North-South disparity in impact of climate change on “outdoor days”

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ABSTRACT

Here, we introduce the concept of “outdoor days” to describe how climate change can affect quality of life for different communities and individuals. An outdoor day is characterized by moderate temperature, neither too cold nor too hot, allowing most people to enjoy outdoor activities. The number of “outdoor days” is a non-linear function of the daily surface air temperature. If the latter falls within a specific range describing assumed thermal comfort conditions, then we assign that day as an “outdoor day”. Using this function, we describe climate change impacts on temperature differently compared to other studies which often describe these impacts in terms of the linear averaging of daily surface air temperature. The introduction of this new concept offers another way for communicating how climate change may impact the quality of life for individuals who usually plan their outdoor activities based on how local weather conditions compare to their preferred levels of thermal comfort.

Based on our analysis of regional variations in “outdoor days”, we present observational and modeling evidence of a north-south disparity in climate change impacts. Under high-emission scenarios, CMIP5 and CMIP6 models project fewer “outdoor days” for people living in developing countries, primarily located in low-latitude regions. Meanwhile, developed countries in middle- and high-latitude regions could gain more “outdoor days”, redistributed across seasons.

SIGNIFICANCE STATEMENT

We introduce a novel concept: outdoor days – characterizing surface air temperature conditions that allow for outdoor activities, such as walking, jogging, cycling, etc., by most people. We project that under high emissions scenarios of anthropogenic greenhouse gases, a north-south disparity of climate change risk will be enhanced considerably towards the end of this century due to more frequent outdoor days in the wealthy global north and less frequent outdoor days in the deprived global south.

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1. Introduction

Climate change has potentially severe and far-reaching impacts that affect nearly every Earth's system and industry, putting the lives and livelihoods of millions of people at risk (Rising et al. 2022; Schewe et al. 2019). The potential risk of climate change is defined by the interaction of climate hazards with the vulnerability and exposure of human and natural systems (IPCC 2022) (Fig. 1; see Fig. S1 for definitions of the three components of climate risk). Since countries exhibit substantial differences in these elements (Shiogama et al. 2019), especially vulnerability and exposure, there are considerable variations in the potential risks from changing climate between regions and countries (Diffenbaugh and Burke 2019). Many previous studies revealed that while some regions may experience severe negative impacts from climate change, others may potentially gain some benefits in some sectors (Kalkuhl and Wenz 2020; Mendelsohn et al. 2006; Tol 2009).

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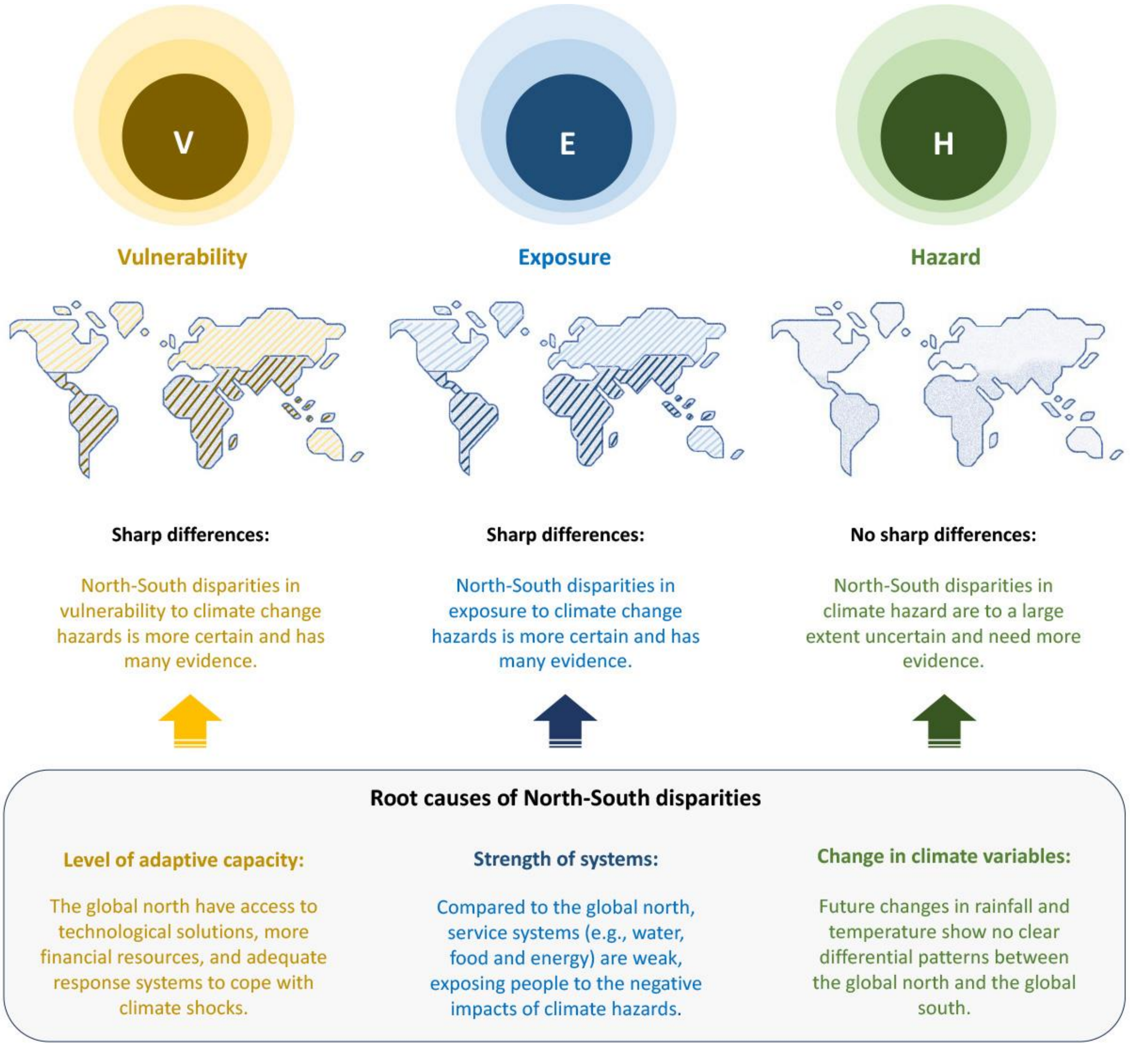

North-South disparities in vulnerability to climate change hazards is more certain and has many evidence.

North-South disparities in exposure to climate change hazards is more certain and has many evidence.

North-South disparities in climate hazard are to a large extent uncertain and need more evidence.

The global north have access to technological solutions, more financial resources, and adequate response systems to cope with climate shocks.

Compared to the global north, service systems (e.g., water, food and energy) are weak, exposing people to the negative impacts of climate hazards.

Future changes in rainfall and temperature show no clear differential patterns between the global north and the global south.

Fig. 1. Climate risk defined by three elements: vulnerability, exposure, and hazard. Vulnerability and exposure to climate change show clear disparities between the global north and the global south (left and middle panels). The level of certainty for these disparities is high. Meanwhile, the evidence for north-south disparities in climate hazard is inconclusive (right panel). Examples of disparities in climate hazard are few, and the contrast between the global north and south shown by these examples is often not particularly pronounced.

The disproportionate impacts of climate change are not limited to a specific sector but emerge in various fields. Some examples of disparities caused by climate change include differences in impacts on economic production (Burke et al. 2015; Callahan and Mankin 2022; Diffenbaugh and Burke 2019; King and Harrington 2018), disparities in how people allocate their time between work and leisure (Zivin and Neidell 2014), effects on poverty, urbanization, and migration (Burzyński et al. 2022), disparities in climate change impacts on gender-based and age-based health (Sorensen et al. 2018; Carleton et al. 2022), and

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contrasting consequences on income in urban and rural regions within countries (Paglialunga et al. 2022).

Compensating for disproportionate loss and damage imposed by climate change is one of the most highly debated topics in international forums (e.g., the 27th Conference of Parties (COP27), held in Egypt in November 2022) that discuss climate change policies (Dorkenoo et al. 2022) (see text in the online supplementary material regarding the concept of loss and damage imposed by climate change). This topic is especially relevant considering the debate about the distribution of responsibility for causing climate change and who should bear the costs (Farber 2007), which are difficult to quantify (Rising et al. 2022). Industrial and relatively rich countries (thereafter, the global north) have historically been the main emitters of greenhouse gases (GHGs) (Althor et al. 2016; Wei et al. 2016). Ironically, the relatively poor developing countries (thereafter, the global south), which have contributed less to the problem, are disproportionately impacted by climate change (IPCC 2022).

In the current research, we emphasize that discussions over differential climate risk have widely been tackled from the lens of disparities between the global north and global south in terms of vulnerability and exposure. This is mainly because vulnerability and exposure display clear differences between these two groups of countries and the evidence for these disparities is compelling, highly certain, and well-established (Fig. 1). But when it comes to climate hazard - the third component that defines climate risk - there are only a few significant evidence of sharp disparities between the global north and the global south. Additionally, evidence for such a differential pattern is either based on variables with relatively less significance to society or the contrast between the global north and south is not sharp. This area of research regarding north-south disparities in climate hazard has received relatively little attention (IPCC 2014) despite its centrality in shaping risks from climate change impacts.

This study takes a fresh look at global disparities in climate hazard by employing the innovative concept of outdoor days – days with moderate temperature, neither too cold nor too hot, allowing most people to enjoy outdoor activities. There are several studies that investigated impacts of climate on mild weather. However, these are limited to local and regional scales (Gao et al. 2018; Hanlon et al. 2021; Heng and Chow 2019; Lin et al. 2019; Spagnolo and de Dear 2003; Wu et al. 2017; Zhang et al. 2022; Zhang 2016). The studies of van der Wiel et al. (2017) and Zhang et al. (2023) are the only ones that investigated mild weather conditions on a global scale. These studies show a clear contrast in the change of mild weather between the global north and the global south. However, both studies considered applying only one or a few Global Climate Models (GCMs). Disparities between the global north and global south were not the main focus of van der Wiel et al. (2017).

The primary goal of this study is to introduce “outdoor days” and then present regional variations in this newly introduced variable. We use state-of-the-art reanalysis data and simulations from CMIP5 and CMIP6 models to project future climate conditions as characterized by the distribution of outdoor days.

2. Data and Methods

a. Observations and CMIP data

The observed 3-hourly dry-bulb temperature, dew point temperature, and surface pressure data with a spatial resolution of 0.25° covering the 1959-2021 period were from the ERA5 reanalysis (Hersbach et al. 2020) (available at http://apps.ecmwf.int/datasets/). In this paper, except when we added “wet-bulb” and “dew point” in front of the word temperature, we used the word temperature to mean dry-bulb surface air temperature. We used statistically bias-corrected and downscaled daily temperature and precipitation data over the 1976–2100 period from the NASA Earth Exchange Global Daily Downscaled Projections (NEX-GDDP) (Thrasher et al. 2012; Thrasher et al. 2022). A detailed description of the NEX-GDDP data set are available online (https://www.nccs.nasa.gov/services/data-collections/land-based-products/nex-gddp; https://www.nccs.nasa.gov/services/data-collections/land-based-products/nex-gddp-cmip6). Twenty-one NEX-GDDP-CMIP5 GCMs were used, which were forced by historical forcing until 2005 and Representative Concentration Pathway 8.5 (RCP8.5) scenario thereafter (Taylor et al. 2012). Thirty-two NEX-GDDP-CMIP6 GCMs were applied, which were forced by historical forcing up to 2014 and Shared Socioeconomic Pathway 5-8.5 (SSP5–8.5) scenario thereafter (O’Neill et al. 2016). The RCP 8.5 scenario has an identical radiative forcing level to SSP5–8.5 (8.5 W m^{-2} at 2100). Although the two high-emissions scenarios are similar, there are significant differences between them (Hausfather 2019). For example, the SSP5-8.5 scenario is characterized by very high economic growth and relatively low population growth, while the opposite is the case for the RCP8.5. Note that controversy remains as to whether these high-emissions scenarios are realistically feasible in

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the future (Hasfather and Peters 2020). For each model, one ensemble member was used. The list of global climate models and their details are provided in Table S1. The anomalies in the model outputs are obtained for the period 1976-2005. The observed global pattern of outdoor days was well captured by the NEX-GDDP-CMIP5 and NEX-GDDP-CMIP6 climate models (Fig. S2). This extensive dataset fortifies the robustness of our evidence on the impacts of climate change on outdoor days.

The gridded global GDP was provided by Kummu et al. (2018). The gridded population density for the year 2020 was from the Gridded Population of the World (CIESIN 2018). We used the gridded global population projection for 2000–2100 under the SSP5 scenario (O'Neill et al. 2016), which is available at https://sedac.ciesin.columbia.edu/data/set/popdynamics-1-8th-pop-base-year-projection-ssp-2000-2100-rev01/data-download. The annual population numbers for 2000–2100 were estimated at each grid point using the decadal population projection of the SSP5 scenario by applying linear interpolation, with the assumption that there are no abrupt population changes during the ten-year periods. To calculate population exposure to outdoor days, the population at each grid point is multiplied by the projected outdoor days for each year. The total exposure for a country is calculated by aggregating all grid points that fall within the country boundary. In earlier studies, a similar approach has been utilized to estimate the exposure of populations to climate extremes (Saeed et al. 2021).

b. Derivation of wet-bulb temperature

Wet-bulb temperature (TW) was computed by adopting a method developed by Davies-Jones (Davies-Jones 2008) using dry-bulb surface air temperature, humidity, and pressure, derived from the 3-hourly CMIP6 outputs (available at https://esgf-node.llnl.gov/projects/cmip6/) and the ERA5 reanalysis. The TW outputs derived from CMIP6 data were re-gridded to a common 1° × 1° grid and their biases were statistically corrected using the quantile mapping approach (Thrasher et al. 2022).

c. Outdoor days

The novel concept of outdoor days is defined as the number of days with moderate temperature, neither too cold nor too hot, that allows most people to enjoy outdoor activities. Here, we estimate outdoor days based on dry-bulb and wet-bulb temperature. That is, the range of dry-bulb temperature from 10 ℃ (corresponding to the 10th percentile of daily

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temperature) to 25 ℃ (corresponding to the 90th percentile of daily temperature) is assumed to be suitable for outdoor activity (Fig. S3). Note that the upper temperature limit used here is lower than the heat stress criteria defined by the National Weather Service (Fig. S4). This range of temperature is comparable to a wet- bulb temperature ranging from 8 ℃ to 17 ℃. We assume this definition is valid for all locations on Earth. However, the exact range of temperature defining an outdoor day may, in general, vary slightly depending on geographical location, tolerance levels of the local population, and what exact fraction of the population is assumed in defining "most people". Our definition of an outdoor day is discussed further below, where it is demonstrated that our results are not sensitive to the exact range of temperature we assume in this analysis. To explore this sensitivity, please visit https://eltahir.mit.edu/globaloutdoordays/.

Climate variables used in previous studies to analyze changes in the characteristics of mild weather (similar to outdoor days presented herein) include temperature (Hanlon et al. 2021; Zhang et al. 2022), dew point temperature (van der Wiel et al. 2017), precipitation (van der Wiel et al. 2017; Zhang 2016), sunshine duration (Lin et al. 2019; Zhang et al. 2022), relative humidity, wind speed, shortwave radiation, diffuse shortwave radiation, and longwave radiation (Spagnolo and de Dear 2003). Temperature is the primary and common variable used in most, if not all, of the previous studies that investigated the impact of climate change on concepts like outdoor days. However, the optimum ranges used for the daily maximum temperature to define mild weather vary considerably. The optimum daily temperature considered in these studies ranges between 18 ℃ and 31.6 ℃. A summary of these literatures can be found in the online supplementary material (Table S2).

3. Results

In the current climate, outdoor days occur frequently in populated regions of the world (Fig. 2). In the mean sense, most people across the land areas of the world may enjoy, on average, 91 outdoor days per year (about 25% of the days of a year) with suitable conditions for their outdoor activities (Fig. 2a), although seasonal and/or regional differences are evident (Fig. 2b-e). If we restrict ourselves to residential areas (assumed, areas with a population density above 1 person per square kilometer), more outdoor days are found (165 days per year; i.e., about 45% of the days of a year). Particularly, the global south stands out due to

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more frequent annual outdoor days, compared to the global north. On a regional scale, high-latitude countries, such as Canada and Russia, are too cold, resulting in fewer outdoor days, especially during cold months (not accounting for skiing days), whereas countries such as Angola and regions like the southern parts of Brazil show frequent outdoor days regardless of season (Fig. 2). The transition from winter to spring and from summer to autumn typically brings more outdoor days as temperatures become milder, especially in temperate regions around 30 degrees North where most people live (Fig. 2b-e and Fig. S5).

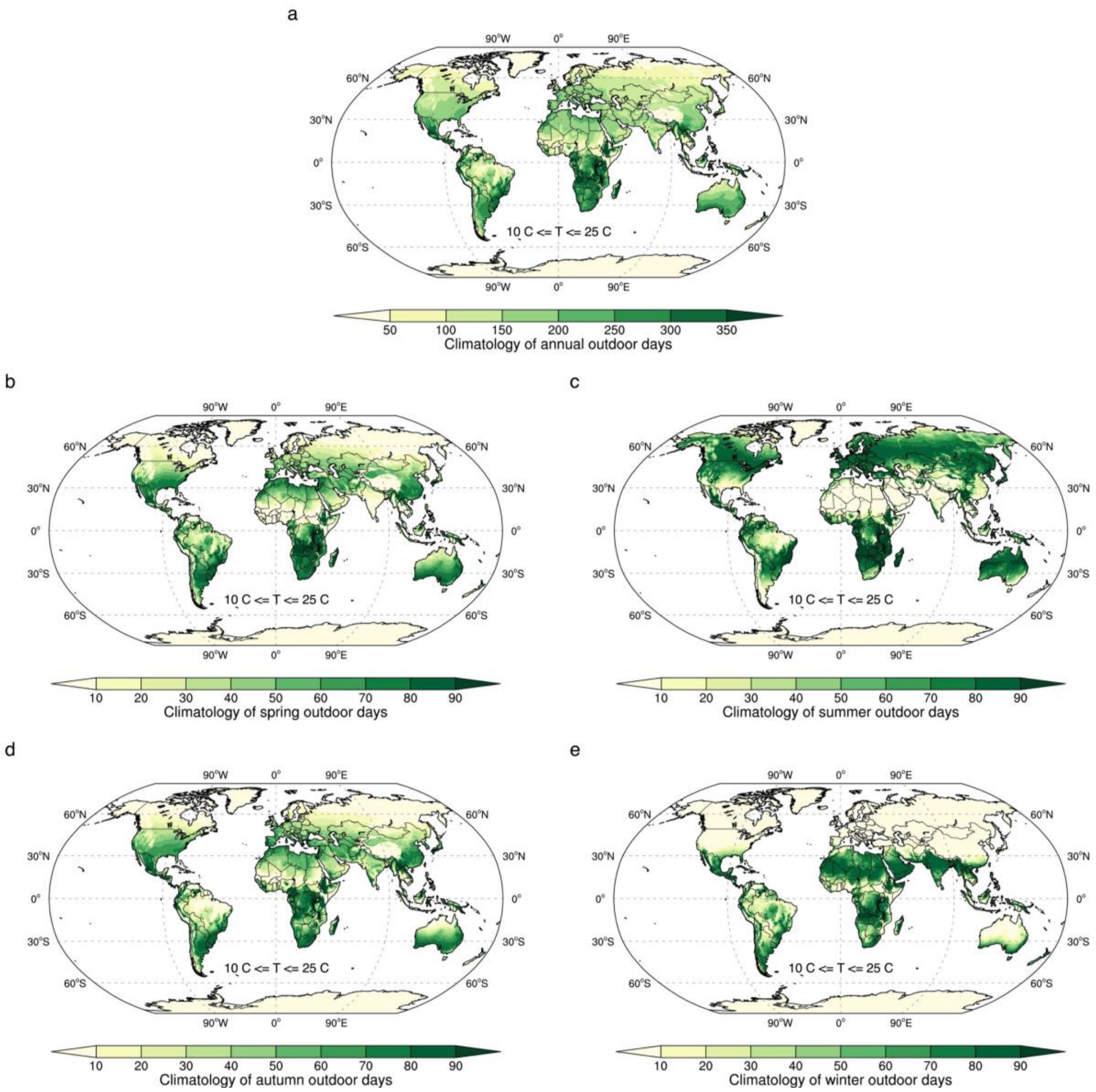

Fig. 2. Global distribution of the number of outdoor days. The long-term average (i.e., climatology) of the number of outdoor days for (a) annual (unit: days per year), (b) spring (unit: days per season), (c) summer (unit: days per season), (d) autumn (unit: days per season), and (e) winter (unit: days per season) during the period 1959-2021. The four boreal seasons are considered (b-e). Darker colors represent a higher number of outdoor days, while

lighter colors signify fewer outdoor days. The range of surface air temperature used to define an outdoor day is indicated in each plot. These global maps are derived from ERA5.

The recent global warming due to climate change has disproportionately affected outdoor days in the global north and south (Fig. 3). Based on the modern climate record, annual outdoor days show a decreasing trend in the global land areas, while exhibiting an asymmetric pattern between developing countries in the south and developed countries in the north (Fig. 3). The enhanced risk of a climate hazard, in the form of reduced outdoor days, is particularly significant in the tropical regions. In these regions, outdoor days have decreased by about 13% in the last three decades compared to the period 1961-1990, showing a significant downward trend ($p\text{-}value < 0.01$). Meanwhile, high-latitude countries have experienced a 13% increase in the number of outdoor days. Furthermore, on a seasonal time scale, outdoor days in the tropical regions show sharp reductions of outdoor days in the relatively warm season (Fig. 4). Meanwhile, the net change of outdoor days in middle-latitude countries is mostly positive but small because of cancellation between increasing and decreasing trends during the winter and summer, respectively (Fig. 4).

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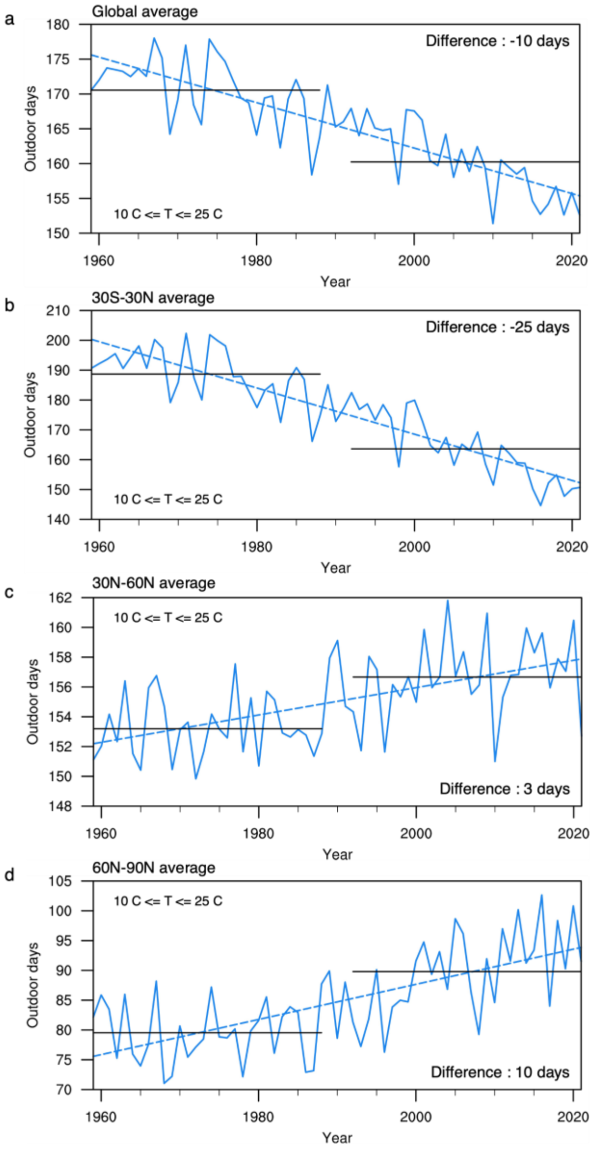

Fig. 3. Trend of the number of outdoor days. Time series of the number of annual outdoor days (unit: days per year) for the (a) global, (b) low-latitude, (c) mid-latitude, and (d) high-latitude residential areas for the period 1959-2021. Residential areas are defined as having a population density above 1 person per square kilometer. Horizontal black lines denote the 1961-1990 mean and the 1991-2020 mean. Difference (1991-2020 minus 1961-1990) in the number of outdoor days is represented in each plot. These time series are derived from ERA5.

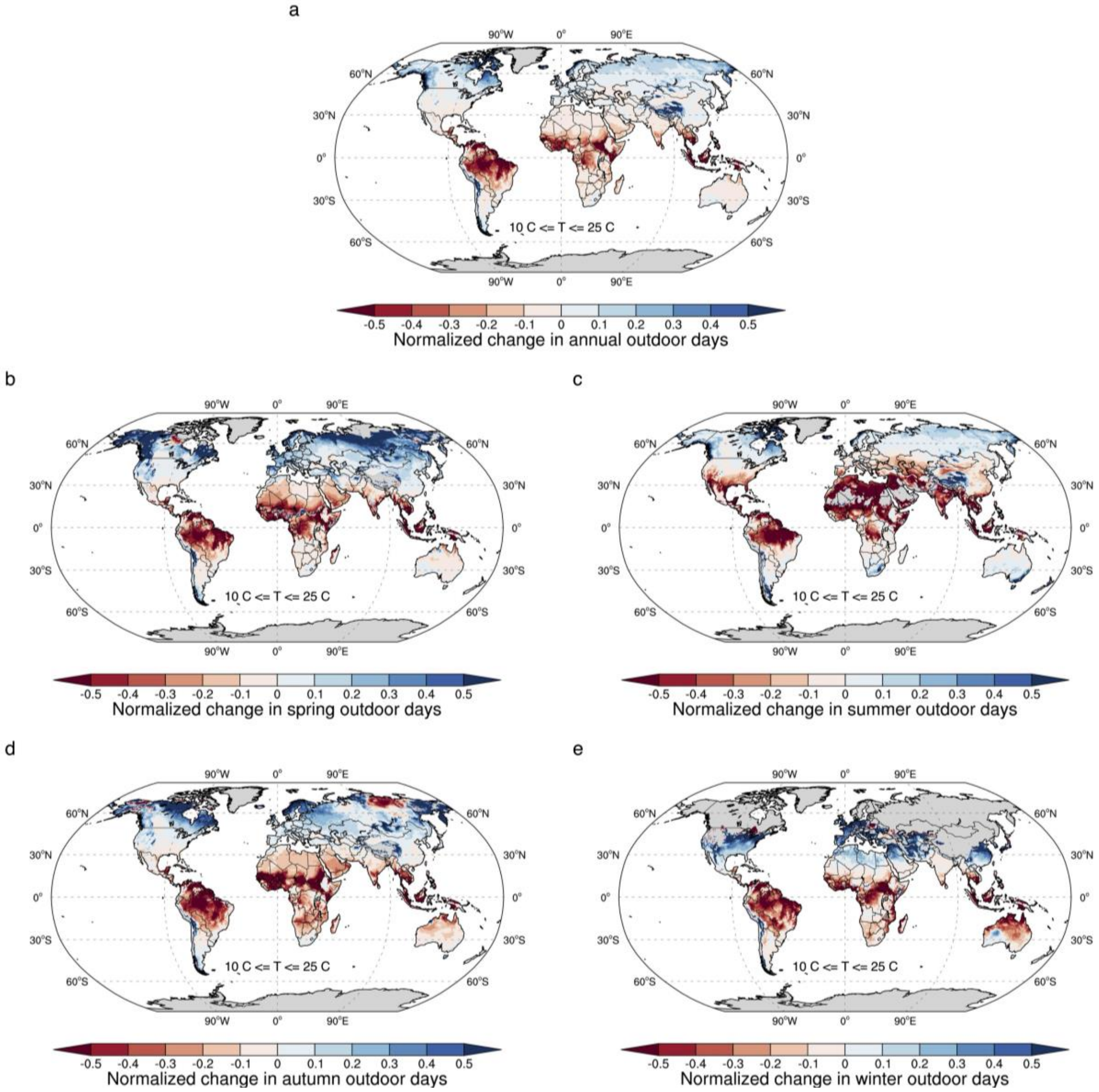

Fig. 4. Observed change in the number of outdoor days. Normalized change in the number of outdoor days in 1991–2020 with respect to 1961-1990. The changes are normalized by the 1961-1990 mean. The four boreal seasons are considered (b-e). The range of surface air temperature used to define an outdoor day is indicated in each plot. These global maps are derived from ERA5.

Based on climate model projections, the observed warming trend is projected to continue towards the end of the 21st century (Fig. 5 and Fig. S6). For the period 2071-2100, most land areas in the globe will likely experience significant warming by an average dry-bulb temperature of 5 ℃ from CMIP5 models and by an average dry-bulb temperature of 6 ℃ from CMIP6 models under high-emissions scenarios, though with some spatial variability. Similarly, climate change could increase global land average TW by 4.9 ℃. The consistency between the CMIP5 and CMIP6 models is robust, suggesting reliability of future projections.

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Although high latitudes may warm more significantly, warming is indeed occurring everywhere. This suggests that there is no strong contrast between the global north and the global south in terms of the sign of the changes in temperatures.

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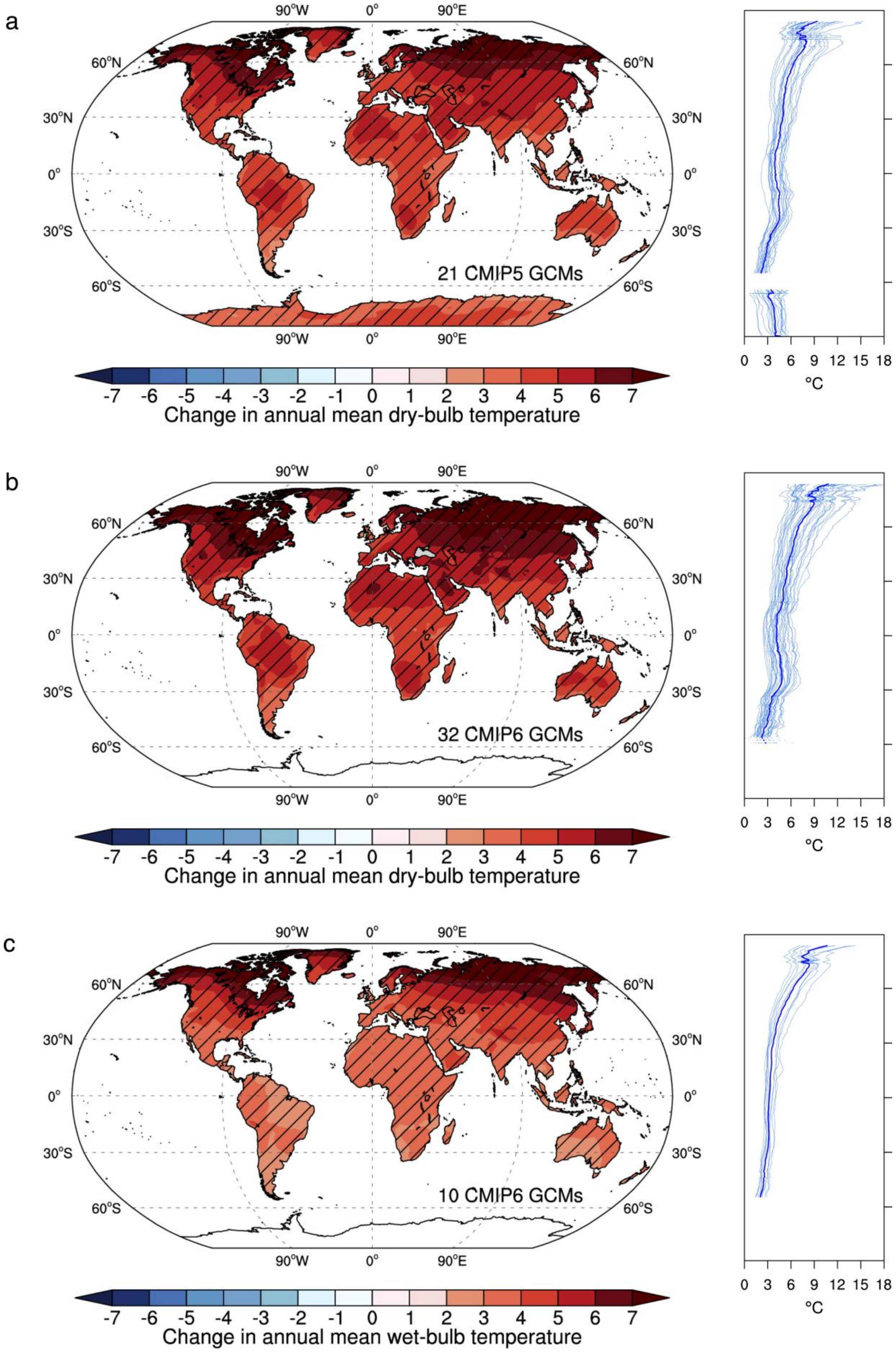

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Fig. 5. Projected changes in temperatures. Spatial distribution of change in annual mean dry-bulb surface air temperature in 2071-2100 with respect to 1976-2005, derived from (a) 21 NEX-GDDP-CMIP5 GCMs and (b) 32 NEX-GDDP-CMIP6 GCMs. (c) Same as (b), but for wet-bulb temperature using 10 CMIP6 GCMs. Superimposed hatching indicates that more than 80% of models agree on the sign of the change. Zonal-mean changes are indicated by the right corner for each panel. Thick solid blue line in each panel indicates an ensemble mean of models.

The projected warming due to elevated greenhouse gas concentrations in the atmosphere could result in a significant north-south disparity in the impact of climate change on number of outdoor days (Fig. 6). Consistent with observed trends in the historical record, we project relatively large drops in the tropical regions and significant increases in the northern high-latitude regions towards the end of the century. It implies that countries in the global south (for example, Colombia, Ivory Coast, Sudan, Indonesia, and Bangladesh), that are contributing less to the emissions of greenhouse gases (Fig. S7), are disproportionately affected by the negative impacts of climate change through reduced outdoor days (Fig. 7 and Fig. S8 derived from CMIP5 models). Meanwhile, developed countries, such as Canada, France, the United Kingdom, Germany, and Japan, are marginally affected or benefit from climate change by gaining more outdoor days (Fig. 7 and Fig. S8 derived from CMIP5 models). Using wet-bulb temperature to define outdoor days (see Data and Methods) results in a similar conclusion, albeit with a smaller magnitude.

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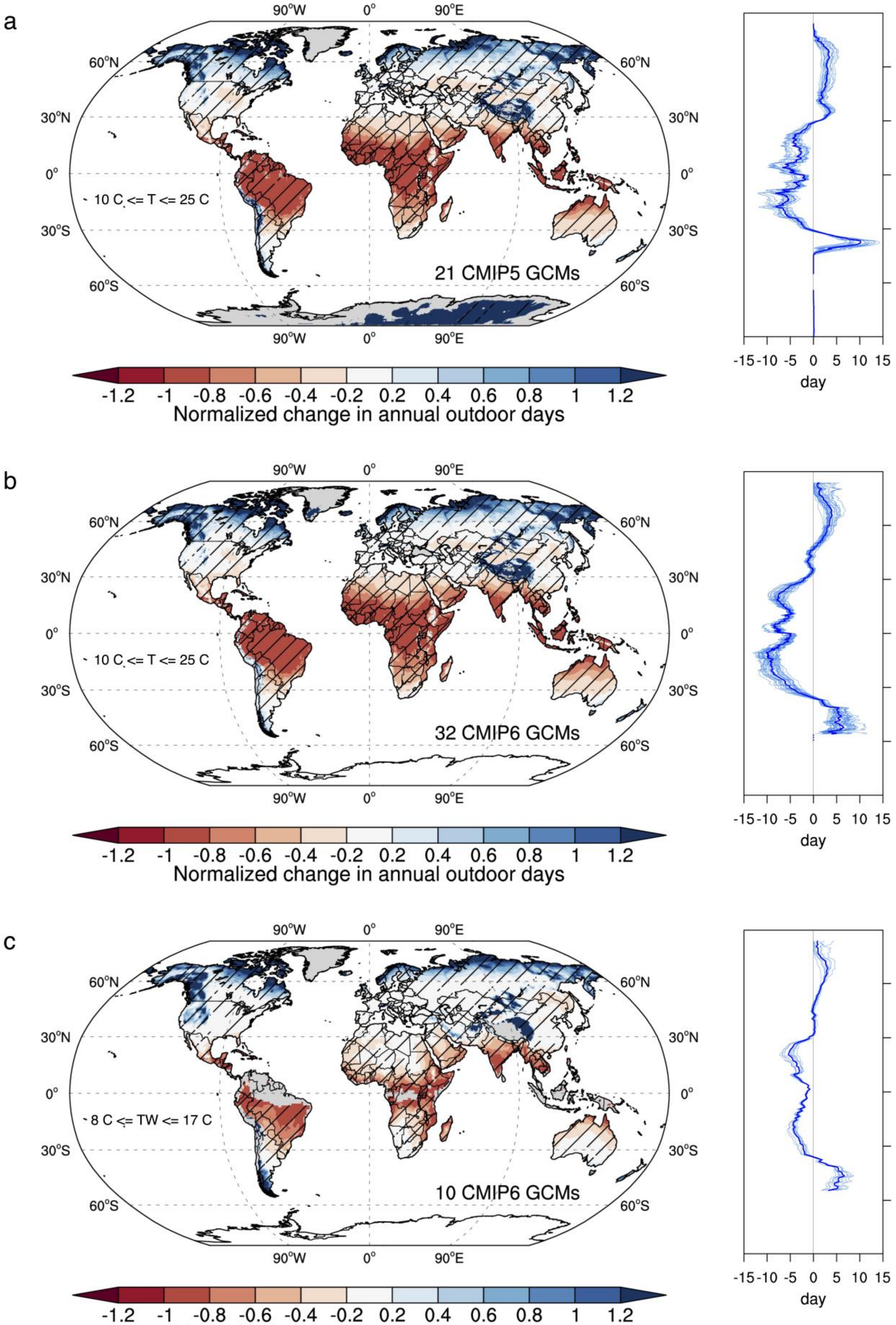

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Fig. 6. Projected change in outdoor days. Spatial distribution of normalized change in the number of annual outdoor days in 2071-2100 with respect to 1976-2005, derived from (a) 21 NEX-GDDP-CMIP5 GCMs and (b) 32 NEX-GDDP-CMIP6 GCMs. (c) Same as (b), but for outdoor days defined using wet-bulb temperature derived from 10 CMIP6 GCMs. The changes in (a-c) are normalized by the 1976-2005 mean. Superimposed hatching indicates that more than 80% of models agree on the sign of the change. Zonal-mean changes (not normalized) are indicated by the right corner for each panel. Thick solid blue line in each panel indicates an ensemble mean of models.

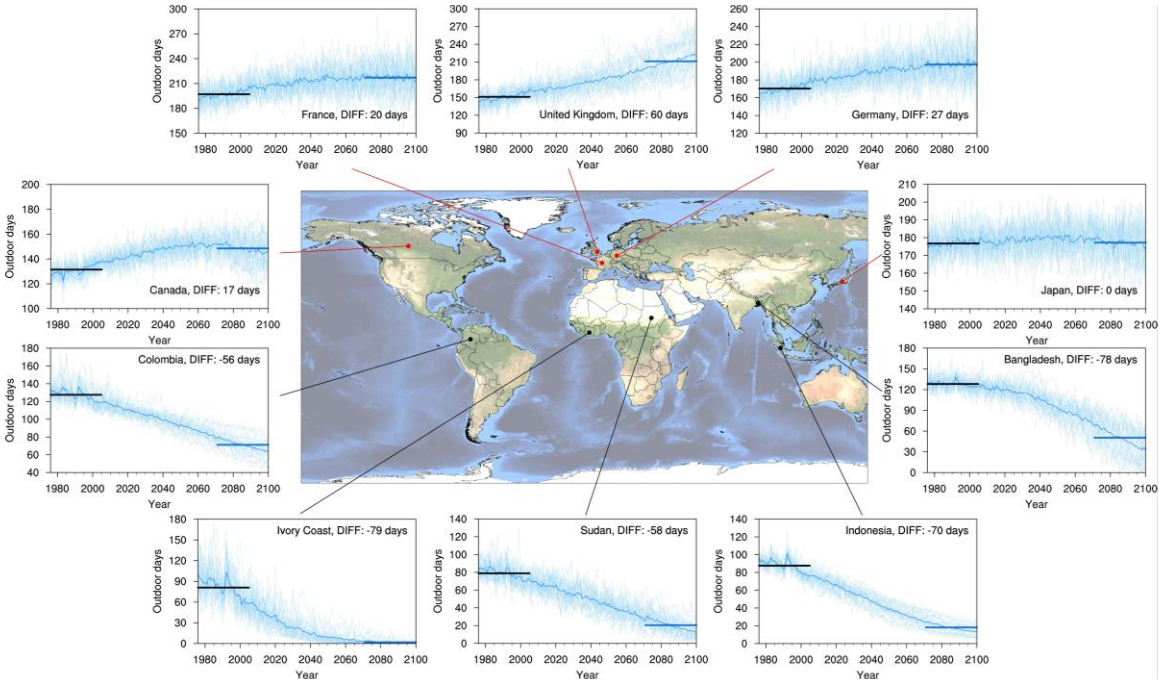

Fig. 7. Temporal evolution of the number of annual outdoor days derived from NEX-GDDP-CMIP6 models. Time series of the number of annual outdoor days (unit: days per year) over residential areas (assumed, areas with a population density above 1 person per square kilometer) derived from 32 NEX-GDDP-CMIP6 GCMs under the historical and SSP5-8.5 scenarios. Thick solid blue line indicates an ensemble mean of models. Horizontal black and blue lines denote the 1976-2005 mean and the 2071-2100 mean, respectively. Difference (2071–2100 minus 1976–2005) in the number of outdoor days is represented in each plot. The background image was obtained from NASA Visible Earth.

Underlying mechanisms responsible for the north-south disparity in the projected climate hazard are investigated by studying changes in the probability distribution of temperature over six selected countries across all climate zones (Fig. 8). Modeling results show an evident shift of the probability distribution of temperature toward warmer temperature across the countries (Fig. 8a). The warming shift of the probability distribution of temperature induces a significant increase in outdoor days in the European Union. In this region, climate change causes fewer outdoor days during the warm season. However, an increase in outdoor days in the cold season compensates for this decreasing trend (Fig. 9). In a similar way, a large fraction of the population in the northern high-latitude regions, such as Russia and Canada, will likely see large increases in outdoor days. In contrast, the projected probability distribution of temperature in Brazil, Nigeria, and India, are likely to move away from the conditions of thermal comfort, limiting outdoor activities significantly in these large population centers of the South (Fig. 8). The results of Figure 8 show clearly that the north-south disparity is rooted in the background climatology of temperature, mainly the position of the probability distribution of temperature relative to the range of values used to define an outdoor day.

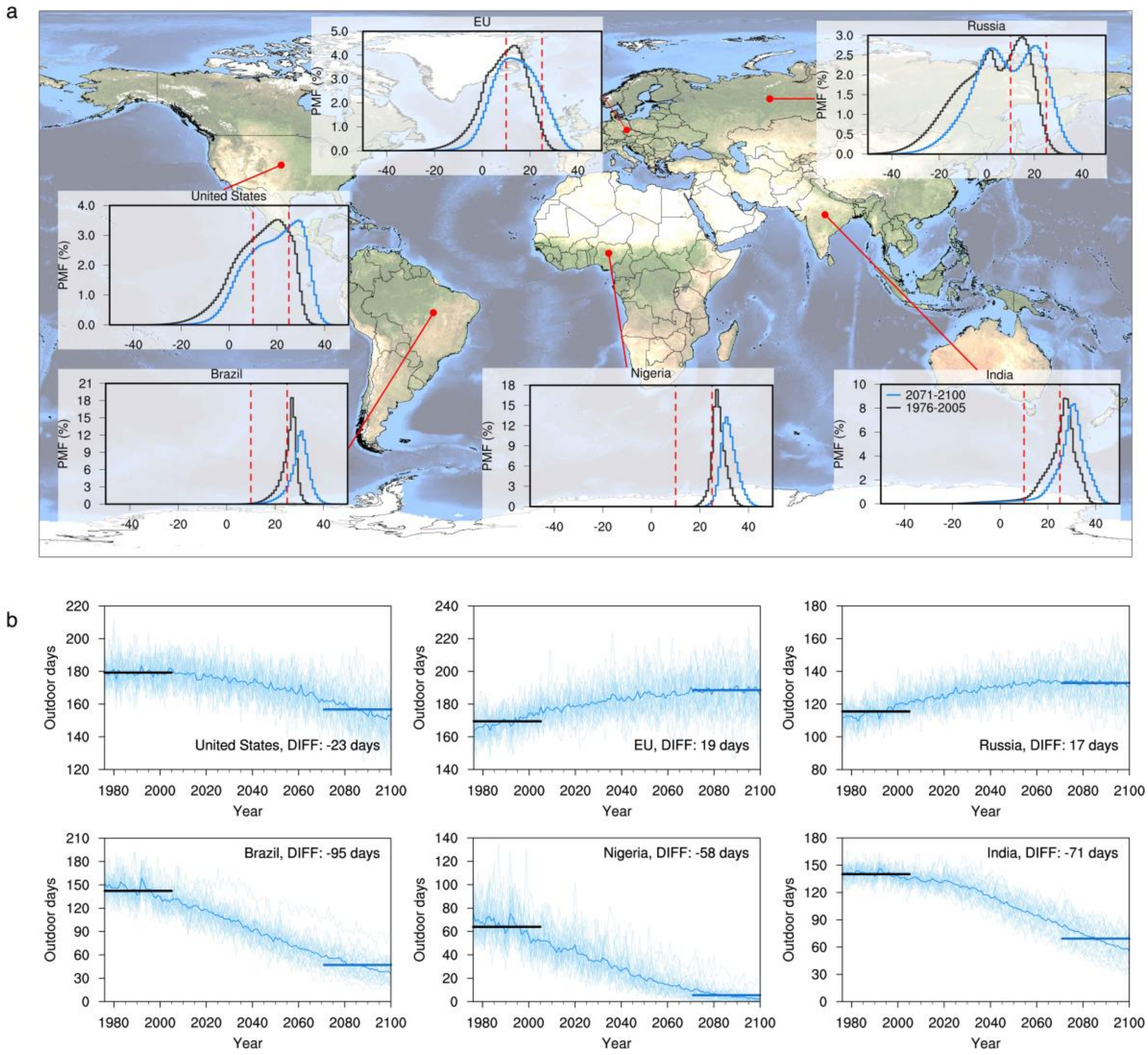

Fig. 8. Probability Mass Function (PMF) of daily mean temperature (℃) and temporal evolution of the number of annual outdoor days (unit: days per year) derived from NEX-

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GDDP-CMIP6 models. a) The PMFs are generated for two groups of countries – developing countries (Brazil, Nigeria, and India) and developed countries (the United States, the EU, and Russia) – for each GHG scenario: historical (black) and SSP5-8.5 (blue). The bin interval is 1 ℃. The vertical dashed red line in a) indicates the range of temperature (from 10 ℃ to 25 ℃), defined in this study for outdoor days. The background image in a) was obtained from NASA Visible Earth. b) Time series of the number of annual outdoor days (days per year) derived from 32 NEX-GDDP-CMIP6 GCMs under the historical and SSP5-8.5 scenarios. Thick solid blue line in b) indicates an ensemble mean of models. Horizontal black and blue lines denote the 1976-2005 mean and the 2071-2100 mean, respectively. Difference (2071–2100 minus 1976–2005) in the number of outdoor days is represented in each plot. Values in a) and b) are estimated over residential areas (assumed, areas with a population density above 1 person per square kilometer).

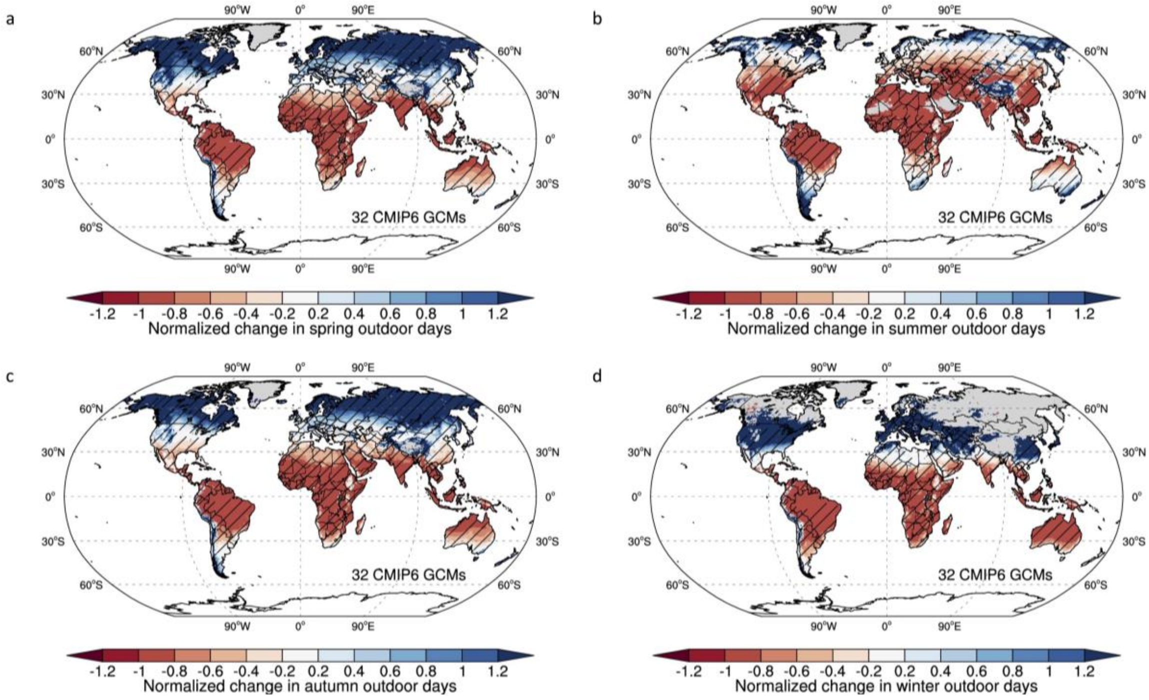

Fig. 9. Projected changes in outdoor days for four seasons. Normalized change in outdoor days in 2071–2100 with respect to 1976-2005 for the four boreal seasons. The changes are normalized by the 1976-2005 mean. Superimposed hatching indicates that more than 80% of models agree on the sign of the change. These global maps are derived from 32 NEX-GDDP-CMIP6 GCMs.

We expanded our analysis to include exposure and vulnerability to changes in outdoor days (Fig. 10 and Fig. S7). The SSP5-8.5 scenario shows an increasing trend of population exposure in the global north and a decreasing trend in the global south (Fig. 10). Specifically, more outdoor days are simulated in countries of the global north characterized by high GDP per capita (i.e., low vulnerability; Fig. S7a), high CO_2 emissions (responsibility for causing

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climate change; Fig. S7b), and population growth (i.e., high exposure; Fig. S9) by the end of this century and vice versa in the global south. It highlights the importance of considering hazards alongside exposure and vulnerability to comprehensively understand the evolving landscape of climate risk, particularly in the context of the global north-south divide. Among all countries considered, Bangladesh stands out with a particularly striking reduction of exposure to outdoor days, which may decrease quality of life and cause substantial loss of labor productivity in this country where most of the population primarily depend on agriculture for their livelihood, in line with previous studies (e.g., Shiogama et al. 2019)

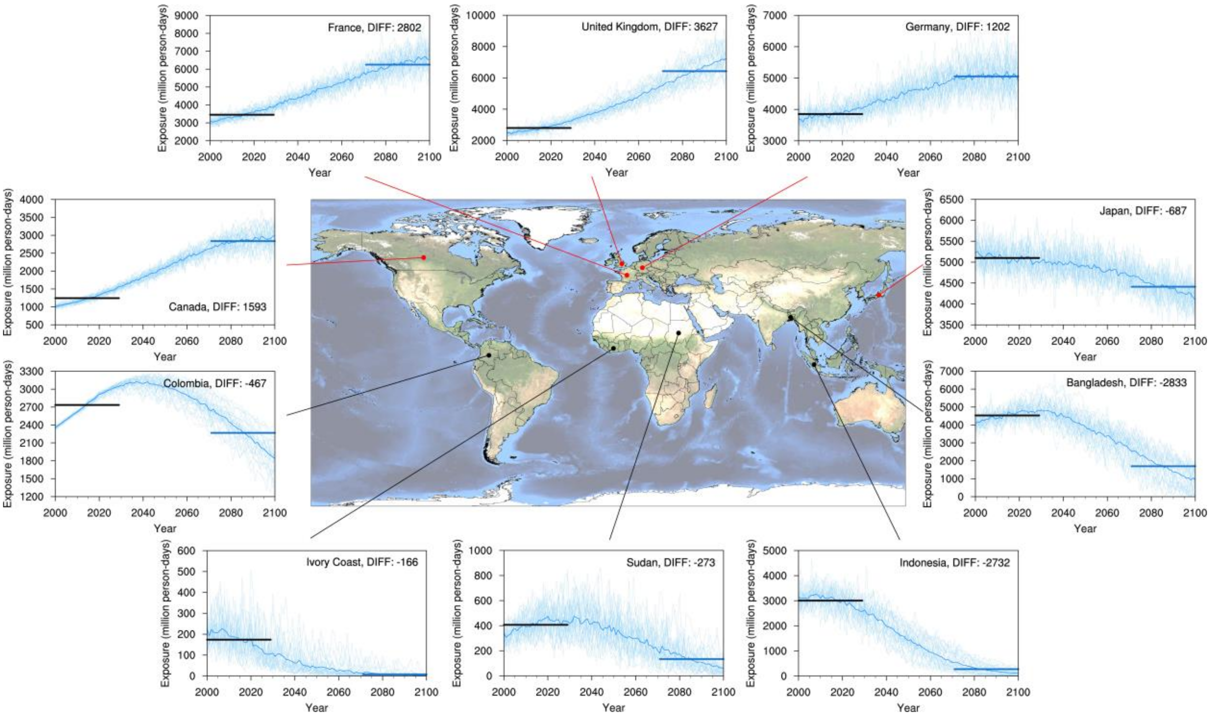

Fig. 10. Temporal evolution of population exposure to annual outdoor days. Time series of population exposure to the number of annual outdoor days (million person-days) over residential areas (assumed, areas with a population density above 1 person per square kilometer) derived from 32 NEX-GDDP-CMIP6 GCMs under the historical and SSP5-8.5 scenarios. Thick solid blue line indicates an ensemble mean of models. Horizontal black and blue lines denote the 2000-2029 mean and the 2071-2100 mean, respectively. Difference (2071–2100 minus 2000–2029) in population exposure is represented in each plot. The background image was obtained from NASA Visible Earth.

4. Discussion

Climate change studies have traditionally placed substantial emphasis on projected changes in mean climate conditions, and changes in climate extremes that have significant negative impacts among populations (Choi et al. 2021, 2022; Choi and Eltahir 2022, 2023; Fischer and Knutti 2015; Pfahl et al. 2017; Zhao et al. 2021). Despite the importance of investigating changes in mild and pleasant weather (Lin et al. 2019; van der Wiel et al. 2017; Zhang et al. 2022), this research topic has received relatively little attention from the climate change research community. As revealed in this study, climate hazard associated with change in outdoor days could result in significant differences in risk of climate change between the global north and the global south. In comparison, future changes in rainfall and temperature – the two main climate variables – show no clear north-south disparity in climate risk (Fig. 5 and Fig. S10). According to IPCC (2022), the overall trend for temperatures is to increase almost uniformly in the future across the globe. An overall wetting trend in precipitation is expected, except for a few regions, such as the Mediterranean (Tuel and Eltahir, 2020). Therefore, future changes in rainfall and temperature do not provide significant evidence for a north-south disparity in climate risk.

Although substantial scientific and public attention has focused on the asymmetric distribution of vulnerability and exposure to climate change (Diffenbaugh and Burke 2019), until recently, north-south disparities induced by climate hazards seem to receive relatively little attention in research, with a few exceptions such as van der Wiel et al. (2017) and Zhang (2016) described in the introduction. In a recent study, Shiogama et al. (2019) suggested that the regions with relatively large increases in several hazard indicators (i.e., extremely hot days, heavy rainfalls, and high stream flow) coincide with countries characterized by small CO_2 emissions, low income, and high vulnerability. However, the north-south contrasting pattern in Shiogama et al. (2019) is not particularly pronounced, compared to the disparity revealed by changes in the number of outdoor days, as described in this study.

Our results present some important caveats:

First, the human feeling of weather is complex and a widely subjective matter, and therefore, the general definition of an outdoor day is non-trivial (like the difficulty in defining mild weather discussed by van der Wiel et al. 2017). Rainy or snowy weather can limit outdoor activities and reduce the number of outdoor days. Snow is also an important tourism resource in northern countries (Steiger et al. 2019), which might be adversely affected by the impact of climate change. Although we defined outdoor days assuming a range of dry-bulb temperature from 10 ℃ to 25 ℃, considering other variables, such as wet-bulb temperature (Fig. 6) and precipitation (Fig. S11) resulted in a broadly similar pattern, supporting the north-south disparity. Note that the exact range of temperature used does not significantly affect the global distribution of the climate risk induced by changes in outdoor days (Fig. S11; Table S3; see interactive visualization at https://eltahir.mit.edu/globaloutdoordays/).

Second, although we present our results sorted by country, analysis for some specific countries might show variable responses of outdoor days to climate change within the same country.

Third, while variation in outdoor days is underscored as a prominent factor accentuating the north-south disparity, this variation is not the only relevant factor. We emphasize that outdoor days should serve as one of several potential indicators in describing how climate hazards exacerbate disparities.

A central question remains unanswered concerning how to define outdoor days that would satisfy most people across diverse climatic regions. In this study, we address that question by incorporating input from the reader using an online interactive tool. We developed a flexible approach that enables users to customize their own definition of an outdoor day using our online interactive tool (available at https://eltahir.mit.edu/globaloutdoordays/) (see text in the online supplementary material for more detailed information on the online interactive tool).

While existing literature often focuses on climate risks posed by climate extremes, projecting changes in outdoor days are tangible and essential for well-being and societal functioning. Our analysis provides robust evidence of how climate hazards contribute to climate inequality, disproportionately affecting regions in the global south, which are less responsible for emissions. Conversely, regions in the global north may gain, or experience marginal losses, in outdoor days, highlighting the differences in climate impacts.

5. Conclusions

Here, we introduced the concept of outdoor days (the number of days with pleasant weather that allows for outdoor activities by most people) to study impacts of climate change on quality of life from a new perspective. In this regard, this new concept offers another way for communicating how climate change may impact the quality of life of individuals who

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usually plan their outdoor activities by comparing local weather conditions to their preferred levels of thermal comfort.

While studying the regional variations of outdoor days, we discovered how these variations may enhance north-south disparities in global climate risk between the wealthy global north and the deprived global south. We used the state-of-the-art reanalysis data and various climate model projections to provide empirical evidence that the climate hazard associated with the change in outdoor days could contribute to the north-south disparity of climate change impacts. We project that this disparity will increase considerably in the future, assuming high emissions scenarios.

We assumed a universal definition of outdoor days based on a daily dry-bulb surface air temperature falling in the range of 10 ℃ to 25 ℃. Although we primarily used this definition in our analyses, one of the innovative aspects of our study is in providing a flexible and intuitive tool to allow readers/users to customize their own definition of outdoor days using our online interactive platform (https://eltahir.mit.edu/globaloutdoordays/) and in doing so we acknowledge the potential diversity of definitions of outdoor days.

Our results have important implications for the climate debate. That is, the negative impacts of climate change accompanied by the decreased outdoor days will significantly affect tropical countries, including Colombia, Brazil, Ivory Coast, Nigeria, Sudan, Indonesia, Bangladesh, and India. These are developing countries with large populations but relatively minor emitters of carbon dioxide (Figs. S7 and S12). Meanwhile, some of the historically largest emitters of carbon dioxide, including Canada, the European Union, Russia, and Japan may benefit to varying degrees from the increased outdoor days. It is important to note that climate risk inferred from the existing literature may be underestimated, especially in tropical regions since they do not consider risk caused by the climate hazard related to outdoor days, as evident from our analysis.

The findings reported here are not only important from the point of view of climate risk and how it varies spatially and temporally, but future research on this topic may better inform the ongoing and related debate regarding compensations for loss and damage imposed by climate change. Also, future research on this topic may provide new insights into the potential effects of climate change on tourism, and related economic activities. We plan to explore how the tourism industry in tropical developing countries may face adverse effects due to the projected decrease in outdoor days resulting from higher temperatures.

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Data Availability Statement.

All original CMIP6 GCMs and the ERA5 reanalysis used in this study are publicly available at https://esgf-node.llnl.gov/projects/cmip6/ and https://doi.org/10.24381/cds.adbb2d47, respectively. NEX-GDDP-CMIP5 and NEX-GDDP-CMIP6 are from https://www.nccs.nasa.gov/services/data-collections/land-based-products/nex-gddp and https://www.nccs.nasa.gov/services/data-collections/land-based-products/nex-gddp-cmip6, respectively. All models used in this study are listed in Table S1. The gridded population density of the world is from the Center for International Earth Science Information Network (CIESIN 2018). The gridded global datasets for GDP are available from Kummu et al. (2018). GDP per capita is from https://ourworldindata.org/grapher/gdp-per-capita-maddison-2020. CO_2 emissions per capita is from https://ourworldindata.org/grapher/co-emissions-per-capita. The gridded global population projection under the SSP5 scenario is available at https://sedac.ciesin.columbia.edu/data/set/popdynamics-1-8th-pop-base-year-projection-ssp-2000-2100-rev01/data-download.

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