

## Climate Impacts: Temperature and Electricity Consumption

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## **Climate Impacts: Temperature and Electricity Consumption**

**Abstract:** One of the aspects of climate change is temperature rise. Temperature rise or fluctuations affect human economic activities and electricity consumption. This paper estimates the changes in electricity consumption due to temperature fluctuation at the county scale in rural China. By using the statistics of counties from 2006 to 2015 in a fixed-effect panel model, the results indicate that a one-degree temperature increase in summer days may lead to 0.015% more electricity consumption per capita, and this correlation may be weaker as income increases. Moreover, a one-degree temperature decrease in winter days may lead to 0.002% more electricity consumption. The northern region may consume 0.021% more electricity than the southern region when facing the same temperature drop. Overall, the effect of temperature on electricity consumption is modest, particularly for a drop in temperature, but the usage of other types of energy may increase to adapt to the cold.

**Key words:** Temperature fluctuation; Electricity consumption; Rural area, Fixed-effect panel model

## 1. Introduction

Many economic activities are exposed to weather changes, and expected revenues may thus be seriously affected by extreme weather. A growing body of literature has estimated the historical effects of temperature on economic growth, human health and armed conflicts with reduced-form statistical methods (Burke et al. 2015, Burke et al. 2009, Deschenes and Greenstone 2012, Hsiang 2010, Nordhaus 1996, Yang and Gao 2007). For countries or cities in the tropical and subtropical regions, warmer/cooler weather induces a higher demand for indoor temperature conditioning. As electricity is the primary energy source for indoor temperature conditioning, for which air-conditioners and electric fans are used, this would in turn lead to a higher demand for electricity. Since temperature fluctuation could cause diverse consequences on electricity through multiple social and economic characters and different temperature patterns may present different regional estimates (Bessec and Fouquau 2008, Fan et al. 2014, Hekkenberg et al. 2009, Istiaque and Khan 2018, Jovanović et al. 2015, Liu et al. 2014, Miller et al. 2008, Sun et al. 2017). However, many questions remain to be explored in China. China is a vast country with complex and diverse climate types. Currently, there is not enough evidence to characterize the temperature-electricity relationship under different climate patterns in multi-locations across China, a country with a wide range of climates and a highly diverse population.

The paper provides a large-scale study on the effects of temperature change on electricity consumption in China. Besides, taking the economic interaction effect on the temperature impact into consideration, it overcomes the bias of estimate on the effects of temperature change from limited observation and comparable solo climate type. The paper also provides an effective and reasonable theoretical basis for policymakers to increase people's ability to adapt to climate change. The potential impacts of climate change on electricity consumption are important to both adaptation and mitigation policies. In particular, electricity consumption plays a crucial role in adapting to climate change in terms of helping to adjust to heating and cooling needs in the face of temperature changes. It is also important in mitigation planning as electricity accounts for more greenhouse gas emissions than any other sector in China(Qi et al. 2007). Therefore, information on the potential impacts of climate change on electricity consumption will be valuable in developing adaptation

and mitigation strategies.

This paper attempts to explore the effects that temperature fluctuation has on rural electricity consumption. Specifically, we attempt to estimate the effect of the higher/lower temperature on household electricity consumption. We also want to answer the following two questions. a) To what extent could a rise/drop in temperature affect rural household electricity consumption? b) How would the temperature that is induced by a different climate affect rural household electricity consumption?

The paper proceeds as follows. Section 2 briefly provides the hypothesis and literature review regarding temperature and electricity consumption. Section 3 explains the methodology and the data sources that are used in the paper. Section 4 reports the results of temperature fluctuation's effects. Section 5 discusses a mechanism from the result. Section 6 concludes and provides practical implications.

## **2. Literature review and Hypothesis**

### **2.1 Literature review on related works**

There exists abundant literature on how the temperature affects electricity consumption. Brown et al. (2014) summarize earlier studies, noting that it is unclear which is a better predictor of electricity demand-temperature or heating/cooling degree days and whether this relationship follows a U-shape with a flat bottom or a sharp V.

From the perspective of model used in the issue of temperature and electricity consumption, the statistical models have been developed by using two sets of independent variables: a) primitive variables, such as temperature, precipitation, relative humidity, wind speed, atmospheric pressure and solar radiation; b) derived variables, including heating degree-days (HDD) (Narayan et al. 2007, Valor et al. 2001), cooling degree-days (CDD) (Lam et al. 2008, Sailor 2001). These earlier literatures have econometrically estimated the relationship between electricity load and temperature using total load from all users. Alternatively, they have used model-based approaches to build bottom-up estimates of the change in electricity

usage under future climate scenarios, as in Dirks et al. (2015), whose approach is strictly based on the existing stock of buildings in the US, and Afshari and Friedrich (2017), who modelled urban energy systems using hourly electricity demand and weather measurements.

From the perspective of area of interest, the regional heterogeneity, which is induced by social and economic factors, determines the extent of the consequences in climatic impacts. For example, Auffhammer et al. (2017) use daily data from the balancing authorities in US, from 2006 to 2014, and find that while in certain zones, the temperature-load relationship is symmetric around  $21^{\circ}\text{C}$ , for others on the East Coast loads grow much more sharply as the temperature rises above  $21^{\circ}\text{C}$ . Franco and Sanstad (2008) and Khanna and Cropper (2012) concluded that annual electricity demand in California can be expected to increase by 0.8 - 17.8% relative to the 1961-1990 base period and 15%, respectively, over the course of the century. Studies for the European Union reach different conclusions. For most countries in European Union, the relationship between electricity demand and temperature has a hockey-stick shape.

As for cases in China, Chen et al. (2006) reported that the winter heating energy consumption reduced by 5% to 30% in northern China and by more than 30% in the Yangtze delta from 1985 to 2004 due to global warming. Yi-Ling et al. (2014) used data of daily electricity consumption and temperature for the period 2003-2007 in Shanghai and analysed the variation of electricity consumption and the correlations between electricity consumption and temperature. Ang et al. (2017) estimated that total annual electricity consumption would increase by between 4% and 5% in Hong Kong in 2015 if there were to be a  $1^{\circ}\text{C}$  rise in temperature.

Among the literatures mentioned above, the different conclusions are drawn from different regions. Their conclusions are drawn from resident sector based on limited observations and comparable solo climate type. What's more, they ignored the interaction effect about economic factors and temperature on response. In fact, the response from the residents to temperature fluctuation differed with multi climate types and social lifestyles. When facing to temperature shocks, the individual's income would be a significant factor that determines the adaption and response to temperature. It's necessary

to provide a large-scale research in resident sector about the relationship between temperature and electricity consumption in China, to estimate the precise impact of temperature on electricity consumption with consideration of adaption.

## **2.2 Hypotheses on temperature impact on electricity consumption**

In term of pattern of life, temperature affects rural residents more seriously than urban residents. First, in China, rural families have their own land to engage in agricultural activities with the 'Family Contract Responsibility System'. This land reform has stimulated the production desire of farmers and has greatly improved agricultural output. Temperature and precipitation are direct inputs for agriculture production.

Higher temperatures have greatly impact on rural residents. Electricity consumption in rural household is affected by two aspects: agricultural production by households and households' daily living demand. Temperature is a key factor that affects agricultural output, because extreme temperature may interrupt the field crop growth. As a result, electric appliances for household agriculture may place upward pressure on the power grid load. In the short term, higher temperatures that are caused by climate change would likely lead to less precipitation. Farmers may use electrical machinery to irrigate the field crops to compensate for the lost precipitation. Moreover, higher temperatures may lead to decreases in the amount of oxygen in the water and contribute to fish dying from hypoxia. Fisherman may artificially increase the oxygen level in the water with electric motors. When temperatures increase, residents may prolong the usage time of electrical appliances (e.g., refrigerators, electric fans, and air conditioning).

However, low temperatures have a minor impact on rural residents. Lower temperatures always occur in winter when the harvest period has passed, which requires less time for agricultural activities. Production activities may not result in a significant increase in electricity consumption. When temperatures drop, there are two reasons that electricity consumption may not increase as strongly as with rising temperatures. The first reason is the residents may choose various heating systems to live through the winter according to their income level (Luo and Wang 2007, Peng and Pan 2008). In urban areas, residents economically adopt a water-heating system in winter rather than an electric heating system. In heating

efficiency, electric heating to adapt to falling temperatures is used only after the adoption of heating systems that are based on coal combustion and natural gas, but in winter, residents may choose to shift the activity space from outdoors to indoors, which causes an increased possibility of using electric devices reserved in the households. As a result, the common choice of fuels in heating systems has saved considerable expenditures for residents, leaving residents scarcely sensible to energy saving behaviours in using household electric appliances. The second reason that electricity consumption may not increase when temperatures drop is that the grid load capacity of the rural areas does not operate as well as in the urban areas (Shen 2014). Due to the dispersed rural population, the power voltage in rural areas fails to sustain a normal operation in high-power heating appliances. Moreover, when the temperature drops, the growing season for agriculture has already concluded, and the supply of electricity for rural areas may not be as essential as it is in the growing season (Zhang et al. 2009, Zheng et al. 2014, Zhou et al. 2009). Thus, these two reasons determine that temperature drops may not greatly increase electricity consumption.

According to the review above, we build a hypothesis on the relationship between temperature fluctuation and electricity consumption: when the temperature rises, electricity consumption will increase, while electricity consumption may increase slightly with drops in the temperature. In the following sections of the paper, we will test the hypothesis with the data and econometric model that we use.

### **3. Methodology and Data**

#### **3.1 Methodology**

We interpret how climate change would impact rural household electricity consumption based on Deschênes and Greenstone (2011). We set the consumer utility function as  $U = U(LF, EC, RE)$ , where  $LF$  refers to the consumption of daily-life goods. We assume that the electricity consumption in rural areas is a function of  $LF$  because electricity is supposed to provide utilities with the consumption of  $LF$  ( $\partial EC / \partial LF > 0$ ). Meanwhile, we set  $LF$  to be a function of temperature.

Then, we define  $EC$  as the electricity consumption and set  $EC = EC[LF(T)]$ . We build the assumption that daily life and production activities are both affected by temperature.  $RE$  is denoted as other aggregated consumption goods.

$$U = U(LF, EC, RE) = U(LF, RE) \quad (0)$$

An individual faces a budget constraint of the form  $I - RE - LF - pEC = 0$ , where the prices of  $RE$  and  $LF$  are 1, and the price of  $EC$  is  $p$ .  $I$  refers to income. In this case, temperature is a key factor that affects agricultural output, and rural household income heavily depends on one's own agriculture output ( $\partial I / \partial T > 0$ ). Therefore, we denote  $I = I'(T)$ . Consequently, for a given level of utility and fixed  $p$ , there is an associated equation:  $EC(I, T, p) = EC[I'(T), T]$

We consider the impact of temperature on  $EC$  in the following equation:

$$\frac{dEC}{dT} = EC_I \frac{dI}{dT} + \frac{\partial EC}{\partial T} \quad (0)$$

According to equation (0), the first term  $EC_I \frac{dI}{dT}$  is the change in electricity consumption due to the income fluctuation that is induced by weather shock (through weather's effect on quantity). The first term can be considered the change that is derived from rural production activities because rural productive activities are the main source of household income. The second term in equation (0),  $\frac{\partial EC}{\partial T}$ , is considered to be the direct temperature impact on electricity, which is called the change in daily life electricity consumption.

According to the description of equation (0), we attempt to estimate the direct effect of temperature on electricity and the indirect effect of this direct effect on electricity combined with income. The baseline estimation strategy is shown in equation (0):

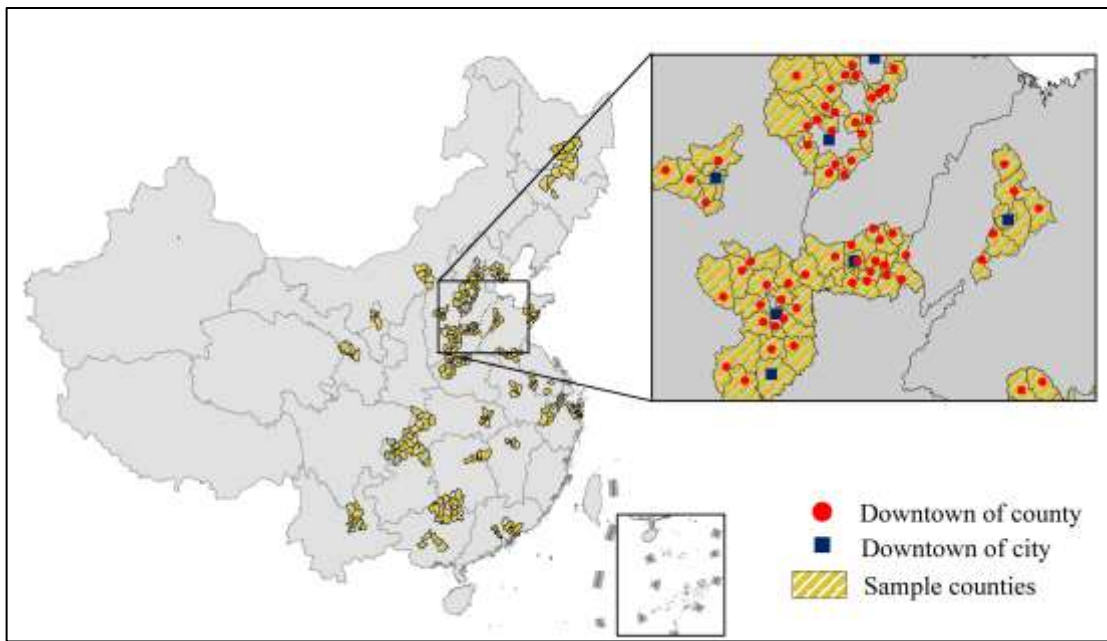
$$\ln(recper)_{i,t} = \beta_0 + \beta_1 \ln(income)_{i,t} + \beta_2 HDDK_{i,t} + \beta_3 CDDK_{i,t} + \varepsilon_{i,t} \quad (0)$$

where  $\ln(recper)$  is the natural logarithm of electricity consumption per capita,  $\ln(income)$  is the natural logarithm of net income per capita,  $HDDK$  is the annual aggregation centigrade degree of the daily temperature that is lower than  $5^\circ C$ ,  $CDDK$  is the annual aggregation centigrade degree of the daily temperature that exceeds  $26^\circ C$ , and  $\varepsilon_{i,t}$  is the error term.



### 3.2 Data

To guarantee that the statistical data has high quality, we choose the counties that are located in provincial capitals as the target samples for two reasons. First, the yearbooks of provincial capitals provide many detailed pieces of data on subordinate counties. Second, the socio-economic indexes of the counties near the provincial capital are more likely to be affected by the development of their provincial capital. Thus, we have data from 33 cities in 24 provinces and 330 counties as the sample. The location of the sample counties is shown in Figure 1.



**Figure 1** The geographic location of the selected counties

*Temperature.* The daily weather data are drawn from the National Climatic Data Center (NCDC) of the National Oceanic and Atmospheric Administration (NOAA). Alternatively, we reshape the resolution of the data files into  $1\text{ km} \times 1\text{ km}$  and use the daily temperature to calculate the heating degree-days and cooling degree-days. Deschênes and Greenstone (2011) noted that the temperature effect from climate change on economic activities is modest. In aiming to amplify the effect of temperature on electricity consumption, we build two indexes: heating degree-days in 1,000 degrees (*HDDK*) and cooling degree-days in 1,000 degrees (*CDDK*) are used to make the estimated value of the coefficient not very small and distinguishable from zero. The threshold setting for heating and cooling is critical to the result. We set threshold to take the

non-linear effect on temperature into consideration. In winter the main appliances for heating is radiator rather than air conditioner. What's more, in north of China the standard of heating policy is the successive 5 days with daily average temperature below  $5^{\circ}\text{C}$ . In summer, the main appliances for cooling is the air conditioner. In current regulation of energy-saving design standards, cooling degree days is calculated at the threshold of  $26^{\circ}\text{C}$ . Consequently, different from previous work that sets  $18^{\circ}\text{C}$  as the threshold temperature, we set  $5^{\circ}\text{C}$  as the threshold for heating and  $26^{\circ}\text{C}$  as the threshold for cooling based on Wei's works (Wei et al. 2014) since China is a vast country with complex and diverse climate types. The detailed procedures to calculate the heating degree-days in 1,000 degrees (*HDDK*) and cooling degree-days in 1,000 degrees (*CDDK*) are shown as follows:

$$HDDK_{i,t} = \sum_{i=1}^{n_t} \Delta Tem_{i,t} / 1000, \Delta Tem_{i,t} = \max(0, 5 - T_{i,t}^{\min}), i = 1, 2, 3, \dots, 330, t = 1, 2, 3, \dots, 365 \quad (0)$$

$$CDDK_{i,t} = \sum_{i=1}^{n_t} \Delta Tem_{i,t} / 1000, \Delta Tem_{i,t} = \max(0, T_{i,t}^{\max} - 26), i = 1, 2, 3, \dots, 330, t = 1, 2, 3, \dots, 365 \quad (0)$$

where  $T_{i,t}^{\max}$  and  $T_{i,t}^{\min}$  are the daily highest and lowest temperatures, respectively, in the unit of centigrade degrees.

*Rural population and households.* Rural population refers to the residents who lived in a certain county for more than 6 months. Rural households refer to the number of families whose members lived there for over one year.

*Electricity consumption per capita.* National Statistical of Bureau of China hopes to separate household electricity consumption from total rural electricity consumption. However, at the county scale, the statistics on the electricity consumption for rural households are not available and are aggregated in total rural electricity consumption (excluding electricity consumption by the rural public sector). Therefore, electricity consumption per capita is equal to the rural households electricity consumption divided by the rural population. Moreover, *electricity consumption per household* is equal to electricity consumption divided by the number of rural households.

*Gross farm production* is the total production value of the primary sector in which rural residents are mainly engaged. Furthermore, to make production values comparable, deflator indexes for the agriculture value that is added are used to eliminate the effect of the price fluctuation in different years.

*Rural household annual net income.* The rural household annual net income is measured at the current year's price level. To keep the net income comparable, the consumer price indexes for each city from 2006-2015 are used to eliminate the effects of inflation.

*Rural population and households, Gross farm production, Electricity consumption and Rural household annual net income* at the county scale are collected from the yearbooks of the administrative affiliation cities for 2006-2015.

*Precipitation.* The dataset is provided by the Data Center for Resources and Environmental Sciences at the Chinese Academy of Sciences (RESDC) (<http://www.resdc.cn/>). We control for the precipitation to avoid the effect from farmer's agricultural production customs that are induced by long-term precipitation trends.

*Distance.* We acquired the geographical coordinates not only of the downtown in each county but also of the downtown in the corresponding prefecture-level city. The distances are calculated by the ARCGIS in the equidistant projection. The shorter the distance between the county and city, the more numerous the economic connections. Moreover, the infrastructure of the counties that are located at a shorter distance from a city will be better than the infrastructure of the other counties that are further from a city.

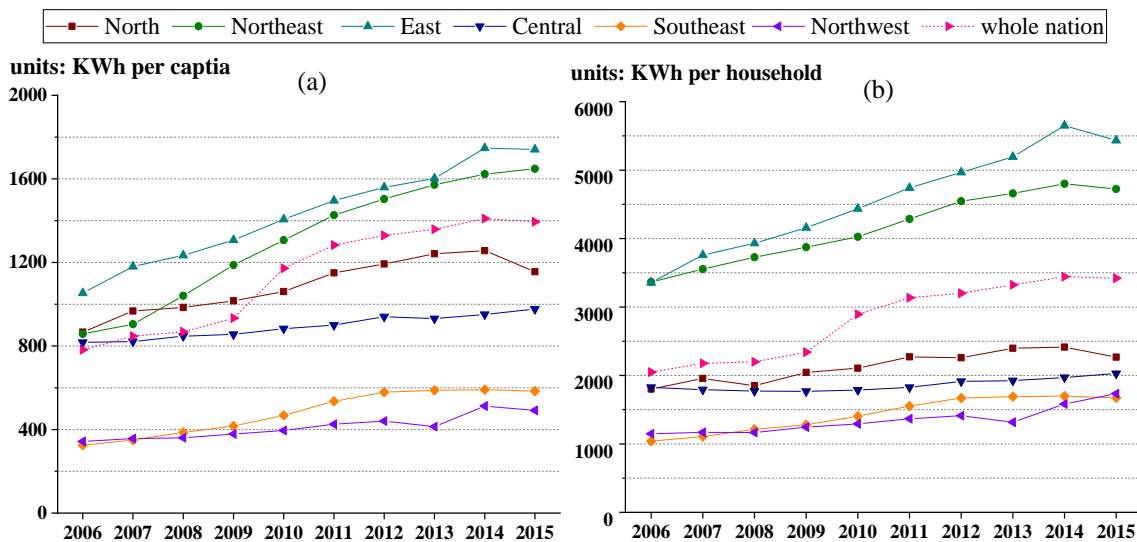
## **4. Results**

This section includes three parts. Section 4.1 shows the situation of the electricity consumption in rural China. Section 4.2 reports the results from the model. Section 4.3 explores the further determinants that affect electricity consumption.

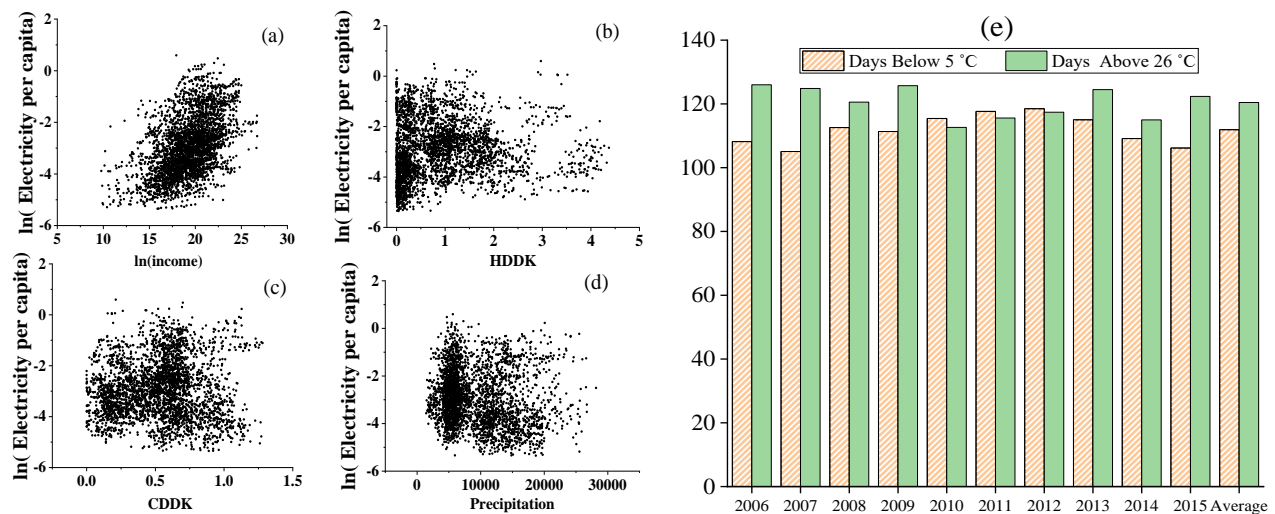
### **4.1 Electricity consumption in rural China**

As shown in Figure 2(a), electricity consumption per capita has been increasing since 2006. At the national level, the average electricity consumption per capita increased from 782 *KWh* in 2006 to 1,393 *KWh* in 2015 with an annual increase rate of 6.7%. Electricity consumption per household has a similar trend with the above electricity per capita in Figure 2(b). In total, the average annual increase rate at the national level is 5.8%, and electricity per household increased from 2,048

*KWh* in 2006 to 3,420 *KWh* in 2015. According to the scatter plots of Figure 3, the net income per capita has a significant positive correlation with electricity consumption. However, it is not obvious that *HDDK* has a significant correlation with electricity consumption or that *CDDK* has an insignificant correlation with electricity consumption. Concerning precipitation, there is no significant correlation with electricity consumption.



**Figure 2** (a) The change in the annual rural electricity consumption per capita from 2006-2015. (b) The change in the annual rural electricity consumption per household from 2006-2015. Source: the authors’ calculation from the collected dataset. North group includes four provinces (109 counties): Beijing, Hebei, Shanxi and Neimenggu. Northeast group includes two provinces (13 counties): Jilin and Heilongjiang. East group includes five provinces (64 counties): Jiangsu, Anhui, Zhejiang, Jiangxi and Shandong. Central group includes five provinces (85 counties): Henan, Hubei, Hunan, Guangdong and Guangxi. Southwest group includes one province and one municipality (44 counties): Yunnan and Chongqing. Northwest group includes 2 provinces (10 counties): Qinghai and Ningxia.



**Figure 3** (a) Scatter plots of the net income and rural electricity consumption per capita. (b) Scatter plots of the heating degree-days and rural electricity consumption per capita. (c) Scatter plots of the cooling degree-days and rural electricity consumption per capita. (d) Precipitation and rural electricity consumption per capita. (e) Annual

number of days below 5°C or above 26°C between 2006 and 2015.

## 4.2 Main Results: CDDK and HDDK with Electricity Consumption

Table 1 reports the correlation between electricity consumption per capita and *HDDK* and *CDDK* with the OLS (Ordinate Least-Square method) and panel model. As we discussed above, Table 1 shows the correlation between electricity consumption and *HDDK* and *CDDK* in the baseline estimation. The result in column A1 shows that *HDDK* and *CDDK* both have a significant positive correlation with electricity consumption and *CDDK*; specifically, *CDDK* has a more positive correlation with electricity consumption than *HDDK*. Column A2 shows that by considering *HDDK* and *CDDK* and controlling for precipitation, *CDDK* still has a positive relationship with electricity consumption. However, *HDDK* seems to have a negative correlation with electricity consumption without satisfying any significant levels.

Since the time span of the dataset that we use is from 2006-2015 and the samples that we collect include 33 cities in 24 provinces, it is evident that the heterogeneity in the samples from the year, regional and individual effects may influence the estimate of the effect from *HDDK* and *CDDK* on electricity consumption. Deschenes and Greenstone (2012) noted that the absence of a regional effect would obviously underestimate the effect of climate change on socio-economic activities. Therefore, we consider the regional effect to employ the fixed-effect panel data model.

In Table 1, columns B1-B3 show the results of the panel model considering the year and region effects. After adding the income and its interaction with *HDDK* and *CDDK*, column B3 shows that *CDDK* shares approximate coefficients with column A2. Moreover, the coefficient of  $\ln(\text{income}) * CDDK$  shows that the positive relationship between *CDDK* and electricity consumption may become lower as income increases. However, *HDDK* still has no significant impact on the electricity consumption in the models that are shown in columns B1-B3 of Table 1.

**Table 1** Income, Temperature and Electricity Consumption

	OLS		Panel Model		
	A1	A2	B1	B2	B3
<i>CDDK</i>	0.039*** (-4.121)	0.504*** (-5.264)	-0.151* (-1.921)	-0.128 (-1.632)	0.492* (-1.842)
<i>HDDK</i>	0.148*** (-5.123)	-0.006 (-0.173)	-0.007 (-1.463)	-0.004 (-0.885)	0.024 (-0.401)

$\ln(\text{income})$				0.345***	0.440***
				(-10.237)	(-8.652)
$\ln(\text{income}) * CDDK$					-0.146**
					(-2.443)
$\ln(\text{income}) * HDDK$					-0.006
					(-0.483)
<i>Year &amp; Regional effect</i>	No	No	Yes	Yes	Yes
<i>Precipitation</i>	No	Yes	No	No	No
<i>Observations</i>	3,228	3,228	3,228	3,228	3,228
<i>R- Square</i>	0.11	0.28	-	-	-

Note: The  $t$  statistics are in parentheses; \*  $p < 0.1$ , \*\*  $p < 0.05$ , \*\*\*  $p < 0.01$ .

### 4.3 North-South division determines diverse modes of electricity consumption

Columns C1-C3 of Table 2 show that the coefficients of  $CDDK$  and  $\ln(\text{income}) * CDDK$  keep their significance after controlling for *precipitation*, *distance*, *household*, and *gross farm production*. The geographic differences form different climate patterns. Particularly in China, the geographical division of the north and south gradually shapes the diverse lifestyles in each region (Ebenstein et al. 2017). Here, we define the North effect as being equal to 1 if the county is located in the north with 800 mm of annual isohyet in meteorology; otherwise, the North effect is 0. The remarkable feature of the North-South difference is the way that the residents live through winter. Moreover, in winter, the formation of the habit of winter heating helps the residents to live through the cold winter. Due to income inequality, the different choices of heating fuel and devices may affect energy and electricity consumption (Zheng et al. 2014). In column D3, we estimate the effect of  $CDDK$  and  $HDDK$  on electricity consumption under the average net income. According to Figure 2(e), the average amount of cooling days in summer is approximately 120, and the average amount of heating days in winter is 111. With the average net income fixed, a one-degree temperature increase in the summer days may lead to a 0.015% ( $0.128\% \times 0.12$ ) increase in electricity consumption with a significance level of 10%. Moreover, a one-degree temperature decrease in winter days would lead to a 0.002% ( $0.016\% \times 0.11$ ) increase in electricity consumption with a significance level of 10%. Furthermore, the North effect would lead to 0.021% ( $0.189\% \times 0.11$ ) more electricity consumption than the South effect.

**Table 2** Temperature and Electricity Consumption Conditions and the North-South Effect

	No habits of winter heating			Habits of winter heating		
	C1	C2	C3	D1	D2	D3
$CDDK$	0.603**	0.572**	0.560**	0.549**	0.610*	0.128*
	(2.231)	(2.093)	(2.054)	(2.012)	(1.814)	(1.732)

<i>HDDK</i>	0.027 (0.441)	0.035 (0.573)	0.046 (0.753)	0.038 (0.627)	0.019* (0.767)	0.016* (0.756)
$\ln(\text{income})$	0.446*** (8.753)	0.440*** (8.563)	0.422*** (8.243)	0.415*** (8.101)	0.392*** (8.115)	0.394*** (8.116)
$\ln(\text{income}) * CDDK$	-0.150** (-2.524)	-0.0142** (-2.343)	-0.143** (-2.362)	-0.135** (-2.215)	-0.114** (-2.001)	
$\ln(\text{income}) * HDDK$	-0.007 (-0.492)	-0.008 (-0.642)	-0.011 (-0.852)	-0.010 (-0.711)		
<i>North* HDDK</i>					0.229* (1.801)	0.189* (1.801)
$[\ln(\text{income}) - \overline{\ln(\text{income})}] * CDDK$						-0.09** (-2.321)
<i>Year&amp; Regional effect</i>	Yes	Yes	Yes	Yes	Yes	Yes
<i>Precipitation</i>	Yes	Yes	Yes	Yes	Yes	Yes
<i>Distance</i>	No	Yes	Yes	Yes	Yes	Yes
<i>Amount of rural household</i>	No	No	Yes	Yes	Yes	Yes
<i>Gross farm production</i>	No	No	No	Yes	Yes	Yes
<i>Observations</i>	3,234	3,234	3,151	3,151	3,151	3,151

Note: Dependent variable:  $\ln$  (electricity consumption per capita). The  $t$  statistics are in parentheses; \*  $p < 0.1$ , \*\*  $p < 0.05$ , \*\*\*  $p < 0.01$ .

To determine the distinct effect of temperature fluctuation on rural household electricity consumption in various regions, we divide all samples into 5 groups by the administration code of county, which are the north group, northeast group, east group, central group, and southwest group as Fig.2. Each group was processed with a regression with the same model in column D2 of Table 2.

Column (1) in Table 3 shows that *CDDK* has a positive correlation with electricity consumption in the north region. A one-degree temperature increase in summer days may cause a 0.39% ( $3.256\% \times 0.12$ ) increase in electricity consumption. In addition, column (2) shows a similar result for the northeast region. The north and northeast regions share a similar result with column D3 in Table 2. However, Table 3 shows that income has a significant positive correlation with electricity consumption in the eastern, central and southwestern regions. Thus, temperature fluctuation is not the key factor that affects rural electricity consumption.

**Table 3** Temperature and Electricity Consumption from a Regional Perspective

	North (1)	Northeast (2)	East (3)	Central (4)	Southwest (5)
<i>CDDK</i>	3.256***	41.550*	-0.578	-0.624	0.462

	(3.157)	(1.779)	(-0.491)	(-0.712)	(0.853)
<i>HDDK</i>	0.474	5.414**	1.365*	-0.520	-0.886
	(1.182)	(2.241)	(1.674)	(-0.589)	(-0.986)
$\ln(\text{income})$	0.885***	7.150**	0.504*	0.615***	0.380***
	(3.472)	(2.371)	(1.773)	(3.212)	(2.631)
$\ln(\text{income}) * CDDK$	-0.8413***	-10.07*	0.223	0.200	-0.171
	(-3.589)	(-1.831)	(0.928)	(1.067)	(-1.302)
$\ln(\text{income}) * HDDK$	-0.1601*	-1.442**	-0.290*	0.115	0.121
	(-1.756)	(-2.404)	(-1.912)	(0.693)	(0.522)
<i>North* HDDK</i>	-	-	0.0543	0.517	-
	-	-	(0.171)	(1.412)	-
<i>Year &amp; Regional effect</i>	Yes	Yes	Yes	Yes	Yes
<i>Observations</i>	1,054	130	786	774	440

Note: Dependent variable is  $\ln$  (electricity consumption per capita). Control variables include precipitation, distance, rural household and gross farm production. The  $t$  statistics are in parentheses; \*  $p < 0.1$ , \*\*  $p < 0.05$ , \*\*\*  $p < 0.01$ .

## 5. Discussion

This section is divided into two parts. The first part explains how the change in temperature affects rural electricity consumption in diverse ways. The second part clarifies the origin of how temperature fluctuation affects electricity consumption in different regions under different climate conditions.

### 5.1 Temperature affects electricity consumption in rural China

#### 5.1.1 An increase in temperature impacts productive activities

We explain how an increase in temperature affects the electricity of rural households in two ways. As Figure 4(a) shows, currently, colour TVs, refrigerators and washing machines are three of the most popular electric appliances in rural households. In 2015, the average number of air conditioners in rural households was approximately 38 sets in every 100 houses. This number is much higher (114 sets) in urban households. When the temperature increases in summer, the use of air conditioners, refrigerators and electric fans may increase the small consumption of electricity. As income increases, families tend to increase their living standard by purchasing more efficient devices, which means that with the same electricity consumption, a family would achieve a better living environment. Furthermore, an increase in income may help the residents to own or construct homes with better heat preservation to allow the indoors to be less susceptible to outdoor

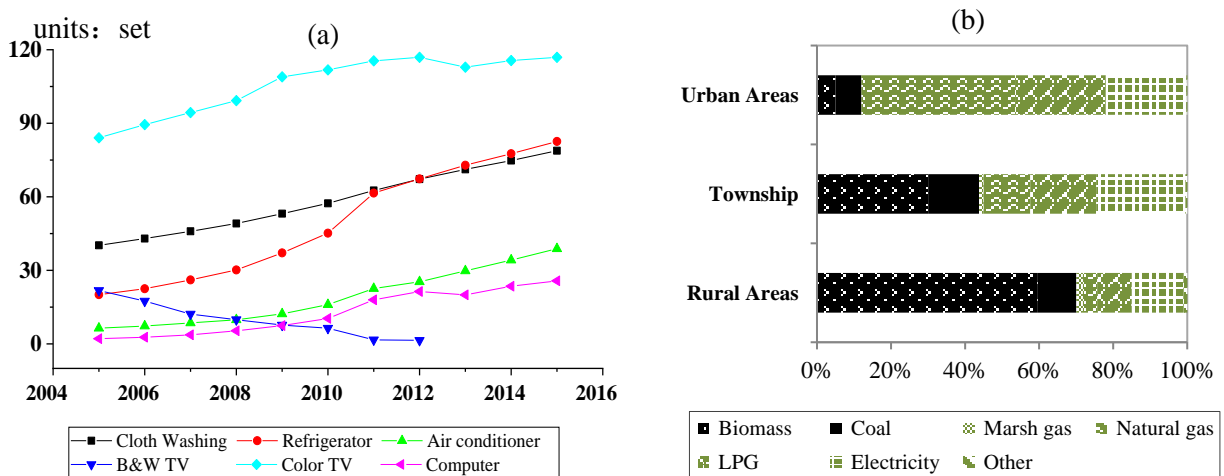


weather changes.

In terms of productive activities, a sustained increase in temperature generally occurs in the summer, which is the busy farming season. Take agricultural activities as an example. Field crops are more sensitive to temperature and precipitation. A high dew-point temperature may accelerate the evaporation of water in the field. To compensate, farmers may choose to use electric motors to irrigate the fields with river or reservoir water in case of drought. Consequently, more frequently increasing temperatures would lead to more electricity consumption.

### 5.1.2 A decrease in temperature increases the time spent indoors

A decrease in temperature below 5°C mainly affects rural electricity consumption in terms of daily life. A sustained decrease in temperature occurs in the winter when the autumn harvest has finished. At this time, field crop productive activities have finished, and the decrease in temperature leads to less willingness for outdoor farming. As a result, the productive activities in winter make an insignificant contribution to electricity consumption. However, in terms of daily life, the primary energy demand for rural households in winter is cooking and heating. Based on Hou et al. (2017) work, there are significant rural-urban deviations in cooking fuel choices (see Figure 4(b)). The electricity for cooking occupies only a small portion (14.4% for rural areas in Figure 4(b)) and is not the conclusive factor that changes the rural household electricity in winter.



**Figure 4** (a) Quantity of rural household electric appliances for every 100 households. Source: *Chinese Statistical Yearbook* (2006-2016), NBS National Bureau of Statistics. (b) Different energy sources of cooking fuels in Chinese rural households in 2012. Source: (Hou et al. 2017).

It is very cold in northern China during the winter, and people traditionally adopt winter heating. Although a heating policy is implemented in urban areas, heating customs may inevitably be introduced into some portion of rural households. Moreover, rural areas have economically adopted a water heating system in winter rather than the electric heating system of urban areas. Two of the most common types of heating systems are the Chinese Kang (23.78%) and stove heating (28.72%) (Zheng et al. 2016, Zhuang et al. 2009). We believe that the direct increase in electricity consumption that is induced by electric heating appliances occupies a small proportion of the total winter electricity consumption in rural areas. The results evidently support the estimates that we obtained in column D3 of Table 2. The counties with habits of winter heating are mainly located in the north China plain and northeast region. The average temperature level is lower than  $0^{\circ}\text{C}$  in winter in these regions. Therefore, the residents who live in houses with heating systems in winter may tend to reduce their time outdoors. The shift in the activity space from outdoors to indoors increases the possibility of using electric devices in the household. Moreover, the common choice of fuels for heating systems has saved considerable expenditures for residents and leaves residents scarcely aware of energy-saving behaviours when using household electric appliances.

### **5.1.3 Comparison with related works**

In section 4, our results show that temperature fluctuations may increase electricity consumption. Due to the limitation of the available data, there is no similar research on China. Chong (2012) indicates that a rising temperature may increase electricity consumption. With the threshold temperature of  $18^{\circ}\text{C}$  for cooling and heating, Chong (2012) work showed in California's residential sector that a one-degree temperature increase in CDD would lead to 0.056% more of daily electricity use, while a one-degree temperature increase in HDD would lead to 0.027% more of daily electricity use. We use annual electricity consumption to estimate the aggregate effect in the long run. As a result, we obtain similar correlations between temperature and electricity consumption although the short-term temperature effect that Chong estimated on electricity is much more than our short-term temperature effect.

It is evident that the effects of climate on electricity consumption are elastic in the short term, while it may be inelastic

in the long term, which leads to the short-term effect being greater than the long-term effect. Moreover, the progress of agriculture electrification and an under-developed grid infrastructure restrain the effects of temperature on electricity. Specifically, the difference between Chong's findings and our findings is that we provide an estimate regarding the remarkable effect of temperature that is induced by the division of the North and South effects on electricity consumption in China. The underlying disparity in lifestyle between the north and south forms considerable electricity consumption behaviours. Although our results contradict the hypothesis that '*global warming decreases energy use in winter but it may increase it in summer*' (Pilli-Sihvola et al. 2010), we believe that the shock of a decreasing temperature and adaption definitely have an impact on electricity consumption.

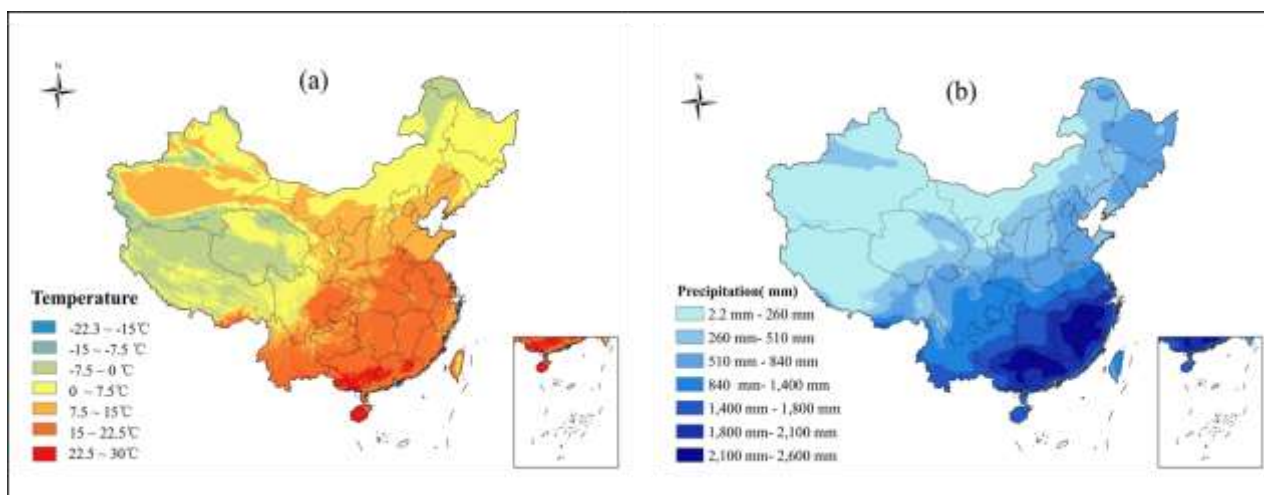
## **5.2 Effects of climate type on electricity consumption by region**

As Figure 5 shows, the annual temperature distribution in China is gradually shifting from north to south, and the average precipitation of the northern region is approximately 20 mm. The certain level of precipitation is much lower than the level of precipitation that is needed for field crop growth. To some extent, the initiative of manual irrigation to compensate for the loss in precipitation is a measure of adaptation to weather change. The even lower level of precipitation makes a substantial contribution to the rural electricity increase in the northern region, while a sustainable increase in temperature occurs in the summer. Moreover, the counties all have habits of winter heating, which leads to the decrease in temperature having no significant upward impact on rural electricity consumption.

In addition, the situation in the northeast is quite similar to the northern region and leaves field crops heavily dependent on agriculture irrigation. However, the situation in the eastern and central regions is different from the situation in the north. The *CDDK* has no significant correlation with rural electricity consumption. In the central and eastern regions, the hot temperature and humid climate may combine with heavy precipitation because of the rainy season. The productive activities in the summer have a minor impact on the rural electricity consumption increment. Regarding the eastern region,

in the winter, the perceived temperature would be much lower than the actual temperature due to the humidity. The coldness that is induced by the humid climate causes the incremental change in rural electricity consumption in the winter. The effect of an increase in income would help residents to choose a more comfortable shelter accommodation from the cold.

Concerning the central and southwestern regions, the major factor determining rural electricity consumption is income. The average levels of precipitation and temperature are much higher than the national average levels. Furthermore, the share of the productive values of animal agricultural such as husbandry and fisheries is much smaller than in the northern and north-eastern regions. Consequently, the climate condition and the structure of industries result in the insignificant correlation between temperature fluctuations and rural electricity consumption.



**Figure 5** (a) Annual average temperature from 2006 to 2015 in China. (b) Annual average precipitation from 2006 to 2015 in China.

## 6. Conclusions

This paper attempts to estimate the effect of temperature fluctuations on electricity consumption in rural China due to weather changes. We use annual electricity consumption to estimate the temperature effect on the rural residential sector with a fixed-effect panel model. The results show that CDDK has a positive correlation. Simultaneously, this correlation tends to disappear as the net income per capita increases. Moreover, a one-degree temperature increase in the summer days leads to a 0.015% increase in electricity consumption with the average net income. To explore the correlation between

HDD and electricity consumption, we divide the samples into two groups: north and south. The results show that the electricity consumption in the counties in the south increases by 0.002% with a one-degree temperature decrease in the winter days. In addition, the households in north China tend to use 0.021% more electricity than the households in the south with a one-degree temperature increase in the winter days.

Global warming contributes to the occurrence of extreme weather, which leads to higher temperatures in the summer and lower temperatures in the winter. In our analysis, the effect of the increase in temperature is more powerful than the decrease in temperature, which is consistent with the works of Chong (2012) and Pili-Sihvola et al. (2010). Additionally, income and the reduction in the time that is spent outdoors are both remarkable adaptations to the weather changes in rural China. Income would help the residents to live in comfortable shelter accommodations from the temperature changes (Aroonruengsawat and Auffhammer 2011). Furthermore, the reduction in the time that is spent outdoors may directly reduce the exposure to the cold (NIEH 2010, IPCC 2014). We conclude that the extreme weather that is induced by global warming may increase energy use, particularly electricity consumption. Our hypothesis that is presented in section 2 is therefore supported. Global warming increases electricity consumption in rural China during both the winter and the summer.

We attempted to collect the statistical data of 330 counties from 2006-2015 as much as possible. Unfortunately, some limitations still exist, such as the lack of information for households (e.g., by age, gender, and education level) (Chen et al. 2013, Santamouris et al. 2007, Zhou and Teng 2013) and the recognition of energy saving behaviours (Bhattacharyya and Ohiare 2012). These two aspects of the variables help to emphasize the effect that temperature has on electricity consumption indirectly. Climate change has influenced rural households in China, and these effects should not be overlooked.

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