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Deadly Heat Stress to Become Commonplace Across South Asia Already at 1.5°C of Global Warming

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Key Points:

- Deadly heat stress conditions might become commonplace across South Asia even at 1.5°C warming
- Previous estimates of exposure to heat stress might have been conservative due to data biases
- Limiting global warming to 1.5°C instead of 2°C can reduce the projected population exposures to hazardous hot extremes by almost half

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract

South Asia (SA) is one of those hotspots where earliest exposure to deadly wet-bulb temperatures (T_w >35°C) is projected in warmer future climates. Here we find that even today parts of SA experience the upper limits of labor productivity (T_w >32°C) or human survivability (T_w >35°C), indicating that previous estimates for future exposure to T_w-based extremes may be conservative. Our results show that at 2°C global warming above pre-industrial levels, the per person exposure approximately increases by 2.2 (2.7) folds for unsafe labor (lethal) threshold compared to the 2006–2015 reference period. Limiting warming to 1.5°C would avoid about half that impact. The population growth under the middle-of-the-road socioeconomic pathway could further increase these exposures by a factor of ~2 by the mid-century. These results indicate an imminent need for adaptation measures, while highlighting the importance of stringent Paris-compatible mitigation actions for limiting future emergence of such conditions in SA.

Plain Language Summary

Wet bulb temperature (T_w) thresholds of 32°C and 35°C are respectively considered as the upper limits of labor productivity and human survivability. Some areas in South Asia (SA) have already witnessed such heat stress conditions and their occurrences with larger geographical footprint are projected to become commonplace even at the 1.5°C Paris Agreement temperature. Risks at 2°C warming would be about twice as high compared to 1.5°C. Presently, the world is already 1°C warmer than the pre-industrial period, and it may reach 1.5°C level by 2040, reflecting an imminent need for out of the box adaptation measures in SA.

1. Introduction

Heat-related socioecological risks are one of the major challenges associated with rising temperature that often result in potentially repairable but significant economic damages and irreparable losses of human lives (Coumou & Rahmstorf, 2012; Lelieveld et al., 2016; Russo et al., 2015, 2017). In addition to the climatic characteristics, demographic and socioeconomic factors also play a major role in determining the vulnerability of a population to heat stress, and their confluence can compound the overall exposure to heat related hazards. South Asia (SA) is one of those regions where vulnerability to extreme heat is particularly elevated due to the coexistence of both natural and human stressors, such as high population density, poverty-driven low adaptive capacity and background hot and humid climate conditions (Byers et al., 2018; Schleussner et al., 2018; Tucker et al., 2015). The risk is particularly high for approximately 60% of the working population in SA that is engaged in outdoor labor activities in the agriculture sector, which serves as the mainstay of economies of South Asian countries (Aryal et al., 2019; Dunne et al., 2013; Wang et al., 2017).

SA has experienced several deadly heatwaves in the recent past. For instance, the fifth deadliest heatwave in the global recorded history spanned large parts of Pakistan and India in 2015, causing approximately 3,500 direct heat related deaths (Anon, 2015; Im et al., 2017). Unlike countries in temperate regions that have experienced high heat-related mortalities in recent years (Vicedo-Cabrera et al., 2018), the population in SA is naturally highly adapted to hot and humid climate characteristics. However, despite the natural heat acclimatization, heat stress related mortalities emerge from the interplay of natural (hot and humid background conditions) and human (demographic and socioeconomic factor) systems that unfavorably elevates the risk of exposure to hot extremes in this region.

There are several approaches that are commonly used to quantify heat related risks. Oftentimes, extremes in dry-bulb temperatures (T_{max}) are used as a measure of heat stress (Ali et al., 2018; Diffenbaugh & Ashfaq, 2010; Lelieveld et al., 2016; Perkins-Kirkpatrick et al., 2017; Saeed et al., 2017). However, heat related impacts on humans cannot be fully manifested through the use of T_{max} alone as perspirative cooling allows a human body to tolerate high levels of dry-bulb temperatures. The efficiency of perspirative cooling depends on the humidity levels in the atmosphere, meaning that a human body will feel varying impacts of identical T_{max} extremes at different levels of relative humidity (Coffel et al., 2017; Mora et al., 2017; Rastogi et al., 2020). Therefore, a true measure of the potential impacts of heat on humans requires the use of indicators that are based on a combination of temperature and relative humidity, such as wet-bulb temperature (T_w) (Ahmadalipour & Moradkhani, 2018; Im et al., 2017; Kang & Eltahir, 2018; Pal & Eltahir, 2016; Saeed et al., 2020). These combined measures of heat are based on physiological studies with a long history of use in different fields, such as athletics, military and workplace safety (Chong & Zhu, 2017). The role of relative humidity in the calculation of heat stress is particularly important over SA where irrigation strongly modulates atmospheric moisture content and moist heat stress over Indo-Gangetic Plains (Devanand et al., 2019; Krakauer et al., 2020; Mishra et al., 2020).

T_w is defined as the temperature that an air parcel would attain if cooled at a constant pressure by evaporating water within it until saturation (Coffel et al., 2017). It always remains less or equal to T_{max}, and high values of T_w imply hot and humid conditions (Stull, 2011). Therefore, a region with high magnitudes of T_{max} may not have equally strong magnitudes of T_w and vice versa (Figure 1). Given the fact that physiological attributes of the human body and its tolerance to heat is distinct in different regions of the world (Ahmadalipour & Moradkhani, 2018), a variety of metrics and thresholds have been used to quantify the impact of T_w-based heat stress (Kang et al., 2019). However, T_w threshold of 35°C is often considered as a physiological limit of human tolerance to heat stress, given that a human body is unable to cool itself beyond this point (Im et al., 2017; Pal & Eltahir, 2016; Sherwood & Huber, 2010), while empirical evidences suggest that most physical labor becomes unsafe once T_w crosses 32°C (Buzan et al., 2015; Coffel et al., 2017; Liang et al., 2011).

Several studies have been conducted to determine future risk of heatwaves over SA in response to increase in radiative forcing. However, most of these studies either have made use of T_{max} for defining a heatwave (e.g., Mishra et al., 2017; Murari et al., 2015; Saeed et al., 2017) or have only focused on the environmental conditions in determining the changes in exposure to heat stress in the future climates (e.g., Im et al., 2020; Monteiro & Caballero, 2019). Additionally, after the adoption of Paris Agreement in 2015, there has been growing interest to quantify impacts of global mean warming at policy relevant targets, such as 1.5°C and 2°C above pre-industrial level. Within this context, we investigate T_w-based hot extremes using an ensemble of future climate projections from the Half a degree additional warming, Prognosis and Projected Impacts (HAPPI) project, which is specifically designed to investigate climate change and its impacts at Paris Agreement targets of 1.5°C and 2°C (Mitchell et al., 2017). Additionally, we make use of population projections from various Shared Socio-economic Pathways (SSPs) in determining future risks of exposure to hot extremes as a result of changes in environmental and socioeconomic factors.

2. Data and Methods

2.1. Data

We use three set of experiments from the HAPPI project (Mitchell et al., 2017), representing reference climate (2006–2015), climate at 1.5°C above pre-industrial (1.5°C) and climate at 2.0°C above pre-industrial (2°C). Each set consists of simulations from four (ECHAM6, MIROC5, CAM4-2° and NorESM1) Global Climate Models (GCMs). For each experiment, every GCM consists of 20 ensemble members, each spanning 10 years. For our analyses, we bias-correct daily precipitation, maximum temperature and relative humidity from each GCM output at 0.5° × 0.5° grid spacing using the EWEMBI as a reference (Saeed et al., 2018), which is based on EartH2Observe, WFDEI and ERA-Interim data Merged and Bias -corrected for ISIMIP (EWEMBI) (Lange, 2018) and described in the Intersectoral Impact Model Intercomparison Project Phase

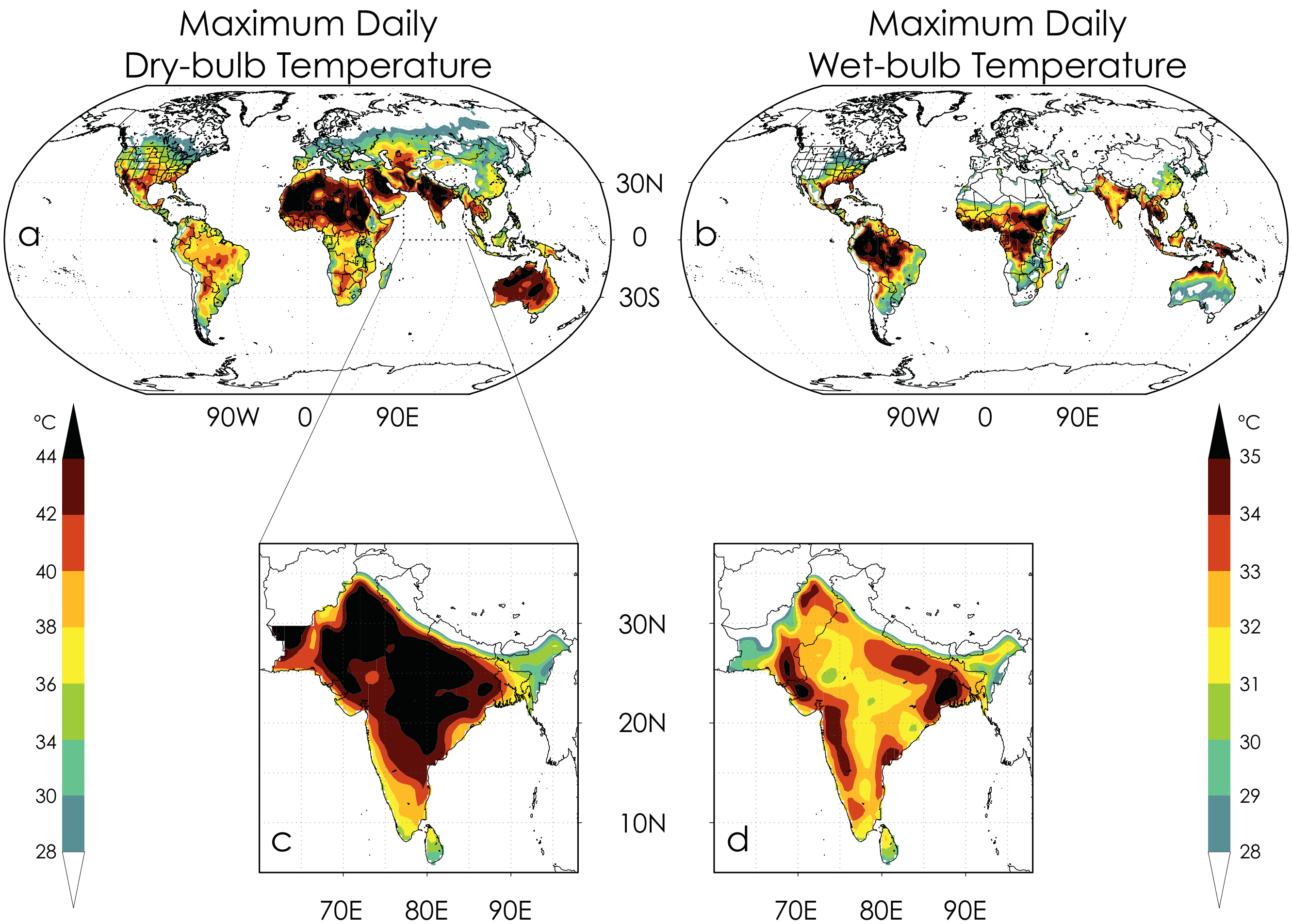

Figure 1. Spatial distribution of extreme dry-bulb temperature (T_{max}; a, c), and extreme wet-bulb temperature (T_{wmax}; b, d), calculated as the annual maximum over the daily maximum values in the 1979–2013 historical period of the EWEMBI data (°C). EWEMBI, EartH2Observe, WFDEI and ERA-Interim data Merged and Bias -corrected for ISIMIP.

2 (ISIMIP2b) (Frieler et al., 2016). It is important to note that in the making of EWEMBI, the ERA-Interim undergoes sequential elevation correction for meteorological variables in addition to monthly bias correction using the Climate Research Unit (CRU) observations (Weedon et al., 2014). The SSPs-based population projections data is based on Jones and O'Neill (2016) at 0.5° × 0.5° grid spacing, which is available at https://www.isimip.org/gettingstarted/input-data-bias-correction/details/62/.

2.2. Methods

Following Stull (2011), we calculate daily T_w using maximum temperature and relative humidity. The choice of this method is partly due to data constraints, as other methods such as Davies-Jones (2008) require additional variables for the calculation of T_w, which are not available through the HAPPI project. Moreover, we calculate different recurrence intervals of T_w in each experiment (reference, 1.5°C and 2°C) as an inverse of the exceedance probability, using the 800 years (20 ensembles multiplied by four GCMs) of simulated data. Additionally, we define a Heat Stress Event (HSE) as exceedance of daily maximum T_w continuously for 3 days or more above certain thresholds. We have considered two kinds of HSE events; one using the T_w threshold of 35°C, which corresponds to the upper limits of human survivability, and one using T_w threshold of 32°C, which corresponds to the upper limits of labor productivity. Using HSE, we calculate population exposure to heat stress for climate only and combined (climate and population) cases. In the climate only case, we multiply 2005 population at each grid point with the corresponding values of HSE at 35°C and 32°C T_w thresholds in the reference, 1.5°C and 2°C experiments. In the combined case, we account for the effects of future changes, which is achieved by multiplying future population projections at each grid point with the HSE in the 1.5°C and 2°C experiments. Population projections are considered for two time periods in the 21st century, representing the mid-century (2050) and the late century (2090) under each of the five SSPs. Finally, all the grid points that fall within a country boundary are aggregated to obtain the total exposure for that country. Similar approach has been used in earlier studies to calculate population exposure to climate extremes (Batibeniz et al., 2020). See Text S1 for further details regarding methodology.

3. Results

3.1. Fatal Heat Stress in the Reference Climate

Globally, there are distinct features in the observed spatial distribution of the maximum daily dry-bulb temperatures (T_{max}) and maximum daily wet-bulb temperatures (T_{wmax}) that require highlighting. The strongest magnitudes of T_{max} are mostly observed over the inland subtropical regions, while moist and hot conditions result in the strongest magnitudes of T_{wmax} in the tropics and regional monsoon belts (Figure 1). The spatial distinction between the patterns of T_{max} and T_{wmax} is similar over SA with the strongest values of T_{max} over the inland central and western regions and the strongest values of T_{wmax} over the coastal and northern regions. The spatial heterogeneity in the magnitudes of T_{wmax} over SA aligns well with the moist westerly monsoonal flow through Arabian Sea and southwesterly flow through the Bay of Bengal, and with the irrigation-induced moist heat stress over the heavily cultivated Indo-Gangetic basin in the northern stretches of SA (Devanand et al., 2019; Mishra et al., 2020). The observed spatial heterogeneities in the T_{wmax} over SA are captured well by all four GCMs that have been analyzed in this study with relatively low magnitudes in MIROC5 and high magnitudes in NorESM1 (Figure S1).

More importantly, over a number of areas in SA, including parts of southern Sindh province in Pakistan and coastal strips in southwestern and eastern India, T_{wmax} exceeds 35°C; a threshold often considered as the human physiological survivability limit (Figure 1d). These historical occurrences of such T_{wmax} magnitudes in our analyses of EWEMBI and simulated data are in contrast to the findings of an earlier T_w-based modeling study (Im et al., 2017) that projected occurrences of days meeting this threshold over SA only at the substantially high levels of radiative forcing (RCP 8.5) in the late 21st century. While there are methodological differences between this study and Im et al. (2017) in the calculation of T_w, it is unlikely that the choice of method can cause such substantial disagreements in the magnitudes of T_{wmax}. Interestingly, several recent observations-based studies also affirm that such deadly threshold has been exceeded in the past at many locations in SA (Monteiro & Caballero, 2019; Raymond et al., 2020; Zahid et al., 2017). One of the probable causes for the lack of such T_{wmax} occurrences in Im et al. (2017) during the historical climate is perhaps their choice of reference data for the bias correction of model simulations. We explain this point through the comparison of T_{max} biases in the ERA-Interim reanalysis, used in Im et al. (2017) for bias correction, and the EWEMBI, used in this study for bias correction (Figure S2). It has been previously noted that the ERA-Interim underrepresents the extreme magnitudes of critical heat stress across the tropics and subtropics (Raymond et al., 2020). When the climatological means of T_{max} from the two reference datasets (ERA-Interim and EWEMBI) are compared with those from the CRU observations, a significant and spatially robust underestimation of up to >3°C in the ERA-Interim based T_{max} is found (Figure S2). Such a mean bias in ERA-interim should lead to substantial underestimation in the occurrence of days with T_{wmax} reaching 35°C in the historical climate and could delay their occurrences in a warmer future climate of ERA-Interim-based bias corrected simulated data. However, we also note that while the GCMs used in our analyses exhibit similarities with observations regarding the location of areas where T_{wmax} reaches 35°C in the reference period, their overall spatial footprint of these areas is relatively large (Figure S1).

3.2. Projection of Heat Stress at the Paris Agreement Targets

With the recognition that 35°C T_{wmax} is not a rarity in SA, we analyze the recurrence of T_{wmax} at 2-, 4-, 6- and 8-years intervals in each experiment (Figure 2), also known as return periods, using the 800 years of T_{wmax} from four GCMs (see Methods). Return period is a useful statistical measure for risk analysis as it provides an assessment of how the probability of occurrence of an event may change in the analysis period in response to changes in the driving mechanisms. In our analysis, most of SA exhibits a magnitude of T_{wmax} ≥30°C in

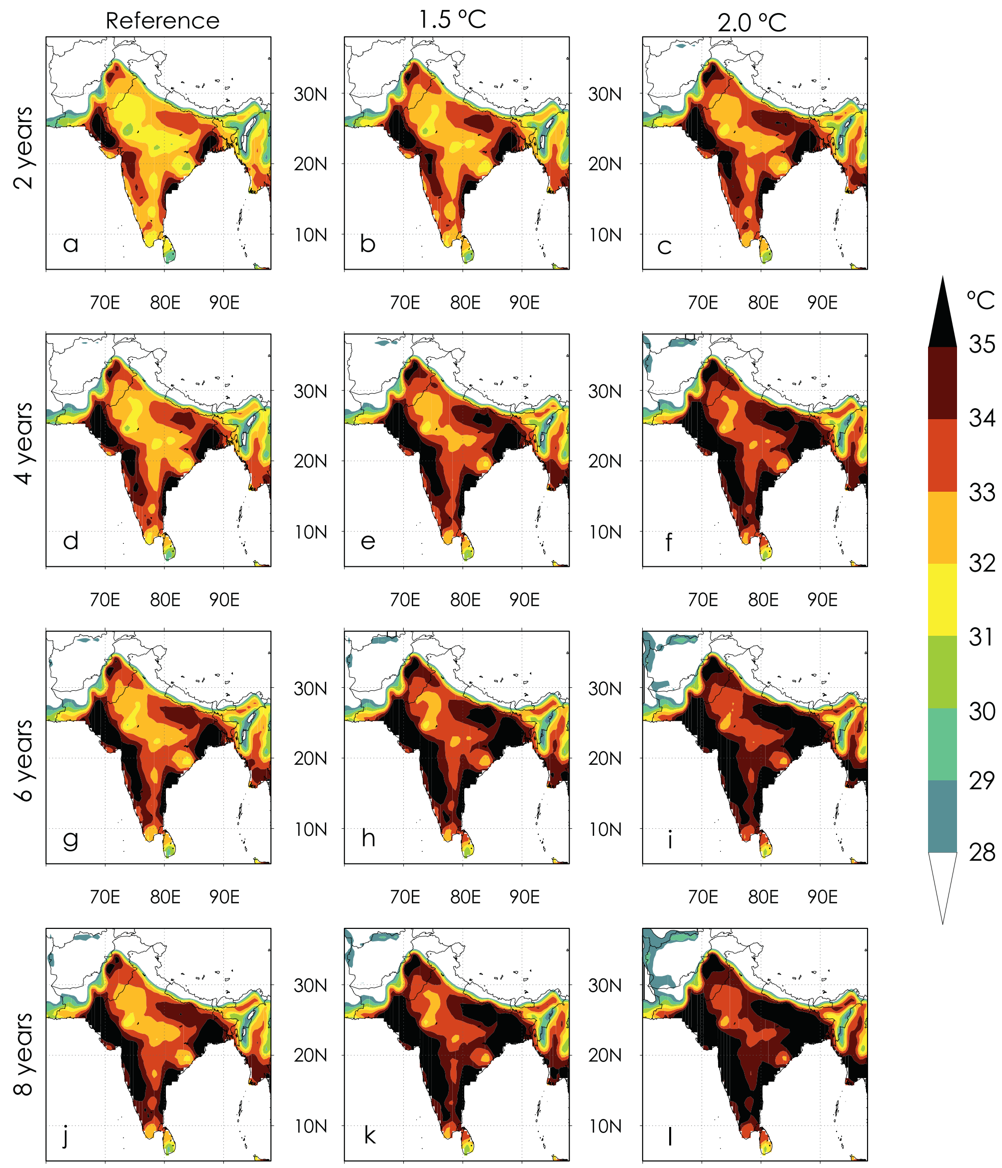

Figure 2. T_{wmax} magnitudes (°C) over South Asia for different recurrence intervals. The recurrence magnitudes are calculated for the reference period (first column), 1.5°C warming level (2nd column), and 2°C warming level (3rd column) at 2 years (a–c), 4 years (d–f), 6 years (g–i), and 8 years (j–l) intervals. The calculations are based on 800 years of simulated data, representing 20 ensembles each for four GCMs.

the reference climate (2006–2015) at 2 years return period, while it crosses the critical threshold of 35°C in parts of southeastern Pakistan (Sindh) and adjoining areas in India (Gujarat), in addition to the regions surrounding Kolkata in the eastern state of West Bengal and Chennai in the southern state of Tamil Nadu (Figure 1). Moreover, the Indo-Gangetic plains exhibit high magnitudes of T_{wmax} of up to 33°C. As we move toward the less frequent return periods in the reference climate, the value of T_{wmax} also increases gradually with a most noticeable increase along the coastal strip from southeastern Pakistan to southern India along the western boundary of the Deccan Plateau. Notably, two most populated cities of Karachi and Mumbai, which have experienced heat related mortality and morbidities in the past (Ghumman & Horney, 2016; Xu et al., 2020), are located within the stretch of these regions exhibiting high T_{wmax} magnitudes.

Expectedly, 1.5°C and 2°C experiments exhibit higher magnitudes of T_{wmax} for each return period (Figure 2). At a 4-year return period, the region reaching the critical threshold of 35°C extends over Ganges and northern Indus plains in the 1.5°C experiment, and its spatial footprint expands further in the 2°C

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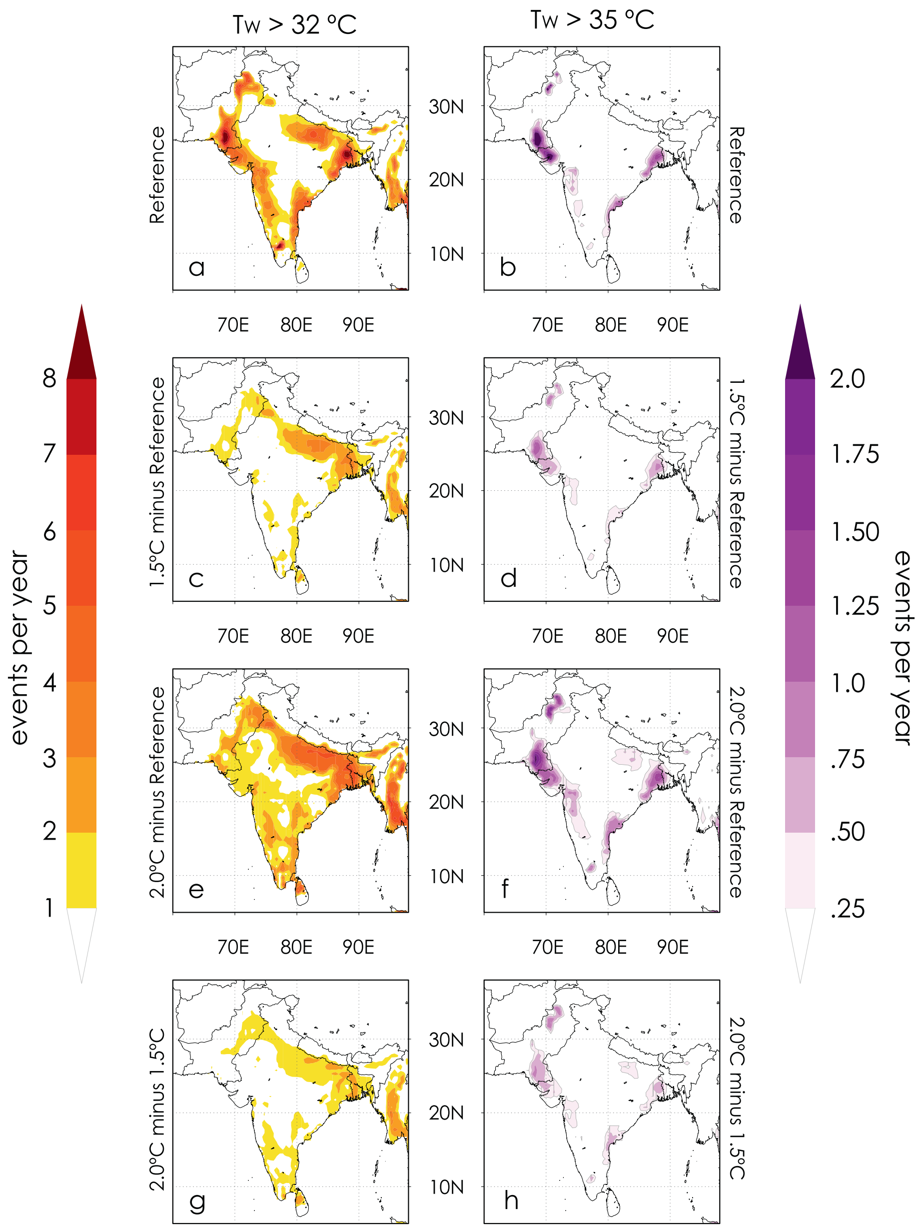

Figure 3. Spatial distribution of Heat Stress Events (HSE) per year in the reference period, and their changes in the 1.5°C and 2°C experiments. The HSE events are calculated at T_{wmax} thresholds of 32°C, representing the upper limits of labor productivity, and 35°C, representing the upper limits of human survivability. The reference period (a and b), 1.5°C minus reference (c and d), 2°C minus reference (e and f), and 2°C minus 1.5°C (g and h).

experiment. There is relatively limited further spatial expansion of regions exposed to 35°C threshold at higher recurrence intervals or warming level as most of the central plains are still spared at the highest return period (8 years) and the warmest future scenario (2°C), where T_{wmax} magnitudes reach up to 34°C (Figure 2).

Using the 35°C and 32°C T_{wmax} thresholds as upper limits of human survivability and labor productivity respectively, we further analyze changes in the occurrences of HSE (three consecutive days above thresholds, see Methods). In the reference climate, labor productivity threshold of HSE (32°C) is exceeded in the Indo-Gangetic plains, and regions surrounding many major urban centers such as Karachi, Kolkata, Mumbai, Hyderabad, and Peshawar (Figure 3). Increase in the occurrences of HSE at the labor productivity threshold is mostly confined to the Indo-Gangetic plains in the 1.5ºC experiment, but it expands to every region that

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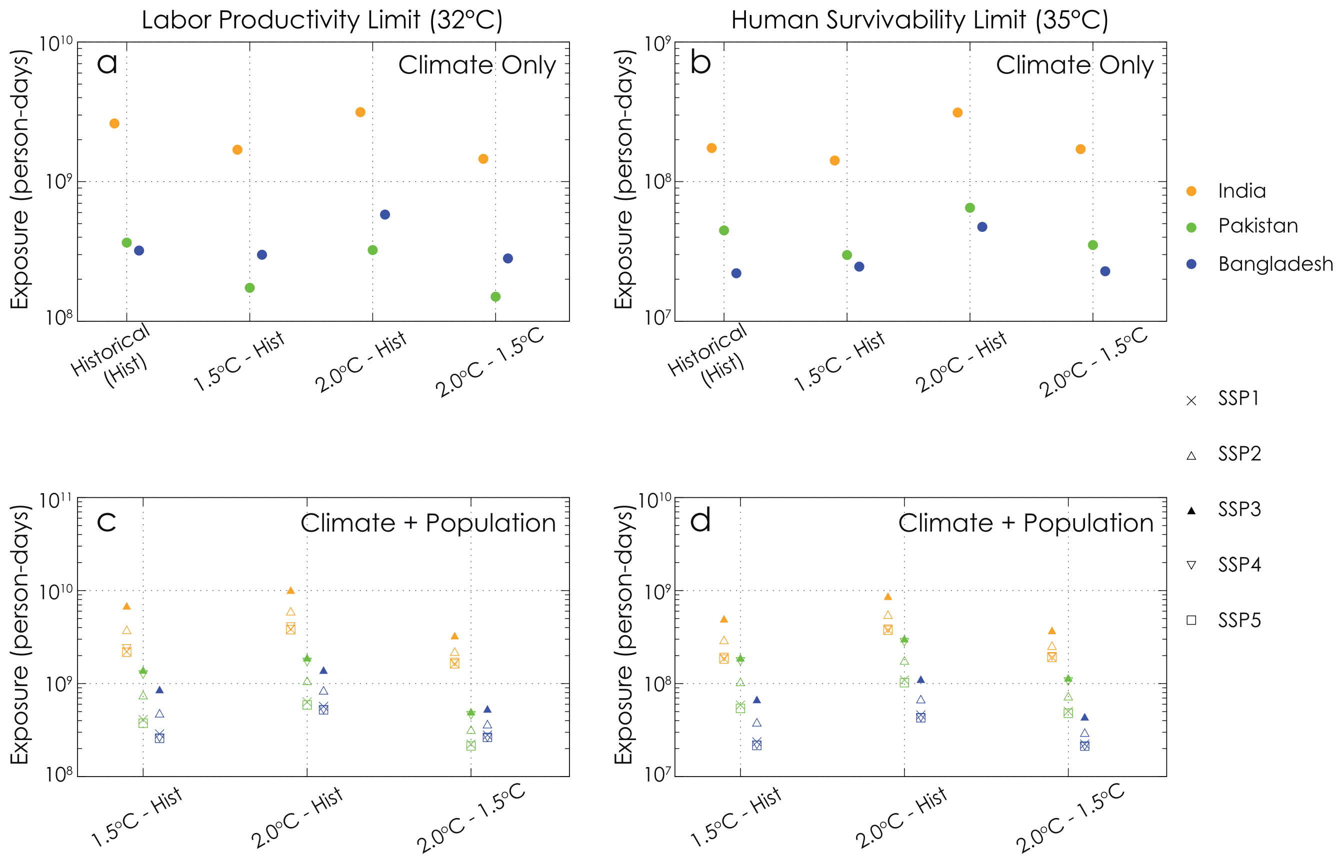

Figure 4. Population exposure to HSE events (person-days), calculated as the multiplicative product of number of HSE events per year and population at each grid point. Climate Only effect (a and b) considers population levels of 2005 while combined effect (c and d) considers changes in both climate and population. Population projections are based on five Shared Socioeconomic Pathways (SSPs) and represent changes in 2090s with respect to the 2005 levels. The exposures are calculated for HSE events at 32°C (a), (c) representing the upper limits of labor productivity, and 35°C (b), (d), representing the upper limits of human survivability.

is historically exposed to these conditions in the 2°C experiment. For the human survivability threshold of HSE (35ºC), regions adjacent to Karachi, Kolkata and Peshawar again stand out as the most exposed areas in the reference climate. However, unlike the widespread increase in the HSE at labor productivity threshold, future increase in the HSE at human survivability threshold at 1.5°C and 2°C warming levels is mostly limited to those regions that are already the hotspots in the reference climate.

3.3. Population Exposure to Dangerous Heat Thresholds

In the reference climate, over 3.3 billion (B) person-days (240 million (M)) of 32°C (35°C) HSE are experienced across the three most populous countries in SA (Bangladesh, India, and Pakistan) (Figure 4). Without any consideration of future increase in population, exposure to 32°C (35°C) HSE is projected to increase by more than 2B and 4B (190M and 420M) at 1.5°C and 2°C warming levels, respectively, due to climate changes. Alternatively, if the global warming is limited to 1.5°C instead of 2°C, it can reduce 32°C HSE by 1.4B person-days and 35°C HSE by 170M person-days over India alone. Similarly, future increase in the HSE-based exposure at 32°C (35°C) threshold stands at approximately 150M (35M) and 280M (23M) person-days higher for 2°C compared to 1.5°C for Pakistan and Bangladesh respectively.

As previously noted, environmental changes are not the only factors that determine the risk of a human population to increased heat stress hazards. Among other factors that can influence this risk, population increase in the 21st century is expected to be a key contributor. Projected increases in population can substantially exacerbate the exposure to dangerous T_w levels in SA. Among the five SSPs, projected population in three South Asian countries (Bangladesh, India, and Pakistan) under SSP2 is 2.2B by 2050 and 2.1B by 2090,

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which represents a middle-of-the-road scenario with moderate challenges for adaptation and mitigation (Jones & O'Neill, 2016). If global warming is contained at 1.5°C but population grows following the SSP2 trajectory, the projected increase in exposure to 32°C (35°C) HSE will exceed 5B (420M) person-events by the mid-century and 4.9B (425M) person-events by the late century in the three countries. Compared to the exposure without population increase, these projected changes in 32°C (35°C) HSE are approximately 2.31 (2.16) times more for the mid-century and 2.25 (2.18) times more for the late century. Similarly, increases in 32°C (35°C) HSE at 2°C warming level will be 1.95 (1.82) times more for mid-century and 1.91 (1.83) times more for the late century. The changes in projected exposure due to other SSP-based population growth scenarios have been provided in Table S1.

4. Discussion and Summary

Global mean temperatures are currently rising at an average rate of around 0.2°C per decade (Drancourt & Zingue, 2020; IPCC, 2018), and presently the net increase in temperatures with respect to the pre-industrial period is around 1°C. With the current trajectory of emissions and pace of warming, it is expected that a 1.5°C warmer world compared to pre-industrial levels could be reached by 2040 (IPCC, 2018). While countries are worried about the adverse future consequences of continued warming, some areas in SA are already getting exposed to deadly heat stress conditions (T_w >35°C) even at the current warming levels (Raymond et al., 2020; Zahid et al., 2017), a finding highly relevant for assessments assessing climate-related loss and damage. An addition of half a degree to the current global warming levels would further expose substantially large population to more prevalent deadly hot extremes in many new geographical areas in SA, including several major urban centers and Indo-Gangetic Plains.

The emergence of frequent occurrences of deadly heat waves within the limits of the Paris Agreement in our analyses is in sharp contrast to the earlier findings that projected such changes only toward the end of the 21st century at exceptionally high radiative forcing levels of RCP8.5 (Im et al., 2017). Therefore, the current pace of global warming potentially leaves little room for adaptation in a region like SA that exhibits limited elasticity due to unique socioeconomic and environmental factors. Keeping the adversity of situation in view, the speed of emergence of a climate state which is 1.5°C warmer than the pre-industrial or about 0.5°C warmer than the present-day will be key in determining the preparedness of the most vulnerable regions like SA to deal with hazardous climate conditions. Stringent climate mitigation in line with the Paris Agreement 1.5°C limit could almost half mean warming rates over the next two decades compared to a current policies scenario, thereby substantially broadening the adaptation window for SA countries (McKenna et al., 2020). However, our results clearly indicate that impact of heat extremes at 1.5°C in SA will still be very severe and widespread, exceeding human adaptability thresholds, and provide an illustration of climate-related loss and damage even at low levels of warming. However, there are substantial benefits in limiting global warming to 1.5°C instead of 2°C as half a degree difference between two warmer future climate states can reduce the projected exposures to hazardous heat conditions by almost half. Limiting warming to 1.5°C has also been shown to have impacts on South Asian climate which are well within the range of historical climate variability that communities are already accustomed to (Ashfaq, Cavazos, et al., 2020). Furthermore, reduction in inequalities and lower population growth associated with scenarios of sustainable socio-economic development (SSP1) will reduce future exposure while also increasing societal adaptive capacities (Andrijevic et al., 2020).

We would like to highlight some caveats which should be kept in my mind while interpreting these results. The coarse resolution of GCMs lacks the representation of fine-scale climate system feedbacks that oftentimes regulate regional scale responses. In particular, GCMs have historically struggled in the representation of key processes that influence summer climate over SA (Ashfaq et al., 2017). We also note that HAPPI experiments make use of prescribed SST, which tend to underestimate natural variability and thereby overestimate increases in probability ratios particularly in tropical regions (Fischer et al., 2018). Moreover, the experimental design and analytical framework do not consider the effect of urban heat islands, which can raise urban temperature by several degrees as compared to non-urban areas. Furthermore, use of daily scale data and relatively simple formulation for T_w calculation in this study, which is due to data constraints, warrants further research to test the sensitivity of T_w to variations in methodological choices. Lastly, the use of fixed thresholds as heat stress proxies has its own caveats as health impacts are expected to scale non-linearly with increases in T_w. The resilience of population to heat stress also varies with age and geographical location, therefore, region specific heat stress proxies which are derived from actual observations, such as those in Mora et al. (2017), can be useful in robust risk assessments. Nonetheless, the projected increases in heat stress have serious implications for social-ecological systems in SA that inherently exhibit low adaptive capacity and serve as a wake-up call for South Asian countries to collaborate in their fight against climate change.

Data Availability Statement

The data are accessible from the repository through the following link https://redmine.dkrz.de/projects/happi-de/wiki/How_to_get_data_from_HAPPI_data_portal. The population data are available at https://www.isimip.org/gettingstarted/input-data-biascorrection/details/62/. This manuscript has been co-authored by employees of Oak Ridge National Laboratory, managed by UT Battelle, LLC, under contract DE-AC05-00OR22725 with the U.S. Department of Energy. The publisher, by accepting the article for publication, acknowledges that the United States Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce the published form of this manuscript, or allow others to do so, for United States Government purposes. The Department of Energy will provide public access to these results of federally sponsored research in accordance with the DOE Public Access Plan (http://energy.gov/downloads/doe-public-access-plan).

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