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The impact of extreme weather events on green innovation: Which ones bring to the most harm?

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ABSTRACT

This research investigates the effect of extreme weather events on green innovation by using unbalanced panel data covering 117 countries from 1971 to 2018 and documents strong evidence that extreme weather has a significantly negative impact on green innovation. We also find among the four extreme weather events such as droughts, extreme temperature, floods, and storms that floods have the most prominent adverse impact on green innovation. Furthermore, the significantly negative effect of extreme weather is manifested in countries with a high level of corruption and low level of trade openness, but not in the countries with a low level of corruption and a high level of trade openness. Lastly, we show that extreme weather events have an adverse impact on green innovation by decreasing economic growth level, hindering financial development, widening income inequality, damaging the accumulation of human capital, and increasing the political risk.

1. Introduction

Extreme climate events have caused widespread concern (Luterbacher et al., 2004; Barriopedro et al., 2011; Zeng et al., 2008; Lewis et al., 2011),[1] as the world has reached a consensus that industrial production methods based on fossil energy have resulted in a large amount of greenhouse gas emissions, which are the main culprits of global warming that causes extreme weather to occur more and more frequently (Field et al., 2012). Although there are great uncertainties in the predictions of the earth system's model, IPCC (2013) believes in the 21st century that the frequency of global extreme climate events will increase rapidly and the scope of their influence will show an expanding trend. Extreme weather events driven by global warming increase the possibility of serious, universal, and irreversible impacts on human life (McMichael et al., 2003; Singh and Dhiman, 2012), agriculture (Jamil et al., 2021),[2] ecosystems (Roderfeld et al., 2008; Hoegh-Guldberg and Bruno, 2010; Gordo and Sanz, 2010),[3] socio-economic development (Fankhauser and Tol, 2005; Bowen et al., 2012; Tol, 2020), global water resources (Piao et al., 2010), food security (Wheeler and Von Braun, 2013; Bandara and Cai, 2014; Hertel, 2016), and other things.[4] It is

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[1] In fact, extreme weather is nothing new. In 2007, the United Kingdom suffered the heaviest rains in 200 years; in 2010, there was a largest flood in Pakistan and a drought in Russia in a century; in 2011, a tornado in the United States killed hundreds of people; in 2017, an extremely active hurricane season battered the North Atlantic Ocean one after another. Extreme weather events such as these occur every year and even now more frequently. Extreme weather is rampant, and China has not been spared. In November 2021, heavy snowfall hit Inner Mongolia, Northeast China, North China, and other places. Among them, Shenyang, Dalian, Anshan, Jinzhou, and elsewhere in China experienced heavy to extremely heavy snowstorms.

[2] The nexus between climate shocks and agriculture is the focus of many scholars (Jamil et al., 2021), and the relevant literature is also reasonably informative. For example, Adams et al. (1995) indicated that climate change could have serious effects on U.S. crop yields. There are also documents that clarify the impact of climate change on farmers' income by studying crop yields and prices. For example, Wang et al. (2009) selected temperature and precipitation as indicators to measure climate, distinguished farmers into irrigated and non-irrigated types, and concluded that every 1 °C increase in temperature will reduce the annual net income per hectare by US$10, while a monthly increase of precipitation by 1 mm will increase the annual net income per hectare of land by US$15. Rahman (2016) noted that climate change and land use diversity are inseparable.

[3] For example, Hoegh-Guldberg and Bruno (2010) concluded that climate change brings irreversible ecosystem risks, causing severe harm to the social development of developing countries.

[4] For example, Kling et al. (2021) indicated that climate vulnerability increases the difficulty and cost of financing for companies.

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against this background that this research further analyzes the economic consequences of extreme climates, linking extreme climates, a natural disaster shock, and green innovation together (Lee and Hussain, 2022; Long et al., 2022; Maiti, 2022; Omonijo and Yunsheng, 2022; Peng et al., 2022; Wen et al., 2023; Yin et al., 2022a).

Countries are facing many challenges brought about by environmental changes while promoting economic growth in parallel (Beckerman, 1992; Zhang and Wen, 2008). One global issue is to seek a sustainable development strategy for "harmonious symbiosis" between development and the environment (Naustdalslid, 2014; Zhou et al., 2019). The implementation of a sustainable development strategy is done not only to follow the inherent requirements of green economic development, but also to actively respond to environmental challenges (Zhang et al., 2011; Malysheva et al., 2016). Currently, the viewpoint widely recognized by stakeholders such as governments and consumers is that green innovation is an important strategy for achieving Sustainable Development Goals (SDGs) (Dey et al., 2022; Feng et al., 2021; Feng and Zheng, 2022; Hao et al., 2022; Hu et al., 2022; Jiang et al., 2022). As an organic combination of the two development concepts of green and innovation, green innovation plays an important role in solving current resource constraints, environmental pollution, and other issues.[5] Correspondingly, academia has also conducted a series of studies on green innovation (Wang et al., 2021a, 2021b, 2022c, 2022e; Yang et al., 2022a; Yin et al., 2022b; Zheng et al., 2022a, 2022c; Fu et al., 2020; Zhao et al., 2022; Zheng et al., 2022b; Wang et al., 2022b, 2022d). How to find the key factors and action paths that affect green innovation from the green innovation system and its development mechanism is clearly an important subject of academic research (Rennings and Rammer, 2011; Li et al., 2018; Zhang et al., 2020).

Existing studies analyze the influencing factors of green innovation from various levels (Chen et al., 2006; Chen, 2008; Chang, 2011; Singh et al., 2020; Yuan et al., 2021). More specifically, due to the negative externality of environmental pollution, most existing literature focuses on environmental regulation (Brunnermeier and Cohen, 2003). For instance, Portney (2016) indicated that command-and-control environmental regulation is strict on the environmental protection goals that enterprises must achieve and the technical standards adopted, and the means are too rigid. Market-motivated environmental regulation means that the government makes relevant policies and regulations, encourages enterprises to make behavioral decisions through market signals, and stimulates enterprises to carry out green innovation.[6] Other factors, such as R&D personnel input, FDI, and economies of scale, also have a non-negligible impact on green technology innovation (Song et al., 2015; Bai et al., 2019; Chen et al., 2021). However, to our limited knowledge, up to now only a few empirical investigations have looked into the impact of natural disasters such as droughts and floods on technological innovation; see Chen et al. (2021) as an example. They analyzed the nexus between climate shocks such as drought, extreme temperature, and flood and innovation and concluded that these extreme events do hinder the innovation level significantly. However, there is scant research, if any, conducted on the nexus between extreme weather events and ecological innovation. Therefore, we fill the gap in the literature through our investigation.

The contributions of this article are as follows. First, this is the only empirical research to explore the nexus between weather shocks and green innovation, which further expands innovation economics in the direction of the ecological economy. Based on a global panel dataset of 117 countries from 1971 to 2018, we first examine the connection between extreme weather shocks and green innovation by employing a panel fixed-effect model. We confirm a significantly negative impact of overall extreme weather events on green innovation. More specifically, patent applications with environmental-related technologies decrease when the number of people affected by extreme weather events increases. Additionally, to achieve consistent results we use replaceable variables, analyze a time lag effect of one to five years, utilize the panel Poisson and panel Negative Binomial estimators based on the characteristics of the *Patent* variable and PCSE (panel-corrected standard error) method that considers heteroscedasticity between the panel data, intergroup simultaneous correlation, and intra-group autocorrelation based on the basic regression, employ the system GMM and two-stage instrumental-variables (2SIV) approach developed by Cui et al. (2021), and add more possible variables that may affect green innovation to deal with endogenous problems due to omitted variables and reverse causality in the basic regression model. The resulting estimates for the influence of extreme weather events on green innovation are similar to the primary results. Furthermore, this study explores the impacts for different kinds of countries, documenting evidence that the negative influence of extreme weather events is more evident in those countries with high corruption levels and low trade openness. Last but not least, we also explore the possible channels through which extreme weather events have an adverse effect on green innovation. We conclude that extreme weather events hamper green innovation by decreasing economic growth level, hindering financial development, widening income inequality, damaging the accumulation of human capital, and increasing the political risk.The rest of this article is arranged as follows: Section 2 is a review of the literature and hypothesis development. Section 3 presents the empirical data and methodology. Section 4 offers empirical findings, including basic results, robustness tests and heterogeneity analysis. Section 5 tests the potential channels through which extreme weather events affect green innovation. Section 6 concludes this paper.

2. Literature review and hypothesis development

Global warming has led to a more unstable climate throughout the world. Extreme cold and warm events are occurring frequently, and their intensities have risen or become the new normal.[7] Following the previous literature, we find that there are several possible channels through which climate extremes may impact green innovation.

The first possible mechanism is that climate extremes hinder a country's green innovation by reducing the level of economic growth. More specifically, Dell et al. (2012) examined the relationship between weather fluctuations and economic growth in the global dimension. Using large-scale cross-country data from 125 countries spanning 1950 to 2005 and data on surface temperature and rainfall for empirical analysis, they found that rainfall has no influence on the economy, while temperature has a significant impact on the national economy, but the related effects are different. There are significant differences across countries. For a per Celsius increase in temperature, the growth rate of national income in poor countries fell by 1.4 %, while economic growth in rich countries was barely affected. In addition, they used a distribution lag model (introducing temperature variables with lags 1, 5, and

[5] The most important feature of green innovation different from general innovation is "dual externality". "Dual externality" means that green innovation produces positive spillover effects in the innovation stage and the diffusion stage. Different from innovation in the general sense, green innovation generates environmental benefits by improving energy efficiency and reducing resource consumption, which is positive for society.

[6] Command-control regulation is a mandatory policy tool. It is a rule and system in which the legislative or administrative department directly stipulates the limits and methods of polluters' pollution discharge according to relevant laws, regulations, and technical standards. Enterprises must follow it; otherwise they will be punished by law or administration. Market incentive regulation encourages enterprises to make behavioral decisions through market signals such as prices and taxes and takes into account the cost differences of different enterprises.

[7] In the future, the world may face hotter summers, more violent convection events, and more frequent cold waves during winter. In addition to the ensuing casualties, extreme climates also have a serious and profound impact on the socio-economic and ecological environments.

10) and found that the adverse effect of temperature did not disappear in the next period, indicating that temperature changes not only affect the absolute level of income, but also directly affect revenue growth. This finding greatly strengthens the power of climate shocks, because their small effects on economic growth will accumulate over time, causing large negative effects on the national economy over a long period of time.[8] As is widely known, the argument that economic growth can effectively promote green innovation has been confirmed by many scholars such as Yang et al. (2022b) and Wen et al. (2022b). Hence, from the perspective of theory, extreme weather events have a significant impact on green innovation by decreasing economic growth level.

Second, extreme weather events may affect green innovation by destroying the finance system of one country. For example, some researchers presented that financial risk increases due to the occurrence of extreme weather (Labatt and White, 2011; Wen et al., 2021a). Gai and Kapadia (2010) pointed out that environmental risks and financial risks caused by climate change are interactive, and climate risks will spread across markets and regions to the entire financial industry. The physical risks of climate change can cause damage to personal, corporate, and government property through extreme weather events that lead to macroeconomic instability and ultimately impact financial operations through bank credit, insurance operations, and the balance sheets of listed companies. In addition, previous literature has shown that financial development can improve financing efficiency by broadening financing channels (Desbordes and Wei, 2017), alleviating information asymmetry, and reducing transaction costs, which ultimately help to promote economic growth and thus promote technological innovation (Maskus et al., 2012; Hsu et al., 2014). Therefore, extreme weather may affect green innovation through the channel of finance development.

Third, extreme weather events and green innovation are connected closely through income inequality to a certain degree. More specifically, using field research data, Keerthiratne and Tol (2018) explored the impact of natural disasters on income inequality in Sri Lanka and found that the occurrence of natural disasters increased income inequality in seasonal agriculture. Alamgir et al. (2021) also used the data of 600 households in Mymensingh in Bangladesh and find that the occurrence of extreme climates has reduced rice production in the region and ultimately increased the proportion of rural residents living in poverty and income inequality. Moreover, it is worth noting that the negative impact of the widening income gap, especially in poor areas, on green innovation is obvious, which has also been confirmed by some scholars, such as Zhang et al. (2022). Hence, income inequality is another perspective to connect the nexus between extreme weather events and green innovation.

Fourth, extreme weather events caused by climate change also have an important impact on the accumulation of human capital. Beegle et al. (2006) used household survey data in Tanzania and found that in areas with insufficient material materials and backward production conditions, in order to resist the production and living difficulties caused by natural disasters, people will choose to give up human capital investment. The occurrence of extreme weather will also crowd out human capital investment and lead to a shortage of educational resources, lowering the average educational level of people. In addition, the results of the empirical study by Kim (2010) of three countries, Cameroon, Burkina Faso, and Mongolia, showed that extreme climate events have a long-term negative impact on the acceptance of education. The lack of national welfare policies caused by climate disasters makes women in these three countries choose to drop out of primary school when facing extreme climate disasters. More generally, the level of human capital brings new economic value by changing the traditional knowledge base in the region and provides the main support and impetus for green technology innovation (Yang et al., 2022b). Thus, the occurrence of extreme weather events may hinder green innovation by decreasing the human capital level of one country/region.

Fifth, climate change and the labor market are closely linked. The first concrete impact of climate change on the labor market is its impact on labor productivity (Wargocki and Wyon, 2007; Deschenes, 2014; Hasegawa et al., 2016); the other is the impact of climate change on labor mobility (Deschenes and Moretti, 2009; Feng et al., 2015; Kirchberger, 2017); the third is the impact of climate changes on the structure of the labor force (Barreca et al., 2016). More specifically, Deschenes (2014) argued that climate change can negatively impact people's health by reducing labor productivity. Moreover, some researchers have indicated that changes in factors such as precipitation, temperature, and extreme weather events will trigger the transfer of labor between countries, regions, industries, and departments (Feng et al., 2015; Kirchberger, 2017; Kolsuz and Yeldan, 2017). Furthermore, in terms of labor structure, the supply of labor exposed to the outdoors drops in hot weather, especially extreme high temperatures. Therefore, extreme weather events reduce working hours and labor turnover, impacting labor market supply. Labor supply is one of the important input factors for innovation activities. Therefore, we conclude from the perspective of theory that extreme weather can have a negative impact on green innovation by reducing the labor market supply.

Sixth, research on the relationship between climate shocks, conflict, and political stability has grown rapidly, and research in this area has now become a new hot spot in the political economy literature (Miguel et al., 2004). Miguel et al. (2004) provided an explanation for the transmission mechanism of weather fluctuations and conflicts: lower rainfall negatively impacts national economies and triggers conflict events. New institutional economics points out that lower political risk can provide a good institutional environment for a country's technological innovation activities, and the same is true for green technological innovation activities (Allard et al., 2012; Wang et al., 2022a). Therefore, political risk is one of the important channels linking extreme climate and green innovation.

The above arguments taken together show that the occurrence of extreme weather events may have a significantly negative impact on green innovation by decreasing economic growth level, hindering financial development, widening income inequality, damaging the accumulation of human capital, reducing the labor market supply, and increasing the political risk. According to the above analysis on the green innovation consequences of extreme weather events, we present the following.

H1. : Extreme weather events have a negative impact on green innovation.

3. Data and methodology

3.1. Data and variables

We explore whether extreme weather events affect green innovation and employ panel data covering 117 countries from 1971 to 2018. The data of green innovation are obtained from the OECD environmental statistics database. The data of extreme weather events are obtained from EM-DAT, which is one of the most essential free disaster data resources in the world and is widely used in international disaster management and research circles. The data of control variables are collected from WDI. The reasons for the selection and treatment of each variable are as follows.

3.1.1. Patent

Existing studies mainly measure the level of technological innovation from two aspects: innovation input and innovation output. Most researchers have used R&D spending to measure the innovation input of a country (Van Beveren and Vandenbussche, 2010), but taking innovation input to measure innovation cannot avoid the following two

[8] This discovery points out a new direction for the expansion of traditional climate-economic comprehensive assessment models.

problems. First, the innovation motivation of some companies is not simple, such as the existence of fraudulent research funds, resulting in R&D investment not being entirely used for innovation. Second, investment does not necessarily lead to output, which makes it impossible to measure true innovation efficiency. Both of these problems will lead to the inherent bias of the original data. Thus, this study uses the innovation output indicator of patents to measure innovation level (Wang et al., 2019; Zheng et al., 2020; Wen et al., 2021b; Wen et al., 2022a). When it comes to green innovation, we follow Sun et al. (2019) and utilize patent applications with environment-related technologies (proxied by *Patent*) to measure green innovation. More specifically, environment-related technologies can be divided into environmental management technologies and climate change mitigation technologies.

3.1.2. *Affected*

Based on the EM-DAT database, extreme weather events mainly include the following four types: drought, extreme temperature, flood, and storm. We therefore define the occurrence of the above four natural disaster events as extreme weather events. Following Chen et al. (2021), this study measures the extreme weather events variable by using the total number of people affected by the above four extreme weather events (proxied by *Affected*). We suppose extreme weather events can significantly negatively affect green innovation.

According to existing research, in addition to extreme weather events, a region's economic development level, industrialization level, human capital, etc. also affect the level of green innovation. In order to improve the effectiveness of the regression model, this paper follows some research such as Elert et al. (2017), Wen et al. (2018), and Wang et al. (2019) and controls the influence of the following variables. (1) *Pop*: this study uses the total population of each country at the end of the year to control the impact of population on green innovation, denoted as *Pop*. (2) *GDP*: we use per capita GDP to estimate a country's economic development, proxied by *GDP*. (3) *FDI*: on the one hand, foreign direct investment can promote technological innovation through technology spillovers and ease the financing constraints of a country's domestic enterprises (Hottenrott and Peters, 2012; Song et al., 2015); from the other side, FDI may also inhibit the level of domestic technological innovation through technological dependence on multinational companies. The "spillover effect" of technology transfer by foreign investors to local companies or industries is minimal and sometimes even negative (Aitken and Harrison, 1999; Veugelers and Cassiman, 2004). Thus, we use net inflows of the FDI divided by GDP to measure *FDI*. (4) *Industry*: the adjustment of the industrial structure will definitely have requirements for technological innovation so as to promote the development, evolution, and innovation of technology. (5) *Education*: a higher level of human capital means that the enterprise has a strong ability to learn and imitate in technological innovation, can effectively use external resources, and has a positive direct effect on enterprise innovation. Therefore, we control human capital (proxied by *Education*), using the gross secondary school enrollment rate, and expect it to be as greatly positive as possible. (6) *Urban*: this indicator is provided by urban population divided by total population. (7) *Size*: the scale of government inevitably also affects the level of innovation (Herath, 2012; Asimakopoulos and Karavias, 2016). Thus, we use final consumption expenditure divided by GDP to measure government size (proxied by *Size*).

3.2. *Data description*

We get the following conclusions from Table 1. First, similar to the green innovation level of other countries, the number of people affected by extreme weather events also varies significantly in different countries. Moreover, from the descriptive statistics results of *Pop*, *GDP*, and *FDI*, we also find that the population situation, economic development level, and FDI level are so great among different sample countries. Furthermore, the mean values of *Industry*, *Education*, *Urban*, and *Size* are greater than that of their standard deviation values, meaning that the differences ion industrial structure, human capital, urbanization, and government size of the sample countries are not as large as their populations, economic development, and FDI.

3.3. *Estimation method*

We define our benchmark model as follows:

$$Patent_{it} = \alpha_0 + \alpha_1 Affected_{it} + \gamma X_{it} + \theta_t + \mu_i + \varepsilon_{it}) \tag{1}$$

Here, $Patent_{i,\,t}$ is the dependent variable (*Patent*) for measuring green innovation; *Affected* is the main independent variable for extreme weather events, including drought, extreme temperature, flood, and storm; Z is a vector of control variables; μ_i is the fixed effect variable of country; θ_t is the fixed effect variable of year; and $\varepsilon_{i,\,t}$ represents the error term in the regression model. Standard errors are clustered by country pair.

4. Empirical results

4.1. *Baseline estimates of extreme weather events and green innovation*

We only investigate the relationship between *Affected* and *Patent* without any control variables in column (1). Next, we add more and more control variables from the second column until all control variables are added in column (5). Therefore, we only explain the results of column (5). The estimated coefficient of *Affected* is −0.3230 and significantly negative at the 1 % level, indicating that extreme weather events have an adverse effect on green innovation. In addition, this paper assesses the economic significance by multiplying the coefficient on *Affected* by the standard deviation of *Affected*, divided by the standard deviation of green innovation (*Patent*). A one-standard-deviation increase in *Affected* is associated with a decrease of 0.97 % of a standard deviation in the number of patent applications with environment-related technologies [(−0.3230*13.9421)/461.9742].

This finding is consistent with Chen et al. (2021), who declared that the occurrences of extreme temperature, flood, and storm show a significantly negative impact on technological innovation. The possible

Table 1
Data description.

Variable	Observations	Mean	Std. Dev.	Min	Max
Patent	1725	123.9885	461.9742	0.14	5067.27
Affected	1725	1.3203	13.9421	0	342.0153
Pop	1725	51.6565	154.8726	0.0605	1352.642
GDP	1725	19,487.34	21,043.51	225.622	111,968
FDI	1725	4.3458	13.855	−58.3229	280.132
Industry	1725	27.7498	8.7775	4.8583	75.3107
Education	1725	87.6058	27.5687	8.2713	163.935
Urban	1725	64.8058	18.9909	8.541	100
Size	1725	76.7269	10.5736	23.2247	122.679

Note: (1) *, **, and *** denote significance at the 10 %, 5 %, and 1 % levels, respectively.

Table 2
Estimation results of the two-way panel fixed effect model.

Variable	(1)	(2)	(3)	(4)	(5)
Affected	−0.5706***	−0.3059***	−0.3035***	−0.3208***	−0.3230***
	(−5.27)	(−4.18)	(−4.10)	(−6.61)	(−7.41)
Pop		0.4524***	0.4501***	0.5214***	0.5020***
		(3.11)	(3.07)	(5.10)	(4.57)
GDP		0.0067	0.0066	0.0056	0.0044
		(1.60)	(1.60)	(1.64)	(1.29)
FDI			−0.5287**	−0.6243**	−0.6799***
			(−2.39)	(−2.53)	(−2.68)
Industry				−2.8589	−1.4711
				(−1.17)	(−0.63)
Education				−3.4543	−3.0139
				(−1.56)	(−1.39)
Urban					−6.0133**
					(−1.99)
Size					0.9575
					(0.77)
Constant	−120.6036	−128.5981	−127.2536	133.2618	324.9694
	(−0.92)	(−0.91)	(−0.91)	(0.90)	(1.22)
Country	Yes	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes	Yes
N	1725	1725	1725	1725	1725
R^2	0.1418	0.1611	0.1622	0.1906	0.1962

Notes: The values in parentheses denote the t-statistics. *, **, and *** denote significance at the 10 %, 5 %, and 1 % levels, respectively.

explanations are as follows. In the beginning, the increase in the frequency and intensity of extreme climate events has varying degrees of impact on various forms of transportation. Therefore, a government has to reduce investment in green innovation for the smooth progress of post-disaster reconstruction. Additionally, after extreme weather occurs, the reduction of government spending on R&D will directly lead to a decline in the innovation efficiency of scientific research institutions. Moreover, after a climate shock, international and domestic road infrastructure will be damaged, people will not be able to move as usual, and the reduction of personnel retention will hinder the effective use of human capital to promote innovation by reducing the spillover effect of knowledge. When road traffic is affected by extreme weather, cross-border trade cannot be carried out normally, and a country's degree of foreign trade opening is negatively impacted, which will further spread to the financial market, resulting in increased financial risks, reduced national capacity, and ultimately the field of green technology innovation.

4.2. Different types of extreme weather events

We define each type of extreme weather variable by using the number of people affected by this kind of extreme event (proxied by *Drought*, *Temperature*, *Flood*, and *Storm*). Table 3 lists the results of each type of extreme weather event respectively. From column (1), we find that the occurrence of drought events has a strongly negative impact on green innovation by reducing the patents with environment-related technology. In other words, the more people affected by drought, the fewer patent applications appear related to environmental technology. In addition, the coefficient of *Temperature* is −6.6719, but not significant even at the 10 % level, indicating that extreme temperature has no influence on green innovation. Moreover, from the estimated coefficient of *Flood*, we find that flood events do hamper the green innovation level of a country. Furthermore, similar to extreme temperature, the occurrence of a storm also has no effect on green innovation. Finally, we incorporate the above four variables (*Drought*, *Temperature*, *Flood*, and *Storm*) into a model for regression, and the results are in column (5) of Table 3. By comparing the coefficients of the above four variables, we easily find that the coefficient of *Flood* is more extensive than that of *Drought*, which suggests that the adverse green innovation effect of a flood event is more prominent than drought. For coping with the adverse influence on environmental quality, the government is bound to squeeze part of the investment for technological innovation.

4.3. Effect heterogeneity

The above empirical analysis shows in the case of a large sample that climate shocks are an important factor affecting green technology innovation. However, whether the results of these empirical analyses vary for different kinds of countries is worthy of further discussion.

Existing studies have shown that increasing the level of trade openness in a country can significantly promote the improvement of that country's innovation level (Edwards, 1998; Laursen and Salter, 2006; Dahlander and Gann, 2010). In parallel, a higher degree of openness will make it easier for countries to absorb the impact of disasters, because the greater availability of foreign funds and investment products accelerates the replenishment of capital stock. Hence, we suppose that countries with a high degree of trade openness are better able to withstand the negative impact of extreme climate events on green innovation, while countries with a low degree of trade openness are more vulnerable to external shocks. This study uses the proportion of a country's total import and export to GDP to measure the degree of foreign trade openness and divides the data into sample countries above the median and those below the median according to the median of this indicator. The results of high and low groups are in column (1) and column (2), respectively. We easily find that the coefficient of the extreme weather variable is significant for the low group samples, but not for the high group samples, implying that the strong connection between extreme weather events and green innovation only exists in those countries with a low level of trade openness.

There are undoubtedly differences in the characteristics of technological innovation in countries around the world, and the external governance environment faced by enterprises is also not the same. According to the logic of new institutional economics, as an incentive an institution fundamentally determines the generation of innovation

Table 3
Estimation results of different types of extreme weather events.

Variable	(1)	(2)	(3)	(4)	(5)
Drought	−0.2207***				−0.2070***
	(−4.09)				(−3.35)
Temperature		−6.6719			−2.0838
		(−0.33)			(−0.09)
Flood			−1.2824***		−1.2438***
			(−3.07)		(−2.97)
Storm				−0.8703	−0.8237
				(−0.40)	(−0.25)
Pop	0.5194***	0.5326***	0.4924***	0.5286***	0.4781***
	(4.72)	(4.89)	(4.58)	(5.00)	(4.63)
GDP	0.0044	0.0044	0.0044	0.0044	0.0044
	(1.29)	(1.31)	(1.28)	(1.29)	(1.29)
FDI	−0.6805***	−0.6808***	−0.6806***	−0.6809***	−0.6795***
	(−2.69)	(−2.68)	(−2.69)	(−2.68)	(−2.68)
Industry	−1.4818	−1.4885	−1.4755	−1.4913	−1.4620
	(−0.63)	(−0.63)	(−0.63)	(−0.63)	(−0.62)
Education	−3.0113	−3.0072	−3.0177	−3.0058	−3.0172
	(−1.39)	(−1.39)	(−1.39)	(−1.39)	(−1.39)
Urban	−6.0151**	−6.0045**	−6.0266**	−6.0018*	−6.0119**
	(−1.99)	(−1.99)	(−1.99)	(−1.98)	(−1.99)
Size	0.9543	0.9395	0.9204	0.9325	0.9353
	(0.77)	(0.75)	(0.74)	(0.75)	(0.76)
Constant	446.5524	445.9836	450.7756	446.8929	449.2830
	(1.57)	(1.57)	(1.59)	(1.57)	(1.59)
Country	Yes	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes	Yes
N	1725	1725	1725	1725	1725
R^2	0.1960	0.1959	0.1965	0.1959	0.1966

Notes: Same as Table 2.

(Acemoglu et al., 2005).[9] In addition, countries with low levels of corruption tend to have high levels of democratization, are more capable of internalizing the exogenous impact of natural disasters, and take effective measures to actively respond to the harmful effects of extreme climates (Felbermayr and Gröschl, 2014). Hence, according to the median level of corruption in a country, we divide our samples into high corruption level countries and low corruption level countries. The data of corruption are from the ICRG database.[10] From columns (3)–(4) in Table 4, we see that the coefficient of the climate shock variable in high corruption countries is significantly negative at the 1 % level, but not significant in low corruption level countries, indicating in countries with more corruption that the negative impact of extreme climate on green innovation is more remarkable. Thus, countries with low levels of corruption demonstrate stronger coping skills to extreme weather events.

Table 4
Estimation results of country heterogeneity.

	High	Low	High	Low
Variable	(1)	(2)	(3)	(4)
Affected	−1.0086	−0.3450***	−0.1546***	−0.0981
	(−0.74)	(−5.70)	(−7.22)	(−0.21)
Pop	1.7469	0.5793***	0.9403***	0.3678*
	(0.28)	(4.66)	(11.06)	(1.66)
GDP	0.0027**	0.0185*	−0.0020	−0.0017
	(1.99)	(1.76)	(−0.49)	(−0.45)
FDI	−0.3034***	−0.4222	0.0613	−1.0704**
	(−3.59)	(−0.04)	(0.31)	(−2.47)
Industry	1.2076	−4.2524	−0.5244	−1.0862
	(0.97)	(−1.58)	(−0.92)	(−0.32)
Education	−0.6142***	−5.4955	0.0522	−4.0534
	(−2.64)	(−1.57)	(0.20)	(−1.31)
Urban	−4.2574*	−2.5265	−3.6073	−3.7606
	(−1.72)	(−0.64)	(−1.60)	(−0.71)
Size	1.2068	0.4026	0.3377	1.5634
	(1.45)	(0.20)	(0.57)	(0.61)
Constant	230.2463*	309.3871	182.7932	463.0656
	(1.95)	(0.90)	(1.26)	(1.19)
Country	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes
N	888	838	806	920
R^2	0.1968	0.3970	0.5445	0.2487

Notes: Same as Table 2.

4.4. Robustness tests

The specific robustness tests are as follows. (i) We use replaceable variables to further conduct empirical analysis. (ii) This study further checks the time lag effect of extreme weather events on green innovation. (iii) We also apply the panel Poisson estimator, panel Negative Binomial regression and PCSE (panel-corrected standard error) method for robust estimation. (iv) We further employ system GMM to deal with the endogenous problems of the basic regression model.

4.4.1. Alternative variables

In the beginning we use alternative independent and dependent variables to confirm that the basic finding is consistent with the change of variables' measurement. More specifically, except for the number of people affected by extreme weather events, we also follow Chen et al. (2021) and use the number of occurrences of extreme weather events (proxied by *Affected1*) and the economic losses caused by extreme weather events (proxied by *Affected2*) to measure the intensity of extreme weather events. Their results are in columns (1) and (2), respectively, in Table 5. From the results of Table 5, we find that both coefficients of *Affected1* and *Affected2* are significantly negative at the 1

[9] As a result of the operation of institutions, government corruption causes negative consequences such as a decline in private investment (Mauro, 1995), a decline in foreign direct investment (Wei, 2000), political instability (Mo, 2001), distortion of government investment (Croix and Delavallade, 2009), reduction in government credibility (Morris and Klesner, 2010), and a decline in investment efficiency (O'Toole and Tarp, 2014), which eventually hinder the technological innovation of a country.

[10] For more details on the setting of this variable, the reader may refer to the ICRG database.

Table 5
Robustness tests: alternative independent and dependent variables.

			Total
Variable	(1)	(2)	(3)
Affected1	−0.1518***		
	(−5.15)		
Affected2		−0.7464***	
		(−2.71)	
Affected			−4.7649***
			(−9.53)
Pop	0.3590***	0.5217***	9.9820***
	(2.70)	(4.03)	(11.54)
GDP	0.0046***	0.0044***	0.0893**
	(3.61)	(3.38)	(2.17)
FDI	−0.6983*	−0.6846*	−6.0346**
	(−1.94)	(−1.89)	(−2.32)
Industry	−1.2463	−1.4837	−18.9367
	(−0.90)	(−1.06)	(−0.98)
Education	−3.1151***	−3.0098***	−11.7775
	(−5.66)	(−5.44)	(−1.11)
Urban	−5.3442***	−5.8504***	−26.0646
	(−2.92)	(−3.19)	(−1.34)
Size	0.9831	0.8665	−0.6613
	(0.92)	(0.81)	(−0.10)
Constant	408.6742*	444.5258**	1988.4413
	(1.86)	(2.01)	(1.14)
Country	Yes	Yes	Yes
Year	Yes	Yes	Yes
N	1725	1725	2709
R^2	0.2093	0.1996	0.2396

Notes: Same as Table 2.

% level, indicating that both *Affected1* and *Affected 2* do have a substantial adverse effect on green innovation. Patent applications related to environmental technology decrease as the number of deaths from extreme weather increases and economic losses caused by extreme weather events increase. Moreover, green innovation includes not only technological innovation related to the environment, but also technological innovation related to climate and sustainable development. In addition to patents for environmental technology, we thus also use a more comprehensive range of patent applications related to ecological technology (proxied by *Total*) as a measure of green innovation. The data on total patent applications are from the OECD environmental statistics database. The results are listed in column (3) in Table 5. We find when the dependent variable is *Total* that the significantly negative impact of extreme weather events on green innovation still exists. Therefore, the basic finding is robust.

4.4.2. Time lag effect

The occurrence of extreme climate may additionally hinder green technology innovation with a certain time lag. This study tests the hindering effect of green technology with a 5-year lag of extreme climate. The test results are in in Table 6. The correlation coefficients of the core explanatory variables pass the significance test at lags of 1–5 years and show a downward trend in volatility. More specifically, from the first year to the fourth year after the extreme weather has occurred, it decreases year by year, until the negative impact reaches the minimum in the fourth year. Although the negative impact has risen in the fifth year, the overall trend does not change as a result. Hence, this paper argues that the negative impact of extreme weather on green innovation has a lag effect and the negative impact decreases over time.

4.4.3. Alternative methods

Except for the panel fixed effect model, this paper also uses panel Poisson estimator and panel Negative Binomial regression as alternative methods to clarify the robustness of the basic results. The reasons are as follows. The Poisson regression estimator is often applied when the dependent variable is a count variable, such as *Patent* variable, which generally can only take non-negative integers within a limited range. However, there is a problem of over-dispersion of the *Patent* variable - that is, the average number of patent applications is much smaller than the variance, which will lead to a small standard error of the estimated value of the model parameters and is also the inadequacy of Poisson regression. Hence, we further adopt the panel Negative Binomial regression (NB regression) to make up for the deficiency of Poisson regression and conduct a robustness test. The empirical results are listed in columns (1) and (2) in Table 7. We conclude from the coefficient of *Affected* that there exists a strong connection between extreme weather events and green innovation, which is consistent with the basic results. Furthermore, this research also uses the panel-corrected errors (PCSE) estimator to further investigate the nexus between extreme weather events and green innovation. The reason for this method is that the panel fixed effects model has not yet considered the possible

Table 6
Robustness tests: time lag effect of 1–5 years.

	Lag of 1 year	Lag of 2 years	Lag of 3 years	Lag of 4 years	Lag of 5 years
Variable	(1)	(2)	(3)	(4)	(5)
Affected	−0.4664***	−0.3584***	−0.3164***	−0.3026***	−0.3510***
	(−6.83)	(−7.22)	(−7.66)	(−8.48)	(−8.24)
Pop	0.5110***	0.5031***	0.5358***	0.5344***	0.5766***
	(4.52)	(4.42)	(4.82)	(4.65)	(5.46)
GDP	0.0045	0.0046	0.0050	0.0053	0.0054
	(1.30)	(1.32)	(1.39)	(1.39)	(1.41)
FDI	−0.8721**	−0.9226**	−0.8989**	−0.8355**	−0.8051**
	(−2.55)	(−2.38)	(−2.25)	(−2.17)	(−2.15)
Industry	−1.8697	−2.3921	−2.8245	−2.8419	−2.7876
	(−0.76)	(−0.91)	(−1.04)	(−1.03)	(−1.00)
Education	−2.9430	−2.7326	−2.4362	−2.2155	−1.9525
	(−1.41)	(−1.42)	(−1.46)	(−1.46)	(−1.46)
Urban	−6.2102**	−5.9489*	−5.6946*	−5.8731*	−6.1000*
	(−2.03)	(−1.95)	(−1.89)	(−1.86)	(−1.87)
Size	0.4521	0.1938	−0.0540	−0.2368	0.1671
	(0.37)	(0.17)	(−0.05)	(−0.21)	(0.17)
Constant	410.9274	471.0153*	442.4053*	464.4654*	422.4804*
	(1.53)	(1.76)	(1.68)	(1.74)	(1.73)
Year	Yes	Yes	Yes	Yes	Yes
Country	Yes	Yes	Yes	Yes	Yes
N	1684	1650	1616	1573	1526
R^2	0.1985	0.1997	0.2018	0.2071	0.2157

Notes: Same as Table 2.

Table 7
Robustness tests: other empirical methods.

	Poisson	NB	PCSE	System-GMM	2SIV
Variable	(1)	(2)	(3)	(4)	(5)
L. Patent				1.0363***	0.9466***
				(650.27)	(67.09)
Affected	−0.0011***	−0.0116***	−1.5632***	−0.3831***	−0.9411***
	(−2.66)	(−3.96)	(−3.77)	(−11.63)	(−14.29)
Pop	0.0055***	0.0021***	0.4701***	0.0217***	0.0129
	(11.48)	(2.81)	(9.39)	(10.91)	(1.03)
GDP	−0.0000	0.0000***	0.0071***	0.0001	0.0005***
	(−1.45)	(2.67)	(8.67)	(0.50)	(2.61)
FDI	−0.0023	−0.0012	−2.2728***	0.0081	−0.0410**
	(−1.47)	(−1.18)	(−5.27)	(0.06)	(−2.07)
Industry	0.0185	−0.0080*	1.5845	0.1349	0.0400
	(1.38)	(−1.88)	(1.57)	(0.64)	(0.24)
Education	0.0033*	0.0081***	−0.4866	−0.0263	−0.0477
	(1.88)	(7.57)	(−1.29)	(−0.74)	(−0.67)
Urban	0.0256*	0.0253***	1.6207***	−0.0135	−0.0111
	(1.65)	(6.70)	(5.26)	(−0.23)	(−0.07)
Size	0.0108	−0.0031	4.9742***	0.1020	0.0797
	(1.22)	(−0.83)	(5.67)	(0.52)	(0.88)
Constant	−4.9582***	−1.6285***	−604.5773***	−10.6476	0.8354
	(−8.31)	(−2.96)	(−4.18)	(−0.58)	(0.05)
Country	Yes	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes	Yes
N	1710	1710	1725	1482	1267
P-AR (1)				0.004	
P-AR (2)				0.370	
P-Hansen				0.354	0.626
R^2			0.1042		

Notes: Same as Table 2.

heteroscedasticity between the panel data and inter-group simultaneous correlation. The results of the PCSE estimator are in column (3) of Table 7. The results of the PCSE model mean that after considering heteroscedasticity between the panel data, inter-group simultaneous correlation, and intra-group autocorrelation based on the basic regression, the negative influence of extreme weather events on green innovation is still significant.

4.4.4. Endogeneity concerns

To consider the dynamic trend and the endogenous problem caused by reverse causality, this study lastly uses GMM to re-estimate the negative impact of extreme weather events on green innovation (Blundell and Bond, 1998; Bond et al., 2001). Therefore, we only employ system GMM to re-test the robustness of the basic regression. More specifically, we select a two-period lag of *Affected* and *Patent* variables and their higher orders as instrumental variables. The results appear in column 4 of Table 7. This estimation method requires an over-identification test and sequence correlation test for the estimation results. The *P* values of AR (2) and Hansen tests show that the model regression is practical. We easily conclude that green innovation is sustainable, and that the level of green innovation in the previous year has a positive impact on the level of green innovation in the current year. From the coefficient of *Affected*, this paper documents strong evidence that a significant relationship exists between extreme weather events and green innovation. In other words, the occurrences of extreme weather disasters such as droughts, extreme temperature, floods, and storms significantly reduce a country's green innovation level, which is consistent with the primary finding.

In order to better solve the endogeneity problem caused by unobservable factors and reverse causality, this paper further uses the two-stage instrumental-variables (2SIV) approach developed of Cui et al. (2021). The underlying idea of this approach is to project out the common factors from exogenous covariates using principal-components analysis and to run IV regression in both of the two stages, using defactored covariates as instruments. Kripfganz and Sarafidis (2021) indicated that the basic idea of this approach is to use principal component analysis to project common factors from exogenous covariates and to run an IV regression in two stages, using the decomposed covariates as instrumental variables. One of the biggest advantages of the 2SIV estimator is being able to deal with endogeneity problems to a certain extent without looking for external instrumental variables. In addition, this method also concurrently accounts for cross-sectional dependence. The results appear in column 5 in Table 7. The p-values of the Hansen test are well above 0.1, thus implying the validity of the choice of instrument variables. The result of the coefficient of *Affected* confirms again the finding that extreme weather events hinder the green innovation level of one country significantly.

Except for system GMM and 2SIV methods, we also add some variables that may affect green innovation for further dealing with the possible endogeneity problem caused by omitted variables. More specifically, a loose monetary policy is conducive to alleviating the problem of corporate financing constraints and prompting enterprises to carry out exploratory innovations that are conducive to their long-term development. Therefore, this paper uses the ratio of broad money to GDP to measure a country's monetary policy, denoted as *M2*. We thus add the *M2* variable based on the baseline regression in column (1) in Table 8. In addition, the institutional strength and quality of the bureaucracy are other factors that tend to affect green innovation of one country/region (Sharma et al., 2022). Thus, we use Bureaucracy Quality, which comes from the ICRG database, to represent institutional strength (proxied by *BQ*). This paper further adds the *BQ* variable based on column (1) in column (2) in Table 8. Furthermore, existing studies have pointed out that the level of innovation highly correlates with R&D expenditure, and that more R&D expenditure may lead to more patent and trademark applications. Therefore, this paper follows the method of Marino et al. (2016), using the proportion of a country's R&D expenditure to GDP to measure a country's innovation input and to control it (proxied as *R&D*). The results of adding all three omitted variables are listed in columns (3) in Table 8. We conclude from columns (1)–(3) in Table 8 that the adverse effect of extreme weather on green innovation is robust even if we add more omitted variables.

Table 8
Robustness tests: adding omitted variables.

Variable	(1)	(2)	(3)
Affected	−0.2884***	−0.2884***	−0.1312***
	(−18.39)	(−18.39)	(−4.71)
Pop	0.6506***	0.6506***	1.7224***
	(13.76)	(13.76)	(33.46)
GDP	0.0043**	0.0043**	0.0100***
	(2.40)	(2.40)	(3.00)
FDI	−0.4018	−0.4018	−0.5631
	(−1.01)	(−1.01)	(−1.16)
Industry	−0.8340*	−0.8340*	0.6745
	(−1.88)	(−1.88)	(0.71)
Education	0.0739	0.0739	−0.0721
	(0.27)	(0.27)	(−0.17)
Urban	−2.4586*	−2.4586*	−3.9937**
	(−1.75)	(−1.75)	(−2.11)
Size	−0.0384	−0.0384	1.6659**
	(−0.09)	(−0.09)	(2.20)
M2	0.0493	0.0493	0.1711
	(0.18)	(0.18)	(0.32)
BQ			14.0339
			(1.06)
R&D			74.3819*
			(1.91)
Constant	102.5424	102.5424	−208.2433
	(1.14)	(1.14)	(−1.49)
Country	Yes	Yes	Yes
Year	Yes	Yes	Yes
N	1240	1240	562
R^2	0.5701	0.5701	0.6899

Notes: Same as Table 2.

5. Possible mechanisms

We put forward from the literature review and hypothesis development section that the occurrence of extreme weather events may affect green innovation from the perspective of literature and theory through the following channels: economic growth, financial development, income inequality, human capital, labor market, and political risk. Hence, we further verify the above six possible mechanisms respectively. More specifically, we examine the impact of extreme weather events on the above six channel variables. This paper uses per capita GDP to represent economic growth (proxied by *GDP*), uses total private credit provided by the banking industry to measure the proportion of GDP to measure the variable of financial development level (proxied by *Finance*), adopts the Gini coefficient for each country to represent the level of income inequality (proxied by *GINI*), employs the labor force participation rate (as a percentage of the total population aged 15–64) to measure the labor market supply (proxied by *Labor*), utilizes the gross secondary school enrollment rate to measure the human capital level (proxied by *Education*), and uses political risk index to represent the political risk (proxied by *PRI*) respectively.[11] The empirical results are listed in Table 9.

From the results of column (1), we find that the coefficient of *Affected* is significantly negative at the 1 % level, implying that extreme weather events do hamper green innovation through the channel of GDP. The possible reasons are as follows: Extreme weather causes inevitable casualties as well as damage to infrastructure, equipment, and inventory, which inhibit economic growth to a certain extent (Lopez et al., 2016). In this context, a government will struggle to cope with a sluggish economy and try to restore productivity (Gül et al., 2020). There are no excess funds due to investment in technological innovation, not to mention green innovation related to environmental protection and sustainable development.

The results of column (2) imply that the mechanism of financial development is also significantly established, which effectively validates the existing literature and theories in literature review and hypothesis formulation. The coefficient of *Affected* in column (3) shows that extreme weather destroys green innovation level by widening income equality. This argument is similar with Keerthiratne and Tol (2018) and Urama et al. (2019), who indicated that extreme weather can further increase the risk of poverty and income inequality, which has led governments to take measures to adapt to climate change and implement poverty eradication plans, further squeezing out investment in technological innovation, especially in the environmental field, and ultimately leading to a decline in the level of green innovation.

The results of column (4) show that the channel of human capital exists. Previous literature also indicates that severe natural disasters cause output fluctuations and also crowd out human capital investment, leading to more serious education inequality (Groppo and Kraehnert, 2017), which further hampers the green innovation level. The coefficient of *Affected* in column (5) is not significant, implying that the mechanism of labor market supply does not hold. The results of column (6) reveal that climate extremes significantly increase political risk, and hence the mechanism of political risk exists. In other words, the occurrence of climate extremes has a significant impact on green innovation by increasing political risk, which also confirms the existing argument that harsh climate shocks fuel political uncertainty and social unrest (Anderson et al., 2017).[12] In an environment of increasing political and social risks, nations' leaders will spend most of their energy on maintaining political and social stability and have no time to consider policies or technology subsidies dedicated to promoting technological innovation. Thus, the motivation of enterprises and scientific research institutions for scientific research has declined, which ultimately hinders green innovation.

6. Conclusion and policy implications

This paper documents strong evidence that extreme weather severely hurts green technology innovation. More specifically, patent applications for environmental-related technologies decrease when the number of people affected by extreme weather events increases. In addition, this study finds that compared with droughts, the adverse impact of flood events is greater, which is similar to the research of Hrdinka et al. (2012). Moreover, the negative influence of extreme weather events is more evident in those countries with high corruption levels and low trade openness, but not in those countries with low corruption levels and high trade openness. The reason for this finding is that these countries are more vulnerable to coping with natural disasters. This research not only extends the field of natural disaster economics and further deepens our understanding about the consequences of extreme weather along the direction of climate change, but also expands related research in the field of innovation and the environment by analyzing the impacts of extreme weather on green innovation.

The advantages and contributions of our investigation are as follows. Extreme climate is a hydrological and meteorological disaster among the many natural disasters. The scope of related natural disaster research such as extreme weather in general has expanded rapidly. Additionally, empirical methods continue to improve. Most early studies used cross-sectional regression methods (including eigenvalue models), while most recent studies applied dynamic panel data models and distributed lag models to overcome the problems of omitted variable bias and model misspecification, using binomial, polynomial, and interval models. The regression method examines non-linear effects and uses long-term

[11] Notably, the data of GDP, Finance, GINI, Labor, and Education variables are from WDI database. The data of PRI come from The International Country Risk Guide (ICRG) database. The value of PRI ranges from 0 to 100. The higher the value is, the lower political risk is. On the contrary, the lower the value is, the higher political risk is.

[12] Anderson et al. (2017) noted that climate change has partly contributed to the deportation and violence of Jews.

Table 9
The results of possible channels.

	Economic growth	Financial development	Income inequality	Human capital	Labor market	Political risk
Variable	(1)	(2)	(3)	(4)	(5)	(6)
Affected	−0.0681*	−0.0235*	−0.0095***	−0.0182***	−0.0110	−0.0151***
	(−1.70)	(−1.89)	(−7.37)	(−3.03)	(−1.37)	(−3.39)
Constant	251.9225***	94.7018**	53.2821***	72.8678**	70.6385***	98.9224***
	(3.38)	(2.41)	(12.17)	(2.55)	(8.80)	(5.92)
Control variables	Yes	Yes	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes	Yes	Yes
Country	Yes	Yes	Yes	Yes	Yes	Yes
N	1725	1498	1709	1725	1988	2220
R^2	0.5714	0.4071	0.1867	0.5688	0.1055	0.2588

Notes: Same as Table 2.

average, long-term difference, and interaction term methods to measure the performance of human adaptation to climate change. The use of high-frequency meteorological data has further contributed to the advancement of research methods. However, up to now, scant research investigates the impact of extreme weather events on green innovation. In addition, existing studies are still not comprehensive enough to deal with endogeneity problems. Therefore, we extend along the economics of natural disasters to further analyze the socio-economic consequences of the subdivisions, which also supplements related research. Moreover, we deal with the possible endogeneity problems due to omitted variables and reverse causality to the greatest extent by conducting different empirical strategies, such as system GMM and 2SIV estimators. Based on the results of this paper, we thus put forward the following policy implications for those countries that more easily suffer from extreme weather events.

First, as a common sudden natural disaster, climate events are proving that governments must incorporate their emergency management into their daily public management operations. They should not just treat them as temporary emergency tasks.

Second, the occurrences of extreme climate have a sudden impact on a wide range of areas and can do great harm. Thus, governments, especially those in countries with high corruption levels and low trade openness should establish a pre-disaster warning mechanism and in-disaster emergency handling mechanism according to local conditions in their disaster emergency management, so as to improve the ability to deal with all aspects of climate disaster emergency management. The adverse effects of extreme weather can be effectively reduced by establishing a perfect emergency response mechanism for pre-disaster warning, emergency treatment, and post-disaster recovery. The sample countries herein can further comprehensively improve the level of opening up to the outside world and enhance the quality of domestic institutions.

Third, among all extreme weather events, the occurrence of flooding has the greatest negative impact on green innovation. Hence, governments should pay more attention to preventing the negative effects of floods. In short, governments have a long way to go in dealing with the negative impact of green innovation caused by extreme climate events and at improving the level of green innovation in their country.

Finally, it is worth it that everyone should try to pay more attention to the climate, because it impacts the environments in which human beings live. It helps breed human life and hope, but also brings disaster at the same time. Actions to hinder severe climate events should not be limited to technical and leadership levels, but should also involve all sectors of society and the public at large. Therefore, it is necessary to establish society-wide awareness campaigns of climate protection at the broader and more universal epistemological level in regards to "the relationship between humans and nature".

With regard to the perspectives of future research, this paper suggests exploring the following aspects. First, we can further investigate the influence of extreme climate on the sub-fields of green innovation, such as the impact of extreme weather on energy technology and water innovation. Second, the long-term impact of extreme climates is also a direction worthy of in-depth research and exploration. From a longer-term perspective, it is possible that the occurrences of extreme weather events may force the emergence of green technologies, and studies can target how future green technology innovations act in the environmental field, effectively mitigate the negative impacts of global warming, and reduce the occurrence of extreme weather. Lastly, future research on the economic effects of climate change should be further extended to micro-level aspects, by exploring the relationship between climate shocks and rural poverty traps, household mobility constraints, household investment decisions, and individual short-term and long-term income growth and by exploring more abundant micro-transmission channels. Examining micro-individual climate change adaptation measures and using economic policy assessment tools to evaluate the actual effects of various potential adaptation measures can assist in strengthening the practical significance of the climate change economics literature.

CRediT authorship contribution statement

Jun Wen: Data collection and quantitative investigation.

Xin-Xin Zhao: Set up the theoretical frame and review the relevant literature.

Qiang Fu: Propose the research idea, motivate and revise the whole paper.

Chun-Ping Chang: Summary the revised work, contact the journal in the name of the corresponding author, and act as the role in the integration of the opinions of all authors.

Data availability

Data will be made available on request.

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