 2020), a positive firm response to these climate change risks can also serve as a clear signal that reduces investor concern (Fatica and Panzica, 2021). Hence, we put forward our hypothesis H3:

H3. Proactive responses can mitigate the impact of climate change on debt financing costs.

Finally, we argue that another potential influencing mechanism is that climate change increases debt financing costs by blocking travel. In extreme weather conditions caused by climate change, such as high temperatures, drivers' moods will become worse (Xianglong et al., 2018), and may even cause serious emotional instability (Wijesuriya et al., 2007), which may more likely cause traffic accidents, resulting in road congestion and hindering travel. High temperatures will also reduce a machine's working performance (Zhang et al., 2018). For cars, high temperatures will increase the failure rate and ultimately increase the occurrence of traffic accidents (Hammad et al., 2019). Extreme rainfall may lead to the closure of some roads, subways, aircraft, ships, and other public transportation systems that cannot operate normally or may even be paralyzed (Zhou et al., 2021; Wu et al., 2023). Climate change leads to difficulties for people to travel, often requiring extra costs, similarly affecting the staff's ability to go out for financing-related activities. On the other hand, it may make it impossible for firms to obtain the optimal financing solution within a certain range, as on a sunny day. Due to extreme weather conditions, like heavy rain, firms might face limitations in terms of travel distance, hindering their ability to explore and compare different capital sources to find the lowest-cost financing plan, leading to higher financing costs for firms. Hence, we put forward our hypothesis H4.

H4. Climate change increases firms' debt financing costs by blocking travel.

Based on the above review and hypothesis design, the next section will present the conceptual model, the empirical model with variables designed based on the conceptual model, as well as the data for the empirical study.

3. Methods and data

3.1. Conceptual model

According to the hypothesis setting, Fig. 1 shows our conceptual model. With climate change, investors require additional risk compensation in their investment in firms, which ultimately leads to an increase in the firms' financing costs. More vulnerable firms are more affected. However, firms' proactive response to climate change activities can mitigate investors' concerns. Finally, climate change may also influence firms' debt financing costs by blocking travel. We test hypotheses H1 to H4 in the following sections.

3.2. Empirical model

3.2.1. Treatment of weather variables

In this section, we detail our dependent and independent variables using the daily weather data.

Firms' debt financing costs are the dependent variable in this article. They are winsorized at the 1% level. Interest expense was not used due to its late inclusion into China's financial statements, and the financial expense contains not only the interest expense but also other expenses necessary for debt financing activities. Financial expenses are a more comprehensive accounting category and a common concern for investors.

We use high temperatures and torrential rain as the independent variables to represent climate change. To estimate the effect of daily temperature and precipitation on the firm's annual debt financing cost, we set up the temperature bins and precipitation bins, respectively. This approach can address possible endogeneities between temperature or precipitation and firm activities because what it creates an almost exogenous annual set of "bins".

For temperature bins, we set up eight bins. Each bin's width is 3 °C (5.4 °F). The width of the distribution of the bins follows Deryugina and Hsiang (2014). $TB_{c,t}^m$ represents the number of days with temperatures in the range of bin m in year t in county c . For example, $TB_{c,t}^1$ represents the number of days with temperatures below 12 °C (53.6 °F) in county c during year t . At the upper end, $TB_{c,t}^8$ represents the number of days with temperatures above 30 °C (86 °F), which represents the number of high-temperature days. This is one of the core independent variables in this article.

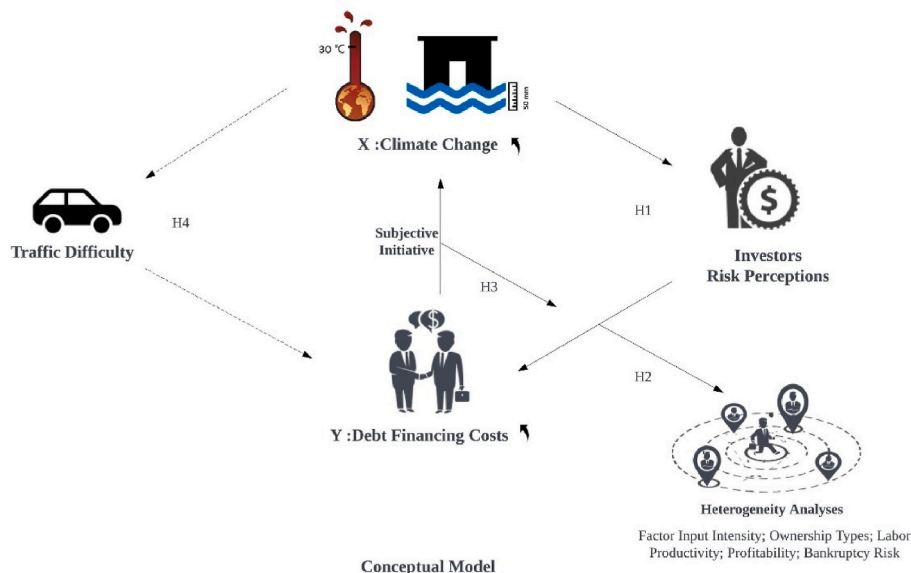


Fig. 1. Conceptual model.

For precipitation, we set up five bins, following the classification criteria for precipitation by the China Meteorological Administration. Specifically, $PB_{c,t}^m$ represents the number of days when the precipitation was in the range of bin m in year t in county c . $PB_{c,t}^1$ represents the number of sunny (without precipitation) days in county c in year t . $PB_{c,t}^2$ to $PB_{c,t}^5$ represent the number of days with precipitation of 0–10 mm, 10–25 mm, 25–50 mm, and over 50 mm, respectively. $PB_{c,t}^5$ thus, represents extreme precipitation conditions (above 50 mm, i.e., torrential rain) and is one of the main independent variables of concern.

Finally, we use the temperature bins and precipitation bins to match firms' annual debt financing costs, where we can estimate the impact of daily temperature and daily precipitation on firms' debt financing costs instead of directly using the annual mean in the regression. Detailed regression model settings will be reported in the next section.

3.2.2. Empirical specification

Equations (1) and (2) are the regression models in this study. $DFC_{i,c,t}$ represent the firm's debt financing costs. In equation (1), $TB_{c,t}^m$ represents the temperature bins constructed based on daily temperature. In equation (2), $PB_{c,t}^m$ represents the precipitation bins constructed based on daily precipitation.

$$DFC_{i,c,t} * 100 = \alpha_0 + \sum_m \beta^m TB_{c,t}^m + \lambda * C_{i,c,t} + \varepsilon_{i,c,t} \quad (1)$$

$$DFC_{i,c,t} * 100 = \alpha_0 + \sum_m \beta^m PB_{c,t}^m + \lambda * C_{i,c,t} + \varepsilon_{i,c,t} \quad (2)$$

We focus on the coefficient of semi-elasticity β^m in equations (1) and (2). In equation (1), the reference bin with an optimum temperature of 15–18 °C (59–64.4 °F) is omitted; hence, the coefficient β^m represents the temperature's marginal effect on the firm's debt financing cost compared with an optimum temperature day, if there is an additional day in bin m . In equation (2), the reference bin without precipitation is omitted; hence, the coefficient β^m represents the precipitation's marginal effect on the firm's debt financing costs, compared with a sunny day, if there is an additional day in bin m . This construction method ensures that the regression coefficient obtained is exogenous to the firms (Deschênes and Greenstone, 2007).

$C_{i,c,t}$ is a vector containing the control variables. It includes all weather control variables in the sample except for the independent variables in the equation. This article also adds weather variables' quadratic terms, aiming to control for the potential nonlinear relationship. Furthermore, as a vector, $C_{i,c,t}$ also contains a series of fixed effects. It includes three fixed effects: the firm, year-region, and year-industry fixed effects. Finally, $\varepsilon_{i,c,t}$ is the error term clustered both at the firm level and the year-county level.

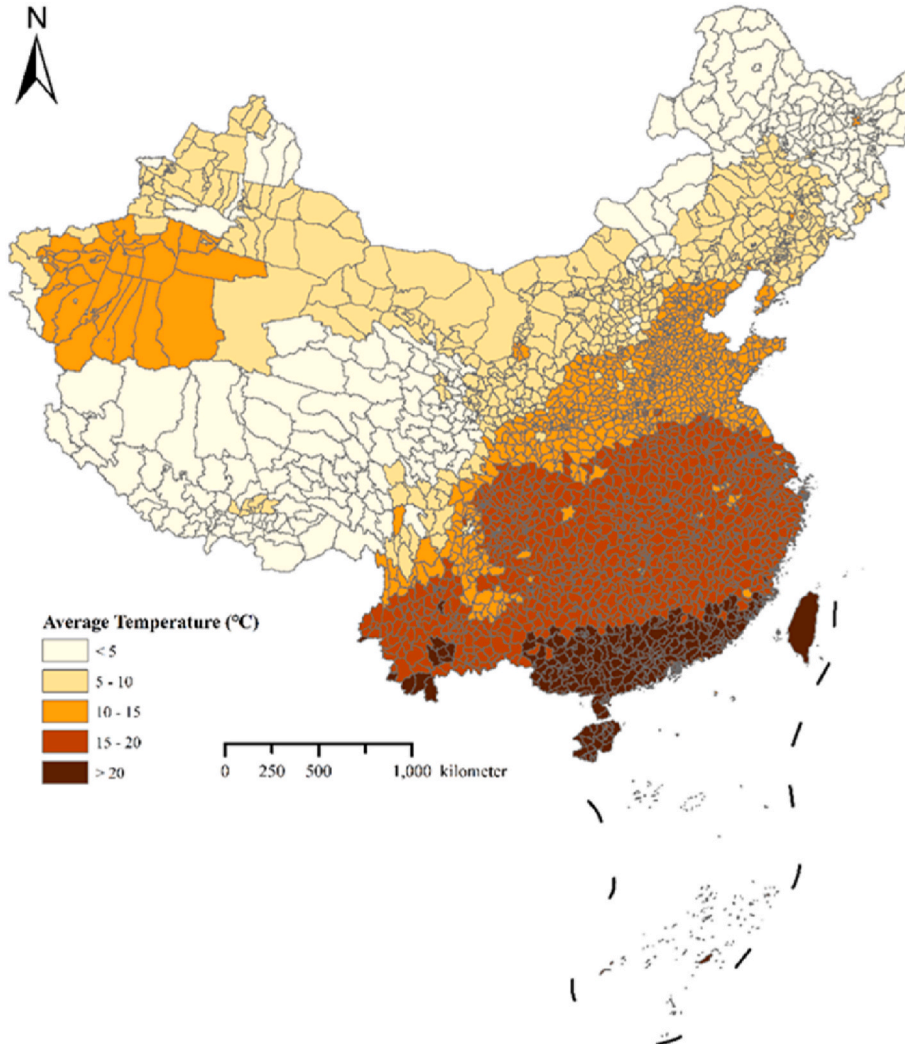


Fig. 2. Average temperature distribution map of counties in China.

3.3. Data

3.3.1. Weather data

This study used county-level weather data from the China Meteorological Administration. It contains a range of commonly used weather data, including temperature and precipitation in China, based on its more than 800 weather stations. We preprocessed the weather data before use. We filled in the daily-level missing values with the previous day's data. Using historical data as a reference, we used 0 to replace the absence of precipitation data for several consecutive days because it usually means there was no rainfall on those days. Finally, we used the nearest neighboring county's data for counties or regions without a weather station to replace the missing data, following [Chen and Yang \(2019\)](#).

Figs. 2 and 3 show the differences in the geographical distribution of annual average temperature and annual cumulative precipitation, respectively. It can be observed that both the distribution of temperature and precipitation in China has strong spatial heterogeneity. Additionally, the southern regions and coastal regions are significantly higher than the northern regions and inland regions.

3.3.2. Firm data

This study used the data of China's A-share listed firms from 1990 to 2017 from the CSMAR database. We processed the firm's data to address several issues. First, using the 2012 version of the classification

standards for listed firms in the CSRC, we exclude firms in the finance industry following previous studies, because their financing demand and financial statements are significantly different from those of other industries. We next drop firms flagged for special treatment by the CSRC and whose asset-liability ratio is greater than 1, because these firms usually exhibit serious financial issues and dishonest performance. Last, to limit the effects of outliers, the dependent variable and other financial variables used in later sections are winsorized at 1%. Our dataset is an imbalanced panel of 25,402 firm-year data points. The results of detailed descriptive statistics are presented in the following sections.

3.3.3. Matching firm data and weather data

In our original dataset, weather data is at the county level. We use a firm's registered address to identify the county in which it is located and match it with the weather data. We use the office address published in the firm's annual report for firms whose registered address is outside China. We unify the new administrative region and name with the old to address issues arising from the administrative region and name changes.

We acquire knowledge regarding the presentation methodology of data through the study conducted by [Zhang et al. \(2018\)](#). First, we show that the summary statistics match the result of the annual weather data, including temperature and precipitation, with firms' annual data in this section. Then, we convert the daily temperature and precipitation data into near-exogenous temperature bins and precipitation bins for firms' activities in the next section to perform the regression analysis and

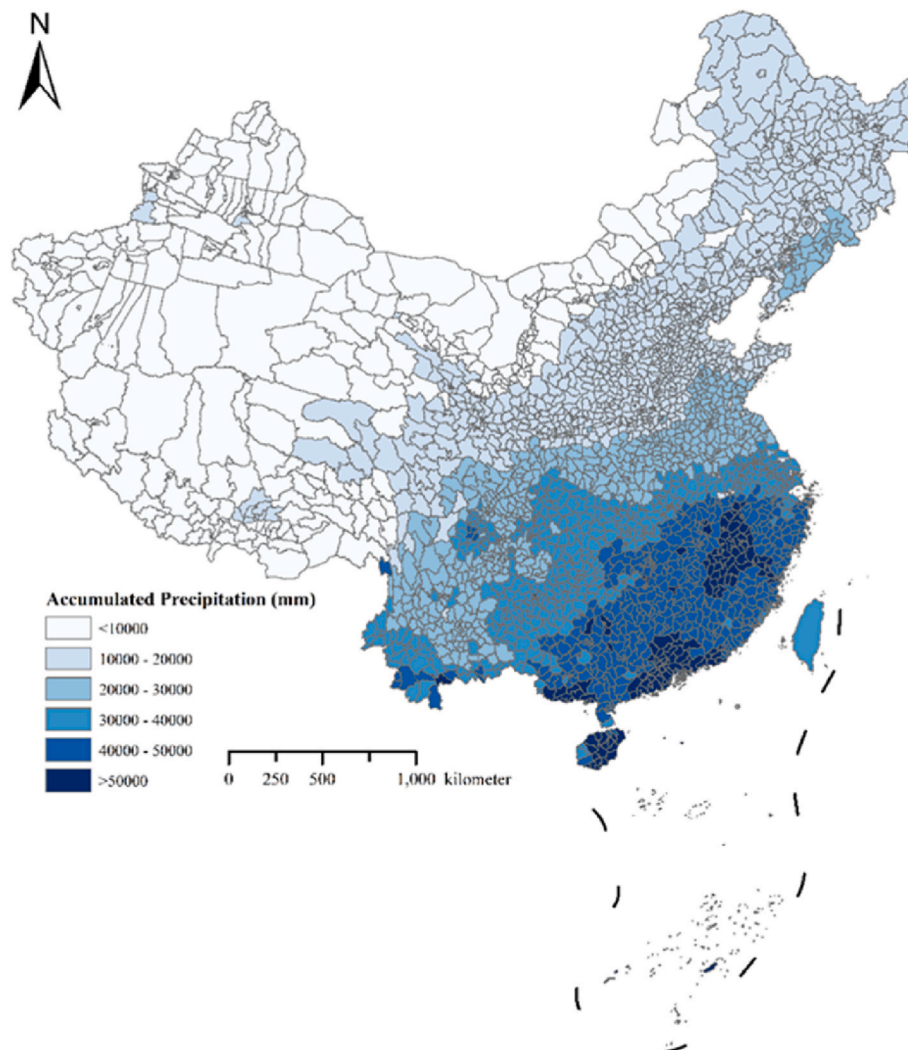


Fig. 3. Cumulative precipitation distribution map of counties in China.

identify the impact on firms' debt financing costs.

Table 1 shows the sample's summary statistics after matching. All variables are annual data. The unit of observation is recorded at the firm-year level. The sample includes all non-financial listed firms with healthy operating conditions and trading in CNY in China during 1990–2017. The manufacturing industry is the largest sector in the sample, comprising more than 60% of the sample, while the health and social work industry is the smallest sector, consisting of less than 1% of all firms. The dependent variable DFC (debt financing cost) is measured by the financial expense divided by the sum of long-term and short-term liabilities, following Pittman and Fortin (2004), and is winsorized at 1%. From 1990 to 2017, the annual average debt financing costs were 1.17%, and the standard deviation was 0.3029, indicating that this variable fluctuates relatively greatly and the difference between firms is obvious.

The summary statistics of the weather variables are also shown in Table 1. Precipitation is the annual cumulative precipitation. The others are calculated as the annual mean. The average observed temperature is around 16 °C, and the average total precipitation is around 1180 mm from 1990 to 2017. The dispersion degree of precipitation is the highest compared with other weather variables.

4. Results and discussions

4.1. Baseline results

First, we test hypothesis H1. For conciseness, in equations (1) and (2), we only report the results of the regression coefficients for variables representing high temperature $TB_{c,t}^8$ and variables representing torrential rain $PB_{c,t}^5$. Results for all bins are presented in Figs. 4 and 5, and the full regression output is available in the Appendix. Tables 2 and 3 show the results under different fixed effects.

In both Tables 2 and 3, column (1) shows the results with only firm fixed effects and year fixed effects. Then, column (2) shows the results with the stricter fixed effect, and the year-region fixed effect replaces the year fixed effect. The geographic region is divided into seven parts by provinces, following Zhang et al. (2018), as detailed in the Appendix.

Column (3) shows the results of replacing the year fixed effect with the year-industry fixed effect. The classification of industry types follows the industry classification of listed firms by the CSRC. Column (4) presents our preferred fixed effect specification, which includes firm, year-region, and year-industry fixed effects. The coefficients remain significant under all different controls. Figs. 4 and 5 display all the estimation results for all bins in equations (1) and (2), with the most stringent control results.

In Table 2, the positive coefficients on the high-temperature bin indicate that the debt financing costs rise on hot days compared with days at the preferred temperature. In Table 3, the positive coefficients on the highest precipitation bin indicate that the debt financing costs rise on days of torrential rain compared with sunny days. Under the strictest of controls, the coefficient of 0.2411 in Table 2 indicates that an extra high-temperature day (above 30 °C) will lead to an increase of 0.2411% in firms' debt financing costs compared with an optimum-temperature

Table 1
Summary statistics.

Variable	Mean	Std. dev.	Min	Max	Obs
Debt Financing Costs	0.0117	0.3039	−2.2967	0.7222	22,305
Temperature (°C)	16.4135	4.5230	−2.1205	25.7200	25,394
Sunshine (hours)	5.2918	1.1643	1.7357	9.1188	25,394
Precipitation (mm)	1180.5430	557.6733	77.9385	3111.6080	25,394
Humidity (%)	70.4113	8.6831	31.2664	88.4023	25,394
Windy (m/s)	2.3242	0.5860	0.3085	6.7887	25,394

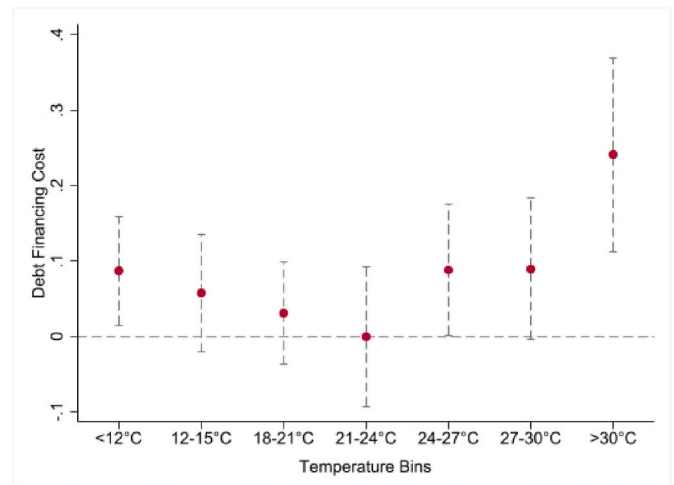


Fig. 4. Estimated effects of temperature on debt financing costs.

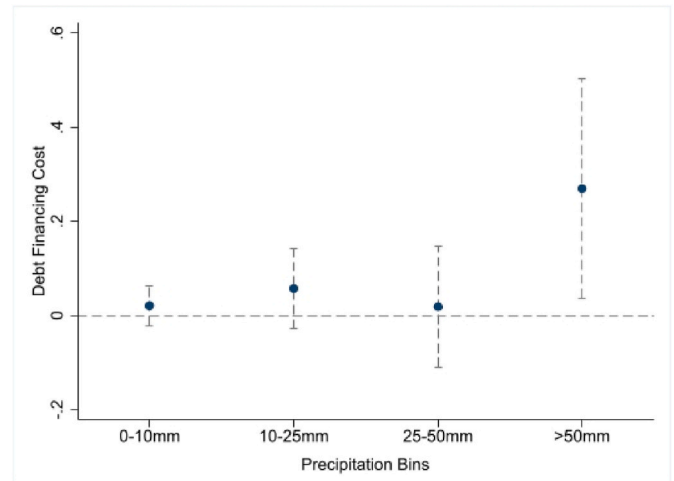


Fig. 5. Estimated effects of precipitation on debt financing costs.

Table 2

Estimated effects of temperature on financing costs.

Dependent variable	Debt Financing Costs			
	(1)	(2)	(3)	(4)
>30 °C	0.1534*** (0.0535)	0.2420*** (0.0751)	0.1570*** (0.0566)	0.2411*** (0.0781)
Firm FE	Yes	Yes	Yes	Yes
Year FE	Yes	No	No	No
Year*Region FE	No	Yes	No	Yes
Year*Industry FE	No	No	Yes	Yes
Controls	Yes	Yes	Yes	Yes
Observations	22,050	22,046	21,831	21,828
R-squared	0.3342	0.3387	0.3741	0.3778

Significance: *significant at 10%; **significant at 5%; ***significant at 1%.

day. Similarly, the coefficient of 0.2697 in Table 3 indicates that an extra day with precipitation above 50 mm will lead to an increase of 0.2697% in firms' debt financing costs compared with a sunny day.

As mentioned, the debt financing costs are generally regarded as the risk assumed by the borrower and the risk-return required (Stellner et al., 2015). When a firm tries to raise debt in the financial markets, investors will perceive the risk to enterprises due to climate change, which will lead to higher debt financing costs for firms (Frondel et al., 2017). These regression results support hypothesis H1: Climate change

Table 3
Estimated effects of precipitation on financing costs.

Dependent variable	Debt Financing Cost			
	(1)	(2)	(3)	(4)
>50 mm	0.2385** (0.1130)	0.2881** (0.1405)	0.2459** (0.1183)	0.2697* (0.1417)
Firm FE	Yes	Yes	Yes	Yes
Year FE	Yes	No	No	No
Year*Region FE	No	Yes	No	Yes
Year*Industry FE	No	No	Yes	Yes
Controls	Yes	Yes	Yes	Yes
Observations	22,050	22,046	21,831	21,828
R-squared	0.3338	0.3381	0.3735	0.3772

Significance: *significant at 10%; **significant at 5%; ***significant at 1%.

increases firms' debt financing costs. Subsequently, we attempt to use the sample data to calculate the specific losses of climate change on firms' debt financing costs.

Specifically, the average financial expenses of sample firms in 2017 were 15.25 million USD (converted into USD based on 2017 exchange rates). This indicates that an extra high-temperature day will result in an additional cost of 0.0368 million USD for firms. In 2017, on average, 20 days in the sample exceeded 30 °C, leading to an approximate 4.822% increase in debt financing costs over a year due to high temperatures. For precipitation, an extra torrential rain day will result in an additional cost of 0.0411 million USD for firms and contribute to a 0.8091% increase in debt financing costs over a year.

For temperature, an extra high-temperature day instead of a suitable temperature day would increase the firms' total financing costs by approximately 122.13 million USD in 2017, based on the sample. Similarly, for precipitation, an extra torrential rain day instead of a sunny day would increase the firms' total financing costs by approximately 20.49 million USD in 2017, based on the sample. A loss of this magnitude is worth taking seriously.

4.2. Robustness check

In Tables 2 and 3, the dependent variable debt financing costs is measured by financial expenses over short-term and long-term liabilities, and the independent variable temperature bins is measured by daily temperature. In Table 4, we use different variable calculation methods and model estimation methods to test robustness.

When constructing the financing costs variable, in columns (1) and (3), we use the ratio of financial expenses to total liabilities to measure a firm's financing costs. In column (2), we use the heat index to set up temperature bins (see supplementary materials for details) following Zhang et al. (2018). These robustness tests indicate that the baseline regression results are stable.

Considering a possible intertemporal influence between climate

Table 4
Robustness test.

Dependent variable	Debt financing costs		
	(1)	(2)	(3)
>30 °C	0.0158*** (0.0067)		
>30 °C.Heat Index		0.1197* (0.0627)	
>50 mm			0.0246** (0.0127)
Firm FE	Yes	Yes	Yes
*Region FE	Yes	Yes	Yes
Year*Industry FE	Yes	Yes	Yes
Controls	Yes	Yes	Yes
Observations	24,925	21,827	24,925
R-squared	0.5780	0.2664	0.5081

Significance: *significant at 10%; **significant at 5%; ***significant at 1%.

change and economic activities (Zhang et al., 2018), we perform placebo testing by examining lagged independent variables (Table 5). We do not find a significant intertemporal relationship based on our sample, which indicates that the increase in a firm's debt financing costs is only influenced by the high temperature and torrential precipitation in that year. These results provide robustness test results for our main conclusions.

4.3. Heterogeneity analyses and influencing mechanisms

In this section, we test hypothesis H2 through a series of heterogeneity analyses. These heterogeneity analyses include factor input intensity heterogeneity analysis, ownership heterogeneity analysis, labor productivity heterogeneity analysis, profitability heterogeneity analysis, and bankruptcy risk heterogeneity analysis.

4.3.1. Heterogeneity analyses: factor input intensity

We apply two types of indices to classify firms by factor input intensity. The first index is calculated by the ratio of labor and sales (Dewenter and Malatesta, 2001). The second measurement is labor over output, a common index used to measure labor intensity. As our sample not only includes industrial firms but also many non-industrial firms, we use profit to represent the output. Table 6 presents the results.

To intuitively observe the difference between labor-intensive and capital-intensive industries, we adopted the method of Fan et al. (2018). We set two dummy variables to classify whether the firms' ratio is greater or less than the mean of all firms. Firms with ratios larger than the mean are considered labor-intensive firms, while firms with ratios below the mean are considered capital-intensive firms (Zhang et al., 2018). We interact the highest temperature bins (above 30 °C) with the dummy variables and retain both in the model. Then, we use the same method to process the precipitation bins.

Labor-intensive and capital-intensive industries experience different climate change impacts on their economic activities (Zhang et al., 2018). Table 6 shows that labor-intensive industries are more negatively affected by high temperatures and torrential precipitation than capital-intensive industries. This difference between industries may be caused by the greater impact of high temperatures and torrential precipitation on manual laborers, affecting firms' performance and increasing borrowing costs. As mentioned by Zhang et al. (2018), due to the relatively poor working environment, labor-intensive firms are often the most exposed to climate change's negative effects due to the harsh working environment.

4.3.2. Heterogeneity analyses: ownership types

In this section, we analyze the differences between ownership types. Firms with different ownership types have different regulatory pressures, financing channels, and social relationships. Hence, the effects brought by climate change on such firms are also likely to differ across different ownership types. Generally, compared with private firms, due

Table 5
Robustness test – placebo test.

Dependent variable	Debt financing costs	
	(1)	(2)
>30 °C (lagged)	0.0433 (0.0702)	
>50 mm (lagged)		0.1934 (0.1456)
Firm FE	Yes	Yes
Year*Region FE	Yes	Yes
Year*Industry FE	Yes	Yes
Controls	Yes	Yes
Observations	19,938	19,938
R-squared	0.3985	0.3982

Significance: *significant at 10%; **significant at 5%; ***significant at 1%.

Table 6
Heterogeneity across factor input intensity.

Dependent variable	Debt financing costs (Labor/Sales)		Debt financing costs (Labor/Output)	
	(1)	(2)	(3)	(4)
>30 °C*Labor intensive	0.3168*** (0.0829)		0.2341*** (0.0809)	
>30 °C*Capital intensive	0.2151*** (0.0714)		0.2091*** (0.0814)	
>50 mm*Labor intensive		0.6916*** (0.2523)		0.4271** (0.1683)
>50 mm*Capital intensive		0.3269*** (0.1396)		0.2854* (0.1587)
Firm FE	Yes	Yes	Yes	Yes
Year*Region FE	Yes	Yes	Yes	Yes
Year*Industry FE	Yes	Yes	Yes	Yes
Controls	Yes	Yes	Yes	Yes
Observations	19,457	19,458	19,929	19,929
R-squared	0.3892	0.3887	0.3875	0.3870

Significance: *significant at 10%; **significant at 5%; ***significant at 1%.

to more stable credit endorsements and more stringent enforcement of labor laws in state-owned firms, climate change's negative effects may have a lower impact on state-owned firms.

We use two ownership measurements to classify firms. The first is a direct division of state-owned and private firms based on the nature of the firm's shareholders in their annual reports. In some cases, individuals or institutions control a firm through investment agreements or other contacts, even if they are not shareholders. We also use the information regarding the actual controllers behind the firms as a second method to distinguish between state-owned and private firms.

In Table 7, state and private are dummy variables representing state-owned and private firms, respectively. Columns (1) and (2) are classified directly by shareholder information. Columns (3) and (4) are classified by the actual controller information.

Columns (1) and (3) show that financing costs for both state-owned and private firms rise because of high temperatures. As expected, state-owned firms are less affected than private firms. In columns (2) and (4), private firms are also more affected than state-owned firms on days of torrential rain. We argue that this difference is caused mainly by two factors. First, state-owned firms provide more comprehensive protection measures for labor production on bad weather days compared to private firms. Second, they tend to have more reliable credit in the financial market and can obtain lower interest rates compared to private firms. Private firms often face more difficult financing issues compared to state-owned firms, a problem that persists under climate change.

Table 7
Heterogeneity across firm ownership types.

Dependent variable	Debt financing costs (Shareholders)		Debt financing costs (Actual controller)	
	(1)	(2)	(3)	(4)
>30 °C*State	0.1798** (0.0829)		0.1743** (0.0831)	
>30 °C*Private	0.3074*** (0.0787)		0.3113*** (0.0788)	
>50 mm*State		0.2024 (0.1600)		0.1840 (0.1607)
>50 mm*Private		0.3363** (0.1688)		0.3536** (0.1700)
Firm FE	Yes	Yes	Yes	Yes
Year*Region FE	Yes	Yes	Yes	Yes
Year*Industry FE	Yes	Yes	Yes	Yes
Controls	Yes	Yes	Yes	Yes
Observations	21,828	21,828	21,829	21,830
R-squared	0.3781	0.3772	0.3782	0.3772

Significance: *significant at 10%; **significant at 5%; ***significant at 1%.

4.3.3. Heterogeneity analyses: labor productivity

Studies show that climate change leads to decreased labor productivity (Zhang et al., 2018). Given this concern, investors may reduce their investments in firms whose output is more vulnerable to climate change. Hence, we argue that firms with higher labor productivity should be less negatively affected by extreme weather. Firm labor productivity is calculated by dividing operating profit by employment. Table 8 shows that firms with higher labor productivity are less negatively affected by climate change. We used total profit and net profit as replacements, and the results remained stable.

4.3.4. Heterogeneity analyses: profitability

Firms' profitability and risk level in harsh environments are usually considered the first concern of investors. We argue that firms with higher profitability and less risk are less affected by climate change due to higher investor confidence.

We use two common variables, ROA and ROE, to measure a firm's profitability in Table 9. All variables are obtained from CSMAR and are winsorized at 1%. Firms with higher levels of profitability are less affected by extreme weather, as expected.

4.3.5. Heterogeneity analyses: bankruptcy risk

In Table 10, columns (1) and (2) present the results of the interaction term of high temperature and firm bankruptcy risk. Columns (3) and (4) present the results of the interaction term of torrential precipitation and firm bankruptcy risk. Both the O-score and the Z-score are commonly used to measure a firm's bankruptcy risk. However, they are different in this representation.

Higher O-score represents a higher bankruptcy risk, while higher Z-score represents lower bankruptcy risk. These economic implications thus meet the expectation that firms at higher risk levels are more negatively affected by climate change.

4.4. Influencing mechanisms: the cost of summer welfare

In this section, we test hypothesis H3. We consider that firms' subjective initiative can mitigate the negative effects of climate change. Specifically, if firms can provide enough measures to improve the working environment and sufficient financial support frequently to stimulate the enthusiasm of employees, we believe these measures can simultaneously allay concerns from borrowers in regard to climate change. We tested this idea by observing how firms behave during periods of high temperatures and torrential rain.

The negative effect of climate change may be mitigated for firms with comfortable work environments, especially cooling facilities such as air conditioning, fans, or readily available cold drinks and foods. If firms actively accept their legal obligations to pay extra heat relief allowances

Table 8
Heterogeneity across labor productivity.

Dependent variable	Debt financing costs	
	(1)	(2)
>30 °C	0.2300*** (0.0808)	
>30 °C*Productivity	−0.0137*** (0.0049)	
>50 mm		0.3809** (0.1521)
>50 mm*Productivity		−0.0569*** (0.0166)
Firm FE	Yes	Yes
Year*Region FE	Yes	Yes
Year*Industry FE	Yes	Yes
Controls	Yes	Yes
Observations	19,929	19,929
R-squared	0.3878	0.3872

Significance: *significant at 10%; **significant at 5%; ***significant at 1%.

Table 9
Heterogeneity across profitability.

Dependent variable	Debt financing costs			
	(1)	(2)	(3)	(4)
>30 °C	0.2661*** (0.0780)	0.2516*** (0.0782)		
>30 °C*ROA	−0.6575*** (0.2491)			
>30 °C*ROE		−0.1311** (0.0628)		
>50 mm			0.3889*** (0.1409)	0.2974** (0.1412)
>50 mm*ROA			−3.289*** (0.9443)	
>50 mm*ROE				−0.4956** (0.2301)
Firm FE	Yes	Yes	Yes	Yes
Year*Region FE	Yes	Yes	Yes	Yes
Year*Industry FE	Yes	Yes	Yes	Yes
Controls	Yes	Yes	Yes	Yes
Observations	21,720	21,720	21,721	21,722
R-squared	0.3789	0.3787	0.3784	0.3780

Significance: *significant at 10%; **significant at 5%; ***significant at 1%.

Table 10
Heterogeneity across bankruptcy risk.

Dependent variable	Debt financing costs			
	(1)	(2)	(3)	(4)
>30 °C	0.6044*** (0.1235)	0.3846*** (0.0903)		
>30 °C *O-score	0.0578*** (0.0141)			
>30 °C *Z-score		−0.0500*** (0.0125)		
>50 mm			2.9148*** (0.4135)	1.0441*** (0.2023)
>50 mm*O-score			0.3155*** (0.0530)	
>50 mm*Z-score				−0.2067*** (0.0387)
Firm FE	Yes	Yes	Yes	Yes
Year*Region FE	Yes	Yes	Yes	Yes
Year*Industry FE	Yes	Yes	Yes	Yes
Controls	Yes	Yes	Yes	Yes
Observations	17,416	19,352	17,416	19,352
R-squared	0.4120	0.4101	0.4127	0.4095

Significance: *significant at 10%; **significant at 5%; ***significant at 1%.

on hot days, labor productivity may improve while allaying investor concerns. Following this line of logic, in columns (1) and (2) of [Table 11](#), we add the interaction items of the third quarter's management expenses and the high-temperature bin, the interaction items of the third quarter's employee compensation payable, and the high-temperature bin. The same settings apply to the precipitation bins in columns (3) and (4). We argue that additional refrigeration equipment and cooling supplies costs should only occur during the summer months. For the same reason, the extra cost of a high-temperature allowance should only occur in the summer months. Hence, we choose the third-quarter financial data to measure the impact of these two charges (see [Table 11](#)).

It is worth noting that, as a firm's legal responsibility, high-temperature allowance was put forward very late in China and was only formally established in 2004. In 2006, because China's accounting standards were updated, their high-temperature allowances were recorded in the accounting items for employee compensation payable. Hence, we use the third-quarter employee compensation payable starting from 2006 to measure the high-temperature allowance.

[Table 11](#) shows that all interaction terms are negative and significant, indicating that firms that actively respond to climate change can reduce the negative effects. These results support hypothesis [H3](#).

Table 11
The cost of summer welfare.

Dependent variable	Debt financing costs			
	(1)	(2)	(3)	(4)
>30 °C	0.2368*** (0.0875)	0.2753*** (0.0774)		
>30 °C*Expense	−0.0093** (0.0039)			
>30 °C *Salary		−0.0124*** (0.0033)		
>50 mm			0.3606** (0.1655)	0.2773* (0.1518)
>50 mm*Expense			−0.0414** (0.0183)	
>50 mm*Salary				−0.0112*** (0.0032)
Firm FE	Yes	Yes	Yes	Yes
Year*Region FE	Yes	Yes	Yes	Yes
Year*Industry FE	Yes	Yes	Yes	Yes
Controls	Yes	Yes	Yes	Yes
Observations	17,494	16,030	17,494	16,030
R-squared	0.4144	0.4340	0.4137	0.4333

Significance: *significant at 10%; **significant at 5%; ***significant at 1%.

Table 12
Travel difficulties.

Dependent variable	Debt financing costs			
	(1)	(2)	(3)	(4)
>30 °C	0.2752*** (0.0794)	0.2765*** (0.0796)		
>30 °C*Dist5km	−0.00031* (0.0001)			
>30 °C*Dist10km		−0.0001 (0.0001)		
>50 mm			0.3769** (0.1560)	0.3959** (0.1596)
>50 mm*Dist5km			−0.0013* (0.0008)	
>50 mm*Dist10km				−0.0006* (0.0003)
Firm FE	Yes	Yes	Yes	Yes
Year*Region FE	Yes	Yes	Yes	Yes
Year*Industry FE	Yes	Yes	Yes	Yes
Controls	Yes	Yes	Yes	Yes
Observations	21,811	21,811	21,811	21,811
R-squared	0.3781	0.3781	0.3773	0.3774

Significance: *significant at 10%; **significant at 5%; ***significant at 1%.

4.5. Influencing mechanisms: travel difficulties

In this section, we test hypothesis [H4](#). We argue that another potential mechanism, where extreme weather conditions increase the difficulty of travel, affects opportunities and accrues costs for firms to obtain financing from investment institutions. As mentioned by [Wu et al. \(2023\)](#), this paper argues that firms' travel becomes more difficult during extreme weather. Hence, on the one hand, this increases the cost of travel. Travel cost is a type of cost of firm financing activities, so the increase in cost will lead to the increase of firms' debt financing costs. On the other hand, it may make it impossible for firms to obtain the optimal financing solution within a certain range, compared to a sunny day. Due to extreme weather conditions like heavy rain, firms might face limitations in terms of travel distance, hindering their ability to explore and compare different capital sources to find the lowest-cost financing plan. This will also lead to higher financing costs for firms.

Specifically, the greater the financial concentration around a firm, the less difficult and costly it is for a firm to obtain financing in extreme weather conditions because firms can access financial services over relatively short times and distances.

We use variables Dist5km and Dist10km to represent the financial

institutions' number with a firm as the center and within a radius of 5 km and 10 km in that year, respectively. This is a firm-level variable observed annually.

The results indicate that the greater the number of financial institutions around the firm, the weaker the negative impact on firm financing. When we expand our range from 5 km to 10 km, the relationship changes from significant at the 10% level to marginal significance (p-value of 0.12). When we further expand our range to 15 km and 20 km, the negative relationship remained, although it is not statistically significant. For conciseness, we omit the results for 15 km and 20 km. We argue that these results reflect that higher financial concentration around a firm, results in less climate change impact. These results support hypothesis H4.

5. Conclusions and implications

This paper estimated the impact of climate change on firms' debt financing costs. We found that days with a temperature above 30 °C increases firms' debt financing costs by 0.2411%, or by \$122.13 million in 2017 for all listed firms in total, while precipitation above 50 mm increases firms' debt financing costs by 0.2697%, or by \$20.49 million in 2017 for all listed firms in total. Then, as expected, firms with good profitability, higher labor productivity, and lower risk levels are less affected. State-owned firms are less affected than private firms. Finally, this study found some influencing mechanisms. Extreme weather conditions hinder financing activities and increase debt financing costs. Firms can improve the level of welfare as an effective measure to combat climate change.

According to the results, this article puts forward the following policy recommendations for firm managers and policymakers: First, firm managers should be aware of the risks brought by climate change to firm financing and adopt proactive measures based on the firm's nature and characteristics. The TCFD (Task Force on Climate-related Financial Disclosures) framework provides scientific theoretical guidance for firms to systematically understand their own impacts of climate change. It can be integrated into the whole process of identifying, managing, and responding to the risks associated with climate change. For the specific response measures, as pointed out in this paper, more positive and perfect welfare policies should be adopted to mobilize the production enthusiasm of employees. It can also alleviate the negative emotions of employees in high temperatures and rainy weather by creating a more comfortable office environment. Then, local government departments can set up special funds and consult support for firms to cope with the difficulties caused by climate change, such as by providing more favorable loan interest rates and providing professional consulting. They can also improve the local climate risk assessment system to help firms affected by climate change to conduct timely assessments of climate change risks and help firms cope. Financial institutions, such as commercial banks and insurance companies, can give full play to their intermediary role in the financial market. Scientifically and accurately measure the risks that firms may be exposed to due to climate change, to avoid exaggerating the damage brought by climate change and making firms suffer from unfair situations. Financial institutions can alleviate the financing difficulties of firms by launching climate change credit products to help firms cope with climate change.

CRedit authorship contribution statement

Yuanshuang Zhao: Conceptualization, Data curation, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Yunxiao Liu:** Conceptualization, Methodology, Supervision, Visualization, Writing – original draft. **Yuhang Sun:** Conceptualization, Data curation, Writing – original draft, Writing – review & editing. **Ning Zhang:** Conceptualization, Data curation, Methodology, Supervision, Visualization, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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