Will climate change make Chinese people more comfortable? A scenario analysis based on the weather preference index

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Abstract

Assessing the climate change impact (CCI) on weather conditions is important for addressing climate change and promoting sustainable development. This study used a weather preference index (WPI) as an indicator to evaluate the CCI on weather conditions in China under different scenarios from 2025 to 2100. First, we analyzed the change in the WPI in China from 1971 to 2013. Then, we estimated the trends in the WPI in China from 2025 to 2100 under different representative concentration pathways (RCPs) based on global climate models. We found that China’s weather conditions improved from 1971 to 2013, as the national average WPI increased from 1.34 to 1.59 with a change rate of 0.03 per decade (0.03/10 a). Under all climate change scenarios, the weather conditions in China will deteriorate. The change rates of the WPI will be −0.19/10 a ~ −0.01/10 a. The number of people experiencing deteriorated weather conditions will be 0.71 billion ~ 1.22 billion, accounting for 53.28% ~ 91.58% of the total population in China. We also found that the area of the regions with deteriorated weather conditions under all three climate change scenarios will be 2.34 million km², accounting for 24.31% of China’s total land area. At the same time, as the emissions concentrations increase from RCP2.6 to RCP8.5, the area of the regions with severely deteriorated weather conditions in China will increase from 0 to 3.27 million km². Therefore, we suggest that China needs to implement effective measures to address climate change in the future and focus on the mitigation of and adaptation to climate change in regions with deteriorated weather conditions.

1. Introduction

Weather conditions refer to the state of the atmosphere at a specific time in a specific place (National Oceanic and Atmospheric Administration 2011). Weather conditions can influence human well-being by affecting the quality of life and ecosystem productivity (Rappaport 2007). Thus, improving weather conditions is the fundamental goal of achieving regional sustainable development. Climate change refers to a statistically significant change in the average state of the climate or a climatic fluctuation that lasts for a long time (typically 30 years or more) (IPCC 2013). Currently, climate change profoundly affects weather conditions and regional sustainability (Milly et al 2002, IPCC 2013, 2018). On the one hand, climate change can change the trend of weather elements, such as precipitation and temperature (Liu and Allan 2013, Trnka et al 2014). On the other hand, climate change may alter the fluctuation of weather elements and change the frequency of extreme weather events (e.g. droughts, rainstorms, floods, hurricanes, heat waves and extremely cold temperatures) (Gasparrini et al 2015; Winsemius et al 2016, Guerreiro et al 2018). China has experienced significant climate change in recent years. For example, China’s average surface temperature increased at a rate of 0.23 °C/10 a from 1951 to 2009, which was approximately 1.8 times that of the
global average (IPCC 2013, Shi et al 2014). In addition, the climate warming trend in China will be further intensified in the future (Zhu et al 2017, 2019, Li et al 2017, 2018a). Compared with the average climate conditions from 1961 to 1990, the temperature in 2100 will increase by 3.9 to 6.0 °C (Qin et al 2005; Li et al 2018b). Therefore, it is important to evaluate the future climate change impact (CCI) on weather conditions in China, and this information can be used to address climate change and promote regional sustainable development.

At present, the future CCI on weather conditions in China is mainly assessed by evaluating the changes of weather elements and the frequency and intensity of extreme weather events. Weather elements, e.g. the temperature, precipitation and humidity, can directly reflect the changes of weather conditions (Trnka et al 2014, Warnatzsch and Reay 2019). Extreme weather events are rare meteorological events that occur in a specific area and time. When the weather conditions in a certain place deviate significantly from its climatic average, an extreme event can be considered to have occurred (Zhai and Liu 2012, IPCC 2013, Wang et al 2017). Both of them provide a simple way to assess the CCI on weather conditions. For example, Li et al. (2018c) projected the future precipitation changes from 2006 to 2100 over China to evaluate the CCI on weather conditions. Zhou and Liu (2018) evaluated the CCI on weather conditions in China from 2021 to 2080 based on the likelihood of concurrent weather extremes and variations. However, these methods only objectively describe the changes in weather conditions, they do not consider the population exposure and people's perceptions to the changes of weather conditions, which limits the significance of the evaluation results in improving human well-being and promoting regional sustainable development (Egan and Mullin 2016).

The weather preference index (WPI) is a systematic assessment indicator that was proposed by Egan and Mullin (2016) to evaluate the CCI on weather conditions. The WPI can reflect the 'change of weather conditions based on the population-weighted exposure, and evaluate this change in light of the trade-offs people have been shown to make among different weather conditions' (Egan and Mullin 2016). The WPI not only measures the CCI on weather conditions but also reflects people's perceptions of weather conditions. Thus, the WPI provides a new and effective way to comprehensively evaluate the CCI on weather conditions (Haurin 1980, Rapaport 2004, Egan and Mullin 2016). Recently, the WPI was successfully applied to evaluate the CCI on weather conditions in the United States from 2025 to 2099 (Egan and Mullin 2016). However, there is a lack of research on using the WPI to assess the CCI on weather conditions in China.

The purpose of this study is to evaluate the CCI on weather conditions in China from 2025 to 2100 using the WPI as an indicator. First, we quantified the WPI in China from 1971 to 2013 based on meteorological observation data. Then, we estimated the WPI trend in China from 2025 to 2100 under different representative concentration pathways (RCPs) by using global climate model (GCM) data. Finally, we discussed the reliability of the WPI, the CCI on urban sustainability, and the impact of RCPs on regional sustainability to provide a scientific foundation for addressing climate change.

2. Study area and data

2.1. Study area

Our study area is China. According to the ‘Geographic Atlas of China’ compiled by Wang et al. (2009), we divided the country into 12 climatic zones based on the annual accumulated temperature (figure 1). These climatic zones consist of the cold temperate zone, middle temperate zone, warm temperate zone, north subtropical zone, middle subtropical zone, south subtropical zone, marginal tropical zone, plateau tropical zone, plateau subtropical zone, plateau temperate zone, plateau subfrigid zone and plateau frigid zone (Wang et al., 2009).

2.2. Data

The meteorological observation data were obtained from the China Meteorological Data Network (http://data.cma.cn/data/detail/dataCode). The data included the average daily maximum temperatures in January and July, the average daily relative humidity in July and precipitation data from 756 meteorological stations nationwide from 1971 to 2013. After obtaining the meteorological data from each station, we used the Kriging interpolation method to carry out the spatial interpolation of the station data and obtain historical meteorological data with a spatial resolution of 1 km. Specifically, we selected the spherical function model of ordinary Kriging and used the surrounding 16 meteorological stations as the search radius to carry out the interpolation. Finally, we calculated the mean values of these data using the county as the basic unit.

The climate simulation data included GCM data from 2025 to 2100 under the RCP2.6, RCP4.5 and RCP8.5 emission scenarios, which were derived from the World Climate Research Programme (WCRP) Coupled Model Intercomparison Project Phase Five (CMIP5) climate model data (https://esgf-node.llnl.gov/search/cmip5) published by the Program for Climate Model Diagnosis and Intercomparison (PCMDI). The GCM data used included 7 models, which are listed in table 1.

In terms of the climate model data, the RCP2.6 scenario indicates that greenhouse gas emissions will rise first, then fall, and finally reach a stable state in the next 100 years. In 2100, the radiative forcing will be less than 2.6 W m⁻² under this scenario. The RCP4.5
Figure 1. Study area.

Figure 2. Flow chart.
scenario indicates that the greenhouse gas emissions will rise first; then, the upward trend will gradually slow and finally stabilize in the next 100 years. In 2100, the radiative forcing will stabilize at 4.5 W m\(^{-2}\) under this scenario. The RCP8.5 scenario indicates that greenhouse gas emissions will continue to rise over the next 100 years. In 2100, the radiative forcing will reach 8.5 W m\(^{-2}\) under this scenario (Vuuren et al. 2011).

The county-level population data were obtained from China's 2010 population census data (the census office of the state council in the national bureau of statistics of population and employment statistics, China, 2012).

### 3. Methods

#### 3.1. Integrating climate model data

Based on the methods in the study by Ai and Cheng (2015), we first resampled the data of the seven GCMs by using the nearest neighbor method to unify the resolution and then obtained the GCM simulation results with resolution of 1° by averaging the values of the simulation results of the seven models each year (figure 2). Specifically, we averaged the values of the five indicators in the simulation results of the seven models each year from 2025 to 2100, including the average daily maximum temperatures in January and July, the average daily relative humidity in July, annual precipitation and the number of days in which precipitation occurred annually.

#### 3.2. Calculating WPI

The WPI indicates the changes in the population in a region caused by weather conditions. According to Egan and Mullin (2016), the WPI is calculated based on five meteorological indicators, and the calculation process can be expressed as follows:

\[
WPI_{jt} = A \times JANMAX_{jt} + B \times JANMAX_{jt}^2 + C \times JULYHI_{jt} + D \times JULYHI_{jt}^2 + E \times JULYRH_{jt} + F \times JULYRH_{jt}^2 + G \times PRECIPIN_{jt} + H \times PRECIPIN_{jt}^2 + I \times PRECIDAYS_{jt} + J \times PRECIDAYS_{jt}^2
\]  

(1)

where \(WPI_{jt}\) represents the WPI of region \(j\) in year \(t\). \(JANMAX_{jt}\) represents the average daily maximum temperature in January in this region in year \(t\). \(JULYHI_{jt}\) represents the daily heat index in July in this region in year \(t\) (Stull and Ahrens 2000), \(JULYRH_{jt}\) represents the average daily relative humidity in July in this region in year \(t\). \(PRECIPIN_{jt}\) represents the annual precipitation in this region in year \(t\), and \(PRECIDAYS_{jt}\) represents the number of days in which precipitation occurs annually in this region in year \(t\). \(A-J\) are the coefficients before each meteorological indicator. According to Egan and Mullin (2016), these coefficients can be obtained through multiple regression analysis based on the historical time series of the population and climate data. However, China currently lacks such long-term population and climate data. Considering that people’s perception of bioclimatic comfort is similar, we directly adopted the coefficients of various meteorological indicators obtained by Egan and Mullin (2016), which were based on the population and climate data in the United States from 1880 to 2000. The calculation formulas for the WPI after determining the coefficients can be expressed as:

\[
WPI_{jt} = 0.0488 \times JANMAX_{jt} + 0.0013 \times JANMAX_{jt}^2 - 0.0170 \times JULYHI_{jt} - 0.0008 \times JULYHI_{jt}^2 - 0.0385 \times JULYRH_{jt} - 0.0003 \times JULYRH_{jt}^2 - 0.0048 \times PRECIPIN_{jt} + 0.0002 \times PRECIPIN_{jt}^2 + 0.0065 \times PRECIDAYS_{jt} - 0.0002 \times PRECIDAYS_{jt}^2
\]  

(2)

Using the above formula, we first calculated the WPI of each county in China from 1971 to 2013 based on meteorological observation data. Then, the WPI of each county in China from 2025 to 2100 was calculated under different climate change scenarios using GCM data. To ensure the comparability between historical and future WPI values, we followed the methods in Egan and Mullin (2016) and used the WPI from 1971 to 2005 based on climate model data and the WPI from the observation data in the same period for regression analysis. The regression analysis results were used to correct the WPI from 2025 to 2100. The calibration process can be expressed as follows:

\[
WPI_{jt} = 0.35 \times WPI_{jt} + 1.17
\]  

(3)
where \( WPI_{kt} \) represents the corrected WPI, and \( WPI_{kj} \) represents the WPI before correction. Finally, we followed Egan and Mullin (2016) and calculated the population-weighted mean WPI for the regions of China and climatic zones from 1971 to 2013 and the population-weighted mean WPI from 2025 to 2100 under different climate scenarios. The calculation of the population-weighted mean WPI can be expressed as:

\[
WPI_{kt} = \frac{\sum_{i=1}^{m} WPI_{ki} \cdot P_i}{\sum_{i=1}^{m} P_i}
\]

where \( WPI_{ki} \) represents the population-weighted mean WPI of region \( k \) in year \( t \), \( P_i \) represents the population of county \( j \), and \( m \) is the total number of counties in region \( k \). According to Egan and Mullin (2016), we used imperial units of measure to calculate the WPI and then transformed results into SI units to analyze the trend of WPI.

### 3.3. Analyzing the process and trend of WPI

Trend analysis is a common method used to analyze climate change (Shi et al. 2014). Therefore, based on the study of Shi et al. (2014), we utilized trend analysis to evaluate the changes in the WPI from 1971 to 2013 and the trend of the WPI from 2025 to 2100. The trend analysis can be expressed as:

\[
WPI_{jt} = a_j + b_j t
\]

where \( WPI_{jt} \) represents the WPI of region \( j \) in year \( t \), \( a_j \) is the regression constant, and \( b_j \) is the trend value, which is obtained by the least squares method:

\[
a_j = \frac{1}{n} \sum_{t=t_1}^{t+n-1} WPI_{jt} - \frac{1}{n} \sum_{t=t_1}^{t+n-1} t,
\]

\[
b_j = \frac{\sum_{t=t_1}^{t+n-1} WPI_{jt} - \frac{1}{n} \left( \sum_{t=t_1}^{t+n-1} WPI_{jt} \right) \left( \sum_{t=t_1}^{t+n-1} t \right)}{\sum_{t=t_1}^{t+n-1} t^2 - \frac{1}{n} \left( \sum_{t=t_1}^{t+n-1} t \right)^2}
\]

where \( t_1 \) is the starting year and \( n \) is the length of time in years. When \( b_j \) is greater than 0, the WPI in region \( j \) increases over time. When \( b_j \) is less than 0, the WPI in region \( j \) decreases over time. The size of \( b_j \) reflects the rate of WPI change in region \( j \).

### 4. Results

#### 4.1. The process of WPI from 1971 to 2013

China’s weather conditions improved from 1971 to 2013 (figure (c)). Specifically, China’s WPI increased from 1.34 to 1.59 with a change rate of 0.03 per decade (0.03/10 a) (table (2)). There were 1567 counties experiencing an increase in WPI, which accounted for 68.40% of the total number of counties in China. These counties had a total area of 7.17 million km\(^2\) (74.50% of the land area in China) and a total population of 0.94 billion (70.36% of the total population in China). The increase in maximum daily January temperature (0.04 °C/10 a) and the decrease in July relative humidity (−1.31%/10 a) were the main factors related to the improvement in China's weather conditions (table (2)).

Among the 12 climatic zones, the plateau frigid zone had the most obvious improvement in weather conditions. The WPI of the plateau frigid zone was 0.19 in 1971 and 0.53 in 2013, with a change rate of 0.24/10 a. In the plateau frigid zone, the entire region experienced improved weather conditions (figure (3(d))).

In 2013, the WPI was high in the southwest and low in the northeast. Among the climatic zones, the marginal tropical zone had the highest WPI, with the WPI reaching 6.15, which was 2.87 higher than the national average. The cold temperate zone had the lowest WPI, with the WPI values of −1.51, which was 1.95 lower than the national average (figure (3(c))).

(a-the change in WPI in China, b-the spatial pattern of WPI in 1971, c-the spatial pattern of WPI in 2013, d-the spatial pattern of change rate of WPI from 1971 to 2013)

#### 4.2. The trend in WPI from 2025 to 2100

Under the RCP2.6 scenario, the weather conditions in China will slightly deteriorate from 2025 to 2100 (figure (4)). The WPI in China will decrease from 1.38 to 1.33 with a change rate of −0.01/10 a. Specifically, 1522 counties (66.43% of the total number of counties in China), which cover 6.53 million km\(^2\) (67.85% of the total area of China), are projected to experience deteriorated weather conditions.

In these counties, 0.85 billion people will experience deteriorated weather conditions, which account for 64.15% of the total population in China. The increase in maximum daily July heat index (0.14 °C/10 a) will be the main cause of the deteriorated weather conditions (table (3)). Among the 12 climatic zones, 7 climatic zones will have more than 50% of the counties experiencing deteriorated weather conditions, accounting for 58.33% of the total number of climatic zones (figure (5(a))). Specifically, of the climatic zones, the warm temperate zone will have the greatest amount of people that will experience deteriorated weather conditions. In this climatic zone, 0.41 billion people (97.48% of the regional population) will experience deteriorated weather conditions, and the middle subtropical zone (0.17 billion people, 61.89% of the regional population), the north subtropical zone (0.16 billion people, 58.35% of the regional population), and the middle temperate zone (0.10 billion people, 66.29% of the regional population) have the second, third, and fourth greatest amount of people, respectively, that will experience deteriorated weather conditions.

(a-comparison of the changes in WPI in the past and future; b-change in the WPI in the future)
Figure 3. The change in the WPI in China from 1971 to 2013.

Table 2. Changes in the WPI and the relevant weather indicators per decade in China from 1971 to 2013.

| Indicator                                      | 25th percentile | 50th percentile | 75th percentile | Unweighted mean | Mean weighted by 2010 population |
|------------------------------------------------|-----------------|-----------------|-----------------|-----------------|----------------------------------|
| Maximum daily January temperature (°C)         | −0.12           | 0.00            | 0.13            | 0.02            | 0.04                             |
| Maximum daily July heat index (°C equivalent)  | 0.07            | 0.28            | 0.52            | 0.29            | 0.42                             |
| July relative humidity (%)                     | −1.27           | −0.78           | −0.32           | −0.80           | −1.31                            |
| Annual precipitation (mm)                      | −11.85          | −0.97           | 10.13           | −1.97           | −1.80                            |
| Annual precipitation (days)                    | −4.23           | −2.55           | −1.43           | −2.81           | −3.13                            |
| WPI                                            | −0.01           | 0.02            | 0.06            | 0.04            | 0.03                             |

Under the RCP4.5 scenario, the weather conditions in China will also slightly deteriorate from 2025 to 2100 (figure 4). The WPI in China will decrease from 1.39 to 1.28 with a change rate of −0.02/10 a. There will be 0.71 billion people experiencing deteriorated weather conditions, which accounts for 53.28% of the total population in China. The increase in the maximum daily July heat index (0.53 °C/10 a) will be the main cause of the deteriorated weather conditions (table 3). Among the 12 climatic zones, the warm temperate zone will have the greatest amount of people that experience deteriorated weather conditions (figure 5(b)). Specifically, 0.35 billion people or 84.58% of the total population in the warm temperate will experience deteriorated weather conditions, and the north subtropical zone (0.16 billion people, 58.49% of the total population) and the middle temperate zone (0.12 billion people, 79.01% of the total population) will have the second and third greatest amount of people, respectively, that experience deteriorated weather conditions.

Under the RCP8.5 scenario, the weather conditions in China will clearly deteriorate from 2025 to 2100 (figure 4). The WPI in China will decrease from 1.37 to 0.45 with a change rate of −0.19/10 a. A total of 1.22 billion people or 91.58% of the total population in China will experience deteriorated weather conditions. The increase in the maximum daily July heat index (1.72 °C/10 a) will be the main cause of the deteriorated weather conditions.
Figure 4. The trends in the WPI in China from 2025 to 2100 under different RCPs.

Table 3. Changes in the WPI and relevant weather indicators per decade in China from 2025 to 2100.

| Indicator                        | RCP2.6          | RCP4.5          | RCP8.5          |
|----------------------------------|-----------------|-----------------|-----------------|
|                                  | Unweighted mean | Unweighted mean | Unweighted mean | Unweighted mean |
| Maximum daily January temperature (°C) | 0.01            | 0.29            | 0.56            |
| Maximum daily July heat index (°C equivalent) | 0.13            | 0.49            | 1.61            |
| July relative humidity (%)       | −0.11           | −0.20           | −0.42           |
| Annual precipitation (mm)        | −0.03           | 5.95            | 16.68           |
| Annual precipitation (days)      | −0.32           | −0.11           | −0.14           |
| WPI                              | 0.02            | 0.01            | −0.07           |

3). Among the 12 climatic zones, in 9 climatic zones, more than half of their populations will experience deteriorated weather conditions, accounting for 75.00% of the total number of climatic zones (figure 5(c)). Specifically, the warm temperate zone will have the greatest amount of people (0.39 billion people, 94.78% of the total population) experiencing deteriorated weather conditions, and the north subtropical zone (0.25 billion people, 94.55% of the total population) and the middle subtropical zone (0.23
Figure 5. The change rate of the WPI from 2025 to 2100 in China under different RCPs.
billion people, 84.85% of the total population) will have the second and third greatest amount of people, respectively, experiencing deteriorated weather conditions.

5. Discussion

5.1. The WPI can effectively reflect the CCI on weather conditions

The comfort of the human body (CHB) index is a widely used indicator to assess the CCI on weather conditions in China (Cao et al. 2012, Guo et al. 2015). The CHB index consists of three indicators: temperature, humidity and wind speed (Oliver 1973). Among them, the temperature is the main indicator of bioclimatic comfort, with humidity and wind speed acting as auxiliary indicators (Oliver 1973). Please refer to supporting information for the formula for calculating CHB index. Within a certain range, a higher CHB index represents a more comfortable climate (Guo et al. 2015). To verify the reliability of the WPI, we used the CHB index to quantify bioclimatic comfort in China from 1971 to 2013. Then, we conducted a correlation analysis between the CHB index and WPI.

We found that the WPI can accurately reflect the CCI on weather conditions in China. The correlation coefficient between the WPI and the CHB index from 1971 to 2013 reached 0.91, passing the 0.001 level of significance (figure 6). The correlation coefficients between the WPI and CHB index in all climatic zones exceeded 0.33, passing the 0.05 level of significance (figure S1[https://stacks.iop.org/ERL/15/084028/mmedia]). Among the 12 climatic zones, the correlation coefficient between the WPI and CHB index was highest in the plateau frigid zone, reaching 0.86 and passing the 0.001 level of significance. Our results showed that the WPI exhibits a high consistency with the CHB index.

Our results were consistent with the findings from existing studies. For example, Li et al. (2016) used a method based on the statistical bioclimatic comfort period and found that the national bioclimatic comfort showed an upward trend from 1961 to 2010, and in comparison to the first 25 years, the last 25 years had a total increase of 3.6 d in the bioclimatic comfort period.

5.2. The need to focus on the CCI on weather conditions in urban areas

The most important reason for the deterioration of China’s future weather conditions is the rise in the July heat index. Therefore, the deterioration of weather conditions in the future is mainly manifested in the hotter summer. The continuous high temperature in summer directly affects human health, increases the incidence of cardiovascular, respiratory and digestive diseases, resulting in a large number of deaths (Stott et al. 2004, Wang et al. 2019). Due to the dense population, buildings and infrastructure, cities are more vulnerable to extreme weather events such as heat waves (Guerreiro et al. 2018). Therefore, the CCI on weather conditions in urban areas has been an important part of climate change and urban sustainability research (Guerreiro et al. 2018, Liu et al. 2019a, 2019b, 2020). In 2012, more than half of the population in China lived in cities (Bai et al. 2014). In 2014, the Chinese government began to implement the ‘National Plan on New Urbanization’, which promised people-oriented, urban-rural integrated, economic-intensive and harmonious development. This plan is expected to increase China’s urbanization level to 60.0% by 2020, with an average annual increase of 1% (Bai et al. 2014). In the context of future climate change, in comparison to other types of changes, changes in weather conditions in China’s urban areas will have a more important impact on regional sustainable development (Cao et al. 2018).

We found that nearly half of China’s urban population will live in regions with deteriorated weather conditions.
conditions by 2100. The total area of the regions with deteriorated weather conditions under the RCP2.6, RCP4.5 and RCP8.5 scenarios will be 2.34 million km$^2$ in China, accounting for 24.31% of the total area in China. These regions with deteriorated weather conditions will be mainly distributed in the middle temperate zone, the warm temperate zone, and the north subtropical zone (figure 7(a)). In particular, seven megacities (i.e. Beijing, Tianjin, Wuhan, Chengdu, Nanjing, Xi’an, and Shenyang) will be located in regions with deteriorated weather conditions. During the same period, 0.30 billion urban residents will live in regions with deteriorated weather conditions, accounting for 43.19% of the total urban population in China (figure 7(b)).

Our findings were consistent with existing findings. For example, Zhou and Liu (2018) found that the frequency of extreme weather events in northern cities (e.g. Beijing, Tianjin, and Shenyang) will increase from 2021 to 2100. Li et al. (2018b) showed that in the future, Beijing, Shenyang and other northern cities would have a higher number of heat-related deaths. The continuous high temperature in summer in urban areas has already affected human health (Sun et al 2014, Wang et al 2019). Heat waves had killed nearly 4.5 million people in 31 major cities including Beijing, Tianjin and Shenyang from 2007 to 2013 (Yang et al 2019). The high temperature heat wave in Beijing in July 2010 led to 558 excess deaths. Among them, the excess deaths of cardiovascular and respiratory disease increased by 28% and 40%, respectively (Luan et al 2015). In the summer of 2010, the number of high-temperature deaths in Xi’an increased by 54% over the same period of the previous year (Xie et al 2015). To make matters worse, the heat-related mortality caused by high temperature will increase significantly in the future (IPCC 2018).

Therefore, we need to pay attention to the CCI on weather conditions in urban areas, especially in cities located in regions with deteriorated weather conditions in Beijing, Tianjin and Shenyang. Additionally, we should implement efforts to improve the comprehensive prevention of heat wave risks during summer and extremely cold temperature risks in winter, as well as extreme drought and rain events, by integrating climate change adaptation into urban economic construction and social development planning. Specifically, we need to increase urban green space, e.g. parks and street trees (Hickman 2013, Wolch et al 2014, Georgescu et al 2014). Moreover, building shading design, green buildings design and block cooling design can also be adopted (Cao et al 2018, Chen and Tang 2019). These efforts could help improve public infrastructure and living conditions.
to improve resilience to climate change (Zhai et al. 2019).

(a)-distribution of regions with deteriorated weather conditions, b—percentage of the area and urban population in region with deteriorated weather conditions in China.

Note: Only the area of the region with deteriorated weather conditions under all three RCPs are shown. The population data are from the History Database of the Global Environment (HYDE) for 2100 (Goldewijk et al. 2010).

Figure 8. Differences in regions with severely deteriorated weather conditions from 2025 to 2100 under different RCPs (a-spatial pattern, b-China, c-north subtropical zone, d-warm temperate zone).

5.3. The area of the regions with severely deteriorated weather conditions in China will increase as emissions concentrations increase

We found that as the emissions concentrations increase, the area of regions with severely deteriorated weather conditions (i.e. the WPI change rate is less than $-0.1/10$ a) will gradually increase in the future. With the increase in emissions concentrations from RCP2.6 to RCP8.5, the area of regions with severely deteriorated weather conditions in China will increase from 0 under RCP2.6 to 0.06 million km².
under RCP4.5 and to 3.27 million km\(^2\) under RCP8.5 (figure 8(a), b). The number of people living in the regions with severely deteriorated weather conditions will increase from 0.03 billion under RCP4.5 to 0.87 billion under RCP8.5, representing a 29-fold increase (figure 8(b)).

Furthermore, we found that the weather conditions in the north subtropical zone and the warm temperate zone are more sensitive to changes in emissions concentrations. With the increase in emissions concentrations from RCP4.5 to RCP8.5, the area of the regions with severely deteriorated weather conditions will increase almost 100-fold, from 0.05 million km\(^2\) to 0.49 million km\(^2\) in the north subtropical zone (figure 8(c)). The number of people living in regions with severely deteriorated weather conditions will increase almost 10-fold, from 0.02 billion to 0.22 billion (figure 8(c)). In the warm temperate zone, the area of the regions with severely deteriorated weather conditions will increase from 0.01 million km\(^2\) to 0.76 million km\(^2\), representing 57-fold increase (figure 8(d)). The number of people living in the regions with severely deteriorated weather conditions will increase from 0.01 billion to 0.36 billion, representing a 34-fold increase (figure 8(d)).

If greenhouse gas emissions are not controlled, the regions with severely deteriorated weather conditions will further expand, and more residents will live in regions with severely deteriorated weather conditions. Therefore, we need to emphasize the great importance of mitigating regional climate change, especially in areas sensitive to emissions concentration changes such as the north subtropical zone and the warm temperate zone. In addition, mitigation is needed to optimize the regional industrial structure, reduce the proportion of fossil fuels used in the energy sector, and promote the utilization of clean energy (Haines et al 2007). However, regional carbon sequestration capacity can be enhanced to reduce the concentration of greenhouse gases and mitigate climate change through ecological restoration and afforestation (Harris et al 2006).

5.4. Future perspectives
Our study used WPI for the first time to assess the CCI on weather conditions in China. The WPI was developed on the basis of the assumption that weather conditions have significant effects on both life quality and land productivity, which in turn affect the change rate of the local population (Rappaport 2007, Egan and Mullin 2016). Thus, the index can both measure the CCI on weather conditions and reflect people's perceptions of weather conditions. We found that the weather conditions will deteriorate over the next few decades and the deteriorated weather conditions will influence more than half of China's total population. Moreover, such situation will get worse if greenhouse gas emissions are not controlled. Our findings provide new insights into the CCI on weather conditions and references for policy makers to mitigate and adapt to climate change in the pursuit of sustainable development in China.

The climate model data used in this study are the GCM data with coarse resolution and considerable uncertainty. Therefore, the simulated results do not necessarily reflect the exact future weather conditions, and they are only projected weather conditions under the different scenarios. However, this scenario simulation provided a possible projection of the future CCI on weather conditions in China. In addition, due to the limitation of data availability, we used the formula proposed by Egan and Mullin (2016) to calculate the WPI, which may cause errors if used directly in China.

In a subsequent study, we will attempt to localize the WPI calculation formula and use the high-resolution Weather Research and Forecasting (WRF) model simulation data to assess the future CCI on weather conditions in China (Skamarock et al 2008).

6. Conclusions
The weather conditions in China will deteriorate under all three climate change scenarios. Under the RCP2.6 and RCP4.5 scenarios, China's future weather conditions will slightly deteriorate, and the WPI change rates will be \(-0.01/10\) a and \(-0.02/10\) a, respectively, from 2025 to 2100. Under the RCP8.5 scenario, China's future weather conditions will clearly deteriorate, and the WPI change rate will be \(-0.19/10\) a from 2025 to 2100. The number of people that will experience deteriorated weather conditions will be 0.85 billion under RCP2.6, 0.71 billion under RCP4.5, and 1.22 billion under RCP8.5, accounting for 64.15%, 53.28%, and 91.58% of the total population in China, respectively.

In the future, nearly half of China's urban population will live in regions with deteriorated weather conditions. The area of the regions with deteriorated weather conditions in China will be 2.34 million km\(^2\), accounting for 24.31% of the total area in China. In particular, 0.30 billion urban residents will live in regions with deteriorated weather conditions, accounting for 43.19% of the total urban population in China.

As the concentration of emissions increases, the area of regions with severely deteriorated weather conditions will gradually increase in the future. With the increase in emissions concentrations from RCP2.6 to RCP8.5, the area of regions with severely deteriorated weather conditions in China will increase from 0 to 3.27 million km\(^2\). The number of people living in regions with severely deteriorated weather conditions will increase from 0 to 0.87 billion.

Therefore, we suggest that China implement active measures to address climate change in the future and focus on the mitigation of and adaptation to
climate change in regions with severely deteriorated weather conditions. For cities located in regions with severely deteriorated weather conditions, such as Beijing, Tianjin and Shenyang, we should focus on comprehensive prevention of heat wave risks in summer and extremely cold temperature risks in winter, as well as extreme droughts and rain, by integrating climate change adaptation into urban economic construction and social development planning. These measures could improve public infrastructure and living conditions to improve resilience to climate change. At the same time, in areas sensitive to changes in emissions concentrations such as the north subtropical zone and the warm temperate zone, it is necessary to adjust the regional industrial structure, reduce the use of fossil fuels, and promote the utilization of clean energy to reduce greenhouse gas emissions and mitigate climate change.

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Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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