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# THE EFFECTS OF EXTREME CLIMATE EVENTS ON GREEN TECHNOLOGY INNOVATION IN MANUFACTURING ENTERPRISES

Chengyuan WANG[1,2], Wanyi LI[1], Jun LI[3]✉, Liang WAN[4]

*[1]School of Management, Hefei University of Technology, Hefei, Anhui, P.R. China*
*[2]NSFC Fundamental Research Center on Smart Interconnected System Engineering, Hefei, Anhui, P.R. China*
*[3]School of Economics, Hefei University of Technology, Hefei, Anhui, P.R. China*
*[4]School of Public Affairs, University of Science and Technology of China, P.R. China*

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**Abstract.** The increasing intensity and frequency of extreme climate events have made improving the adaptability to extreme climate events a strategic imperative for manufacturing companies. This paper investigates whether manufacturing enterprises increase green technology innovation affected by different extreme climate events. Based on panel data of Chinese listed manufacturing enterprises, we show that extreme precipitation events can positively promote green technology innovation, yet extreme temperature events do not. Heterogeneity analyses suggest that the effect of extreme precipitation events on green technology innovation is more significant for non-state-owned enterprises, poor performance enterprises, and high R&D intensity enterprises than other enterprises. Furthermore, the facilitating effect of extreme precipitation events on green technology innovation is merely temporary.

**Keywords:** extreme climate events, climate change, extreme precipitation events, extreme temperature events, green technology innovation, manufacturing enterprises.

**JEL Classification:** O32.

✉Corresponding author. E-mail: ***economics-lijun@hfut.edu.cn***

## 1. Introduction

Extreme climate events have attracted widespread social concerns because of their serious adverse effects on human life and activities (Roxburgh et al., 2019). A typical phenomenon is that extreme climate events in recent years have broken historical meteorological records around the globe, causing serious ecological damage and economic losses. For instance, in 2023, China's capital city Beijing suffered from its heaviest rainfall in at least 140 years, leading to major flooding that affected approximately 1.29 million people and caused economic losses of more than 10 billion yuan. Furthermore, what's worse, abundant evidence shows an ongoing increase in both the frequency and intensity of extreme climate events globally (Intergovernmental Panel on Climate Change [IPCC], 2023; Stott, 2016). In this context, it is of great importance for enterprises to establish adaptation strategies, and learn how to cope with extreme climate events through managerial practice (Linnenluecke et al., 2012).

This paper addresses this topic by investigating whether manufacturing enterprises would adopt green technology innovation affected by extreme climate events. Manufacturing enterprises are sensitive to climate extremes (Wang et al., 2023b). As an eco-friendly behavior, green technology innovation can improve the adaptability of manufacturing enterprises to extreme climate events in various ways. For instance, green technology innovation can improve total factor productivity by conserving and recycling production resources (Takalo et al., 2021; Wang et al., 2021a). Green technology innovation could be also conducive to developing green products, that can create new sales channels for improving a firm's performance (Ma et al., 2021; Wang et al., 2021b; Xie et al., 2019). Hence, after undergoing an extreme climate event, manufacturing enterprises are likely to have an incentive to increase green technology innovation behaviors, so as to improve their resilience in coping with future extreme climate events. In addition, the sudden onset of extreme climate events can strength managers' perceptions of climate change risks, which in turn promote their willingness to invest in green technology innovation. Accordingly, we argue that extreme climate events can drive manufacturing enterprises to increase green technology innovation.

To test the above conjecture, we employ composite panel data collected from Chinese listed manufacturing enterprises and national meteorological surface stations, and thereby use an ordinary least squares (OLS) fixed effects model to investigate the effects of two most studied types of extreme climate events, i.e., extreme temperature events and extreme precipitation events, on green technology innovation. The findings suggest that only extreme precipitation events positively affect green technology innovation in manufacturing enterprises. By benchmarking the mean of average daily precipitation during the previous decade, one millimetre increase in the average daily precipitation would be expected to increase the number of green invention patents of manufacturing enterprises by 1.03%, if other conditions hold constant. We then analyze the potential heterogeneity effects of extreme climate events on green technology innovation, across different enterprise ownerships, performance outcomes, and R&D intensities. In addition, we explore whether the effects of extreme climate events will be sustained in the long run.

There are several gaps in the literature that motivate us to conduct this study. First, although the existing literature has examined the various adverse effects of extreme climate events on businesses, little is known about the adaptation activities of manufacturing enterprises to extreme climate events. The manufacturing sector acts as a pillar of social and economic development, such that the sensitivity of manufacturing enterprises to extreme climate events leads the society and economy to be exposed to a high-level climate risk (Wang et al., 2023b). Improving the adaptability of manufacturing enterprises to extreme climate events plays an important role in not only their sustainable development, but also in the stability of economic and social systems. Second, it is still unclear how the firm-level green technology innovation is affected by extreme climate events. Finally, there is a need to explore whether green technology innovation of manufacturing enterprises would show heterogeneity under different extreme climate events.

The rest of the paper is organized as follows. Section 2 reviews the related literature regarding the adverse effects of extreme climate events on manufacturing enterprises and their adaptation actions to extreme climate events. Section 3 develops the hypotheses. Section 4 shows our research design, including data collection, variable measurements and regression model specification. Section 5 reports primary regression results, and conducts robustness checks and heterogeneity analyses. Section 6 investigates whether extreme climate events will have a sustained impact on green technology innovation in manufacturing enterprises. Section 7 discusses theoretical and managerial implications. Finally, we conclude the paper.

## 2. Literature review

To explore the relationship between extreme climate events and green technology innovation, it is necessary to understand the harm caused by extreme climate events to manufacturing enterprises, and research advancements in the adaptation activities of manufacturing enterprises to extreme climate events. Thus, in this section, we first review the related literature about the adverse effects of extreme climate events on manufacturing enterprises, and then summarize existing studies on the adaptation activities of manufacturing enterprises to cope with extreme climate events.

### 2.1. Adverse effects of extreme climate events on manufacturing enterprises

The IPCC Sixth Assessment Report defines an extreme weather event as "an event that is rare at a particular place and time of year", and an extreme climate event as "a pattern of extreme weather that persists for some time, such as a season" (Seneviratne et al., 2021). The literature suggests that extreme climate events can have considerable adverse effects on manufacturing enterprises in various aspects. First, in terms of sales performance, extreme climate events may lead to a decrease in sales, especially for small or new businesses (Agarwal et al., 2021; Bergmann et al., 2016; Bertrand & Parnaudeau, 2019). Second, in regard to production operations, extreme climate events can increase energy costs (Bâra et al., 2023), reduce operation efficiency (Furrer et al., 2022; Liang et al., 2023), and cause unforeseeable operational risks (Huang et al., 2018; Singh & Goyal, 2023) for manufacturing enterprises. For instance, empirical analyses based on manufacturing enterprise samples from different countries uniformly demonstrate that extreme temperature shocks would give rise to emotional and physical discomfort of workers and reduce machine performance (Zhang et al., 2018), decreasing both labor productivity and total factor productivity. Furthermore, manufacturing enterprises are likely to be terminated supply chain relationships by customers if their exposure to extreme climate risks exceeds ex-ante expectations of customers (Pankratz & Schiller, 2021). Finally, with respect to financial outcomes, extreme climate events may cause cash flow pressure (Wang et al., 2023a), and increase financing costs (Brown et al., 2021) for manufacturing enterprises. Yan et al. (2022) suggests that relative to the agricultural and forestry firms, the stock returns of listed manufacturing firms are more sensitive to temperature changes. Overall, the manifold adverse effects of extreme climate events on manufacturing enterprises might increase the probability of business failure, and thus need to be continuously focused on.

### 2.2. Manufacturing enterprises' adaptation behaviours to extreme climate events

To cope with the adverse effects of extreme climate events, manufacturing enterprises are likely to adopt manifold adaptation behaviours to achieve strategic improvement. First, in operations management, manufacturing enterprises optimize their operational tactics in a timely manner. For instance, plants adjust working hours, and adopt flexible employment and labor reallocation when they encounter extreme heat waves (Shayegh et al., 2021). Firms would also change their inventory in respond to sudden extreme climate events. Chen et al. (2022a) find that for each additional day when the temperature exceeds 30 °C, food processing firms will increase their inventory by 0.43%. Second, manufacturing enterprises tend to adjust financial behaviours to adapt to extreme climate risks. Benincasa et al. (2022) indicate that firms easily affected by extreme climate events are likely to invest in long-term assets. Huang et al. (2018) suggest that firms in countries with severe climate risks are prone to hold more cash and pay lower cash dividends. Moreover, corporate tax avoidance is a feasible action after extreme climate events (Ni et al., 2021). Finally, manufacturing enterprises increase socially responsible investments, in response to unpredictable climate change shocks (Fiordelisi et al., 2023).

According, relative to the existing literature, the advantages of this paper lie in the following points. First, this paper highlights the pro-environmental practice of firms under climate extremes. Since prior studies on adaptation behaviors of firms to extreme climate events mainly focus on operational and financial management improvements, sufficient insights into the pro-environmental behaviors that firms would adopt to cope with extreme climate events are lacking. This paper addresses this gap by identifying whether manufacturing enterprises would increase green technology innovation after extreme climate events. Second, this paper highlights the relationships between extreme climate events and green innovation at the firm level. Two recent studies have revealed that extreme climate events negatively influence the regional-level outcomes of green innovation (Hu et al., 2022; Li & Lu, 2023). This paper expands the research horizon to the firm level, by investigating the potential effects of different extreme climate events on green technology innovation of manufacturing enterprises.

## 3. Research hypotheses

### 3.1. Extreme climate events and green technology innovation of manufacturing enterprises

Given the increasing frequency and intensity of extreme climate events, it's urgent for manufacturing enterprises to integrate extreme climate risks into strategy management framework (Ghadge et al., 2020). Past value creation patterns which manufacturing enterprises rely on may make it difficult to adapt to extreme climate events. Thus, firms must slug off existing value creation patterns, and develop new resources and capabilities (Pinkse & Kolk, 2010). This can help firms enhance organizational resilience to mitigate the survival threats posed by sudden extreme climate events, thus reducing the likelihood of business failure (Nikolaou et al., 2015).

Green technology innovation is an important potential way for manufacturing enterprises to improve value creation patterns, and enhance their adaptability to extreme climate events (Tamošiūnas, 2014). Green technology innovation refers to innovative activities that incorporates green elements into production operations, such as product design and manufacturing process (El-Kassar & Singh, 2019). Therefore, green technology innovation has been recognized as a crucial approach toward climate change risk adaptability (Matos et al., 2022).

Manufacturing enterprises are likely to increase green technology innovation after experiencing extreme climate events. On the one hand, green technology innovation can help manufacturing enterprises improve total factor productivity (Wang et al., 2021a), so as to resist the adverse effects of extreme climate events. For instance, by strengthening resource conservation and recycling, green technology innovation can increase the efficiency of resource utilization, and hence alleviate the problem of insufficient energy supply caused by extreme climate events. Moreover, green technology innovation can enhance labor productivity (García-Pozo et al., 2018), thus hedging against the loss of labor efficiency due to extreme climate events. On the other hand, green technology innovation is an important environmental responsibility practice of manufacturing enterprises to handle extreme climate risks

(Li et al., 2017). Relative to the slow-onset climate change events (e.g., global warming and sea-level rise), the impact of extreme climate events on manufacturing enterprises is generally direct, immediate, and significant. This could largely strengthen their managers' perceptions of the uncertainty and mutability of climate change risks. Thus, it is reasonable to image that extreme climate events are more likely to enhance managers' pro-environmental awareness, leading to an increase in environmental responsibility practices including green technology innovation. Based on the above arguments, we propose that:

**Hypothesis 1:** *Extreme climate events have a positive effect on green technology innovation of manufacturing enterprises.*

## 3.2. Potential heterogeneities

Heterogeneous effects of extreme climate events on green technology innovation may exist among manufacturing enterprises. First, relative to state-owned enterprises, private manufacturing enterprises are more likely to adopt green technology innovation driven by the adverse influences of extreme climate events. This is because that private enterprises often receive less public support when facing unforeseen events including extreme climate events. As a result, they are compelled to take actions to boost resilience and recovery capabilities, leading to active engagement in green technology innovation to enhance organizational adaptability to extreme climate events (Blundel et al., 2014; Buliga et al., 2016; Gupta, 2023; Wang & Ahmed, 2007). Second, manufacturing enterprises are more motivated to increase green technology innovation if they suffer from poorer performance due to extreme climate events. The strategy management literature has suggested that poor performance may trigger firms to carry out more innovative behaviours (Greve, 2003). As previously mentioned, extreme climate events can affect manufacturing enterprises' production operations, leading to adverse performance outputs (Chen et al., 2022a; Zhang et al., 2018). When manufacturing enterprises encounter poor performance outcomes caused by extreme climate events, they are more likely to adopt green technology innovation to improve organisational resilience, so as to build adaptability to extreme climate events. Finally, given that manufacturing enterprises with high R&D intensity might be more able to choose green technology innovation as an adaptation measure to reduce potential disruptions and losses from extreme climate events. Based on these arguments, we predict that:

**Hypothesis 2:** *There exist heterogeneity effects of extreme climate events on green technology innovation among manufacturing enterprises, such that those enterprises are more likely to increase green technology innovation (1) when they are private firms, (2) when they experience poor performance outcomes, and (3) when they have a high R&D intensity.*

Based on the above, Figure 1 shows the research conceptual model.

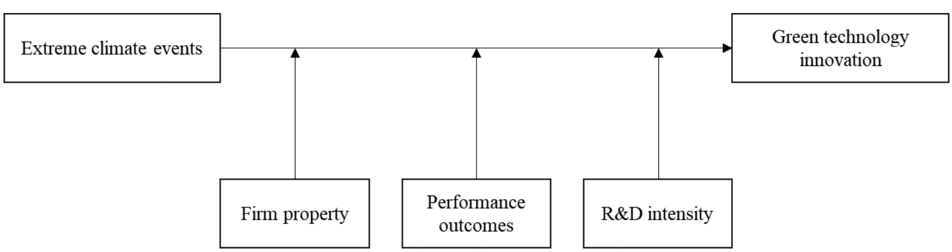


**Figure 1.** Research conceptual model

# 4. Research design

## 4.1. Sample and data

The sample of this paper covers Chinese listed manufacturing enterprises over the period 2009 to 2019. The sample data are collected from multiple sources. First, the data used to measure extreme climate events are obtained from China Meteorological Data Service Centre (CMDSC), which is China's official collector and manager of meteorological information and archives. CMDSC provides hourly meteorological data from national surface stations, including hourly observational values of weather elements such as temperature, pressure, relative humidity, moisture pressure, wind and precipitation. We obtain original hourly meteorological data from more than 800 surface stations between 1999 and 2019. Second, the data of measuring green technology innovation, i.e., green invention patents, are collected from China National Research Data Service Platform (CNRDS). Finally, the geographic information and financial data of listed manufacturing enterprises are collected from the CSMAR database. Because we use the previous decade as a reference window to construct the measurements of extreme climate events which will be introduced below, the sample observation window is from 2009 to 2019. Then, we exclude: (1) observations with missing data; (2) samples in which the geographic distance between the sample firm and its nearest meteorological surface station exceeds 50 kilometres; and (3) special treatment firms. In total, 7,983 firm-year observations are obtained.

## 4.2. Variable measurements

*Extreme climate events*. Considering various types of extreme climate events, we focus on the two most studied types of extreme climate events in the literature (Gray et al., 2023; Li et al., 2021; Martin et al., 2011; Rao et al., 2022; Zhang et al., 2018), i.e., extreme temperature events and extreme precipitation events. Furthermore, extreme temperature events are divided into extreme heat waves (denoted by *Extreme Heat*) and extreme cold waves (denoted by *Extreme Cold*). These extreme climate events can often have a direct, and significant adverse impact on manufacturing enterprises.

To measure extreme climate events that a focus firm experienced in a certain year, we match the focus firm with its nearest meteorological surface station based on the longitudes and latitudes of the focus firm and the meteorological station. Then, following prior studies (e.g., Brown et al., 2021; Trewin, 2013), *Extreme Heat* that a focus firm suffered in a certain year is measured by the number of days when the daily maximum temperature of the focus firm's nearest meteorological station was higher than the 90th percentile of the daily maximum temperature on all days during the previous 10 years of the station. Similarly, *Extreme cold* that a focus firm encountered in a certain year is measured by the number of days when the daily minimum temperature of the focus firm's nearest meteorological station was lower than the 10th percentile of the daily minimum temperature on all days during the previous 10 years of the station. In addition, extreme precipitation events, denoted by *Extreme Precipitation*, that a focus firm experienced in a certain year are measured by the difference between the average daily precipitation during this given year and the mean of average daily precipitation during the previous 10 years of the focus firm's nearest meteorological station.

It should be noted that we use the climate conditions during the previous decade as a benchmark in order to take into account the adaptability of manufacturing enterprises to climate change. As argued above, manufacturing enterprises are likely to dynamically adjust and improve their production operations in the face of severe weather conditions. If extreme climate events in a certain year are not more severe than those in previous years, manufacturing enterprises' adaptation activities including green innovation behaviours might not be obvious. Therefore, adopting climate conditions during the previous decade as a benchmark can capture the severity of extreme climate events in a given year that manufacturing enterprises are not already prepared for (Brown et al., 2021).

*Green technology innovation*. In this paper, we focus on whether manufacturing enterprises adopt substantial green technology innovation behaviours after extreme climate events. Thus, following Liu et al. (2021), manufacturing enterprises' green technology innovation is measured by the number of their green invention patent applications. To eliminate the right-skewed problem, we adopt the natural logarithm of one plus the number of green invention patent applications (Liu & Xiong, 2022).

*Control variables*. A set of variables that might affect green innovation activities of manufacturing enterprises are controlled. First, we control for several firm-level variables, including: (1) Size, measured by the natural logarithm of total assets; (2) Age, measured by the natural logarithm of firms' established years; (3) Property, equals one if the firm is state-owned, otherwise equals zero; (4) Leverage, measured by the ratio of total debts to total assets; (5) Book-to-market Ratio, measured by the ratio of shareholders' equity to total market value; (6) ROE, measure by the ratio of net income to shareholders' equity; (7) Duality, equals one if the firm's CEO also serves as the chairman of the board, otherwise equals zero; (8) Board Independence, measured by the proportion of independent directors; (9) Ownership Concentration, measured by the shareholding ratio of the largest shareholder. Second, we control for the extra competition conditions faced by manufacturing enterprises, i.e., Industry Competition. We use the reverse Herfindahl-Hirschman index, which equals to the sum of squares of each firm's percentage of total industry revenue, to measure the degree of industry competition.

Table 1 presents descriptive statistics of above defined variables. The continuous variables are winsorized at the top and bottom 1% levels.

**Table 1.** Descriptive statistics

| Variables | Obs. | Mean | Std. dev. | Min | Max |
|---|---|---|---|---|---|
| Extreme Precipitation | 7983 | 2.176 | 7.732 | –23.210 | 38.270 |
| Extreme Heat | 7983 | 37.770 | 11.870 | 4 | 76 |
| Extreme Cold | 7983 | 34.350 | 11.050 | 4 | 84 |
| Green technology innovation | 7983 | 0.656 | 1.015 | 0 | 6.585 |
| Size | 7983 | 9.487 | 0.492 | 8.592 | 10.970 |
| Age | 7983 | 2.652 | 0.389 | 1.386 | 3.367 |
| Property | 7983 | 0.308 | 0.462 | 0 | 1 |
| Leverage | 7983 | 0.372 | 0.504 | 0.010 | 3.023 |
| Book-to-market Ratio | 7983 | 0.384 | 0.251 | 0.039 | 1.384 |
| ROE | 7983 | 0.058 | 0.122 | –0.678 | 0.315 |
| Duality | 7983 | 0.298 | 0.457 | 0 | 1 |
| Board Independence | 7983 | 0.372 | 0.053 | 0.333 | 0.571 |
| Ownership Concentration | 7983 | 0.345 | 0.142 | 0.088 | 0.719 |
| Industry Competition | 7983 | –0.064 | 0.050 | –0.251 | –0.015 |

As expounded above, given that we use the previous 10 years as the benchmarking window for each year, the positive mean values of each extreme climate events (i.e., *Extreme Precipitation*, *Extreme Heat*, and *Extreme Cold*) in Table 1 provide evidence that there may indeed present a rising tendency of climate extremes in China over the past decade.

### 4.3. Regression model

Given that green technology innovation is measured as a continuous variable, we follow prior studies (e.g., Hu et al., 2022; Kim et al., 2021; Lai et al., 2022) and adopt the OLS panel fixed effects model below to estimate the effects of extreme climate events on green technology innovation of manufacturing enterprises:

$$Innvoation_{i,j,t+1} = \beta_0 + \beta_1 Extreme\,Heat_{i,t} + \beta_2 Extreme\,Cold_{i,t} + \beta_3 Extreme\,\Pr ecipitation_{i,t} + \beta_4 Controls_{i,j,t} + w_j + \varepsilon_t + \theta_{i,j,t}, \quad (1)$$

where $i$, $j$, $t$ denote the firm, industry and year, respectively. We use the one-year lag of green technology innovation, considering that applying for green invention patents takes time. $Controls_{i,j,t}$ contains the set of control variables defined above. Extreme climate events (i.e., *Extreme Precipitation*, *Extreme Heat*, and *Extreme Cold*) are synchronously incorporated into the regression such that for each extreme climate event, the other two extreme climate events can act as control variables. In addition, we add the industry fixed effects ($w_j$) to control for industry specific and time invariant unobservables, and year fixed effects ($\varepsilon_t$) to control for factors changing over time that are common to manufacturing enterprises (He & Jiang, 2019; Li et al., 2022; Wang, 2023c). $\theta_{i,j,t}$ is the error term. Standard errors are clustered at the firm level.

## 5. Main results

### 5.1. Primary results

Table 2 shows the primary regression results. We first independently add each extreme climate event into the regression model, shown as column (1) to (3). The coefficient of extreme precipitation events in columns (1) is positive, and statistically significant at the 1% level ($\beta$ = 0.0039, $p$ < 0.01). Whereas, in columns (2) and (3), the coefficient estimates on extreme heat events and extreme cold events are both negatively, but statistically insignificant. Furthermore, Column (4) presents the results by incorporating all extreme climate events synchronously into the regression. In this step, the coefficient of extreme precipitation events is still positive, and statistically significant at the 5% level ($\beta$ = 0.0038, $p$ < 0.05). The coefficients of extreme heat events and extreme cold events remain negative, and statistically insignificant. In addition, it's worth noting that the coefficient of extreme precipitation events in column (4) is very close to that in column (1), suggesting that the coefficient estimates on extreme precipitation events are robust after controlling for other extreme climate events.

Overall, the above regression results demonstrate that only extreme precipitation events can have a positive effect on green technology innovation of manufacturing enterprises, while extreme heat events and extreme cold events do not.

**Table 2.** Primary regression results

| Variables | Green technology innovation | | | |
|---|---|---|---|---|
| | (1) | (2) | (3) | (4) |
| Extreme Precipitation | 0.0039*** (0.0015) | | | 0.0038** (0.0015) |
| Extreme Heat | | –0.0011 (0.0010) | | –0.0003 (0.0010) |
| Extreme Cold | | | –0.0009 (0.0022) | –0.0010 (0.0022) |
| Size | 1.0952*** (0.0733) | 1.0955*** (0.0732) | 1.0961*** (0.0732) | 1.0957*** (0.0733) |
| Age | –0.0511 (0.0550) | –0.0514 (0.0550) | –0.0512 (0.0549) | –0.0514 (0.0550) |
| Property | 0.0903 (0.0564) | 0.0897 (0.0565) | 0.0895 (0.0564) | 0.0908 (0.0563) |
| Leverage | –0.0487 (0.0751) | –0.0483 (0.0750) | –0.0490 (0.0750) | –0.0488 (0.0750) |
| Book-to-market Ratio | –0.3548*** (0.1104) | –0.3572*** (0.1104) | –0.3577*** (0.1104) | –0.3545*** (0.1103) |
| ROE | 0.4196*** (0.1134) | 0.4234*** (0.1133) | 0.4254*** (0.1132) | 0.4191*** (0.1134) |
| Duality | 0.0753* (0.0407) | 0.0744* (0.0407) | 0.0754* (0.0406) | 0.0753* (0.0407) |
| Board Independence | 0.0346 (0.3148) | 0.0253 (0.3151) | 0.0249 (0.3149) | 0.0344 (0.3147) |
| Ownership Concentration | –0.0034** (0.0014) | –0.0034** (0.0014) | –0.0034** (0.0014) | –0.0034** (0.0014) |
| Industry Competition | –1.4056*** (0.4787) | –1.3945*** (0.4787) | –1.3943*** (0.4785) | –1.4056*** (0.4786) |
| Industry fixed effects | Yes | Yes | Yes | Yes |
| Year fixed effects | Yes | Yes | Yes | Yes |
| Observations | 7983 | 7983 | 7983 | 7983 |
| R-Square | 0.3531 | 0.3526 | 0.3525 | 0.3532 |

*Note:* that * $p < 0.1$, ** $p < 0.5$, and *** $p < 0.01$. Robust standard errors are reported in the parentheses.

## 5.2. Robustness checks

To test the robustness of our findings, we follow the literature and execute several additional checks. First, we add city fixed effects into the primary regression model. Manufacturing enterprises' green technology innovation is often affected by local features, e.g., the local government's environmental regulations. Thus, adding city fixed effects can absorb the impact of unobserved time-invariant city-level factors on green technology innovation in manufacturing enterprises, reducing estimation biases caused by omitted variables. Column (1) and (2) in Table 3 indicate that although there are decreases in the coefficient estimates on extreme precipitation events after adding city fixed effects, the coefficient estimates are still positive and statistically significant, at the 5% level. In addition, the coefficient estimates on extreme heat events and extreme cold events remain statistically insignificant.

**Table 3.** Robustness checks

| Variables | Green technology innovation | | | | | |
|---|---|---|---|---|---|---|
| | Adding city fixed effects | | SMEs | Large enterprises | Negative binomial regression | |
| | (1) | (2) | (3) | (4) | (5) | (6) |
| Extreme Precipitation | 0.0028** (0.0011) | 0.0031*** (0.0012) | 0.0040** (0.0017) | 0.0034** (0.0016) | 0.0102** (0.0049) | 0.0102*** (0.0033) |
| Extreme Heat | | 0.0006 (0.0008) | 0.0014 (0.0011) | –0.0002 (0.0011) | 0.0019 (0.0028) | 0.0015 (0.0022) |
| Extreme Cold | | 0.0001 (0.0013) | –0.0026 (0.0021) | 0.0013 (0.0018) | –0.0047 (0.0072) | 0.0047 (0.0040) |
| Control variables | Yes | Yes | Yes | Yes | Yes | Yes |
| Industry fixed effects | Yes | Yes | Yes | Yes | Yes | Yes |
| Year fixed effects | Yes | Yes | Yes | Yes | Yes | Yes |
| City fixed effects | Yes | Yes | Yes | Yes | No | Yes |
| Observations | 7983 | 7983 | 2806 | 5177 | 7983 | 7983 |
| R-square/ Pseudo R-square | 0.4382 | 0.4382 | 0.4710 | 0.4738 | 0.1129 | 0.1600 |

*Note:* that * $p < 0.1$, ** $p < 0.5$, and *** $p < 0.01$. Robust standard errors are reported in the parentheses.

Second, we execute sum-sample analyses. We divide the samples into two groups, i.e., large enterprises and small and medium enterprises (SMEs). Moreover, following the above test, we add city fixed effects into regressions. Column (3) and (4) in Table 3 show that the coefficient estimates of extreme precipitation events for both large enterprises and SMEs are positive, and statistically significant at the 5% level. In addition, tests for difference in coefficients between two groups suggest that the coefficient estimates on extreme precipitation events have no significant difference. This indicates that the effects of extreme precipitation events on green technology innovation are almost identical across manufacturing enterprises of varying sizes.

Finally, we utilize a negative binomial regression model to conduct robustness analyses. Given that the number of green invention patent applications is a type of count data, using logarithm transformation to measure the degree of green technology innovation, and thereby adopting the OLS regression model might raise concerns about estimation bias (Campbell & Mau, 2021). To address this issue, following Campbell and Mau (2021), we directly use the number of green invention patent applications as a measure of green technology innovation, and employ the negative binomial regression model to test the impact of extreme climate events on green technology innovation. Column (5) and (6) of Table 3 present the negative binomial regression results. In column (5), we only control for industry fixed effects and year fixed effects, same as the primary regression model. Moreover, in column (6), we add city fixed effects into the negative binomial regression. The coefficient estimates on extreme precipitation events are still positive, and statistically significant ($\beta = 0.0102$, $p < 0.01$). The negative binomial regression coefficients of extreme precipitation events imply that when using the mean of average daily precipitation during the previous decade as a benchmark, one millimetre increase in the average daily precipitation would be expected to increase the number of green invention patents of manufacturing enterprises by 1.03% (calculated by $e^{0.0102} - 1$), if other conditions hold constant. In addition, the coefficient estimates on extreme heat and cold events remain statistically insignificant. In summary, the additional tests confirm the robustness of our primary regression findings.

## 5.3. Heterogeneity analyses

*Firm property*. Column (1) and (2) of Table 4 present the heterogeneity effects of extreme climate events on green technology innovation between state-owned and private manufacturing enterprises. The results indicate that the coefficient of extreme precipitation events is positive and statistically significant at the 1% level ($\beta$ = 0.0051, $p$ < 0.01), when the enterprises are private. On the contrary, the coefficient of extreme precipitation events is positive, but statistically insignificant for state-owned manufacturing enterprises. This suggests that the effects of extreme precipitation events on green technology innovation differ between state-owned and private manufacturing enterprises. In addition, we find that extreme heat events can have a negative effect on green technology innovation in stated-owned manufacturing enterprises, at the 10% significance level. This provides partial evidence for Li and Lu (2023), which indicates that a high annual average temperature can inhibit firms' green innovation.

*Performance outcomes*. Following Lys et al. (2015), we adopt return on assets (ROA) as a measure of firm performance, and utilize historical performance as a benchmark to judge whether firms experience poor performance. We constructed two dummy variables: (1) ROA_dummy1, equals one if the firm's ROA in the current year is less than the average value of ROA during the previous three years, otherwise equals zero; and (2) ROA_dummy2, equals one if the firm's ROA in the current year is less than that in the previous year, otherwise equals zero. Column (3) to (6) of Table 4 present the heterogeneous effects of extreme climate events on green technology innovation across performance outcomes. It can be seen that when manufacturing firms' performance is worse than their historical performance, the coefficient estimates on extreme precipitation events are positive and statistically significant at the 1% level. By contrast, when their performance is better than historical performance, the coefficient estimates on extreme precipitation events are positive, but statistically insignificant. This suggests that the impact of extreme precipitation events on green technology innovation is heterogeneous across performance outcomes. In addition, consistent with the primary regression results, the effects of extreme heat events and extreme cold events on green technology innovation remain statistically insignificant regardless of performance outcomes.

*R&D intensity*. Following prior studies (Jefferson et al., 2006; Leung & Sharma, 2021), we use the ratio of R&D expenditure to total revenue to measure R&D intensity. Then, we divide the observations into two groups-firms with high R&D intensity firms and firms with low R&D intensity-based on the industrial annually median value of R&D intensity. The results are similar when use the industrial annually mean value. Column (7) and (8) of Table 4 suggest that when manufacturing enterprises have high R&D intensity, the coefficient of extreme precipitation events is positive and statistically significant at the 5% level. However, for firms with low R&D intensity, the coefficient of extreme precipitation events is positive but statistically insignificant. This indicates that there exist heterogeneity effects of extreme precipitation events on green technology innovation of manufacturing firms. In addition, the coefficient estimates on extreme heat events and extreme cold events are still statistically insignificant in both groups.

**Table 4.** Heterogeneity analyses

| Variables | Firm property | | Performance outcomes | | | | R&D Intensity | |
|---|---|---|---|---|---|---|---|---|
| | State-owned enterprises | Private enterprises | ROA_dummy1 = 1 | ROA_dummy1 = 0 | ROA_dummy2 = 1 | ROA_dummy2 = 0 | High R&D intensity | Low R&D intensity |
| | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) |
| Extreme Precipitation | 0.0017<br>(0.0027) | 0.0051***<br>(0.0017) | 0.0071***<br>(0.0024) | 0.0033<br>(0.0030) | 0.0047***<br>(0.0018) | 0.0030<br>(0.0024) | 0.0046**<br>(0.0020) | 0.0032<br>(0.0021) |
| Extreme Heat | –0.0032*<br>(0.0019) | 0.0009<br>(0.0011) | 0.0001<br>(0.0015) | 0.0002<br>(0.0019) | 0.0007<br>(0.0012) | –0.0012<br>(0.0015) | 0.0012<br>(0.0014) | –0.0021<br>(0.0014) |
| Extreme Cold | –0.0009<br>(0.0040) | –0.0016<br>(0.0026) | 0.0004<br>(0.0030) | –0.0060*<br>(0.0036) | –0.0007<br>(0.0022) | –0.0019<br>(0.0031) | –0.0020<br>(0.0028) | 0.0000<br>(0.0027) |
| Control variables | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Industry fixed effects | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Year fixed effects | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Observations | 2457 | 5526 | 3330 | 2352 | 4741 | 3242 | 4273 | 3710 |
| R-square | 0.4012 | 0.3374 | 0.3878 | 0.3542 | 0.3566 | 0.3545 | 0.3588 | 0.3818 |

*Note:* that $^{*}$ $p$ < 0.1, $^{**}$ $p$ < 0.5, and $^{***}$ $p$ < 0.01. ROA_dummy1 equals 1 if the firm's ROA is less than the average value of ROA during the previous three years, otherwise equals 0. ROA_dummy2 equals 1 if the firm's ROA is less than that in the previous year, otherwise equals 0. Robust standard errors are reported in the parentheses.

## 6. Will the effects of extreme climate events be sustained?

The above analyses demonstrate that extreme climate events, mainly extreme precipitation events, can trigger manufacturing enterprises to increase green technology innovation. This provides evidence that green technology innovation is an important adaptation behaviour to cope with extreme precipitation for manufacturing enterprises. However, the low-probability of extreme climate events might allow manufacturing enterprises to have a fluke mind, such that they tend to temporarily increase rather than persistently implement green technology innovation activities. Thus, this section examines whether extreme climate events will have a sustained impact on green technology innovation in manufacturing enterprises.

Column (1) and (2) of Table 5 present the lagged two- and three-years effects of extreme climate events on green technology innovation, respectively. The results show that the coefficient estimates on extreme climate events are all statistically insignificant. Specifically, the coefficient of extreme precipitation events is positive in the lagged two years, and turns to be negative in the lagged three years. Combing with above primary regression results, it can be seen that green technology innovation behaviours affected by extreme climate events are indeed temporarily, rather than sustained adaptation activities in manufacturing enterprises.

**Table 5.** The effects of extreme climate events on green technology innovation in a long-run

| | Green technology innovation | |
|---|---|---|
| | t+2 | t+3 |
| | (1) | (2) |
| Extreme Precipitation | 0.0025<br>(0.0017) | –0.0010<br>(0.0018) |
| Extreme Heat | –0.0002<br>(0.0010) | –0.0008<br>(0.0012) |
| Extreme Cold | –0.0012<br>(0.0023) | –0.0001<br>(0.0023) |
| Control variables | Yes | Yes |
| Industry FE | Yes | Yes |
| Year FE | Yes | Yes |
| Observations | 6880 | 5813 |
| R-square | 0.3420 | 0.3269 |

*Note:* Robust standard errors are reported in the parentheses.

## 7. Discussion

In terms of the originality and utility, this study contributes to the literature as follows. First, it enriches the nascent literature on extreme climate events. Although recent studies have identified the broad adverse effects of extreme climate events on firms (e.g., Huang et al., 2018, 2022; Rao et al., 2022), research on how firms adapt to climate extremes remains insufficient. Existing studies on adaptation behaviors of firms to extreme climate events mainly focus on financial management, such as adjusting debt structure (Huang et al., 2018; Javadi et al., 2020), increasing cash holding (Zhang et al., 2023), and even tax avoidance (Ni et al., 2021). This study contributes to the literature by documenting that manufacturing enterprises may increase green technology innovation as an adaptation response to extreme precipitation events.

Second, this study adds to the ongoing literature on the firm-level green innovation. The literature demonstrates that firms' green innovation could be affected by internal causes (e.g., firm size, financing constraints, executives' characteristics and perceptions, and organizational resources) (Arena et al., 2018; Bai et al., 2019; De Jong & Den Hartog, 2007; Hao et al., 2019; He et al., 2021; Quan et al., 2021; Roper & Tapinos, 2016; Song & Yu, 2018; Wang et al., 2022; Yousaf, 2021; Zhai et al., 2022), and external conditions (e.g., government regulation, media's supervision, and green pressure from stakeholders) (Berrone et al., 2013; Chen et al., 2022b; Huang et al., 2009; Kammerer, 2009; Lin & Chen, 2017; Peng et al., 2021). However, there still lacks insights about the influences of climate extremes on green innovation at the firm level. Two recent studies closely related to this paper reveal the negative influence of extreme climate events on the regional-level outcomes of green innovation (Hu et al., 2022; Li & Lu, 2023). Moreover, Li and Lu (2023) suggest that rising annual average temperature can weaken green innovation of firms. However, this study indicates that at the firm level, extreme precipitation events could promote manufacturing enterprises to increase green technology innovation, whereas extreme temperature events including heat and cold waves do not. Thus, our findings contribute to the literature by highlighting the multilevel relationships between extreme climate events and green innovation in different horizons.

Our findings have important managerial implications. For managers of manufacturing enterprises, they should incorporate the risks of extreme climate events into the framework of strategic risk management. Our findings demonstrate that manufacturing enterprises only increase green technology innovation affected by extreme precipitation events. However, the literature has provided evidence that extreme temperature events could also adversely impact their production operations. Thus, managers should consciously increase green innovation investments after extreme temperature events. In addition, managers should insist on implementing green technology innovation on a consistent basis, rather than treat it as a contingency strategy to deal with extreme climate events.

## 8. Conclusions

This paper investigates whether manufacturing enterprises increase green technology innovation affected by extreme climate events, based on composite panel data collected from listed manufacturing enterprises and national meteorological surface stations in China. We provide evidence that extreme precipitation events positively promote green technology innovation of manufacturing enterprises. While the influences of extreme temperature events, including heat and cold waves, on green technology innovation are negative but almost statistically insignificant. The results are robust after additional checks. Furthermore, we reveal that the effect of extreme precipitation events on manufacturing enterprises' green technology innovation is more significant for non-state-owned enterprises, poor performance enterprises, and high R&D intensity enterprises than other enterprises. In addition, we find that the effect of extreme precipitation events is merely temporary, rather than sustained. It implies that manufacturing enterprises are likely to adopt green technology innovation as an emergency coping measure, instead of a persistent adaptation action after extreme precipitation events.

This paper has some limitations. First, owing to the accessibility of climate data, several other extreme climate events are not considered in this paper. Future research can explore the effects of other important extreme climate events (e.g., droughts and typhoons) on green technology innovation of manufacturing enterprises. Second, this paper investigates the effects of extreme climate events on green technology innovation based on only Chinese manufacturing enterprises. Future research may conduct additional validation analyses based on cross-national samples of manufacturing enterprises, thereby offering more management implications. Third, this paper lacks a deeper understanding of the underlying mechanisms that motivate manufacturing enterprises to increase green technology innovation in response to extreme climate events. Future research could use questionnaire surveys and case studies to explore the potential mechanisms.

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## Author contributions

Chengyuan Wang, Wanyi Li and Jun Li conceived the study and were responsible for the design and development of the data analysis. Chengyaun Wang, Jun Li, and Wanyi Li were responsible for data collection and analysis. Chengyuan Wang, Wanyi Li, Jun Li, and Liang Wan wrote the first draft of the article, and were responsible for the revision.

## Disclosure statement

The authors declare that they have no any competing financial, professional, or personal interests from other parties.

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