LETTER

Increases of extreme heat-humidity days endanger future populations living in China

Huopo Chen \textsuperscript{1,2,∗}, Wenyue He \textsuperscript{1,4}, Jianqi Sun \textsuperscript{1,2} and Lefeng Chen \textsuperscript{3}

\textsuperscript{1} Nansen-Zhu International Research Centre, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, People’s Republic of China
\textsuperscript{2} Collaborative Innovation Center on Forecast and Evaluation of Meteorological Disasters, Nanjing University for Information Science and Technology, Nanjing, People’s Republic of China
\textsuperscript{3} Wenzhou Water Conservancy Construction Management Center, Wenzhou, People’s Republic of China
\textsuperscript{4} University of Chinese Academy of Sciences, Beijing, People’s Republic of China

∗ Author to whom any correspondence should be addressed. E-mail: chenhuopo@mail.iap.ac.cn

Keywords: wet-bulb temperature, extreme heat-humidity event, population exposure, CMIP6

Supplementary material for this article is available online

Abstract

Changes in heat stress due to climate change affect living and working conditions. A wet-bulb temperature (TW) of 35 °C is identified as the upper physiological limit for human survivability. On the basis of Coupled Model Intercomparison Project phase 6 model simulations, our evaluations show that the daily maximum TW is expected to significantly intensify throughout China and is likely to exceed this critical threshold in some regions by the end of this century, especially under the high emission scenario of the shared socioeconomic pathway (SSP)5-8.5. The most dangerous hazard from extreme heat-humidity events is concentrated around the most densely populated regions of eastern China as well as the Sichuan basin. Under SSP5-8.5, the significant increase of extreme heat-humidity days with a daily maximum TW exceeding 35 °C results in a large fractional population of approximately 81% being exposed to these extremes in China by the end of this century. This is true for different future warming scenarios, and a population fraction of up to 51% would also be exposed to such extremes even if early mitigation was conducted via SSP1-2.6. Our findings in this study thus have significant implications to ongoing considerations for climate-change policy in China.

1. Introduction

Significant increases in the intensity and frequency of heat waves have been reported around the world during recent decades, which have already caused large losses for society, the economy, and natural ecosystems (IPCC 2021). Attribution studies have documented that the occurrences of extreme heat events, such as the deadly 2003 European and 2010 Russian heat waves, which were responsible for tens of thousands of additional deaths, are more likely due to anthropogenic warming (Stott \textit{et al} 2004, Rahmstorf and Coumou 2011, Christidis \textit{et al} 2015) and rapid urbanization (Jones \textit{et al} 2008, Sun \textit{et al} 2016, Wang \textit{et al} 2021). Furthermore, an extensive body of research supports that the occurring risks of such extreme heat events would be further increased as the climate continues to warm in the future and there would be more population exposure to them (Jones \textit{et al} 2015, IPCC 2021). Expected increases in heat waves due to climate change have thus become a matter of growing public health concern.

Heat extremes directly endanger human health via both temperature and humidity. High ambient temperature and humidity would reduce the efficiency of evaporative cooling of the human body, which easily weakens the body’s ability to maintain a stable core temperature and generally increases both morbidity and mortality (Basu and Samet 2002, Sherwood and Huber 2010). A variety of heat stress indices are thus proposed to measure the potential impacts of heat on humans (Epstein and
Moran 2006) and a popular index is the wet-bulb temperature (TW), which is defined as the combination of temperature and humidity (Sherwood and Huber 2010). High values of TW mean hot and humid conditions, and increases in TW can reduce the differential between human body skin temperature and core temperature, which weakens the body’s ability to cool itself (Hanna and Tait 2015). If ambient TW exceeds the body’s skin temperature of about 35 °C, metabolic heat dissipation will be significantly less effective and people who are exposed would easily suffer heat illness in the absence of well-ventilated conditions (Sherwood and Huber 2010, Pal and Eltahir 2016).

There have been few reports of the TW exceeding 35 °C in the current climate (Schär 2016). Values of TW in regions affected by the deadly 2003 European and 2010 Russian heat waves were limited to 28 °C (Raymond et al 2020). However, with continued anthropogenic warming in the future, heat stress is projected to strongly increase and present-day extreme TW events would increase by a factor of at least 100 over most parts of global land by the end of this century, subsequently causing population exposure to extreme heat-humidity events to increase substantially (Fischer et al 2012, Andrews et al 2018, Coffel et al 2018, Raymond et al 2020). Especially for densely populated regions of South Asia, the TW could frequently reach 35 °C this century (Im et al 2017, Dimitrova et al 2021).

As the largest population in the world, China has many laborers engaged in outdoor working. The rapid increases in air temperature this century result in more frequently and intensified heat waves that can pose dangerous conditions for most humans throughout China (Zhou et al 2016, Gao et al 2018, Jiang et al 2020, Chen and Sun 2021a, Tang et al 2021a, 2021b, Zhu et al 2021). Except for anthropogenic influences (Wang et al 2021), climate internal variabilities such as mid-high latitude circulation anomalies (Xu et al 2019) and the sea surface temperature anomaly over the mid North Atlantic (Sun 2014) are also partly responsible for the increase of heat events throughout China during past decades. In the relevant literature to date, there are some studies that have documented the observed spatial-temporal changing characteristics of heat-humidity events using the TW metric (e.g. Ding et al 2014, Li and Zha 2018); however, there is almost no study evaluating its future change and associated impact over China. Here, we present the first analysis of future changes in extreme TWs and corresponding population exposure throughout China using the Coupled Model Intercomparison Project phase 6 (CMIP6) model simulations. Our findings would be beneficial to the policymaking of mitigation and adaptation measures for climate change for the coming decades.

2. Data and methods

Outputs from 18 CMIP6 model simulations (table S1 available online at stacks.iop.org/ERL/17/064013/mmedia) of the daily maximum air temperature, daily mean relative humidity, and daily mean surface pressure available are employed to calculate the daily maximum TW (TW$_{\text{max}}$) using the algorithm proposed by Davies-Jones (2008). Historical simulations and future projections under four major warming scenarios of the new shared socioeconomic pathways (SSPs) are used here, including SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5. The gridded daily datasets with a high resolution of 0.25° × 0.25°, which are derived from more than 2400 stations throughout China (Wu and Gao 2013), are considered as observations for comparison. Note that the daily mean surface pressure from ERA5 (the fifth generation of European Center for Medium Weather Forecasting atmospheric reanalysis) reanalysis is employed here instead of observation because it is unavailable in observation. Both the observations and CMIP6 model data are re-gridded using a first-order conservation remapping procedure to a common grid of 1.5° × 1.5° to facilitate comparison via the Climate Data Operator software.

For impact research, bias correction is often desirable for climate-model simulations, which can reduce the likelihood of the impact assessments being biased due to model deficiencies. Cold bias is clear for the TW over China simulated by the CMIP6 models (figure S1) and the same methodology for bias correction proposed by Pal and Eltahir (2016) is applied here. Climate means of the TW$_{\text{max}}$ are first computed for each day on each grid for both observations and CMIP6 models. The value of bias for each day is estimated by the difference between the two climate means and the daily bias is then applied to the model-simulated TW$_{\text{max}}$ for present-day and future climates. The corrected values are finally used to calculate the annual maximum TW$_{\text{max}}$ and extreme TW$_{\text{max}}$ events as well as the impact assessments in this study.

Spatially explicit population projections of a horizontal resolution of 1/8° from the SSP project are up-scaled to a 1.5° × 1.5° grid to match the model simulations. Four SSPs of SSP1, SSP2, SSP3, and SSP5 for population projections are used here along with SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5, respectively. The population exposure to TW threshold is calculated by multiplying the populations in each grid cell by the number of days of extreme TW events (Jones et al 2015). According to the definition of population exposure, changes in population exposure are mainly attributed to three components, including the population effect, the climate effect, and their interaction effect, as Jones et al (2015) proposed, which are further investigated here. The 25th–75th percentile ranges across 18 models are estimated for the
uncertainty of changes in extreme TW and population exposure.

3. Results

Eastern China, including the Sichuan basin, is most at risk for extreme TWs; it is the most densely populated region in China, in which many people work outdoors without shelter or air conditioning (figure S2). The high values of TWs partly result from rapid urbanization in these regions of China during recent decades (Fischer et al 2012). CMIP6 models can reasonably reproduce the spatial patterns of extreme TWs, including the highest TWmax on record, annual maxima of TWmax, and extreme days of TWmax exceeding 35 °C, although these values are still underestimated by the bias-corrected simulations (figure S3).

In response to future warming, changes in TWs are expected to be smaller and more spatially uniform than for air temperatures (figure 1). By the end of this century, we project multi-model median increases in daily TWmax across China, notably in northeastern China, some parts of eastern China, the Sichuan basin, and the Tibetan Plateau, in which TWmax are expected to increase by more than 4.0 °C under SSP5-8.5 scenario. Considering China as a whole, the averaged TWmax over China is estimated to increase by approximately 4.5 °C by the end of this century under SSP5-8.5 scenario with respect to the current climate. This projected increase is similar to those found in other scenarios and the TWmax is reported to increase by 1.3 °C, 2.3 °C, and 3.5 °C under SSP1-2.6, SSP2-4.5, and SSP3-7.0, respectively. This stands in contrast to the daily maximum air temperatures, which are projected to increase by 1 °C–2 °C more than the daily TWmax in many regions of China.

Aligning with TWmax increase, it is expected that the annual maximum of TWmax is also projected to significantly increase across China (figure 1(c)), which results in remarkable increases of extreme TWmax events, especially over regions of eastern China (figures 2 and S3). Steeply and statistically significant upward trends in extreme TWmax frequency

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Figure 1. Projected changes in daily maximum temperature and daily maximum wet-bulb temperature over China. (a) and (b) are the changes in daily maximum temperature and daily maximum wet-bulb temperature by the end of the 21st century (2081–2100) under the SSP5-8.5 scenario with respect to the current climate (1995–2014), respectively. (c) Projected mean of the annual maximal values of daily maximum wet-bulb temperature by the end of the 21st century under the SSP5-8.5 scenario. (d) and (e) are the averaged changes of daily maximum temperature and daily maximum wet-bulb temperature over China for different future scenarios. The solid lines show the ensemble median of the CMIP6 simulations and the shaded areas indicate the interquartile ensemble spread, i.e. the range between the 25th and 75th percentiles of the model ensemble, representing the inter-model uncertainty. The low-pass filtering process with a 21-year window is applied to these changes. The box-and-whisker plots on the right side of the panels present the changes by the end of this century against the reference period.
in exceedance of 30 °C and 35 °C are present across grids of eastern China. Under the high emission scenario of SSP5-8.5, each frequency trend represents about ten times the occurrence of exceedances of 30 °C by the end of this century against the current climate. The corresponding averaged days are expected to increase from less than three days in the current record to more than 18 days by the end of this century in China. An increase is also expected even if early mitigation is conducted via SSP1-2.6, with more than four days. We also find a sharp increase in the number of extreme heat-humidity days that exceed the physiological survivability limit of 35 °C of \( TW_{\text{max}} \) across China. At the current climate, there are few records of this extreme reported across China, but it becomes common in the future, especially under the no-mitigation scenario of SSP5-8.5 over some regions of eastern China, in which more than 20 days are expected for each year by the end of this century. There would be approximately 0.2, 0.6, 2.1, and 3.4 days of such extremes averaged over China by the end of this century under the SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5 scenarios, respectively. Furthermore, more grid cells are expected to be exposed to such extreme heat-humidity events in the future, and the exposed area would extend to regions of northeastern China and northwestern China. These expected increases of extreme heat-humidity events would make living situations more dangerous, especially for children, the elderly, and people with pre-existing health conditions.

To examine the robustness of our estimates of the changing characteristics of heat events, we also investigate the potential changes of frequency and intensity of extreme heat-humidity events that occur once in 10 or 20 years in the future (figures 3 and S4). As global mean temperatures increase, the intensity of such extremes is projected to steeply and statistically significant increase across China, and more extremes of such events present a more rapid increase, which are true across all future warming scenarios. The peak increases are expected to occur over some grids of northeastern China and eastern China, in which the intensity is projected to increase by more than 5.0 °C for the historically recorded 1-in-20-year extreme heat-humidity events by the end of this century under SSP5-8.5 scenario. At least a 2.0 °C increment could be found in the other regions. The multi-model median ensemble shows that the average intensity is expected to increase by approximately 3.7 °C by the end of this century. There will also be a
significant increase of about 1.6 °C even if early mitigation is conducted via SSP1-2.6. Under the scenarios of SSP2-4.5 and SSP3-7.0, the intensity of such extremes is projected to rise by approximately 2.4 °C and 2.9 °C, respectively. Similar changes can be found for 1-in-10-year extreme heat-humidity events but with slightly weak increasing magnitudes of intensity.

A steep increase in the intensity of historically recorded extreme heat-humidity events implies greater frequency of such extremes in the future. The return periods of both 1-in-10- and 1-in-20-year extreme heat-humidity events are estimated to be significantly reduced in response to future warming (figures 3 and S4). Taking the 1-in-20-year extreme event as an example, the return period of such events is expected to reduce by at least 10 years by the end of this century under SSP5-8.5 scenario, implying at least a doubling of the risk of such extremes occurring across China. Especially for the regions of southern China, including some parts of southwestern China, the Sichuan basin, and the Tibetan Plateau, the historically recorded 1-in-20 year extreme events would happen once every 5 years in the future. Further evaluation shows that the return period of 1-in-20-year events would be expected to reduce to about 7 years by the end of this century under SSP5-8.5 scenario, and approximately 13, 10, and 9 years under SSP1-2.6, SSP2-4.5, and SSP3-7.0, respectively.

Many urban population centers in eastern China are expected to frequently experience the extreme heat-humidity events featured by the $T_{W_{\text{max}}}$ well beyond the survivability threshold of 35 °C by the end of this century under SSP5-8.5 scenario (figure 4). For example, in Beijing, Shanghai, Guangzhou, and Chongqing, which are super cities in China, the $T_{W_{\text{max}}}$ reaches and exceeds the survivability

![Figure 3. Projected changes in 1-in-20-year extreme heat-humidity events from historical simulations. Left panels show the changes in intensity and right panels present the projected return period of the extreme events by the end of this century under SSP2-4.5 (top) and SSP5-8.5 (middle) scenarios. The bottom panels are the plots of the corresponding regional means and the error bar indicates the interquartile ensemble spread (25th and 75th percentiles) representing the inter-model uncertainty.](image-url)
threshold frequently in the future. In these locations, the threshold of the 1-in-20-year annual $TW_{\text{max}}$ event in the current climate, for instance, is also projected to increase by at least 5.0 °C under SSP5-8.5 and at least 3.0 °C under SSP2-4.5, implying significant increases in risk levels of such extremes. Living conditions would be better in the high latitudes of China, such as in the cities of Urumqi and Harbin, in which there is low probability or no occurrence of the $TW_{\text{max}}$ exceeding the survivability threshold of 35 °C in the future. Additionally, if early mitigation is conducted via SSP1-2.6, the occurring probability of deadly heat-humidity events would be limited to a low level across China, even in locations where extreme events are concentrated in the present climate.

To further assess the effects of changes in extreme heat-humidity events on humans, population exposure to extreme heat-humidity events are also estimated here in terms of person-days (one person exposed on one day) to the high $TW_{\text{max}}$ in each decade through the 21st century (figures 5 and S6). Our results indicate that populations in China are likely bear the brunt of the deadly heat-humidity events in the future, despite the fact that populations are anticipated to substantially decrease in our country (Chen and Sun 2021b). Aligning with the present climate, the high values of exposure in the future are mainly located in eastern China, which is a densely populated region that frequently suffers extreme heat-humidity events. Under SSP5-8.5, a large fraction of the population, approximately 81%, is expected to have the chance to experience the $TW_{\text{max}}$ exceeding 35 °C by the end of this century, compared to 11% in the current climate. Similarly, the fractional population exposed to such extremes is anticipated to significantly increase to about 61% and 73% under SSP2-4.5 and SSP3-7.0, respectively, and there would be also a large fraction of about 51% even if early mitigation is conducted via SSP1-2.6. Furthermore, by the end of this century, even approximately 50% of the population across China is anticipated to be exposed to living conditions where the $TW_{\text{max}}$ exceeds 40 °C under the high-emission scenario of SSP5-8.5. This fraction would be reduced to a low level of approximately 9% under SSP1-2.6. Serious mitigation is thus strongly suggested to improve our living conditions in the future.

Figure 4. Histograms of daily maximum wet-bulb temperature and corresponding climate mean plots. (a) The histograms are generated for the most populous cities in China for different scenarios: Hist (black), SSP1-2.6 (cyan), SSP2-4.5 (green), SSP3-7.0 (orange), and SSP5-8.5 (red). Values within each panel correspond to 10- and 20-year return period of daily maximum wet-bulb temperature. The x and y axes indicate the daily maximum wet-bulb temperature and the number of occurrences, respectively. (b to d) are the climate means of daily maximum wet-bulb temperature over China for different scenarios: (b) Hist (1995–2014), (c) SSP2-4.5 (2081–2100), and (d) SSP5-8.5 (2081–2100).
Figure 5. Maps of population exposure to extreme heat-humidity events. (a) Population fraction exposed at least once to the median of annual maxima of daily maximum wet-bulb temperature. (b) Population exposure to extreme heat-humidity events of daily maximum wet-bulb temperature exceeding 35 °C by the end of this century (2081–2100) under SSP5-8.5 scenario, and (c) the corresponding changes in averaged population exposure throughout China with respect to the current state. (d) Contributions of climate, population, and their interaction effects to changes in total population exposure.

Increased exposure to extreme TW$_{max}$ events is significant but depends heavily on future greenhouse gas emissions. The expected exposure under the four emission scenarios sharply diverges above the TW$_{max}$ of about 35 °C, with an increase by a factor of 3 times by the end of this century under SSP1-2.6 scenario with respect to the current climate, but a great factor of about 50 times under SSP5-8.5 scenario. We further decompose population exposure into three components, including the population effect with constant climate but growing population, climate effect with constant population but changing climate, and the interaction effect that results from both changes in climate and population at the same location. Our results show that the population effect would be almost neglected as the vast majority of additional exposure is due to climate change throughout China. The interaction effect generally reduces the annual exposure mainly due to population decrease in the future throughout China. This is true for all warming scenarios. Quantitative evaluation identified that the contribution of climate effect to the additional exposure increase could be greater than 100% (116% ~ 175% among scenarios) by the end of this century.

4. Conclusion and discussion

We first analyzed the expected changes in extreme heat-humidity events in the future across China and also discussed the potential impacts on populations using the CMIP6 model simulations. In response to future warming, extreme heat-humidity events that exceed the physiological survivability limit of 35 °C of the TW$_{max}$ are projected to intensify throughout the 21st century. Some regions in eastern China including the Sichuan basin, which are most densely populated, are also most susceptible to these dangerous heat extremes. Consequently, there is the potential for widespread exposure to the TW$_{max}$ that frequently exceeds postulated theoretical limits of human tolerance by the end of this century. Our evaluations show that the number of extreme heat-humidity events of the TW$_{max}$ exceeding 35 °C presents a sharp increase across China by the end of this century. Especially under the no-mitigation scenario of SSP5-8.5, such extremes are expected to increase by more than 20 days in some regions of eastern China. In addition, more grid cells are anticipated to be exposed to such extreme heat-humidity events in the future and the exposed areas would
be extended to regions of northeastern China and northwestern China.

Further evaluations indicate that climate change would exert a significant effect on additional population exposure to these extreme heat-humidity events throughout China by the end of this century, while the population effect could be generally neglected. Annual exposure is expected to increase by a factor of about 50 times under the SSP5–8.5 scenario; approximately 81% of the population throughout China are anticipated to have at least one chance to experience such extremes by the end of this century. These heat extremes generally pose a severe threat to human health, energy infrastructure, and outdoor activities ranging from agricultural production to military training (Coffel et al 2018). Heat stress would thus be one of the most widely experienced and directly dangerous aspects of climate change throughout China in the coming decades. In this regard, the findings in our study have significant implications to ongoing considerations for climate-change policy.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://esgf-node.llnl.gov/search/cmip6/.

Acknowledgments

This research was jointly supported by the National Natural Science Foundation of China (Grant Nos. 41991284, 42088101, and 42075021).

ORCID iD

Huopo Chen https://orcid.org/0000-0003-0760-8353

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