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Projected changes in mild weather frequency over China under a warmer climate

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Abstract

Previous studies largely focus on changes in mean climate state and climate extremes under a warmer climate, and little is known about changes in mild weather, which is a positive and pleasant condition and is highly related to human outdoor activities. Although changes in observed mild weather frequency over China and their drivers have been revealed, the understanding of how mild weather evolves with projected warming is still limited. Here, we examine future changes in mild weather frequency over China based on comprehensive thermal comfort indices and dynamically downscaled climate projections produced by the Regional Climate Model version 4 (RegCM4) within the framework of Coordinated Regional Climate Downscaling Experiment - Coordinated Output for Regional Evaluations (CORDEX-CORE). We demonstrate that changes in mild weather frequency in a warmer future exhibit remarkable regional discrepancy. Particularly, the densely populated southeastern China will experience a robust decrease in mild weather relative to the current level, although a general increasing trend is observed in this area during the past decades. On a seasonal scale, the decrease in mild weather in summer overwhelms the increase in spring and autumn, and this is more prominent in warmer regions. For the drivers, it is suggested that changes in mild weather frequency are dominated by elevated temperatures, with little contribution from relative humidity, wind speed, and sunshine duration.

Keywords: Mild weather; Thermal comfort; CORDEX; Climate change; China;

1 Introduction

Global-scale warming has dominated the various aspects of climate change since the early 1900s (IPCC, 2021). A large body of climate change studies is devoted to the changing character of the mean climate state (e.g., global mean temperature, sea level; Gillett et al., 2021; Hermans et al., 2021) or climate extremes (e.g., heatwaves, heavy precipitation, droughts; Dong et al., 2022; Perkins-Kirkpatrick and Lewis, 2020; Ukkola et al., 2020; Luo et al., 2022; Luo and Lau, 2021). While these aspects are important for public health, the multiple facets of society, and the environment, the focus on the above neglects the study of meteorological conditions that occur more regularly and are of societal significance in a different way. Here, we focus on mild weather, a condition that is neither too cold nor too hot, i.e., a weather condition that could be considered as being "pleasant" or "comfortable" (Lin et al., 2019; van der Wiel et al., 2017). Mild weather occurs frequently in many regions and is directly associated with human outdoor activities, such as sports, agricultural labor, building construction, tourism, and transport. Understanding changes in mild weather in the context of global warming is of great importance for a diverse range of businesses, industries, and populations. Although the definition of mild weather may vary for different activities or personal preferences, it is generally accepted that mild weather is closely related to thermal comfort conditions, which considers the aggregate effects of temperature, relative humidity, wind, and radiation on human thermal perception (Li et al., 2016; Lin et al., 2019).

The purpose of this study is to investigate future changes in mild weather under a warmer climate with the example of China. China is a vast country with a wide variety of climate types, and the impact of climate change on mild weather changes may be of significant spatial heterogeneity. A few studies have investigated climatology and the trend of mild weather over China during the historical period. For example, Lin et al. (2019) suggested that the annual number of mild days over China increased during 1971–2014, and a clear increasing trend exhibits in most parts of China. Wu et al. (2017) generally supported these results but emphasized that the number of comfortable days during summer decreases in warm areas. Other studies have yielded similar results (Li et al., 2016; Wu et al., 2019). However, the information on future changes in mild weather over China under a warmer climate is still limited: although Gao et al. (2018) and Zhang et al. (2022b) have shown initial results of changes in comfortable days by the end of the 21st century under the Representative Concentration Pathway (RCP; van Vuuren et al., 2011) scenarios, some aspects that determine thermal comfort (temperature, relative humidity, wind, and radiation, etc.) are neglected in these studies, and the drivers of changes in comfortable days are not revealed. Given the context, the spatial patterns and causes of mild weather changes with higher global warming levels (e.g., 1.5, 2, and 3°C above the pre-industrial level) will be systematically examined in this study. To the best of our knowledge, this is an early attempt to reveal a holistic image of how mild weather over China evolves with escalating global warming in the future. Although we focus on China in the current study, our approach to assessing mild weather is expected to be generalized to address similar problems worldwide.

2 Data and methods

2.1 Data description

This study is based on an ensemble of dynamically downscaled climate projections in the East Asia domain, produced by the latest version of the Regional Climate Model version 4 (RegCM4; Giorgi et al. 2012) within the Coordinated Regional Climate Downscaling Experiment - Coordinated Output for Regional Evaluations framework (CORDEX-CORE; Giorgi et al., 2022). RegCM4 is used with 25 km horizontal grid spacing and driven by three global climate projections generated 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-MR; Giorgetta et al., 2013), and the Norwegian Earth System Model (NorESM1-M; Bentsen et al., 2013), respectively. Dynamically downscaled simulations of RegCM4 driven by HadGEM2-ES, MPI-ESM-MR, and NorESM1-M named HdR, MdR, and NdR, respectively. Here, we used daily mean near-surface temperature, relative humidity, wind speed, and sunshine duration from historical simulations (1980–2005) and future projections (2006–2099) forced by the RCP8.5 emission scenario. This dynamically downscaled projection dataset was chosen because it has all the variables required to calculate the index, and it has been successfully applied for quantifying future changes in near-surface mean temperature and precipitation (Teichmann et al., 2021), climate extreme and hazard indices (Coppola et al., 2021), and heat stress (Im et al., 2020).

The gridded observational dataset CN05.1 with a 0.25° horizontal resolution (Wu and Gao, 2013; Wu et al., 2017), including daily mean near-surface temperature, relative humidity, wind speed, and sunshine duration, is used as the reference data for evaluating the model results. It was provided by China Meteorological Administration based on more than 200 meteorological stations, unevenly covering the whole of China mainland (Wu and Gao, 2013). This dataset has been widely used in research on climate change in China (e.g., Gao et al., 2018; Wang et al., 2020; Zhang and Wang, 2019).

To account for the impact of mild weather changes on population, we used the current population (2010) from the Chinese census and the projected population for 2011–2100 within the framework of the Shared Socioeconomic Pathway (SSP), with a 1km horizontal resolution (Figure S1; Chen et al., 2020). The SSP contains five scenarios (Riahi et al., 2017): SSP1 (Sustainability), SSP2 (Middle of the road), SSP3 (Regional rivalry), SSP4 (Inequality), and SSP5 (Fossil-fueled development), all of which were adopted in this study.

2.2 Definition of mild weather

Mild weather is defined by an official standard "Climatic suitability evaluating on human settlement" (GB/T 27963-2011) as recommended by the China Meteorological Administration (Table S1; Lin et al., 2019). Here, we focus on mild weather frequency, i.e., the annual number of mild weather days. A day is considered as mild if the daily temperature-humidity index (THI; Thom, 1959) is between 17 and 25.4°C for May to October or the wind effect index (WEI; Terjung, 1966) is between −299 and −100 $kcal/m^2 \cdot h$ for November to April. THI (°C) incorporates the effects of temperature and humidity on the human body and is commonly used for characterizing human thermal comfort in warm environments, which is defined as

$$\mathrm{THI} = T - 0.55 \times (1 - RH/100) \times (T - 14.4) \quad (1)$$

where T and RH denote daily mean near-surface temperature (°C) and relative humidity (%), respectively. WEI considers the effects of temperature, wind speed, and solar radiation on human thermal comfort, and is more applicable to cold environments. The definition of WEI ($kcal/m^2 \cdot h$) is

$$\mathrm{WEI} = -\left(10\sqrt{V} + 10.45 - V\right)(33 - T) + 8.55S \quad (2)$$

where V is the wind speed (m/s) and S is the sunshine duration (hours per day). The combination of THI and WEI enables the assessment of thermal comfort throughout the year. Previous studies on the impact of climate changes on mild weather over China adopted THI (Zhang et al., 2022b) or net effective temperature (Gao et al., 2018; Wu et al., 2017) that ignores the effect of one or more of wind and radiation on human thermal comfort. Although two studies (Li et al., 2016; Lin et al., 2019) adopted a similar strategy to the present study, they focus on historical changes and the projected changes in a warmer future have not been revealed.

To assess the possible effects of individual variables (i.e., temperature, relative humidity, wind speed, and sunshine duration) on the change in mild weather, we recomputed the mild days using a method similar to the 'factor separation method' (Stein and Alpert, 1993). 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 1986–2005). Then the trend from this new computation can be considered as the contribution of the corresponding variable to the change in mild weather (Lin et al., 2019; J. Wu et al., 2017).

In this study, mild weather changes at specific global warming levels, i.e., 1.5, 2, and 3°C relative to the pre-industrial level (1861–1880), are examined based on a time sampling approach (Zhang and Wang, 2022; Zhang and Zhou, 2020). Given that RCMs do not provide global datasets, the warming thresholds are determined using the 11-year running average global mean surface air temperature separately for each GCM. The specific warming periods are then aggregated over the 11-year windows that are centered on the years when respective warming levels occur (Table S2). In contrast to traditional emission scenario-based approaches that are designed to model responses to different levels of greenhouse gas forcing (e.g., RCP; van Vuuren et al., 2011), this approach yields insights into how regional climate evolves with escalating global warming (James et al., 2017). Note that our results regarding specific global warming thresholds represent a transient response, which is different from the stabilized response at the same global warming level (King et al., 2020; Zhang et al., 2022a).

2.3 Other methods used

Simulated THI and WEI were calculated at the native grid of RCMs and then remapped to the CN05.1 grid for comparison. The population dataset was aggregated to the CN05.1 grid for further analysis. Given that China's urban areas are shown to be particularly vulnerable to climate change (Wang et al., 2020; Yu et al., 2018), in addition to examining national average changes, we focus on three vast urban agglomerations in China (Figure 1(a)), i.e., Beijing-Tianjin-Hebei urban agglomeration (BTH: 114–119°E, 36–41°N), Yangtze River Delta urban agglomeration (YRD: 118–123°E, 28.5–33.5°N), and Pearl River Delta urban agglomeration (PRD: 111–116°E, 20–25°N), which account for ~25% of the population and more than 40% of the GDP in China mainland (Wang et al., 2020). The statistical significance of changes in mild weather frequency is evaluated using Wilcoxon's rank-sum test imposing $p < 0.05$. The ensemble mean signal is the mean of three individual signals. If at least one significant individual signal differs in the sign of the ensemble mean change, it is considered "uncertain"; if the uncertainty condition is not fulfilled and less than half of the individual signals are significant, it is considered as “negligible”; otherwise, the ensemble mean signals are referred to as “robust”.

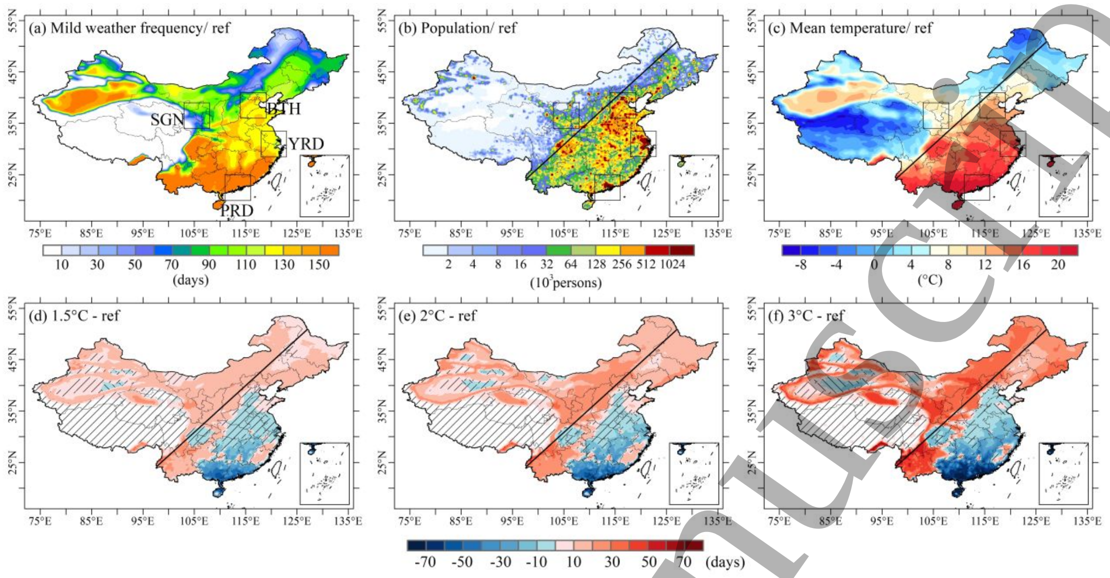

Figure 1. (a) Spatial distribution of mild weather frequency for the reference period (1986–2005). (b) Spatial distribution of population for the reference year 2010 based on the Chinese census. (c) Spatial distribution of annual mean near-surface temperature for the reference period. (d–f) Spatial distribution of changes in mild weather frequency with 1.5, 2, and 3°C global warming relative to the reference period, based on the ensemble mean. The hatching with forward-slash (/) indicates negligible changes, the hatching with backslash (\) indicates uncertain changes, and the remaining area exhibits robust changes. Black boxes in (a) indicate the three vast urban agglomerations (BTH, YRD, and PRD) and another typical region (the Shaanxi-Gansu-Ningxia border region, SGN: 103–108°E, 34–39°N), respectively. The Hu Huanyong Line (also named Heihe-Tengchong Line, a geographic division line of great significance in China; M. Chen et al., 2016) is labeled as a black line in (b–f).

3 Results

Before examining future changes, we first evaluated the performance of dynamically downscaled simulations in representing the mild weather frequency over China in the reference period (1986–2005). The results show that all three individual simulations reproduce well the spatial pattern of annual mild days in the observations, with the spatial correlation coefficients all above 0.96; despite the regional average mild days over China are slightly lower in the three simulations than those in the observations (Figure S2), probably partially due to the overestimate because of the urbanization effect in the observed surface air temperature data (Ren et al. 2014; Tysa et al. 2019). However, the overall consistency between models and observations builds more confidence for future projection.

There is a divergent response of mild weather frequency over China to escalating global warming, based on dynamically downscaled projections (Figure 1(d)–(f)). The projected changes in regional average (traditional areal-weighted) mild weather frequency over China relative to the reference period are 4.8, 6.6, and 8.9 days under the 1.5, 2, and 3°C warming futures, respectively; however, the corresponding changes in population-weighted average mild weather frequency is –2.7, –3.0, and –6.4 days, respectively, implying that the regions with a decrease in mild weather frequency concentrate in densely populated regions. Here, we emphasize the population-weighted averages because of the importance of mild weather for the human habitat. In terms of spatial distribution, the vast majority of southeastern China will experience a decrease in mild weather frequency, while the rest of China will generally experience an increase in mild weather frequency. Although the increase in mild weather is projected to cover most parts of China (except for the alpine Tibetan Plateau), the decrease in mild days coincided with the densely populated warm regions in southeastern China (Figures 1(b–f) and S3) dominate the decrease in population-weighted averages. It is noted that regions with robust decreases in mild weather are all located on the southeast side of the Hu Huanyong Line (the densely populated half of China; Chen et al., 2016), or in the eastern China monsoon region. Although the above analysis is generally based on the ensemble mean, results from three individual simulations are broadly consistent (Figures 2(a) and S4). Regarding the three vast urban agglomerations, the PRD is projected to experience the most remarkable decrease in mild weather frequency, ranging from –31.0, –37.5, and –59.6 days with 1.5, 2, and 3°C global warming, based on the ensemble mean. The YRD is also projected to experience a decrease in mild weather frequency but to a lesser extent. There is a slight increase in mild weather frequency in the BTH, although not all simulations generate this signal (Figure 2(a)).

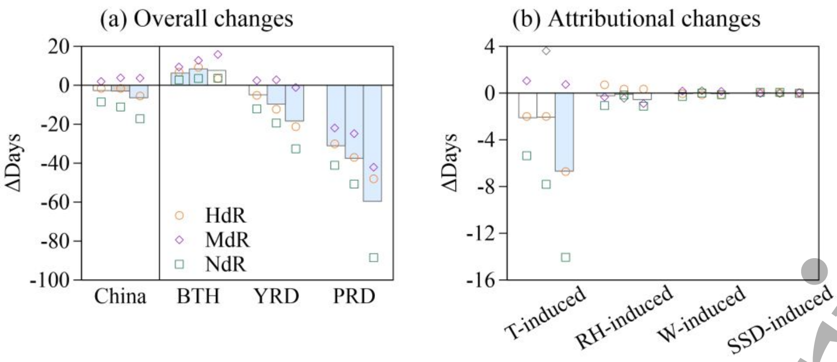

Figure 2. (a) Changes in national (population-weighted) and regional average mild weather frequency with 1.5, 2, and 3 °C global warming relative to the reference period (corresponding to three adjacent bars from left to right). (b) Effects of temperature (T), relative humidity (RH), wind speed (V), sunshine duration (SSD) on changes in population-weighted national average mild weather frequency with 1.5, 2, and 3°C global warming relative to the reference period (corresponding to three adjacent bars from left to right). Results from individual simulations are depicted by dots (see legend). Bars represent the ensemble mean signals: colored, grey, or white if robust, negligible, or uncertain, respectively.

Moreover, we examine seasonal changes in mild weather. In the context of warming, days that were previously mild may become hot, while days that were previously cold may become mild. Furthermore, the direction of changes in mild weather depends on the relative contribution of these two processes. Here, the above finding is supported by the climate projection (Figures 3 and S5) that the mild days will generally decrease in the warm season and generally increase in the cold season. For example, in the subtropical PRD, the substantial decrease in mild days from April to September greatly exceeds the increase in those during other months, resulting in a remarkable decrease in annual mild weather frequency; while in the temperate BTH, the decrease in mild days in summer (June to August) is overweighed by the increase in those in spring (March to May) and autumn (September to November).

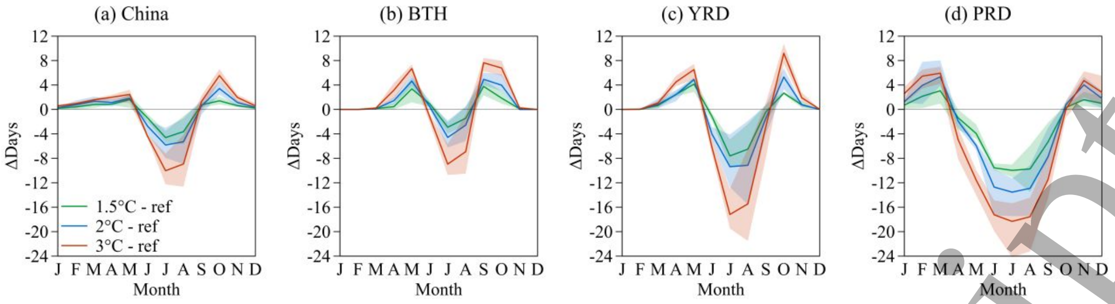

Figure 3. Monthly variation of projected changes in mild weather frequency with 1.5, 2, and 3°C global warming relative to the reference period. Solid lines and shadings indicate the ensemble means and ranges, respectively.

It is noted that observation-based studies suggest a clear increasing trend of mild weather frequency during the past few decades in most parts of China (Li et al., 2016; Lin et al., 2019; Wu et al., 2017). However, our results indicate that this increasing trend could be reversed in most parts of southeastern China in a warmer future. To illustrate the reason for the differentiated change of mild weather frequency more clearly, we investigate the shift of probability distribution curves of THI/WEI in four typical regions (Figure 1(a)) during the historical period and under the future scenario (Figures 4 and S6). Take the warm YRD as an example, for the historical period (1961–2015), the rightward shift of the probability distribution curves of WEI and THI results in an increase in mild days during both November to April and May to October (Figure 4(a)–(b)); however, the rightward shift of the probability distribution curves of WEI and THI between the future scenario (the 3°C warming level) and the reference period results in a slight increase in mild days during November to April but a remarkable decrease during May to October (more mild weather getting hotter; Figure 4(c)–(d)). An example of the opposite is the cold SGN, the rightward shift of the probability distribution curves of THI results in an increase in mild days for both the historical period and under the future scenario, while changes in mild days during November to April (defined based on WEI) is negligible (Figure 4(e)–(h)). The above analysis suggests that the differentiated change of mild weather frequency is somewhat related to the background climatology. In the context of warming, an increase in THI causes more days in the warm season to go from mild to hot, although the increase in WEI is favorable to an increase of mild days in the cold seasons, this increase could be overwhelmed by the decrease in the warm season, especially when the local climatology annual average temperature is high (Figures 4(c–d) and S6(g–h)). Previous observation-based studies have shown a decrease in summer mild days in warm areas during the past decades (Lin et al., 2019; Wu et al., 2017), and our results indicate that this decrease is projected to be more pronounced and to expand to a wider area in southeastern China. Although the negative effects described above are not expected to occur in the vast colder regions even in a warmer future, the fact that the vast majority of China's population concentrates in warm southeastern China implies that the impact of climate change on future thermal comfort conditions over China is overall negative.

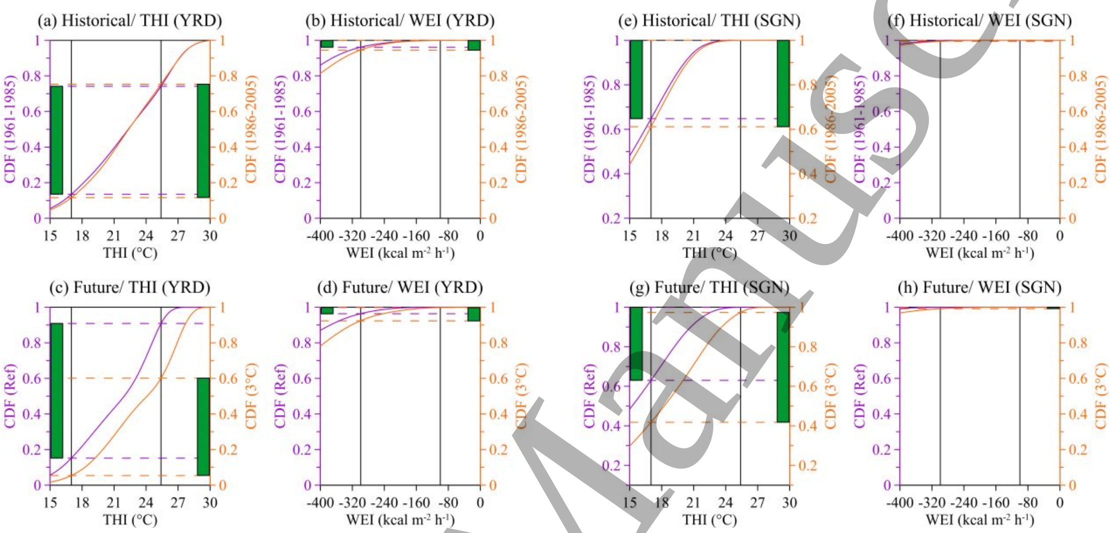

Figure 4. Cumulative distribution function (CDF) of THI (for May to October) and WEI (for November to April) for YRD (118–123°E, 28.5–33.5°N; a–d) and SGN (103–108°E, 34–39°N; e–h), based on the ensemble mean. The time periods (scenarios) represented by the curves are shown on the y-axis in the corresponding color. CDF is fitted to the empirical distribution of the climate signal using the Gaussian kernel density estimator. Green bars on the y-axis indicate mild weather frequency. Mild weather frequency in the YRD increases during the historical period but decreases under the future scenario. However, mild weather frequency in the SGN maintains the increasing trend during the historical period and under the future scenario.

We further examine the effects of temperature, relative humidity, wind speed, and sunshine duration on projected changes in mild weather frequency over China. For the national average, changes in mild weather frequency are dominated by changes in temperature, with negligible contributions from the other three variables (Figure 2(b)). Regarding the spatial distribution of changes in mild weather frequency, the temperature-induced changes generally coincide fairly well with the overall changes, implying the dominant role of temperature. Meanwhile, changes induced by three other variables are negligible in the vast majority of China (Figure S7). We acknowledge that, in addition to temperature, relative humidity, wind speed, and sunshine duration may have an obvious effect on the thermal comfort conditions at a given time. However, our study suggests that there is a little contribution of changes in relative humidity, wind speed, and sunshine duration to projected long-term changes in mild weather frequency over China.This study focuses on population-weighted national average changes in mild weather frequency because of the importance of mild weather for humans and the high heterogeneity of population distribution in China. However, the spatial distribution of the population might change in long-term projections (Chen et al., 2020; Jones and O'Neill, 2016). Therefore, we estimate the impacts induced by future population redistributions, derived from the differences in population-weighted average changes between the projected population in 2100 (SSP1–5) and that observed in 2010. The results show that the population-weighted averaged changes in mild weather frequency are fairly similar among SSPs, implying the influence of future population redistributions on the total population-weighted average changes is weak (Figure S8), which further support the robustness of our findings.

Given that the scientific community and policymakers are more concerned with regional climate signals at specific global warming levels (James et al., 2017; Seneviratne et al., 2016), here we focus on changes in mild weather frequency over China with 1.5–3°C global warming based on a time sampling approach (see Section 2.3). Nevertheless, we also present the corresponding projections based on the traditional RCP scenario-based approach (Figure S9–S11). The population-weighted national average changes in mild weather frequency are –3.3 and –11.7 days in mid-term (2040–2059) and long-term (2080–2099) relative to the reference period, respectively, under the RCP8.5 scenario. The spatial pattern, seasonal variation, and major driver of changes under the RCP8.5 scenario are similar to those at specific global warming levels, albeit with differences in magnitude.

4 Conclusion and discussion

This study examines how mild weather frequency over China evolves with escalating global warming in the future based on an ensemble of dynamically downscaled climate projections. Although previous observation-based studies reported an increasing trend in mild weather frequency in most parts of China during the past decades, we demonstrate that this increasing trend is not expected to persist in densely populated southeastern China under a warmer climate. The projected changes in population-weighted national average mild weather frequency relative to the reference period are –2.7, –3.0, and –6.4 days in 1.5, 2, and 3°C warming futures, respectively, based on the ensemble mean. This adverse impact of climate change on mild weather may be outlooked when focusing on the traditional areal-weighted national average change, but it is essential for the human habitat. We further demonstrate that changes in mild weather frequency are dominated by elevated temperatures, with little contribution from relative humidity, wind speed, and sunshine duration. Compared with a large number of previous studies focusing on future changes in mean temperature and warm/cold extremes, a novel aspect of this study involves examining future changes in mild weather, a condition that is neither too cold nor too hot, with high resolution and accuracy. Our work indicates that an overall decrease in mild weather associated with climate warming can pose a threat to future human well-being in China.

Most previous studies on climate change projections for a warmer future investigate changes in the mean climate state that are difficult for the public to relate to, or climate extremes that occur rarely and with potentially catastrophic effects . In contrast, mild weather is a positive concept (often considered to be “pleasant weather” or “comfortable weather”) and occurs frequently. Given the significance of mild weather for human outdoor activity and the fact that mild weather is highly relatable to the public, the information presented here may therefore be used to communicate climate change impacts to a broad audience. Given its association with various activities, the impact of projected changes in mild weather on various industries (e.g., tourism, sports, construction, and transportation) could also be explored in future works.

The definition of mild weather used here is based on temperature, relative humidity, wind speed, and sunshine duration, as recommended by the China Meteorological Administration. However, apart from this, other variables such as precipitation (including both its timing and intensity) and air pollution also play an important role in determining mild or severe weather (van der Wiel et al., 2017; Zhang et al., 2021). In addition, here we do not consider the differentiated acclimatization of people to mild and severe weather. For instance, it is easier for the people in southern China familiar with sultry weather to be more accustomed to unpleasant weather in summer than those in the north. The dynamically downscaled simulations used here contain only one RCM that is driven by three GCM simulations because of the limited data availability, which caused uncertainty in the ensemble projections (Ozturk et al., 2021; Vautard et al., 2021). Moreover, the current simulations do not include the parameterization to represent the urban canopy process and thus fail to capture the impact of the urban heat island effect on changes in mild weather (Chen and Frauenfeld, 2016; Olesen et al., 2012). These uncertainties are expected to be addressed in future work, especially within the context of the CORDEX framework under shared socioeconomic pathway scenarios, which will produce a new generation of high-resolution projections over the region (Gutowski Jr. et al., 2016).

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Conflict of interest

The authors declare no conflicts of interest relevant to this study.

Data availability statement

The data that support the findings of this study are openly available at the following URL: https://esgf-data.dkrz.de/search/cordex-dkrz/.

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