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RESEARCH ARTICLE

Does haze pollution damage urban innovation? Empirical evidence from China

Chunkai Zhao [1] · Min Deng [1] · Xiguang Cao [1]

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Abstract

The continuous outbreak of haze pollution attracted full attention and became one of the most severe environmental problems in China. Based on the panel data of 266 prefecture-level cities from 2000 to 2016, this paper investigates the effects of haze pollution on China's urban innovation. Results show that (1) haze pollution does not damage urban innovation but forms a crisis-driven effect to stimulate it. (2) Haze pollution enhances the public's environmental awareness, which induces the government to invest more in science and technology, and finally forces the improvement of urban innovation. (3) Haze pollution causes the loss of human capital and leading to a decrease in the number of people who engaged in scientific research, which weakens the city's technological innovation ability. (4) The crisis-driven effect caused by haze pollution boosts the improvement of technological innovation in eastern cities, large cities, and northern cities. This study enriches the evidence on the relationship between haze pollution and urban innovation, which is significant for local governments to formulate green development and innovation-driven strategies.

Keywords China · Crisis-driven effect · Haze pollution · Public awareness · Urban innovation

Introduction

The fine particle pollution represented by haze pollution is one of the most important environmental problems worldwide. With the growth of the global economy, the concentration of fine particles in the air in developing countries is increasing significantly, especially the increase of PM2.5 concentration which causes the phenomenon of urban atmospheric acid rain and photochemical smog, resulting in reduced atmospheric visibility. These pollutants not only affect traffic safety (Pui et al. 2014) and endanger the public health (Brunekreef and Holgate 2002; Chen et al. 2016; Chung et al. 2015; Zhou et al. 2015) seriously but also induce social risk (Sun et al. 2016) and generates some unpredictable public behavior (Ostro et al. 2014; Zheng et al. 2019).

Over the past four decades of reform and opening-up, China's economic growth has made remarkable achievements. However, with rapid economic growth, the Chinese government and people have been plagued by severe environmental problems such as high energy consumption, high emissions, and high pollution. One of the most prominent environmental problems is the concentrated outbreak of haze pollution in recent years. In 2013, "Haze" became China's annual keyword, with less than 1% of China's 500 top cities met the World Health Organization's air quality standards. Severe haze pollution is a "warning light" from nature to the extensive economic growth mode in the past few decades, which forces China to think more about the high-quality development of the economy (Chen and Chen 2018; Wang and Liu 2020). In order to achieve sustainable economic development, China's economic development model will be forced to change from factor-driven to innovation-driven (Zhang et al. 2014). Innovation is not only the source of economic growth but also an important force to cultivate a competitive advantage and improve economic strength (Lin 2003). As the economy enters a "new normal," China's economy relies more on innovation to drive its growth. Therefore, China is deeply

Responsible Editor: Philippe Garrigues

✉ Min Deng
demi.dm@163.com

[1] School of Urban and Regional Science, Institute of Finance and Economics Research, Shanghai University of Finance and Economics, No. 777, Guoding Road, Yangpu District, Shanghai 200433, People's Republic of China

aware that the high-efficiency growth model driven by technological innovation is the best choice for achieving the "win-win" goal of economic growth and environmental protection.

Continuous fermentation of the haze problem undoubtedly forces Chinese governments at all levels to re-examine the mechanism relationship between green development vision and innovation-driven strategy. At present, the Chinese government and the public concern about haze pollution reached unprecedented levels (Zheng et al. 2019). How can China breakthrough the predicament of this haze pollution to achieve green development? Does haze pollution necessarily harm the urban innovation and economic performance? Are China's cities be more motivated to seek a way out in technological innovation when they face the dilemma caused by haze pollution? Research on these issues will help to explore the sustainable development and high-quality development in China and even developing countries. The primary purpose of this study is to explore the relationship between haze pollution and urban innovation.

In addition, with the aggravation of haze pollution, on the one hand, the public's awareness of environmental protection is continuously growing; on the other hand, the government pays more attention to environmental problems and invests more in environmental protection technologies, such as providing tax incentives and technology R&D subsidies for enterprises' green development. These induced behaviors provide a market for green consumption and "haze economy," which have a positive crisis-driven effect on the development of cities, especially urban innovation ability. It is also worth pointing out that haze pollution, to some extent, reduces the quality of factor accumulation, leading to the loss of human capital and other innovative elements (Aragón et al. 2017). So, whether haze pollution promotes or restrains urban innovation depends on further discussion.

Based on the above background, this paper uses panel data of 266 prefecture-level cities in China from 2000 to 2016 to investigate the effects of haze pollution on urban innovation in China. We also examine the impact mechanism of haze pollution on urban innovation from four aspects: public environmental awareness, government support for science and technology, pollution governance technology, and technology human capital. Besides, this paper uses the instrumental variable method and a series of robustness tests to prove the reliability of the empirical results. We expect to deepen our understanding of the relationship between haze and innovation through this study and explain why China is still able to achieve innovative breakthroughs in the face of environmental crises.

The contributions of this article are as follows. First, the perspective of urban innovation research is expanded by investigating the relationship between haze pollution and urban innovation. Second, the potential mechanisms of haze problems on urban innovation behavior are deeply discussed, which will help us better understand how the continuous fermentation of haze pollution has a crisis-driven effect on technological innovation. Third, this study employs more observations that cover almost all prefecture-level cities in China, thus obtains more complete empirical evidence. Besides, the conclusions of this paper have clear policy implications, which not only provide empirical data from the municipal level for achieving green development and national innovation-driven strategic policies but also have reference value for the technological innovation practice activities of the government departments and enterprise sectors.

The remainder of this paper is organized as follows. The "Literature review and mechanism analyses" section briefly reviews the existing literature and expounds the theoretical mechanism. The "Methodology and data" section introduces the data, variables, and estimation strategy. The "Empirical results" section presents the empirical results. The conclusion and policy recommendations are given in the "Conclusion and policy implications" section.

Literature review and mechanism analyses

Brief literature review

As a gathering place for various economic resources, cities provide tangible facilities for innovative activities. However, there are significant differences in technological innovation capacity between cities. In recent years, more and more scholars have begun to pay attention to the level of urban innovation, and they have carried out systematic researches on the factors influencing urban innovation from a variety of perspectives.

First, some scholars have paid attention to the impact of innovation factor input on urban or regional innovation (e.g., Caragliu et al. 2016; Faggian and McCann 2008; Ottaviano and Peri 2006). A representative study comes from Faggian and McCann (2008), and they found that the migration and inflow of human capital played a very important role in promoting regional innovation performance. Second, from the perspective of policy or policy uncertainty, scholars believed that urban innovation support policies usually promote urban innovation, while policy uncertainty inhibits innovation (Bhattacharya et al. 2017; Guan and Chen 2012). Third, in environmental management, a large number of scholars verified Porter's hypothesis by discussing the relationship between environmental regulation and technological innovation (Ambec et al. 2013; Brunnermeier and Cohen 2003; Chintrakarn 2008; Hamamoto 2006). Forth, economic agglomeration is also a vital factor, and scholars generally believe that economic agglomeration can significantly promote technological innovation, among which knowledge spillover is a very important channel (e.g., Andersson et al. 2005; Audretsch and Feldman 1996; Berliant and Fujita 2009). Lastly, in term of foreign direct investment (FDI), previous studies considered that FDI can benefit urban innovation activity in the host country via spillover channels such as reverse engineering, demonstration effects, skilled labor turnovers, and supplier-customer relationships (Cheung and Ping 2004; Ning et al. 2016).

In fact, there have been some latest studies on the relationship between air pollution and innovation (Fan et al. 2020; Liu 2018; Yi et al. 2020), but most of the literatures focus on the research of technological innovation on haze control and air improvement. However, few scholars have investigated the impact and mechanism of air pollution or haze pollution on urban innovation, and this study will expand existing relevant researches from this direction.

Mechanism analyses

Mechanism analyses of haze pollution promoting urban innovation

With the aggravation of the haze problem, haze pollution has a crisis-driven effect on urban innovation through the following three channels.

As environmental issues become more and more involved in everyone's daily life, the public's awareness of environmental protection is naturally enhanced, which inevitably changes the behavior of social economy, such as people pay more attention to green travel modes and environmentally protection consumption behavior (Nazelle et al. 2010; Zhang and Mu 2018). At the same time, as the concept of green consumption gradually gains wide recognition from the whole society, consumers are likely to consider whether the company provides environmental protection products or fulfills its social responsibilities when they choose to purchase products (Kim et al. 2016). In an environmentally oriented market, companies are required to carry out green technology innovations while maintaining product functionality to reduce energy consumption and costs (Yang et al. 2017). Therefore, along with the public attach importance to green-life, consumers who are plagued by haze pollution enhances their awareness of environmental protection and raise their desire to purchase green products, which creating a new green market and attracting companies to invest more in R&D of green products (Noailly and Ryfisch 2015), ultimately contributing to the overall improvement of urban technology innovation. Therefore, the first hypothesis is presented:

Hypothesis 1. Haze pollution promotes urban innovation by raising public awareness of environment protection.

Haze pollution is a kind of public goods with negative externalities and belongs to the field of market failure, which requires the government to take the leading role in governance. Faced with this persistent "hazy campaign," the Chinese government has made active efforts in many aspects and take responsibility for pollution control and environmental protection. In the 2018 government work report, it was pointed out that the national investment in science and technology should be tilted to the people's livelihood to strengthen the governance of haze pollution and to overcome major diseases such as cancer. Certainly, haze control not only enables the development of science and technology to benefit the people, but also helps China to build an innovative country comprehensively. The change of energy-saving endogenous technology induced by R&D investment is an important driving force to reduce China's industrial energy intensity (Brunel 2019), and a large amount of money is invested in the process of enterprise innovation can stimulate more innovative behavior.

The increasing haze problems have spurred the government to increase investment in technological innovation, and the more investment in R&D, the greater potential for urban innovation will be. On the one hand, the government's R&D investment provides innovative resources for urban innovation activities directly (Niosi 2010), which reducing the marginal cost and uncertainty of the company's own innovation efforts, and decentralizing the risk of corporate innovation activities (Klette and Møen 2012; Kang and Park 2012), and finally promoting the city's technological innovation capabilities. On the other hand, government R&D investment as a good signal can be passed to investors, which demonstrating the local government's image of supporting innovation and its determination to tackle haze problems, and helping companies be labeled with government-approved to strengthen their investment confidence, and inspiring urban innovative enthusiasm ultimately (Kleer 2010). Accordingly, we consider that haze pollution stimulates the governments at all levels to increase investment in science and technology spending, thereby enhancing the level of urban innovation. Hence, the second hypothesis is drawn:

Hypothesis 2. Haze pollution promotes urban innovation by stimulating the growth of government tech expenditure.

After years of experience, China has realized that energy conservation and emission reduction are the right directions to achieve control of haze pollution. Urban management is an eternal theme of urban development. The extensive economic development pattern (EEDP) not only reflects the loopholes of the relevant government departments on urban management issues but also exposes the various contradictions and problems in the comprehensive management of the urban environment. The economic and environmental costs brought by the EEDP force cities to accelerate the pace of environmental governance system and technological upgrading in the new era. The core technical difficulties in the comprehensive management of urban air pollution are the integrated control of pollutants under heavy pollution and the synergistic emission reduction of PM2.5 (Ryswyk et al. 2017). In order to improve air quality, local governments issued a series of relevant schemes to control air pollution, and actively explore new technologies and methods in air pollution prevention, and make due contributions to the "Blue Sky Protection Campaign" and the "Green Dream Home" (Chang and Wang 2010; Cheng et al. 2019; Hao et al. 2000). In addition, as environmental pollution problems become more and more serious, the entire society has higher requirements for pollution governance technology and performance (Wang and Liu 2020). This urgent demand inevitably forces the government to make greater efforts in ecological conservation and environmental technology upgrading, and ultimately lead to the improvement of urban innovation behavior. Thus, the third hypothesis is drawn:

Hypothesis 3. Haze pollution promotes urban innovation by forcing cities to improve pollution governance technology.

Mechanism of haze pollution inhibiting urban innovation

Human capital is likely to be an important transmission channel for haze pollution affecting the quality of economic development and urban innovation (Chang et al. 2016; Greenstone and Hanna 2014). In recent years, a series of talent introduction policies are increased throughout China, and local governments have fully recognized the importance of human capital to the high-quality development of the urban economy. Talents are not only the indispensable production resource but also the most promising market factor. The reason why large cities maintain a strong innovation and development momentum is because of having innovative talents advantage with absolute quantity and quality. As smog pollution intensifies, it not only damages human health (Hanna and Oliva 2015) and lead to a decline in labor productivity (Zivin and Neidell 2012; Lichter and Pestel 2017) but also reduces the attractiveness of haze cities to high-quality talents (Li et al. 2020; Qin and Zhu 2018). Therefore, this paper analyzes that haze pollution does not have a positive crisis-driven effect on urban innovation from this mechanism, but inhibits urban innovation behavior by reducing the technology human capital. Thus, the following proposition is drawn:

Hypothesis 4. Haze pollution restrains urban innovation by affecting the accumulation of technology human capital.

In summary, theoretically, haze pollution can affect urban innovation through multiple channels. We have constructed a theoretical framework for the impact of haze pollution on urban innovation, as shown in Fig. 1.

Methodology and data

Empirical analysis has been used to verify the effects of haze pollution on urban technology innovation. This section provides more details of the data and testing models used in this study.

Empirical strategy

Based on previous studies (Chang et al. 2016; Lichter and Pestel 2017), we set a benchmark model for the impact of haze pollution on urban technological innovation.

$$Innovation_{it} = \alpha_0 + \alpha_1 PM2.5_{it} + \alpha X + \rho_i + \delta_t + \mu_{it} \quad (1)$$

In the above formula, i and t represent city and year, respectively. $Innovation_{it}$ represents the urban technological innovation, measured by number of patent applications. $PM2.5_{it}$ represents urban haze pollution, which is the core explained variable we focus on. X_{it} represents a set of control variables, mainly composed of some urban characteristics. ρ_i and δ_t represent provincial fixed effect and year fixed effect, respectively, and μ_{it} is a random error term.

In order to accurately identify the causal relationship between haze pollution and urban technological innovation, we must eliminate the interference of endogenous problems. On the one hand, there may be a bothway causal relationship between haze pollution and urban technological innovation. In other words, technological innovation may also cause air pollution. For example, some high-polluting industries generate a large amount of patents while inevitably produce PM2.5 particles. On the other hand, factors that affect PM2.5 and urban technological innovation are very complex according to previous studies, and some unobservable variables are likely to interfere with causality.

Therefore, the instrumental variable method is mainly used to solve the endogenous problems caused by bothway causality and omitted variable bias. We utilize the average temperature as an instrumental variable (IV). Many studies emphasized that temperature is a major factor affecting PM2.5 concentration (Arceo et al. 2016; Chen et al. 2018; Deschenes et al. 2020; Jans et al. 2018). Compared with low temperature, high temperature is less suitable for the diffusion of PM2.5. Hence, the IV we use here meets the correlation assumption. Furthermore, at present, innovation activities mainly rely on high-tech companies, and weather conditions hardly affect urban innovation output (Lichter and Pestel 2017). Thus, the IV also meets the exclusion restriction assumption. We propose the following model to estimate the causal effect of haze pollution on urban technological innovation:

$$PM2.5_{it} = \theta_0 + \theta_1 AT_{it} + \theta X + \rho_i + \delta_t + \mu_{it} \quad (2)$$

Formula (2) is the first stage of 2SLS, and AT_{it} denotes the instrumental variable. The definition of other variables is consistent with the formula (1). Furthermore, in order to examine the hypotheses about the theoretical mechanisms, we adopt the following mediation model (Baron and Kenny 1986):

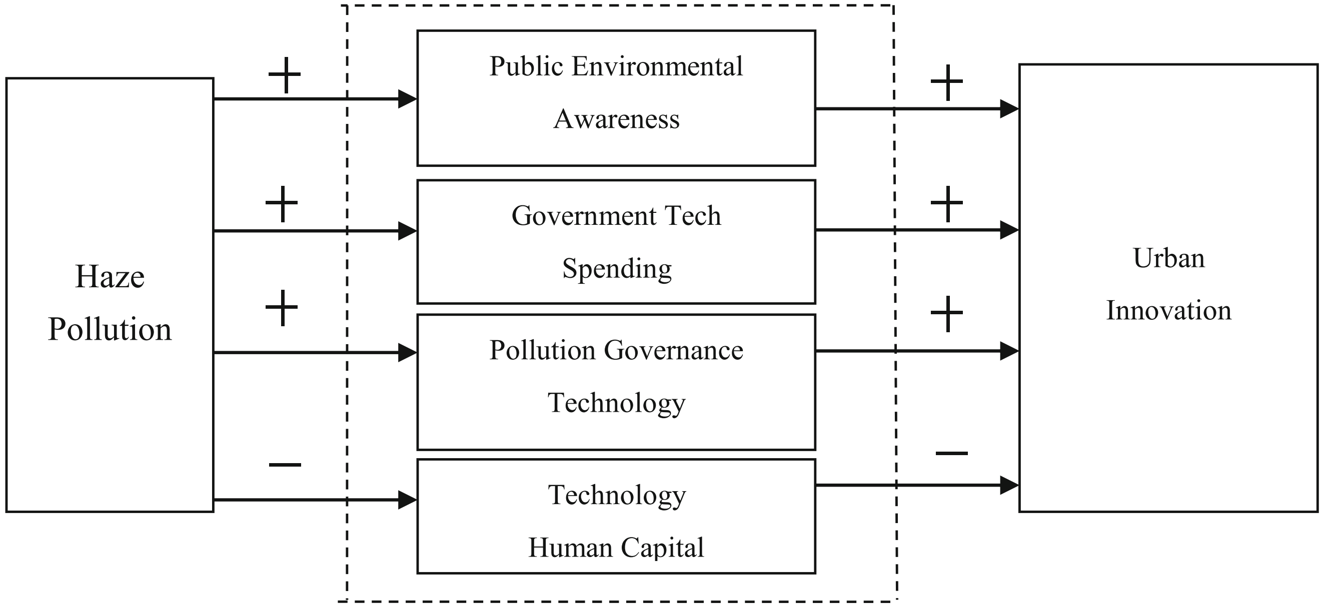

Fig. 1 The mechanism of haze pollution and urban innovation

$$M_{it} = \beta_0 + \beta_1 AT_{it} + \beta_2 X + \rho_i + \delta_t + \mu_{it} \quad (3)$$

$$Innovation_{it} = \lambda_0 + \lambda_1 AT_{it} + \lambda_2 M_{it} + \lambda_3 X + \rho_i + \delta_t + \mu_{it} \quad (4)$$

In formula (3), M_{it} represents the channel variables, containing a series of variables about public environmental awareness, government tech expenditure, pollution governance technology, and technological talents' outflow. If there is a significant correlation between the core explanatory variable PM2.5 and the channel variables, and the absolute value of coefficient on PM2.5 changes compared with the estimated result of formula (2), we can consider the mediation effect is established.

Data and variables

Technological innovation

As the output of technological innovation activities, patents are widely adopted by scholars in the measurement of technological innovation (Archibugi and Planta 1996; Johnstone et al. 2010; Kim 2019; Li et al. 2019; Xuan and Yue 2014). The patent data comes from the Chinese Patent Database, which covers 29,175,479 patent information in China since 1985. This database provides the patent application number, name, affiliated unit and city, applicant and priority in details, as well as the aggregated data on patent applications at the city level (Jiang et al. 2017). In addition, in order to eliminate the impact of urban population size on innovation output, we utilize the number of patent applications per 10,000 persons as the core explained variable.

Haze pollution

Our explanatory variable is haze pollution, which is represented by the average concentration of PM2.5 on the surface of each city. The data of PM2.5 comes from the annual World PM2.5 density map published by Columbia University, which is an indicator used to reflect the urban haze pollution in plenty of previous studies (Van Donkelaar et al. 2010; Ma et al. 2015; Li et al. 2017). Compared with PM10, PM2.5 with a smaller diameter can penetrate deep into the human respiratory organs and easily carry pathogenic bacteria, viruses, and organic pollutants, which greatly increases the risk of cancer, deformity, and mutation (Brunekreef and Holgate 2002; Gao et al. 2015; He et al. 2020; Neidell 2004; Ye et al. 2016). Therefore, PM2.5 has received wide attention from the Chinese government and the public.

We have mapped the spatial distribution of PM2.5 in China from 2000 to 2016. In Fig. 2, the PM2.5 concentration and pollution range are increased in most parts of China, especially in the North China Plain[1]. In 2016, the five cities with the highest average concentrations of PM2.5 are Dezhou, Liaocheng, Hengshui, Zhangzhou, and Langfang, all of which are located in the North China Plain. Comparing Fig. 2c and Fig. 2d, although the haze pollution in some areas has mitigated in recent years, such as the Chengdu-Chongqing urban agglomeration and the middle reaches of the Yangtze River, the situation is still not optimistic. China's haze pollution shows that the east is more serious than the central and western regions, and the north is more severe than the south.

[1] The North China Plain mainly covers Beijing, Tianjin, Hebei, Shandong, and parts of Henan, Anhui, and Jiangsu.

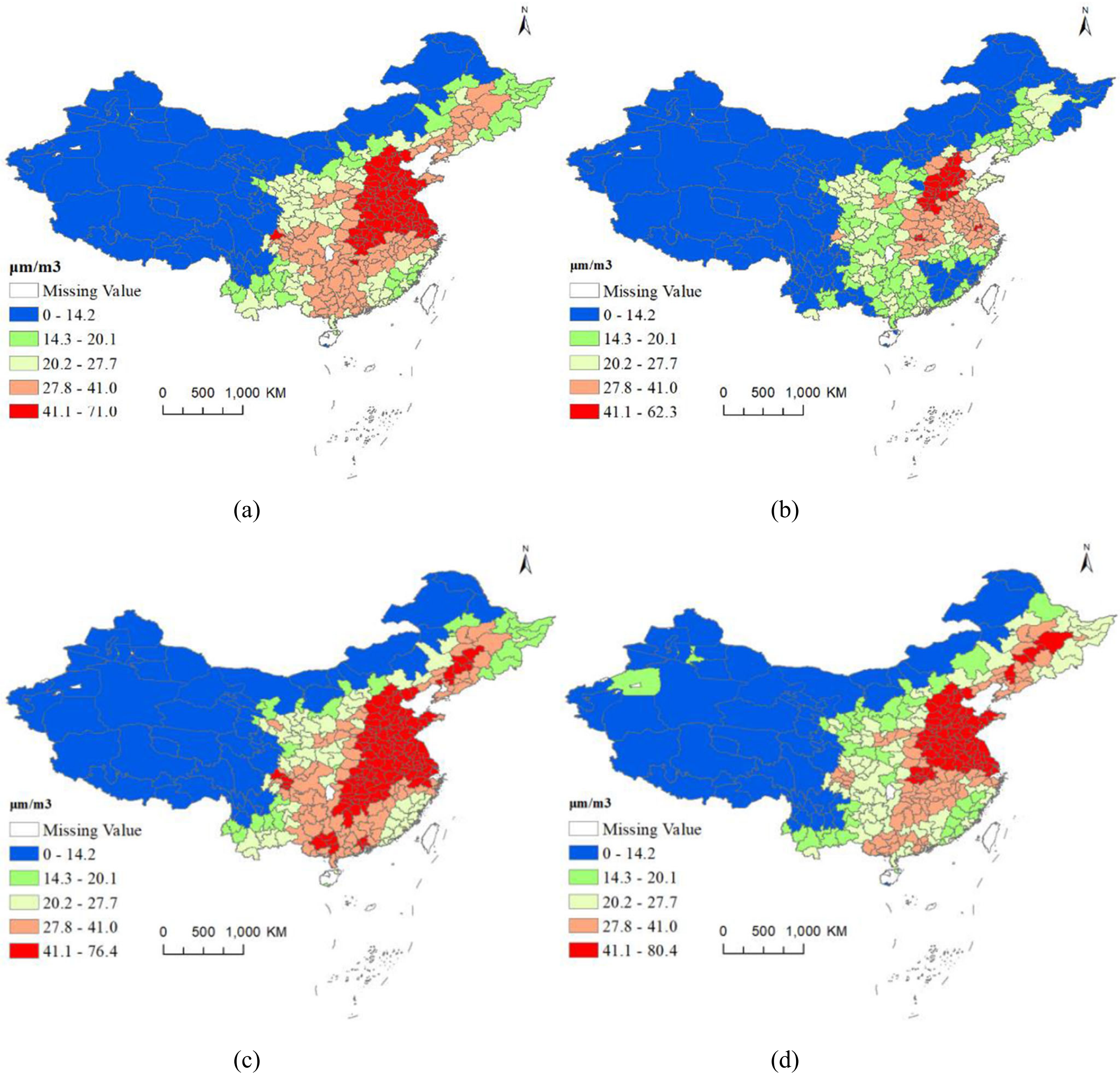

Fig. 2 Distribution and evolution of PM2.5 in Chinese cities. **a** Average value of PM2.5 concentration in 2000–2016. **b** PM2.5 concentration value in 2000. **c** PM2.5 concentration value in 2008. **d** PM2.5 concentration value in 2016

Average temperature

The average urban temperature data comes from 331 weather stations in China. These weather stations recorded the temperature of the host city on daily basis from 1984 onwards. We add up these daily temperature data and calculate the average to get the annual average temperature of each city, and then match it with the other city-level data. It is worth mentioning that some weather stations in the western region are lack of data, which lead to a decrease in the sample size of the instrumental variable method.

Control variables

According to existing studies (Caragliu et al. 2016; Chen and Chen 2018; Wang et al. 2020; Zhang et al. 2019), we control a set of urban characteristic variables in this paper. First, as an important driving force for the improvement of the urban innovation capabilities, *economic growth* is expressed by the growth rate of real GDP. Second, physical capital includes three variables, namely foreign direct investment (*FDI*), *government expenditure*, and *financial development*. In China, foreign capital, government, and financial institutions are the main sources of funding for the innovation sector. Third, urban human capital also provides basic elements for innovative activities, but it is difficult to be measured by selecting appropriate indicators (Mankwi et al. 1992; Jones 2014)[2]. We have to select several indicators from the perspective of urban education, namely *number of college students*, *number of college teachers*, *number of middle school students*, and *education expenditure*. Fourth, technological innovation may also be affected by the consumer market and infrastructure. Subject to the availability of data, we adopt *per capita salary* as a substitute indicator of consumption, and use road transportation to measure *infrastructure*. Lastly, two variables that affect both haze pollution and urban innovation, namely *industrial structure* and *manufacturing*, are included in the set of our control variables to further reduce estimation bias.

Descriptive statistics

Table 1 presents the definition and descriptive statistics of our main variables used in the analysis, and all variables are winsorized by replacing samples among the top 1% and the bottom 1%. In order to ensure the comparability of the research objects, we deleted the four municipalities: Beijing, Shanghai, Tianjin, and Chongqing. In addition, due to the excessive dispersion of some variables, such as the number of college students and college teachers, we take the logarithm to reduce the heteroscedasticity. After deleting other missing values of core variables, our final sample size is 3,407, which consists of unbalanced panel data with 266 cities[3] from 2000 to 2016. In our samples, on average, there are 4.533 patent applications per 10,000 persons, and the standard deviation of *technological innovation* is higher, suggesting that the urban innovation capabilities are likely to be unbalanced in China. In addition, the results of descriptive statistics suggest that the average PM2.5 concentration is 34.95 mg/m^3, the average economic growth rate is 12.2%, the intensity of education expenditure is 17.3%, and the industrial structure index is 2.225.

[2] Some studies use the average years of education per capita to measure the human capital of a certain region or province (e.g., Chen and Chen 2018; Chamarbagwala and Hilcías 2011; Földvári and Leeuwen 2009; Lan et al. 2012), but this indicator is not available at the city level.

[3] The city in our samples is distributed in 28 provinces or autonomous regions except Tibet. Specifically, we include all prefecture-level cities in 21 provinces or autonomous regions, like Jiangsu, but there are incomplete in seven provinces or autonomous regions, including Xiangyang in Hubei, Yingkou in Liaoning, Yuncheng in Shanxi, and Guyuan and Zhongwei in Ningxia. In addition, among the cities in Xinjiang, only Urumqi and Karamay are involved, and Qinghai only covers Xining and Haidong.

Empirical results

Baseline results

Table 2 reports our baseline results of the effects of haze pollution on urban technological innovation in China. In columns (1), we only control the province and year fixed effects without any urban characteristic variables, and we find that the coefficient on PM2.5 is significantly positive. In column (2), we add some control variable, and the result remains unchanged. In column (3), we include two vital control variables, namely industrial structure and manufacturing, which simultaneously affect the production of PM2.5 and urban innovation capability. The OLS estimations show that there is a positive correlation between haze pollution and urban technological innovation.

Our results seem to be inconsistent with some previously related studies (Chang et al. 2016; Chen and Chen 2018; Fang et al. 2016; Greenstone and Hanna 2014), so we presume that there is a nonlinear relationship between haze pollution and urban technological innovation. In column (4), we further add the square of PM2.5, and find the estimates are both insignificant, suggesting that the nonlinear relationships are not supported.

IV estimations

Since the estimation results in Table 2 are likely to be disturbed by potential endogeneity, we further use the IV method to identify the causal relationship between haze pollution and urban technological innovation. Table 3 presents the IV estimation results for 2SLS, with the first stage estimation results are reported in columns (1) and (3). The instrumental variable, average temperature, is strongly positively correlated with PM2.5 at the 1% significance level. Besides, the first stage F value is 48.652 in column (3), and the P values of the Anderson-Rubin (AR) Wald test is less than 0.05 in column (4), indicating that our IV meets the correlation restriction and avoid the weak instrument variable problem (Stock and Yogo 2005). More importantly, the IV estimate of haze pollution in column (4) is positive at the 1% significance level, indicating that the crisis-driven effect of haze pollution in driving urban technological innovation is indeed established. However, the estimated coefficients on PM2.5 under the IV method framework are larger in magnitude than the OLS estimate. The possible reason is the overestimation caused by the local average treatment effect (LATE) of the IV approach (Angrist and Pischke 2008), but it does not affect the identification of causality.

Mechanism tests

In this section, we explore several mechanisms to explain why haze pollution has a crisis-driven effect on promoting urban

Table 1 Statistical description of main variables

Variables	Definition	Number	Mean	SD
Technological innovation	The number of urban patent applications per 10,000 persons	3407	4.533	11.53
PM2.5	The urban average concentration of PM2.5 (10 mg/m^3)	3407	3.493	1.571
Average temperature	Urban annual average temperature	3353	15.70	4.576
Economic growth	The annual growth rate of real GDP	3407	0.122	0.037
FDI	The ratio of 100 times the total of actually utilized foreign capital to GDP	3407	0.332	0.458
Government expenditure	Per capita government expenditure (yuan)	3407	0.403	0.381
Financial development	The ratio of total deposits and loans of financial institutions to GDP	3407	2.293	1.693
Number of college students	The logarithm of the number of college students	3407	10.29	1.476
Number of college teachers	The logarithm of the number of college teachers	3407	7.510	1.411
Number of middle school students	The logarithm of the number of middle school students	3407	12.24	0.646
Education expenditure	The ratio of government education expenditure to total expenditure	3407	0.173	0.064
Per capita salary	The logarithm of the urban per capita salary (yuan)	3407	10.22	0.553
Infrastructure	Annual road transport volume (100 million tons)	3407	0.791	0.695
Industrial structure	The primary industry*1 + the secondary industry*2 + the tertiary industry*3	3407	2.225	0.131
Manufacture	The number of manufacturing employees per 10 persons	3407	0.349	0.618

technological innovation. The sample sizes vary for different mechanism tests, depending on data availability.

Public environmental awareness

As noted above, the green economy brought about by the public awareness of environmental protection helps promote technological innovation. We consider two channel variables, namely *number of petitioners* and *number of complaint reports*, to measure public environmental awareness. Although existing literature rarely involves the measurement of residents' environmental awareness, urban residents' petitions or complaint reports to government departments due to environmental issues may partly reflect the public's concern for environmental protection. Unfortunately, we only found provincial petition data in the China Environmental Yearbook. According to the handling method from Hausmann et al. (2007) and Xu and Lu (2009), we use the proportion of urban industrial output value in the province as a weight to obtain indicators at urban level.

Table 4 reports the mediation effect of public environmental awareness. In columns (1) and (2), what we present is the estimated results of OLS and IV after removing the missing values of the intermediate variables. In column (3) of panel A, the estimated coefficient on PM2.5 is positive and very close to significance at the 10% level. More importantly, regardless of column (3) or column (4), the absolute value of the coefficients on the core explanatory variable has become smaller after adding the variable of public environmental awareness, implying that the public awareness of environmental protection caused by hazy pollution does have an intermediary effect on the promotion of urban technological innovation. In addition, Panel B of Table 4 shows the mediation effect estimation result using the number of complaint reports about environmental issues as a proxy indicator. We find that the conclusion is consistent with the study in Panel A.

In summary, these results provide supportive evidence for Hypothesis 1 that haze pollution has brought about the improvement of public awareness of environmental protection and the development of green economy, thus creating the crisis-driven effect for promoting urban technological innovation.

Government tech expenditure

As highlighted in the "Literature review and mechanism analyses" section above, severe haze pollution is likely to prompt the government to invest more tech funds for pollution control and help enterprises green production. To confirm this mechanism, the variable *government tech expenditure* is measured by the per capita urban annual government expenditure on science and technology, and the results are shown in Table 5.

Columns (1) and (2) report the results of eliminating missing values as before. In column (3), the estimated result shows that there is a definite correlation between PM2.5 and urban technological innovation, suggesting that the more serious the haze pollution is, the more government tech investment is likely to be. Comparing the results in column (1) and column (4), the coefficient on PM2.5 decreases, indicating that the mediating effect of government tech expenditure in the OLS estimation is valid. Similarly, the IV estimation result in Table 5 also indicates that the increase in government tech investment caused by haze pollution can enhance the urban technological innovation capabilities.

Table 2 The impact of haze pollution on urban technological innovation, baseline results

Variables	(1)	(2)	(3)	(4)
PM2.5	0.7224***	0.4241***	0.3539**	0.4968
	(0.1717)	(0.1594)	(0.1594)	(0.5098)
Square of PM2.5				− 0.0175
				(0.0613)
Economic growth		− 8.1879	− 8.7227	− 8.7429
		(5.7060)	(5.5519)	(5.5477)
FDI		0.7070	0.3999	0.3932
		(0.7285)	(0.7006)	(0.7004)
Government expenditure		11.4136***	6.0411***	6.0437***
		(1.5076)	(1.6267)	(1.6280)
Financial development		0.1448	0.1302	0.1316
		(0.1187)	(0.1108)	(0.1112)
Number of college students		− 0.4273	− 0.1975	− 0.2008
		(0.3054)	(0.2824)	(0.2831)
Number of college teachers		1.2361***	0.6172*	0.6199*
		(0.3792)	(0.3442)	(0.3452)
Number of middle school students		0.2557	0.4880	0.4811
		(0.4544)	(0.4384)	(0.4428)
Education expenditure		4.6713	0.9429	0.9537
		(6.5008)	(6.4127)	(6.4178)
Per capita salary		8.0368***	7.6009***	7.5996***
		(1.5920)	(1.5511)	(1.5514)
Infrastructure		0.5179	0.4477	0.4456
		(0.3630)	(0.3494)	(0.3497)
Industrial structure			6.2777***	6.2608***
			(1.8940)	(1.8949)
Manufacture			3.8394***	3.8349***
			(1.2114)	(1.2134)
Constant	0.7224***	0.4241***	0.3539**	0.4968
	(0.1717)	(0.1594)	(0.1594)	(0.5098)
Province FE	YES	YES	YES	YES
Year FE	YES	YES	YES	YES
R-square	0.1344	0.2998	0.3224	0.3223
Number	3407	3407	3407	3407

The significance levels of 1%, 5%, and 10% are denoted by ***, **, and *, respectively. Robust standard errors are reported in parentheses

To sum up, our estimated result supports our Hypothesis 2 and confirms that government tech expenditure is one of the intermediary factors in the promotion of urban technological innovation capabilities by haze pollution.

Pollution governance technology

As discussed in the "Literature review and mechanism analyses" section, the intensification of haze pollution may encourage more resources to flow to the field of pollution control, which helps improve the urban pollution governance capacity and brings a large number of innovative output and new green industrial products. It is a pity that we cannot find an appropriate indicator to measure urban PM2.5 governance technology, therefore, we utilize industrial smokes governance technology as a substitute indicator, which is represented by the urban annual industrial smokes removal rate.

Table 6 shows the results of mediation effect of urban pollution governance technology. In column (3), the coefficient on PM2.5 is significantly positive, which means the better pollution control technology in cities with more severe hazy pollution. However, the coefficient of *pollution governance technology* is negative in column (4) and column (5), and comparing column (1) and column (2), the estimated

Table 3 The impact of haze pollution on urban technological innovation, IV estimations

Variables	(1) PM2.5	(2) Technological innovation	(3) PM2.5	(4) Technological innovation
PM2.5		4.0978***		3.1126***
		(1.2100)		(1.2069)
Average temperature	0.1161***		0.1009***	
	(0.0154)		(0.0145)	
Control variables	No	No	Yes	Yes
Province FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
First stage *F* value	56.8804		48.6520	
Anderson-Rubin Wald test		11.3429		7.0007
P value		0.0008		0.0081
Number	3353	3353	3353	3353

The significance levels of 1%, 5%, and 10% are denoted by ***, **, and *, respectively. Robust standard errors are reported in parentheses. The control variables are consistent with the column (3) of Table 2

coefficient on PM2.5 has increased respectively, which implies that there is an inhibiting effect in pollution governance technology (Mackinnon et al. 2000). The possible reason is that the industrial smokes control technology is relatively mature in China, which is not enough to reflect the pollution control technology of a city. But at least, our results reflect

Table 4 Haze pollution and public environmental awareness

Variables	(1) Technological innovation OLS	(2) Technological innovation IV	(3) Public environmental awareness OLS	(4) Technological innovation OLS	(5) Technological innovation IV
Panel A—the number of petitioners					
PM2.5	0.3595**	3.1342***	0.0129	0.3418**	2.7516**
	(0.1657)	(1.2030)	(0.0081)	(0.1649)	(1.1892)
Public environmental awareness				1.3631***	1.1798***
				(0.3258)	(0.3259)
Control variables	Yes	Yes	Yes	Yes	Yes
Province FE	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes
First stage *F* value		49.3629			48.2615
Anderson-Rubin Wald test		7.1362			5.5411
P value		0.0076			0.0186
Number	3183	3129	3183	3183	3129
Panel B—the number of complaint reports					
PM2.5	0.3595**	3.1342***	0.0226**	0.3306**	2.8710**
	(0.1657)	(1.2030)	(0.0090)	(0.1648)	(1.2014)
Public environmental awareness				1.2755***	1.0323***
				(0.3237)	(0.3324)
Control variables	Yes	Yes	Yes	Yes	Yes
Province FE	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes
First stage *F* value		49.3629			48.1409
Anderson-Rubin Wald test		7.1362			5.9569
P value		0.0076			0.0147
Number	3183	3129	3183	3183	3129

The significance levels of 1%, 5%, and 10% are denoted by ***, **, and *, respectively. Robust standard errors are reported in parentheses. The control variables are consistent with the column (3) of Table 2

Table 5 Haze pollution and government tech expenditure

Variables	(1) Technological innovation OLS	(2) Technological innovation IV	(3) Government tech expenditure OLS	(4) Technological innovation OLS	(5) Technological innovation IV
PM2.5	0.3539**	3.1126***	0.3195***	0.3243**	3.0211**
	(0.1594)	(1.2069)	(0.0979)	(0.1584)	(1.2009)
Government tech expenditure				0.0926*	0.0778
				(0.0488)	(0.0491)
Control variables	Yes	Yes	Yes	Yes	Yes
Province FE	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes
First stage *F* value		48.6520			48.0348
Anderson-Rubin Wald test		7.0007			6.6673
P value		0.0081			0.0098
Number	3407	3353	3407	3407	3353

The significance levels of 1%, 5%, and 10% are denoted by ***, **, and *, respectively. Robust standard errors are reported in parentheses. The control variables are consistent with the column (3) of Table 2

the positive relationship between haze pollution and environmental control technologies.

Taken together, our empirical results do not support Hypothesis 3, but if we find a suitable indicator to measure urban haze pollution control technology in further studies, some useful conclusions may be obtained.

Technology brain drain

As mentioned in Hypothesis 4, we consider a negative effect that haze pollution may cause the loss of technological talents, which is not conducive to the improvement of urban technological innovation capabilities. We employ the proportion of the employed population in scientific research and technology industries to measure the mediating variable *technology employees*, and the results of the mediation effect test are shown in Table 7.

In column (3), the coefficient on PM2.5 is significantly negative, indicating that haze pollution is harmful to the accumulation of urban technological talents, which is consistent with the findings of some existing literature based on micro-data (Aragón et al. 2017; Chang et al. 2016; Greenstone and

Table 6 Haze pollution and urban pollution governance technology

Variables	(1) Technological innovation OLS	(2) Technological innovation IV	(3) Pollution governance technology OLS	(4) Technological innovation OLS	(5) Technological innovation IV
PM2.5	0.3495**	3.3257***	0.0063***	0.3543**	3.3627***
	(0.1609)	(1.2034)	(0.0018)	(0.1614)	(1.2150)
Pollution governance technology				-0.7682	-1.8950*
				(0.8436)	(1.0202)
Control variables	Yes	Yes	Yes	Yes	Yes
Province FE	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes
First stage *F* value		48.8399			47.9835
Anderson-Rubin Wald test		8.2824			8.3397
P value		0.0040			0.0039
Number	3329	3275	3329	3329	3275

The significance levels of 1%, 5%, and 10% are denoted by ***, **, and *, respectively. Robust standard errors are reported in parentheses. The control variables are consistent with the column (3) of Table 2

Hanna 2014; Li et al. 2020; Qin and Zhu 2018; Zivin and Neidell 2012). In columns (4) and (5), the coefficient of PM2.5 has changed after adding the *technology employees*. However, since the intermediary variable is statistically insignificant, the magnitude of the change in the estimated coefficient on PM2.5 is not large, which imply that although haze pollution has caused urban technology brain drain, it has not led to excessive losses in technological innovation.

Generally speaking, these findings partially support Hypothesis 4 and suggest that haze pollution is likely to suffer adverse consequences of urban technology brain drain, while it is not enough to bring about an obvious decline in the urban innovation capabilities.

Heterogeneity analysis

The influence of haze pollution on urban technological innovation may be heterogeneous. First, due to the differences in economic development and technological innovation among various regions in China, we divided into three sub-samples of the eastern, central, and western to analyze the heterogeneity according to the previous literature (Fan et al. 2016; Wei et al. 2009; Yao and Zhang 2001)[4]. In the first three columns of Table 8, the IV estimation results show that the technological innovation effect of haze pollution only appears in the samples from the eastern region. The underlying reasons are as follows. On the one hand, as shown in Fig. 2 of the "Methodology and data" section, the hazy pollution in the eastern region may be more serious than that in the central and western regions, therefore, governments and citizens in the east are more worried about the harm of hazy pollution. On the other hand, the eastern region has stronger economic development and innovation vitality, and it is easier to develop products to prevent and control haze pollution, thus increasing the number of related patent applications.

Second, we divide into two sub-samples based on whether the non-agricultural population reaches 1 million or not[5]. In columns (4) and (5) of Table 8, we find that the coefficient on PM2.5 is positive and very close to the statistically significant at the 10% level in the sample of large cities. The reason is similar to the previous results. The economic strength, innovation capability, and public resources of big cities are better, and the crisis-driven effect of haze pollution on urban technological innovation is also more obvious.

Third, due to China's special climate distribution, most northern cities need to burn coal for central heating in winter, while southern cities do not, which may result in more severe haze pollution in northern Chinese cities (Almond et al. 2009). Therefore, we further discussed the north-south differences in the impact of pollution on urban technological innovation[6]. In columns (6) and (7), the results show that the effect of technological innovation forced by haze pollution is only significant in northern cities, which implies that cities with more severe haze pollution can improve their technological innovation.

Robustness checks

We conduct several robustness checks. First, we exclude some extreme samples, such as sub-provincial cities, capital cities,and mega cities with a population of more than 5 million. In the first three columns of Table 9, no matter which extreme observations are eliminated, the results are qualitatively similar to our main results, which mean the crisis-driven effect of haze pollution on promoting urban technological innovation is still established, both in OLS and IV estimations.

Second, we utilize the logarithm of the annual urban patent applications as the substitute explained variable. In column (4) of Table 9, although the estimated coefficient on PM2.5 is insignificant by OLS method in panel A, according to IV estimation, we can still conclude that haze pollution does not damage urban technological innovation.

Third, we make a few changes to the set of our control variables. In column (5), we add three weather variables, namely rainfall, sunshine time, and relative humidity. In column (6), we control the two available air pollution variables, including sulfur dioxide and industrial smoke and dust emissions. In column (7), we lag all previous control variables by one period. Certainly, we find that these changes have little effect on our main results.

Lastly, we use the city-level cluster standard errors, and the result is shown in column (8) of Table 9. Whether adopting OLS or IV estimation method, the statistical significance is consistent with the previous results, and the finding that haze pollution promotes urban technological innovation under the influence of forced effects is not challenged.

[4] The eastern region includes eight provinces, namely Hebei, Shandong, Liaoning, Jiangsu, Zhejiang, Fujian, Guangdong, and Hainan. There are eight provinces in the central region, and they are Heilongjiang, Jilin, Shanxi, Jiangxi, Anhui, Henan, Hubei, and Hunan. The remaining 11 provinces or autonomous regions belong to the western region, namely Xinjiang, Inner Mongolia, Ningxia, Gansu, Qinghai, Tibet, Yunnan, Guizhou, Sichuan, Guangxi, and Shaanxi.

[5] The division standard comes from the "Notice on Adjusting the Dividing Standards of Urban Size" issued by the China's state council in 2014.

[6] Following conventional practices, we employ the Qinling Mountains and Huai River as the dividing line between China's north and south. However, in the southern provinces, due to the central heating in Xuzhou, we regard it as a northern city. In contrast, in the northern provinces, Xinyang, Luohe, Zhoukou, Nanyang, and Hanzhong do not have central heating, so they are considered as southern cities in the samples.

Table 7 Haze pollution and technology brain drain

Variables	(1) Technological innovation OLS	(2) Technological innovation IV	(3) Technology employees OLS	(4) Technological innovation OLS	(5) Technological innovation IV
PM2.5	0.4454***	2.4362**	-0.0282*	0.4496***	2.4549**
	(0.1694)	(1.0629)	(0.0148)	(0.1693)	(1.0647)
Technology employees				0.1486	0.2373
				(0.1953)	(0.1979)
Control variables	Yes	Yes	Yes	Yes	Yes
Province FE	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes
First stage *F* value		46.2444			45.6727
Anderson-Rubin Wald test		5.3664			5.4410
P value		0.0205			0.0197
Number	2933	2892	2933	2933	2892

The significance levels of 1%, 5%, and 10% are denoted by ***, **, and *, respectively. Robust standard errors are reported in parentheses. The control variables are consistent with the column (3) of Table 2

Conclusions and policy implications

In recent years, haze pollution has become an environmental issue that is widely concerned by the Chinese government and the general public. So it is a great practical significance to explore the internal relationship between haze pollution and urban innovation under the background of innovation-driven and green development strategy. In this paper, we empirically examine the impact of haze pollution on urban technological innovation in China. Our benchmark result shows that haze pollution has promoted the progress of urban technological innovation capabilities. Moreover, to identify the causal effect, we employ an instrumental variable method to overcome potential endogenous problems. The IV-estimated results remain unchanged, which indicates that the crisis-driven effect of haze pollution on the improvement of urban technological innovation does exist. In addition, we explore several potential mechanisms of why haze pollution is conducive to promoting urban technological innovation. The estimated results indicate that haze pollution can raise public environmental awareness and encourage local governments to invest more in technology. Meanwhile, although haze pollution inevitably leads to the loss of some scientific and technological talents, it has little impact on urban technological innovation. Moreover, our heterogeneity tests show that the positive impact of haze pollution on technological innovation is more obvious in eastern cities, large cities, and northern cities. The possible reason is that residents and governments in these cities pay more

Table 8 Heterogeneity test by cities, IV estimations

Variables	(1) Eastern region	(2) Central region	(3) Western region	(4) Large cities	(5) Small–medium cities	(6) Northern cities	(7) Southern cities
PM2.5	3.9459***	3.4650	− 4.6984	3.7586	0.2922	0.6651*	− 10.1342
	(1.4512)	(4.9156)	(2.9863)	(2.3524)	(0.9283)	(0.3613)	(8.0604)
Control variables	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Province FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
First stage F value	44.1108	0.8362	10.9633	19.8639	25.9922	88.2249	4.8233
Anderson-Rubin Wald test	8.2155	1.0449	3.9681	2.7657	0.0984	3.3906	3.1288
P value	0.0042	0.3067	0.0464	0.0963	0.7537	0.0656	0.0769
Number	1304	1145	904	1710	1643	1481	1872

The significance levels of 1%, 5%, and 10% are denoted by ***, **, and *, respectively. Robust standard errors are reported in parentheses. The control variables are consistent with the column (3) of Table 2

Table 9 Robustness checks using alternative specifications or removing extreme observations

Variables	(1) Deleting sub-provincial cities	(2) Deleting capital cities	(3) Deleting mega cities	(4) Logarithm of patents	(5) Adding weather variables	(6) Adding other air pollution variables	(7) Control variables all lagging one period	(8) Clustering at the city level
Panel A—OLS								
PM2.5	0.3980**	0.3429**	0.3062*	0.0422	0.4870***	0.3438**	0.3247*	0.3539**
	(0.1552)	(0.1625)	(0.1691)	(0.0266)	(0.1738)	(0.1600)	(0.1681)	(0.1562)
Panel B—IV								
PM2.5	2.9975***	3.3423***	3.6879**	0.6549***	2.7095**	3.5004***	3.2953**	3.1126*
	(1.0615)	(1.1037)	(1.4859)	(0.2362)	(1.0736)	(1.2177)	(1.3473)	(1.7089)
First stage *F* value	52.1270	55.9569	32.5575	48.6520	73.2141	51.3860	43.3733	48.6520
Anderson-Rubin Wald test	8.6203	9.9985	7.1660	8.5311	6.5238	9.0764	6.3480	
P value	0.0033	0.0016	0.0074	0.0035	0.0106	0.0026	0.0118	
Control variables	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Province FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Number	3161	3028	2987	3353	3006	3311	3005	3353

The significance levels of 1%, 5%, and 10% are denoted by ***, **, and *, respectively. Robust standard errors are reported in parentheses in the first seven columns. The control variables are consistent with the column (3) of Table 2

attention to smog and respond more actively. Lastly, some methods have been adopted for robustness checks excluding some extreme samples, replacing the explained variable, or tighter controlling, and we find that our main results are still stable and convincing.

Based on the above analysis, the policy implication can be conclude that firstly, government authorities should try its best to cooperate with the role of the market mechanism to achieve the balanced development of product and factor markets, and reduce the adverse effects such as the loss of high-tech talents of haze pollution on urban innovation. Secondly, local government should focus on improving and optimizing the urban pollution control system to mitigate the pressure of social pollution control, and provide better public goods and services to the public, to further release the innovation impetus and vitality of the city.

However, although we argue that haze pollution can stimulate urban innovation, this study does not suggesting to improve the urban innovation by indulging haze pollution. We actually want to reveal a series of reactions made by the Chinese governments, enterprises, and citizens from the perspective of "Cities trapped by hazy," which have forced the urban innovation. Obviously, the technological innovation effect triggered by haze is unsustainable and more dangerous, so the prevention and control of haze pollution by all government levels is still important. It should be emphasized that this paper is not intended to deny the damage caused by haze pollution or environmental pollution to China's economic growth, but rather to reveal that a series of government and enterprise actions caused by haze pollution in a developing country with strong administrative power and urban innovation vitality. Therefore, this implies that other countries may not necessarily have such innovative induced or reverse effects, but still need to pay attention to the complex impact of haze and other environmental pollution on socio-economic development.

Authors' contributions All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by Chunkai Zhao. The first draft of the manuscript was written by Min Deng and Xiguang Cao, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Compliance with ethical standards

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