The Nonlinear Impacts of Global Warming on Regional Economic Production: An Empirical Analysis from China

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ABSTRACT: China, the second largest economy in the world, covers a large area spanning multiple climate zones, with varying economic conditions across regions. Given this variety in climate and economic conditions, global warming is expected to have heterogeneous economic impacts across the country. This study uses annual average temperature to conduct an empirical research from a top-down perspective to evaluate the nonlinear impacts of temperature change on aggregate economic output in China. We find that there is an inverted U-shaped relationship between temperature and economic growth at the provincial level, with a turning point at 12.2°C. The regional and national economic impacts are projected under the shared socioeconomic pathways (SSPs) and representative concentration pathways (RCPs). As future temperature rises, the economic impacts are positive in the northeast, north, and northwest regions but negative in the south, east, central, and southwest regions. Based on SSP5, the decrement in the GDP per capita of China would reach 16.0% under RCP2.6 and 27.0% under RCP8.5.

SIGNIFICANCE STATEMENT: To estimate the economic consequences of climate change, we need to understand the relationship between temperature and economic activity. Economic responses to temperature could vary across regions due to climatic, geographic, and socioeconomic conditions. To better quantify the economic impacts of global warming in China, there is a need for understanding temperature–economy relationship at a regional scale. This study demonstrates that economic growth increases with temperature up to an annual temperature average of 12.2°C and decreases thereafter. The effect of global warming could reduce China's gross domestic product per capita by as much as 27% by 2090. The regional pattern is different, however, with the northeast, north, and northwest regions potentially seeing economic benefits from warming.

KEYWORDS: Social Science; Societal impacts

1. Introduction

Global warming is expected to affect society and economy (Corringham and Cayan 2019; Esplin et al. 2019; Sullivan and White 2019; Zander et al. 2019). Previous studies have estimated the effects of global warming on economic production from global level to regional level (Burke et al. 2015; Carleton and Hsiang 2016; Hsiang et al. 2017; Zhang et al. 2018), providing important implications for appropriate resources allocation and reasonable policy design so as to address challenges in climate change mitigation and adaptation (Neumayer and Barthel 2011; Van Vuuren et al. 2011; Hochrainer-Stigler et al. 2014; Howarth et al. 2014; Krishnamurthy et al. 2014; Ray et al. 2017). China is one of the largest economies over the world and faced with significant global warming effects (Chen and Yang 2019). Its economic structure became more coordinated after 1978, with the proportion of agricultural sector declining and those of industry and service sectors rising. Recent studies have examined the effects of temperature on agricultural and industrial sectors, which are the crucial components in China's economy (Bai et al. 2014; Zhang et al. 2018; Chen and Yang 2019; Hsieh et al. 2019). However, the macrolevel aggregate economic impacts in the future climate are still unclear.

As China covers a large area, the climate characteristics in different regions vary significantly. For example, the northeast provinces have a subfrigid zone coniferous forest climate, and the adjacent province Inner Mongolia has a temperate grassland climate. As a result, the average temperatures across provinces cover a wide range of 0°–25.36°C. Also, there are significant differences in population distribution, utilization of land resource, ecological environment, policy support, and so on. The economic development in the east region is much ahead of that in the west region, and the south region develops

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faster than the north region (Lin 2003). Due to the various climate and economic conditions across the country, an investigation of regional economic impacts of global warming would provide helpful insights for national development.

Climate would affect the economically relevant elements such as agriculture (Schlenker et al. 2005; Schlenker and Roberts 2009), industrial production (Hsiang 2010; Chen and Yang 2019), energy (Auffhammer and Aroonruengsawat 2012; Davis and Gertler 2015), forestry (Lindner et al. 2010; Hallegatte et al. 2016; Sartori and Roson 2016; Hsiang et al. 2017), travel (Lise and Tol 2002; Sartori and Roson 2016), human health (Caminade et al. 2014; Barreca et al. 2016), total factor productivity (TFP) (Zhang et al. 2018), capital (Zhang et al. 2018), labor force (Graff Zivin and Neidell 2014), and so on. Generally, there are significant temperature effects on not only the components of economy including agricultural, industrial, and service sectors, but also the economic factors including total factor productivity: labor and capital. Through these channels, the total economic production is eventually impacted.

The macrolevel climate change impacts can be investigated in two ways. The bottom-up way is to aggregate the impacts of climate on various sectors (Nordhaus and Boyer 2000). Yet, it cannot easily identify many sector-specific impacts and there exists interaction effects that are difficult to diagnose among sectors. The top-down way is to measure the potential impacts by gross domestic product (GDP) in a given year, which implies how sector-specific impacts interact and aggregate. Such an aggregate approach partly avoids the need for explicit representation of individual impact sectors and the related critiques of omission of impact types, interaction effects, and adaptation. (Lemoine and Kapnick 2016; Diaz and Moore 2017; Burke et al. 2018). Recently, this approach for estimating economic impacts has been employed in the integrated assessment model (IAM).

An important thing is that it is suggested that global warming would cause higher economic impacts by affecting the growth of economic output rather than the level of economic output (Pindyck 2013; Dell et al. 2014). According to the empirical framework of Dell et al. (2014), the aggregate output of economy is impacted by labor productivity. They derive that the growth of per capita output could be indirectly affected by temperature because temperature can directly affect labor productivity. Specifically, Hancock et al. (2007) find that high temperatures could reduce labor productivity by causing discomfort, fatigue, and cognitive impairment in works. Graff Zivin and Neidell (2014) find the impacts of temperature on labor supply in the United States. In addition, according to the Cobb–Douglas production function, the growth of output can also be affected by total factor productivity (Pindyck 2013; Dell et al. 2014). For example, Zhang et al. (2018) show that temperature has nonlinear effects on TFP in China. Overall, these suggest that temperature could affect economic growth indirectly through multiple channels.

Previously, temperature is expected to have negative linear effects on economically relevant outputs (Hsiang 2010; Bansal and Ochoa 2011; Dell et al. 2012; Hsiang et al. 2017). However, recent studies reveal the nonlinear impacts of temperature. For example, Fezzi and Bateman (2015) use farm-level data of the United Kingdom to indicate the nonlinear effects of climate on crop yield. Hsiang et al. (2017) find the nonlinear effects of temperature and rainfall on agriculture, mortality, and energy demand by microlevel data in the United States. Colacito et al. (2019) show the nonlinear effects, in the United States, between seasonal temperatures and economic growth at the aggregate and sectoral levels. For China, Chen et al. (2016) suggest the inverted U-shaped relationships between corn and soybean yields and weather variables. Besides, Zhang et al. (2018) show the nonlinear temperature effects on TFP, and Chen and Yang (2019) find that industrial output nonlinearly responds to temperature changes. Thus, it is necessary to focus on the nonlinear effects of temperature on aggregate economy in China.

Using a panel dataset of 31 provinces in China from 1978 to 2015, we estimate the effects of temperature on the growth of GDP per capita. Our study contributes to the literature on the economic responses to temperature in several directions. First, apart from temperature and precipitation this study considers some other weather variables including air pressure, wind speed, relative humidity, and sunshine hours in the empirical model. Second, we project future economic impacts caused by global warming at the national and regional levels in China under the representative concentration pathway scenarios (RCPs) and the socioeconomic shared pathways (SSPs). Third, there are many different political and economic systems for the countries around the world. However, for China, the provinces are geographically connected and administratively part of the country, and thus there are some similar characteristics between provinces. To avoid estimation biases from these factors, we consider spatial correlation in the error terms of our model. We find that there exist the inverted U-shaped relationships between temperature and the growth of GDP per capita. The turning points of the inverted U-shaped curve are broadly consistent with that estimated by Burke et al. (2015) for the global. The analysis indicates that global warming would result in economic losses at the national level of China. Based on SSP5, the losses in GDP per capita would reach 16.0% and 27.0% by 2090 under RCP2.6 and RCP8.5, respectively. At the regional level, there are economic benefits for the northeast, north, and northwest regions but economic losses for the south, east, central, and southwest regions. Our findings could imply regional development under climate change, and eventually bridge the empirical results and regional damage functions for China (Diaz and Moore 2017; Wei et al. 2018, 2019).

The rest of this paper is organized as follows. Section 2 describes the model, datasets, and scenario settings. Section 3 presents the main results of empirical analysis and the associated projected economic impacts. Section 4 concludes our analysis.

2. Method

a. *Empirical approach*

1) MODEL SPECIFICATION

The annual average temperatures and the associated squared terms are used as variables to estimate the temperature effects on economic growth:

TABLE 1. Region classification and abbreviations.

Regions	Provinces
	Geographical regions
North	Beijing (BJ), Tianjin (TJ), Hebei (HB), Shanxi (SX), and Inner Mongolia (IM)
Northeast	Liaoning (LN), Jilin (JL), and Heilongjiang (HLJ)
East	Shanghai (SH), Jiangsu (JS), Zhejiang (ZJ), Anhui (AH), Fujian (FJ), Jiangxi (JX), and Shandong (SD)
Central	Henan (HeN), Hubei (HuB), and Hunan (HuN)
South	Guangdong (GD), Guangxi (GX), and Hainan (HN)
Southwest	Chongqing (CQ), Sichuan (SC), Guizhou (GZ), Yunnan (YN), and Tibet (Tb)
Northwest	Shanxi (ShX), Gansu (GS), Qinghai (QH), Ningxia (NX), and Xinjiang (XJ)
	Economic regions
"E-Northeast"	LN, JL, and HLJ
"E-East"	BJ, TJ, HB, SH, JS, ZJ, FJ, SD, and GD
"E-Central"	SX, AH, JX, HeN, HuB, and HuN
"E-West"	IM, GX, CQ, SC, GZ, YN, Tb, ShX, GS, QH, NX, and XJ

$$\Delta \ln(Y_{r,t}) = \eta_0 T_{r,t} + \omega_0 T_{r,t}^2 + \gamma_0 \mathbf{W}_{r,t} + \theta \mathbf{Z}_{r,t} + \varepsilon_{r,t}, \qquad (1)$$

where provinces are indexed by r and years are indexed by t. The first difference of GDP per capita for province r in year t is denoted by $\Delta \ln(Y_{r,t})$ to represent economic growth. To accurately identify the effects of temperature on economic growth, we consider not only temperature and precipitation variables but also some other weather variables including air pressure, wind speed, relative humidity, and sunshine hours. The linear and quadratic terms of weather variables other than temperature are included as control variables (Zhang et al. 2017), which are denoted by the vector $\mathbf{W}_{r,t}$. Variable $\mathbf{Z}_{r,t}$ is a vector that includes province fixed effects (FE) to control time-invariant province-level characteristics, year FE to control unobserved factors that are common to all provinces, and year-by-geographic region FE (Zhang et al. 2018) to remove unobserved factors such as regional policy/regulation that are common to all provinces in a region but are different across regions. Geographical and economic region classifications are shown in Table 1. Term $\varepsilon_{r,t}$ is the error term that identifies other factors' effects on the explained variable. There may be potentially spatial and serial correlations in the error term that need to be controlled. First, the provinces have similar climate characteristics within a geographical region so that the variations of climate in one province can affect others. Second, some spatially correlated explanatory variables may be omitted, such as economic policies/regulations implemented by different levels of local government in certain regions to give specific supports or to achieve specific policy goals (Chen et al. 2016; Hsieh et al. 2019). Third, the interprovincial migration was toward the neighboring wealthier provinces or municipalities, and thus the population changes are correlated across provinces (Liang and Ma 2004). To account for spatial and serial correlation, we cluster standard errors within province and geographical region years using the two-way clustering methods. The heteroskedasticity of the error term is also considered in our model.

2) DATA FOR EMPIRICAL MODEL

From the China Statistical Yearbooks, we obtain the provincial GDP per capita index, urbanization rate, and population from 1978 to 2015. The observation for Hainan province in 1978 is unavailable. The daily climate data in 699 weather stations are taken from the China Meteorological Data Sharing Service System including temperature, precipitation, air pressure, wind speed, relative humidity, and sunshine hours. By averaging the data of weather stations within a province, we get the provincial climate data associated with the annual average values of climate variables. The socioeconomic and climate variables from provincial level to national level are displayed in Figs. S1–S3 in the online supplemental material. In general, there is no spurious correlation between temperature and economic growth. The correlation coefficients of the socioeconomic and climate variables between the provinces are shown in Figs. S4–S8 in the online supplemental material. As shown in Figs. S4–S6, the correlation coefficients of GDP per capita, GDP, and population between provinces are very large regardless of geographical locations. It can be found from Figs. S7 and S8 that there are high correlations of temperature and the growth in GDP per capita between some provinces because of their adjacent locations. Thus, it is necessary to consider spatial correlation in the empirical model.

b. *Economic impact projections*

To project future economic impacts of global warming, we use the GDP growth of China from 2016 to 2090 under SSP5, which assumes the rapid speed in economic development and the convergence process of per capita income between rich and poor regions (O'Neill et al. 2014).

1) CLIMATE AND SOCIOECONOMIC SCENARIOS

The 1978–2090 monthly average temperatures under RCPs with 0.5° × 0.5° resolution are obtained through the multimodel mean of five climate models (HadGEM2-ES, IPSL-CM5A-LR, MIROC-ESM-CHEM, GFDL-ESM2M, and NorESM1-M), which are provided by the Intersectoral Impact Model Intercomparison Project (ISI-MIP). To integrate temperature data from grid level to province level, we first assume that the temperature in each weather station is equal to that in the grid where the weather station locates. Then the mean temperature of all stations within a province represents the provincial temperature.

TABLE 2. Temperature (temp) effects on the growth in GDP per capita from 1978 to 2015. The dependent variable is $\Delta\ln(Y_{r,t})$. All models include linear and quadratic (indicated by the superscript 2) terms of precipitation (precip; m), air pressure (airpre; MPa), relative humidity (humi; %), average wind speed (windspe; $10\ \mathrm{m\ s^{-1}}$), and sunshine hours (sunhour; kh). We use data from 1978 to 2015 for the 31 provinces in China examined in this study. The detailed meanings of the columns labeled 1–3 are given in the text. The column labeled 3 is our baseline model. The optimum in the last row is the turning point of the inverse U-shaped curve. Standard errors, shown in parentheses, are clustered within provinces and within geographical region years. Asterisks represent statistical significance: 1% (***), 5% (**), or 10% (*).

	1	2	3
Temp	0.011 78** (0.005 65)	0.008 83* (0.004 57)	0.013 36*** (0.005 20)
Temp^2	−0.000 30 (0.000 20)	−0.000 31* (0.000 16)	−0.000 55*** (0.000 20)
Precip	0.018 52 (0.031 20)	0.000 94 (0.019 71)	−0.006 62 (0.022 20)
Precip^2	−0.014 12 (0.009 94)	−0.007 66 (0.006 82)	−0.006 03 (0.007 73)
Windspe	−0.008 75 (0.010 08)	0.003 20 (0.008 15)	0.002 42 (0.007 92)
Windspe^2	0.001 44 (0.002 38)	−0.000 42 (0.001 93)	−0.000 92 (0.002 04)
Humi	−0.000 37 (0.001 87)	0.001 78 (0.002 00)	0.002 13 (0.002 41)
Humi^2	−0.000 000 1 (0.000 01)	−0.000 01 (0.000 01)	−0.000 01 (0.000 02)
Sunhour	−0.000 46 (0.001 50)	0.000 93 (0.001 24)	0.000 67 (0.001 37)
Sunhour^2	0.000 04 (0.000 04)	−0.000 02 (0.000 03)	−0.000 01 (0.000 03)
Airpre	−0.778 45 (0.598 11)	−0.991 56** (0.464 35)	−0.956 19** (0.485 32)
Airpre^2	0.038 37 (0.028 12)	0.048 09** (0.021 89)	0.045 80** (0.022 90)
Obs	1177	1177	1177
R squared	0.03	0.43	0.62
Adjusted *R* squared	−0.002	0.39	0.49
Province FE	Yes	Yes	Yes
Year FE	No	Yes	No
Year-by-region FE	No	No	Yes
Optimum (°C)	19.60	14.24	12.15

The 2016–90 GDP growth and population are taken from the projections of the Organisation for Economic Co-operation and Development (OECD) in the SSP database (https://secure.iiasa.ac.at/web-apps/ene/SspDb) (O'Neill et al. 2017; Riahi et al. 2017). The SSP database provides the 10-yr interval GDP growth and population projections at the national level. It is assumed that the ratio of growth of each province is equal to the ratio in the base year (2015) to get the provincial economic growth (Yuan et al. 2016). In addition, the provinces' population coefficients are adjusted in accordance with their variations during 2005–15 to get future provincial population (O'Neill et al. 2014).

2) ESTIMATING ECONOMIC IMPACTS

Equation (2) describes how to calculate the effects of temperature change on the growth of GDP per capita:

$$\mathrm{ic}_{r,t} = \eta_0(T^{+}_{r,t} - \overline{T}_{r,t}) + \omega_0\left(T^{+^2}_{r,t} - \overline{T}^2_{r,t}\right). \tag{2}$$

The $\mathrm{grnc}_{r,t}$ is the GDP per capita growth without global warming obtained from SSP5, $\mathrm{ic}_{r,t}$ is the effect of future global warming on the growth in GDP per capita and can be calculated by Eq. (2), $T^{+}_{r,t}$ is the future temperature under RCPs, and $\overline{T}_r$ is the average temperature of province r from 1990 to 2015. This study assumes that the temperature in a world without global warming is always $\overline{T}_r$. Here, the temperature change is the difference between $T^{+}_{r,t}$ and $\overline{T}_r$. Because it is impossible to recognize how economic output responds to temperature that has never been observed in our historical data, we assume that $\mathrm{ic}_{r,t}(T) = \mathrm{ic}_{r,t}(T_{\max})$ for all $T > T_{\max}$. The $T_{\max}$ is set as 25.36°C, which is the upper bound of the annual average temperature observed in the historical samples so that our projected impacts in the hottest provinces are likely conservative. However, for most provinces substantial warming (e.g., +4°C in RCP8.5) leaves them well within the observed distribution of historical temperatures. Based on Eq. (3), we can get the GDP per capita over the period 2016–90 with/without climate change:

$$\mathrm{GDPcap}_{r,t} = \mathrm{GDPcap}_{r,t-1} \times (1 + \mathrm{grnc}_{r,t} + \mathrm{ic}_{r,t}). \tag{3}$$

By calculating the difference between them, the change in GDP per capita caused by global warming is obtained.

3. Results and discussion

a. Empirical results

1) CONTEMPORANEOUS TEMPERATURE EFFECTS

As shown in Table 2, we use data from 1978 to 2015 for each of the 31 provinces to examine the effects of temperature on annual growth of GDP per capita with various specifications based on Eq. (1). Columns 1–3 set different FE. In column 1, the specification includes only province FE considering the time-invariant factors such as geographical and climate conditions. In column 2, we additionally add year FE to purge the potential biases coming from annualwide shock such as national policy or technological changes common to all provinces. In column 3, we replace year FE with year-by-geographical region FE to allow spatial heterogeneity in those annual shocks in column 2. Basically, the results indicate that

TABLE 3. Temperature effects with time trend. The dependent variable is $\Delta \ln(Y_{r,t})$. All models include linear and quadratic terms of precipitation (m), air pressure (kPa), relative humidity (%), average wind speed ($10\,\mathrm{m\,s^{-1}}$), and sunshine hours (kh). We use data from 1978 to 2015 for the 31 provinces in China examined in this study. Relative to the model specifications in Table 2, all models add linear time trends for geographical regions. The columns are defined as in Table 2. The optimum in the last row is the turning point of the inverse U-shaped curve. Standard errors, shown in parentheses, are clustered within provinces and within geographical region years. None of the values are statistically significant.

	1	2
Temp	0.000 96 (0.005 81)	0.006 20 (0.004 69)
Temp^2	−0.000 19 (0.000 19)	−0.000 19 (0.000 16)
Time trend	Yes	Yes
Weather variables	Yes	Yes
Obs	1177	1177
R squared	0.07	0.44
Adjusted *R* squared	0.03	0.40
Province FE	Yes	Yes
Year FE	No	Yes
Year-by-region FE	No	No
Optimum (°C)	2.53	16.32

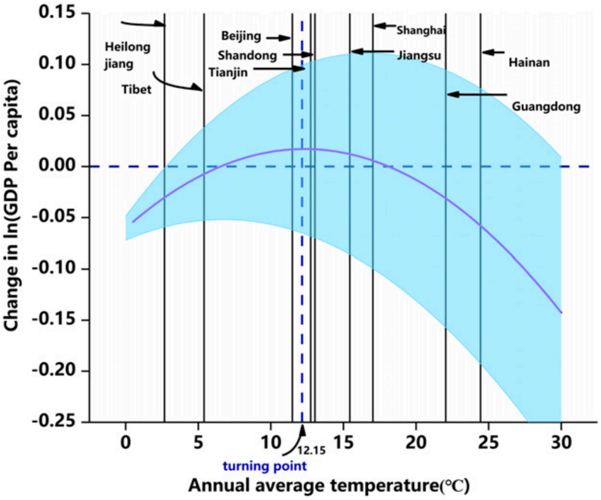

FIG. 1. The inverse U-shaped relationship between annual average temperature and change in the growth of GDP per capita (%). The vertical dotted line indicates the turning point, and the vertical solid lines are the provinces' average temperatures. The blue-shaded area represents the 95% confidence interval.

there are nonlinear relationships between temperature and economic growth. Besides, air pressure, which serves as a control variable corelated with temperature to reduce estimation bias (Wooten 2011), instead of precipitation shows statistically significant effects. The changes in air pressure would alter regional hydrologic cycle to induce more drought and floods, and ultimately have impacts on regional economy (Lian et al. 2015). It is also found in the literature that air pressure could cause discomfort in human body and thus reduce labor productivity to ultimately affect economic output (Xia et al. 2000; Zhang et al. 2018). As a result, accounting for air pressure in the temperature–economy relationship is important. The changes in *R* squared and adjusted *R* squared indicate that adding time FE could increase the fitting performance. However, in comparing with the results in Table 3, it is seen that there are only slight changes in *R* squared and adjusted *R* squared after the time trends are included.

As shown in Fig. 1, the turning point of this inverse U-shaped curve is 12.15°C, which is close to that of 13.06°C for the global (Burke et al. 2015). The annual growth of GDP per capita would be promoted by temperature rise in some provinces such as Qinghai, Heilongjiang, and Tibet. The provinces whose average annual temperatures during 1990–2015 are greater than the turning point would be strongly suppressed by temperature rise.

We set different specifications in Table 4 from column 2 to column 6 to check robustness. To account for autocorrelation and spatial correlation of error terms, we estimate standard errors clustered within geographical region years in our baseline model but within economic region years in column 2. China started reforming its economic system since 1978, and some informal arrangements began in 1990 (Huang 2008; Bai et al. 2014; Hsieh et al. 2019). Therefore, in column 3, we select research sample with the year after 1990. The growth of GDP per capita can be influenced by both GDP and population. As a result of interprovincial migration (Liang and Ma 2004), the population may migrate from developing villages to developed cities. To account for this, in column 4, we add annual population change rate and urbanization rate. The migration from the developing provinces to the developed provinces mainly occur in a bad agricultural year, and this could decrease GDP and population of rural provinces. To purge potential biases, we drop all samples with negative growth in added value of agricultural sector in column 5. There are four municipalities among the 31 provinces in China, which are established by the central government to develop regional economy. When compared with other provinces, the municipalities have higher proportion of industry and service sectors. They have the same administrative level as other provinces, but their geographical area and population are smaller. Therefore, we exclude municipalities from our sample in column 6.

In general, the identified temperature effects on economic growth are broadly consistent across the models in Table 4. The associated turning points range between 12.15° and 13.48°C. Even though the samples are reduced, column 3 still suggests significant nonlinear temperature effects. It implies that our results are robust.[1]

The models with only the weather variables of temperature and precipitation are also considered in Table 5. Columns 1–3 exclude the squared terms, and the coefficients of temperature are inconsistent and insignificant. It implies that the linear terms cannot reveal the complex effect mechanism of temperature on economic growth. Furthermore the squared terms are considered

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[1] We further check robustness by using temperature bins. The results can be found in the online supplemental material. In general, the coefficients of most temperature bins were insignificant.

TABLE 4. Robustness check. Unless otherwise indicated, all models include linear and quadratic terms of precipitation (m), air pressure (kPa), relative humidity (%), average wind speed (10 m s^{-1}), and sunshine hours (kh), provinces FE and geographical region × year FE, and errors cluster at the provinces and geographical region years. We use data from 1978 to 2015 for the 31 provinces in China examined in this study. Column 1 is the baseline specification; column 2 is as in column 1, but the errors cluster at the provinces and economic (''eco'') region years; column 3 is as in column 1, but only including samples with years after 1990; column 4 is as in column 1, but adding urbanization rate and population change rate as control variables to account for internal migration; column 5 is as in column 1, but dropping samples with negative growth in added value of agriculture (''bad agr''); column 6 is as in column 1, but excluding municipalities samples. More details on the meanings of columns 1–6 are given in the text. The optimum in the last row is the turning point of the inverse U-shaped curve. Asterisks represent statistical significance: 1% (***), 5% (**), or 10% (*).

	Baseline	Cluster eco region	≥1990 yr	Migration	No bad agr	No municipalities
Temp	0.013 36***	0.013 36**	0.008 20**	0.011 61**	0.011 59**	0.013 09**
	(0.005 20)	(0.005 34)	(0.005 46)	(0.005 68)	(0.004 88)	(0.005 35)
Temp^2	−0.000 55***	−0.000 55***	−0.000 32*	−0.000 47**	−0.000 43**	−0.000 51**
	(0.000 20)	(0.000 21)	(0.000 19)	(0.000 20)	(0.000 18)	(0.000 22)
Obs	1177	1177	806	1095	1052	1025
R squared	0.62	0.62	0.72	0.62	0.68	0.64
Optimum (°C)	12.15	12.15	12.81	12.35	13.48	12.83

in columns 4–6, but the estimated temperature effects in column 6 are less significant relative to those with additional weather variables in Table 2. Notably, the statistically significance of precipitation in Table 5 disappears when the quadratic terms are added. In fact, the annual variability in precipitation is very large, and thus there are more complex effects of precipitation on economic growth (Dell et al. 2012).

2) CUMULATIVE TEMPERATURE EFFECTS

The models with lags are made to investigate the cumulative temperature effects on income from 1°C of warming. As shown in Table 6, the cumulative temperature effects are reflected by the sum of marginal effects for both the contemporaneous and lagged responses at different temperature points. The results show that the cumulative temperature effects for cool provinces are complex. For example, at the point of 10°C the cumulative effect becomes negative with more lags. As pointed by Burke et al. (2015), the uncertainty in the cumulative effect increases when more lags are included. This is a potential reason to cause insignificance. By comparison, hot provinces would become worse with significant additional warming. These results are consistent with those of Burke et al. (2015).

Besides, the cumulative temperature effects could reveal the growth effect on economy. In a distributed lag model, if there is growth effect, the summed effects are indistinguishable from the contemporaneous effect (or larger in absolute magnitude) (Pindyck 2013; Dell et al. 2014). As temperature is 20°, 25°, and 30°C, the negative cumulative effects, many of which are significant, show a descend trend with more lags included. Thus, the results suggest that the provinces with higher temperature are more likely to have growth effect of temperature. Accordingly, they would be faced with higher economic losses.

TABLE 5. Temperature effects without other weather variables. The dependent variable is $\Delta \ln(Y_{r,t})$. Only temperature and precipitation (m) are included. We use data from 1978 to 2015 for the 31 provinces in China examined in this study. The optimum in the last row is the turning point of the inverse U-shaped curve. Standard errors, shown in parentheses, are clustered within provinces and within geographical region years. Asterisks represent statistical significance: 1% (***), 5% (**), 10% (*).

	1	2	3	4	5	6
Temp	0.003 92	0.000 54	−0.001 94	0.010 37*	0.008 35**	0.011 69*
	(0.002 52)	(0.001 97)	(0.002 56)	(0.005 48)	(0.004 08)	(0.006 06)
Temp^2				−0.000 26	−0.000 34**	−0.000 56***
				(0.000 20)	(0.000 16)	(0.000 21)
Precip	−0.021 27***	−0.017 91***	−0.019 24**	0.018 03	0.006 54	−0.000 48
	(0.008 22)	(0.005 19)	(0.007 65)	(0.030 71)	(0.017 86)	(0.021 15)
Precip^2				−0.014 85	−0.009 35	−0.007 98
				(0.010 10)	(0.006 60)	(0.007 61)
Other weather variables	No	No	No	No	No	No
Obs	1177	1177	1177	1177	1177	1177
R squared	0.01	0.42	0.61	0.02	0.43	0.61
Adjusted *R* squared	−0.02	0.38	0.48	−0.01	0.39	0.49
Province FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	No	Yes	No	No	Yes	No
Year-by-region FE	No	No	Yes	No	No	Yes
Optimum (°C)	—	—	—	19.94	12.28	10.44

TABLE 6. Cumulative effects from 1°C of warming. The marginal effects are calculated for both the contemporaneous and lagged terms at each temperature point and added up over time to represent the cumulative effect on economic growth from 1°C of warming. We use data from 1978 to 2015 for the 31 provinces in China examined in this study. These cumulative effects are shown at 10°, 20°, 25°, and 30°C with up to 7 lags. All models include linear and quadratic terms of precipitation (m), air pressure (MPa), relative humidity (%), average wind speed ($10\,\mathrm{m\,s^{-1}}$), sunshine hours (kh), provinces FE and geographical region × year FE, and errors cluster at the provinces and geographical region years. Asterisks represent statistical significance levels: 1% (***), 5% (**), 10% (*).

Cumulative effects	Lag = 0	Lag = 1	Lags = 3	Lags = 5	Lags = 7
10°C	0.0024 (0.0030)	0.0018 (0.0037)	0.0020 (0.0053)	0.0033 (0.0057)	−0.0013 (0.0068)
20°C	−0.0085* (0.0046)	−0.0001 (0.0060)	−0.0106 (0.0075)	−0.0146 (0.0100)	−0.0221* (0.0118)
25°C	−0.0140** (0.0062)	−0.0011 (0.0088)	−0.0169* (0.0099)	−0.0236* (0.0136)	−0.0325** (0.0158)
30°C	−0.0194** (0.0080)	−0.0020 (0.0118)	−0.0232* (0.0127)	−0.0326* (0.0174)	−0.0429** (0.0201)

3) HETEROGENEOUS TEMPERATURE EFFECTS

As shown in Table 7, the coefficients of the interaction term for temperature and developing provinces dummy variable are not significant. This suggests that we cannot reject that developed and developing provinces have the same economic response to temperature. The robustness check is made in column 2 to column 4. In China, there are 60% of developed provinces with baseline temperatures above 11.31°C, which is the turning point of nonlinear relationship for developed provinces and 20% of those with baseline temperatures slightly lower than this turning point. It means that more than 80% developed provinces may be faced with the negative impacts on economic outputs if the temperature rises 2°C.

b. *Economic impacts of global warming*

On the basis of the baseline model in Table 2, we project the change in GDP per capita under RCP2.6 and RCP8.5. The provincial economic impacts are then aggregated to get the regional and national economic impacts.

1) PROVINCIAL ECONOMIC IMPACTS

The provincial economic impacts of global warming by 2090 under RCP2.6 and RCP8.5 are shown in Fig. 2. There are 65.0% of the provinces experiencing losses in GDP per capita under RCP2.6, and the associated average change reaches −30.6%. By comparison, ~68.0% of the provinces would suffer from economic losses under RCP8.5, and the associated average change is as much as −54.1%.

In general, the provinces whose baseline temperatures are lower (higher) than the turning point (Fig. 1) would experience economic benefits (losses). Under RCP8.5, for example, global warming would bring ~33.0% economic benefits for Liaoning and ~42.8% for Xinjiang by 2090 yet may cause economic losses of ~64.4% in Chongqing and ~84.4% in Guangdong.[2] The changes in GDP per capita in some provinces seem huge. On one hand, the temperature effects could be amplified over time. As suggested by previous research, a 1.0% per effect on the growth rate of output implies that an instantaneous 1.0°C increase would lower output by ~62.0% 100 years later (Pindyck 2013; Dell et al. 2014). On the other hand, the estimated economic response to temperature cannot fully reveal the adaptation. This may result in an overestimation for future economic losses.

However, large temperature rise could also lead to small change in economic output. For example, global warming would bring economic benefits of 60.8% in Tibet (temperature change: +3.1°C) but 55.1% in Ningxia (temperature change: +5.9°C) under RCP8.5. It is mainly because that the baseline temperature of Ningxia is closer to the turning point (12.2°C). Since the quadratic equation is concave, the positive marginal effect of temperature on economic growth would decrease with the increase of temperature, and even become negative when the temperature exceeds the turning point. This explanation can also be adapted for some provinces experiencing the same warming but having different benefits. For example, Beijing has the same temperature change with Shanxi by 2090 under RCP2.6, but its economic benefits are much smaller due to the higher baseline temperature of 11.5°C.

Similarly, the economic losses by 2090 would be 73.9% in Shanghai (temperature change: +4.5°C) but 83.7% in Guangxi (temperature change: +3.7°C) under RCP8.5, since there are larger negative marginal effects of temperature for Guangxi. However, it should be noticed that the marginal effects are likely to become weaker or remain constant due to the emerge of unprecedented adaptation techniques, or increase suddenly due to the emerge of unprecedented tipping points (Cai et al. 2015).

In addition, Hainan has the highest baseline temperature among the provinces. Although it would experience substantial warming (+4.9°C) by 2090 under RCP8.5, its economic loss is not the largest. This study sets an upper bound of temperature to ensure future temperature of all provinces well within the historical records. However, global warming would make the temperature in Hainan exceed the upper bound. It means that the projected economic losses are conservative.

In fact, projecting future economic impacts is difficult due to high uncertainties. The projections in our analysis could serve as a reference for climate change decision making.

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[2] For Guangdong, the GDP per capita in 2015 was 67 500 (2015 CNY), and the baseline temperature was 22.05°C. If the temperature effect on economic growth is not considered, the GDP per capita by 2090 could reach 538 600 (2015 CNY) according to the projections of SSP5. The associated increment in economy is high relative to the historical observations worldwide. However, by 2090 the temperature under RCP8.5 would rise to 25.36°C, and the GDP per capita would decrease to 83 900 (2015 CNY) with the effect of global warming. The loss rate of GDP per capita is $[(538.6 - 83.9)/538.6] \times 100\% = 84.4\%$.

TABLE 7. Comparing temperature effects on economic growth from 1978 to 2015 in developed vs developing regions. Unless otherwise indicated, all models include linear and quadratic terms of precipitation (m), air pressure (MPa), relative humidity (%), average wind speed ($10\,\mathrm{m\,s^{-1}}$), sunshine hours (kh), provinces FE and geographical region × year FE, and errors cluster at the provinces and geographical region years. We use data from 1978 to 2015 for the 31 provinces in China examined in this study. A province whose mean GDP per capita over 1990–2015 ranks among the top 16 is defined as developed. Column 1 is the main specification with the climate variables interacted with an indicator for whether a province is developing. Column 2 is as in column 1, but errors cluster at the provinces and economic region years. Column 3 is as in column 1, but adding urbanization rate and population change rate as control variables to account for internal migration. Column 4 is as in column 1, but dropping samples with negative growth in added value of agriculture. The optimum in the last row is the turning point of the inverse U-shaped curve. Asterisks represent statistical significance: 1% (***), 5% (**), 10% (*).

	Baseline	Cluster eco region	Migration	No bad agr
Temp	0.015 84*** (0.005 42)	0.015 84*** (0.004 57)	0.017 41*** (0.005 30)	0.013 19** (0.005 69)
Temp^2	−0.000 70*** (0.000 20)	−0.000 70*** (0.000 20)	−0.000 62*** (0.000 19)	−0.000 46** (0.000 20)
Temp × dummy (developing)	−0.006 67 (0.007 85)	−0.006 67 (0.007 69)	−0.010 48 (0.007 59)	−0.002 15 (0.008 85)
Temp^2 × dummy (developing)	0.000 42 (0.000 27)	0.000 42 (0.000 28)	0.000 34 (0.000 27)	0.000 13 (0.000 29)
R squared	0.63	0.63	0.63	0.68
Observations	1177	1177	1095	1052
Effect of Temp in developing provinces	0.009 17 (0.007 27)	0.009 17 (0.008 00)	0.006 93 (0.007 33)	0.011 03 (0.007 15)
Effect of Temp^2 in developing provinces	−0.000 28 (0.000 26)	−0.000 28 (0.000 30)	−0.000 28 (0.000 27)	−0.000 33 (0.000 26)
Developed-province optimum (°C)	11.31	11.31	12.38	14.30
Developing-province optimum (°C)	16.36	16.36	13.82	16.71

2) REGIONAL AND NATIONAL ECONOMIC IMPACTS

The economic impacts are transformed from provincial level to regional level. It shows that the south, east, central, and southwest regions of higher average temperatures would have continuous losses in GDP per capita (Fig. 3). Under RCP8.5, by 2090 the east and south regions would have economic losses by 59.2% and 83.4%, respectively. However, they could avoid losses of 29.6% and 25.1%, respectively, if global warming is mitigated from RCP8.5 to RCP2.6. By comparison, the northeast, north, and northwest regions of lower average temperatures would have continuous economic benefits with temperature rising. The northeast region in particular might own more than twofold GDP per capita by 2090 under RCP8.5.

For the whole country, there would be economic losses resulted from global warming. The national GDP per capita would have the losses of 27.0% under RCP8.5 and 16.0% under RCP2.6 by 2090 (Fig. 3). It means that there could be 11.0% economic losses to be avoided if temperature change is controlled as RCP2.6 instead of RCP8.5.

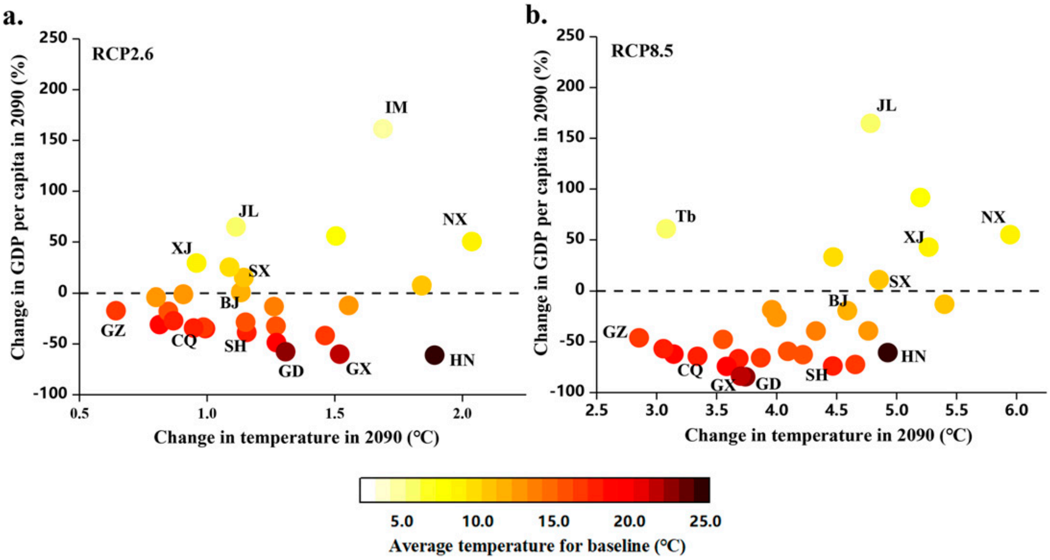

FIG. 2. Changes in GDP per capita for provinces by 2090 and the associated temperatures in 2090 under (a) RCP2.6 and (b) RCP8.5. Each dot represents a province, and the color shading indicates the average temperature during 1990–2015. The abbreviations of some provinces are shown near their associated dots.

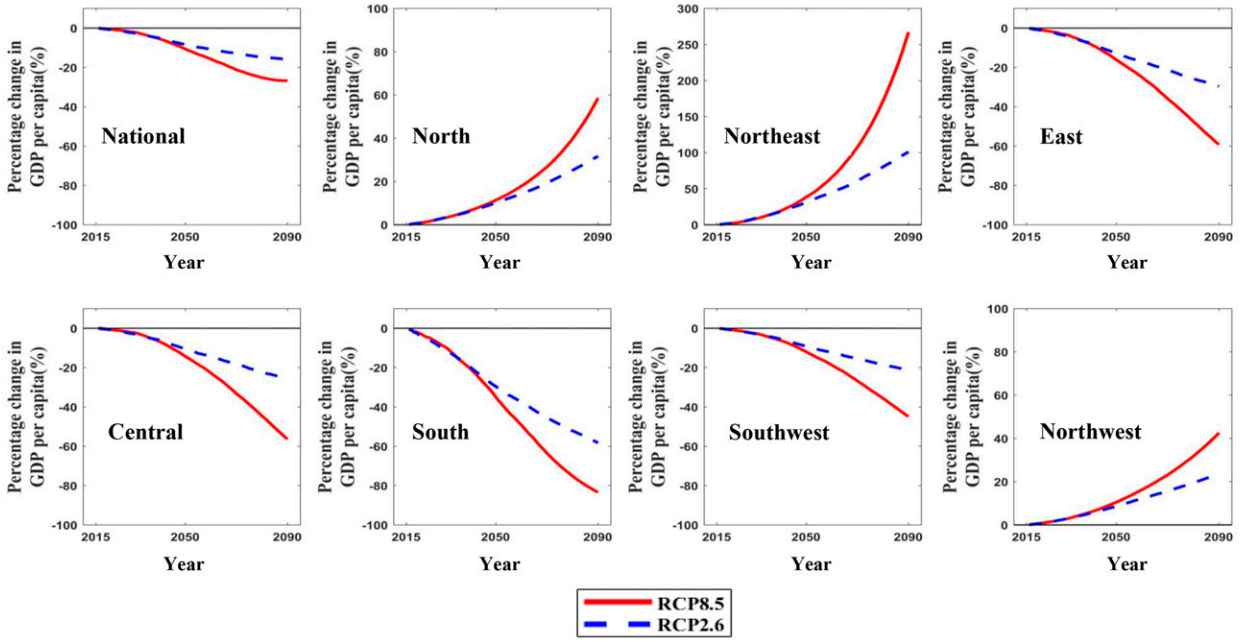

FIG. 3. Projected impacts of global warming on national and regional GDP per capita by 2090 (RCP2.6 and RCP8.5; SSP5).

4. Conclusions

This study first examines the effects of temperature on economic growth of China, and then projects the impacts of global warming on economy under climate and development scenarios. Our results suggest that there is an inverse U-shaped nonlinear relationship between temperature and the growth of GDP per capita. We use annual average temperature to identify the turning point, which is 12.15°C. The results are broadly consistent with the estimates for the global analysis.

Global warming is expected to cause economic losses for China. Based on SSP5, the losses in GDP per capita would reach 16.0% and 27.0% by 2090 under RCP2.6 and RCP8.5, respectively. Yet, the northeast, north, and northwest regions could experience continuous benefits, especially under RCP8.5. The south, east, central, and southwest regions exhibit continuous losses in GDP per capita. For example, the south region would experience the largest losses of more than 80.0% by 2090 under RCP8.5, while the southwest region would have the least of 21.3% by 2090 under RCP2.6. Mitigating global warming from RCP8.5 to RCP2.6 could reduce economic losses by up to 30.0% for the regions and 11.0% for the whole country.

The empirical results estimated by this study could be used to modify the damage pathway in the IAM so that global warming affects either TFP growth or capital depreciation (Moore and Diaz 2015), which could be further investigated. There are also large uncertainties in the science of climate change (Wei et al. 2020). Future work will introduce an uncertainty analysis framework to conduct risk assessment.

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