Are the Economic Consequences of Climate Change Really "Pro-Poor"?

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In order to comprehensively study the influence of climate change on economic growth and energy conservation & emission reduction, this paper first uses the non-radial directional distance function (NDDF) to calculate the city-level green economic efficiency in China during 2003–2016. The causal effect of daily temperature changes on green economic efficiency is then identified to evaluate the economic consequences of climate change. It finds that relative to the 6~12℃ temperature benchmark, any decrease or increase in temperature will pose negative influence on green economic efficiency; moreover, such effects are only observed in developed cities, but not significant in less-developed ones. This reflects that the economic consequences of climate change are "robbing the rich" to some extents, which differs widely from the "pro-poor" conclusion in the majority of literature previously. Subject to the robustness test and with possible competitive explanations excluded, this finding still stands. The mechanism test reveals that temperature rise brings about economic consequences that "rob the rich" by affecting labor productivity, efficiency of energy conservation & emission reduction and execution of environmental regulations by local government. This study brings a different perspective for understanding the economic consequences of climate change and offers empirical basis for identifying responsibilities of local government in climate governance.

Keywords: climate change, green economic efficiency, adaptive behavior, energy conservation & emission reduction

1. Introduction

In the context of global warming, how climate change affects economic development has been a topic of great interest for policymakers and in the academic

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community. Some researchers investigated from various perspectives the influence of rise in average temperature on agriculture (Mendelsohn *et al*., 1994; Schlenker *et al.*, 2005; Schlenker and Roberts, 2009; Zhang *et al*., 2017), industrial output or economic growth (Dell *et al.*, 2012; Chen and Yang, 2019), health or mortality (Heutel *et al*., 2017; Yu *et al.*, 2019; Kim *et al*., 2019), international trade (Jones and Olken, 2010; Li *et al.*, 2015), and labor productivity or total factor productivity (Zhang *et al*., 2018; Letta and Tol, 2019; Kumar and Khanna, 2019). They unanimously found that rise in average temperature posed negative influence on all of these economic variables. However, further to which areas, developed or backward, have been most susceptible to the economic consequences of climate change, these researchers failed to reach any consensus.

More studies believed that the adverse effects of climate change were observed mainly in backward areas, rather than developed ones; in another word, the economic consequences of climate change were "pro-poor" to some degrees (Dell *et al*., 2012; Deryugina and Hsiang, 2014; Letta and Tol, 2019; Kumar and Khanna, 2019). However, some other studies came to different conclusions. For instance, Burke *et al*. (2015) used data on productivity of 166 countries worldwide in 1960–2010 and found no obvious discrepancy between rich and poor countries in productivity loss caused by climate change. Regrettably, though regional heterogeneity in economic consequences of climate change has been controversial, studies that pay attention to negative effects of climate change in rich areas are rare to see. It's generally neglected that compared with less-developed areas, rich areas tend to take adaptive behaviors that incur enormous cost of energy consumption and pollution emission in response to climate change, which may affect the economic consequences of climate change in rich areas.

So, if productivity, energy consumption and pollution emission are all taken into consideration with respect to the effects of climate change on green economic efficiency, will the conclusion that the economic consequences of climate change are "pro-poor" still stand? Answer to this question will be both supplement to prior theoretical researches and realistic reference for China to realize win-win results in economic development and climate governance. As the second largest economy in the world, China has been actively coping with climate change since the 18th National Congress of the CPC. Domestically, it released multiple documents such as *China's National Plan on Implementation of the 2030 Agenda for Sustainable Development*, *China's National Climate Change Programme (2014–2020)* and *Development Programme on National Carbon Emissions Trading Market (Power Generation Industry)* to push forward climate governance; internationally, the country proactively engaged in negotiations on the *United Nations Framework Convention on Climate Change*, and took the lead to propose its intended nationally determined contributions to cope with climate change. While actively taking greater responsibilities in climate governance, China is shifting from fast economic growth to high-quality growth and pursuing green development of industrial economy (Shi and Li, 2019). In such a context, to clarify the influence of climate change on green development and understand regional heterogeneity will be helpful for optimizing the design of green development-oriented climate governance policies in China and stimulating the internal driving force of local government for engaging in climate governance collaboration.

On such basis, this paper first adopts the non-radial directional distance function (NDDF) to calculate the green economic efficiency of Chinese cities in 2003−2016; then, it estimates the causal effects of temperature change on the efficiency. It finds that relative to the 6~12℃ temperature benchmark, any decrease or increase in temperature will pose significant negative influence on green economic efficiency of developed cities, but influence fails to pass the significance test on less-developed cities.

This paper is possibly innovative in the following areas. First, it takes a different perspective of cost of adaptive behaviors and thus expands the study on relationships between climate change and economic productivity. Though some researchers have recently started to realize human adaptive behaviors in response to climate change incur cost in non-productive energy consumption and pollution emission, no study has been conducted yet to empirically test the influence of such non-productive cost on economy and its regional heterogeneity. This paper effectively makes up for it by identifying the causal effects of climate change on green economic efficiency. Second, this paper verifies for the first time the possible "over-adaptive" behaviors in developed areas to cope with climate change, and the non-productive energy consumption and pollution emission behind such behaviors will undermine green economic development. This result demonstrates that reasonable adaptive behaviors in developed areas will contribute to win-win benefits in climate governance and economic development and offer valuable insights for backward areas and countries to design reasonable climate governance policies during economic development. Third, this paper makes up for China's lack of experience in studies on economic consequences of climate change. For China, a country in transition featuring imbalanced regional development, the key to greater supply of public goods in climate governance lies in enhanced governance incentives for developed areas that are more competent in participating in climate governance. When making decisions on climate governance participation, areas have to weigh their benefits and cost; areas that are less affected tend to be less motivated to participate since their benefits of climate governance are not high enough to cover the cost. The finding in the paper that the economic consequences of climate change are "robbing the rich" makes clear the benefit of climate governance participation for developed areas and helps reinforce incentives for the areas to participate.

The remaining parts of this paper are structured as follows. The second part reviews the literature and analyzes the mechanism; the third part presents the design of empirical strategies; the fourth part introduces the empirical results and analysis; conclusions and policy suggestions are proposed in the last part.

2. Literature Review and Mechanism Analysis

Early literature on climate change economics was concentrated in exploring the influence of climate change on agriculture (Mendelsohn *et al.*, 1994). As research was deepened, the target of study was gradually shifted to manufacturing, real estate and other economic sectors (Chen and Yang, 2019; Hauer *et al.*, 2016; Zhang *et al.*, 2018). Meanwhile, going beyond the boundary of any single sector, some studies systematically investigated the effects of climate change on total economic output (Burke *et al.*, 2015; Dell *et al*., 2012; Caldeira and Brown, 2019). In these researches, the adverse effects of global warming, either on single sectors or on total economic output, were basically a consensus. Such consensus further highlighted the necessity of global climate governance. However, controversy existed regarding regional heterogeneity in economic consequences of climate change, which had direct effects on how areas at different development stages weighed their benefits and cost for participating in global climate governance and how they developed governance policies correspondingly.

Quite a few studies held that climate change adversely impacted poor countries or regions, and explained the result from two perspectives. The first was industrial structure in backward areas that differed from developed ones. In comparison, agriculture took a higher share in backward areas, while this sector was always to be hit hard first by negative economic effects of climate change, if any. Correspondingly, a higher proportion of outdoor physical work due to local low-end industrial structure was another key factor. The second was greater competence of developed areas in technology and capital and better adaptability to climate change. In the face of climate change, developed areas were able to take more effective adaptive behaviors to cope with temperature rise as a way to stay safe from negative effects of climate change. For instance, popularized use of air-conditioners was an effective way for factors in developed areas to cope with high temperature, but backward areas found it unlikely to bear the cost of air-conditioner popularization and other adaptive behaviors (Deryugina and Hsiang, 2014). On this account, compared with developed areas, economic development in backward areas was subject to greater loss in climate change.

Though through the lenses of industrial structure and adaptive behaviors, it was reasonable to conclude the economic consequences of climate change were “pro-poor” (Letta and Tol, 2019), undeniably, the influence of climate change may be exerted on developed areas as well in theory. On the basis of previous studies, this paper elaborates the mechanism of green economic effects of climate change working on developed areas from the three perspectives of labor productivity, energy conservation & emission reduction and environmental governance by government.

2.1. Labor Productivity

Quite a few researchers believed climate change affected economic sectors other than agriculture mainly through its influence on labor productivity (Caldeira and Brown, 2019). Therefore, the labor productivity theory is an important mechanism for climate change posing effects on green productivity. According to studies on climate change economics, excessively low or high temperature would distract laborers from work and thus undermine their productivity (Cai *et al*., 2018; Qiu and Zhao, 2019). High-temperature environment would especially intensify fatigue of laborers and drive labor productivity to drop more significantly (Galloway and Maughan, 1997). Though instinctively, people tended to believe laborers engaged in outdoor physical work were more susceptible to climate change compared with those engaged in indoor mental work, ergonomic research showed that compared with simple physical labor, complex mental labor was subject to greater interference of high temperature (Ramsey and Kwon, 1992; Zander and Mathew, 2019). The high-end industrial structure in developed areas determines a larger share of complex mental labor. As a result, compared with backward areas, green productivity in developed areas may be more vulnerable to negative impact of climate change.

2.2. Energy Conservation & Emission Reduction

Prior literature mostly highlighted positive effects of human adaptive behaviors in response to climate change, but neglected the usual heavy cost in energy consumption and pollution emission behind such behaviors (Carleton and Hsiang, 2016). For example, wide use of air-conditioners eased the adverse influence of high temperature on labor productivity, but caused non-productive energy consumption and pollution emission to surge, reduced performance in energy conservation & emission reduction and worked against economic sustainability. Deschênes and Greenstone (2011) found a U-shaped relationship between temperature change and power consumption, indicating that either excessively low or high temperature would increase power consumed. In the face of the same climate change problem, different areas at various levels of economic development took differentiated adaptive behaviors, and therefore climate change posed different influence on energy consumption and pollution emission in various areas. For China, Wiedenhofer *et al*. (2017) held because of different consuming modes and power, rich and poor areas showed evident discrepancy in energy consumption and corresponding pollution emission; rich population, only 5% of the total, emitted up to 19% carbon through household consumption. Yu *et al*. (2019) pointed out more distinctly that urban residents would significantly increase energy consumption to cope with climate change, whereas rural ones took much less adaptive behaviors in response. It can be deduced that energy consumption and pollution emission in areas of different urbanization rates will be affected by climate change to different extents. Compared with backward areas, people in developed areas are more willing and also more capable of taking adaptive behaviors to address climate change, making performance of the areas in energy conservation & emission reduction more susceptible to the impact of climate change. On such basis, this paper holds that energy conservation & emission reduction may also be a major mechanism for climate change to affect green productivity in developed areas more.

2.3. Execution of Environmental Regulations

How green productivity in an area is impacted by climate change is related not only with adaptive behaviors of the area, but also with execution of environmental regulations by local government to some degrees. In China in particular, performance in energy conservation & emission reduction is subject to great influence of such execution. Under constantly intensified pressure on pollution governance, local government gradually changes from incompletely executing environmental policies of central government in general to "racing to outperform others" and at the same time "competing to the bottom" for executing the regulations. In this process, modes of environmental governance between developed and backward areas are differed, with the former executing environmental policies more forcefully, while the latter staying at a lower level of execution (Jin and Shen, 2018). For developed areas, despite their effective regulation execution, when temperature excessively rises, local government may ease the execution efforts out of their expectations for the negative effect on economic output to promote the output increase and mitigate the negative effect. For backward areas, since local level in execution of environmental regulations has been low, space for further lowering the level to alleviate adverse influence of climate change is limited. On this account, this paper believes climate change may affect developed areas more through execution of environmental regulations by local government.

3. Empirical Design

3.1. Econometric Modeling

In order to estimate the causal effect of temperature change on green economic efficiency, this paper refers to the practice of Deryugina and Hsiang (2014), and constructs the variable of temperature range based on daily average temperature to calculate the number of days that fall into each range in a year. The following regression equation is adopted:

$$Gtfp_{it} = \alpha^{m} Tbin_{it}^{m} + \lambda Weather_{it} + \eta_{i} + \sigma_{t} + \varepsilon_{it} \tag{1}$$

$Gtfp_{it}$ refers to green economic efficiency of city i in year t and $Tbin_{it}^{m}$ refers to total number of days that fall into the *m-th* temperature range with respect to daily average temperature of city i in year t. In the benchmark regression, this paper divides daily average temperature into nine ranges, namely <−12℃, −12~−6℃, −6~0℃, 0~6℃, 6~12℃, 12~18℃, 18~24℃, 24~30℃ and >30℃, by an interval of 6℃. In order to avoid multicollinearity, the paper takes the 6~12℃ range as benchmark. $Weather_{it}$ refers to other weather variables of city i in year t. In reference to prior literature (Li *et al*., 2015), this paper covers the following controlled weather variables: precipitation, duration of sunshine, atmospheric pressure, dew-point temperature and average wind velocity. With these exogenous variables being controlled, exogenous changes of temperature can be properly utilized to identify causal effects (Auffhammer *et al*., 2013). η_i means city fixed effect and σ_t means year fixed effect. ε_{it} shows robust standard errors clustered on the city level.

3.2. Variable Selection and Data Source

In the paper, NDDF proposed by Zhou (2012) is adopted to calculate the green economic efficiency $Gtfp_{it}$ of 284 cities in China in 2003−2016, and the detailed calculation takes reference from Li and Xu (2018). Data on daily average temperature required for construction of the temperature range variable $Tbin_{it}^{m}$ and on controlled variables such as precipitation, duration of sunshine, atmospheric pressure, dew-point temperature and average wind velocity is both derived from the ERA-Interim database of European Centre for Medium-Range Weather Forecasts (ECMWF). This paper first collects data on each weather variable on the daily basis corresponding to the 0.75°×0.75° grid in the scope of China, and then matches the grid data on weather variables to the city level according to longitude and latitude. Other than daily average temperature, other weather variables are all converted from daily data to annual mean value. Given the suspension of production activities on weekends and thus the limited influence from temperature, the paper excludes the temperature data on weekends and only considers temperature of working days in a year when constructing the core explanatory variable $Tbin_{it}^{m}$.

4. Empirical Result and Analysis

4.1. Result of Benchmark Regression

Table 1 lists the estimated result of benchmark regression, and estimated coefficient of all the temperature ranges takes the 6~12℃ range as benchmark. Column (1) reports the regression result based on the entire city samples. It is found that temperature change and green economic efficiency generally show an inverted U-shaped relationship; in another word, relative to the 6~12℃ temperature benchmark, both decrease and increase in temperature pose negative influence on green economic efficiency. However, when temperature is lower than the 6~12℃ range, the negative influence is statistically significant only in the temperature ranges of 0~6℃ and −12~−6℃; when temperature is higher than 6~12℃, the negative effect is statistically significant only in the 18~24℃ temperature range and no longer significant when temperature is higher than 24℃. The cause of the result may lie in heterogeneity in effects of climate change on backward and developed cities. Mixture of results of different samples reduces the significance of coefficient estimation. Given so, this paper mainly focuses on the respective estimation result based on backward cities and developed ones.

Column (2) presents the regression result based on backward cities. As revealed, temperature, both lower and higher than 6~12℃, has no statistically significant influence on green economic efficiency of backward cities. Besides, influential effect of the temperature ranges all approaches 0. In column (3), the regression result based on developed cities is introduced and it is shown for developed cities, there exists an obvious inverted U-shaped relationship between temperature change and green economic efficiency. Neither lower nor higher temperature compared with the 6~12℃ benchmark is helpful for green economic efficiency, which is consistent with the estimated result of the entire samples, indicating the "robbing the rich" rather than "pro-poor" economic consequences of climate change. In the ranges lower than the benchmark, when temperature gradually rises from <−12℃ to 6℃, green economic efficiency exhibits an upward trend in general, but only in the ranges of −12~−6℃ and 0~6℃, influence of climate change on the efficiency is statistically significant; in the higher ranges, when temperature increases from 12℃ to >30℃, climate change poses significant and persistent negative influence on green economic efficiency. Moreover, in comparison with the benchmark, as temperature keeps rising, absolute value of estimated coefficient of the temperature range variable continues to grow, indicating an increasingly more distinct negative effect. Based on estimated coefficient of all the temperature ranges, economic consequences of temperature rise on developed cities can be calculated. Take the 12~18℃ range as example. Estimated coefficient of this temperature range variable is −0.0016, which passes the 5% significance test. This result indicates compared with a day with a 6~12℃ average temperature, whenever the number of days in the 12~18℃ range is increased by one, green economic efficiency of developed cities will be reduced by 0.0016 unit. Assuming green economic efficiency of 365 days in a year is identical, as mean value of the efficiency of developed cities in the sampling period is 0.2627, when the number of days in the 12~18℃ range is increased by one, the efficiency of developed cities will be lowered by up to 0.6091%. If converted to marginal effect of temperature, it will be −0.1015%/℃. To sum up, in developed cities, the negative influence of temperature rise on green economic efficiency is not only significant statistically, but also significant economically.

Table 1. Result of Benchmark Regression

	(1)	(2)	(3)
	All cities	Backward cities	Developed cities
<−12℃	−0.0003 (0.0007)	0.0004 (0.0007)	−0.0016 (0.0015)
−12~−6℃	−0.0014** (0.0006)	−0.0004 (0.0005)	−0.0047** (0.0019)
−6~0℃	−0.0005 (0.0004)	−0.0001 (0.0004)	−0.0011 (0.0010)
0~6℃	−0.0006** (0.0003)	−0.0002 (0.0002)	−0.0013** (0.0006)
12~18℃	−0.0002 (0.0003)	0.0001 (0.0002)	−0.0016** (0.0007)
18~24℃	−0.0006* (0.0004)	−0.0002 (0.0004)	−0.0021*** (0.0008)
24~30℃	−0.0005 (0.0005)	0.0000 (0.0005)	−0.0025** (0.0010)
>30℃	−0.0006 (0.0005)	−0.0000 (0.0005)	−0.0029** (0.0012)
Observed value	3903	2883	1020
R^2	0.6123	0.5199	0.6725
Controlled variable	Yes	Yes	Yes
City fixed effect	Yes	Yes	Yes
Year fixed effect	Yes	Yes	Yes

Note: *, ** and *** represent significance at the level of 10%, 5% and 1% respectively. The benchmark is 6~12℃ temperature range. Controlled variables include precipitation, duration of sunshine, atmospheric pressure, dew-point temperature and average wind velocity. Standard errors are clustered on the city level. Explained variable is green economic efficiency. Constant terms are included, but the result is not reported. It is the same thereinafter.

4.2. Robustness Test

In order to ensure reliability of the benchmark conclusion of the paper, the following robustness test is conducted.[1]

(1) The area-year combined fixed effect is controlled. In the benchmark regression, though this paper has controlled city fixed effect and year fixed year, some variables that change by year at the area level may have been omitted. In response, the paper replaces year fixed effect with area-year fixed effect, and meanwhile controls city

[1] Detailed result of the robustness test is available on request.

fixed effect and area-year combined fixed effect. The empirical result indicates even if city fixed effect and area-year combined fixed effect are controlled, the benchmark conclusion of the paper still stands.

(2) Standard errors are adjusted. In the benchmark regression, this paper clusters robust standard errors to the city level and takes into consideration possible serial correlation of standard errors on the city level. But standard errors on the prefectural level within the same province every year may also be correlated. Given so, the paper adopts two methods to adjust standard errors. First, it clusters standard errors to two dimensions, city and province-year, simultaneously. Second, by referring to Shen and Jin (2018), it uses the spatial HAC method. To be specific, space-correlated geographical distance is set as 50km and serial correlation as 1 phase for testing. According to the empirical result, the benchmark conclusion of the paper is safe from the interference of standard error adjustment.

(3) Interval of temperature ranges is adjusted. In the benchmark regression, this paper sets temperature ranges by an interval of 6℃, and implicit assumption behind is that within the same range, increase of days of different temperatures by one produces homogeneous green economic effect. Take the 12~18℃ range for example. Compared with the 6~12℃ benchmark, increase of one day with temperature averaged at 13℃ and increase of one day with temperature averaged at 18℃ have the same influential effect on green economic efficiency. Obviously, as the interval of temperature ranges extends, the assumption becomes stronger. In order to free the benchmark conclusion from interference of this prior setting, the range interval is shortened to 3℃ for robustness testing, and the benchmark range now is 9~12℃. As indicated by the empirical result, the benchmark conclusion in the paper is not subject to any influence of artificially set range intervals.

(4) Backward cities and developed cities are re-defined. In the benchmark regression, the criterion for distinguishing backward and developed cities is GDP mean value of the cities during the sampling period. In order to avoid interference from the dividing standard of samples for the conclusion that the economic consequences of climate change are "robbing the rich", this paper adopts three standards to re-define backward and developed cities for robustness testing: GDP median of the cities in 2003−2016 as in practice of Kumar and Khanna (2019), upper and lower quartiles of GDP of the cities in 2003−2016, and GDP mean value of the cities in 2003 at the beginning of the sampling period. The empirical result demonstrates that no matter which standard is used for re-definition, the benchmark conclusion stays valid.

(5) The method of calculating green economic efficiency is adjusted. Calculation result of the efficiency not only depends on weight of input and output variables, but is subject to the influence of input and output indicators that are selected. This paper re-calculates green economic efficiency in the following three ways for robustness testing. First, it gives labor and capital a weight of 0 and energy input a weight of 1/3 to re-calculate the

efficiency. Second, as the energy input indicator in the paper is power consumption and main pollutants from thermal power plants are SO_2 and smoke/dust, the paper takes SO_2 and smoke/dust respectively as the pollution output variable for re-calculation. Third, in reference to Lin and Tan (2019), data on smoke/dust in the *China City Statistical Yearbooks* is directly adopted, rather than smoke/dust data collected after statistical calibers that are adjusted. As shown by the empirical result, the benchmark conclusion is free from interference from calculation methods of green economic efficiency.

(6) Controlled variables are adjusted. Two robustness tests are conducted with respect to controlled variables. First, natural exogenous variables are adjusted. Amid studies on effects of temperature change on economic output, some found it controversial to add precipitation as a controlled variable (Auffhammer *et al*., 2013). Given so, precipitation is deleted as controlled variable for robustness testing. Second, economic variables are added as controlled variables. Though the addition may result in the problems of "excessive control" and "bad control", no control may lead to omitted variable bias. On this account, this paper refers to controlled variables selected by Lin and Liu (2015), and further controls such economic variables as per capita GDP, degree of environmental regulations, industrial structure, share of foreign investment in GDP, fiscal autonomy and population density. As disclosed by the empirical result, adjustment of controlled variables fails to change the benchmark conclusion of the paper.

(7) Balanced panel data is used. Unbalanced panel data is adopted in the benchmark regression, while in order to avoid interference from discontinuous data of some cities in the sampling period, the paper uses balanced panel data in the sampling period for testing. The result proves the benchmark conclusion remains valid.

(8) Lag term of the explained variable is controlled. As green economic efficiency may show multi-period correlation, this paper further uses two methods to control the lag term of the explained variable for testing. First, it adopts DIFF-GMM for regression. Second, it refers to Dell *et al*. (2014) and replaces lag term of the explained variable with interaction term between initial value of the explained variable and year dummy variable for regression. The empirical result indicates that despite considerations on multi-period correlation of green economic efficiency, the benchmark conclusion still stands.

4.3. Exclusion of Alternative Explanations[1]

In the previous testing, this paper comes to an important conclusion that relative to the 6~12℃ range, temperature rise poses significant negative influence on green economic efficiency and such influence is intensified as temperature increases. More importantly, the influence is observed only in developed cities, but not in backward cities, showing

[1] Detailed result of the exclusion of alternative explanations is available on request.

that economic consequences of temperature change are “robbing the rich” to some extents. However, it is possible that such consequences might not be shown in cities that are economically developed, but cities with certain characteristics, while such cities happen to be developed ones. Specifically, three potential alternative explanations may challenge the core conclusion of the paper. First, temperature rise does not exert adverse effect on green economic efficiency in economically developed areas in particular, but in hot areas (Letta and Tol, 2019; Kumar and Khanna, 2019). In China, average temperature in economically developed cities happens to be higher than that in backward cities. Second, such negative effect is “robbing the rich” possibly because these areas happen to have higher precipitation, which is irrelevant to their level of economic development. In China, economically developed cities happen to have high precipitation. As for the logic behind this alternative explanation, in cities of heavy precipitation, people spend less time on outdoor work. Consequently, outdoor work may be exposed more to high temperature, further highlighting the negative influence of temperature rise on such cities. Third, the adverse effect of temperature rise may be posed only in cities of higher humidity, rather than economically developed ones. In China, economically developed cities happen to be more humid. The logic behind is that apparent temperature for human depends on both atmospheric temperature and relative humidity. Relative humidity will magnify the atmospheric temperature sensed by human; in other words, in places of higher relative humidity, people feel hotter in the high-temperature environment. On this account, the negative influence of temperature rise may be posed only in cities where people are more sensitive to high temperature. Testing result shows that the benchmark conclusion of the paper is safe from the challenge of the three alternative explanations.

4.4. Mechanism Discussion

It has been pointed out in the prior mechanism analysis that temperature rise may affect green productivity through labor productivity, efficiency of energy conservation & emission reduction, and execution of environmental regulations. Then, what is the main mechanism behind the adverse influence of temperature rise relative to the 6~12℃ benchmark on green economic efficiency of developed cities?

First, in this paper, data on the number of workers engaged in physical work and mental work in the cities and their corresponding economic output is not available. But in theory, if labor productivity of workers engaged in mental work is the main mechanism behind the negative influence of temperature rise on green economic efficiency of developed cities, it is predictable that temperature rise beyond the 6~12℃ benchmark poses adverse effects on labor productivity mainly in developed cities, instead of backward ones. This paper calculates labor productivity of prefectural-level cities as explained variable based on their GDP and quantity of labor force during the sampling period, and distinguishes backward cities and developed cities for regression analysis. As revealed by Table 2, when temperature is higher than 12℃, negative effects of temperature rise on labor productivity are only shown in developed cities, while the relationship between the two in backward cities fails to pass the significance test. This is consistent with the expectation of the paper. Besides, when temperature is beyond 24℃, though the influence of temperature rise on labor productivity remains negative, it is no longer statistically significant. The possible reason behind may be that places of mental work in developed cities have taken adaptive behaviors in response to high temperature, which eases the adverse effects of temperature rise on labor productivity to some degrees.

Table 2. Mechanism Analysis: Influence of Temperature Rise on Labor Productivity

	(1)	(2)
	Backward cities	Developed cities
<−12℃	0.0034** (0.0017)	0.0034 (0.0044)
−12~−6℃	0.0015 (0.0014)	−0.0026 (0.0042)
−6~0℃	−0.0002 (0.0011)	−0.0006 (0.0021)
0~6℃	−0.0017** (0.0007)	−0.0020 (0.0015)
12~18℃	0.0007 (0.0008)	−0.0037*** (0.0013)
18~24℃	0.0001 (0.0011)	−0.0039** (0.0018)
24~30℃	0.0014 (0.0014)	−0.0024 (0.0022)
>30℃	0.0010 (0.0018)	−0.0039 (0.0026)
Observed value	2,883	1,020
R^2	0.7041	0.7446
Controlled variable	Yes	Yes
City fixed effect	Yes	Yes
Year fixed effect	Yes	Yes

Note: Explained variable is labor productivity of the cities.

Second, in the previous testing in the paper, when average temperature exceeds 24℃, temperature rise still exerts negative influence on green economic efficiency of developed cities. In this temperature range, if the mechanism behind the influence of temperature rise is not labor productivity, can it be other mechanisms such as energy conservation & emission reduction? Or answer this question, the paper replaces the explained variable of green economic efficiency with energy efficiency, environmental efficiency, and energy and environmental efficiency respectively for regression analysis. According to the result in Table 3, in the range beyond 12℃, temperature rise basically exerts significant negative influence on energy efficiency, environmental efficiency, and energy and environmental efficiency in developed cities.

Also, as temperature keeps climbing, the influential effect is continuously enhanced in general. As a sharp contrast, such effect is rare to see in backward cities. It can be seen that in the range beyond 12℃, temperature rise triggers excessive non-productive energy consumption and pollution emission in developed cities and causes both energy efficiency and environmental efficiency to decline, which is also an important mechanism behind the "robbing the rich" economic consequences of temperature change. It's worth noticing that in backward cities, in the range beyond 12℃, only when temperature is higher than 30℃, negative influence of temperature change on energy efficiency passes the 5% significance test. This result tells us that in order to lower the cost of energy consumption, backward cities initiate adaptive behaviors in response to temperature change only in the highest-temperature circumstance.

Table 3. Mechanism Analysis: Influence of Temperature Rise on the Efficiency of Energy Conservation & Emission Reduction

	Backward cities			Developed cities		
	(1)	(2)	(3)	(4)	(5)	(6)
	Energy efficiency	Environmental efficiency	Energy and environmental efficiency	Energy efficiency	Environmental efficiency	Energy and environmental efficiency
<−12℃	0.0005 (0.0010)	−0.0000 (0.0011)	0.0002 (0.0008)	−0.0021 (0.0023)	−0.0025 (0.0015)	−0.0023 (0.0017)
−12~−6℃	−0.0002 (0.0008)	−0.0007 (0.0008)	−0.0004 (0.0006)	−0.0060** (0.0024)	−0.0050** (0.0023)	−0.0055** (0.0021)
−6~0℃	0.0004 (0.0007)	−0.0002 (0.0005)	0.0001 (0.0004)	−0.0012 (0.0015)	−0.0014 (0.0012)	−0.0013 (0.0012)
0~6℃	−0.0003 (0.0004)	−0.0001 (0.0003)	−0.0002 (0.0003)	−0.0018* (0.0009)	−0.0020*** (0.0007)	−0.0019** (0.0008)
12~18℃	−0.0007* (0.0004)	0.0006 (0.0004)	−0.0001 (0.0003)	−0.0029** (0.0012)	−0.0017** (0.0008)	−0.0023** (0.0009)
18~24℃	−0.0010 (0.0006)	0.0003 (0.0006)	−0.0003 (0.0005)	−0.0036** (0.0014)	−0.0025** (0.0010)	−0.0031*** (0.0011)
24~30℃	−0.0012 (0.0008)	0.0004 (0.0008)	−0.0004 (0.0006)	−0.0029* (0.0017)	−0.0034** (0.0015)	−0.0031** (0.0014)
>30℃	−0.0018** (0.0009)	0.0009 (0.0009)	−0.0005 (0.0007)	−0.0028 (0.0017)	−0.0036** (0.0016)	−0.0032** (0.0015)
Observed value	2,883	2,883	2,883	1,020	1,020	1,020
R^2	0.5456	0.3393	0.4337	0.5335	0.6442	0.5823
Controlled variable	Yes	Yes	Yes	Yes	Yes	Yes
City fixed effect	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effect	Yes	Yes	Yes	Yes	Yes	Yes

Note: Explained variable in columns (1) and (4) is energy efficiency of the cities; explained variable in columns (2) and (5) is environmental efficiency of the cities; explained variable in columns (3) and (6) is energy and environmental efficiency of the cities.

At last, this paper holds that the fact that temperature rise in the range beyond 12℃ reduces the environmental efficiency of developed cities and thus undermines their green economic efficiency may be not only the result of excessive adaptative behaviors of the cities, but also the result of strategic choice of local government in environmental regulation execution. In order to test this possible mechanism, the paper gets access to information on number of enterprises in environmental violations disclosed by the cities in 2004–2013 from Institute of Public and Environmental Affairs, and also uses the number of industrial enterprises in these cities to construct the execution intensity of environmental regulations on the city level as explained variable for regression analysis. According to Table 4, beyond 12℃, temperature rise poses persistent negative influence on execution intensity of environmental regulation by local government in developed cities, and the influential effect continues to be enhanced. Once temperature is higher than 24℃, the negative effect becomes statistically significant. It can be seen that in the high temperature range, lower execution intensity of environmental regulations by government is another mechanism behind the result that temperature rise reduces green economic efficiency in developed cities. It should be pointed out that in the range higher than 30℃, temperature rise also poses significant negative influence on the regulation execution in backward cities, but such negative influence does not undermine local environmental efficiency. Regarding possible reasons, execution intensity of environmental regulations in backward cities is already low and the effect of temperature rise on the execution is limited as well, which is not strong enough to change local environmental efficiency.

Table 4. Mechanism Analysis: Influence of Temperature Rise on Execution of Environmental Regulations

	(1)	(2)
	Backward cities	Developed cities
<−12℃	−0.0008 (0.0007)	−0.0021* (0.0012)
−12~−6℃	−0.0003 (0.0009)	−0.0010 (0.0010)
−6~0℃	−0.0007 (0.0004)	−0.0009 (0.0007)
0~6℃	−0.0001 (0.0003)	0.0003 (0.0005)
12~18℃	−0.0002 (0.0002)	−0.0004 (0.0005)
18~24℃	0.0002 (0.0003)	−0.0006 (0.0006)
24~30℃	−0.0006 (0.0004)	−0.0018** (0.0009)
>30℃	−0.0013*** (0.0005)	−0.0025* (0.0012)
Observed value	1,801	697
R^2	0.4201	0.5246
Controlled variable	Yes	Yes
City fixed effect	Yes	Yes
Year fixed effect	Yes	Yes

Note: Explained variable is execution of environmental regulations.

5. Conclusions and Policy Suggestions

This paper collects the data on daily average temperature of 284 Chinese cities on and above the prefectural level in 2003−2016, matches it to urban green economic efficiency calculated with the NDDF model, constructs the temperature range variable with an interval of 6℃, and on such basis identifies the causal effect of temperature change on green economic efficiency. It finds that relative to the 6~12℃ benchmark, both decrease and increase in temperature have negative influence on green economic efficiency of the cities. In particular, negative effect of temperature rise continues to be statistically significant and keeps expanding; besides, such effect is only observed in developed cities, but not in backward ones. In the range greater than 12℃, temperature rise exerts adverse influence on green economic efficiency of developed cities by reducing labor productivity, lowering efficiency of energy conservation & emission reduction and relaxing environmental regulation execution by local government.

In investigating the influential effect of climate change on green economic efficiency, this study offers a different perspective for understanding the economic consequences of climate change and provides valuable policy insights for promoting the realization of win-win results in climate governance and green economic development in China.

(1) In the long run, China can participate in global climate governance more actively and strive to play a leading role. As the world's largest developing country, China has been performing responsibilities of a large power and proactively responding to climate change, and it takes initiative to promote implementation of international governance frameworks on climate change such as the Paris Agreement. In the meantime, after 40 years of fast growth since the reform and opening-up, Chinese economy has shifted to the path of high-quality development, and to maintain stable economic growth and promote improvement of ecological environment is the core objective of economic development. Study in this paper shows that climate change will pose negative influence on green economic efficiency of developed cities in China. In response, to participate in global climate governance more actively not only can demonstrate the image of China as a responsible large power, but also is necessary for promoting the high-quality development of Chinese economy. To this end, it is necessary to comprehensively practice the concept of green development, drive increase in share of clean energy in the energy structure, build national carbon emissions trading market and deepen the clean development mechanism, contributing Chinese wisdom to global climate governance.

(2) In the short term, it is advised to conduct adaptive behaviors more reasonably to cope with climate change and improve the efficiency of energy conservation & emission reduction in the process of adapting to climate change. As indicated by this study, a possible reason behind the fact that climate change exerts more obvious

negative influence on green economic efficiency of developed cities is the excessive adaptive behaviors of these cities in coping with climate change. Such excessive behaviors result in heavy energy consumption and unnecessary pollution emission, and keeps Chinese economy from transforming to high-quality development rapidly. On this account, developed cities should boost initiative for climate governance collaboration among local government and proactively assume greater responsibility in governance; more importantly, they should strive to build low-carbon cities, promote reasonable adaptive behaviors and avoid energy waste. Moreover, this paper also finds government of developed cities may weaken the execution of environmental regulations to address the adverse influence of climate change on economic development. Given so, it is critical to drive local government to execute environmental regulations in a standardized way, eradicate environmental opportunism, and promote energy conservation & emission reduction to progress in order, which need be aligned with the transformation and upgrading of the industrial structure. This is also the core principle for developed cities to participate in climate governance.

References

Auffhammer, M., Hsiang, S. M., Schlenker, W., & Sobel, A. (2013). Using Weather Data and Climate Model Output in Economic Analyses of Climate Change. *Review of Environmental Economics & Policy*, 7 (2), 181–198.

Burke, M., Hsiang, S. M., & Miguel, E. (2015). Global Non-Linear Effect of Temperature on Economic Production. *Nature*, 527(7577), 235–239.

Cai, X., Lu, Y., & Wang, J. (2018). The Impact of Temperature on Manufacturing Worker Productivity: Evidence from Personnel Data. *Journal of Comparative Economics*, 46 (4), 889–905.

Caldeira, K., & Brown, P. T. (2019). Reduced Emissions through Climate Damage to the Economy. *Proceedings of the National Academy of Sciences*, 116 (3), 714–716.

Carleton, T. A., & Hsiang, S. M. (2016). Social and Economic Impacts of Climate. *Science*, 353 (6304), 1112–1112.

Chen, X., & Yang, L. (2019). Temperature and Industrial Output: Firm-Level Evidence from China. *Journal of Environmental Economics and Management*, 95, 257–274.

Dell, M., Jones, B. F., & Olken, B. A. (2012). Temperature Shocks and Economic Growth: Evidence from the Last Half Century. *American Economic Journal: Macroeconomics*, 4 (3), 66–95.

Dell, M., Jones, B. F., & Olken, B. A. (2014). What Do We Learn from the Weather? The New Climate-Economy Literature. *Journal of Economic Literature*, 52 (3), 740–798.

Deryugina, T., & Hsiang, S. M. (2014). Does the Environment Still Matter? Daily Temperature and Income in the United States. NBER Working Paper No. 20750.

Deschênes, O., & Greenstone, M. (2011). Climate Change, Mortality, and Adaptation: Evidence from Annual Fluctuations in Weather in the US. *American Economic Journal: Applied Economics*, 3 (4), 152–185.

Galloway, S. D. R., & Maughan, R. J. (1997). Effects of Ambient Temperature on the Capacity to Perform Prolonged Cycle Exercise in Man. *Medicine and Science in Sports and Exercise*, 29 (9), 1240–1249.

Hauer, M. E., Evans, J. M., & Mishra, D. R. (2016). Millions Projected to Be at Risk from Sea-Level Rise in the Continental United States. *Nature Climate Change*, 6 (7), 691–695.

Heutel, G., Miller, N. H., & Molitor, D. (2017). Adaptation and the Mortality Effects of Temperature across US Climate Regions. NBER Working Paper No.23271.

Jin, G., & Shen, K. (2018). To Shift Troubles to Neighbors or Take Neighbors as Partners? — Environmental Regulation Execution in Interaction and Urban Productivity Growth. *Management World (Guanli Shijie)*, 12, 43–55.

Jones, B. F., & Olken, B. A. (2010). Climate Shocks and Exports. *American Economic Review*, 100 (2), 454–459.

Kim, J., Lee, A., & Rossin-Slater, M. (2019). What to Expect When It Gets Hotter: The Impacts of Prenatal Exposure to Extreme Heat on Maternal and Infant Health. NBER Working Paper No. 26384 .

Kumar, S., & Khanna, M. (2019). Temperature and Production Efficiency Growth: Empirical Evidence. *Climatic Change*, 156 (1–2), 209–229.

Letta, M., & Tol, R. S. J. (2019). Weather, Climate and Total Factor Productivity. *Environmental and Resource Economics*, 73 (1), 283–305.

Li, C., Xiang, X., & Gu, H. (2015). Climate Shocks and International Trade: Evidence from China. *Economics Letters*, 135, 55–57.

Li, J., & Xu, B. (2018). Curse or Blessing: How Does Natural Resource Abundance Affect Green Economic Growth in China? *Economic Research Journal (Jingji Yanjiu)*, 9, 151–167.

Lin, B., & Liu, H. (2015). Do Energy and Environment Efficiency Benefit from Foreign Trade? — The Case of China's Industrial Sectors. *Economic Research Journal (Jingji Yanjiu)*, 9, 127–141.

Lin, B., & Tan, R. (2019). Economic Agglomeration and Green Economy Efficiency in China. *Economic Research Journal (Jingji Yanjiu)*, 2, 119–132.

Mendelsohn, R., Nordhaus, W. D., & Shaw, D. (1994). The Impact of Global Warming on Agriculture: A Ricardian Analysis. *American Economic Review*, 89 (4), 753–771.

Qiu, Y., & Zhao, J. (2019). Too Hot to Focus: The Mean and Distributional Effects of Heat on Labor Productivity. SSRN Working Paper.

Ramsey, J. D., & Kwon, Y. G. (1992). Recommended Alert Limits for Perceptual Motor Loss in Hot Environments. *International Journal of Industrial Ergonomics*, 9 (3), 245–257.

Schlenker, W., Hanemann, W. M., & Fisher, A. C. (2005). Will US Agriculture Really Benefit from Global Warming? Accounting for Irrigation in the Hedonic Approach. *American Economic Review*, 95 (1), 395–406.

Schlenker, W., & Roberts, M. J. (2009). Nonlinear Temperature Effects Indicate Severe Damages to US Crop Yields under Climate Change. *Proceedings of the National Academy of Sciences*, 106 (37), 15594–15598.

Shen, K., & Jin, G. (2018). The Policy Effects of Local Governments' Environmental Governance in China: A Study Based on the Evolution of the "River-Director" System. *Social Sciences in China (Zhongguo Shehui Kexue)*, 5, 92–115.

Shi, D., & Li, P. (2019). Quality Evolution and Assessment of China's Industry over the Past Seven Decades. *China Industrial Economics (Zhongguo Gongye Jingji)*, 9, 5–23.

Wiedenhofer, D., Guan, D., Liu, Z., Meng, J., Zhang, N., & Wei, Y. M. (2017). Unequal Household Carbon Footprints in China. *Nature Climate Change*, 7 (1), 75–80.

Yu, X., Lei, X., & Wang, M. (2019). Temperature Effects on Mortality and Household Adaptation: Evidence from China. *Journal of Environmental Economics and Management*, 96, 195–212.

Zander, K. K., & Mathew, S. (2019). Estimating Economic Losses from Perceived Heat Stress in Urban Malaysia. *Ecological Economics*, 159, 84–90.

Zhang, P., Deschênes, O., Meng, K., & Zhang, J. (2018). Temperature Effects on Productivity and Factor Reallocation: Evidence from a Half Million Chinese Manufacturing Plants. *Journal of Environmental Economics and Management*, 88, 1–17.

Zhang, P., Zhang, J., & Chen, M. (2017). Economic Impacts of Climate Change on Agriculture: The Importance of Additional Climatic Variables other than Temperature and Precipitation. *Journal of Environmental Economics and Management*, 83, 8–31.

Zhou, P., Ang, B. W., & Wang, H. (2012). Energy and CO_2 Emission Performance in Electricity Generation: A Non-Radial Directional Distance Function Approach. *European Journal of Operational Research*, 221 (3), 625–635.