Climate change impact on “outdoor days” over the United States

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August 22, 2023

Abstract

Here, we introduce the concept of “outdoor days” defined as those relatively pleasant days when most people may enjoy outdoor activities such as walking, jogging, and cycling. Although most climate studies primarily focus on changes in climate mean and/or extremes, projecting response of outdoor days to climate change is particularly important given their relevance to quality of life for communities. Here, we project how climate change reshapes seasonality of US outdoor days: relatively large drops in summer, late spring, and early fall; and a significant increase in winter. However, despite of global warming, annual outdoor days are projected to change only slightly, with notable exceptions. Consistent with recent observations, we project relatively large drops in southeast (-23%), south (-19%), and Ohio Valley (-18%), and a significant increase in northwest (14%) towards the end of the century. Our findings have implications for quality of life in different regions, and for nationwide travel and tourism.

Teaser

We provide new evidence of the impact of global warming on the quality of human life, travel, and tourism in the US.

MAIN TEXT

Introduction

Climate change is a threat multiplier that has significant impacts on all systems and sectors in the world. Future climate projections suggest that the intensity and frequency of climate extremes will increase disproportionately around the globe (*1*, *2*). For instance, global warming at 1.5 and 2 above pre-industrial levels is expected to result in spatially non-uniform increases in climate extremes, such as hot days, heavy rainfalls, and high streamflow (*3*). Some of these impacts tend to expose disparities in vulnerability between developing and developed countries (*2*, *4*, *5*), increasing inequality between countries (*6*), which is among the most serious implications of climate change. Disparity imposed by climate change is manifested not only at a global level but also at local and regional levels. For example, the United States (US), characterized by various climate regimes (*7*) (Fig. S1), a wide range of physical and ecological systems (*8*), and large diversity in socio-economic conditions (*9*, *10*), is facing different types of climate risks across the regions (*11–14*). The disproportionate risks of climate change can, for instance, differentially affect the states’ economies. Tourism, which is one of the largest and fast-flourishing economic industries in the US, is projected to be adversely affected by climate change, especially in prominent metropolitan areas and protected areas of the country (*15*), triggering shifts in tourist preferences and recreation destinations (*16*). It is important to note that this industry is generally susceptible to the number of days with moderate and pleasant temperatures (with no precipitation) in a given region.

We define outdoor days as those days with pleasant weather allowing for outdoor activities (see Materials and Methods section). We assumed that an outdoor day can be defined as a day with an average temperature within the range of 10 to 25 . As shown and discussed later, including in the Supplementary Materials, our conclusions are not sensitive to this assumption. Although we mainly utilized the range of dry-bulb temperature from 10 to 25 to define an outdoor day, an online interactive tool is provided at https://eltahir.mit.edu/globaloutdoordays/ to enable the user to invent their own definition of an outdoor day using dry-bulb temperature, wet-bulb temperature, and precipitation, which also allows comparison between various definitions of outdoor days.

The concept of outdoor days is of significant importance to quality of life for communities since a pleasant day occurs more frequently compared to days with extreme temperature (*17–19*). Somewhat similar concepts to outdoor days have been proposed previously at multiple spatial and temporal scales. Examples include global-scale studies (*18*, *20*), national-scale studies (*17*,*19*, *21–23*), and local-scale studies (*16*,*24–26*). However, previous studies for the US are limited in their number and largely confined to local scales. A few studies considered how climate change is likely to increase the number of hot days and reduce the number of days with mild weather (*16*).

To mitigate climate change, the participation of the US in global efforts is crucial since the US is a significant emitter of anthropogenic greenhouse gases - the main drivers of global warming - and consequently in part responsible for climate change (*27*). The success of these mitigation policies depends largely on public opinion, support, and behavior (*28*, *29*). However, there is a large portion of the US population who considers climate change as a hoax (*30*). Recent surveys found that more than half of Americans do not perceive climate change as a threat in their lifetime, with a great variation based on political views (*31*), indicating a largely politicized issue. The divide between these two groups may stem from a lack of awareness regarding the impacts of climate change. For instance, a study by Maibach et al. (*32*) reported that around 61% of the US population lacks adequate knowledge about the impacts of climate change on human health. Differences in Americans' perspectives on climate change are leading to conflicting climate policies (*28*). The withdrawal of the US from the Paris Agreement in 2017 was partially a manifestation of these debates and has its roots in these different political perspectives.

Achieving global climate change mitigation requires a substantial increase in public awareness and subsequent public support for climate change policies (*33*). A wealth of theoretical, empirical, and experimental evidence of climate change processes from various perspectives could improve public understanding of the science of climate change. To date, studies on the impacts of climate change mostly focus on mean climate conditions and/or frequency and magnitude of climate extremes (*7*, *34–44*). However, we propose a novel perspective that highlights the potential impact of climate change on the patterns of outdoor days. This approach has the capacity to bring the science of climate change closer to human societies, resulting in broader implications for public awareness and engagement.

Temperature rise associated with climate change might trigger irreversible changes in the spatial and temporal patterns of outdoor days. Studying the change in patterns of outdoor days – a highly relevant variable to people's everyday activities – would provide more convincing evidence as to why we should address climate change. The spatial-temporal disparity in the intensity of these changes and their impacts across the US are still understudied. Therefore, the aim of the current research is twofold: (i) investigate, based on observations, the spatiotemporal variation of outdoor days across the US and their historical trends, and (ii) project future regional climate change in terms of outdoor days in the US based on multiple climate models.

Results

Observed changes in outdoor days

Here, we use the state-of-the-art ERA5 reanalysis to present a snapshot of outdoor days (Fig. 1). Based on our analysis, most of the population living in the US enjoyed frequent outdoor days (on average, about 172 days per year in the continental US) over the past several decades, although significant regional differences exist (Fig 1a). In particular, the southern US areas located south of 40° N, such as Hawaii, California, and Florida, stand out with more frequent outdoor days, compared to the northern regions. From a seasonal perspective, a peak of outdoor days occurs during summer when warm temperatures prevail (on average, about 56 days per summer in the continental US; Fig. S2). Meanwhile, outdoor activities are highly limited during winter due to cold conditions (on average, about 1 day per winter in the areas located north of 40° N).

A trend analysis reveals that the unprecedented recent warming, as a consequence of anthropogenic climate change, has led to marginal changes in annual outdoor days across the US (Fig. 1b) but a significant shift in the seasonality (Fig. S3). The results of the trend analysis in annual outdoor days show a weak north-south gradient (Fig. 1b). Northern regions, including Northeast, Upper Midwest, Northern Rockies and Plains, and Northwest, show weak increasing trends of outdoor days (Fig. S4), benefiting from recent climate change. Whereas weak declining trends are found in the South and Southeast. However, it is important to note that responses of outdoor days to increasing greenhouse gas concentration are likely to vary substantially across seasons (Fig. S3). The largest reduction is found in boreal summer over the south-eastern US, while the increasing trend is evident in relatively cold months in the north-western US. These trends in outdoor days may contribute to the evident disparity in climate impacts between the northwest (e.g., Washington) and the southeast (e.g., Florida).

Projected changes in temperature and outdoor days

By utilizing NASA Earth Exchange Global Daily Downscaled Projections (NEX-GDDP-CMIP6), we project how the climate system in the US responds to externally imposed radiative forcing, in terms of temperature, assuming low and high emissions scenarios (Fig. 2). It is projected that an increase in temperature will exceed at least 5 °C across the US by 2100 under the SSP5-8.5 scenario, while the largest increases in temperature are expected in the northern US (Fig. 2a). Regionally, the Northeast, Upper Midwest, and Northern Rockies and Plains are likely to experience significant warming of 6 to 7 (Fig. 2b). A similar but relatively weak warming trend is projected in the Northwest, West, South, and Southeast. The overall trends in temperature indicate nearly uniform warming across the different climate regions in the country. Note that there is a high inter-model agreement on the sign of the change across different generations of models (Fig. 2 and Fig. S5), and the rate of warming is significantly lower under the low emissions scenario compared to the high emissions scenario (Fig. 2).

The story is different for future anticipated changes in outdoor days. The projected warming is likely to alter the seasonality of outdoor days significantly, which has important implications for the quality of life in different communities (Fig. 3). For example, statistically significant and robust decreases in outdoor days are expected especially in the middle of summer (i.e., days too hot for outdoor activities), while some more days in early spring and late fall and a significant increase in winter are projected (i.e., "broadening of the shoulders"; Figs. S6-S7). Interestingly, the balance of annual outdoor days is little changed over most US climate regions with two notable exceptions. The northwest exhibits higher increases in outdoor days, by 14 %, driven by small decreases in outdoor days during summer and relatively large increases during winter. Meanwhile, we project considerable decreases in outdoor days during warm months that exceed the projected increases during cold months, leading to significant drops of outdoor days in the southeast (-23 %), south (-19 %), and Ohio Valley (-18 %). These findings highlight the varying impacts of climate change on outdoor days across different regions.

Consequently, the nearly uniform warming translates into a significant northwest-southeast disparity in the projected change of annual outdoor days (Fig. 4). The Ohio Valley, South, and Southeast, which are relatively less prosperous by national standards (Fig. S8), could be disproportionately affected by the negative impacts of climate change, along with reduced annual outdoor days, limiting outdoor activities. At a local scale, major metropolitan areas like Chicago, Houston, and Charlotte, known for their high tourism rates, may face a shortage of outdoor days by the end of this century (Fig. S9). Note that people in these regions are relatively more skeptical about climate change and are less supportive of policies to mitigate climate change (*45,46*). Meanwhile, despite of global warming, the overall impact of higher temperatures leads to more, or no change, in annual outdoor days, especially in relatively wealthy states of the north-western US (Fig. S8). Achieving net-zero carbon emissions by the century's second half (i.e., SSP1-2.6 scenario) could significantly address the issue of reduced outdoor days, thereby mitigating the risks of climate change. Failure to do so could pose a threat to the tourism and recreation industries, especially in Los Angeles, Houston, New York, Phoenix, Chicago, and Charlotte (Fig. S9). The projected trends in outdoor days from the NEX-GDDP-CMIP6 Global Climate Models (GCMs) is consistent with the observed trends (Fig. 1b), and the projected trends from CMIP5 models (Fig. S10), indicating a robust signal of climate change.

We propose an explanation for these projections. The changes in outdoor days are dictated by the position of the probability distribution of daily mean temperature relative to the thresholds defining outdoor days (Fig. S11). For example, the projected probability distributions of temperature especially in the Ohio Valley, South, and Southeast are likely to be far away from the conditions for thermal comfort, limiting outdoor activities significantly. On the other hand, the probability distribution of temperature in the northern US, in relatively cold months of the year, is projected to approach favorable conditions for outdoor days, resulting in more days.

Discussion and Conclusions

We reviewed several studies that focused on mild weather conditions using various indices such as thermal comfort (*25*), good weather (*26*), comfortable days (*23*), thermal comfort condition (*20*, *21*), outdoor thermal comfort (*24*), mild weather (*17–19*), and mild days (*16*). However, these studies are geographically limited to a few regions, such as Sydney (*25*), Washington D.C and New York (*26*), Indiana (*16*), China (*17*, *19*, *21*, *23*), and Singapore urban park (*24*). In addition, there is a limited understanding of how pleasant weather conditions could respond to anthropogenic climate change. Although a few studies projected a change in pleasant weather conditions, they applied one or few GCMs, and thus could not address the uncertainty of future projections (*18*,*19*, *21*). To the best of our knowledge, our study is the first to demonstrate the climate change impact on the climate of outdoor days in the US with significant implications for future quality of life in different climate regions, and for the distribution of the economic potential of travel and tourism. In addition, the versatility of data (i.e., ERA5 reanalysis, 31 CMIP5 models, 10 CMIP6 models, and 32 NEX-GDDP-CMIP6 models; Table S1), spatial scale, and various ways to define "outdoor day" (see below for details) are unprecedented in previous studies.

Unlike the nearly uniform warming across seasons and the US, recent accelerated climate change has significantly shifted the seasonality of outdoor days with significant reductions of outdoor days during warmer months and a relatively moderate increase in outdoor days during colder months across all sub-regions. In particular, anthropogenic climate change negatively affected the Southeast, South, and Ohio Valley, featuring a decrease in outdoor days. A comparable climate change might benefit the Northwest by gaining more outdoor days, resulting in a significant northwest-southeast disparity and implying disproportionate risks of climate change. Toward the end of the twenty-first century, high emissions scenarios from CMIP5, CMIP6, and NEX-GDDP-CMIP6 models consistently point to significant, robust, and disproportionate risks of climate change in outdoor days. Where we identified the largest reduction in outdoor days such as in the Southeast, South, and Ohio Valley regions, Howe et al. (*28*) and Marlon et al. (*47*) point out that people largely do not hear about global warming in the media or discuss it at least occasionally compared to other regions in the US.

Despite the large consistency in the patterns of change in outdoor days, as revealed by the results from various models (Table S1) used in the current study, our findings based on raw GCMs from the CMIP5/CMIP6 archive must be interpreted with some caution. First, the systematic biases in temperature projections, especially in GCMs from the CMIP5 archive, could possibly affect the future projections of outdoor days (Figs. S12-S13). Although the general characteristics of outdoor days are well captured by CMIP models for the reference period, biases in GCM outputs can bleed into the conclusions. To address this issue, the bias-corrected NASA NEX-GDDP-CMIP6 dataset was applied.

Second, there is no universal definition of ‘outdoor days’ as defining them is necessarily somewhat subjective (*18*). To define mild weather similar to outdoor days presented herein, previous studies have considered various climate variables, such as temperature (*19*,*22*), dew point temperature (*18*), precipitation (*18*,*26*), relative humidity, wind speed, sunshine duration (*17*,*19*), shortwave radiation, diffuse shortwave radiation, and longwave radiation (*25*). Nevertheless, there is a consensus in the literature that temperature is the primary variable (but not always), although the threshold to define mild weather varies considerably.

In our study, we primarily defined an outdoor day as a day with a temperature ranging from 10 to 25 . However, we find that our analysis and conclusions are robust and not sensitive to the choices of threshold or the specific variable considered, such as daytime temperature, daily mean dry-bulb temperature, wet-bulb temperature, and precipitation (Fig. 5). Rather than adhering strictly to a single definition, our study suggests a more flexible definition of an outdoor day (Fig. 5). To facilitate this, we have developed an online interactive tool available at https://eltahir.mit.edu/globaloutdoordays/. This tool allows users to explore different definitions of an outdoor day, which also allows comparison between various definitions of outdoor days. This operational and flexible definition takes individual differences into account when defining an outdoor day, providing a more tailored understanding of outdoor day patterns.

Unlike previous studies, wet-bulb temperature is used in “outdoor days” definition. Considering relative humidity, which is embedded in the wet-bulb temperature, highlights the important role of humidity in shaping the human’s ability, in physiological terms, to resist hot weather. Similar to the results using dry-bulb temperature, a significant northwest-southeast disparity is found in the projected change of annual outdoor days defined using wet-bulb temperature, but its magnitude is smaller (Fig. S14). For instance, annual outdoor days are likely to decrease by about 10% at the Charlotte city in Southeast (Fig. S15).

The findings reported here have important implications for understanding the regional climate response in the US to rising greenhouse-gas concentrations. We project that some of the US regions where the populations are known to be more skeptical about the anthropogenic cause of climate change, and those with attractive tourism and recreation spots for outdoor activities, are likely to face negative impacts of climate change, in the form of reduced outdoor days. Life, travel, and tourism in Florida will be very different if and when the number of outdoor days is cut as projected in this study. Hence, our findings not only identify specific regional hotspots and better inform communities of future climate change, but can also be interpreted in terms of future quality of life for those communities, and in terms of the future economic potential of travel and tourism in different climate regions of the US.

Integrating reliable information on potential climate change impacts from various perspectives, including those related to pleasant weather conditions (expressed here in terms of outdoor days), will help, from one side, decision-makers to develop effective adaptation strategies (e.g., adjustments in tourism and outdoor activity seasons), and on the other side, consolidate more cogent evidence to gather public support to climate mitigation policies.

Materials and Methods

Observations and CMIP data

Temperature, dew point temperature, and surface pressure data at a spatial resolution of 0.25 and a three-hourly temporal resolution were taken from the ERA5 reanalysis (*48*). Daily temperature projections over the 1976–2100 were obtained from 31 CMIP5 models and 32 bias-corrected NASA Earth Exchange (NEX) Global Daily Downscaled Projections (NEX-GDDP-CMIP6 models at a spatial resolution of 0.25). The CMIP5 models are driven by historical forcing and Representative Concentration Pathway 8.5 (RCP8.5) scenario (*49*) and the CMIP6 and NEX-GDDP-CMIP6 models are driven by historical forcing, Shared Socioeconomic Pathway 1-2.6 (SSP1-2.6), and SSP5-8.5 scenarios (*50*). The radiative forcing in RCP8.5 (referred to as a ‘business as usual scenario’) rises continuously to reach 8.5 Wm^{-2} by the year 2100. RCP8.5 is approximately equivalent to SSP5-8.5 (*51*). As an optimistic climate change scenario, SSP1-2.6 was applied (*51*). Only one ensemble member was used for each model run. The list of GCMs used in this study was provided in Table S1 with more details. Wet-bulb temperature (TW) was computed using 3-hourly surface temperature, humidity, and pressure derived from the CMIP outputs and the ERA5 reanalysis based on the Davies-Jones method (*52*). Outputs from CMIP5 and CMIP6 models were re-gridded to 1.5deg x 1.5deg grid and 1deg x 1deg grid, respectively.

Definition of 'Outdoor days'

The concept of an "outdoor day" in this study was defined as a day with thermal comfort conditions enabling most people to do outdoor activities. Specifically, it is determined based on the daily dry-bulb temperature falling in the range of 10 to 25 , or alternatively, the daily wet-bulb temperature lying within the range of 8 to 15 (Fig. S16). While our study primarily reported results on the range of dry-bulb temperature from 10 to 25 as the one possible defining criterion for outdoor days, we introduced a more flexible definition compared to previous works (Fig. 5; refer to https://eltahir.mit.edu/globaloutdoordays/). This flexibility in defining outdoor days is a novel contribution, making the concept more advanced and applicable in the field for investigating pleasant weather conditions. By considering dry-bulb and wet-bulb temperature ranges in addition to precipitation and providing a more adaptable definition, this study enhances the understanding and assessment of outdoor days in relation to thermal comfort, allowing for a more comprehensive evaluation of weather conditions suitable for outdoor activities.

REFERENCES AND NOTES

1. Y. Hirabayashi, R. Mahendran, S. Koirala, L. Konoshima, D. Yamazaki, S. Watanabe, H. Kim, S. Kanae, Global flood risk under climate change.*Nature Clim Change* . **3** , 816–821 (2013).

2. C.-E. Park, S.-J. Jeong, M. Joshi, T. J. Osborn, C.-H. Ho, S. Piao, D. Chen, J. Liu, H. Yang, H. Park, B.-M. Kim, S. Feng, Keeping global warming within 1.5 degC constrains emergence of aridification.*Nature Clim Change* . **8** , 70–74 (2018).

3. H. Shiogama, T. Hasegawa, S. Fujimori, D. Murakami, K. Takahashi, K. Tanaka, S. Emori, I. Kubota, M. Abe, Y. Imada, M. Watanabe, D. Mitchell, N. Schaller, J. Sillmann, E. M. Fischer, J. F. Scinocca, I. Bethke, L. Lierhammer, J. Takakura, T. Trautmann, P. Doll, S. Ostberg, H. M. Schmied, F. Saeed, C.-F. Schleussner, Limiting global warming to 1.5 degC will lower increases in inequalities of four hazard indicators of climate change. *Environ. Res. Lett.* **14** , 124022 (2019).

4. G. Althor, J. E. M. Watson, R. A. Fuller, Global mismatch between greenhouse gas emissions and the burden of climate change. *Sci Rep* . **6** , 20281 (2016).

5. R. Mendelsohn, A. Dinar, L. Williams, The distributional impact of climate change on rich and poor countries. *Environment and Development Economics* . **11** , 159–178 (2006).

6. N. S. Diffenbaugh, M. Burke, Global warming has increased global economic inequality. *Proceedings of the National Academy of Sciences* . **116** , 9808–9813 (2019).

7. USGCRP, 2017: Climate Science Special Report: Fourth National Climate Assessment, Volume I [Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, 470 pp., doi: 10.7930/J0J964J6.

8. C. N. Jenkins, K. S. Van Houtan, S. L. Pimm, J. O. Sexton, US protected lands mismatch biodiversity priorities. *Proc. Natl. Acad. Sci. U.S.A.* **112** , 5081–5086 (2015).

9. K. E. Salinas, H. B. Nguyen, S. C. Kamran, The invisible minority: A call to address the persistent socioeconomic diversity gap in U.S. medical schools and the physician workforce. *Front. Public Health* . **10** , 924746 (2022).

10. D. R. Williams, S. A. Mohammed, J. Leavell, C. Collins, Race, socioeconomic status, and health: Complexities, ongoing challenges, and research opportunities: Race, SES, and health. *Annals of the New*

York Academy of Sciences . **1186** , 69–101 (2010).

11. A. G. Berberian, D. J. X. Gonzalez, L. J. Cushing, Racial Disparities in Climate Change-Related Health Effects in the United States. *Curr Envir Health Rpt* . **9** , 451–464 (2022).

12. E.-L. Marjakangas, A. Santangeli, A. Johnston, N. L. Michel, K. Prince, A. Lehikoinen, Effects of diversity on thermal niche variation in bird communities under climate change. *Sci Rep* . **12** , 21810 (2022).

13. K. T. Smiley, I. Noy, M. F. Wehner, D. Frame, C. C. Sampson, O. E. J. Wing, Social inequalities in climate change-attributed impacts of Hurricane Harvey. *Nat Commun* . **13** , 3418 (2022).

14. C. Zanocco, J. Flora, H. Boudet, Disparities in self-reported extreme weather impacts by race, ethnicity, and income in the United States. *PLOS Clim* . **1** , e0000026 (2022).

15. N. A. Fisichelli, G. W. Schuurman, W. B. Monahan, P. S. Ziesler, Protected Area Tourism in a Changing Climate: Will Visitation at US National Parks Warm Up or Overheat? *PLoS ONE* . **10** , e0128226 (2015).

16. J. Day, N. Chin, S. Sydnor, M. Widhalm, K. U. Shah, L. Dorworth, Implications of climate change for tourism and outdoor recreation: an Indiana, USA, case study. *Climatic Change* . **169** , 29 (2021).

17. L. Lin, E. Ge, C. Chen, M. Luo, Mild weather changes over China during 1971–2014: Climatology, trends, and interannual variability.*Sci Rep* . **9** , 2419 (2019).

18. K. van der Wiel, S. B. Kapnick, G. A. Vecchi, Shifting patterns of mild weather in response to projected radiative forcing. *Climatic Change* . **140** , 649–658 (2017).

19. J. Zhang, Q. You, G. Ren, S. Ullah, Projected changes in mild weather frequency over China under a warmer climate. *Environ. Res. Lett.* **17** , 114042 (2022).

20. J. Zhang, Q. You, G. Ren, S. Ullah, I. Normatov, D. Chen, Inequality of Global Thermal Comfort Conditions Changes in a Warmer World.*Earth's Future* . **11** (2023), doi:10.1029/2022EF003109.

21. X.-J. Gao, J. Wu, Y. Shi, J. Wu, Z.-Y. Han, D.-F. Zhang, Y. Tong, R.-K. Li, Y. Xu, F. Giorgi, Future changes in thermal comfort conditions over China based on multi-RegCM4 simulations. *Atmospheric and Oceanic Science Letters* . **11** , 291–299 (2018).

22. H. M. Hanlon, D. Bernie, G. Carigi, J. A. Lowe, Future changes to high impact weather in the UK. *Climatic Change* . **166** , 50 (2021).

23. J. Wu, X. Gao, F. Giorgi, D. Chen, 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 (2017).

24. S. L. Heng, W. T. L. Chow, How 'hot' is too hot? Evaluating acceptable outdoor thermal comfort ranges in an equatorial urban park.*Int J Biometeorol* . **63** , 801–816 (2019).

25. J. Spagnolo, R. de Dear, A field study of thermal comfort in outdoor and semi-outdoor environments in subtropical Sydney Australia.*Building and Environment* . **38** , 721–738 (2003).

26. T. H. Zhang, Weather Effects on Social Movements: Evidence from Washington, D.C., and New York City, 1960–95. *Weather, Climate, and Society* . **8** , 299–311 (2016).

27. Intergovernmental Panel On Climate Change, *Climate Change 2021 – The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*(Cambridge University Press, ed. 1, 2023; https://www.cambridge.org/core/product/identifier/9781009157896/type/book).

28. P. D. Howe, M. Mildenberger, J. R. Marlon, A. Leiserowitz, Geographic variation in opinions on climate change at state and local scales in the USA. *Nature Clim Change* . **5** , 596–603 (2015).

29. G. Sparkman, N. Geiger, E. U. Weber, Americans experience a false social reality by underestimating popular climate policy support by nearly half. *Nat Commun* . **13** , 4779 (2022).

30. D. Sarathchandra, K. Haltinner, How Believing Climate Change is a "Hoax" Shapes Climate Skepticism in the United States.*Environmental Sociology* . **7** , 225–238 (2021).

31. M. Brenan, L. Saad, Global warming concern steady despite some partisan shifts. *Gallup Politics* . **8** (2018).

32. E. W. Maibach, J. M. Kreslake, C. Roser-Renouf, S. Rosenthal, G. Feinberg, A. A. Leiserowitz, Do Americans Understand That Global Warming Is Harmful to Human Health? Evidence From a National Survey.*Annals of Global Health* . **81** , 396 (2015).

33. T. M. Lee, E. M. Markowitz, P. D. Howe, C.-Y. Ko, A. A. Leiserowitz, Predictors of public climate change awareness and risk perception around the world. *Nature Clim Change* . **5** , 1014–1020 (2015).

34. Y.-W. Choi, D. J. Campbell, J. C. Aldridge, E. A. B. Eltahir, Near-term regional climate change over Bangladesh. *Clim Dyn* .**57** , 3055–3073 (2021).

35. Y.-W. Choi, D. J. Campbell, E. A. B. Eltahir, Near-term regional climate change in East Africa. *Clim Dyn* (2022), doi:10.1007/s00382-022-06591-9.

36. Y. Choi, E. A. B. Eltahir, Heat Stress During Arba'een Foot-Pilgrimage (World's Largest Gathering) Projected to Reach "Dangerous" Levels Due To Climate Change. *Geophysical Research Letters* . **49** (2022), doi:10.1029/2022GL099755.

37. Y.-W. Choi, E. A. B. Eltahir, Uncertainty in Future Projections of Precipitation Decline over Mesopotamia. *Journal of Climate* .**36** , 1213–1228 (2023).

38. A. Tuel, E. A. B. Eltahir, Why Is the Mediterranean a Climate Change Hot Spot? *Journal of Climate* . **33** , 5829–5843 (2020).

39. W. Thiery, S. Lange, J. Rogelj, C.-F. Schleussner, L. Gudmundsson, S. I. Seneviratne, M. Andrijevic, K. Frieler, K. Emanuel, T. Geiger, D. N. Bresch, F. Zhao, S. N. Willner, M. Buchner, J. Volkholz, N. Bauer, J. Chang, P. Ciais, M. Dury, L. Francois, M. Grillakis, S. N. Gosling, N. Hanasaki, T. Hickler, V. Huber, A. Ito, J. Jagermeyr, N. Khabarov, A. Koutroulis, W. Liu, W. Lutz, M. Mengel, C. Muller, S. Ostberg, C. P. O. Reyer, T. Stacke, Y. Wada, Intergenerational inequities in exposure to climate extremes. *Science* . **374** , 158–160 (2021).

40. E. M. Fischer, R. Knutti, Anthropogenic contribution to global occurrence of heavy-precipitation and high-temperature extremes.*Nature Clim Change* . **5** , 560–564 (2015).

41. E.-S. Im, J. S. Pal, E. A. B. Eltahir, Deadly heat waves projected in the densely populated agricultural regions of South Asia. *Sci. Adv.* **3** , e1603322 (2017).

42. S. Kang, E. A. B. Eltahir, North China Plain threatened by deadly heatwaves due to climate change and irrigation. *Nat Commun* .**9** , 2894 (2018).

43. J. S. Pal, E. A. B. Eltahir, Future temperature in southwest Asia projected to exceed a threshold for human adaptability. *Nature Clim Change* . **6** , 197–200 (2016).

44. S. Pfahl, P. A. O'Gorman, E. M. Fischer, Understanding the regional pattern of projected future changes in extreme precipitation.*Nature Clim Change* . **7** , 423–427 (2017).

45. M. J. Hornsey, E. A. Harris, P. G. Bain, K. S. Fielding, Meta-analyses of the determinants and outcomes of belief in climate change. *Nature Clim Change* . **6** , 622–626 (2016).

46. A. M. McCright, S. T. Marquart-Pyatt, R. L. Shwom, S. R. Brechin, S. Allen, Ideology, capitalism, and climate: Explaining public views about climate change in the United States. *Energy Research & Social Science* . **21** , 180–189 (2016).

47. J. Marlon, L. Neyens, P. Howe, M. Mildenberger, A. Leiserowitz, Yale climate opinion maps 2021. Yale Program on Climate Change Communication. (2022), (available at https://climatecommunication.yale.edu/visualizations-data/ycom-us/).

48. H. Hersbach, B. Bell, P. Berrisford, S. Hirahara, A. Horanyi, J. Munoz-Sabater, J. Nicolas, C. Peubey, R. Radu, D. Schepers, A. Simmons, C. Soci, S. Abdalla, X. Abellan, G. Balsamo, P. Bechtold, G. Biavati, J. Bidlot, M. Bonavita, G. Chiara, P. Dahlgren, D. Dee, M. Diamantakis, R. Dragani, J. Flemming, R. Forbes, M. Fuentes, A. Geer, L. Haimberger, S. Healy, R. J. Hogan, E. Holm, M. Janiskova, S. Keeley, P. Laloyaux, P. Lopez, C. Lupu, G. Radnoti, P. Rosnay, I. Rozum, F. Vamborg, S. Villaume, J. Thepaut, The ERA5 global reanalysis. *Q.J.R. Meteorol. Soc.* **146** , 1999–2049 (2020).

49. K. E. Taylor, R. J. Stouffer, G. A. Meehl, An Overview of CMIP5 and the Experiment Design. *Bulletin of the American Meteorological Society* . **93** , 485–498 (2012).

50. V. Eyring, S. Bony, G. A. Meehl, C. A. Senior, B. Stevens, R. J. Stouffer, K. E. Taylor, Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization. *Geoscientific Model Development* . **9** , 1937–1958 (2016).

51. S. Russo, J. Sillmann, S. Sippel, M. J. Barcikowska, C. Ghisetti, M. Smid, B. O'Neill, Half a degree and rapid socioeconomic development matter for heatwave risk. *Nat Commun* . **10** , 136 (2019).

52. R. Davies-Jones, An Efficient and Accurate Method for Computing the Wet-Bulb Temperature along Pseudoadiabats. *Monthly Weather Review* . **136** , 2764–2785 (2008).

Acknowledgments

General: We acknowledge the World Climate Research Programme's Working Group on Coupled Modelling, which is responsible for CMIP, and we thank the climate modeling groups for producing and making available their model output.

Funding:

Abdul Latif Jameel Water and Food Systems Lab (J-WAFS) at MIT (EE)

MIT Climate Grand Challenges project: Jameel Observatory- Climate Resilience Early Warning System Network (CREWSnet) (EE)

Author contributions:

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Visualization: YC, MK

Supervision: EABE, YC, MK

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Writing—review & editing: EABE, YC, MK

Competing interests: All other authors declare they have no competing interests.

Data and materials availability: All data needed to evaluate the conclusions in the paper are present in the paper and/or the Supplementary Materials.

Figures and Tables

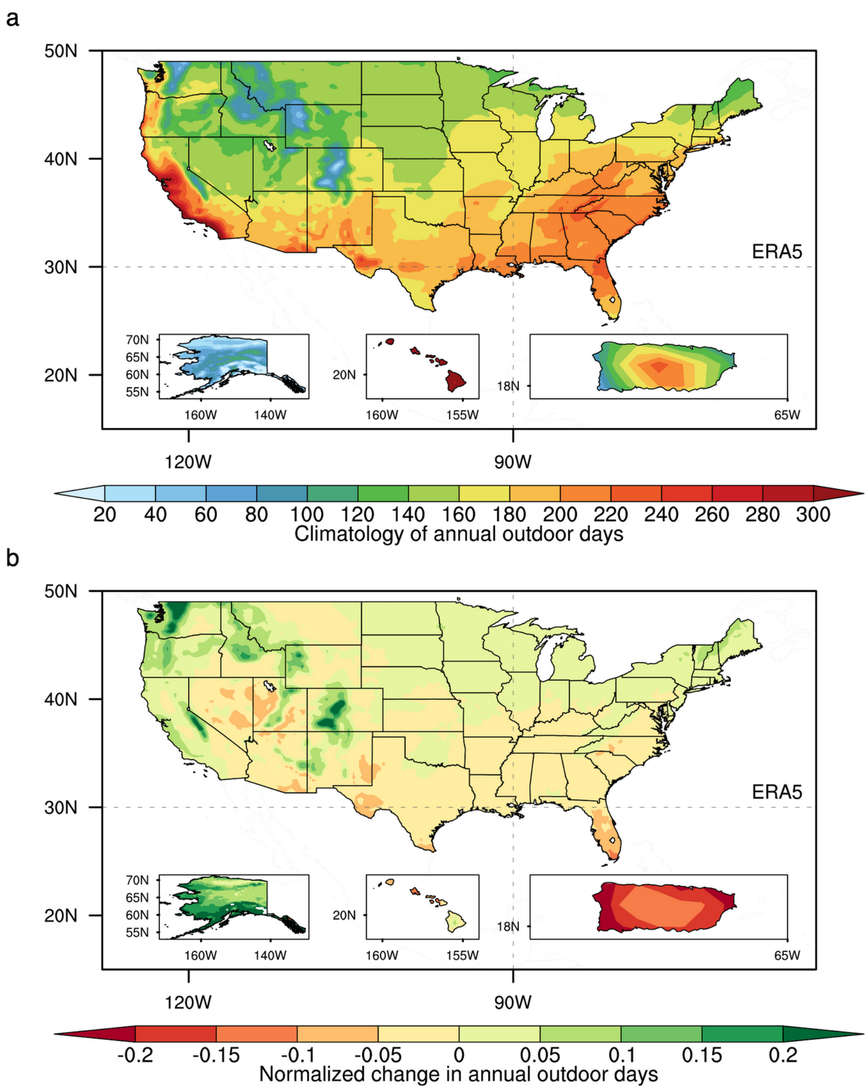


Fig. 1. Spatial distribution of outdoor days in the United States. a) Climatology of annual outdoor days for the period 1959-2021. b) Normalized change in annual outdoor days in 1991–2020 with respect to 1961-1990. The changes are normalized by the 1961-1990 mean. These maps are derived from ERA5.

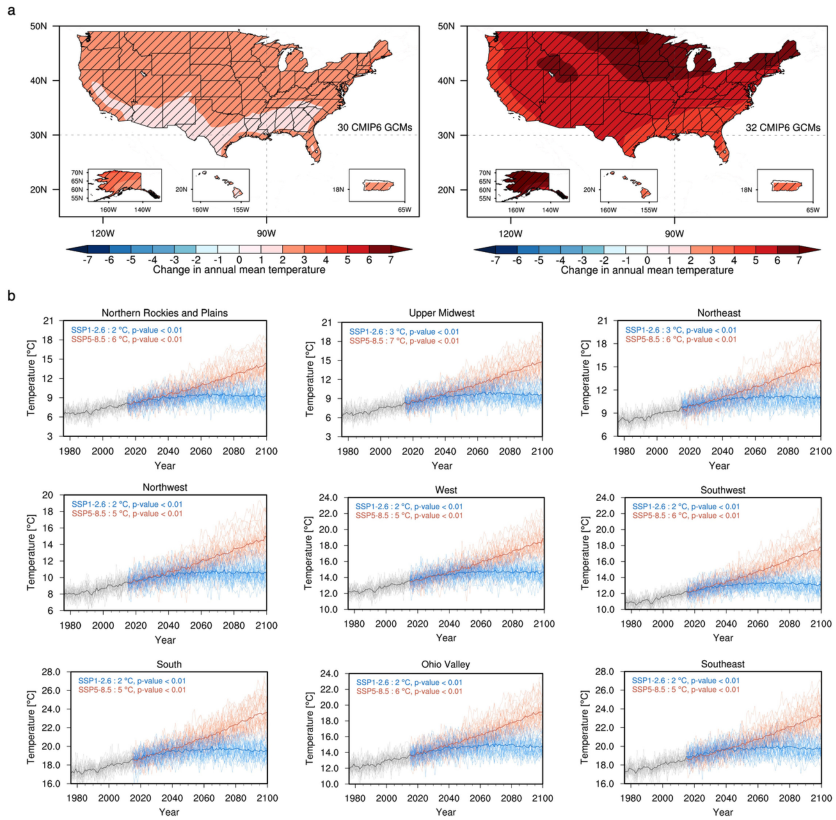


Fig. 2. Projected change in temperature in the United States. a) Spatial distribution of change in annual mean temperature in 2071-2100 with respect to 1976-2005, derived from 30 NEX-GDDP-CMIP6 GCMs under SSP1-2.6 scenario (top left) and 32 NEX-GDDP-CMIP6 GCMs under SSP5-8.5 scenario (top right). Superimposed hatching in a) indicates that more than 80% of the models agree on the sign of the change. b) Time series of temperature for nine sub-regions derived from NEX-GDDP-CMIP6 GCMs under SSP1-2.6 (blue lines) and SSP5-8.5 (red lines) scenarios. Thick solid line in b) indicates an ensemble mean of NEX-GDDP-CMIP6 models. Difference (2071–2100 minus 1976–2005) in temperature is represented in each plot. The p-value for the linear trend is based on the nonparametric Mann–Kendall test.

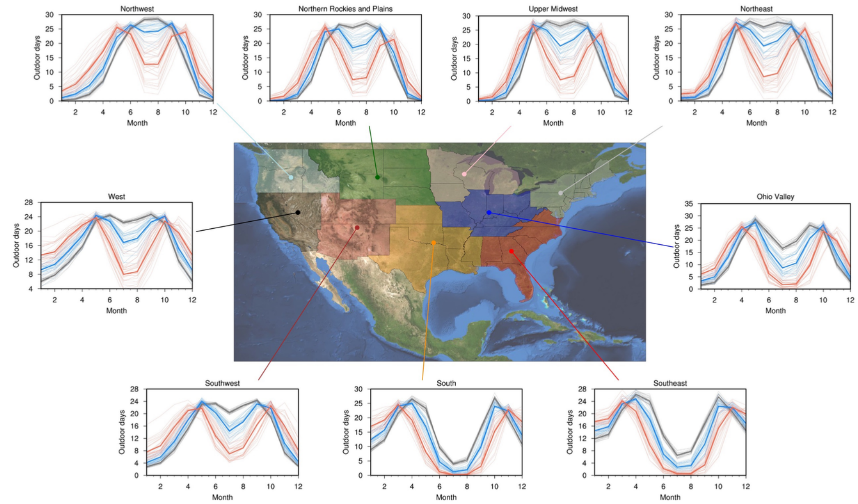


Fig. 3. Seasonal cycle of outdoor days. Seasonal cycle of outdoor days in the United States for the periods 1976-2005 under historical forcing (grey lines) and 2071-2100 under SSP1-2.6 (blue lines) and SSP5-8.5 (red lines) scenarios, derived from NEX-GDDP-CMIP6 GCMs. Thick solid line indicates an ensemble mean of NEX-GDDP-CMIP6 models. The background image was obtained from NASA Visible Earth.

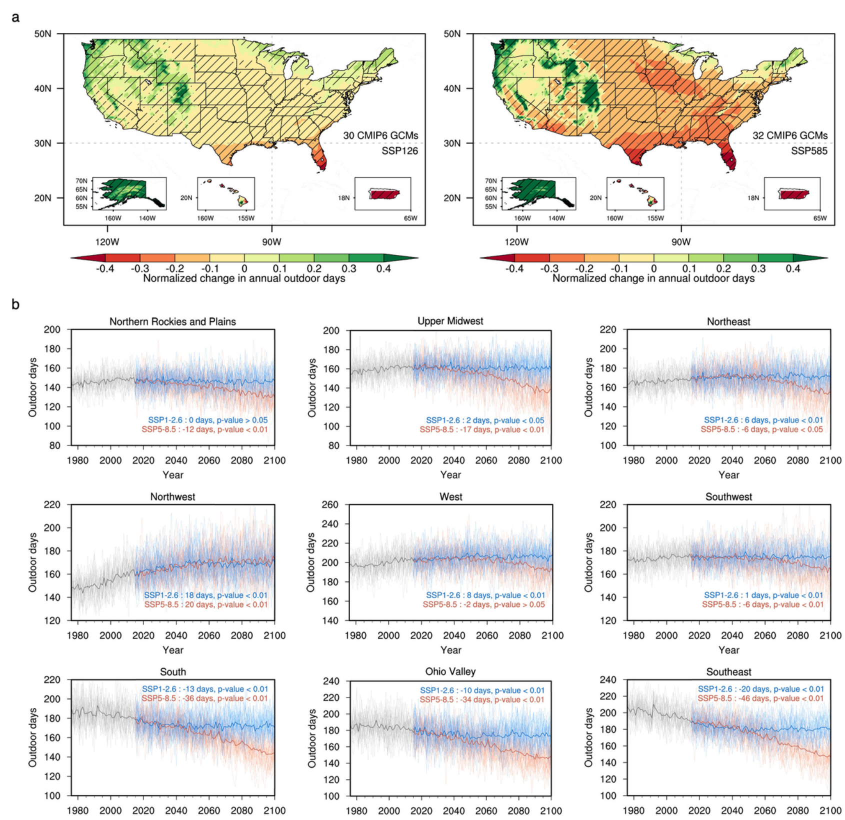
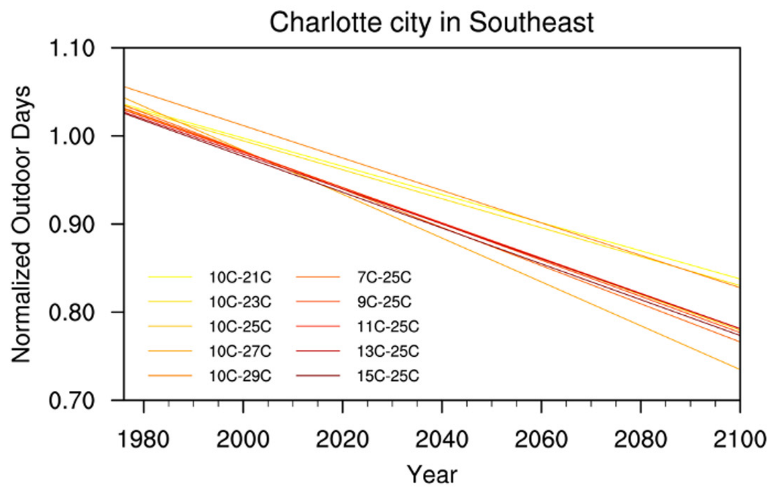
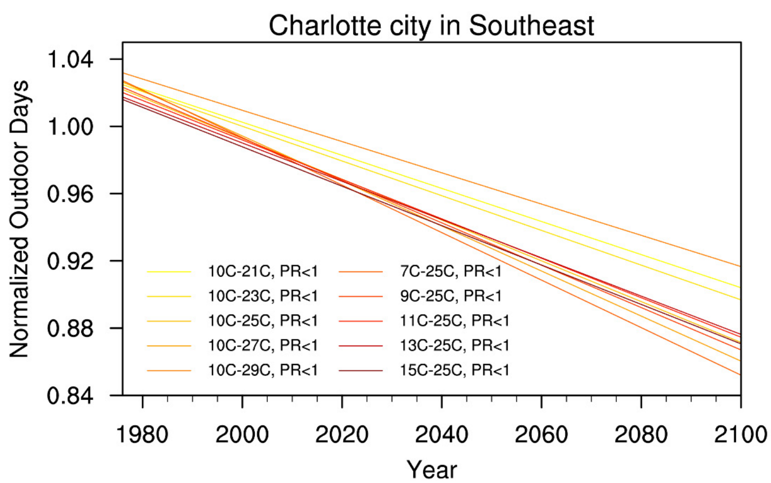


Fig. 4. Projected change in annual outdoor days in the United States. a) Spatial distribution

of normalized change in annual outdoor days in 2071-2100 with respect to 1976-2005, derived from 30 NEX-GDDP-CMIP6 GCMs under SSP1-2.6 scenario (top left) and 32 NEX-GDDP-CMIP6 GCMs under SSP5-8.5 scenario (top right). Superimposed hatching in a) indicates that more than 80% of models agree on the sign of the change. b) Time series of annual outdoor days for nine sub-regions derived from NEX-GDDP-CMIP6 GCMs under SSP1-2.6 (blue lines) and SSP5-8.5 (red lines) scenarios. Thick solid line in b) indicates an ensemble mean of NEX-GDDP-CMIP6 models. Difference (2071–2100 minus 1976–2005) in the number of annual outdoor days is represented in each plot. The p-value for the linear trend is based on the nonparametric Mann–Kendall test.


Charlotte city in Southeast
Normalized Outdoor Days
1.10
1.00
0.90
0.80
0.70
1980
2000
2020
2040
2060
2080
2100
Year
10C-21C
10C-23C
10C-25C
10C-27C
10C-29C
7C-25C
9C-25C
11C-25C
13C-25C
15C-25C


Charlotte city in Southeast
Normalized Outdoor Days
1.04
1.00
0.96
0.92
0.88
0.84
1980
2000
2020
2040
2060
2080
2100
Year
10C-21C, PR<1
10C-23C, PR<1
10C-25C, PR<1
10C-27C, PR<1
10C-29C, PR<1
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13C-25C, PR<1
15C-25C, PR<1

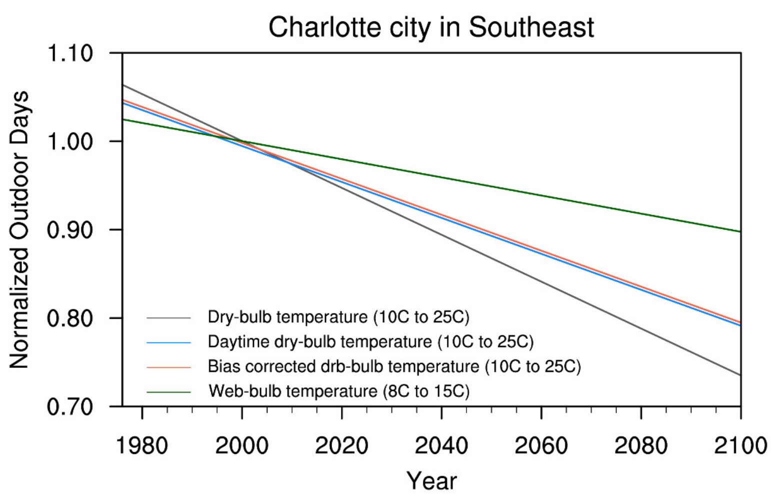
Charlotte city in Southeast
Normalized Outdoor Days
1.10
1.00
0.90
0.80
0.70
1980
2000
2020
2040
2060
2080
2100
Year
Dry-bulb temperature (10C to 25C)
Daytime dry-bulb temperature (10C to 25C)
Bias corrected drb-bulb temperature (10C to 25C)
Web-bulb temperature (8C to 15C)

Fig. 5. Projected change in annual outdoor days at Charlotte city in Southeast, United States. Trends in normalized annual outdoor days for Charlotte city for the period 1976-2100 derived from an ensemble mean of 32 NEX-GDDP-CMIP6 GCMs (top and middle) and MPI-ESM1-2-LR of the CMIP6 archive (bottom) under the historical and SSP5-8.5 scenarios using various definitions of outdoor days. The best-fit linear regression lines are shown. The number of annual outdoor days is normalized by the 1976-2005 mean. Various definitions and variables are indicated in each plot. Dry-bulb temperature is used to define outdoor days in top and middle plots.