

Could Weather Fluctuations Affect Local Economic Growth? Evidence from Counties in the People's Republic of China

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This paper uses historical fluctuations of weather variables within counties in the People's Republic of China to identify their effects on economic growth from 1996 to 2012. We find three primary results. First, higher temperatures significantly reduce the growth rate of county-level gross domestic product per capita: an increase in the annual average temperature of 1°C lowers the growth rate by 1.05%–1.25%. The effect of higher temperatures is nonlinear. Second, fluctuations in temperature and precipitation not only have a level effect, they also have a substantial cumulative effect. Third, weather fluctuations have wide-ranging effects. Beyond their substantial effects on the growth rate of agricultural output, they also affect nonagriculture sectors, labor productivity, and investment. Our findings provide new evidence for the impact of weather changes on economic development and have major implications for adaptation policies.

Keywords: climate change, economic growth, precipitation, temperature, weather shocks

JEL codes: O13, O44, Q54, Q56

I. Introduction

It is a controversial question whether climate conditions are central to economic development. Cross-country analysis shows that hot countries tend to be poor. The average growth rate of tropical countries was 0.9% lower than that of nontropical countries from 1965 to 1990 (Gallup, Sachs, and Mellinger 1999). The income per capita of Africa in 1992 was equivalent to the income level of Western Europe in 1820 (Maddison 1995). The prevalence of tropical climate diseases and

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the lack of suitable weather conditions for agriculture are the major reasons for the underperformance of African countries (Sachs 2001, Masters and McMillan 2001, Sachs 2003). However, many other studies cast doubt on these results. They find that the impacts of geography and climate on economic development are negligible once national characteristics (e.g., institutions and trade policy) are controlled for in cross-sectional regressions (Acemoglu, Johnson, and Robinson 2002; Sachs 2003; Rodrik, Subramanian, and Trebbi 2004). Recent studies using a global database with resolution of 1° latitude by 1° longitude (Nordhaus 2006) and subnational data at the municipal level (Dell, Jones, and Olken 2009) find that the negative effect of temperature on income remains, but that its magnitude is attenuated.¹

In addition to possible omitted variable bias, the cross-sectional analysis utilized in the above studies cannot reflect the contemporaneous effect of weather since cross-sectional regression describes the long-run equilibrium relationship between climate variables and the economy. Recently, a growing number of empirical studies exploit country-level panel data to estimate the effect of weather fluctuations on national income (e.g., Dell, Jones, and Olken 2012; Heal and Park 2013; Burke, Hsiang, and Miguel 2015). The panel approach identifies the effects of weather variables by exploiting their variations within an economy over time. Since variations in weather variables are strictly exogenous and stochastic, this approach can easily yield causative identification (Deschenes and Greenstone 2007, Deschenes 2014, Barreca et al. 2016) and can clearly isolate the effects of weather from time-invariant country characteristics (Dell, Jones, and Olken 2012).

This paper uses county-level panel data on temperature and precipitation in the People's Republic of China (PRC) from 1996 to 2012 to examine their effects on the growth rate of county-level gross domestic product (GDP) per capita.² Our panel estimation shows that the growth rate of the county-level economy is negatively related to the average temperature: increasing the annual average temperature by 1°C reduces the growth rate of county-level GDP per capita by 1.05%–1.25%. Precipitation fluctuations have a negative effect on the growth rate, especially in agricultural counties and poor counties. Panel-distributed lag models show that the impacts of weather variations are persistent over time since the cumulative effects of weather variations are larger than their instantaneous effects. Increasing annual average temperature by 1°C reduces the cumulative growth rate of county-level GDP per capita by 2.03%–3.84%. When 5 or 10 lags of weather variables are incorporated into the regression, the cumulative effect of precipitation becomes

¹For example, when temperature rises by 1°C, the average income per capita of 12 countries in the Americas is reduced by 1.2%–1.9% at the municipal level (Dell, Jones, and Olken 2009). The results from cross-sectional data show that a 1°C increase in temperature is associated with an 8.5% decrease in national income per capita (Horowitz 2009; Dell, Jones, and Olken 2009).

²A longer version of the weather dataset from 1980 to 2012 is employed when lags of weather variables are needed.

significantly negative. In other words, the cumulative effect of precipitation only shows up in the medium run.

By examining the relationship between weather and the growth rate of three sectors, we find that high temperatures have a substantial negative effect on the growth rate of the value added of primary industry and tertiary industry, while the negative effect on the growth rate of secondary industry is insignificant. With seasonal average temperature, we find that only high temperatures in spring and summer have significantly negative effects on the growth rate of GDP per capita. The negative effect of seasonal temperature is mainly caused by the effect on primary industry. We construct temperature bins to detect the nonlinear effect of daily average temperature on growth. Compared with the reference bin $[15, 20)^{\circ}\text{C}$, temperatures above 20°C have significantly negative effects on the growth rate of GDP per capita, while extremely low temperatures and temperatures within $[0, 15)^{\circ}\text{C}$ have no significant effect. The negative effect of temperatures above 20°C is mainly levied on primary industry. Consistent with Colmer (2018) and Emerick (2018), we find that high temperatures have significantly positive effects on the growth rate of secondary industry, which indicates evidence of resource reallocation among economic sectors. Most temperature bins do not show a significant effect on the growth rate of tertiary industry. Regarding other possible effects of weather on county-level economies, we find that high temperatures have a significantly negative effect on the growth rate of labor productivity and fixed asset investment.

The effects identified through short-run weather fluctuations may differ from the long-run effects. For example, counties may adapt to climate change in the long run and mitigate the short-run effects of weather variations. However, our data span only 17 years, and the long-run effects cannot be fully investigated. Following Dell, Jones, and Olken (2012), we make an initial attempt in this direction to explore the effects of changes in weather in the medium run. The medium-run estimates show that temperature change and precipitation change each have a significantly negative effect on the growth rate, and the coefficients are larger in magnitude than their counterparts in the panel analysis. This result implies that counties in the PRC adapt poorly in our sample period and the negative impacts of changes in weather accumulate over time.

Most existing studies on weather fluctuations and growth use cross-country analysis (Dell, Jones, and Olken 2012; Burke, Hsiang, and Miguel 2015; Heal and Park 2013). A notable exception is Burke and Tanutama (2019) who use district-level data from 37 countries. But their study does not control for any weather variable other than temperature, which could cause omitted variable bias. In contrast to the obvious shortcomings in cross-country analysis (Burke and Tanutama 2019), our study enjoys several advantages. First, our cross-county analysis substantially increases the number of cross-sectional observations. Although there are more than 200 countries (regions) in the world, fewer than 140 of them are applicable in cross-country analysis. In contrast, our data contain 1,800 counties. Second,

our cross-county analysis reduces the risk of omitted variable bias. Possible omitted variables—such as institutions, industrial policy, trade policy, and other unobserved time-invariant factors—are similar for different counties within a country. Moreover, our empirical analysis contains all major climatic variables, which further reduces the omitted variable bias. Third, our county-level panel data have rich statistics, and we can explore many possible channels through which weather fluctuations affect economic outcomes. In contrast, studies using country-level data can only test very limited channels due to data deficiencies. To the best of our knowledge, this paper is the first to study the effect of weather fluctuations on the economic growth of counties in the PRC and provide novel evidence on potential channels for weather–economy relationships.³

The remainder of this paper is organized as follows. Section II introduces the data and provides descriptive statistics. In section III, we establish a theoretical framework and describe our estimation strategy. Section IV presents the main results and various robustness checks. Section V examines potential channels through which weather affects the growth of aggregate economic outcomes. In section VI, we estimate the impacts of weather changes in the medium run. The discussion and conclusion are presented in section VII.

II. Data and Summary Statistics

A. Data

Our weather data come from the China Meteorological Data Sharing Service System, which is directed by the National Meteorological Information Center. This grid dataset provides nationwide terrestrial daily average temperature and daily total precipitation data at $0.5^\circ \times 0.5^\circ$ degree resolution, spanning from 1 January 1980 to 31 December 2012. Zhang, Zhang, and Chen (2017) highlight the importance of weather variables other than temperature and precipitation. Thus, other weather variables—including atmospheric pressure, wind speed, sunshine hours, and relative humidity—are introduced into our empirical analysis. Other weather variables are drawn from the United States' National Oceanic and Atmospheric Administration (NOAA). Relative humidity is not reported directly in the data, but is constructed based on the standard meteorological formula provided by NOAA using temperature and dew point temperature.

We use geospatial software ArcGIS to aggregate the grid weather data to the county-day level and eliminate counties with observations that are omitted or

³Deryugina and Hsiang (2014) estimate the effect of temperature on the income per capita of counties in the United States, but they do not examine its effect on GDP growth, which has attracted more attention in the development literature.

have fatal errors.⁴ Then, we calculate the annual average temperature, days in each temperature bin, annual average precipitation, annual average relative humidity, annual average atmospheric pressure, and total sunshine hours for counties. The final balanced panel of weather data contains weather information for 2,376 counties from 1980 to 2012.

The economic data come from the *Support System for China Statistics Application*. The county-level dataset includes various annual statistics of GDP, population, employment, wage, investment, banking, public finance, trade, and social welfare, among others. The economic dataset includes data on 1,800 counties from 1996 to 2012.

B. Summary Statistics

We merge a county's weather data and economic data based on the name and administrative code. The final combined panel covers 1,657 counties and spans from 1996 to 2012, containing each county's weather variables and annual economic statistics. All monetary values are expressed in constant 2013 Chinese yuan. Summary statistics of key variables are presented in Table A.1 of the online Appendix.⁵

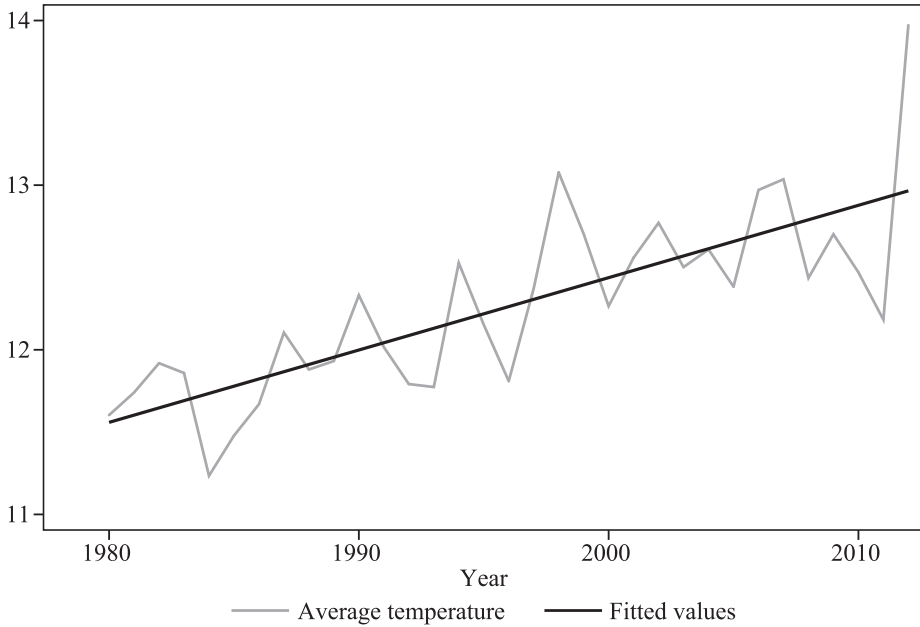
Figure 1 depicts the evolution of the average temperature of sample counties from 1980 to 2012. The average temperature has risen gradually over the past 3 decades. The peak annual average temperature of 13.97°C appears in 2012; the lowest annual average temperature of 11.23°C appears in 1984. Figure 2 describes the evolution of the average precipitation of sample counties from 1980 to 2012. The year of maximum precipitation is 2012, with daily average precipitation of up to 2.8 millimeters (annual precipitation is 1,024.8 millimeters). The year of minimum precipitation is 2011, with an average daily precipitation of 2.1 millimeters (annual precipitation is 766.5 millimeters).

Figure 3 depicts the relationship between counties' average temperature and the growth rate of GDP per capita from 1996 to 2012. Figure 4 presents the relationship between counties' average precipitation and the growth rate of GDP per capita from 1996 to 2012. The growth rate of county-level GDP per capita is negatively correlated with average temperature and average precipitation.

⁴We use a geographic-weighted approach to calculate the average temperature and average precipitation at the county-day level, where the weights are proportions of a county's area within a specific grid. Counties that consistently have 0-value observations for temperature and precipitation are dropped. Weather variables other than temperature and precipitation are constructed following Zhang et al. (2018).

⁵The online Appendix can be found at the corresponding author's homepage: <https://sites.google.com/site/jijiacong/research>.

Figure 1. Annual Average Temperature, 1980–2012



Note: Temperature is measured in degrees Celsius.

Source: Authors' calculation based on weather data from the China Meteorological Data Sharing Service System.

III. Theoretical Framework

In this section, we develop a theoretical framework for how weather variables affect economic growth and present the estimation strategy used for the empirical analysis.

A. Theoretical Framework

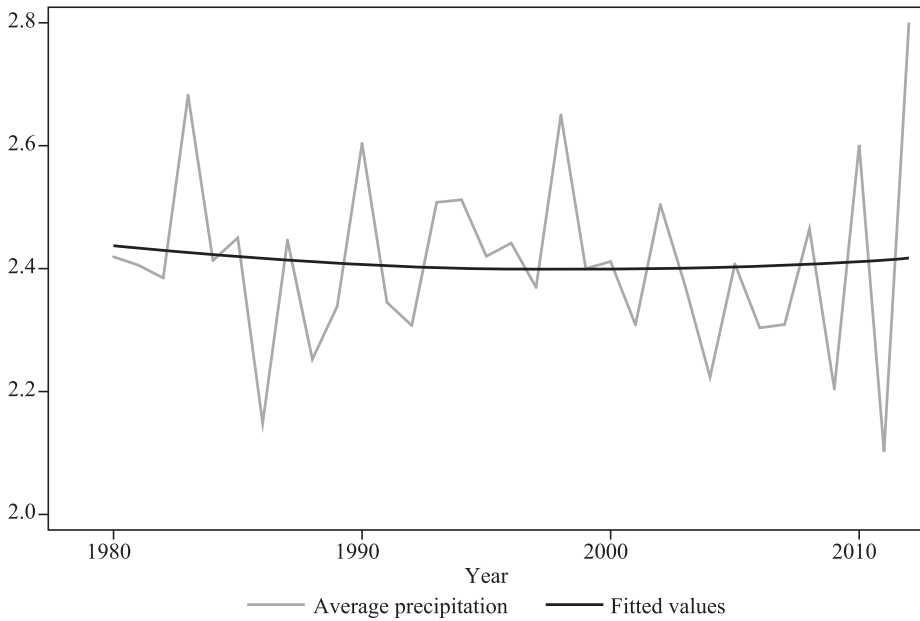
Our theoretical framework is based on Bond, Leblebicioğlu, and Schiantarelli (2010) and Dell, Jones, and Olken (2012). Consider the production function of county i in year t :

$$Y(C_{it}) = e^{\beta C_{it}} A_{it} K(C_{it})^\alpha L(C_{it})^{1-\alpha} \tag{1}$$

$$\frac{\dot{A}_{it}}{A_{it}} = g_i + \gamma C_{it} \tag{2}$$

Y is aggregate output; K measures the capital stock; L measures population; A represents total factor productivity; and C measures the weather conditions of this county. Equation (1) captures the level effect of weather on economic production

Figure 2. Annual Average Precipitation, 1980–2012



Note: Precipitation is measured in millimeters.

Source: Authors' calculation based on weather data from the China Meteorological Data Sharing Service System.

(e.g., the effect of current weather on aggregate output). Equation (2) captures the growth effect of weather (e.g., the effect of weather variables that affect the growth of total factor productivity).

Dividing both sides of equation (1) by population L , we have

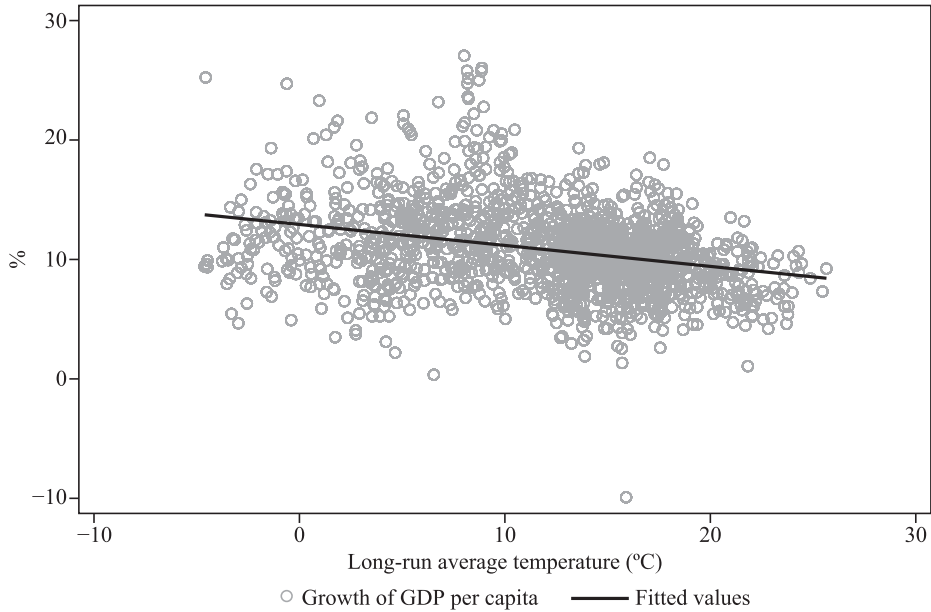
$$y(C_{it}) = e^{\beta C_{it}} A_{it} k(C_{it})^\alpha \tag{3}$$

where y is output per capita and k measures capital stock per capita. Taking logs of equation (3) and differentiating with respect to time, we have a dynamic growth equation as follows:

$$g_y(C_{it}) = g_i + \alpha g_k(C_{it}) + (\beta + \gamma)C_{it} - \beta C_{it-1} \tag{4}$$

where g_y and g_k represent the growth rates of output per capita and capital stock per capita, respectively. Equation (4) indicates two features of weather shocks on economic growth. First, there is a lagged effect of weather on growth. Weather conditions in the previous year affect the growth rate of the current year. Second, weather conditions affect the growth rate through the level effect β , which comes from equation (1) and the growth effect γ from equation (2). Equation (4) clearly identifies these two effects: (i) the level effect β is the coefficient of C_{it-1} , and

Figure 3. **Growth of County-Level Gross Domestic Product per Capita and Average Temperature, 1996–2012**



GDP = gross domestic product.

Sources: Authors' estimation based on weather data from the China Meteorological Data Sharing Service System and the National Oceanic and Atmospheric Administration, and on economic data from the Support System for China Statistics Application.

(ii) the growth effect γ can be derived by summing the coefficients of C_{it} and C_{it-1} . The level and growth effects can still be clearly identified for more general model structures, such as dynamic models including lagged dependent variables and lagged weather variables, as we demonstrate in the online Appendix.

B. Model Specification

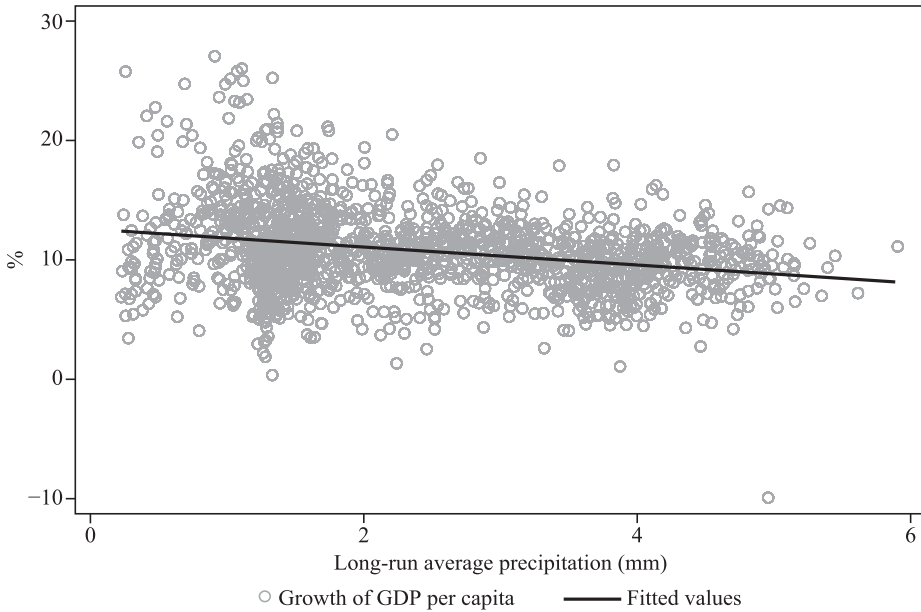
To estimate weather effects, we adopt the following regression specification:

$$g_{it} = \sum_{p=0}^P \lambda_p C_{it-p} + X' \phi + \mu_i + \delta_t + \epsilon_{it} \quad (5)$$

C is a vector of annual average temperature and average precipitation with up to P lags included; X is a vector of control variables containing other weather factors; μ_i are county fixed effects; δ_t are year fixed effects; and ϵ_{it} are error terms.⁶ The error

⁶In the robustness check, we use alternative fixed effects and other specifications to cluster error terms. The growth rate of the capital stock per capita g_k is not controlled for in the regression because, based on our theory, g_k

Figure 4. **Growth of County-Level Gross Domestic Product per Capita and Average Precipitation, 1996–2012**



GDP = gross domestic product, mm = millimeter.

Sources: Authors' estimation based on weather data from the China Meteorological Data Sharing Service System and the National Oceanic and Atmospheric Administration, and on economic data from the Support System for China Statistics Application.

terms are simultaneously clustered by county and province-year to allow arbitrary serial correlation within counties and arbitrary spatial correlation within provinces in a year.

Our estimation proceeds as follows. First, we estimate equation (5) with no lags, focusing on the null hypothesis that weather does not affect growth:

$$H_0(P = 0): \lambda_0 = 0 \tag{6}$$

Failing to reject this null hypothesis indicates the absence of both the level effect and growth effect. Second, we estimate equation (5) with lags and test the null hypothesis that the weather variables have no instantaneous effect on the growth rate:

$$H_0^*(P > 0): \lambda_0 = 0 \tag{7}$$

is a function of C_{it} . Including both g_k and C_{it} in the regression would generate the “over-control problem,” which results in an underestimation of the effects of weather variables (Dell, Jones, and Olken 2014).

and the null hypothesis that the weather variables have no cumulative effect on the growth rate:

$$H_0^{**}(P > 0): \sum_{p=0}^P \lambda_p = 0 \quad (8)$$

The value of $\sum_{p=0}^P \lambda_p$ corresponds to the growth effect γ in equation (4) as well as the more general concept of growth effects in models with longer lag structures, as demonstrated in the online Appendix.

IV. Results

A. Level Effect

We estimate equation (5) without including any lagged weather variables; that is, we test whether fluctuations in the weather variables have a level effect on growth. The null hypothesis is presented in equation (6). Column 1 of Table 1 shows that there is a significantly negative relationship between the growth rate of county-level GDP per capita and average temperature: the growth rate decreases by 1.05% when annual average temperature increases by 1°C. Column 2 shows a negative and significant relationship between the growth rate and average precipitation. These results are robust to controlling for other weather variables including atmospheric pressure, wind speed, and sunshine hours, as shown in column 3. Other weather variables are controlled for in all the following regressions.

Next, we investigate the heterogeneous effects of weather fluctuations on different counties. We define a county's agriculture ratio as its sum of gross output value of agriculture from 1996 to 2012 divided by the sum of its GDP from 1996 to 2012. A county is defined as an agricultural county if its agriculture ratio exceeds the median agriculture ratio of the sample counties. As shown in column 4, the coefficient of the interaction between average temperature and the agricultural county dummy is not statistically significant, indicating that the effects of temperature on agricultural and nonagricultural counties do not differ substantially. However, agricultural counties are more adversely affected by average precipitation than are nonagricultural counties. We define a county as a hot county if its average temperature from 1996 to 2012 exceeds the median of the sample counties. Column 5 shows that the coefficient of the interaction between average temperature and the hot county dummy is insignificant, indicating that the level effects of temperature on hot counties and cold counties are not significantly different. However, hot counties are more negatively affected by average precipitation. We define a county as a poor county if its average wage and average net income per capita of rural residents from 1996 to 2012 are smaller than the corresponding medians of the sample counties. Column 6 shows that

Table 1. Baseline Regression

Variable	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Average temperature	-0.0105*** (0.0037)	-0.0126*** (0.0039)	-0.0122*** (0.0039)	-0.0125*** (0.0039)	-0.0123*** (0.0039)	-0.0121*** (0.0039)	-0.0124*** (0.0039)
Average precipitation		-0.0054*** (0.0020)	-0.0054*** (0.0024)	-0.0002 (0.0032)	0.0027 (0.0050)	-0.0012 (0.0025)	0.0113*** (0.0055)
Average temperature × Agricultural county ^a average				0.0001 (0.0006)			0.0000 (0.0006)
Precipitation × agricultural county average				-0.0075** (0.0032)			-0.0072** (0.0032)
Temperature × hot country ^b average					0.0012 (0.0008)		0.0011 (0.0008)
Precipitation × hot country average					-0.0093* (0.0048)		-0.0087* (0.0048)
Temperature × poor county ^c average						0.0025*** (0.0005)	0.0025*** (0.0005)
Precipitation × poor country						-0.0171*** (0.0028)	-0.0171*** (0.0028)
Average atmospheric pressure			0.0020 (0.0013)	0.0020 (0.0013)	0.0020 (0.0013)	0.0018 (0.0013)	0.0018 (0.0013)
Average wind speed			0.0139* (0.0073)	0.0120 (0.0074)	0.0144* (0.0073)	0.0095 (0.0074)	0.0080 (0.0075)
Total sunshine hours			-0.0000 (0.0000)	-0.0000 (0.0000)	-0.0000 (0.0000)	-0.0000 (0.0000)	-0.0000 (0.0000)
Observations	25,363	25,363	25,318	25,318	25,318	25,318	25,318
R-squared	0.0795	0.0797	0.0801	0.0817	0.0803	0.0817	0.0834

Notes: The dependent variable for all columns is the growth rate of county-level gross domestic product per capita. All columns include county fixed effects and year fixed effects. Standard errors are clustered in province-by-years and counties. * p < 0.1, ** p < 0.05, and *** p < 0.01.

^aA county is defined as an agricultural county if its agriculture ratio exceeds the median agriculture ratio of sample counties.

^bA county is defined as a hot county if its average temperature from 1996 to 2012 exceeds the median of sample counties.

^cA county is defined as a poor county if its average wage and average net income per capita of rural residents from 1996 to 2012 are smaller than the corresponding medians of sample counties.

Sources: Authors' estimation based on weather data from the China Meteorological Data Sharing Service System and the National Oceanic and Atmospheric Administration, and on economic data from the Support System for China Statistics Application.

an increase in average temperature has a significantly negative effect on growth and that the effect is mitigated in poor counties. However, average precipitation has a significantly negative effect only on poor counties. In column 7, we add all interaction terms into the regression. The results show that average temperature still has a significantly negative effect and average precipitation has more adverse effects on agricultural counties and poor counties.

Therefore, we can clearly reject the null hypothesis that weather fluctuations have no level (instantaneous) effect on the growth rate. Increasing the annual average temperature by 1°C would lower the growth rate of county-level GDP per capita by 1.05%–1.25%; average precipitation has a significant and negative effect on the growth rate of agricultural counties and poor counties.

B. Robustness of the Level Effect

In this section, we check whether the results of the level effect are robust to alternative regression specifications and other measures of temperature.

1. Alternative Regression Specifications

Table 2 reports the results under different regression specifications. Many studies have found that temperature may have a joint impact with humidity (Zhang et al. 2018). In column 1 of Table 2, we use the heat index to measure the joint influence of temperature and humidity as a robustness check. The construction of the heat index follows the standard formula provided by NOAA.⁷ The heat index and average precipitation still have significantly negative effects on growth. In column 2, we cluster error terms by counties instead of province-by-years and counties in the main specification. Column 2 shows that the effects of average temperature and average precipitation are significantly negative, consistent with the baseline result. In column 3, we replace the year fixed effect in the baseline regression with a region \times year fixed effect because the eastern, middle, and western regions of the PRC have remarkable development gaps and may have different growth patterns.⁸ The result shows that the significant negative effect of average temperature remains. In column 4, we replace the year fixed effect with 1–4 order time trends because the development of county economies may exhibit nonlinear trends. Column 4 shows that the negative level effect of temperature is still significant. Therefore, our main results, especially the negative level effect of temperature, are robust to different regression specifications.

⁷The formula is available at https://www.wpc.ncep.noaa.gov/html/heatindex_equation.shtml; alternatively, please refer to Zhang et al. (2018).

⁸Following Deryugina and Hsiang (2014), we do not control for province-by-year fixed effects since it may remove too much identification variation, which may produce attenuation bias that would overwhelm the results (Fisher et al. 2012).

Table 2. Robustness Checks with Alternative Regression Specifications

Variable	(1) Heat Index	(2) Alternative Cluster	(3) Region by Year	(4) 1–4 Order Time Trends	(5) Hot Counties Excluded ^a	(6) Hottest Year Excluded ^b
Heat index	-0.0045** (0.0020)					
Average temperature		-0.0122*** (0.0040)	-0.0146*** (0.0040)	-0.0070*** (0.0025)	-0.0117*** (0.0042)	-0.0139*** (0.0047)
Average precipitation	-0.0047* (0.0024)	-0.0054** (0.0026)	-0.0017 (0.0027)	-0.0014 (0.0026)	-0.0079** (0.0031)	-0.0042 (0.0028)
Other weather variables	Yes	Yes	Yes	Yes	Yes	Yes
Country fixed effect	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effect	Yes	Yes	No	No	Yes	Yes
Region × year fixed effect	No	No	Yes	No	No	No
1–4 order time trends	No	No	No	Yes	No	No
Observations	25,318	25,318	25,318	25,318	23,800	23,665
R-squared	0.0799	0.0801	0.0909	0.0720	0.0786	0.0846

Notes: The dependent variable for all columns is the growth rate of county-level gross domestic product per capita. Standard errors are clustered in province-by-years and counties. Temperature is measured in degrees Celsius and precipitation is measured in millimeters. *p < 0.1, **p < 0.05, and ***p < 0.01.

^aIn column 5, counties with an average temperature above 20°C are excluded.

^bIn column 6, the hottest year 2012 is excluded.

Sources: Authors' estimation based on weather data from the China Meteorological Data Sharing Service System and the National Oceanic and Atmospheric Administration, and on economic data from Support System for China Statistics Application.

In column 5 of Table 2, we exclude counties whose average temperatures from 1996 to 2012 are higher than 20°C to test whether the negative effect of temperature is solely driven by hot counties. The result shows that temperature also has a significantly negative effect on cool counties. In column 6 of Table 2, we exclude the year 2012, which has the highest annual average temperature, from the sample, and test whether the main results are driven by this particularly hot year. The negative effect of temperature on the growth rate remains.

2. Different Measures of Temperature

We introduce different measures of temperature by constructing county-level seasonal average temperature and temperature bins. A cross-country analysis of 28 Caribbean countries indicates that high-temperature shocks have a negative effect on income only when they occur during the hottest season (Hsiang 2010). Table A.2 in the online Appendix reports how seasonal average temperature affects the growth rates of county-level GDP per capita and the value added of different sectors. Column 1 shows that only high temperatures in spring and summer have

significantly negative effects on the growth rate of GDP per capita. The negative effect of seasonal temperature is mainly caused by the effect on primary industry.

Many empirical studies have found that temperatures have a nonlinear effect on economic activities (Burke, Hsiang, and Miguel 2015; Zhang et al. 2018; Burke and Tanutama 2019). To check for a possible nonlinear effect of weather variables on growth, we construct temperature bins to measure county-level temperature conditions. These new results are reported in Table A.3 of the online Appendix. Consistent with the literature, our study finds that temperatures have a nonlinear effect on the growth rate of county-level economies. Column 1 shows that compared with the reference bin $[15, 20)^{\circ}\text{C}$, high temperatures above 20°C have significantly negative effects on the growth rate of GDP per capita. Temperatures within $[-10, 15)^{\circ}\text{C}$ and extremely low temperatures have no significant effect. Column 2 shows that temperatures within $[-20, -10)^{\circ}\text{C}$ and high temperatures above 20°C have negative effects on primary industry. In contrast, high temperatures above 20°C have significantly positive effects on the growth rate of secondary industry. This finding is consistent with micro evidence from Colmer (2018) and Emerick (2018), which indicates that the nonagriculture sector (mainly manufacturing) could benefit from weather shocks through labor reallocation between the agriculture sector and nonagriculture sector.⁹ For the growth rate of tertiary industry, most temperature bins show no significant effect.

C. Cumulative Effect

This section uses panel-distributed lag models with up to 10 lags of the weather variables to explore the dynamics of weather effects.¹⁰ The distributed lag models nest both the level effect (instantaneous effect) and the growth effect (cumulative effect). Table 3 reports the results of estimating equation (5) with 0 lags, 1 lag, 3 lags, 5 lags, and 10 lags of the weather variables. The first and second rows present the level effect of the weather variables, and the bottom two rows report the sum of all weather lags (i.e., the cumulative effect).

Columns 2–5 of Table 3 show that a 1°C increase in temperature cumulatively reduces the growth rate of county-level GDP per capita by 2.03%–3.84%. The magnitude of temperature's negative cumulative effect increases as more lagged weather variables are included. The cumulative effect of precipitation is significant

⁹Chen and Yang (2019) and Zhang et al. (2018) use micro-level data from manufacturing industries and find a significant negative effect of high temperatures on output and total factor productivity. Our results are different but not necessarily inconsistent with their findings. First, our focus is the growth rate of output rather than output or productivity per se. Second, the secondary industry here includes many industries other than manufacturing. Third, we study the growth rate of all firms, including small and medium-sized firms, while Chen and Yang (2019) and Zhang et al. (2018) focus on large firms with annual sales above 5 million Chinese yuan.

¹⁰Our panel of economic variables spans from 1996 to 2012, and the panel of weather variables spans from 1980 to 2012. Even with 10 lags of the weather variables, the balanced panel of weather and economies still has 17 years of observations.

Table 3. **Regression with Lags**

Variables	(1) 0 Lags	(2) 1 Lag	(3) 3 Lags	(4) 5 Lags	(5) 10 Lags
Average temperature	-0.0122*** (0.0039)	-0.0116*** (0.0039)	-0.0104** (0.0043)	-0.0112** (0.0045)	-0.0084* (0.0046)
Average precipitation	-0.0054** (0.0024)	-0.0051** (0.0024)	-0.0047* (0.0025)	-0.0052** (0.0026)	-0.0067*** (0.0026)
Other weather variables	Yes	Yes	Yes	Yes	Yes
Observations	25,318	25,318	25,318	25,318	25,318
R-squared	0.0801	0.0805	0.0814	0.0816	0.0833
Cumulative effect of average temperature		-0.0203*** (0.0062)	-0.0244** (0.0111)	-0.0201 (0.0123)	-0.0384*** (0.0148)
Cumulative effect of average precipitation		-0.0024 (0.0032)	-0.0067 (0.0052)	-0.0135** (0.0066)	-0.0541*** (0.0109)

Notes: The dependent variable of all columns is the growth rate of county-level gross domestic product per capita. All columns include county fixed effects and year fixed effects. Standard errors are clustered in province-by-years and counties. Given space constraints, the table only reports the sum of coefficients of all lagged weather variables (cumulative effect). Temperature is measured in degrees Celsius and precipitation is measured in millimeters. *p < 0.1, **p < 0.05, and ***p < 0.01.

Sources: Authors' estimation based on weather data from the China Meteorological Data Sharing Service System and the National Oceanic and Atmospheric Administration, and on economic data from the Support System for China Statistics Application.

only when 5 lags or 10 lags are included. In other words, the cumulative effect of precipitation only shows up in the medium run. Increasing average precipitation by 1 millimeter (i.e., increasing annual precipitation by 365 millimeters) cumulatively reduces the growth rate of county-level GDP per capita by 1.35%–5.41%.

Table 3 demonstrates that the cumulative effect of average temperature is larger in magnitude than its level effect; average precipitation also generates a larger cumulative effect than the level effect when 5 lags and 10 lags are introduced. These results imply that the level effect of weather fluctuations in each period accumulates, rather than reverses, and that counties do not fully adapt to weather fluctuations.

V. Channels

In this section, we explore the channels through which the weather variables exert their effects on growth. Many macroeconomic studies of weather effects focus on limited channels, especially agriculture and income levels, due to data limitations (Dell, Jones, and Olken 2012). Our data contain various economic statistics, so we can explore whether there are other channels for weather to influence economic activities.

A. Primary, Secondary, and Tertiary Industries

We investigate the level effect and cumulative effect of average temperature and average precipitation on the growth rates of primary, secondary, and tertiary

Table 4. Channels: Primary, Secondary, and Tertiary Industry

Growth Rate of	(1)	(2)	(3)
	Value Added of Primary Industry	Value Added of Secondary Industry	Value Added of Tertiary Industry
A. Models with no lags			
Average temperature	-0.0253*** (0.0051)	-0.0110* (0.0061)	-0.0034 (0.0047)
Average precipitation	-0.0091*** (0.0027)	-0.0027 (0.0038)	-0.0049 (0.0033)
Observations	25,760	25,711	24,796
R-squared	0.0673	0.0679	0.0505
B. Models with 5 lags^a			
Average temperature	-0.0313*** (0.0058)	-0.0118* (0.0067)	0.0010 (0.0051)
Average precipitation	-0.0105*** (0.0028)	-0.0022 (0.0040)	-0.0037 (0.0034)
Cumulative effect of average temperature	-0.0338** (0.0158)	0.0005 (0.0199)	-0.0328** (0.0154)
Cumulative effect of average precipitation	-0.0111 (0.0073)	-0.0103 (0.0105)	-0.0077 (0.0088)
Observations	25,760	25,711	24,796
R-squared	0.0703	0.0683	0.0520
C. Models with 10 lags			
Average temperature	-0.0276*** (0.0058)	-0.0103 (0.0068)	0.0031 (0.0052)
Average precipitation	-0.0117*** (0.0028)	-0.0030 (0.0041)	-0.0048 (0.0035)
Cumulative effect of average temperature	-0.0316* (0.0187)	-0.0292 (0.0230)	-0.0534*** (0.0183)
Cumulative effect of average precipitation	-0.0389*** (0.0118)	-0.0465*** (0.0179)	-0.0310** (0.0141)
Observations	25,760	25,711	24,796
R-squared	0.0729	0.0695	0.0539

Notes: All columns include other weather variables, county fixed effects, and year fixed effects. Standard errors are clustered in province-by-years and counties. Given space constraints, part B and part C only report the sum of coefficients of all lagged weather variables (cumulative effect). Temperature is measured in degrees Celsius and precipitation is measured in millimeters. * $p < 0.1$, ** $p < 0.05$, and *** $p < 0.01$.

Sources: Authors' estimation based on weather data from the China Meteorological Data Sharing Service System and the National Oceanic and Atmospheric Administration, and on economic data from the Support System for China Statistics Application.

industries. Part A of Table 4 begins with the model with no lagged weather variables and shows the level effect. Column 1 of part A shows that average temperature and precipitation have significantly negative effects on the growth rate of primary industry. Columns 2–3 of part A show that the negative effects of average

temperature and precipitation on secondary and tertiary industry are negative but insignificant.

Parts B and C introduce 5 lags and 10 lags of the weather variables, respectively, to examine the cumulative effects of average temperature and average precipitation. In part B, temperature has significantly negative cumulative effects on the growth of primary industry and tertiary industry. Precipitation has negative but insignificant cumulative effects on all industries. When 10 lags are introduced, as shown in part C, temperature still has significantly negative cumulative effects on the growth of primary industry and tertiary industry. The cumulative effects of precipitation on all industries become significantly negative. This is consistent with our previous finding that the cumulative effect of precipitation emerges only in the medium run.

B. Average Wage, Investment, and Output of Agriculture and Large Firms

We investigate how average temperature and precipitation affect the growth rate of average wage, fixed asset investment, the gross output value of agriculture, and the gross output value of enterprises above a designated size. Part A of Table A.4 in the online Appendix begins with models without lags and reports the level effect. Column 1 shows that an increase in temperature and precipitation reduces the growth rate of the average wage. Since the average wage represents the productivity of labor, this result implies that the productivity of labor is affected by weather fluctuations. Column 2 shows that average temperature does not have a significant effect on the growth rate of fixed asset investment, while precipitation has a significantly positive effect on it. Column 3 shows that an increase in temperature and precipitation lowers the growth rate of the gross output value of agriculture, which is consistent with our finding that the agriculture sector is substantially influenced by weather fluctuations. Column 4 shows that both average temperature and precipitation have negative effects on the growth of large firms, but only the effect of precipitation is significant.

Parts B and C introduce 5 lags and 10 lags of the weather variables, respectively, to examine the cumulative effects of average temperature and precipitation. The first column of parts B and C show that only temperature has a significantly negative cumulative effect on average wages. The second column shows that the cumulative effect of temperature on fixed asset investment is significantly negative and that the cumulative effect of precipitation is significantly positive.¹¹ As shown by the third column of part C, temperature has a significant cumulative effect on agriculture. The fourth column of parts B and C show that

¹¹One possible reason for this positive cumulative effect is that increasing precipitation accelerates the depreciation of fixed assets. Thus, the growth rate of fixed asset investment has to be increased to compensate for the depreciated fixed assets.

average temperature does not have a significant cumulative effect on the gross output of large firms.

In summary, in addition to the well-studied channel of agriculture, we find that average temperature has significantly negative cumulative effects on the growth rates of average wages and fixed asset investment, and that average precipitation has a significantly positive cumulative effect on the growth rate of fixed asset investment.

VI. Medium-Run Estimates

The comparison of the level effect and cumulative effect implies that the level effect of weather fluctuations in each period accumulates and that counties do not fully adapt to weather fluctuations. To further verify whether counties adapt to weather fluctuations in the medium run, we use a long difference approach to explore the medium-run relationship between the growth rate and weather variables. Our specification is similar to Dell, Jones, and Olken (2012) and Burke and Emerick (2016). Specifically, given two periods, a and b , each period contains n years. We define the average growth rate of county i in period a as $\overline{g_{ia}} = \frac{1}{n} \sum_{t \in a} g_{it}$. We define the vector of average weather variables as $\overline{C_{ia}}$. It contains the average temperature, average precipitation, and other weather variables in period a . The relationship between the average growth rate and average weather variables in period a can be described as

$$\overline{g_{ia}} = \psi + \kappa \overline{C_{ia}} + \mu_i + \overline{\epsilon_{ia}}$$

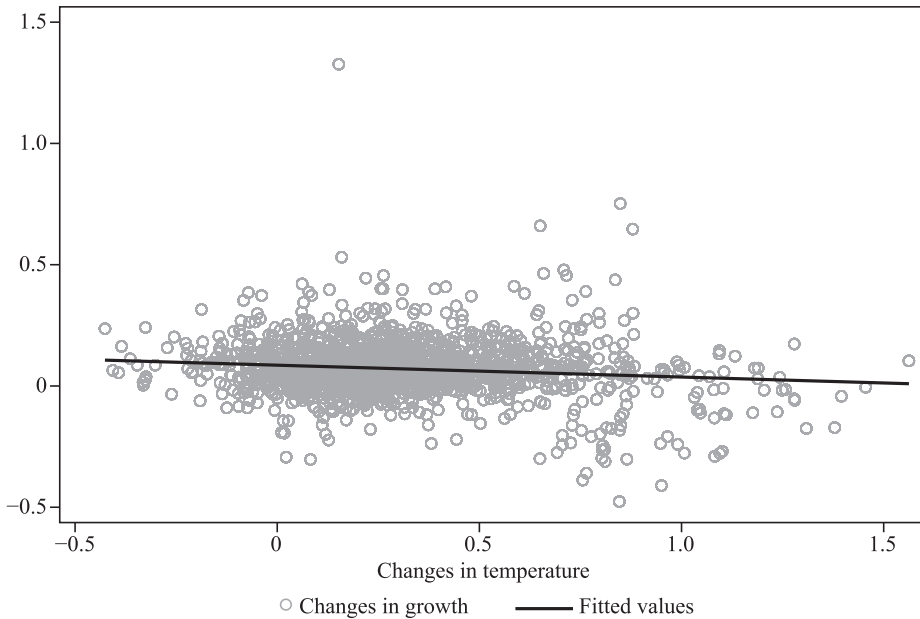
This relationship is derived by taking averages on both sides of equation (5) with 0 lags. The relationship between the average growth rate and average weather variables in period b can be derived similarly. Then, we can have the following regression specification:

$$\overline{g_{ib}} - \overline{g_{ia}} = c + \kappa (\overline{C_{ib}} - \overline{C_{ia}}) + (\overline{\epsilon_{ib}} - \overline{\epsilon_{ia}}) \quad (9)$$

The unobservable county fixed effects μ_i are eliminated. Compared with the cross-sectional models, the long difference approach is free of omitted variable problems caused by heterogeneity μ_i . Compared with panel-data models that investigate the short-run effects, the long difference model investigates the effects of temperature and precipitation on the growth rate in the medium run. If the estimated κ is smaller than the estimated level effect λ_0 in magnitude, the county's economy shows adaptation in the medium run; if not, the effects of weather fluctuations accumulate over time.

In the following analysis, we set each period at 4 years: period a is 1996–1999, and period b is 2009–2012. Figure 5 shows the changes in the average temperature and growth rate across periods a and b . This demonstrates a clear

Figure 5. Changes in Growth Rate and Average Temperature, 1996–1999 and 2009–2012



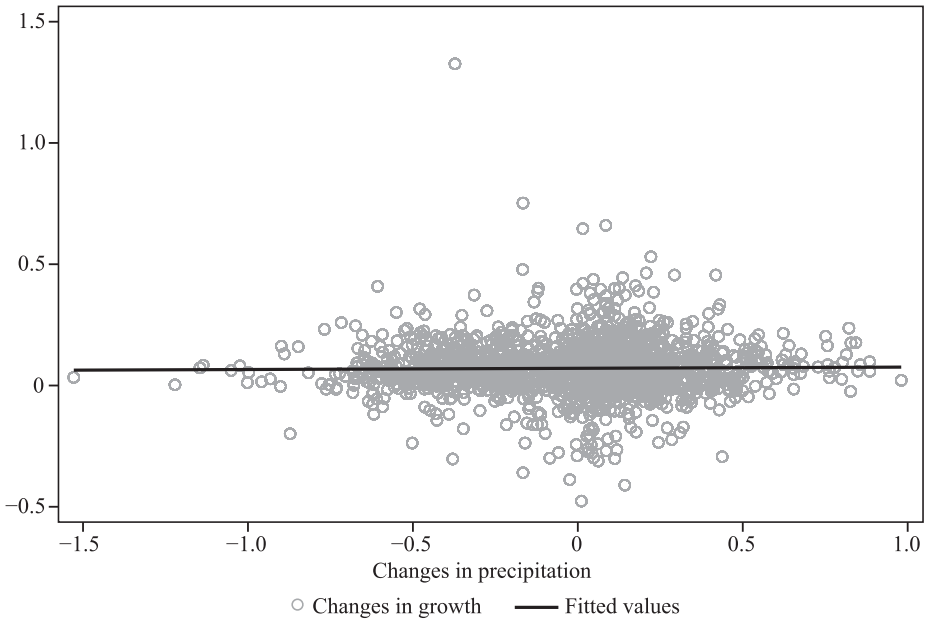
Notes: Temperature is measured in degrees Celsius.

Sources: Authors' calculation based on weather data from the China Meteorological Data Sharing Service System and the National Oceanic and Atmospheric Administration, and on economic data from the Support System for China Statistics Application.

negative relationship between the change in growth rate and average temperature change. Figure 6 shows the changes in average precipitation and the growth rate across these two periods. To facilitate comparison, part A of Table 5 reports the panel results. Column 1 of part B shows that a 1°C increase in temperature would lower the growth rate of county-level GDP per capita by 6.17%; the average precipitation change also has a significantly negative effect on the growth rate. Columns 2–4 of part B show that temperature has a significantly cumulative negative effect on all industries, while precipitation has a significantly negative effect on secondary industry and tertiary industry.

Table A.5 in the online Appendix reports the effects of temperature and precipitation on the growth rates of the average wage, fixed asset investment, the gross output value of agriculture, and the gross output value of enterprises above a designated size across period *a* and period *b*. To facilitate comparison, part A repeats the panel results. Part B shows that temperature change has a significantly negative effect on most variables except the average wage, which is positively affected; precipitation change has a significantly negative effect on the growth rate of gross output of enterprises above a designated size.

Figure 6. Changes in Growth Rate and Average Precipitation, 1996–1999 and 2009–2012



Notes: Precipitation is measured in millimeters.

Sources: Authors' calculation based on weather data from the China Meteorological Data Sharing Service System and the National Oceanic and Atmospheric Administration, and on economic data from the Support System for China Statistics Application.

We introduce region fixed effects and alternative time periods for a and b in equation (9) to check the robustness of our results under a long difference approach. The results are reported in Tables A.6–A.9 of the online Appendix; most results persist. We also use the long difference method in Burke and Tanutama (2019) and find that the negative effect of temperature is larger in magnitude than the level effect, consistent with our results in column 1 of Table 5.

In summary, comparing the coefficients of average temperature in part A and part B of Table 5, the medium-run effect of temperature is larger than its level effect in magnitude, which indicates evidence of intensification. Therefore, we can conclude that counties in the PRC adapt poorly to temperature changes during our sample period. The effects of temperature accumulate over time and lead to a larger loss in the medium run.

VII. Conclusion

This paper exploits weather data and economic data from counties in the PRC during the period 1996–2012 to examine the relationship between weather variables and economic growth. We find a significantly negative relationship between the

Table 5. Long Difference Regression (I)

A. Panel results				
	(1) County-Level GDP per Capita	(2) Value Added of Primary Industry	(3) Value Added of Secondary Industry	(4) Value Added of Tertiary Industry
Growth rate of				
Average temperature	-0.0122*** (0.0039)	-0.0253*** (0.0051)	-0.0110* (0.0061)	-0.0034 (0.0047)
Average precipitation	-0.0054** (0.0024)	-0.0091*** (0.0027)	-0.0027 (0.0038)	-0.0049 (0.0033)
Observations	25,318	25,760	25,711	24,796
R-squared	0.0801	0.0673	0.0679	0.0505
B. Long difference regression				
	(1) County-Level GDP per Capita	(2) Value Added of Primary Industry	(3) Value Added of Secondary Industry	(4) Value Added of Tertiary Industry
Change in growth rate of				
Average temperature change	-0.0617*** (0.0165)	-0.0629*** (0.0184)	-0.1102** (0.0506)	-0.0642** (0.0321)
Average precipitation change	-0.0388*** (0.0103)	0.0092 (0.0111)	-0.0693*** (0.0232)	-0.0347** (0.0161)
Early period	1996–1999	1996–1999	1996–1999	1996–1999
Late period	2009–2012	2009–2012	2009–2012	2009–2012
Observations	1,652	1,600	1,574	1,573
R-squared	0.0314	0.0331	0.0262	0.0226

GDP = gross domestic product.

Notes: Other weather variables are controlled for in all columns. The robust standard errors are reported in parentheses. *p < 0.1, **p < 0.05, and ***p < 0.01.

Sources: Authors' estimation based on weather data from the China Meteorological Data Sharing Service System and the National Oceanic and Atmospheric Administration, and on economic data from the Support System for China Statistics Application.

growth rate and average temperature. Increasing average temperature by 1°C lowers the growth rate of county-level GDP per capita by 1.05%–1.25%. The negative effect of precipitation mainly occurs in agricultural counties and poor counties. Using models with lags, we find that the cumulative effects of temperature are far greater than its level effects. Models with 1–10 lags indicate that a 1°C increase in average temperature cumulatively lowers the growth rate of county-level GDP per capita by 2.03%–3.84%. When 5 lags and 10 lags are introduced, the cumulative effects of precipitation become significantly negative, implying that the cumulative effect of precipitation emerges only in the medium run. In addition to the well-studied agriculture channel, we find that temperature has considerable impacts on tertiary industry, labor productivity, and fixed asset investment. The long difference approach finds that counties in the PRC adapt poorly to weather changes in our sample period.

Our study has significant policy implications. First, we verify that weather fluctuations have a considerable negative impact on economic growth. The unignorable threat of weather changes demands appropriate government responses such as introducing crop diversity to help farmers insulate yields and income against weather extremes (Auffhammer and Carleton 2018). Second, we find that in addition to the agriculture sector, weather fluctuations can influence economic growth by influencing the productivity of labor, fixed asset investment, and the production of nonagriculture sectors. These nonagricultural channels deserve more attention because the share of agriculture in the PRC's GDP continues to decline, and nonagricultural channels will become key channels in the future. Third, we find that counties in the PRC adapt poorly to weather changes. This is the main reason that the cumulative effects of weather fluctuations outweigh their level effects. Adaptability to weather changes requires additional investment and technological innovation.

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Online Appendix

The online Appendix is posted at <https://sites.google.com/site/jiajiacong/research>. It contains the following contents:

Table A.1. Summary Statistics of Key Variables

Table A.2. Seasonal Temperature Effects

Table A.3. Nonlinear Effects with Temperature Bins

Table A.4. Channels: Average Wage, Investment, and Output Values of Agriculture and Large Firms

Table A.5. Long Difference Regression (II)

Table A.6. Robustness of Long Difference Regression: Including Region Fixed Effect (I)

Table A.7. Robustness of Long Difference Regression: Including Region Fixed Effect (II)

Table A.8. Robustness of Long Difference Regression: Alternative Time Interval (I)

Table A.9. Robustness of Long Difference Regression: Alternative Time Interval (II)

Model of the Growth Effect of Weather Fluctuations in a Distributed Lag Model