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Climate-driven changes in CO₂ emissions associated with residential heating and cooling demand by end-century in China

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Abstract

Global climate change affects residential heating and cooling demand that further contributes to carbon dioxide (CO₂) emissions. The spatio-temporal changes in magnitude and distribution of the demands in China are poorly understood. In addition, few studies have focused on the future impact of climate change on long term residential CO₂ emissions in China. Here we investigate regional changes in CO₂ emissions calculated from degree-days. Our results show that heating degree-days (HDD), cooling degree-days (CDD) and their associated CO₂ emissions all have large spatio-temporal variability. We find that average durations of HDD and CDD are predicted to be 34 days shorter and 63 days longer by the end of century (2071–2100) than history (1976–2005). CO₂ emissions from residential cooling and heating are predicted to increase 218% and decrease 30% in China by end-century, respectively. We further examine the CO₂ emissions from residential heating and cooling in five cities representative of five contrasting architectural climate zones in China. The CO₂ emissions from heating of these cities are projected to decrease by end-century: 26% in Harbin, 32% in Beijing, 43% in Shanghai, 42% in Kunming, and 61% in Shenzhen. The CO₂ emissions from cooling of these cities all increase by end-century: 436% in Harbin, 215% in Beijing, 223% in Shanghai, 765% in Kunming, and 149% in Shenzhen.

1. Introduction

China has experienced a large national increase in energy use for the last seventeen years (British Petroleum 2018). In 2017, China accounted for 23.2% of global energy consumption, and contributed 33.6% of global energy consumption increase (British Petroleum 2018). About 25% of the total national energy used for buildings is dominated by residential use (China Ministry of Construction 2010b). These high levels of energy consumption exacerbate carbon dioxide (CO₂) emissions in China, which increase 1.6% in 2017 (British Petroleum 2018). Therefore, China plays a fundamental role in global transition to low-carbon use.

Global climate change affects energy consumption and corresponding CO₂ emissions (Auffhammer and Mansur 2014), thus domestic energy use needs to adapt to the changing climate (Holmes et al 2017). In response to future climate change among different regions of China, it is urgent to understand the spatio-temporal distribution of residential building energy consumption and corresponding CO₂ emissions.

Previous research estimated energy consumption and associated CO₂ emissions by means of degree-days (Moustris et al 2015, Hao et al 2016, Park et al 2018). Heating degree-days (HDDs) and cooling degree-days (CDDs) are accumulated Celsius degree temperature deviations from a defined base temperature within a certain period (CIBSE 2006). The base temperature is the outdoor temperature, above or below which there is no need for domestic heating or cooling (Buyukalaca et al 2001). CDD well reflect the weather dependence of electricity consumption at building scale (Guan et al 2017). As indicators of thermal comfort, CDD were shown to increase, whereas
HDD were shown to decrease at regional or national scale due to climate change (Moursesh 2011, Petri and Caldeira 2015).

Most current studies of degree-days in China only focused on the future changes (You et al 2014, Shen and Liu 2016, Shen et al 2017), rather than energy demand or CO2 emissions. Some studies focused on national future changes in energy consumption, but lacked of comprehensive regional analysis (Shi et al 2016, Gi et al 2018). Furthermore, estimation of energy consumption and CO2 emissions from the architectural climate zones across China employing various designs of building envelopes to conserve energy is deficient (China Ministry of Construction 2016). Without consideration of architectural climate zones, the influence of different building envelopes on energy demand would be ignored, especially the demand for heating. Ignoring such demand will result in inaccurate estimation of energy consumption.

In this paper, we aim to quantify potential impact of climate change on residential heating and cooling degree-days from five contrasting architectural climate zones across China. We select one city from each contrasting architectural climate zone (figure S1 is available online at stacks.iop.org/ERL/14/084043/mmedia), comprising Harbin (severe cold), Beijing (cold), Shanghai (hot summer and cold winter), Shenzhen (hot summer and warm winter), and Kunming (moderate climate) for further analysis and comparison (China Ministry of Construction 2016). We also use historical (1976–2005) and future (2021–2050, 2071–2100) annual degree-day data to estimate associated CO2 emissions.

### 2. Materials and methods

#### 2.1. Data

Daily maximum and minimum temperatures at 828 observation stations (figure S2) from 1976 to 2005 are extracted from the Chinese Daily Surface Climate Dataset (http://data.cma.cn/, accessed in October 2016). Simulated daily maximum and minimum near surface air temperature data (https://esgf-index1.ceda.ac.uk/projects/esgf-ceda/, accessed in October 2016) are from 30 CMIP5 climate models under historical and business as usual RCP8.5 scenarios (Taylor et al 2012) (table S1). Elevation data used in the models were measured by National Aeronautics and Space Administration (NASA) and National Imagery and Mapping Agency (NIMA) in 2000. The dataset is provided by International Scientific & Technical Data Mirror Site, Computer Network Information Center, Chinese Academy of Sciences (http://gcloud.cn, accessed in March 2016).

#### 2.2. Methods

A summary of data processing and analyzing steps is presented as figure S3. First, we use a joint bias correction method (Li et al 2014) to correct CMIP5 data. This method considers the relationship between variables, whereas commonly used bias correction methodologies treat each variable independently (Li et al 2014). After bias correction, the CMIP5 simulations of historical HDD and CDD are consistent with the observations (figure S4, $R^2 > 0.95$). Then we calculate degree-days and CO2 emissions by the methods described below.

#### 2.2.1. Degree-days

We calculate daily degree-days using the United Kingdom Meteorological Office equations (CIBSE 2006) (tables 1 and 2). Base temperatures vary across different regions. For example, heating and cooling base temperatures are 17 °C in Norway (Seljome et al 2011) and 18.3 °C in the United States (Petri and Caldeira 2015). Here, we set the heating and cooling base temperatures at 18 °C ($\theta_h$) and 26 °C ($\theta_c$), respectively (China Ministry of Construction 2010b).

We calculate annual degree-days at each station for each of the three time periods (1976–2005, 2021–2050, and 2071–2100), comprising Harbin (severe cold), Beijing (cold), Shanghai (hot summer and cold winter), Shenzhen (hot summer and warm winter), and Kunming (moderate climate) for further analysis and comparison (China Ministry of Construction 2016). We also use historical (1976–2005) and future (2021–2050, 2071–2100) annual degree-day data to estimate associated CO2 emissions.

#### Table 1. Equations used to calculate daily heating degree-days (CIBSE 2006).

| Case | Condition | Daily HDD (°C day) |
|------|-----------|-------------------|
| 1    | $\theta_{\text{max}} \leq \theta_h$ | $\theta_h - (\theta_{\text{max}} + \theta^{**})/2$ |
| 2    | $\theta_{\text{max}} > \theta_h$; $\theta_{\text{max}} < \theta_c$; $(\theta_{\text{max}} - \theta_h) < (\theta_h - \theta_{\text{min}})$ | $(\theta_h - \theta_{\text{min}})/2 - (\theta_{\text{max}} - \theta_h)/4$ |
| 3    | $\theta_{\text{max}} > \theta_h$; $\theta_{\text{min}} < \theta_c$; $(\theta_{\text{max}} - \theta_h) \geq (\theta_h - \theta_{\text{min}})$ | $(\theta_h - \theta_{\text{min}})/4$ |
| 4    | $\theta_{\text{min}} \geq \theta_h$ | $0$ |

Note. *$\theta_{\text{max}}$: daily maximum temperature; **$\theta_{\text{min}}$: daily minimum temperature.

#### Table 2. Equations used to calculate daily cooling degree-days (CIBSE 2006).

| Case | Condition | Daily CDD (°C day) |
|------|-----------|--------------------|
| 1    | $\theta_{\text{max}} \leq \theta_h$ | $0$ |
| 2    | $\theta_{\text{max}} > \theta_h$; $\theta_{\text{max}} < \theta_c$; $(\theta_{\text{max}} - \theta_h) < (\theta_h - \theta_{\text{min}})$ | $(\theta_{\text{max}} - \theta_h)/4$ |
| 3    | $\theta_{\text{max}} > \theta_h$; $\theta_{\text{min}} < \theta_c$; $(\theta_{\text{max}} - \theta_h) \geq (\theta_h - \theta_{\text{min}})$ | $(\theta_{\text{max}} - \theta_h)/2 - (\theta_h - \theta_{\text{max}})/4$ |
| 4    | $\theta_{\text{min}} \geq \theta_h$ | $(\theta_{\text{max}} + \theta_{\text{min}})/2 - \theta_h$ |
2021–2050, 2071–2100) that are further interpolated to a 25 km × 25 km grid using universal Kriging (Mosammam 2013). We include latitude and elevation as auxiliary variables in the kriging method.

2.2.2. CO₂ emissions

We develop a standardized residential building for each architectural climate zone to allow comparative analysis of 
CO₂ emissions that is a 10 m × 10 m × 3 m single-story building, with a 45% window-to-wall ratio of two of the four walls. The building envelope is based on the local design standard for energy efficiency of residential buildings. We estimate energy demand for heating as (CIBSE 2006):

\[ Q_h = 24 \cdot U' \cdot \text{HDD}_a / \eta, \]

where \( Q_h \) is the energy demand for heating (kWh), \( U' \) is the overall building heat loss coefficient (kW K⁻¹), \( \text{HDD}_a \) is the annual HDD, and \( \eta \) denotes the overall heating system efficiency. Coal-fired boiler plants are used in cities in severe cold and cold zones for space heating. Air conditioners and electric heaters are used for heating in cities in the hot summer and cold winter, hot summer and warm winter, and moderate climate zones. The overall efficiency \( \eta \) of coal-fired boiler plants is 64.4% (i.e. 92% transport efficiency × 70% boiler operation efficiency, China Ministry of Construction 2010b). And the overall mixed energy efficiency ratio equal to the overall heating system efficiency (\( \eta \)), which is 1.7 for air conditioners and electric heaters (China Ministry of Construction 2012).

We calculate the overall building heat loss coefficient \( U' \) (CIBSE 2006) as:

\[ U' = \left( \sum A \cdot U \right) / N \cdot V / 3 \cdot 1000, \]

where \( U \) is the fabric value (W m⁻² K⁻¹), \( A \) is the component area (m²), \( N \) is the air infiltration rate per hour (h⁻¹), and \( V \) is the volume of infiltrated air (i.e. 180 m³) equivalent to 60% of the volume of the standardized building (China Ministry of Construction 2010b). Here, we only consider the heat loss from wall, window, and roof of a residential building. Table 3 summarizes the main design parameters (China Ministry of Construction 2010a, 2010b, 2012, 2017).

Similarly, we use a generalized method to calculate annual energy consumption for cooling demand (CIBSE 2006):

\[ Q_c = 24 \cdot m \cdot C_p \cdot \text{CDD}_a / \text{COP}, \]

where \( Q_c \) is the energy demand for cooling (kWh), \( m \) denotes the mass flow rate of air cooled per second (kg s⁻¹), equivalent to 0.23 kg s⁻¹ for an air conditioner with refrigerator power equal to 3486 W, \( C_p \) is the specific heat of air equal to 1.005 kJ kg⁻¹ K⁻¹, \( \text{CDD}_a \) is the annual sum of CDD, and COP, which represents the energy efficiency ratio of the air conditioner for cooling, is equal to 3.0 (China Ministry of Construction 2012). We assume that two air conditioners (2\( Q_c \)) are in use at the same time in each household.

Finally, we calculate CO₂ emissions from raw coal as:

\[ M = Q \cdot m \cdot r / S, \]

where \( M \) is the mass of CO₂ emissions per square meter (kg m⁻²), \( Q \) is the energy demand for heating (\( Q_h \) or cooling (\( Q_c \)), \( m \) is the net raw coal consumption rate of a thermal power plant or boiler heating system, \( r \) is the CO₂ emissions coefficient based on raw coal (1.9003 kg kg⁻¹) (Zhang et al 2018), and \( S \) is the area of the standardized house (100 m²). The net standard coal consumption rate of a thermal power plant in China in 2016 is 0.312 kg kWh⁻¹ (http://cecc.org.cn, accessed in October 2018), equivalent to a net raw coal consumption rate of 0.437 kg kWh⁻¹ (based on the heat value of 1 kg of raw coal is equal to 0.7143 kg of standard coal, Evans and Lin 1997). The heat value of raw coal equals to 20908 kJ kg⁻¹ (Evans and Lin 1997). Therefore, the raw coal consumption rate of boiler heating system is calculated as 3600 s h⁻¹ 20908 kJ⁻¹ kg⁻¹ = 0.172 kg kWh⁻¹.

### Results

#### 3.1. China annual degree-days

There are large spatial variations in HDD and CDD in history (1976–2005), mid-century (2021–2050), and end-century (2071–2100). HDD and CDD generally decrease and increase from the northwest to the southeast, respectively (figures 1 and S6). HDD are much larger than CDD, and also vary more than CDD in most parts of China, which indicates that heating demand is far more than cooling demand.

During the three periods, regions with the largest HDD and smallest CDD are all located in North Daxinganling, Altai and Tianshan Mountains, and Qingshai-Tibetan Plateau. Such result reflects the demand for heating, but not for cooling in residential buildings of these regions. We find that the regions with the largest CDD, such as Hainan Island and Turpan Basin, all have small HDD (figure 1). The HDD of the 828 stations are positively correlated with elevation (\( r = 0.5 \)) and latitude (\( r = 0.8 \)). This means that HDD are greater at lower elevations and at higher latitudes. For example, HDD are smaller in the low-lying Sichuan

| Table 3. Summary of key design parameters in five architectural climate zones. |
|-----------------------------|---------|---------|---------|---------|
| Architectural climate zones | Wall    | Window  | Roof    | \( U' \) (W m⁻² K⁻¹) |
| Hot summer and warm winter zone | 1.5 | 4 | 0.9 | 1 |
| Hot summer and cold winter zone | 1 | 2.5 | 0.6 | 1 |
| Moderate climate zone | 1.3 | 3.2 | 0.5 | 1 |
| Cold zone | 0.45 | 1.8 | 0.35 | 0.5 |
| Severe cold zone | 0.3 | 1.5 | 0.25 | 0.5 |
and Turpan Basins than in the surrounding regions, while CDD are larger than in the surrounding regions. Elevation and latitude influence degree-days through air temperature. As air temperature decreases with increasing elevation and latitude, there is more demand for heating and less demand for cooling. HDD decrease from history to mid- and end-century, and the decreasing magnitude is greater from mid- to late-century than from history to mid-century. This temporal increasing rate of HDD reduction indicates that heating demand is expected to become less and less in the future (figure 2). Notably, regions with larger HDD in history, such as Qinghai-Tibetan Plateau, experience larger decreases in HDD, compared to the regions with smaller historical HDD. Therefore, the spatial differences in HDD across China are expected to decline in future.

We find that there is a slight increase in overall CDD with a warming climate, except at a few high elevation and high latitude regions (figure 2). Taking Qinghai-Tibetan Plateau with 0 historical CDD for example, there is no change in CDD over the century. Those regions with the largest historical CDD also experience the largest increase. The historical CDD of Hainan Island and Turpan Basin are around 700 °C day, and the CDD increase is approximate 300 °C day from history to mid-century and 600 °C day from mid- to end-century. Our results show that accelerating global warming will lead to increases in magnitude of change in CDD over time.

3.2. Regional daily degree-days
To further examine the changes in degree-days over time, we analyze the durations of HDD and CDD of five cities representing five architectural climate zones (figure 3). We define HDD duration and CDD duration as the numbers of consecutive days when
HDD $> 13\, ^\circ\text{C}$ day and CDD $> 2\, ^\circ\text{C}$ day, respectively. In the future, the start day of HDD duration is projected to be later and its end day is projected to be earlier. Compared with the historical period, the start days of HDD duration during mid-century are expected to be delayed by 8 and 11 days in Harbin and Beijing, while the end days advance by up to 3 and 8 days in these two cities (figure 3). Consequently, the HDD durations are expected to be 11 and 19 days shorter in Harbin and Beijing, respectively. By the end of century, the start days of HDD duration are projected to be delayed by 10 and 16 days in Harbin and Beijing, compared to the mid-century, while end days are projected to advance by up to 9 and 14 days in these two cities. Consequently, the HDD durations are expected to be 19 and 30 days shorter in Harbin and Beijing, respectively. Duration of HDD is 27 days in Shanghai in history, and is 0 during the future periods. HDD durations are 0 in Shenzhen and Kunming for all three time periods. Average duration of HDD across China is predicted to be 34 days shorter by end-century than history.

As expected, future CDD duration is predicted to start earlier and end later due to global warming. Compared with history, the start days of CDD duration during mid-century are projected to 29, 5, and 24 days earlier in Shenzhen, Shanghai, and Beijing, respectively, while end days are projected to be delayed by 18, 21, and 22 days (figure 3). Consequently, the CDD durations are expected to be 47, 26, and 46 days longer in Shenzhen, Shanghai, and Beijing, respectively. From mid- to late-century, the start days of CDD duration are projected to be 29, 27, and 19 days earlier in Shenzhen, Shanghai, and Beijing, respectively, while end days are projected to be delayed by 22, 22, and 20 days. Consequently, the CDD durations in Shenzhen, Shanghai, and Beijing are expected to be 51, 49, and 39 days longer, respectively. The CDD duration in Harbin is predicted to last for 64 days during end-century, and is 0 during history and mid-century. The CDD duration of Kunming is 0 over the three time periods. Average duration of CDD across China is predicted to be 63 days longer by end-century than history.

### 3.3. CO$_2$ emissions

Consistent with the trends in degree-days, our results show less CO$_2$ emitted from heating and more CO$_2$ from cooling over time (figures 4, S8 and S9). In the future, total CO$_2$ emissions will decrease in most regions of China, except a few southern regions (figures 4(e) and (f)). These results indicate that future reductions in CO$_2$ emissions from heating are larger than increases in CO$_2$ emissions from cooling for most regions in China. The spatial distribution of heating CO$_2$ emissions is different from that of HDD. Along the boundary of architectural climate zones, CO$_2$ emissions from heating tend to be fewer in the north than in the south (figures 1, S6 and S8). Such result is
Figure 4. Changes in annual CO₂ emissions from 1976–2005 to 2021–2050 and from 2021–2050 to 2071–2100 from heating (a), (b), cooling (c), (d), and heating and cooling (e), (f). Fewer CO₂ emissions from heating and more CO₂ emissions from cooling contribute to the future fewer CO₂ emissions except some southern regions. Such trend is more pronounced by the end-century.

Figure 5. Annual CO₂ emissions from heating (a), cooling (b), and heating and cooling (c) in Harbin, Beijing, Kunming, Shanghai, and Shenzhen over the three examined time periods. Black bars represent the uncertainty (σ) of CO₂ emissions for future periods. Except for Shenzhen, the other four cities all suggest a trend of decreasing total CO₂ emissions over time.
due to the more stringent and more effective insulation building envelope design in the north.

Spatio-temporal changes in CO₂ emissions from heating in the cities representative of the five architectural climate zones show continuous decreases over time (figure 5). Heating CO₂ emissions in Harbin are the most (101.57, 92.10 and 75.47 kg m⁻² during history, mid- and end-century, respectively), while those in Shenzhen are the fewest (16.10, 12.14 and 6.32 kg m⁻² during the three periods, respectively). CO₂ emissions from heating in the other three cities are of similar magnitude and those in Beijing are a little more than those in Shanghai and Kunming. Conversely, CO₂ emissions from cooling all increase in the five cities. CO₂ emissions from cooling in Shenzhen are the most (14.39, 20.48, and 35.76 kg m⁻² during history, mid- and end-century, respectively) with the greatest increase, while those in Kunming are the fewest with the least growth. However, in terms of the growth from history to end-century, the increasing rate is the largest in Kunming (765%) and is the smallest in Shenzhen (149%). Beijing, Shanghai, and Harbin increase 215%, 223% and 436%, respectively. In general, the magnitude of CO₂ emissions from heating in the five architectural climate zones is similar to their representative cities. However, CO₂ emissions from cooling in severe cold zones are the fewest, which is different from the ranking of five representative cities. CO₂ emissions from cooling in moderate climate and cold zones are similar.

Except for Shenzhen, total emissions of CO₂ from heating and cooling decrease over time. Historical total CO₂ emissions in Shenzhen are primarily from heating, whereas those by mid- and end-century primarily derive from cooling. By end-century, total CO₂ emissions in Shenzhen increase by 11.59–42.07 kg m⁻² relative to historical levels. Among the other four cities, total CO₂ emissions in Kunming are the fewest, and the reductions are the greatest. Reductions in Harbin are of similar magnitude to those in Kunming, where total CO₂ emissions are the most due to the dominant and high level of heating demand. From history to end-century, the patterns of total CO₂ emissions in Beijing and Shanghai are similar. Specifically, total CO₂ emissions are predicted to decrease by 12.83–57.02 kg m⁻² in Shanghai, and to decrease by 10.47–61.30 kg m⁻² in Beijing. The uncertainties of CO₂ emissions caused by climate variability tend to be larger in end-century than mid-century (figure 5).

4. Discussion

The estimated degree-days and associated CO₂ emissions in this work show consistent trend with previous research (Zhou et al 2013, You et al 2014, Hao et al 2016, Shi et al 2016). Our results suggest more accurate spatial variation, because we consider the characteristics of architectural climate zones. Our analyses show that, as temperature increases, CO₂ emissions from CDD increase 218% by the end-century relative to historical levels. However, we may underestimate such emission increase, because the regions with the largest increase in CDD have the highest the economic development and population density (90% of the Chinese population) in China. There is likely more energy demand on maintaining thermal comfort. The rapid growth in cooling demand, especially in southern China, indicates greater requirements for fuel used for electricity generation. It is important to improve the efficiencies of power generation and energy use of air conditioners, and reform of the power sector to reduce carbon is the most effective measure to decrease future CO₂ emissions (British Petroleum 2018). We also conduct the same analysis under the RCP4.5 emission scenario, the overall outcomes of which make not much difference (figures S5, S7 and S10).

One caveat of this research is the uncertainties to HDD and CDD from the selection of base temperatures (Holmes et al 2017), as they may be spatially different. Estimations of residential energy consumption and CO₂ emissions are based on HDD and CDD, and energy consumption in buildings is affected by various factors, such as the energy from lighting or the Sun (CIBSE 2006). In addition to climate change, heating and cooling demand is also affected by economic development, income growth, population density, and continued improvements in technology (Holmes et al 2017). Further research is needed to analyze the effects of other climate change and socioeconomic factors on energy consumption and CO₂ emissions.

Accounting for these limitations, our research confirms the impact of climate change on HDD and CDD and associated CO₂ emissions in China, which can be used to regulate building design to enhance the ability of conserving energy of residential buildings. It is important for policy makers to allocate energy appropriately. Our research also provides foundation for policy makers to adjust the heating period dates, according to the predicted delay in the start day of heating duration (e.g. 27 days later in Beijing by end-century than history) and the advance of end day (e.g. 22 days earlier in Beijing by end-century than history). These future spatio-temporal trends in CO₂ emissions can guide mitigation. There may be more and longer summer cooling demand in China except Qinghai-Tibetan Plateau, which will result in more greenhouse gas emissions. Southern China is more likely to experience such increase in CO₂ emissions.

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