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

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ABSTRACT

In a recent study, we have introduced the concept of "outdoor days" – the number of days with moderate temperature, neither too cold nor too hot, allowing most people to enjoy outdoor activities – to describe how climate change can affect quality of life for communities in a different way compared to previous studies which emphasize changes in surface temperature. Here, we use the same concept to investigate climate risk, defined by the combination of vulnerability, exposure, and hazard. Vulnerability and exposure are known to cause a sharp disparity in climate risk between the wealthy north and the deprived south, implying disproportionate risks of climate change. However, we know little about how climate hazards contribute to this disparity of global climate risk. Here, we present observational and modeling evidence of north-south disparity in climate risk caused by changes in "outdoor days". Under high-emissions 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. Our findings help inform ongoing debates on compensation for losses and damages caused by climate change.

SIGNIFICANCE STATEMENT

Here, we contribute to the understanding of global disparities imposed by climate risk by introducing the concept of outdoor days – thermal comfort conditions allowing for outdoor activities, such as walking, jogging, cycling, and those related to construction and tourism industries, by most people. We project that the north-south disparity of global climate risk is expected to increase considerably by the end of this century with more frequent outdoor days in the wealthy north and less frequent outdoor days in the deprived south under high emissions scenarios. These findings have the potential to provide researchers, policymakers, and climate advocates with evidence-based knowledge informing more accurate depiction of climate risk, and more rational debate regarding compensations for loss and damage.

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 human and natural system's vulnerability and exposure (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 (Kalkuhl and Wenz 2020; Mendelsohn et al. 2006; Tol 2009). The intersection of climate change and inequality, referred to as the climate-inequality nexus (Onbargi 2022), is one of the most pressing challenges of climate change and has significant social, economic, and environmental consequences (IPCC 2022).

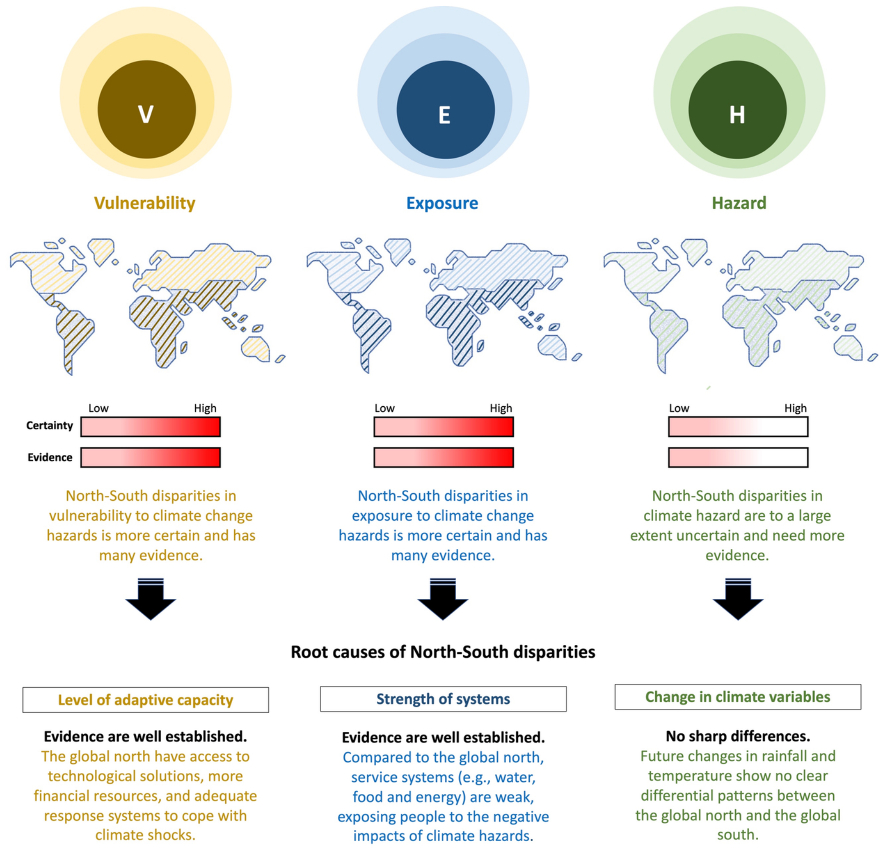

Fig. 1. Climate risk is defined by three elements: vulnerability, exposure, and hazard. While the level of certainty is high and the significance of evidence is well established regarding disparities between the global north and the global south in vulnerability and exposure, certainty is low and evidence is not well established when it comes to climate hazard. Examples of disparities in climate hazard are few, and the contrast between the global north and south shown by these examples is largely not sharp.

The geographically different impacts of climate change are not only limited to a specific sector but emerge in various fields. Some examples of disparities caused by climate change include differences in its impact 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 gender-based health (Sorensen et al. 2018), and 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 has been an integral, however, one of the most debatable and complex subjects in the international forums (e.g., the 27$^{\text{th}}$ 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), but certainly high (Dietz et al. 2018). 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). Being legally liable for GHG emissions has been the main concern of the global north around the issue of responsibilities and compensation over climate change. However, 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 and compensation for the associated loss and damage have widely been tackled mainly 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 are highly significant, 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 are 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) albeit its centrality in shaping climate change impact and defining losses, damages, and responsibilities.

2. Data and Methods

a. Observations and CMIP data

The observed 3-hourly 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/). We used the daily output of temperature over the 1976–2100 period from 31 CMIP5 GCMs forced by historical forcing until 2005 and Representative Concentration Pathway 8.5 (RCP8.5) scenario thereafter (Taylor et al. 2012) and 29 CMIP6 GCMs forced by historical forcing up to 2014 and Shared Socioeconomic Pathway 5-8.5 (SSP5–8.5) scenario thereafter (Eyring et al. 2016). RCP8.5 represents a business-as-usual scenario with radiative forcing, reaching about 8.5 Wm^{-2} in 2100. SSP5-8.5 is approximately equivalent to RCP8.5 (Russo et al. 2019). For each model, one ensemble member was used. The list of global climate models and their details were provided in Table S1. All model outputs from CMIP6 (respectively from CMIP5) were re-gridded to a common 1deg x 1deg grid (respectively 1.5deg x 1.5deg grid). The anomalies in the model outputs are obtained for the period 1976-2005. The gridded population density was from the Gridded Population of the World (CIESIN 2018). The gridded global GDP was provided by Kummu et al. (2018).

b. Derivation of wet-bulb temperature

Wet-bulb temperature (TW) was computed adopting a method developed by Davies-Jones (Davies-Jones 2008) using surface temperature, humidity, and pressure, derived from the 3-hourly CMIP outputs and the ERA5 reanalysis.

c. Outdoor days

Our earlier study introduced the novel concept of "outdoor days" defined as the number of days with moderate temperature, neither too cold nor too hot, that allows most people to enjoy outdoor activities (Choi et al. 2023). Here, we adopt the same definition, following Choi et al. (2023), to estimate "outdoor days" based on dry-bulb and wet-bulb temperature. That is, the range of dry-bulb temperature from 10 to 25 is assumed to be suitable for outdoor activity (This range of temperature is comparable to a wet-bulb temperature ranging from 8 to 15). 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 meant when we say "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/.

Most existing studies that investigated concepts similar to outdoor days presented herein are limited to local and regional scales (Choi et al. 2023; 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). Previous studies referred to pleasant weather conditions as mild weather (Lin et al. 2019; van der Wiel et al. 2017; Zhang et al. 2022), mild days (Day et al. 2021), good weather (Zhang 2016), outdoor thermal comfort (Heng and Chow 2019), thermal comfort condition (Gao et al. 2018), comfortable days (Wu et al. 2017), and thermal comfort (Spagnolo and de Dear 2003).

Climate variables used in previous studies to analyze changes in the characteristics of mild weather include temperature (Choi et al. 2023; Hanlon et al. 2021; Zhang et al. 2022), dewpoint temperature (van der Wiel et al. 2017), wet-bulb temperature (Choi et al. 2023), precipitation (van der Wiel et al. 2017; Zhang 2016), relative humidity, wind speed, sunshine duration (Lin et al. 2019; Zhang et al. 2022), shortwave radiation, diffuse shortwave radiation, longwave radiation, and velocity (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 similar to outdoor days. However, the optimum ranges used for the daily maximum temperature to define mild weather vary considerably. The optimum daily maximum 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).

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 GCMs, limiting the reliability of future projections. Additionally, disparities between the global north and south were not the central focus of van der Wiel et al. (2017). To the best of our knowledge, our study is the first to provide more evidence of its scale in terms of data and models on the north-south disparities in outdoor days, improving our understanding of how disparities in climate hazard shape the contrasting risk of climate change on the global scale.

3. Results

In the current climate, outdoor days occur frequently in most regions of the world (Fig. 2). On average, across the land areas of the world, approximately 91 outdoor days are experienced every year (i.e., about 25% of the days of a year), although seasonal and/or regional differences are evident. If we restrict ourselves to residential areas (i.e., 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 more frequent outdoor days, compared to the global north. On a regional scale, high-latitude countries, such as Canada and Russia, are too cold (Fig. S2a), resulting in fewer outdoor days, especially during cold months, whereas countries such as Angola and regions like the southern parts of Brazil show frequent outdoor days regardless of season (Fig. 2).

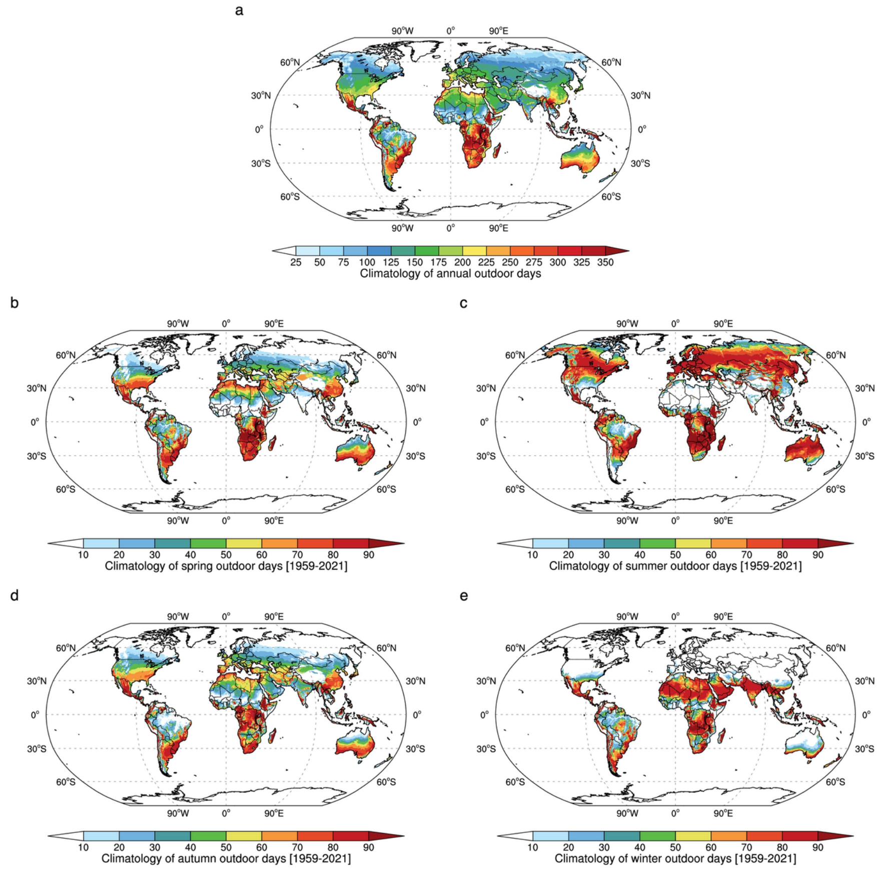

Fig. 2. Global distribution of outdoor days. Climatology of (a) annual, (b) spring, (c) summer, (d) autumn, and (e) winter outdoor days for the period 1959-2021. These global maps and time series are derived from ERA5.

Here, we show that the recent global warming due to climate change has disproportionately affected outdoor days in the global north and south (Fig. 3 and Fig. S2b). 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. Outdoor days in these regions 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 benefited from recent global warming, with a 16% 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).

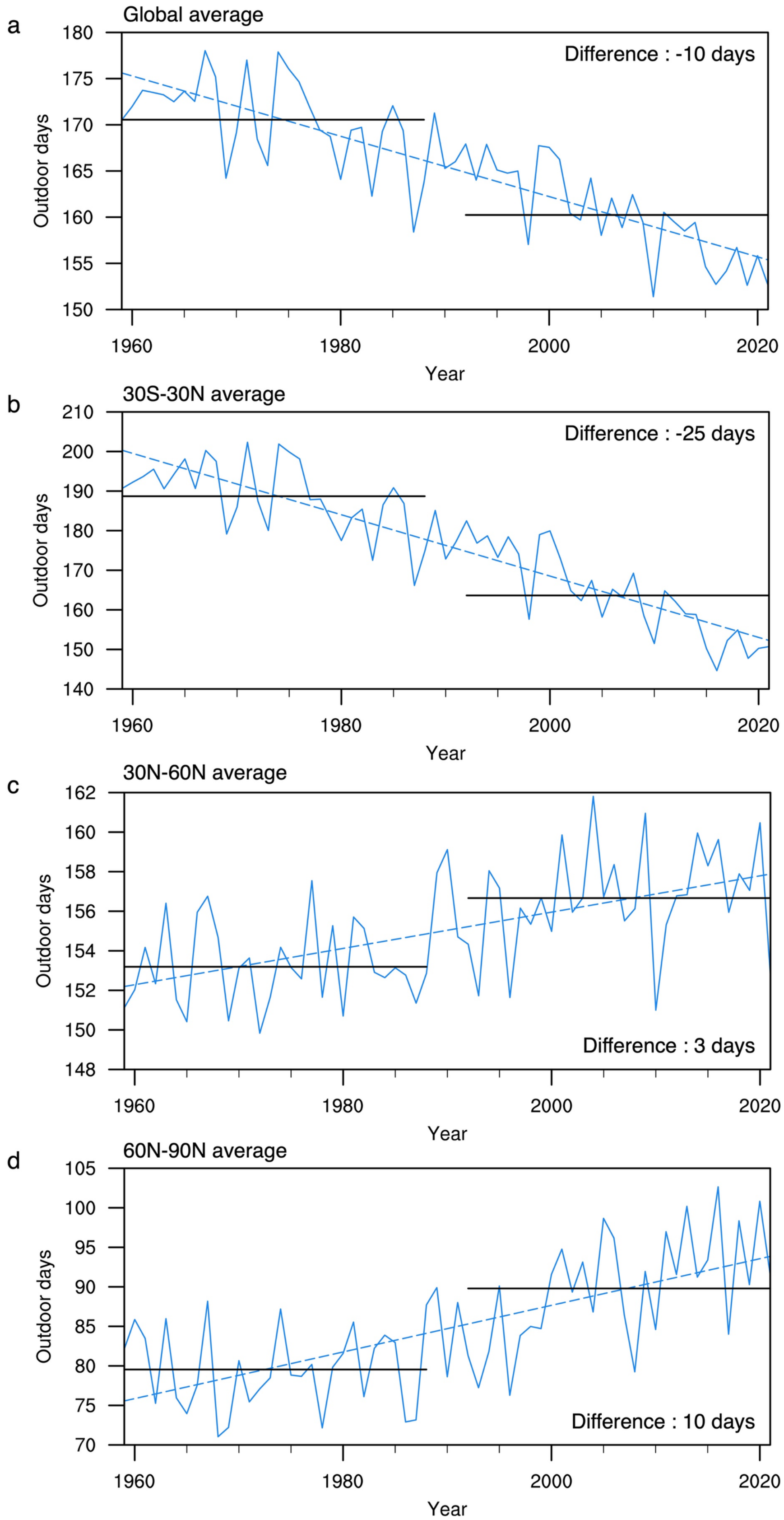
a
Global average
Difference : -10 days
Outdoor days
Year
b
30S-30N average
Difference : -25 days
Outdoor days
Year
c
30N-60N average
Difference : 3 days
Outdoor days
Year
d
60N-90N average
Difference : 10 days
Outdoor days
Year

Fig. 3. Trend of outdoor days. Time series of outdoor days 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.

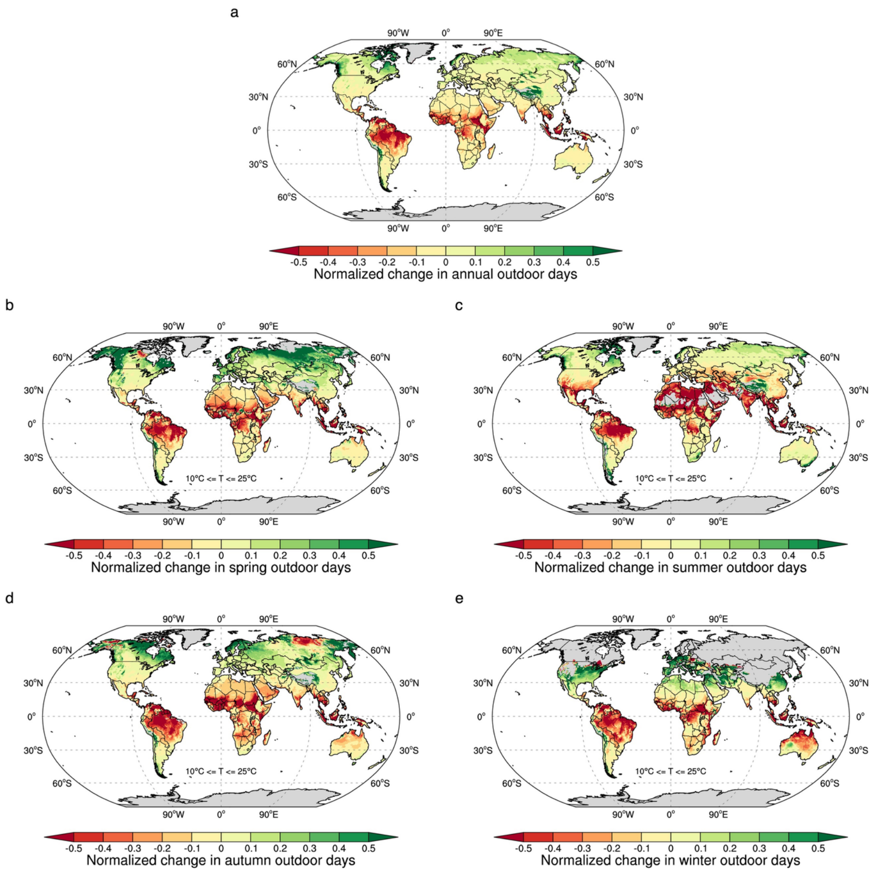

Fig. 4. Observed change in outdoor days. Normalized change in outdoor days in 1991–2020 with respect to 1961-1990. The changes are normalized by the 1961-1990 mean. These global maps are derived from ERA5.

Based on the General Circulation Model (GCM) projections from the CMIP5 and CMIP6 archives, the observed warming trend is projected to continue towards the end of the 21st century (Fig. 5 and Fig. S2). For the period 2071-2100, most land areas in the globe will likely experience significant warming by an average of 5.0 from CMIP5 models and by an average of 5.4 from CMIP6 models under high-emissions scenarios, though with some spatial variability. The overall warming across the global land surface shows no evidence for a north-south disparity, except for the projection that high latitudes may warm more significantly. The consistency between the CMIP5 and CMIP6 models is robust, ensuring the reliability of future projections.

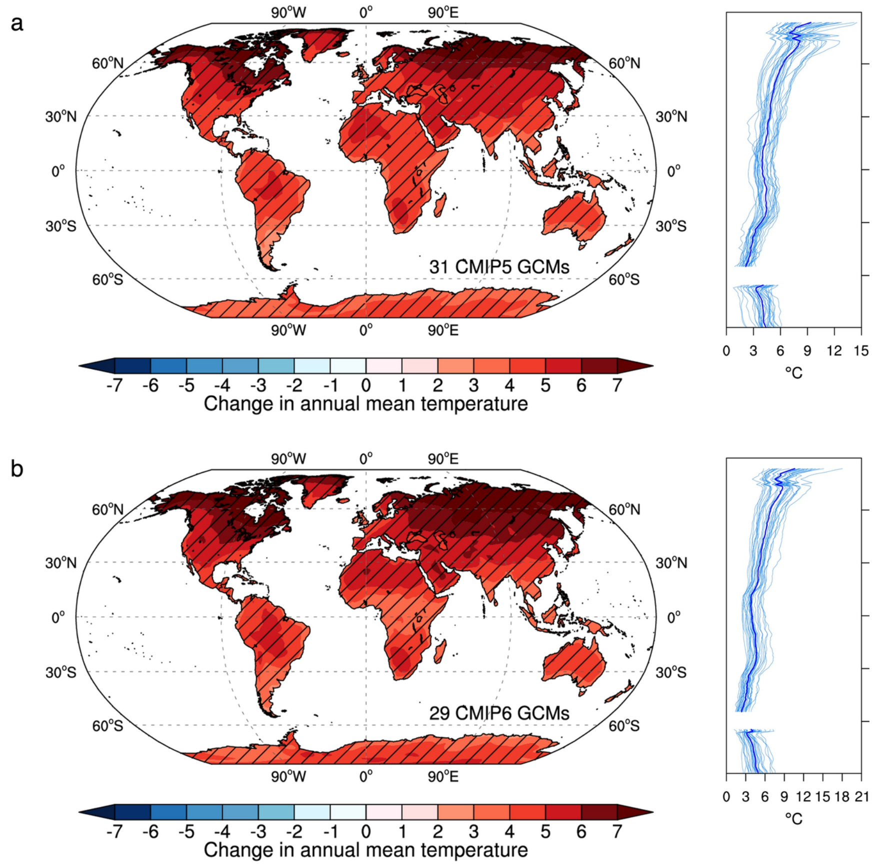

Fig. 5. Projected change in temperature. Spatial distribution of change in annual mean temperature in 2071-2100 with respect to 1976-2005, derived from (a) 31 CMIP5 GCMs and (b) 29 CMIP6 GCMs. Superimposed hatching indicates that more than 80% of models agree on the sign of the change. Zonal-mean changes are indicated by the right corner for each panel. Thick solid blue line in each panel indicates an ensemble mean of CMIP6 models.

The projected warming due to elevated greenhouse gas concentrations in the atmosphere could enhance the north-south disparity in the number of outdoor days (Fig. 6). Consistent with observed trends in the historical record, we project relatively large drops in the tropical regions, and a significant increase 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. S3), are disproportionately affected by the negative impacts of climate change through reduced outdoor days (Fig. 7 and Fig. S4 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. S4 derived from CMIP5 models).

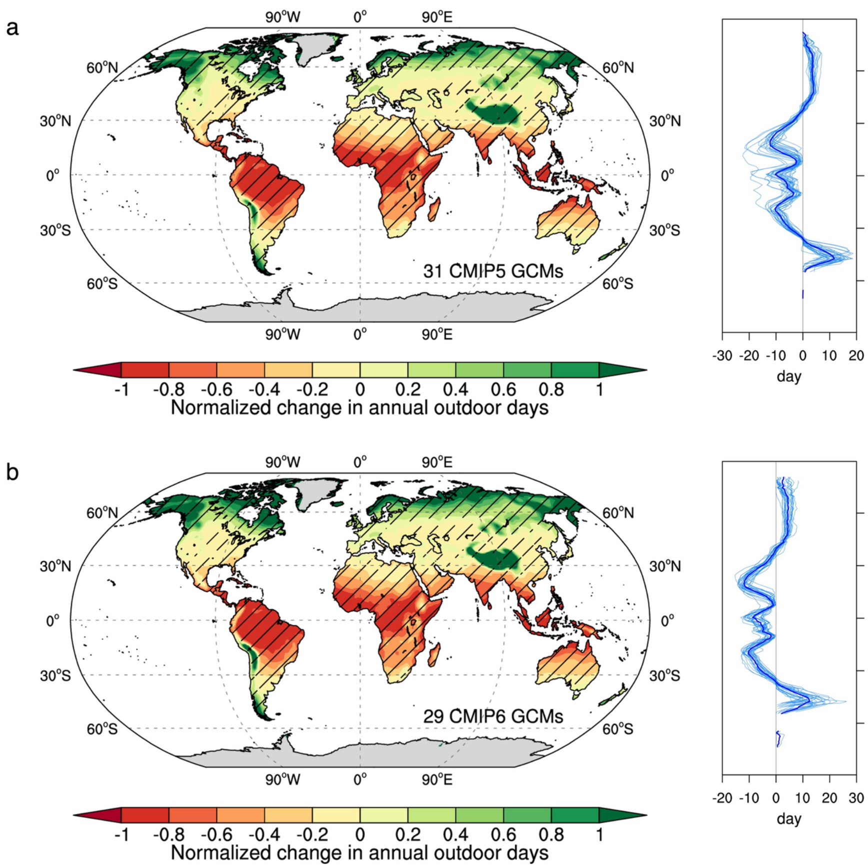

Fig. 6. Projected change in outdoor days. Spatial distribution of change in annual outdoor days in 2071-2100 with respect to 1976-2005, derived from (a) 31 CMIP5 GCMs and (b) 29 CMIP6 GCMs. The changes in (a-b) are normalized by the 1976-2005 mean. Superimposed hatching indicates that more than 80% of 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 CMIP6 models.

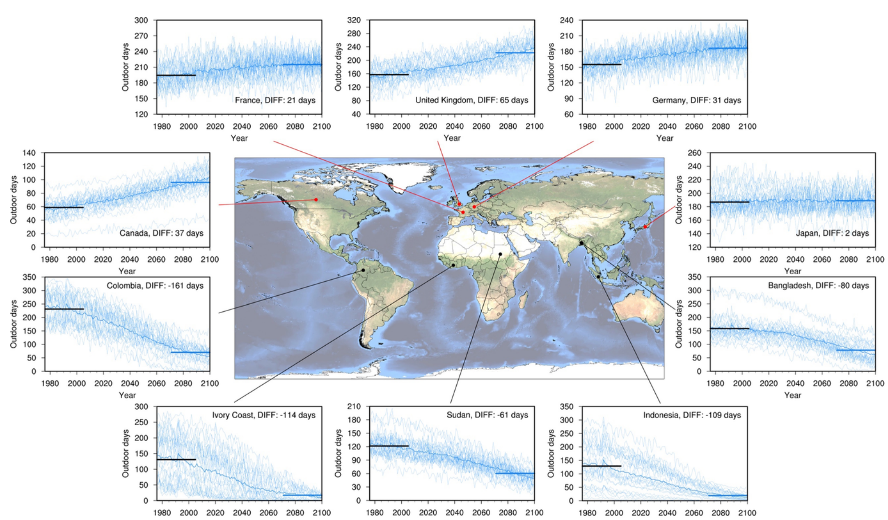

Fig. 7. Temporal evolution of annual outdoor days derived from CMIP6 models. Time series of annual outdoor days (day) derived from 29 CMIP6 GCMs under the historical and SSP5-8.5 scenarios. Thick solid blue line indicates an ensemble mean of CMIP6 models. Horizontal black and blue lines denote the 1976-2005 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 climate hazard have been 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 and to a less degree in the United States. The latter enjoys a broader range of climatic zones than the former. In both regions, 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). 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, benefiting significantly from climate change. 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. Similar results and conclusions are obtained by analyzing projections by CMIP5 models (Fig. S5).

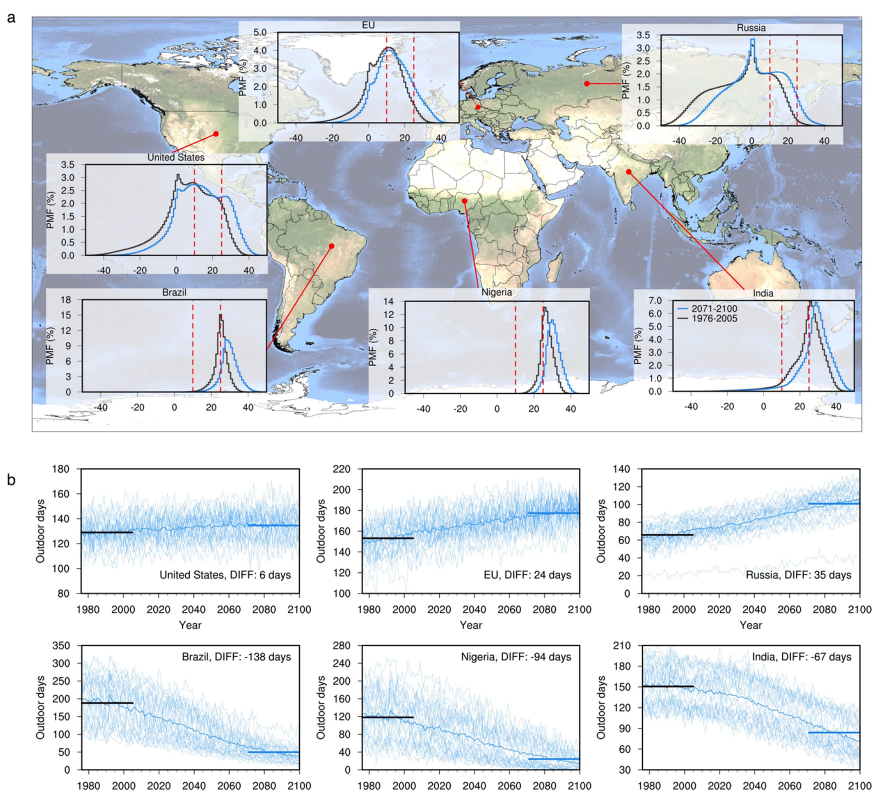

Fig. 8. Probability Mass Function (PMF) of daily mean temperature () and temporal evolution of annual outdoor days derived from CMIP6 models. a) The PMFs are generated for two groups of countries –

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 annual outdoor days (day) derived from 29 CMIP6 GCMs under the historical and SSP5-8.5 scenarios. Thick solid blue line in b) indicates an ensemble mean of CMIP6 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.

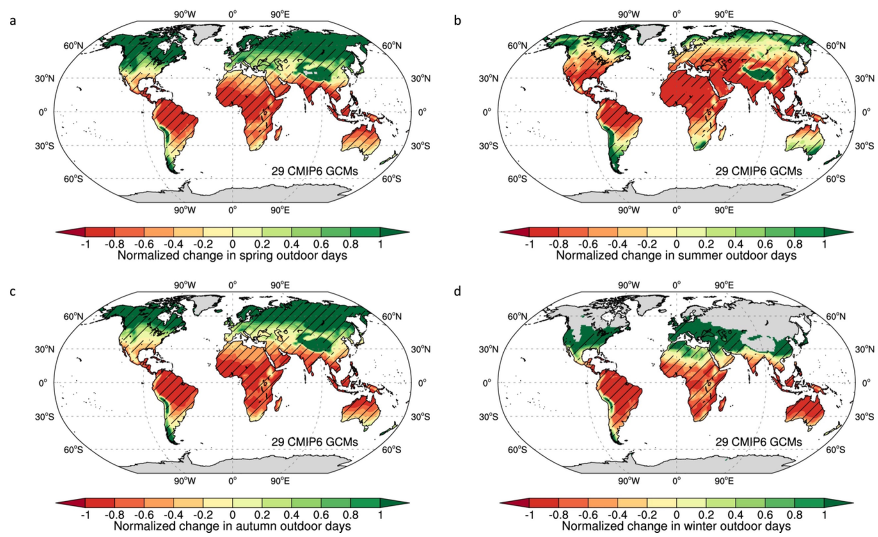

Fig. 9. Projected change in outdoor days for four seasons. Normalized change in outdoor days in 2071–2100 with respect to 1976-2005 for four seasons. The changes are normalized by the 1976-2005 mean. Superimposed hatching indicates that more than 80% of models agree on the sign of the change. These global maps are derived from 29 CMIP6 GCMs.

4. Discussion

Climate change studies usually focus on climate extremes and/or changes in the mean climate conditions, which are certainly important aspects of climate change (Choi et al. 2021, 2022; Choi and Eltahir 2022, 2023; Fischer and Knutti 2015; Im et al. 2017; Kang and Eltahir 2018; Pal and Eltahir 2016; Pfahl et al. 2017; Tuel and Eltahir 2020; Zhao et al. 2021). However, investigating mild weather, as done here for outdoor days, is of significant importance to society (Lin et al. 2019; van der Wiel et al. 2017; Zhang et al. 2022) since it could shape the contrasting risk of climate change on the global scale as revealed in this study. Meanwhile, future changes in rainfall and temperature – the two main climate variables – due to climate change show no clear north-south disparity in climate risk. 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, like 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), some climate extremes could possibly result in somewhat north-south disparity (Carleton et al. 2020; Crowther et al. 2016; Hirabayashi et al. 2013; Kam et al. 2021; Park et al. 2018; Shiogama et al. 2019; Vicedo-Cabrera et al. 2021). For instance, Shiogama et al. (2019) displayed 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. The frequency and pattern of river flood occurrence due to climate change exhibit a north-south gradient (Kam et al., 2021), with flood frequency projected to increase in regions such as Southeastern Asia and Eastern Africa and decrease in regions such as North America and Europe (Hirabayashi et al., 2013). The effect of climate hazard might be extended to soil systems with considerable losses in soil carbon stocks in high-latitude areas and an expected increase in tropical regions (Crowther et al., 2016). This suggests a reverse disparity where developing countries are benefiting from climate change while developed countries are losing. Moreover, the timing of climate hazards also exposes a north-south contrast as reported by Park et al. (2018). According to Park et al. (2018), while the time for the emergence of aridification due to climate change in the global south is expected to mostly occur before 2050, it might occur later than 2050 in the global north. Until recently, climate hazard did not seem to affect the large discrepancies in climate risk between countries - the global north and the global south and/or rich and poor countries and/or high and low emitters of greenhouse gases (Fig. S3).

Our results present some important caveats. First, the simulated temperature from CMIP5/CMIP6 models has systematic biases of temperature (Fig. S6). In turn, the biases may be transmitted to the historical runs and future projections of outdoor days to some degree (Fig. S7). Nevertheless, the overall pattern of outdoor days is well captured by the climate models. Note that, compared to the CMIP5 models, the CMIP6 models tend to better represent the observed spatial patterns of temperature and outdoor days over the world for the historical period, due to their remarkable improvements, in terms of spatial resolution, physical processes, and biogeochemical cycles (Eyring et al. 2016). Second, the human feeling of weather is complex and a widely subjective matter, and therefore, the definition of mild weather is non-trivial (van der Wiel et al. 2017). However, it can broadly be defined as pleasant weather conditions allowing most people to enjoy outdoor activities such as walking, jogging, cycling, or those related to construction and tourism industries (Lin et al. 2019; van der Wiel et al. 2017; Zhang 2016). Although we, here, defined outdoor days assuming a range of temperature from 10 to 25 , the exact range of temperature or variable used does not significantly affect the global distribution of the climate risk induced by changes in outdoor days (Fig. 10; Table S3; see interactive visualization at https://eltahir.mit.edu/globaloutdoordays/). In particular, considering other variables, such as wet-bulb temperature (Fig. S8) and different ranges of temperature resulted in a broadly similar pattern, supporting the north-south disparity. Third, analysis for some specific countries might show contrasting responses of outdoor days to climate change within the different climate regions of a country as shown by Choi et al. (2023) for the United States.

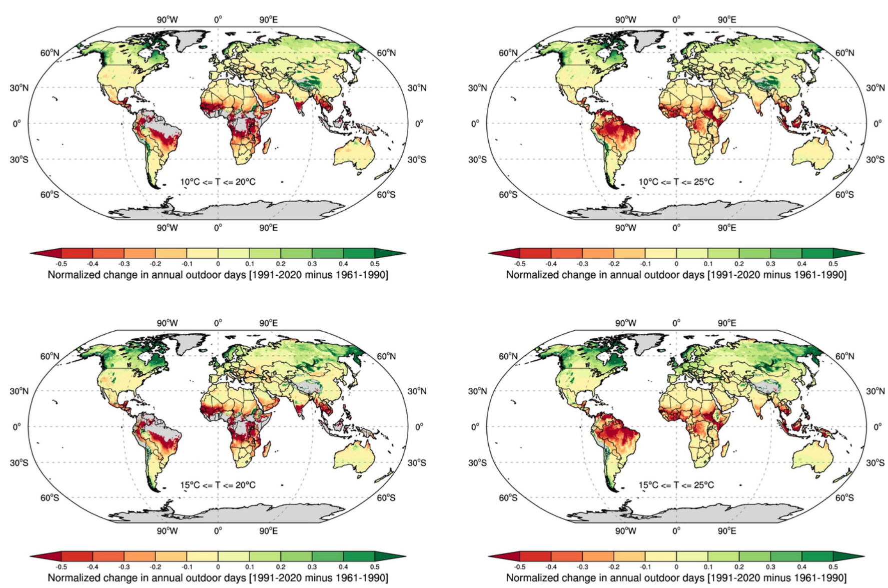

Fig. 10. Change in outdoor days with different definitions. Normalized change in annual outdoor days in

1991–2020 with respect to 1961-1990. Various definitions considered in this study are indicated in each plot. The changes are normalized by the 1961-1990 mean. These global maps are derived from ERA5.

5. Conclusions

Here, we used the state-of-the-art reanalysis data and projections from 60 GCMs (31 CMIP5 and 29 CMIP6) to propose that the climate hazard associated with the change in outdoor days (i.e., the number of days with pleasant weather that allows for outdoor activities by most people) could contribute to the north-south disparity that sustains inequality and injustice of climate change. We project that this disparity is expected to increase considerably in the future, assuming the high emissions scenarios.

Our results have important implications for the injustice of climate change. 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, which are developing countries with large populations but relatively minor emitters of carbon dioxide (Figs. S3 and S9). Meanwhile, some of the historically largest emitters of carbon dioxide, including the United States, 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 substantially 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 they also contribute to informing the ongoing discussions regarding compensations for loss and damage imposed by climate change.

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Data Availability Statement.

All original CMIP5 GCMs, CMIP6 GCMs, and the ERA5 reanalysis used in this study are publicly available at https://esgf-node.llnl.gov/projects/cmip5/, https://esgf-node.llnl.gov/projects/cmip6/, https://doi.org/10.24381/cds.adbb2d47, respectively. CMIP5 and CMIP6 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 and CO_2 emissions per capita are from https://ourworldindata.org/grapher/gdp-per-capita-maddison-2020 and https://ourworldindata.org/grapher/co-emissions-per-capita, respectively.

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