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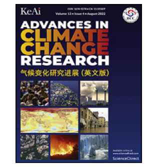

# Detection and projection of climatic comfort changes in China's mainland in a warming world

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**Abstract**

Climatic comfort, which refers to the comfort of the human body's thermal sensations, is important for the human habitat. Although considerable efforts have been provided to examine changes in climatic comfort response to global warming from a partial perspective, the trajectory shift in past and future climatic comfort conditions in China's mainland based on uniform indicators has not been revealed. The spatiotemporal pattern of climatic comfort over historical and future periods was investigated in this study, using China's mainland as an example. The temperature–humidity index was adopted on the basis of homogenised meteorological station observations and high-resolution climate model simulations to analyse the trends of comfort/discomfort days from 1960 to 2017 and project changes in climatic comfort under representative concentration pathway scenarios in the late 21st century (2071−2100). Results show a substantial decrease in cold-uncomfortable days and a moderate increase in comfortable and warm-uncomfortable days from 1960 to 2017. In the late 21st century, the signals of increasing warm-uncomfortable and decreasing cold-uncomfortable days are projected to enhance significantly while the direction of changes in comfortable days exhibits a north–south divergence. The uneven changes in warm- and cold-uncomfortable days and an overall decrease in comfortable days in the late 21st century dominate the future trends in climatic comfort in the densely populated southeast half of China. Effective measures taken for adapting to and mitigating global climate warming can considerably avoid the adverse impact of the projected change.

*Keywords:* Comfort; Climate change; Temperature–humidity index; Projection; China's mainland

## 1. Introduction

Climatic comfort refers to the comfort (or suitability) of the human body's thermal sensations under the combined influence of meteorological factors such as temperature, humidity, wind speed and solar radiation (de Freitas and Grigorieva, 2015; Sun and Li, 2015). Climatic comfort has received considerable attention in the fields of architectural design (Rupp et al., 2015), urban planning (Chen et al., 2015), human health (Di Napoli et al., 2018) and tourism development (Ge et al., 2017) because of its crucial impact on human habitat. Researchers proposed multiple indicators for evaluating climatic comfort. Early attempts have been made to incorporate human subjective feelings or physiological responses in empirical statistical models and develop a number of measures (e.g. effective temperature (ET, Houghten and Yaglou, 1923), temperature–humidity index (THI, Thom, 1959) and wind chill index (Siple and Passel, 1945)). Many mechanistic model

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indicators based on the human thermal exchange model have been developed to overcome the limitations of empirical indicators (e.g., physiological equivalent temperature (Höppe, 1993) and universal thermal climate index (UTCI, Jendritzky et al., 2012). The abovementioned indicators are referred to as human-perceived temperatures in certain cases. The studies of distributions and trends of climate comfort zones can be performed on the basis of the above indicators, and meaningful information can be provided for meteorological services and tourism planning.

In recent decades, the Earth has been experiencing unprecedented rapid warming, and this warming trend is projected to continue in the coming decades (IPCC, 2021). Many efforts have been made to examine changes in the mean climate state and climate extremes at global and regional scales (e.g., Shi et al., 2020, 2018; Zhang and Wang, 2019; Fu et al., 2018; Xu et al., 2017). In recent years, certain studies reported that the use of comfort as an indicator to evaluate the impact of climate change has a clearer practical meaning than that of raw meteorological variables such as temperature and humidity (Buzan and Huber, 2020; Song et al., 2017; Kjellstrom et al., 2016). A typical example is as follows: rather than temperature, certain studies use heat stress indicators to project the increasing heat waves in the 21st century and highlight the potential threats to human health caused by a warming climate considering the significant role of humidity in human health risks in hot environments (Wang et al., 2021; Schwingshackl et al., 2021; Brouillet and Joussaume, 2020). Another study suggests that summertime increases in warm discomfort are expected to outpace the wintertime reductions in cold discomfort in the late 21st century based on human-perceived temperatures (Li et al., 2018). However, most of the published studies considering climatic comfort response to global warming tend to focus more on the hot conditions rather than overall conditions.

China is a vast country with a population of >1.4 billion and has a diverse climate. Changes in climatic comfort over China exhibit a complex spatiotemporal distribution and potentially affect the habitat of large amounts of populations. Previous studies investigated the climate comfort characteristics of different regions and cities in China during the historical period (Lin et al., 2019; Chi et al., 2018; Wu et al., 2017; Li et al., 2016) and explored certain applications in climatic resource assessment and tourism planning (Huang et al., 2019; Kong et al., 2019; Ge et al., 2017). Large reductions in cold days and increments in hot days are observed considering the increase in global mean temperature during the past few decades (Li et al., 2022; Chi et al., 2018; Wu et al., 2017). Moreover, the number of annual comfortable days demonstrates an increasing trend considering the China-wide average (Lin et al., 2019; Wu et al., 2017; Li et al., 2016). However, the summertime number of annual comfortable days decreases in warm areas (Lin et al., 2019; Li et al., 2016). Projected changes in climatic comfort in certain parts of China's mainland in the 21st century have been examined (Li et al., 2022; Jin et al., 2019; Gao et al., 2018; Zhou et al., 2018). However, the abovementioned results focused on changes in climatic comfort from a particular perspective (e.g. observed or projected changes, changes in discomfort or comfort conditions and changes in overall climatic conditions in a specific small region). The authors believe that studies on the past and future shifts of climatic comfort conditions in China's mainland from a holistic perspective are few.

The change in climatic comfort in China's mainland from 1960 to 2017 is examined in this study based on the meteorological station observations, and future changes in climatic comfort at the end of the 21st century are projected under two representative concentration pathway (RCP) scenarios 2.6 and 8.5 based on the output of high-resolution regional climate model (RCM) simulations. Regional and seasonal characteristics of climate comfort changes over the past decades and under future scenarios are revealed. The results will contribute meaningful information in the assessment of climate change impacts and adaptations.

## 2. Data and methods

### 2.1. Data

Quality-controlled and homogenised daily mean temperature ($T$) and relative humidity ($RH$) observation from 739 national reference climatic and basic meteorological stations in China's mainland (Fig. 1) for 1960–2017 was adopted to characterise historical changes in climatic comfort. The detailed information of this dataset is presented in Li et al. (2020, 2016). Furthermore, daily mean T and RH obtained from two ensembles of RCM outputs were adopted to examine future changes in climatic comfort (Table 1). The two RCMs with a 25 km horizontal resolution were driven by the Met Office Hadley Centre Earth System Model (HadGEM2-ES, Jones et al., 2011), the Max Planck Institute for Meteorology Earth System Model (MPI-ESM, Giorgetta et al., 2013) and the Norwegian Earth System Model (NorESM1-M, Bentsen

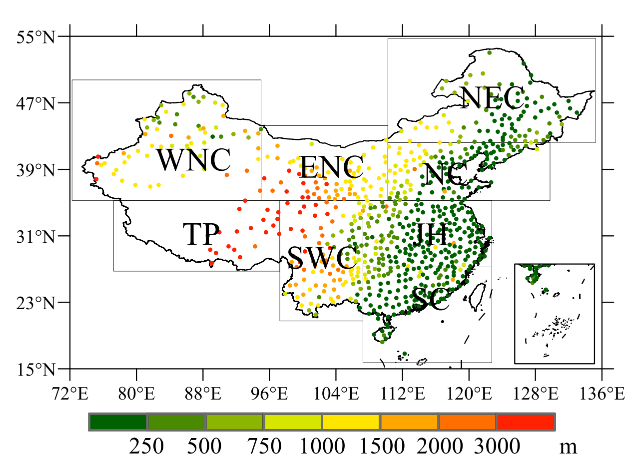


Fig. 1. Spatial distribution of 739 meteorological stations, as well as the division of sub-regions in China's mainland (The elevation of each station is marked with coloured dots. NEC = northeastern China; NC = northern China; JH = Jiang–Huai region; SC = southern China; SWC = southwestern China; TP = Tibetan Plateau; WNC = west northwestern China; ENC = east northwestern China).

Table 1
Basic information on adopted regional climate models.

| RCM | Driving GCM | Period | | | Reference |
|---|---|---|---|---|---|
| | | Historical | RCP2.6 | RCP8.5 | |
| REMO2015 | HadGEM2-ES | 1970–2005 | 2006–2099 | 2006–2099 | Remedio et al. (2019) |
| | MPI-ESM-LR | 1970–2005 | 2006–2100 | 2006–2100 | |
| | NorESM1-M | 1971–2005 | 2006–2100 | 2006–2100 | |
| RegCM4.4 | HadGEM2-ES | 1970–2005 | 2006–2098 | 2006–2098 | Teichmann et al. (2020) |
| | MPI-ESM-MR | 1980–2005 | 2006–2099 | 2006–2099 | |
| | NorESM1-M | 1970–2005 | 2006–2099 | 2006–2099 | |

et al., 2013) under the framework of coordinated regional climate downscaling experiment (CORDEX)-East Asia phase II (Giorgi and Gutowski, 2015). In this framework, 1970–2005 is used for the historical simulation and 2006–2100 is utilised for the RCP2.6 and RCP8.5 simulations. The selection of the three global climate models is primarily attributed to their generally good performance over different CORDEX domains (Giorgi et al., 2021). RCP2.6 is a sustainable future scenario with the lowest warming level, whilst RCP8.5 is a fossil fuel-based future scenario with the highest warming level (van Vuuren et al., 2011). The two scenarios provide lower and upper bounds for the results of future projections, with actual current emission pathways falling somewhere in between.

### 2.2. Indicator for climatic comfort

Note that the selection of climatic comfort indicators (i.e. *THI*) considered applicability and data availability. The evaluation of climate comfort is divided into two categories: empirical and mechanistic indicators (de Freitas and Grigorieva, 2015; Sun and Li, 2015). Mechanistic indicators (e.g. Universal Thermal Climate Index (UTCI), di Napoli et al., 2020) are expected to accurate results because of their rigorous physical basis. However, the calculation of mechanistic indicators involves multiple unconventional meteorological variables (e.g. mean radiation temperature and body wind speed), which is tedious for large-scale calculations. If these variables are parameterised uniformly, additional uncertainty may be introduced in the results (Sun and Li, 2015). Therefore, adopting empirical indicators with relatively high reliability is still the common approach to evaluating climatic comfort changes in the context of global warming (Fotso-Nguemo et al., 2022; Gao et al., 2018; Sylla et al., 2018). The *THI* (Thom, 1959) is adopted to classify comfort and discomfort days by region and season in China's mainland. *THI* (°C) can be calculated as follows:

$$THI = T - 0.55 \times (1 - 0.01 \times RH) \times (T - 14.5) \quad (1)$$

where $T$ and $RH$ are daily mean temperature (°C) and relative humidity (%), respectively. The examination of the applicability of the classification criteria of the *THI* is an indispensable and critical part of climatic comfort assessment. A classification scheme that applies to the climatic characteristics in China's mainland was adopted from a previous study (Yu and Li, 2019): a comfortable day is defined when the *THI* is between 17.5 °C and 23.5 °C, while a warm (cold)-uncomfortable day is defined when the *THI* is greater than 27 °C (below 7 °C). The most comfortable and uncomfortable parts were primarily considered, and the slightly warm or cool parts were disregarded. The combination of warm-uncomfortable, cold-uncomfortable and comfortable days can be considered a rough estimate of the overall climatic comfort. The applicability of the classification criteria of the THI area has been validated in a previous study (Yu and Li, 2019).

### 2.3. Bias correction for data modelling

Raw outputs from the two RCMs must be corrected because climate models are inherently biased in simulating climatology. Therefore, the cumulative distribution function transform (CDF-*t*) approach (Text A1; Michelangeli et al., 2009) was adopted to perform bias correction, which is based on matching the CDF of the models and observations. Model outputs of daily THI were first bilinearly interpolated to station points. The CDF-*t* approach was then calibrated for the historical period (usually 1970–2005, but individual models vary because of data availability, Table A1) and applied to future changes in the period of the last 30 years of RCP simulations (usually 2071–2100, but individual models vary because of data availability, Table A1). The CDF-*t* approach is successfully applied in multiple studies for bias correction, thus obtaining observation-constrained model simulations in this study (e.g. Guo et al., 2020; Yang et al., 2019). Cross-validation was then performed, and the results show that the CDF-*t* approach performs effectively in reducing bias on comfortable/uncomfortable days (c.f., Text A1 and Fig. A1).

### 2.4. Statistical methods

The present climatology of climatic comfort/discomfort days is calculated by the 1981–2010 reference period, while projected comfort/discomfort days in the late 21st century are defined as the mean of the last 30 years of RCP simulations. The trends of comfort/discomfort days during 1960–2017 are obtained by Theil–Sen regression (Theil, 1992; Sen, 1968), and their statistical significances are examined by a modified Mann–Kendall trend test (Hamed and Ramachandra Rao, 1998). The locally weighted regression (LOESS) method was adopted for curve fitting for the time series of climatic comfort/discomfort days (Cleveland and Devlin, 1988). A two-sided *t*-test was used to examine the statistical significance of future changes in climatic comfort/discomfort days based on the multi-model results. The significance level of all statistical tests was considered to be 0.05. Annual and seasonal aggregated climatic comfort/discomfort days were calculated, with the year divided into the following four seasons: spring (March–May), summer (June–August), autumn (September–November, SON) and winter (December–February). Changes in national and sub-regional average climatic comfort/discomfort days were examined. The location of eight sub-regions is displayed in Fig. 1 (You et al., 2017).

## 3. Results

### 3.1. Present climatology of climatic comfort

The national average of annual comfortable, warm-uncomfortable and cold-uncomfortable days are 82.4, 6.9 and 112.1 d, respectively, during the reference period (1981–2010). Annual comfortable days at most sites across the country are between 60 and 120 d, except for the Tibetan Plateau and Yunnan province (Fig. 2a). Because of the cold climate at the high altitude, the annual comfortable days on the Tibetan Plateau are close to zero, whilst the annual cold discomfort period on the Tibetan Plateau is as long as half a year, which is significantly different from other regions. Certain stations in southern and central Yunnan province have the longest comfortable periods in the entire country (up to 180 d or more). Except for certain stations in South China and the Yangtze River basin, the number of annual warm-uncomfortable days at almost all other stations is < 20 d (Fig. 2b). This result agrees with You et al. (2017) and Ye et al. (2014), which emphasise that South China and the Yangtze River basin are the regions having the most severe heat waves in China. Unlike the aforementioned comfortable and warm-uncomfortable days, the spatial distribution of the number of annual cold-uncomfortable days demonstrates a clear north–south contrast (Fig. 2c). Cold discomfort condition is rare in areas south of 25 °N; however, it occurs for at least one-quarter of a year north of 35 °N. Certain stations on the Tibetan Plateau, northeastern China and Xinjiang Uygur autonomous region have the longest cold discomfort periods (up to >180 d).

Fig. 3a shows the national and sub-regional averaged seasonal comfort/discomfort days. For the national average, warm discomfort conditions all occur in summer; cold discomfort primarily occurs in winter (approximately 60%) and followed by autumn and spring (approximately 40%); the comfort period has the most distribution in summer (approximately 50%), with the rest distributed in spring and autumn. Significant regional differences are observed in the seasonal distribution of comfort/discomfort periods (Fig. A2). For example, the comfort period in the north half of China is overwhelmingly distributed in summer, while that in southern China and Jiang–Huai regions is primarily distributed in spring and autumn, respectively.

### 3.2. Observed changes in climatic comfort

Fig. 3b–d show the time series of national averaged comfort/discomfort days. The warm/cold-uncomfortable days in China's mainland tends are extended/shortened during the past six decades, with the shortening of the cold-uncomfortable days (2.1 d per decade, $p < 0.05$) more remarkable than the extension of the warm-uncomfortable days (0.9 d per decade, $p < 0.05$). Moreover, a moderate increase is reported in the

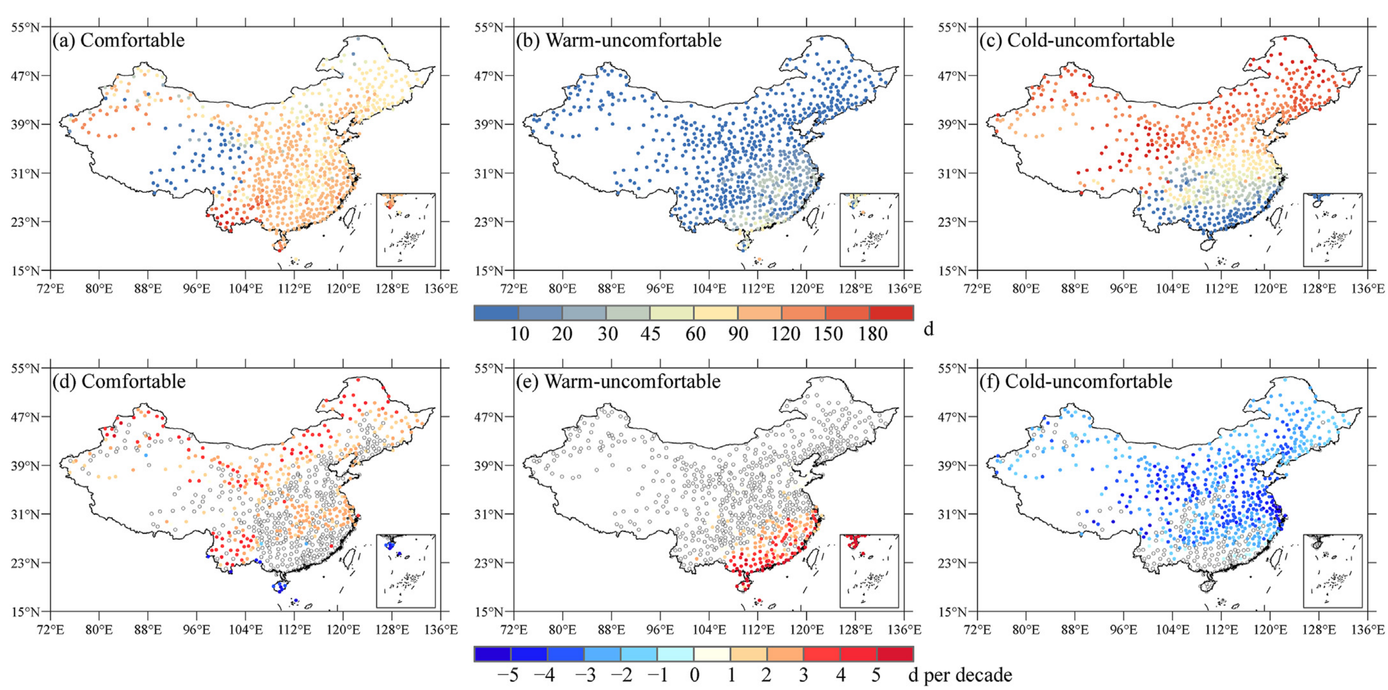


Fig. 2. Spatial distribution of present climatology 1981–2010 (a–c) and trends during 1960–2017 (d–f) in annual comfort/discomfort days (Solid dots with colouring indicate statistically significant trends ($p < 0.05$)).

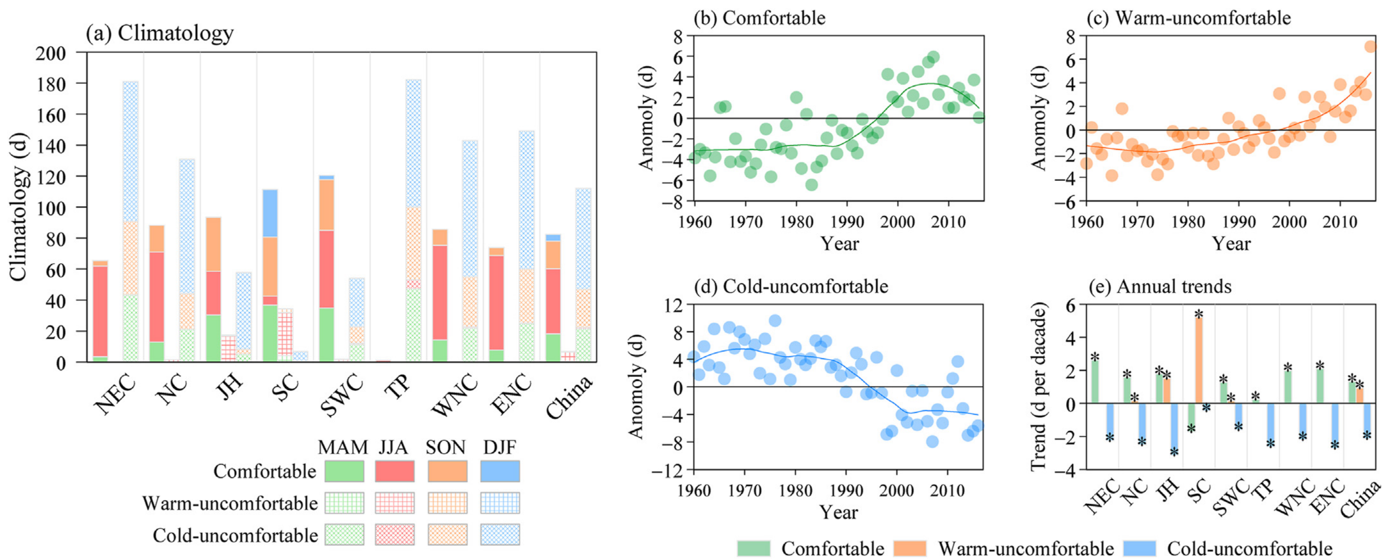


Fig. 3. (a) Climatology of sub-regional and national averaged comfort/discomfort days in the reference period (1981−2010), (b−d) anomalies of national averaged comfort/discomfort days during 1960−2017, and (e) trends in sub-regional and national averaged annual comfort/discomfort days during 1960−2017 (Solid lines in (b−d) indicate the LOESS fitting curves. Asterisks in (e) indicate statistically significant trends ($p < 0.05$)).

number of comfortable days (1.3 d per decade, $p < 0.05$) during this period. The trending comfort/discomfort days before the late 1980s were weak, while a remarkable trend was observed after the late 1980s. A similar variation is observed in most sub-region means (Fig. A3), which agrees with the rapid warming after the late 1980s in China (You et al., 2017; Zhou and Ren, 2011).

A significant decrease in cold-uncomfortable days occurred in all sub-regions, with trends ranging from −3.1 d per decade (Jiang–Huai, $p < 0.05$) to −0.5 d per decade (southern China, $p < 0.05$). A remarkable increase in warm-uncomfortable days was observed in southern China (5.2 d per decade) and Jiang–Huai regions (1.5 d per decade). A moderate increase in comfortable days was observed in most subregions, except for southern China and Tibetan Plateau regions, with trends ranging from 1.3 d per decade (southern China, $p < 0.05$) to 2.6 d per decade (northeastern China, $p < 0.05$). However, a trend of −1.7 d per decade was observed on the comfortable days in southern China.

For seasonal means, the increase in warm-uncomfortable days primarily occurred in summer as expected; the increasing trend in comfortable days is most pronounced in spring and autumn, whereas the decreasing trend in cold-uncomfortable days is evident in winter, spring and autumn (Fig. A4).

The stations with a significant increasing trend in comfortable days are primarily located in northwestern and northeastern China, the Yangtze River basin and Yunnan province, while those with a significant decreasing trend are only sporadically distributed in the southern China region. Most stations with a significant increase in warm-uncomfortable days are distributed south of 25 °N; however, almost all sites with a significant decreasing trend in cold-uncomfortable days are located north of 25 °N. Note that spatial patterns of comfort/discomfort day trends differed significantly amongst seasons (Fig. A5). For example, the most pronounced decrease in cold-uncomfortable days in winter occurs in the Jiang–Huai region, while that in spring and autumn occurs in the north half of China.

### 3.3. Projected changes in climatic comfort

The results of the future projection show a dramatic difference in spatiotemporal patterns of climatic comfort in the late 21st century under RCP8.5 and RCP2.6 scenarios and exhibit remarkable differences in projected results between the scenarios.

Under the RCP8.5 scenario, the warm/cold discomfort period in China continues to extend/shorten in the 21st century (26.6−31.9 d), whilst the comfort days exhibit relatively minimal changes (−1.0 d). The changes are substantially weaker under RCP 2.6 (5.8, −9.5 and 0.6 d) than RCP8.5 (Fig. 4). The result of increasing warm-uncomfortable days and decreasing cold-uncomfortable days is not surprising. However, the asymmetrical changes in the number of warm-uncomfortable and cold-uncomfortable days are notable. The national average increase in the annual number of warm-uncomfortable days is less than the decrease in cold-uncomfortable days, but an unprecedented strong growth (up to 100 d and more) is observed in annual warm discomfort conditions in southern China, the Jiang–Huai region and parts of northern China region, especially under the RCP8.5 scenario. The decrease in annual cold-uncomfortable days is relatively uniform amongst sub-regions other than Tibetan Plateau and Southern China regions, with changes ranging from −27.0 to −37.2 d (RCP8.5) and −8.1 to −9.6 d (RCP2.6). The most pronounced increase in warm-uncomfortable days occurs along the coast of southern

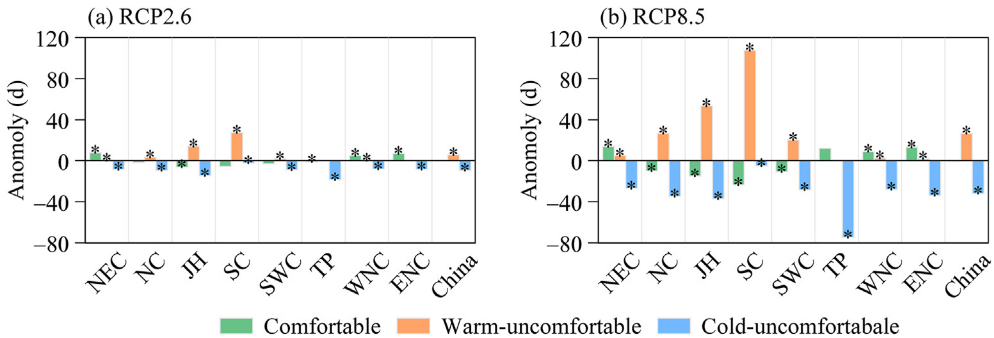


Fig. 4. Sub-regional and national averaged changes in annual comfort/discomfort days in the late 21st century (2070−2100) under RCP2.6 and RCP8.5 scenarios, compared to the reference period of 1981−2010 (Asterisks indicate that changes in comfort/discomfort days are statistically significant ($p < 0.05$)).

China. Moreover, the decrease in cold-uncomfortable days is characterised by a relatively clear latitudinal distribution; the most evident decrease is between 30°N and 35°N (Fig. 5).

The change in annual comfortable days is insignificant based on the national average (<1 d), but some significant changes are observed at the sub-regional scale. For example, changes in annual comfortable days in northeastern China, west northwestern China and east northwestern China are 13.8/7.9, 8.9/5.9 and 13.1/7.0 d in the late 21st century compared to the present climatology under RCP8.5/RCP2.6 scenarios; however, changes in annual comfortable days in southern China and Jiang−Huai regions are −23.5/−5.6 and −15.0/−6.2 d under RCP8.5/RCP2.6 scenarios, respectively (Fig. 4). Considering the spatial pattern, the results show that an increase in comfort days primarily occurs in northwestern and northeastern China and Yunnan province, whereas a decrease in comfort period dominates the rest of China's mainland (Fig. 5). Note that certain regions (e.g. Jiang−Huai and southwestern China regions) with significant increasing trends of annual comfortable days in historical periods exhibit a decrease in annual comfortable days under future scenarios; i.e., in a warm climate, the shift of comfort to warmer condition is more pronounced than that of colder conditions to comfort conditions in those regions.

The changes in seasonal climatic comfort are investigated under future scenarios (Figs. A6–A8). Undoubtedly, the increase in annual warm-uncomfortable days is primarily contributed by summer, whilst an additional increase in these days is projected to occur in spring and autumn (especially under the RCP8.5 scenario). The decrease in cold-uncomfortable days is attributed to varying degrees in winter, spring and autumn. The increasing comfortable days in northeastern China, west northwestern China and east northwestern China regions primarily occur in spring and autumn, whereas the decreasing comfortable days in southern China and Jiang−Huai regions are primarily in summer.

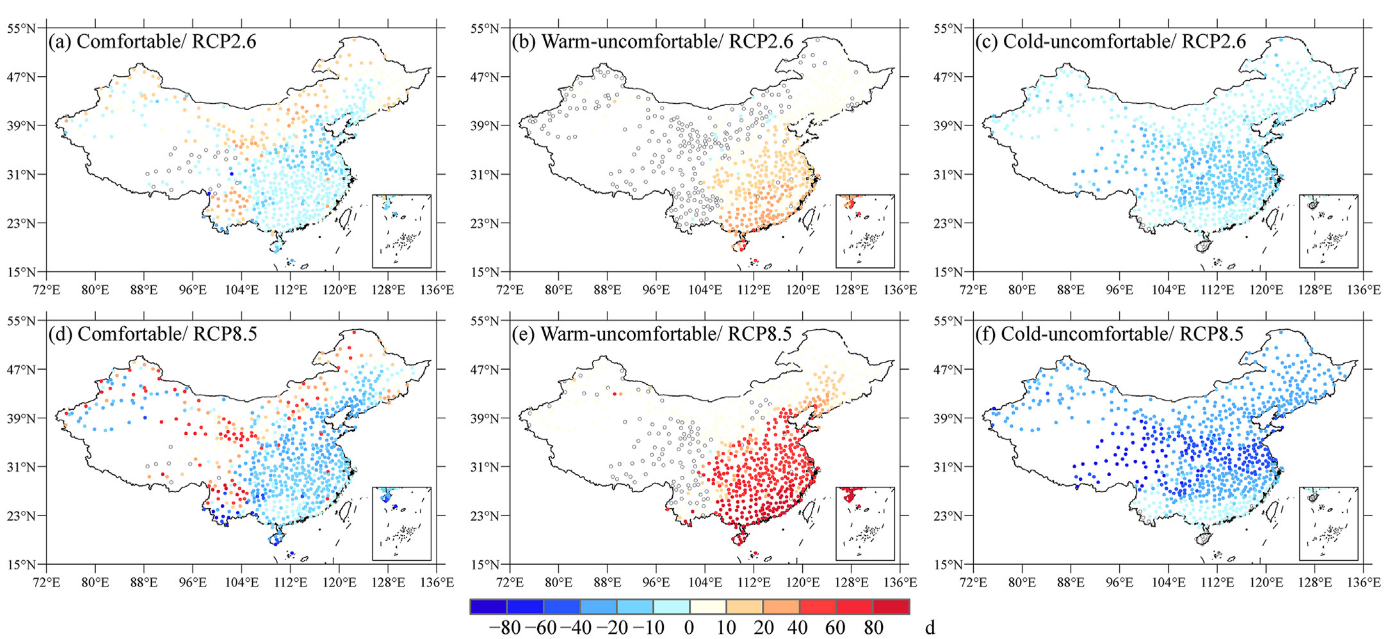


Fig. 5. Spatial distribution of changes in annual comfort/discomfort days in the late 21st century under RCP2.6 (a−c) and RCP8.5 (d−f) scenarios, relative to the reference period (Solid dots with colouring indicate statistically significant changes ($p < 0.05$)).

## 4. Discussion and conclusions

### 4.1. Discussion

The authors believe that this study is an early attempt for revealing a holistic image of changes in climatic comfort conditions in the context of global warming. Unlike previous studies that focus on only one aspect of historical/future changes or warm/cold-discomfort conditions, the results of the current study revealed the trajectory across past and future changes in climatic comfort conditions in China's mainland based on uniform indicators. A consistent trajectory of increasing warm days and decreasing cold days across the past and future, which have been reported by another recent study based on other indicators (Li et al., 2022), is demonstrated. However, multiple possibilities in the direction of changes in comfortable days are identified as follows: days that were previously comfortable may become hot whilst those that were previously cold may become comfortable. The current results highlighted that the increasing trend in comfortable days shown in historical periods does not persist in certain regions (e.g. the Yangtze River basin) under the future warming scenarios (Figs. 2d and 5d). This phenomenon extends the conclusion of Lin et al. (2019) and Li et al. (2016), considering the dimension of time and highlights the potential reversal of the increasing trend in comfort periods at high levels of global warming. Furthermore, the regions where the comfortable days decreased under the future scenario roughly coincide with the densely populated areas of China (i.e. the southeast side of the Hu Huanyong Line, Fig. 5). This condition helps explain the results of Gao et al. (2018), who reported a decreasing population exposure to comfort conditions in the future despite increments in nationally averaged comfortable days. Moreover, the highest number of comfortable days is reported in Yunnan province based on the present climatology and tends to increase in a warm future, which may be related to the special subtropical plateau climate with relatively narrow annual ranges in temperatures (Zhou et al., 2019).

In the cold regions of China, a remarkable decrease in cold-uncomfortable days and a moderate increase in comfortable days will promote an increase in overall climatic comfort. However, in the warm regions, the sharp increase in warm-uncomfortable days will substantially exceed the decrease in cold-uncomfortable days, and a slight decrease in the comfortable days will be observed, ultimately leading to a decrease in overall climate comfort (Fig. 5). The results reveal that the uneven changes in warm and cold conditions when the magnitude of global warming exceeds a dangerous threshold may lead to inhospitable regions at middle-low latitudes. The above results refine the results of Li et al. (2018) in China's mainland. The results of the overall comfort index (defined as comfortable days minus the sum of warm- and cold-uncomfortable days) are displayed to demonstrate this phenomenon. The overall comfort index increases in most regions north of 25°N of China's mainland during the historical period, but most regions in the southeast side of the Hu Huanyong Line (Fig. 6d–f) exhibit a decreasing trend of overall comfort index under future scenarios, particularly under the RCP8.5 scenario. The results show that the rapid global warming may negatively affect human habitat in densely populated southeastern China; however, certain improvements in overall climatic comfort in cold regions in mid-high latitudes in a warmer world (Fig. 6d–f). Furthermore, the most comfortable areas (i.e. with the highest overall comfort index) are currently south of the Yangtze River. However, the north–south contrast of the overall comfort index is projected to reduce, especially under the RCP8.5 scenario (Fig. 6a–c). Yunnan province is always the most comfortable province in the current and future scenarios.

The shift in climatic comfort conditions is dominated by the increased human-perceived temperature (THI and its analogues) after the increase in global mean temperature (Fotso-Nguemo et al., 2022; Li et al., 2022; Wu et al., 2017). Certain studies reported that the warm season relative humidity slightly decreases with rising temperatures in most regions of mid-latitude land (including China) because of the limitation of moisture supply, which potentially mitigates the increase of warm discomfort conditions (Coffel et al., 2019; Luo and Lau, 2019). However, a significantly increased frequency of cautionary and dangerous heat stress days is observed, particularly in southeastern China (Freychet et al., 2020; Li et al., 2020; Luo and Lau, 2019). The results of significantly increased warm-uncomfortable days confirm this result. A small reduction in relative humidity during heat waves in China slightly limits the increase in heat–humidity extremes. However, in warm regions, the number of days above the warm-uncomfortable threshold is still likely to increase remarkably in a warming world because of the high baseline level of THI. Moreover, certain recent studies reported a rise in extreme cold events in China in the early 21st century, which is possibly a regional response to the global warming hiatus (Ding et al., 2021; Li et al., 2015). The warming hiatus in winter in China is more pronounced than that in the annual mean (Du et al., 2019; Sun et al., 2018); a weak cooling of cold extremes is still observed despite the continued warming trend of hot extremes across most regions of China during the global warming hiatus (Li et al., 2021; Shen et al., 2018). The obtained results indicate a significant long-term decreasing trend in cold-uncomfortable days since the 1960s. However, some fluctuations are found in cold-uncomfortable days in the early 21st century (Figs. 3 and A3), which indicates the response of climatic comfort changes to the global warming hiatus during this period. Compared to the fluctuations in cold-uncomfortable days, the increase in warm-uncomfortable days is substantially sustainable, which agrees with the substantial increase of heat waves during the recent global warming hiatus.

Notably, the observations adopted were subjected to strict quality control and homogenisation. However, the systematic bias of urbanisation effects has not yet been removed because of the location of many stations in or near the built-up areas of

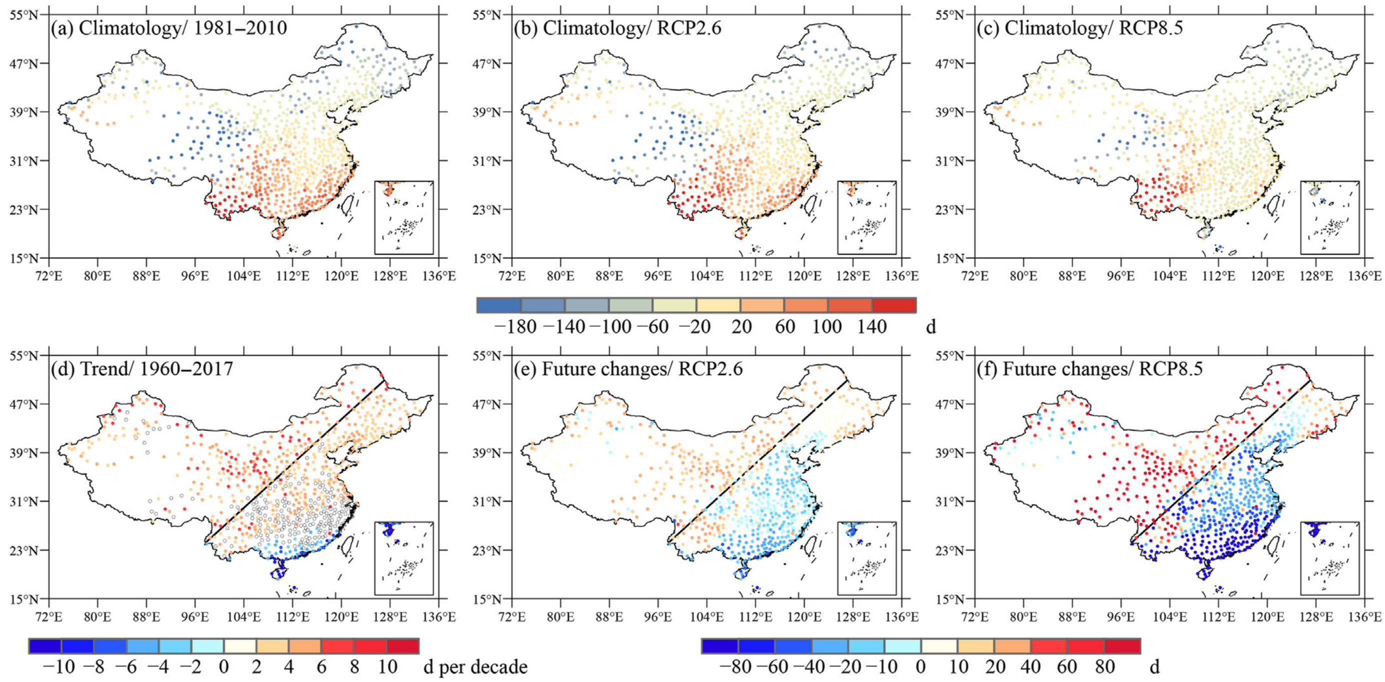


Fig. 6. Overall comfort index in (a) 1981−2010 and (b−c) under future scenarios, (d) trend during 1960−2017, and (e−f) changes in the late 21st century under future scenarios compared to the reference period (The Hu Huanyong Line (named Heihe–Tengchong Line, a geographic division line of great significance in China; Chen et al., 2016) is labelled as a black line in (e−f)).

cities. The climatic regimes at these stations are not representative of conditions in the surrounding rural areas (Wu et al., 2021; Wen et al., 2019; Ren and Zhou, 2014). Therefore, the results of the observed analysis should be interpreted as changes in climate comfort near cities, and the country and sub-region averaged upward/downward trends of the warm/cold-uncomfortable days over the past few decades may have been overestimated. The urban bias in the observations may have affected the results of model verification and calibration, thus leading to an overestimated projected temperature increase in future. However, the limitation does not significantly affect the explanation of the results of this study because most of China's population lives in cities.

The applicability of the adopted classification criteria of the THI in China's mainland is validated in a previous study (Yu and Li, 2019). However, a degree of subjectivity exists in any grading scheme, and distinct individual differences in human thermal perception affect the evaluation of classification criteria. On the one hand, the extent to which the primary results are dependent on the definition of climatic comfort indicators may require to be thoroughly assessed. Thus, this study proposed to confirm the classification criteria of climatic comfort indicators as per the climate characteristics of China before conducting the cross-indicator comparison analysis. On the other hand, future research could specify appropriate classification criteria based on the thermal perception of different populations and investigate changes in climatic comfort in the context of global warming and urbanisation. Moreover, the effects of wind speed and radiation are ignored because of their relatively minor role in most cases at daily averaged scales (Willett and Sherwood, 2012). However, these factors should be considered in studies at high spatiotemporal resolutions (di Napoli et al., 2020).

### *4.2. Conclusions*

From the perspective of a comprehensive indicator (i.e. THI), this study shows the trajectory across past and future changes in climatic comfort conditions in China's mainland based on a set of homogenised station observations and the observation-constrained high-resolution simulation results of CORDEX RCMs. From 1960 to 2017, a substantial decrease and moderate increase are respectively observed in cold-uncomfortable and warm-uncomfortable days. The signal of decreasing/increasing cold/warm-uncomfortable days would enhance further in the late 21st century. A moderate increasing trend in comfortable days in China from 1960 to 2017 is observed, and this trend in quite a few regions of China is projected to reverse in the late 21st century. Particularly, in densely populated southeastern China, a decreasing trend in overall climatic comfort, as well as decreasing comfortable days, can be observed in the future because of asymmetric changes in warm and cold discomfort conditions. The magnitude of this change can be substantially reduced under the RCP2.6 scenario (rather than the RCP8.5 scenario). Therefore, effective greenhouse gas emission reduction can considerably avoid this adverse impact.

## Declaration of competing interest

The authors declare no conflict of interest.


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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.accre.2022.04.008.

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