Impacts of climate change on heating and cooling degree-hours over China

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Abstract
Based on hourly temperature data collected from 2,307 meteorological stations over China and two sets of climate change simulations over East Asia using the regional climate model version 4.4 (RegCM4.4) driven by the global models of HadGEM2-ES and MPI-ESM-MR, future changes of heating and cooling degree-hours (HDH and CDH) at the end of the 21st century under RCP4.5 scenario are investigated. Compared against the observation, the spatial distribution, magnitude and annual cycle of present-day HDH and CDH at different times, as well as the diurnal cycle of them can be realistically simulated by the model. Meanwhile, some bias can also be found and it varies with the times, especially for CDH. At the end of the century, significant decrease of HDH can be found over the Tibetan Plateau, the northern part of Northeast China, and Northwest China at each times while increase of CDH are observed at all the times except some parts of the Tibetan Plateau where the CDH remains zero due to the cold climate there. But for different times, some differences are found in HDH decrease and CDH increase. For example, the changes of HDH at the fifth to the seventh times present a weaker decrease in the northwestern basins compared to other times and the CDH increase are more significant at the fifth and the sixth times. The regional mean changes of HDH and CDH over China in the 21st century (2006–2098) also diverge among different times, which indicates the degree-hours is needed to precisely calculate the hourly heating and cooling energy demand and then the heating and cooling degree days.

KEYWORDS
China, climate change, heating and cooling degree-hours, hourly station-based observation, regional climate model

1 | INTRODUCTION

The Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) states that ‘warming of the climate system is unequivocal’. Over the period 1880–2012, the globally averaged combined land and ocean surface temperature data show a warming trend of 0.85 (0.65–1.06)°C based on multiple...
independently datasets exist. Continued emissions of greenhouse gases will cause further warming and changes in all components of the climate change. By the end of the century (2081–2100), the increase of global mean surface temperature is projected to be in the range of 0.3–4.8°C (relative to 1986–2005) (IPCC, 2013).

Natural and human systems are greatly impacted by the climate change in recent decades (IPCC, 2014). For example, with the increase of global mean temperature, the heat waves will be more frequent and the duration of it will become longer, the extreme precipitation events will become more intense and frequent in some regions which can both lead to a wide range loss of economic, social and people's lives and property. As an important component of energy consumption, building sector accounts for almost one third of total energy use in the world (IEA, 2015). To be specific, the building heating and cooling demand is accounting for nearly 41% of United States’s average household end-use energy expenditures in 2009 (Petri and Caldeira, 2015) and 20% of the China’s total energy consumption in 2012 (SSB, 2013; BERC, 2017). It is well known that the outdoor weather conditions have significant influence on building heating and cooling system design (Cui et al., 2017a; 2017b), retrofitting existing public buildings (Chow et al., 2013), scenario analysis of future building energy consumption (Hu et al., 2016), and so on. As reported from IPCC AR5 that the global mean temperature will continue to rise, a decrease in heating demand and an increase in cooling demand is expected (Chen et al., 2007; Li et al., 2010; Petri and Caldeira, 2015).

In China, due to some historical reasons of the central heating system used, heating or cooling demand are mainly analysed on some specific areas or individual provinces (cities) in previous studies (Ren and Ren, 2009; Li et al., 2010; Shi et al., 2011; Wan et al., 2011; Li and Li, 2015; An et al., 2017), and the widely used method is degree-days, which are defined as the difference between the daily mean temperature and a given reference temperature (You et al., 2014; Shi et al., 2016). This makes the definition and calculation simpler, and assumes that heating or cooling systems do not operate on days where average outdoor temperatures exceed or less than the base temperature. However, in fact, there are some problems in the calculation, especially on the days that the mean temperature exceeds the base, but the minimum temperature may be less than the base in several degrees. On the other hand, realistic degree-day formulas require the knowledge of a building’s unique base temperature, calculated from its heat loss coefficient, thermal capacity, and infiltration, but these factors are not taken into account if we use the 18°C as the base temperature (Day, 2006; Petri and Caldeira, 2015).

Compared to degree-days, the more precise way is to use the mean degree-hours method (Day, 2006) although the differences between degree-days calculated from the mean daily temperature and using hourly temperatures are small. In addition, people in South China start to use air conditioners or individual space heaters during winter in recent years which are not working all day and thus the degree-hours method is more suitable to calculate the heating or cooling energy demand there. However, due to the limit of availability for hourly data, previous studies are mostly focused on degree-days and few studies can be found on degree-hours. Recently, a new set of hourly station-based observation over China (Cui et al., 2017a; 2017b) and two sets of climate change simulations using a high-resolution regional climate model (RegCM4.4) are available (Han et al., 2017; Gao et al., 2018; Shi et al., 2018a; 2018b; 2018c). Considering the accuracy of the degree-hours method and to evaluate the performance of the model in original 3-hourly interval outputs, analysis on the spatial distribution, the annual and diurnal cycle of heating and cooling degree-hours (HDH and CDH) are firstly evaluated in Section 3.1, and then changes of them are investigated (Section 3.2). Compared to the degree days, the analysis can provide some valuable information in the hourly changes of heating and cooling energy demand which can further enlighten us in the future energy management strategies. Section 2 of this paper describes the model, data and metrics, and a summary and discussions are provided in Section 4.

2 | MATERIALS AND METHODS

2.1 | Data

The observed dataset used in this study is the hourly mean temperature from 2,307 meteorological stations during 1961–2014 in China (Figure 1), which is adopted from the data set of literature Cui et al. (2017a; 2017b). It consists of major meteorological parameters such as outdoor dry bulb temperature, relative humidity, solar radiation and so on except precipitation, and is more in line with the characteristics of China's climate (Cui et al., 2017a; 2017b). More information about the data processing methods and data format can also be found in the literature Song et al. (2007).

The model data are from the two sets of climate change simulations over East Asia using the Abdus Salam International Center for Theoretical Physics (ICTP) Regional Climate Model version 4.4 (RegCM4.4) (Giorgi et al., 2012) under RCP4.5 and RCP8.5 scenarios (Moss et al., 2010) driven by the global models of
HadGEM2-ES and MPI-ESM-MR, respectively (Han et al., 2017; Gao et al., 2018; Shi et al., 2018a). RegCM4.4 is a new version of RegCM which is a regional climate model developed and updated by ICTP. Compared to the previous version of RegCM3 (Pal et al., 2007), the RegCM4.4 model has updated both in terms of software code and physical representations. For example, the model includes a new land surface model (CLM), mixed land-ocean convections, the tropical band configuration and all the codes changing from F77 to F90. In the two simulations, the horizontal resolution is 25 km and the model domain covers the whole China and the surrounding areas which is similar to the CORDEX-EA domain (Coordinated Regional Climate Downscaling Experiment-East Asia) (Giorgi et al., 2009). More detailed information of the forcing datasets and the experimental design used in the regional climate model can be found in Gao et al. (2018). For brevity, only the ensemble means (the average of the two climate change simulations) under RCP4.5 scenario are presented and the analysis are focus on the end of the century (2080–2099) relative to the ‘present day’ period of 1986–2005.

2.2 Method

A degree day is a measure of heating or cooling, which is calculated from the total difference between the daily mean temperature and a given reference temperature in a certain period (Thom, 1952, 1954). Similar to a degree day, a degree-hours is defined as the difference between the hourly mean temperature and a given reference temperature. As the temperature varies from hour to hour, the mean degree-hours method should be the more precise way to calculate degree-days (Day, 2006; Petri and Caldeira, 2015). To directly compare the simulation and observation, the model data is interpolated to the station and the analysis are based on the whole China and its eight sub-regions following Xu et al. (2015) to validate the model (Figure 1 and Table 1). Note that the output from the climate change simulations are 3-hourly intervals and the times are the world time, therefore, we select the same hourly data from the observation to match it and reorder the time to make the first time represents 2 a.m. in Beijing time and so on (e.g., time 2 = 5 a.m., time 3 = 8 a.m., etc.). Changes of heating and cooling degree-hours are projected based on the $0.25^\circ \times 0.25^\circ$

**Figure 1** Distribution of 2,307 stations in China and the eight sub-regions (NEC, Northeast China; NC, North China; EC, East China; CC, Central China; SC, South China; SWC1, Southwest China region 1; SWC2, Southwest China region 2; NWC, Northwest China)

**Table 1** Coordinates and number of stations for the eight sub-regions and the whole China used in this study

| Regions  | Latitude | Longitude | Station numbers |
|----------|----------|-----------|-----------------|
| NEC      | 39–54°N  | 119–134°E | 219             |
| NC       | 36–46°N  | 111–119°E | 358             |
| EC       | 27–36°N  | 116–122°E | 287             |
| CC       | 27–36°N  | 106–116°E | 489             |
| SC       | 20–27°N  | 106–120°E | 340             |
| SWC1     | 27–36°N  | 77–106°E  | 132             |
| SWC2     | 22–27°N  | 98–106°E  | 242             |
| NWC      | 36–46°N  | 75–111°E  | 240             |
| CHINA    | 15–55°N  | 70–140°E  | 2307            |
(longitude–latitude) grid to cover the whole China. Multiple metrics are used to evaluate the model performance, including the mean bias, temporal and spatial correlation coefficients (TCOR and SCOR). The statistical significance test for the bias and future changes is performed using the two-tailed Student’s t-test.

3 | RESULTS

3.1 | Validation of the climate model

The biases of HDH between the observation and simulation based on hourly mean temperature over China are shown in Figure 2. For each time, the observed spatial distribution and magnitude over China can be well simulated by the model, with the spatial correlation coefficients (SCORs) all above 0.90. Compared against the observation, a general overestimation in the Tibetan Plateau and underestimation in parts of eastern China can be found at all the times. But in specific, there are also some differences among the eight times. For example, at the first and the third times, a general overestimation over China can be found, except some stations in North China, Northwest China, and Northeast China. Compared to the previous two times, more stations with underestimation are found at the second time. From the fourth to the sixth times, a general overestimation in western China and underestimation in eastern China can be found, with the maxima value above (below) 1,000°C·h (−1,000°C·h). But at the seventh and the eighth times, the underestimation almost disappear and the overestimation become more significant compared to the fourth to the sixth times, with the values greater than 1,000°C·h in most stations over the Tibetan Plateau.

FIGURE 2 The biases of HDH between the model ensemble mean and observation at 3-hourly intervals of 1986–2005 over China (unit: °C·h). Note that the dot in the legend is 10-folds larger than that in the figure to make it clear. Black sign of the crosses indicate the stations where the biases are not significant at the 95% confidence level. (a) 2 a.m.; (b) 5 a.m.; (c) 8 a.m.; (d) 11 a.m.; (e) 2 p.m.; (f) 5 p.m.; (g) 8 p.m.; (h) 11 p.m.
**TABLE 2**  Biases of HDH at 3-hourly intervals on 1 day over the eight sub-regions and the whole China between the model ensemble mean and the observation (unit: °C·h and %) (The first and second values in one cell represent the absolute and percentage biases of HDH, respectively)

| Regions | 2 a.m. | 5 a.m. | 8 a.m. | 11 a.m. | 2 p.m. | 5 p.m. | 8 p.m. | 11 p.m. |
|---------|--------|--------|--------|---------|--------|--------|--------|--------|
| NEC     | 283/5  | −65/−1 | 20/0   | −2/0    | 274/7  | 582/14 | 531/11 | 470/9  |
| NC      | 256/6  | −75/−2 | 51/1   | 20/1    | 273/12 | 284/12 | 340/11 | 336/9  |
| EC      | 244/11 | 118/5  | −15/−1 | −229/−14| −135/−11| −6/0  | 128/7  | 196/10 |
| CC      | 344/14 | 183/7  | 213/8  | 47/2    | 104/8  | 95/7   | 254/14 | 326/15 |
| SC      | 316/31 | 291/24 | 190/17 | −103/−13| −120/−23| −60/−11| 156/21 | 237/26 |
| SWC1    | 801/51 | 622/31 | 736/38 | 324/29  | 260/57 | 218/52 | 578/70 | 734/60 |
| SWC2    | 1,547/41| 1,180/27| 1,262/29| 901/28  | 1,078/52| 1,169/62| 1,587/59| 1,684/51|
| NWC     | 374/8  | −129/−2| 114/2  | 242/6   | 401/13 | 434/15 | 556/15 | 634/15 |
| CHINA   | 463/15 | 225/6  | 268/8  | 108/4   | 225/13 | 290/16 | 453/19 | 509/18 |

**FIGURE 3**  Similar to Figure 2, but for CDH (unit: °C·h) (Grey indicates no cooling in the present day). (a) 2 a.m.; (b) 5 a.m.; (c) 8 a.m.; (d) 11 a.m.; (e) 2 p.m.; (f) 5 p.m.; (g) 8 p.m.; (h) 11 p.m.
### Table 3

Same as Table 2, but for CDH

| Regions | 2 a.m.   | 5 a.m.   | 8 a.m.   | 11 a.m.  | 2 p.m.   | 5 p.m.   | 8 p.m.   | 11 p.m.  |
|---------|----------|----------|----------|----------|----------|----------|----------|----------|
| NEC     | −95/−65  | −63/−55  | −63/−20  | −95/−14  | −184/−20 | −220/−28 | −264/−67 | −190/−71 |
| NC      | −185/−55 | −114/−49 | −84/−19  | −47/−5   | −190/−14 | −205/−16 | −399/−53 | −300/−57 |
| EC      | −376/−50 | −299/−47 | −201/−22 | −20/−1   | −51/−3   | −142/−8  | −448/−40 | −420/−46 |
| CC      | −304/−48 | −206/−44 | −130/−20 | 9/1      | −56/−3   | −65/−4   | −435/−39 | −387/−46 |
| SC      | −397/−34 | −297/−30 | −257/−21 | 29/2     | 44/2     | −48/−2   | −399/−24 | −404/−30 |
| SWC1    | −255/−73 | −141/−71 | −179/−68 | −78/−12  | −230/−14 | −269/−15 | −430/−46 | −356/−65 |
| SWC2    | −140/−52 | −86/−47  | −58/−27  | −45/−11  | −193/−22 | −243/−25 | −305/−53 | −218/−56 |
| NWC     | −59/−27  | 18/22    | −7/−5    | 37/8     | −202/−19 | −326/−26 | −246/−29 | −237/−47 |
| CHINA   | −243/−45 | −163/−40 | −127/−22 | −19/−2   | −114/−7  | −166/−11 | −376/−38 | −326/−45 |

### Figure 4

Annual cycles of HDH and CDH at 3-hourly intervals averaged over China (unit: °C·h) (blue/red solid line: the observed HDH (CDH); blue/red dashed line: HDH (CDH) simulated by the model). (a) 2 a.m.; (b) 5 a.m.; (c) 8 a.m.; (d) 11 a.m.; (e) 2 p.m.; (f) 5 p.m.; (g) 8 p.m.; (h) 11 p.m.
and Southeast China. The biases of HDH at all the times are mostly significant at the 95% confidence level except a few stations in the south and north at the third and seventh time, respectively. The regional mean bias over China at the times from the first to the eighth are 463, 225, 268, 108, 225, 290, 453, and 509°C·h, respectively (Table 2).

Figure 3 shows the biases of CDH between the observation and simulation over China. The model can capture the observed increasing gradient from north to south of CDH. The SCORs are high, at 0.88, 0.89, 0.95, 0.94, 0.90, 0.86, 0.86, and 0.88 for each time, respectively. However, some bias can also be found. From the first to the third time, the CDH are mainly underestimated in China except the Tibetan Plateau and Northeast China where the CDH are zero due to the cold climate there. At the fourth time, an overestimation can be found in most parts of South and Northwest China, while in the northeast and the regions close to the Tibetan Plateau, a general underestimation is observed. The spatial patterns at the fifth and the sixth times are similar to the fourth, with greater magnitude of overestimation and underestimation. While at the seventh and eighth time, the spatial patterns are similar to that at the first, with greater magnitude of underestimation in most stations. The biases of CDH at all the times are mostly significant at the 95% confidence level except several stations in the northeast and north China at the third time. The regional mean bias over China at the times from first to eighth are −243, −163, −127, −19, −114, −166, −376, and −326°C·h, respectively (Table 3).

The annual cycles of HDH and CDH at each time over the entire China from observation and model ensemble mean are presented in Figure 4. The observed HDHs are found to vary from month to month, with a maximum in January and minimum in July at all the times. The model can realistically simulate the annual cycle and the TCOs are all above 0.996. Specifically, the model bias generally becomes greater and greater from winter (December, January, and February) to spring months (March, April, and May), followed by a decline in summer months (June, July, and August) due to the low values of HDH. In fall months (September, October, and November), the bias becomes larger again. The greatest bias (75°C·h) of HDH between the observation and the model is found at the eighth time in May. Compared to HDH, the performance of CDH is a little worse, with the TCOs from 0.993 to 0.998. Compared among the eight times, the bias of CDH is relatively small at the times from the third to the sixth, and more significant at other times, with the largest bias of −83°C·h in August at the seventh time.

Beside the annual cycles, the diurnal cycles of HDH and CDH over the entire China and the eight sub-regions are provided in Figure 5. The observed HDHs show similar pattern in most of the sub-regions and the entire China, characterized by a maximum at the second time (5 a.m.) and minimum at the fifth time (2 p.m.). The model can well capture the diurnal cycle and the TCOs.
are all above 0.96. Due to the cold bias simulated by the model, greater HDH at all the times can be found in CC, SWC1, SWC2 and the entire China, with larger bias during the night times (from 8 p.m. to 5 a.m.) compared to the daytime. In NWC, NEC and NC, HDH are underestimated at 5 a.m., while at other times, it is overestimated with larger values at the times from 5 p.m. to 11 p.m.. In EC and SC, underestimation of HDH is found at four (from 8 a.m. to 5 p.m.) and three (11 a.m., 2 p.m., and 5 p.m.) times out of the eight, respectively. Opposite to HDH, both the observed and simulated CDH present a maximum at 2 p.m. and a minimum at 5 a.m. in most sub-regions (five out of eight) and the entire China except NWC, SWC1, and SWC2 which the maximum is found at 5 p.m.. Compared to the observation, the CDH are underestimated at each time in China and most sub-regions, with larger bias during the night time. As the HDH and CDH are directly related to the temperature, larger bias of them during the night time indicates a relative poor performance of the daily minimum temperature compared to the maximum one, which is similar to the result from 10 RCMs over Africa which shows a generally better performance for mean and maximum temperature than the daily minimum temperature (Kim et al., 2014).

### 3.2 | Changes of HDH and CDH

In the context of global warming, decreased HDH over China at the eight times can be found under RCP4.5 scenario at the end of the 21st century and the changes of it are all significant at the 95% confidence level (Figure 6).
Specifically, the spatial patterns at the first, the second and the eighth times are similar with each other, with larger values above $-1,000^\circ C\cdot h$ over the Tibetan Plateau and north of northeast China and lower values of less than $-500^\circ C\cdot h$ in the south. At the third and the fourth times, greater decrease in the west and northeast China is found with the value exceeding $-1,000$ and $-750^\circ C\cdot h$ over the Tibetan Plateau, respectively. At the fifth and the sixth times, the decrease is lower than the previous times, especially in the northwest. For the seventh time, the decrease is relative weaker in the Tarim Basin and stronger in the northeast and the Tibetan Plateau compared to the fourth one. For the changes averaged in the sub-regions and the entire China, the largest decrease of HDH in most sub-regions (seven out of eight) and the whole China can be found at the second time (5 a.m.) and the whole China can be found at the second time (5 a.m.), while the smallest of that is observed at the fifth or the sixth time (2 p.m. or 5 p.m.; Figure 7). Generally, the maximum and minimum temperature on a day occurs at the fifth (2 p.m.) and the second (5 a.m.) time, respectively. The largest and smallest decrease of HDH are directly related with the changes of temperature, which are in line with the results from IPCC AR5 which shows the coldest night (related to the minimum temperature) of the year undergoes larger increases than the hottest day (related to the maximum temperature) in the globally averaged time series (Collins et al., 2013).

Different from the changes in HDH, CDH will increase at the end of the 21st century over the entire China except the Tibetan Plateau at all the times (Figure 8). Generally, an increasing trend from north to south in the eastern China and a topography-depended in the western China can be found. Specifically, at the first and the second time, the increase is less than 250$^\circ C\cdot h$ and mostly in the range of 100–500$^\circ C\cdot h$ in other regions. At the third time, greater increase (more than 100$^\circ C\cdot h$) is presented in Northeast China compared to the previous two times. While at the fourth time, greater than 500$^\circ C\cdot h$ increase can be found in some parts of North China, the Sichuan Basin and south coastal areas, and the increase in other regions is observed mainly in the range of 100–500$^\circ C\cdot h$. At the fifth time, in addition to the regions at the fourth time, greater increase with the value exceeding 500$^\circ C\cdot h$ can also be found in the northwestern basins and the parts from the north of the Yellow River to the south of the Yangtze River. The increase at the sixth time is similar to the fifth one, but a relative lower increase is presented in the northeast. From the seventh to the last
time, the increase is lower compared to the fifth and the sixth one, with the value mostly in the range of 100–500°C·h except the northwestern basins at the seventh time. The changes of CDH at all the times are significant at the 95% confidence level. For the changes averaged in the sub-regions and the entire China, the largest increase of CDH can be found at the fifth or the sixth time (2 p.m. or 5 p.m.), while the smallest of that is observed at the second time (5 a.m.) in most sub-regions (seven out of eight) and the whole China, which is opposite to that of HDH (Figure 7). This is mainly due to the relative lower temperature at night and thus it does not satisfy the criteria for cooling degree hours even under the global warming conditions. In other words, this is also reflecting the cooling energy demand mainly occurs during the hotter periods in 1 day.

The annual cycles of HDH and CDH under RCP4.5 at each time over China by the end of the 21st century, as well as that in the reference period are shown in Figure 9. Compared to that at present day, decrease of HDH and increase of CDH are found at all the times, with greater value of the decrease and increase in cold and warm months, respectively. The maxima decrease of HDH can be found in December at each time, while the decrease in summer months (June, July and August) are relatively small, mainly in the range of −30 to 0°C·h. The maxima increase of CDH is expected in July or August, and the increase in cold months (December, January and February) are much lower than other months (mainly close to 0), as the daily temperature are well below the reference temperature even with future warming. Compared among the times,
greater CDH increases are projected during the day time (from 8 a.m. to 5 p.m.) compared to the night time (from 8 p.m. to 5 a.m.), while the HDH decreases show an opposite sign. Similar to the spatial distribution changes of HDH and CDH, significant decrease of HDH and increase of CDH averaged over China can be found in the 21st century (2006–2098) in general (Figure 10). For different times, at the beginning such as the first 20 years, little difference of HDH and CDH is observed. But after that, changes show some difference although the trends of them are similar. The most significant decrease of HDH can be found at the second time, while that of CDH is observed at the fifth (sixth) time, which is in line with the changes of spatial patterns. The trends of HDH are $-8.4^\circ C\cdot h/10a$, $-8.6^\circ C\cdot h/10a$, $-8.2^\circ C\cdot h/10a$, $-6.6^\circ C\cdot h/10a$, $-5.9^\circ C\cdot h/10a$, $-6.0^\circ C\cdot h/10a$, $-7.4^\circ C\cdot h/10a$, and $-8.1^\circ C\cdot h/10a$, under RCP4.5 at each time, respectively, while that of CDH are $1.6^\circ C\cdot h/10a$, $1.4^\circ C\cdot h/10a$, $1.8^\circ C\cdot h/10a$, $2.7^\circ C\cdot h/10a$, $3.3^\circ C\cdot h/10a$, $3.3^\circ C\cdot h/10a$, $2.5^\circ C\cdot h/10a$, and $1.9^\circ C\cdot h/10a$ (all significant at 95% confidence level).

### 4 CONCLUSIONS AND DISCUSSION

Using the precise degree-hours method, future changes of HDH and CDH under RCP4.5 scenario at 3-hourly intervals in 1 day are investigated based on the ensemble mean of two high-resolution regional climate change simulations over East Asia. The results can be summarized as follows:

1. The spatial distribution, the annual cycles at different times in 1 day, and the diurnal cycles over the eight sub-regions and the entire China of HDH and CDH can be well simulated by the RegCM4.4 model. However, different spatial patterns of bias can also be found, especially for CDH.
2. Significant decrease in HDH and increase in CDH in both the spatial distribution and the regional mean are projected by the model, with greater changes at the second time in HDH and the fifth or the sixth time in CDH, which are directly related to the changes of temperature. For the changes of spatial distributions, generally, the maxima decrease of HDH can be found over the Tibetan Plateau, while the maxima increase of CDH is observed in southeast coast, the Sichuan Basin and the basins in Northwest China at each time, which are the areas with great values in the present day.

According to the analysis of Shi et al. (2018c), if the degree-days method is taken, a significant decrease of heating degree days (HDD) and increase of cooling degree days (CDD) can be found over China which is similar to that of HDH and CDH (figures not shown). But for specific times in 1 day, the spatial distributions of HDH decrease show some different, so does the CDH. This is mainly due to the different changes in temperature at different times and can help us to identify the times for the maximum heating or cooling energy demand. Therefore, using the degree-hours method is a more precise way compared to degree-days, especially for individual heating or cooling. But in our country, due to some historical reasons, the central heating system are used in northern China in cold season (Shen and Liu, 2016; Shi et al., 2016; 2018b), which means the threshold for heating cannot be changed during the heating period. How to make the heating system more efficient and meanwhile to save energy is worthwhile to consider in the future.

In addition, as HDH and CDH is directly related to the surface air temperature which is significantly regulated by local surface condition, such as land use and land cover, urbanization, vegetation growth, and so on, dynamic vegetation representation should be coupled to the regional climate model. Unfortunately, the vegetation is static in our simulation which is common in many other global or regional climate simulations. Therefore, the impact of dynamic vegetation feedback on this will be further investigated in our following studies using the coupled regional vegetation-climate model.

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CONFLICTS OF INTEREST
The authors declare no conflict of interest.

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