Inequality of Global Thermal Comfort Conditions Changes in a Warmer World

Article *in* Earth's Future · January 2023

DOI: 10.1029/2022EF003109

6 authors, including:

Jintao Zhang
Fudan University
17 PUBLICATIONS 92 CITATIONS

Qinglong You
Fudan University
127 PUBLICATIONS 6,145 CITATIONS

Guoyu Ren
China Meteorological Administration (CMA), Beijing/China University of Geoscienc…
352 PUBLICATIONS 10,490 CITATIONS

Safi Ullah
Fudan University
32 PUBLICATIONS 516 CITATIONS

ADVANCING EARTH AND SPACE SCIENCE

Earth's Future

RESEARCH ARTICLE
10.1029/2022EF003109

Special Section:
CMIP6: Trends, Interactions, Evaluation, and Impacts

Key Points:

- In low-income regions, a sharp increase in warm-uncomfortable days is projected to be accompanied by a marked decrease in comfortable days
- In high-income regions, cold-uncomfortable days are projected to decrease, while comfortable days are projected to increase
- This divergent response highlights the fact that developed countries should take greater responsibility in combating climate change

Supporting Information:

Supporting Information may be found in the online version of this article.

Correspondence to:

Q. You,
qlyou@fudan.edu.cn

Citation:

Zhang, J., You, Q., Ren, G., Ullah, S., Normatov, I., & Chen, D. (2023). Inequality of global thermal comfort conditions changes in a warmer world. *Earth's Future*, *11*, e2022EF003109. https://doi.org/10.1029/2022EF003109

Received 18 AUG 2022
Accepted 10 JAN 2023

Author Contributions:

Conceptualization: Jintao Zhang, Qinglong You
Methodology: Jintao Zhang
Supervision: Qinglong You, Guoyu Ren
Writing – original draft: Jintao Zhang

Inequality of Global Thermal Comfort Conditions Changes in a Warmer World

Jintao Zhang[1,2], Qinglong You[1,3], Guoyu Ren[4,5], Safi Ullah[1], Inom Normatov[6], and Deliang Chen[7]

[1]Department of Atmospheric and Oceanic Sciences, Fudan University, Shanghai, China, [2]Chinese Academy of Meteorological Sciences, China Meteorological Administration, Beijing, China, [3]Innovation Center of Ocean and Atmosphere System, Zhuhai Fudan Innovation Research Institute, Zhuhai, China, [4]National Climate Center, China Meteorological Administration, Beijing, China, [5]Department of Atmospheric Science, School of Environmental Studies, China University of Geosciences, Wuhan, China, [6]Meteorology and Climatology Department, Tajik National University, Dushanbe, Tajikistan, [7]Regional Climate Group, Department of Earth Sciences, University of Gothenburg, Gothenburg, Sweden

Abstract Changes in the thermal comfort condition of the living environment of human beings are one of the main concerns related to global warming. While previous studies largely focused on mean temperature and warm/cold extremes, changes in thermal comfort conditions (both comfort and discomfort conditions) have not been adequately revealed. Based on climate projections from the Coupled Model Intercomparison Project phase 6 (CMIP6), future thermal comfort conditions over global land using net effective temperature index that considers the aggregate effects of temperature, relative humidity, and wind on human thermal perception were investigated. The focus was on the projected changes in thermal comfort conditions in different regions based on gross domestic product per capita, an indicator of adaptive capacity. An inequitable impact of escalating global warming on thermal comfort conditions emerges: in high-income regions (mostly distributed in cool mid-high latitudes), a diminishing number of cold-uncomfortable days and an increasing number of comfort days collectively would contribute to an improvement in thermal comfort conditions; however, in low-income regions (mostly distributed in warmer low latitudes), thermal comfort conditions are expected to worsen as a result of a dramatic increase in the number of warm-uncomfortable days that greatly exceeds the decrease in the number of cold-uncomfortable days and a decrease in the number of comfortable days. Moreover, analysis accounting for population exposure suggests that the overall impact of future changes in thermal comfort conditions on the global population is negative. Therefore, prioritized support for climate mitigation and adaptation to developing nations is justified and urgently needed.

Plain Language Summary In the context of global warming, the number of warm-uncomfortable (cold-uncomfortable) days is expected to increase (decrease). There are various possibilities in the direction of changes in the number of comfortable days, as days that were previously comfortable may become hotter and thus uncomfortable, while days that were previously cold may become comfortable, which motivates in-depth studies. There is also an expectation that cool regions tend to benefit in a warmer world (become more comfortable), while warmer regions are harmed (become too hot). Here we demonstrate that in presently cool mid-high latitudes, a diminishing number of cold-uncomfortable days and an increasing number of comfort days collectively contribute to an improvement in thermal comfort conditions; however, in the warm low latitudes, thermal comfort conditions are expected to worsen as a result of a dramatic increase in the warm-uncomfortable days that greatly exceeds the decrease in the number of cold-uncomfortable days and a decrease in the number of comfortable days. Given that today the wealthiest regions of the world tend to be located in mid-high latitudes, while many of the world's poorest people live in tropical regions. Such changes in thermal comfort conditions are inequitable.

1. Introduction

The thermal environment is related to a range of meteorological factors such as air temperature, humidity, wind, and radiation. The ever-changing thermal environment in the real world, determined by a range of meteorological factors such as air temperature, humidity, and wind, challenges the human body's ability to maintain its core temperature within the range required for optimal comfort, performance, and health (Kjellstrom et al., 2016). Exposure to an extreme thermal environment can lead to the failure of this thermoregulatory mechanism. In a hot

Writing – review & editing: Qinglong You, Guoyu Ren, Safi Ullah, Inom Normatov, Deliang Chen

environment, for instance, the human body may produce or absorb more heat than it dissipates, thus increasing its core temperature to values that can potentially cause discomfort, heat-related illnesses, and ultimately death (Kovats & Hajat, 2008; Sailor et al., 2019). Furthermore, mild weather, which describes a condition that is neither too cold nor too hot (i.e., comfortable), is also of great societal significance; for example, human outdoor activities such as tourism, sports, building construction, and transport can benefit from mild weather (Lin et al., 2019; van der Wiel et al., 2017; Zhang, You, Ren, et al., 2022).

Previous studies have developed a few biometeorological indices that describe the human perception of heat and cold based on a combination of meteorological elements, and these indices provide a more reasonable solution for quantifying past and future changes in the thermal comfort conditions as opposed to simply using air temperature alone (de Freitas & Grigorieva, 2015; Schwingshackl et al., 2021).

The earth has been experiencing unprecedentedly rapid warming since the 20th century, and this trend is projected to continue in the coming decades (IPCC, 2021). Thermal comfort conditions are expected to change accordingly in the context of warming. An increase in the number of hot days and simultaneously a decrease in the number of cold days is not surprising under future global warming, although asymmetries in magnitude may be evident (J. Li et al., 2018). However, there are multiple possibilities for changes in mild weather, as days that were previously comfortable may become hotter, while days that were previously cold may become comfortable. Thus, future changes in overall thermal comfort conditions may exhibit remarkable differences across regions and should be examined in a closer inspection.

According to previous studies, the potential for compound heat-humidity extremes to cause unprecedented discomfort conditions under a warming climate is an issue of growing concern (e.g., Luo & Lau, 2021; Raymond et al., 2020; Sherwood & Huber, 2010; Sylla et al., 2018; F. Wang & Zhang, 2019). The number of cold discomfort days is projected to decrease (Gao et al., 2018; J. Li et al., 2018; W. Li et al., 2022; Zhang, You, Ren, et al., 2022; Zhang, You, Wu, et al., 2022), although extreme cold events are likely to persist across continents even under the 21st-century warming scenarios (Kodra et al., 2011; Zhu et al., 2019). Besides, compared with the efforts focused on the change of mean climate state and climate extremes, less attention has been paid to the behavior of mild weather. Only a few studies have shown a slight global mean decrease in the annual number of mild days projected in the future, but with divergent responses at regional scales (van der Wiel et al., 2017; Zhang, Ren, & You, 2022; Zhang, You, Wu, et al., 2022). Although the above studies project changes in thermal comfort conditions in a warmer future from various perspectives, how thermal comfort conditions across the globe respond to elevating global warming has not yet been quantified within a unified framework. For example, a common view is that the presently cool regions tend to benefit in a warmer world (become more comfortable), while the warm regions are harmed (become too hot), but this view has yet to be confirmed. Such information is essential for climate change adaptation planning but is currently limited.

The inequality of climate change is also of particular concern. There is growing evidence that poorer countries are more negatively affected by a changing climate, either because they will experience greater changes in local climate and/or because they are less able to adapt to climate change (Ahmadalipour et al., 2019; Diffenbaugh & Burke, 2019; King & Harrington, 2018; Shiogama et al., 2019). Given that developed countries are responsible for the vast majority of historical greenhouse gas emissions, any clear evidence of inequality in the impacts of climate change raises critical international justice issues. The wealthiest regions of the world are concentrated in mid-high latitudes, while many of the world's poorest people live in tropical regions. Multiple studies prove that the most perceptible climate changes in the future would generally occur in tropical regions, based on the signal-to-noise ratio approach (King et al., 2015; Mahlstein et al., 2011; Schleussner et al., 2016). Other studies have also shown that low-income regions are expected to face significantly higher risks of facing extreme heat events compared to high-income regions (Alizadeh et al., 2022; Harrington et al., 2016; Lee et al., 2021; Ullah et al., 2022; F. Wang et al., 2022). These results highlight the negative impacts of climate change, such as severe losses of labor productivity (Kjellstrom et al., 2009; Orlov et al., 2020) and increasing morbidity and mortality from heat-related illness (Ahmadalipour et al., 2019; Mora et al., 2017), may fall mostly on low-income populations that are least capable of adapting. It has also been suggested that some high-income countries in cool regions could benefit from additional warming, while most low-income countries are likely to suffer, based on the combination of empirical evidence and projections of future climate change (Burke et al., 2015; Diffenbaugh & Burke, 2019). An accompanying reasonable hypothesis is that high-income countries in cool regions will benefit from an improvement in thermal comfort conditions in a warmer future, but vice versa for low-income countries in the tropics. However, this hypothesis about the inequality of climate change has yet to be proven.

Table 1
Basic Information on the Five Global Climate Models Adopted in the Present Study

Model name	Modeling center	Reference
GFDL-ESM4	Geophysical Fluid Dynamics Laboratory, Princeton (USA)	Dunne et al. (2020)
IPSL-CM6A-LR	Pierre Simon Laplace Institute (France)	Boucher et al. (2020)
MPI-ESM1-2-HR	Max Planck Institute for Meteorology (Germany)	Müller et al. (2018)
MRI-ESM2-0	Meteorological Research Institute (Japan)	Yukimoto et al. (2019)
UKESM1-0-LL	Met Office Hadley Center (UK)	Sellar et al. (2019)

Given the context, the present study aims to quantify future changes in the numbers of comfortable and warm/cold-uncomfortable days over the global land within a unified framework, based on projections from an ensemble of the latest generation of global climate models (GCMs). Whether the hypothesis that cool regions become more comfortable and warmer regions become more uncomfortable holds in a warmer future will be examined. In addition to investigating spatiotemporal patterns, special attention is given to the potential relationship between changes in thermal comfort conditions and wealth, which may imply inequality. Given that the change in thermal comfort conditions is primarily relevant to the human habitat, our analysis also accounts for exposure as measured by distributed population amount scenarios. To the best of our knowledge, the present study is an early attempt to reveal a holistic image of the response of changes in thermal comfort conditions to future global warming, and the results are expected to be instructive for climate change mitigation and adaptation planning.

2. Data and Methods

2.1. Data Description

Daily climatic data during the historical (1850–2014) and future periods (2015–2100) were obtained from five GCMs (Table 1) precipitating in the Coupled Model Intercomparison Project phase 6 (CMIP6; Eyring et al., 2016; O'Neill et al., 2016). The raw outputs from the first realization of the five GCMs have been downscaled and bias-corrected by Lange (2019), with a uniform spatial resolution of 0.5° × 0.5°. The models were chosen with due consideration to process representativeness, structural independence, climate sensitivity, and performance in the historical period (Lange, 2021). The bias adjustment and statistical downscaling method successfully adjust the simulated data to match the observation more closely than the raw GCM data, but still preserves the global warming trend and the climate sensitivities of the GCMs, which ensures the credibility of the simulated data (Hempel et al., 2013; Lange, 2019). Historical simulations and future projections under Shared Socioeconomic Pathway (SSP) 1–2.6, 3–7.0, and 5–8.5 scenarios are available.

Spatially explicit global population and gross domestic product (GDP) data during 2010–2100 under SSP1–3 scenarios were derived from Jiang et al. (2022), with a spatial resolution of 0.5° × 0.5° (Figures S1 and S2 in Supporting Information S1). This includes population and GDP projections from the International Institute for Applied Systems Analysis (Kc & Lutz, 2017) and the Organization for Economic Cooperation and Development (Dellink et al., 2017), respectively. Note that the above results are biased in the estimation of population and GDP in China, according to the new fertility policy and new parameters from the latest Chinese census. Hence the results about China are replaced by the projections from Huang et al. (2019). The assumptions for SSP1–3 scenarios are summarized as follows: SSP1 envisions a society with low population growth and rapid social and economic development, whereas SSP3 corresponds to a society with low-income growth and relatively high population growth rates in the currently high fertility countries. SSP2 describes a world assuming that demographic outcomes are consistent with middle-of-the-road expectations about population growth and spatial patterns of development (Jones & O'Neill, 2016).

2.2. Thermal Comfort Metrics

In the present study, thermal comfort conditions were quantified using net effective temperature (NET), which originates from the ET first introduced by Houghten and Yaglou (1923). The original ET seemed exclusively appropriate for hot weather conditions. Further modifications included the effect of winds and extended its use to cold conditions (Hentschel, 1987; Li & Chan, 2000). The presently well-established formula for NET is as follows (Gao et al., 2018; Juzbašić et al., 2022; Wu et al., 2017):

$$\text{NET} = 37 - \frac{37 - T}{0.68 - 0.0014RH + \frac{1}{1.76 + 1.4v^{0.75}}} - 0.29T(1 - 0.01RH) \quad (1)$$

where T, RH, and v are daily mean near-surface temperature (°C), relative humidity (%), and wind speed (m/s), respectively. NET considers the aggregate effects of temperature, relative humidity, and wind on human thermal perception. NET has been successfully applied in different regions of the world and several evaluation criteria have been proposed, here we adopted a commonly used classification of thermal comfort based on the NET values, see Table S1 in Supporting Information S1 (Blazejczyk et al., 2012; Wu et al., 2017). In the present study, a comfortable day is defined when the NET is between 9°C and 23°C; a warm (cold)-uncomfortable day is defined when the NET is above 27°C (below 1°C). We mainly considered the most comfortable and least comfortable parts, which are the most important for the human habitat, while the transition parts were not considered (Zhang, Ren, & You, 2022; Zhang, You, Wu, et al., 2022).

NET is a choice with a balance of accuracy and feasibility. Of the many metrics tested to quantify thermal comfort conditions, NET is found to be the most suitable for operation purposes (Li & Chan, 2000). It is applicable in both hot and cold situations and displays similar sensitivity as wind chill equivalent temperature (Osczevski & Bluestein, 2005) and apparent temperature (Steadman, 1984), the two commonly used indices for cold and hot weather respectively. Moreover, it can be calculated directly from the standard outputs of the climate models. We recognize that mechanistic indicators based on the human heat exchange model are expected to give more accurate results for human thermal comfort conditions due to their rigorous physical basis (Jendritzky et al., 2012); however, the calculation of mechanistic indicators involves many non-conventional meteorological variables (e.g., mean radiation temperature and mean body wind speed), which are computationally expensive and typically cannot be calculated from climate model outputs. If these variables are parameterized uniformly, additional uncertainty may be introduced in the results (Zhang, Ren, & You, 2022; Zhang, You, Wu, et al., 2022). Nevertheless, to test the sensitivity of results to the choice of thermal comfort indicators, we have also reperformed an analysis based on the simplified universal thermal climate index (UTCI; Bröde et al., 2012; Schwingshackl et al., 2021). Detailed information can be found in Text S1 and Table S2 in Supporting Information S1.

To assess the possible effects of individual variables (i.e., temperature, relative humidity, and wind speed) on the changes in thermal comfort conditions, the comfortable/uncomfortable days were recomputed using a method similar to the "factor separation method" (Lin et al., 2019; Wu et al., 2017; Zhang, You, Ren, et al., 2022). In each computation, we allowed one variable to evolve across the time but keep others at the climatological levels (i.e., the mean over the reference period of 1995–2014). Then the change from this new computation can be considered as the contribution of the corresponding variable to the change of comfortable/uncomfortable days.

2.3. Scenarios

In contrast to traditional approaches that presuppose ideal emission scenarios (e.g., Representative Concentration Pathways; van Vuuren et al., 2011), one may be more concerned with how different characteristics of regional climate change relative to mean global warming (James et al., 2017; Seneviratne et al., 2016; J. Zhang & Wang, 2022; W. Zhang & Zhou, 2020; You et al., 2022). Therefore, here we did not directly investigate climate change under the CMIP6 SSP emission scenarios. Instead, we investigate changes in thermal comfort conditions with 2°C, 3°C, and 4°C global warming levels based on CMIP6 simulations. Among them, 2°C warming is the long-term temperature control target set out in the Paris Agreement (United Nations, 2015), and 3°C warming is similar to late-century warming projected based on current mitigation policies (Raftery et al., 2017; J. Zhang et al., 2020), and 4°C warming is closer to the "business-as-usual" scenario (X. Wang et al., 2018). Following the recommendation of King et al. (2017), we determined the scenario of 2°C global warming above the pre-industrial baseline for all years within decades in the SSP3–7.0 and SSP5–8.5 simulations when decadal-average temperatures are between 1.8°C and 2.2°C warmer than the pre-industrial baseline (1861–1880). The scenarios of 3°C and 4°C global warming levels can also be determined similarly but for decadal-average temperatures at 2.8°C–3.2°C and 3.8°C–4.2°C above the pre-industrial baseline, respectively (Figure S3 in Supporting Information S1). The reference period in the present study is 1995–2014. Given that many climate indicators scale linearly with global mean temperature (GMT; Seneviratne et al., 2016), our analysis also accounts for changes in global and regional thermal comfort conditions as a function of GMT, following

10.1029/2022EF003109

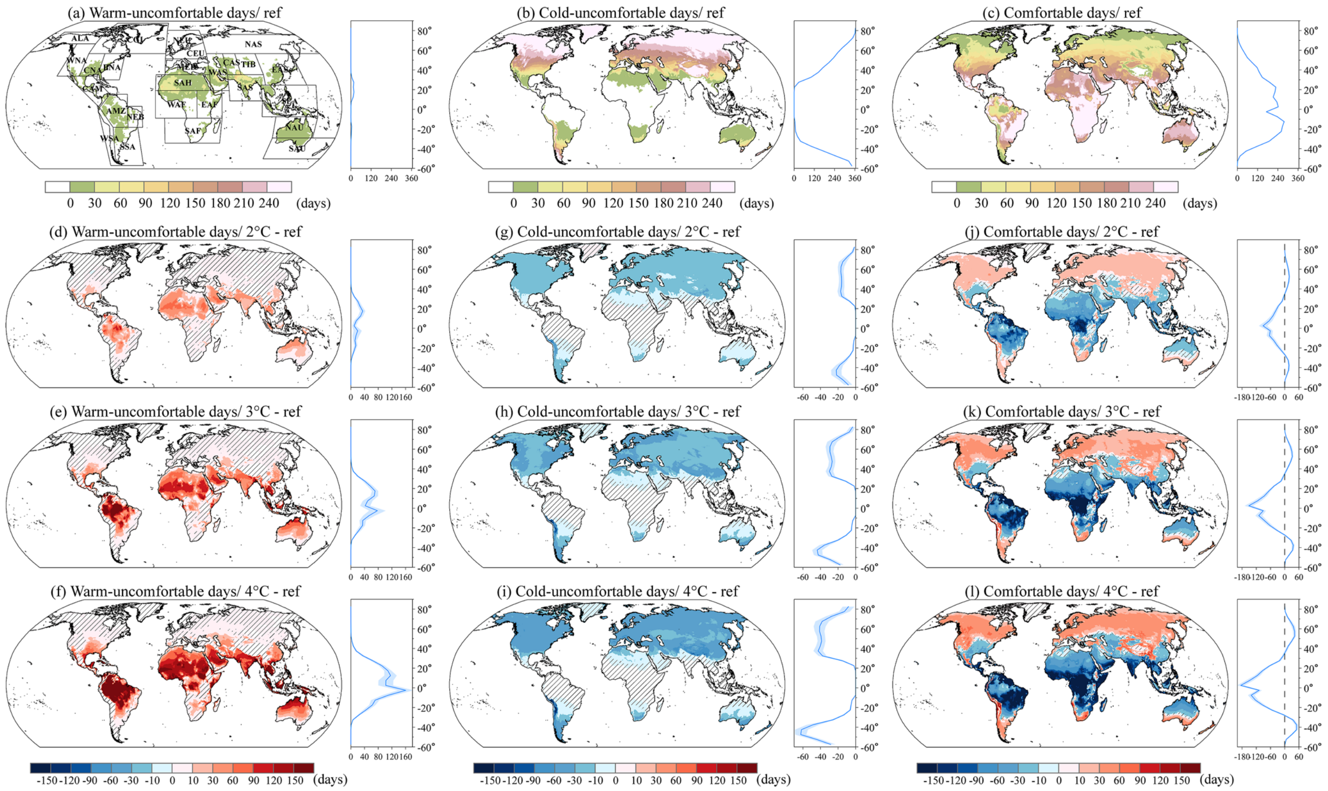

Figure 1. Spatial pattern of the climatology of the numbers of warm-uncomfortable, cold-uncomfortable, and comfortable days for the reference period (a–c), and their future changes (d–l) associated with 2°C, 3°C, and 4°C global warming levels relative to the reference period (1995–2014). Zonal averages are presented as the curves to the right of each panel, where the solid line and shading indicate the multi-model mean and ± one standard deviation range, respectively. The statistical significance of changes in the number of comfortable/uncomfortable days is evaluated using Wilcoxon's rank-sum test imposing $p < 0.05$. The signal of the multi-model ensemble mean is the mean signal of the five ensemble members. If at least one significant individual signal differs in the sign of the projected change, it is considered uncertain (hatching with backslash "\"); else if the uncertainty condition is not fulfilled and less than half of the individual signals are significant, it is considered as negligible (hatching with forward-slash "/"); otherwise, the ensemble mean signals are referred to as robust. The definition of the 26 SREX regions in panel (a) refers to Table S3 in Supporting Information S1.

the method of Schwingshackl et al. (2021). Note that our results regarding specific global warming levels represent a transient response, which is different from the stabilized response at the same global warming level (King et al., 2020; Zhang, You, Wu, et al., 2022; You et al., 2022).

We employed GDP per capita for the reference year 2010 as an indicator of adaptive capacity, to analyze the heterogeneity of potential changes in thermal comfort conditions in regions for different levels of wealth. The relative percentile of GDP per capita for each grid point (Figure S1b in Supporting Information S1) is assumed to be fixed into the future, as in Lee et al. (2021). Our analysis also accounts for exposure as measured by distributed population amount scenarios. According to Jones et al. (2015), population exposure to different thermal comfort conditions (i.e., comfortable/uncomfortable weather) is defined as the product of population counts with comfortable/uncomfortable days at each grid cell. Following previous studies (Z. Liu et al., 2017; Y. Liu et al., 2020; F. Wang et al., 2022), a low, moderate, and high GHG concentration scenario is paired with SSP1, SSP2, and SSP3, respectively. The 2°C, 3°C, and 4°C global warming scenarios generally correspond to low, moderate, and high GHG concentration scenarios, respectively. The combination of 2°C global warming and SSP1 represents the most sustainable future projection. By contrast, the combination of 4°C global warming and SSP3 represents the worst projected climatic and socioeconomic conditions. The combination of 3°C global warming and SSP2 reflects an intermediate pathway between 2°C global warming-SSP1 and 4°C global warming-SSP3. In addition to examining changes in the number of comfortable/uncomfortable days and their population exposure, we characterized regional features of changes in thermal comfort conditions in 26 regions (Figure 1a and Table S3 in Supporting Information S1) as defined by Intergovernmental Panel on Climate Change Special Report on Extreme Events (SREX; Seneviratne et al., 2012), nine of which were highlighted (Figure 1a; Schwingshackl et al., 2021): the five most populated regions in the world (southern Asia [SAS], EAS, and SEA in Asia, WAF, and EAF in Africa) and the two most populated regions in Europe (MED and CEU) and America (CAM and ENA).

3. Results

3.1. Changes in the Number of Comfortable/Uncomfortable Days Relative to the Reference Period

Before projecting future changes, the climatology of thermal comfort conditions in the reference period (1995–2014) was investigated. The spatial pattern of annual warm-comfortable, cold-uncomfortable, and comfortable days in the reference period are displayed in Figures 1a–1c. Cold-uncomfortable weather is widely distributed in the area of mid-high latitudes and high altitudes, such as the Tibetan Plateau and the Andes, while warm-uncomfortable weather is only sporadically distributed in low latitudes. The spatial pattern of comfortable weather is relatively complex, with the highest frequency located in parts of sub-Saharan Africa, Central and South America, southeastern Asia (SEA), and Australia, and the highest frequency located in high latitudes and/or high altitudes. In terms of zonal averages, the numbers of comfort days in low latitudes are generally higher than those in mid-high latitudes, but they are relatively low near the equator.

The signals of an increase in the number of warm-uncomfortable days and a decrease in the number of cold-uncomfortable days are projected to significantly enhance in a warmer future. The number of warm-uncomfortable days in the future is expected to substantially increase, especially in low latitudes (Figures 1d–1f). A robust increase in the number of warm-uncomfortable days is projected in western, southern, and SEA, parts of eastern Asia, and most regions of Africa, South America, and Australia, based on the multi-model ensemble. However, the characteristics of changes in the number of cold-uncomfortable days are considerably different from those of warm-uncomfortable days. Under future scenarios, a wide area above 25° latitude is projected to experience a robust decrease in the number of cold-uncomfortable days, and this change is less spatially heterogeneous relative to the change in warm-uncomfortable days (Figures 1g–1i). Changes in the number of warm-uncomfortable days are characterized by a greater magnitude (up to more than 160 days near the equator under the scenario of 4°C global warming) but a narrower distribution, while changes in cold-uncomfortable days are characterized by a smaller magnitude (typically up to no more than 60 days under the same scenario) but a wider distribution (Figures 1d–1i). This asymmetry has a clear impact on the overall change in thermal comfort conditions.

Changes in the number of comfortable days are a little more complicated. The global average number of comfortable days is projected to decrease slightly in a warmer future, but changes vary markedly across regions (Figures 1j–1l). In terms of zonal averages, a moderate increase in the number of comfortable days is expected north or south of 30° for the northern and southern hemispheres, respectively, while a remarkable decrease in the number of comfortable days is expected in lower latitudes. Except for a few high-latitude, high-altitude areas, and transition regions, changes in the number of comfortable days are robust, based on the multi-model ensemble. A noteworthy result is that the areas of increasing numbers of warm-uncomfortable days and decreasing numbers of comfortable days are roughly coincident, for example, large areas in South America, Africa, and low latitude regions of Asia experiencing a sharp decrease in the number of comfortable days (up to more than 150 days under the scenario of 4°C global warming). Such a phenomenon highlights the worsening of thermal comfort conditions in low latitudes.

The multi-model mean evolution of changes in the number of comfortable/uncomfortable days as a function of GMT for the global and the nine selected SREX regions is shown in Figure 2. In the GMT range covered by all models in the period 1995–2100 (see solid lines), the increase in the number of warm-uncomfortable days accelerates as global warming intensifies, with this phenomenon most prominent in SEA, but the decrease in the number of cold-uncomfortable days with increasing GMT is quasi-linear for both global and regional averages. In addition, the global average number of comfortable days is projected to decrease quasi-linearly with increasing GMT, but changes markedly across regions. At very high GMT changes (see dashed lines), there are large differences in the changes in the number of comfort/uncomfortable days in several regions, which can be attributed to the diverging trends in different models and the decreasing model number toward higher GMT levels (Schwingshackl et al., 2021). Note that the results displayed in Figure 2 are derived from SSP5–8.5 simulations, but similar results can be obtained from SSP3–7.0 simulations (Figure S4 in Supporting Information S1), which supports our findings. This phenomenon that the GMT-based response is broadly independent of the emissions scenarios has also been reported in previous studies (e.g., Seneviratne & Hauser, 2020; W. Zhang & Zhou, 2020).

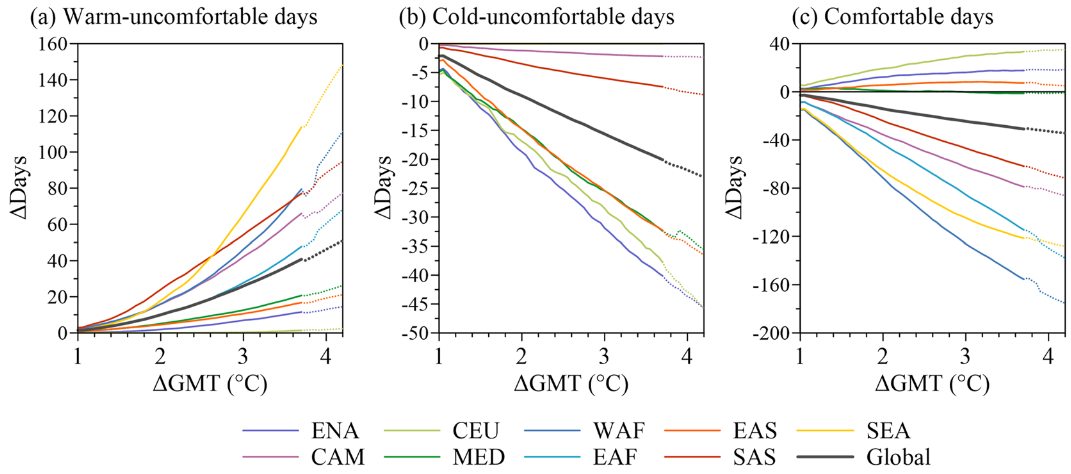

Figure 2. Changes in global and regional numbers of warm-uncomfortable, cold-uncomfortable, comfortable days, and overall comfort index (defined as comfortable days minus the sum of warm- and cold-uncomfortable days) relative to the reference period as a function of global mean temperature rise above pre-industrial baseline (ΔGMT). The above results are derived from SSP5–8.5 simulations and are based on the multi-model means. Solid lines indicate the evolution of comfortable/uncomfortable days in the ΔGMT range for which all models are available, and dashed lines indicate a reduced model set. Meaning of the abbreviations in legend: SAS = southern Asia, EAS = eastern Asia, SEA = southeastern Asia, WAF = West Africa, EAF = East Africa, MED = southern Europe/the Mediterranean, CEU = Central Europe, CAM = Central America, ENA = eastern North America.

In summary, there is a moderate decrease in the number of cold-uncomfortable days in most regions, a prominent increase in the number of warm-uncomfortable days concentrated in low latitudes, and a general decrease in the number of comfortable days in low latitudes but an increase in mid-high latitudes. The above results suggest a relationship between changes in the number of comfortable/uncomfortable days and the local climatology mean temperature. To illustrate this phenomenon more clearly, we select several regions as typical cases and investigate the shift of probability distribution curves of NET in these regions between the reference period and a warmer future (Figure S5 in Supporting Information S1). In cool regions, such as Central Europe (CEU) and eastern North America (ENA), NET rarely reaches the warm discomfort threshold even under future warming scenarios, but a decrease in the number of cold-uncomfortable days and an increase in the number of comfortable days are evident. However, in warmer regions, such as SAS, the increase in the number of warm-uncomfortable days greatly exceeds the decrease in the number of cold-uncomfortable days (in fact, cold-uncomfortable days are already rare in the reference period); the number of comfortable days decreases too, dominating the worsening of the thermal comfort conditions.

Given that NET is a function of temperature (T), humidity (RH), and wind speed (V), we also evaluate the relative contribution of individual variables including T, RH, and V at the global and regional levels (Figures S6–S8 in Supporting Information S1) to further investigate the dominant factor of changes in thermal comfort conditions. It is found that, at both global and regional levels, T is the dominant factor contributing to the change of comfortable/uncomfortable days, while the contributions of RH and V were generally very small.

We further define an overall comfort index as comfortable days minus the sum of warm- and cold-uncomfortable days, and the change of this index can approximate the change in overall thermal comfort conditions (Zhang, Ren, You, 2022; Zhang, You, Wu, et al., 2022). Changes in the number of comfortable days, warm- and cold-uncomfortable days, as well as changes in the overall comfort index in all 26 SREX regions under the scenarios of 2°C, 3°C, and 4°C global warming levels, are displayed in Figure 3. Generally, in areas where the number of warm-uncomfortable days increases remarkably, the number of comfortable days decreases remarkably; in areas where the number of cold-uncomfortable days decreases remarkably, the number of comfortable days increases in varying degrees. Such coincidences lead to a strong contrast in overall comfort index changes across regions, with the most prominent reductions in warmer tropical regions, such as Amazon (AMZ), Northeast Brazil (NEB), SEA, West Africa (WAF), and East Africa (EAF), and a remarkable increase in cool mid-high latitude regions such as northern Europe (NEU), CEU, northern Asia (NAS), western North America (WNA), and southern Australia/New Zealand (SAU).

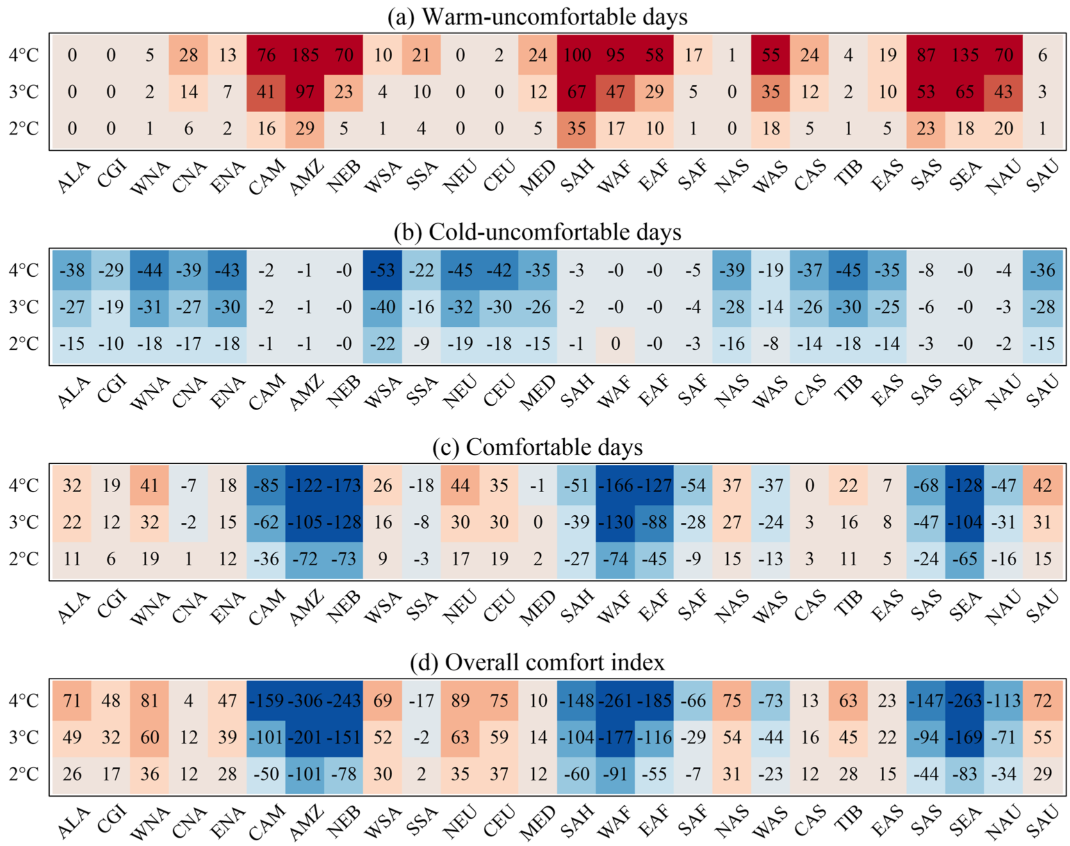

Figure 3. Changes in regional average numbers of warm-uncomfortable days, cold-uncomfortable days, comfortable days, and overall comfort index (defined as comfortable days minus the sum of warm- and cold-uncomfortable days) in 2°C, 3°C, and 4°C warming futures relative to the reference period, based on the multi-model mean. The definition of the 26 regions refers to Table S3 in Supporting Information S1.

3.2. Population Exposure to Comfort/Uncomfortable Weather

In terms of global averages, in the reference period, comfortable weather is the most frequent, followed by cold- and warm-uncomfortable weather. This difference is more evident in the corresponding population exposure, which suggests that most people generally live in comfortable condonations in the current climate (Figures 4a and 4b). However, this pattern is likely to be broken under future scenarios. As noted earlier, some regions are expected to benefit from an increase in the overall comfort index, while others are not. So, will the overall impact of future change on the global population be positive or negative? Here the analysis of future changes in population exposure is performed in two steps (Harrington & Otto, 2018; F. Wang et al., 2022): first, we use the same population (i.e., the reference year 2010) for all warming levels, to show the climatic effect alone (excluding the effect of population growth on exposure changes), and then we use projected population for 2100 under SSP1–3 scenarios to pair the scenarios of 2°C, 3°C, and 4°C global warming levels, respectively (see Section 2.3), to show the combined effect of climate and population changes.

An increase (decrease) in population exposure to warm-uncomfortable (cold-uncomfortable) weather is not surprising, but the asymmetry between them needs further investigation. Changes in the numbers of global average warm- and cold-uncomfortable days in 2, 3, and 4°C warming futures relative to the reference period are 9.9 (−8.9), 25.5 (−15.4), and 47.3 (−21.7) days, respectively, based on the multi-model mean. However, the inclusion of population exposure strongly modulates the climate-only signal. Specifically, if the population is fixed at the 2010 level, the corresponding changes in population exposure are 105.6 (−50.9), 258.7 (−88.9), and 451.5 (−124.4) billion person-days, respectively, that is, the increase of warm-uncomfortable "person-days" is ~3 times greater than the decrease in cold-uncomfortable "person-days" (Figure 4b). This asymmetry is expected to reach a maximum of ~8 times when future population changes are further considered (Figure 4c). The reason for such

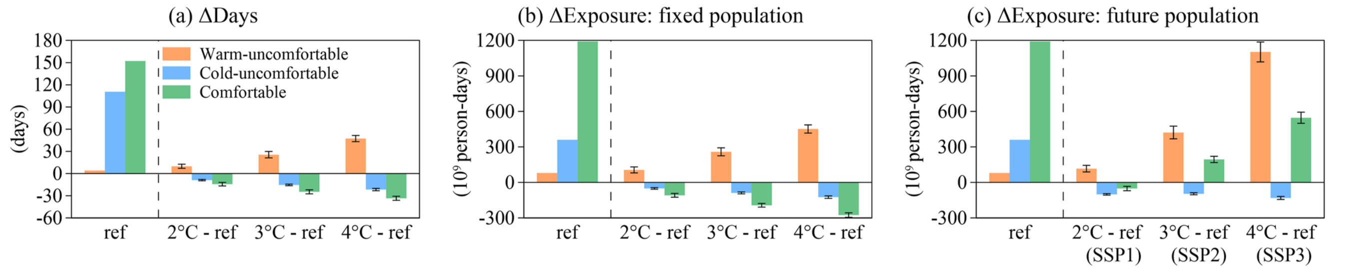

Figure 4. (a) Changes in global average numbers of warm-uncomfortable, cold-uncomfortable, and comfortable days in 2°C, 3°C, and 4°C warming futures relative to the reference period. (b) Changes in global aggregated population exposure to warm-uncomfortable, cold-uncomfortable, and comfortable weather in 2°C, 3°C, and 4°C warming futures relative to the reference period, calculated based on fixed population (2010). (c) Similar to (b), but global aggregated population exposure under future scenarios is calculated based on the projected population (2100) under SSP1–3 scenarios (see Section 2.3). Bars and shadings indicate the multi-model mean and ± one standard deviation range, respectively.

asymmetry is that in low latitudes, the strongly nonlinear increase in warm-uncomfortable days and the rapid population growth (Figure S2 in Supporting Information S1) combine to exacerbate population exposure to warm discomfort conditions, especially at higher levels of warming and under the SSP3 (regional rivalry pathway) scenario; in contrast, the decrease in the number of cold-uncomfortable days is quasi-linear and the population change in mid-to-high latitudes is moderate, which results in a limited decrease in population exposure to cold discomfort conditions.

Although the asymmetry between changes in warm and cold discomfort conditions has been reported in previous studies. As examples, J. Li et al. (2018) point out that the summertime increases in thermal discomfort are expected to outpace the wintertime decreases in thermal discomfort in mid-low latitudes, and J.-T. Zhang, Ren, and You (2022) indicated that the increase in the number of warm-uncomfortable days will outweigh the decrease in cold-uncomfortable days in southeastern China in the late 21st century relative to the current level. However, the impact of future changes in warm/cold discomfort conditions on the population on a global scale was not dealt with in these studies. Here we first present an asymmetry between changes in warm and cold discomfort conditions, where the increase in the former is mainly concentrated in low latitudes and is greater in magnitude, while the decrease in the latter is widely distributed and moderate in magnitude; we then find that the asymmetry of the effect of warm/cold discomfort conditions changes on population is more pronounced. Although climate warming is expected to improve the thermal comfort conditions in cold mid-high latitudes, where typically sparsely populated (even under future scenarios), the benefit from warming in cold regions will not be felt by large segments of the population (Figure 1g–1i and Figure S1 in Supporting Information S1). On the contrary, a considerable population lives in warm regions, which will undergo a substantial worsening of thermal stress, especially under future scenarios with delayed mitigation action and regional rivalry development (Figure 1d–1f and Figure S2 in Supporting Information S1).

The characteristics of future population exposure to comfortable days are a little more complicated. Changes in global average comfortable days in 2°C, 3°C, and 4°C warming futures relative to the reference period are −14.3, −24.8, and −33.5 days, respectively, based on the multi-model mean. If the population is fixed at the 2010 level, the corresponding changes in population exposure are −109.3, −193.4, and −276.3 billion person-days (i.e., −9.2%, −16.2%, and −23.2% of the reference period level), respectively. However, if future population changes are considered, the corresponding changes would be much different, −51.7, 194.2, and 546.6 billion person-days, respectively. Although the comfort conditions respond differentially to the projected warming, the above results (based on the fixed population counts) imply that the global population-weighted changes in comfortable days in a warmer future are still negative. Some of the results showing an increase in the population exposure to comfortable weather when considering future population changes can be explained by the dramatic population growth under these scenarios overwhelming the decrease in the number of comfortable days (Figure 1j–1l and Figure S2 in Supporting Information S1).

In summary, the increase in population exposure to warm-uncomfortable weather is projected to overwhelm the decrease in population exposure to cold-uncomfortable weather, especially under the scenario of higher levels of warming and accompanied by sharp population growth. Changes in population exposure to comfortable weather are generally decreasing moderately, and in some cases considering future population changes, population

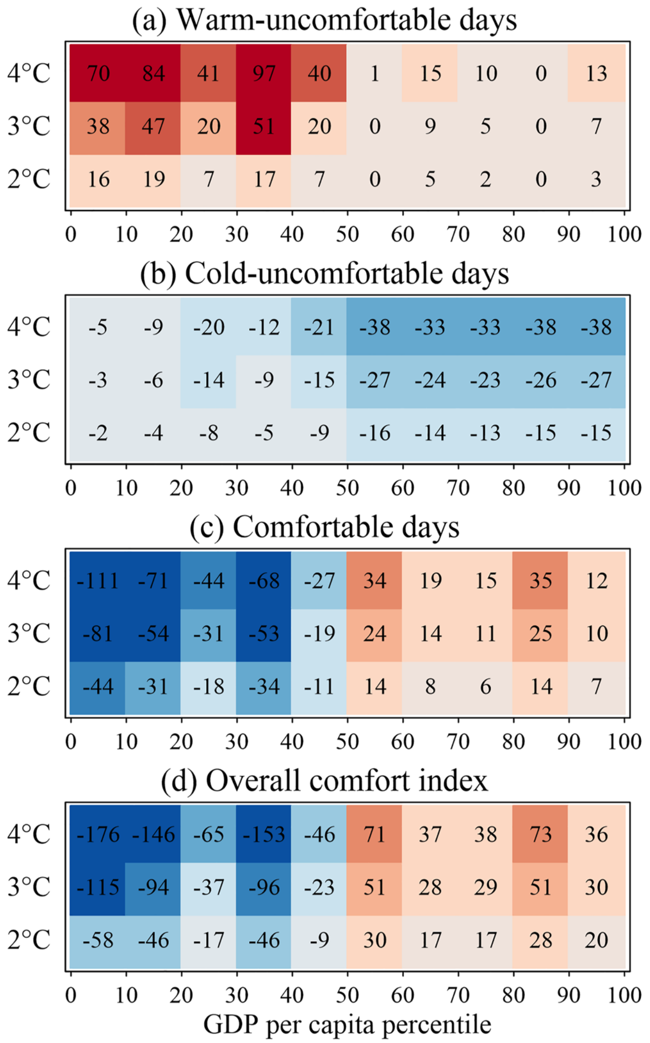

Figure 5. Changes in global average warm-uncomfortable, cold-uncomfortable, comfortable days, and overall comfort index in 2°C, 3°C, and 4°C warming futures relative to the reference period, binned by the percentile of gross domestic product per capita, based on the multi-model mean.

exposure to comfortable weather is expected to increase. However, changes in population exposure to comfort conditions are not sufficient to offset the negative effects of the asymmetric change in population exposure to warm/cold discomfort conditions (Figures 4b and 4c). As a result, the overall impact of future changes in thermal comfort conditions on the global population is negative. This result also illustrates the importance of including exposure (measured here by the population amount) in analyses of impacts.

3.3. Inequality of Global Thermal Comfort Conditions Changes

As noted earlier, the response of thermal comfort conditions to climate warming varies across latitudinal zone (see Section 3.1). Moreover, the high-income regions tend to be located in mid-high latitudes, while many of the low-income regions are located in tropical regions (Figure S1 in Supporting Information S1). A question that arises is how changes in thermal comfort conditions depend on wealth. This issue is important because adaptation to non-stationary climate risks (such as the worsening thermal comfort conditions) is generally more rapid in societies with higher levels of wealth.

To address this issue, changes in the number of comfortable days, warm- and cold-uncomfortable days, as well as the overall comfort index, are grouped into 10 socioeconomic clusters based on the GDP per capita in 2010 (Figure 5). We find that changes in overall comfort index are positive above the 50th percentile of GDP per capita, while those below the 50th percentile of GDP per capita are negative. Further analysis of the causes shows that a remarkable increase in the number of warm-uncomfortable days and a limited decrease in cold-uncomfortable days, as well as a remarkable decrease in the number of comfortable days, dominate the decrease in overall comfort index in the poorest 50%, while a remarkable decrease in the cold-uncomfortable days and a slight decrease in the number of warm-uncomfortable days, as well as a clear increase in the number of comfortable days, dominate the increase in overall comfort index in the wealthiest 50%. The above results indicate that in a warmer future, the thermal comfort conditions would worsen in hot, poor countries—but improve in many cool, wealthy countries.

We recognize that the inequitable impact of projected climate change on heat stress in poor and rich areas has been demonstrated by previous studies. On the one hand, due to geographical differences, heat wave indicators may increase at a greater rate in low-income areas compared to high-income areas. On the other hand, economic factors, which govern access to forecasts of extremes and air conditioning and healthcare facilities, can play a critical role in the translation of heat stress-induced mortality risk into actual mortality occurrence. Lee et al. (2021) reported that the increase in "deadly days" (daily maximum wet bulb temperature exceeding 26°C) and "tropical nights" (daily minimum temperature exceeding 25°C) is broadly greater in lower GDP regions worldwide. Another study focused on the Middle East and North Africa further suggested that the mortality risk from heat stress (measured by risk ratio) is higher in the poorest countries (Ahmadalipour et al., 2019). The projected results of heat stress exposure indicate that areas with the greatest population exposure all have relatively low GDP per capita, except for a sustainable scenario via highly mitigated GHG emissions and low population growth (F. Wang et al., 2022). Alizadeh et al. (2022) further emphasize that the difference in the rate of increase in heatwave exposure in the poorest regions compared to the richest regions will be magnified if macroscopic societal efforts to adapt to thermal impacts are assumed to be proportional to GDP per capita in terms of the rate of adaptation to changing environmental conditions. However, the above studies are limited to warm discomfort conditions. Here we extend it to thermal comfort conditions (both comfort and discomfort conditions). Based on an ensemble of bias-adjusted high-resolution climate projections, we find that there is a substantial increase in the number of warm-uncomfortable days in regions with lower GDP per capita, along with a notable decrease in the number of comfortable days; on the contrary, in regions with higher GDP per capita, a remarkable decrease in cold-uncomfortable days coincides with an increase in comfortable days. Simultaneously, the changes in cold-uncomfortable (warm-uncomfortable) days are comparatively negligible in poorer (wealthier) regions. The overall thermal comfort index is further introduced to quantify the overall effect of the above change (see Figure 5d). Our results highlight that under conceivable scenarios for socioeconomic development over the next few decades the poorest parts of the world will experience more unfavorable changes in thermal comfort than the wealthiest areas. Given the very limited adaptive capacity for uncomfortable weather (e.g., limited access to air conditioning, underdeveloped infrastructure, and less-effective public health systems), the adverse effects of warming on low-income countries will likely be further exacerbated.

Compared to earlier industrialized countries that already emitted a large amount of greenhouse gases, less developed countries with much lower cumulative greenhouse gas emissions are expected to experience greater changes in local mean climate states and disasters, such inequality has been reported (Alizadeh et al., 2022; King & Harrington, 2018; Lee et al., 2021; Shiogama et al., 2019; F. Wang et al., 2022). Building on previous efforts, this study further identifies a link between changes in thermal comfort conditions and inequality. Our results show that, in addition to the direct benefits of fossil fuel use, wealthy countries will likely benefit from the improvement of thermal comfort conditions, but the opposite is true for poor countries. If further mitigation action is not taken to meet the Paris Agreement goals (Raftery et al., 2017; F. Wang et al., 2022), then the most serious negative impact of worsening thermal comfort conditions will be borne by the poorest. In previous studies of equitable mitigation efforts, "GDP per capita" has been used as an indicator of the "Respective Capabilities" (i.e., countries with higher per capita GDP have greater mitigation capability) principles of the United Nations Framework Convention on Climate Change (Clarke et al., 2014; Shiogama et al., 2019). Therefore, our results highlight the importance of developed countries assuming greater responsibility in addressing climate change, as is outlined in the Paris Agreement. Meanwhile, support for climate mitigation and adaptation in developing countries is urgently needed to avoid the worst impacts of climate change and to maintain economic development in these countries.

4. Discussion and Conclusion

Based on statistically downscaled and bias-corrected CMIP6 climate projections, the present study reveals a holistic image of global thermal comfort conditions changes in response to escalating warming, using index NET that considers the combined effects of temperature, relative humidity, and wind speed on human thermal perception.

This study provided strong evidence that cool regions tend to benefit in a warmer world (become more comfortable), while warmer regions are harmed (become too hot). Specifically, we show a quasi-linear decrease in the number of cold-uncomfortable days in most regions and a nonlinear accelerated increase in the number of warm-uncomfortable days in low latitudes as the global average temperature increases. The number of comfortable days in different regions exhibits divergent responses to escalating global warming. There is a clear spatial mismatch in the change of the numbers of comfortable/uncomfortable days: a diminishing number of cold-uncomfortable days and an increasing number of comfort days collectively contribute to an improvement in the overall thermal comfort conditions in mid-high latitudes. Meanwhile, a dramatic increase in the number of warm-uncomfortable days that greatly exceeds the decrease in the number of cold-uncomfortable days, as well as a decrease in the number of comfortable days, would worsen the overall thermal comfort conditions in low latitudes. We further show that changes in thermal comfort conditions are dominated by rising temperatures in the context of warming, with little contribution from relative humidity and wind speed.

Uneven changes in thermal comfort conditions in different regions associated with socioeconomic development are further emphasized in the present study. Since the wealthiest regions of the world tend to be located in mid-high latitudes, while many of the world's poorest people live in low latitudes, the spatial pattern of global thermal comfort conditions changes presented above represents an inequality, as the most severe negative impacts of climate change on thermal comfort conditions is expected to fall mostly on low-income populations that are least capable of adapting. In particular, the dramatic increase in the occurrence of warm-uncomfortable weather coincides with rapid population growth, exacerbating the negative impact of escalating global warming in low latitudes. Moreover, our analysis also accounts for exposure as measured by distributed population amount scenarios, and the results show that the overall thermal comfort conditions are deteriorating from the perspective of population exposure, regardless of the scenarios.

Here we investigate future changes in thermal comfort based on NET, a well-established metric; however, we also recognize that the extent to which the main findings are dependent on the choice of thermal comfort metric needs to be assessed. Given this, we have reperformed our analysis based on UTCI and the main results are considerably consistent with that based on NET, and this consistency adds more confidence to our findings (Figures S9–S11 in Supporting Information S1). While the present study aims to estimate changes in thermal comfort conditions in a consistent way across broad expanses of the globe, we recognize that the thresholds of NET for the different comfort categories should probably be adjusted in different regions because populations in different climate zones have different adaptations to heat/cold stress (Gao et al., 2018). Subject to the coarse resolution of the GCM, the urban heat island effect is also not considered here, which may have a significant impact on human thermal comfort because many people live in large megacities (Ren et al., 2022; P. Wang et al., 2021; Zhao et al., 2021). Another limitation of the present study is the use of climate projections from a limited number of CMIP6 GCMs. While the use of a subset of high-resolution climate model output is consistent with many climate change impact studies (e.g., Jones et al., 2015; Y. Liu et al., 2020; F. Wang et al., 2022), we recognize that five models cannot fully represent the range of outcomes (potentially) present in the full suite of CMIP6 GCMs (Ito et al., 2020; McSweeney & Jones, 2016), although as noted we find the pattern of changes in thermal comfort conditions, and the relationship between changes in thermal comfort conditions and GDP per capita, are similar across all five models (Figures S12 and S13 in Supporting Information S1), suggesting that the overall results presented here are robust to the inclusion of a larger suite of models.

Despite some uncertainties, our work demonstrates that the stress associated with climate warming can pose a serious threat to humans, especially those in low-income countries. Effective measures taken for adapting to and mitigating global climate warming can considerably avoid the adverse impact of these projected changes.

Data Availability Statement

The statistically downscaled and bias-corrected climatic data from GCMs are available online (https://data.isimip.org/search/simulation_round/ISIMIP3b/product/InputData/climate_scenario/historical/climate_scenario/ssp370/climate_scenario/ssp585/climate_forcing/gfdl-esm4/climate_forcing/ipsl-cm6a-lr/climate_forcing/mpi-esm1-2-hr/climate_forcing/mri-esm2-0/climate_forcing/ukesm1-0-ll/climate_variable/tas/climate_variable/hurs/climate_variable/sfcwind/). The population and GDP data under SSP scenarios are available online (https://doi.org/10.57760/sciencedb.01683).

Acknowledgments

This study is supported by the National Key Research and Development Program of China (2022YFF0801703), National Natural Science Foundation of China (41971072) and the Research Fund for International YoungScientists of the National Natural Science Foundation of China (42150410381). We sincerely thank two anonymous reviewers for their excellent comments and suggestions. We also thank the climate modeling groups for producing and making available their model output.

References

Ahmadalipour, A., Moradkhani, H., & Kumar, M. (2019). Mortality risk from heat stress expected to hit poorest nations the hardest. *Climatic Change*, *152*(3–4), 569–579. https://doi.org/10.1007/s10584-018-2348-2

Alizadeh, M. R., Abatzoglou, J. T., Adamowski, J. F., Prestemon, J. P., Chittoori, B., Akbari Asanjan, A., & Sadegh, M. (2022). Increasing heat-stress inequality in a warming climate. *Earth's Future*, *10*(2), e2021EF002488. https://doi.org/10.1029/2021EF002488

Blazejczyk, K., Epstein, Y., Jendritzky, G., Staiger, H., & Tinz, B. (2012). Comparison of UTCI to selected thermal indices. *International Journal of Biometeorology*, *56*(3), 515–535. https://doi.org/10.1007/s00484-011-0453-2

Boucher, O., Servonnat, J., Albright, A. L., Aumont, O., Balkanski, Y., Bastrikov, V., et al. (2020). Presentation and evaluation of the IPSL-CM6A-LR climate model. *Journal of Advances in Modeling Earth Systems*, *12*(7), e2019MS002010. https://doi.org/10.1029/2019MS002010

Bröde, P., Fiala, D., Błażejczyk, K., Holmér, I., Jendritzky, G., Kampmann, B., et al. (2012). Deriving the operational procedure for the universal thermal climate index (UTCI). *International Journal of Biometeorology*, *56*(3), 481–494. https://doi.org/10.1007/s00484-011-0454-1

Burke, M., Hsiang, S. M., & Miguel, E. (2015). Global non-linear effect of temperature on economic production. *Nature*, *527*(7577), 235–239. https://doi.org/10.1038/nature15725

Clarke, L., Jiang, K., Akimoto, K., Babiker, M., Blanford, G., Fisher-Vanden, K., et al. (2014). Summary for policymakers. In *Climate change 2014: Mitigation of climate change*. Cambridge University Press. https://doi.org/10.1017/CBO9781107415416.005

de Freitas, C. R., & Grigorieva, E. A. (2015). A comprehensive catalogue and classification of human thermal climate indices. *International Journal of Biometeorology*, *59*(1), 109–120. https://doi.org/10.1007/s00484-014-0819-3

Dellink, R., Chateau, J., Lanzi, E., & Magné, B. (2017). Long-term economic growth projections in the shared socioeconomic pathways. *Global Environmental Change*, *42*, 200–214. https://doi.org/10.1016/j.gloenvcha.2015.06.004

Diffenbaugh, N. S., & Burke, M. (2019). Global warming has increased global economic inequality. *Proceedings of the National Academy of Sciences*, *116*(20), 9808–9813. https://doi.org/10.1073/pnas.1816020116

Dunne, J. P., Horowitz, L. W., Adcroft, A. J., Ginoux, P., Held, I. M., John, J. G., et al. (2020). The GFDL Earth system model version 4.1 (GFDL-ESM 4.1): Overall coupled model description and simulation characteristics. *Journal of Advances in Modeling Earth Systems*, *12*(11), e2019MS002015. https://doi.org/10.1029/2019MS002015

Eyring, V., Bony, S., Meehl, G. A., Senior, C. A., Stevens, B., Stouffer, R. J., & Taylor, K. E. (2016). Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization. *Geoscientific Model Development*, *9*(5), 1937–1958. https://doi.org/10.5194/gmd-9-1937-2016

Gao, X.-J., Wu, J., Shi, Y., Wu, J., Han, Z.-Y., Zhang, D.-F., et al. (2018). Future changes in thermal comfort conditions over China based on multi-RegCM4 simulations. *Atmospheric and Oceanic Science Letters*, *11*(4), 291–299. https://doi.org/10.1080/16742834.2018.1471578

Harrington, L. J., Frame, D. J., Fischer, E. M., Hawkins, E., Joshi, M., & Jones, C. D. (2016). Poorest countries experience earlier anthropogenic emergence of daily temperature extremes. *Environmental Research Letters*, *11*(5), 055007. https://doi.org/10.1088/1748-9326/11/5/055007

Harrington, L. J., & Otto, F. E. L. (2018). Changing population dynamics and uneven temperature emergence combine to exacerbate regional exposure to heat extremes under 1.5°C and 2°C of warming. *Environmental Research Letters*, *13*(3), 034011. https://doi.org/10.1088/1748-9326/aaaa99

Hempel, S., Frieler, K., Warszawski, L., Schewe, J., & Piontek, F. (2013). A trend-preserving bias correction—The ISI-MIP approach. *Earth System Dynamics*, *4*(2), 219–236. https://doi.org/10.5194/esd-4-219-2013

Hentschel, G. A. (1987). A human biometeorology classification of climate for large and local scales. In *Proceeding of WMO/HMO/UNEP symposium on climate and human health. WCPA-No.1*. World Meteorological Organization.

Houghten, F. C., & Yaglou, C. P. (1923). Determining lines of equal comfort. *Transactions of the American Society of Heating and Ventilating Engineers*, *29*, 165–176.

Huang, J., Qin, D., Jiang, T., Wang, Y., Feng, Z., Zhai, J., et al. (2019). Effect of fertility policy changes on the population structure and economy of China: From the perspective of the shared socioeconomic pathways. *Earth's Future*, *7*(3), 250–265. https://doi.org/10.1029/2018EF000964

IPCC. (2021). Summary for policymakers. In V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, et al. (Eds.), *Climate change 2021: The physical science basis. Contribution of working group I to the sixth assessment report of the intergovernmental panel on climate change* (pp. 3–32). Cambridge University Press. https://doi.org/10.1017/9781009157896.001.3

Ito, R., Shiogama, H., Nakaegawa, T., & Takayabu, I. (2020). Uncertainties in climate change projections covered by the ISIMIP and CORDEX model subsets from CMIP5. *Geoscientific Model Development*, *13*(3), 859–872. https://doi.org/10.5194/gmd-13-859-2020

James, R., Washington, R., Schleussner, C.-F., Rogelj, J., & Conway, D. (2017). Characterizing half-a-degree difference: A review of methods for identifying regional climate responses to global warming targets: Characterizing half-a-degree difference. *Wiley Interdisciplinary Reviews: Climate Change*, *8*(2), e457. https://doi.org/10.1002/wcc.457

Jendritzky, G., de Dear, R., & Havenith, G. (2012). UTCI—Why another thermal index? *International Journal of Biometeorology*, *56*(3), 421–428. https://doi.org/10.1007/s00484-011-0513-7

Jiang, T., Su, B., Wang, Y., Wang, G., Luo, Y., Zhai, J., et al. (2022). Gridded datasets for population and economy under shared socioeconomic pathways for 2020–2100. *Climate Change Research*, *18*(3), 381–383. https://doi.org/10.12006/j.issn.1673-1719.2022.106

Jones, B., & O'Neill, B. C. (2016). Spatially explicit global population scenarios consistent with the Shared Socioeconomic Pathways. *Environmental Research Letters*, *11*(8), 084003. https://doi.org/10.1088/1748-9326/11/8/084003

Jones, B., O'Neill, B. C., McDaniel, L., McGinnis, S., Mearns, L. O., & Tebaldi, C. (2015). Future population exposure to US heat extremes. *Nature Climate Change*, *5*(7), 652–655. https://doi.org/10.1038/nclimate2631

Juzbašić, A., Ahn, J., Cha, D., Chang, E., & Min, S. (2022). Changes in heat stress considering temperature, humidity, and wind over East Asia under RCP8.5 and SSP5-8.5 scenarios. *International Journal of Climatology*, *42*(12), 7636–6595. https://doi.org/10.1002/joc.7636

Kc, S., & Lutz, W. (2017). The human core of the shared socioeconomic pathways: Population scenarios by age, sex and level of education for all countries to 2100. *Global Environmental Change*, *42*, 181–192. https://doi.org/10.1016/j.gloenvcha.2014.06.004

King, A. D., Donat, M. G., Fischer, E. M., Hawkins, E., Alexander, L. V., Karoly, D. J., et al. (2015). The timing of anthropogenic emergence in simulated climate extremes. *Environmental Research Letters*, *10*(9), 094015. https://doi.org/10.1088/1748-9326/10/9/094015

King, A. D., & Harrington, L. J. (2018). The inequality of climate change from 1.5 to 2°C of global warming. *Geophysical Research Letters*, *45*(10), 5030–5033. https://doi.org/10.1029/2018GL078430

King, A. D., Karoly, D. J., & Henley, B. J. (2017). Australian climate extremes at 1.5°C and 2°C of global warming. *Nature Climate Change*, *7*(6), 412–416. https://doi.org/10.1038/nclimate3296

King, A. D., Lane, T. P., Henley, B. J., & Brown, J. R. (2020). Global and regional impacts differ between transient and equilibrium warmer worlds. *Nature Climate Change*, *10*(1), 42–47. https://doi.org/10.1038/s41558-019-0658-7

Kjellstrom, T., Briggs, D., Freyberg, C., Lemke, B., Otto, M., & Hyatt, O. (2016). Heat, human performance, and occupational health: A key issue for the assessment of global climate change impacts. *Annual Review of Public Health*, *37*(1), 97–112. https://doi.org/10.1146/annurev-publhealth-032315-021740

Kjellstrom, T., Holmer, I., & Lemke, B. (2009). Workplace heat stress, health and productivity—An increasing challenge for low and middle-income countries during climate change. *Global Health Action*, *2*(1), 2047. https://doi.org/10.3402/gha.v2i0.2047

Kodra, E., Steinhaeuser, K., & Ganguly, A. R. (2011). Persisting cold extremes under 21st-century warming scenarios. *Geophysical Research Letters*, *38*(8), L08705. https://doi.org/10.1029/2011GL047103

Kovats, R. S., & Hajat, S. (2008). Heat stress and public health: A critical review. *Annual Review of Public Health*, *29*(1), 41–55. https://doi.org/10.1146/annurev.publhealth.29.020907.090843

Lange, S. (2019). Trend-preserving bias adjustment and statistical downscaling with ISIMIP3BASD (v1.0). *Geoscientific Model Development*, *12*(7), 3055–3070. https://doi.org/10.5194/gmd-12-3055-2019

Lange, S. (2021). ISIMIP3b bias adjustment fact sheet. Retrieved from https://www.isimip.org/gettingstarted/isimip3b-bias-adjustment/

Lee, J., Mast, J. C., & Dessler, A. E. (2021). The effect of forced change and unforced variability in heat waves, temperature extremes, and associated population risk in a CO_2-warmed world. *Atmospheric Chemistry and Physics*, *21*(15), 11889–11904. https://doi.org/10.5194/acp-21-11889-2021

Li, J., Chen, Y. D., Gan, T. Y., & Lau, N.-C. (2018). Elevated increases in human-perceived temperature under climate warming. *Nature Climate Change*, *8*(1), 43–47. https://doi.org/10.1038/s41558-017-0036-2

Li, P. W., & Chan, S. T. (2000). Application of a weather stress index for alerting the public to stressful weather in Hong Kong. *Meteorological Applications*, *7*(4), 369–375. https://doi.org/10.1017/S1350482700001602

Li, W., Hao, X., Wang, L., Li, Y., Li, J., Li, H., & Han, T. (2022). Detection and attribution of changes in thermal discomfort over China during 1961–2014 and future projections. *Advances in Atmospheric Sciences*, *39*(3), 456–470. https://doi.org/10.1007/s00376-021-1168-x

Lin, L., Ge, E., Chen, C., & Luo, M. (2019). Mild weather changes over China during 1971–2014: Climatology, trends, and interannual variability. *Scientific Reports*, *9*(1), 2419. https://doi.org/10.1038/s41598-019-38845-8

Liu, Y., Chen, J., Pan, T., Liu, Y., Zhang, Y., Ge, Q., et al. (2020). Global socioeconomic risk of precipitation extremes under climate change. *Earth's Future*, *8*(9), 803–807. https://doi.org/10.1029/2019EF001331

Liu, Z., Anderson, B., Yan, K., Dong, W., Liao, H., & Shi, P. (2017). Global and regional changes in exposure to extreme heat and the relative contributions of climate and population change. *Scientific Reports*, *7*(1), 43909. https://doi.org/10.1038/srep43909

Luo, M., & Lau, N.-C. (2021). Increasing human-perceived heat stress risks exacerbated by urbanization in China: A comparative study based on multiple metrics. *Earth's Future*, *9*(7), e2020EF001848. https://doi.org/10.1029/2020ef001848

Mahlstein, I., Knutti, R., Solomon, S., & Portmann, R. W. (2011). Early onset of significant local warming in low latitude countries. *Environmental Research Letters*, *6*(3), 034009. https://doi.org/10.1088/1748-9326/6/3/034009

McSweeney, C. F., & Jones, R. G. (2016). How representative is the spread of climate projections from the 5 CMIP5 GCMs used in ISI-MIP? *Climate Services*, *1*, 24–29. https://doi.org/10.1016/j.cliser.2016.02.001

Mora, C., Dousset, B., Caldwell, I. R., Powell, F. E., Geronimo, R. C., Bielecki, C. R., et al. (2017). Global risk of deadly heat. *Nature Climate Change*, *7*(7), 501–506. https://doi.org/10.1038/nclimate3322

Müller, W. A., Jungclaus, J. H., Mauritsen, T., Baehr, J., Bittner, M., Budich, R., et al. (2018). A higher-resolution version of the Max Planck Institute Earth system model (MPI-ESM1.2-HR). *Journal of Advances in Modeling Earth Systems*, *10*(7), 1383–1413. https://doi.org/10.1029/2017MS001217

O'Neill, B. C., Tebaldi, C., van Vuuren, D. P., Eyring, V., Friedlingstein, P., Hurtt, G., et al. (2016). The scenario model Intercomparison project (ScenarioMIP) for CMIP6. *Geoscientific Model Development*, *9*(9), 3461–3482. https://doi.org/10.5194/gmd-9-3461-2016

Orlov, A., Sillmann, J., Aunan, K., Kjellstrom, T., & Aaheim, A. (2020). Economic costs of heat-induced reductions in worker productivity due to global warming. *Global Environmental Change*, *63*, 102087. https://doi.org/10.1016/j.gloenvcha.2020.102087

Osczevski, R., & Bluestein, M. (2005). The new wind chill equivalent temperature chart. *Bulletin of the American Meteorological Society*, *86*(10), 1453–1458. https://doi.org/10.1175/BAMS-86-10-1453

Raftery, A. E., Zimmer, A., Frierson, D. M. W., Startz, R., & Liu, P. (2017). Less than 2°C warming by 2100 unlikely. *Nature Climate Change*, *7*(9), 637–641. https://doi.org/10.1038/nclimate3352

Raymond, C., Matthews, T., & Horton, R. M. (2020). The emergence of heat and humidity too severe for human tolerance. *Science Advances*, *6*(19), eaaw1838. https://doi.org/10.1126/sciadv.aaw1838

Ren, Z., Fu, Y., Dong, Y., Zhang, P., & He, X. (2022). Rapid urbanization and climate change significantly contribute to worsening urban human thermal comfort: A national 183-city, 26-year study in China. *Urban Climate*, *43*, 101154. https://doi.org/10.1016/j.uclim.2022.101154

Sailor, D. J., Baniassadi, A., O'Lenick, C. R., & Wilhelmi, O. V. (2019). The growing threat of heat disasters. *Environmental Research Letters*, *14*(5), 054006. https://doi.org/10.1088/1748-9326/ab0bb9

Schleussner, C.-F., Lissner, T. K., Fischer, E. M., Wohland, J., Perrette, M., Golly, A., et al. (2016). Differential climate impacts for policy-relevant limits to global warming: The case of 1.5°C and 2°C. *Earth System Dynamics*, *7*(2), 327–351. https://doi.org/10.5194/esd-7-327-2016

Schwingshackl, C., Sillmann, J., Vicedo-Cabrera, A. M., Sandstad, M., & Aunan, K. (2021). Heat stress indicators in CMIP6: Estimating future trends and Exceedances of impact-relevant thresholds. *Earth's Future*, *9*(3), e2020EF001885. https://doi.org/10.1029/2020EF001885

Sellar, A. A., Jones, C. G., Mulcahy, J. P., Tang, Y., Yool, A., Wiltshire, A., et al. (2019). UKESM1: Description and evaluation of the U.K. Earth system model. *Journal of Advances in Modeling Earth Systems*, *11*(12), 4513–4558. https://doi.org/10.1029/2019MS001739

Seneviratne, S. I., Donat, M. G., Pitman, A. J., Knutti, R., & Wilby, R. L. (2016). Allowable CO_2 emissions based on regional and impact-related climate targets. *Nature*, *529*(7587), 477–483. https://doi.org/10.1038/nature16542

Seneviratne, S. I., & Hauser, M. (2020). Regional climate sensitivity of climate extremes in CMIP6 versus CMIP5 multimodel ensembles. *Earth's Future*, *8*(9), e2019EF001474. https://doi.org/10.1029/2019EF001474

Seneviratne, S. I., Nicholls, N., Easterling, D., Goodess, C. M., Kanae, S., Kossin, J., et al. (2012). Changes in climate extremes and their impacts on the natural physical environment. In C. B. Field, Q. Dahe, T. F. Stocker, & V. Barros (Eds.), *Managing the risks of extreme events and disasters to advance climate change adaptation: Special Report of the intergovernmental panel on climate change* (pp. 109–230). Cambridge University Press. https://doi.org/10.1017/CBO9781139177245.006

Sherwood, S. C., & Huber, M. (2010). An adaptability limit to climate change due to heat stress. *Proceedings of the National Academy of Sciences*, *107*(21), 9552–9555. https://doi.org/10.1073/pnas.0913352107

Shiogama, H., Hasegawa, T., Fujimori, S., Murakami, D., Takahashi, K., Tanaka, K., et al. (2019). Limiting global warming to 1.5°C will lower increases in inequalities of four hazard indicators of climate change. *Environmental Research Letters*, *14*(12), 124022. https://doi.org/10.1088/1748-9326/ab5256

Steadman, R. G. (1984). A universal scale of apparent temperature. *Journal of Climate and Applied Meteorology*, *23*(12), 1674–1687. https://doi.org/10.1175/1520-0450(1984)023<1674:AUSOAT>2.0.CO;2

Sylla, M. B., Faye, A., Giorgi, F., Diedhiou, A., & Kunstmann, H. (2018). Projected heat stress under 1.5°C and 2°C global warming scenarios creates unprecedented discomfort for humans in West Africa. *Earth's Future*, *6*(7), 1029–1044. https://doi.org/10.1029/2018EF000873

Ullah, S., You, Q., Chen, D., Sachindra, D. A., AghaKouchak, A., Kang, S., et al. (2022). Future population exposure to daytime and nighttime heat waves in South Asia. *Earth's Future*, *10*(5), e2021EF002511. https://doi.org/10.1029/2021EF002511

United Nations. (2015). Adoption of the Paris agreement. In *Treaties and agreements*. United Nations Framework Convention on Climate Change.

van der Wiel, K., Kapnick, S. B., & Vecchi, G. A. (2017). Shifting patterns of mild weather in response to projected radiative forcing. *Climatic Change*, *140*(3–4), 649–658. https://doi.org/10.1007/s10584-016-1885-9

van Vuuren, D. P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., et al. (2011). The representative concentration pathways: An overview. *Climatic Change*, *109*(1–2), 5–31. https://doi.org/10.1007/s10584-011-0148-z

Wang, F., & Zhang, J. (2019). Heat stress response to national-committed emission reductions under the Paris agreement. *International Journal of Environmental Research and Public Health*, *16*(12), 2202. https://doi.org/10.3390/ijerph16122202

Wang, F., Zheng, B., Zhang, J., Zhou, Y., & Jia, M. (2022). Potential heat-risk avoidance from nationally determined emission reductions targets in the future. *Environmental Research Letters*, *17*(5), 055007. https://doi.org/10.1088/1748-9326/ac66f4

Wang, P., Luo, M., Liao, W., Xu, Y., Wu, S., Tong, X., et al. (2021). Urbanization contribution to human perceived temperature changes in major urban agglomerations of China. *Urban Climate*, *38*, 100910. https://doi.org/10.1016/j.uclim.2021.100910

Wang, X., Jiang, D., & Lang, X. (2018). Climate change of 4°C global warming above pre-industrial levels. *Advances in Atmospheric Sciences*, *35*(7), 757–770. https://doi.org/10.1007/s00376-018-7160-4

Wu, J., Gao, X., Giorgi, F., & Chen, D. (2017). Changes of effective temperature and cold/hot days in late decades over China based on a high resolution gridded observation dataset. *International Journal of Climatology*, *37*, 788–800. https://doi.org/10.1002/joc.5038

You, Q., Jiang, Z., Yue, X., Guo, W., Liu, Y., Cao, J., et al. (2022). Recent frontiers of climate changes in East Asia at global warming of 1.5°C and 2°C. *Npj Climate and Atmospheric Science*, *5*, 80. https://doi.org/10.1038/s41612-022-00303-0

Yukimoto, S., Kawai, H., Koshiro, T., Oshima, N., Yoshida, K., Urakawa, S., et al. (2019). The Meteorological Research Institute Earth System Model version 2.0, MRI-ESM2.0: Description and basic evaluation of the physical component. *Journal of the Meteorological Society of Japan*, *97*(5), 931–965. https://doi.org/10.2151/jmsj.2019-051

Zhang, J., Ren, G.-Y., & You, Q.-L. (2022). Detection and projection of climatic comfort changes in China mainland in a warming world. *Advances in Climate Change Research*, *13*(4), 507–516. https://doi.org/10.1016/j.accre.2022.04.008

Zhang, J., & Wang, F. (2022). Future changes in extreme precipitation in central Asia with 1.5–4°C global warming based on Coupled Model Intercomparison Project Phase 6 simulations. *International Journal of Climatology*, *42*(16), 7740–8525. https://doi.org/10.1002/joc.7740
Zhang, J., Wang, F., Tokarska, K. B., & Yang, Z. (2020). Multiple possibilities for future precipitation changes in Asia under the Paris Agreement. *International Journal of Climatology*, *40*(11), 4888–4902. https://doi.org/10.1002/joc.6495
Zhang, J., You, Q., Ren, G., & Ullah, S. (2022). Projected changes in mild weather frequency over China under a warmer climate. *Environmental Research Letters*, *17*(11), 114042. https://doi.org/10.1088/1748-9326/ac9c70
Zhang, J., You, Q., Wu, F., Cai, Z., & Pepin, N. (2022). The warming of the Tibetan plateau in response to transient and stabilized 2.0°C/1.5°C global warming targets. *Advances in Atmospheric Sciences*, *39*(7), 1198–1206. https://doi.org/10.1007/s00376-022-1299-8
Zhang, W., & Zhou, T. (2020). Increasing impacts from extreme precipitation on population over China with global warming. *Science Bulletin*, *65*(3), 243–252. https://doi.org/10.1016/j.scib.2019.12.002
Zhao, L., Oleson, K., Bou-Zeid, E., Krayenhoff, E. S., Bray, A., Zhu, Q., et al. (2021). Global multi-model projections of local urban climates. *Nature Climate Change*, *11*(2), 152–157. https://doi.org/10.1038/s41558-020-00958-8
Zhu, J., Huang, G., Baetz, B., Wang, X., & Cheng, G. (2019). Climate warming will not decrease perceived low-temperature extremes in China. *Climate Dynamics*, *52*(9–10), 5641–5656. https://doi.org/10.1007/s00382-018-4469-8

References From the Supporting Information

Fiala, D., Havenith, G., Brode, P., Kampmann, B., & Jendritzky, G. (2012). UTCI-Fiala multi-node model of human heat transfer and temperature regulation. *International Journal of Biometeorology*, *56*(3), 429–441. https://doi.org/10.1007/s00484-011-0424-7
Napoli, C. D., Pappenberger, F., & Cloke, H. L. (2018). Assessing heat-related health risk in Europe via the universal thermal climate index (UTCI). *International Journal of Biometeorology*, *62*(7), 1155–1165. https://doi.org/10.1007/s00484-018-1518-2
Urban, A., & Kyselý, J. (2014). Comparison of UTCI with other thermal indices in the assessment of heat and cold effects on cardiovascular mortality in the Czech Republic. *International Journal of Environmental Research and Public Health*, *11*(1), 952–967. https://doi.org/10.3390/ijerph110100952