ADVANCING EARTH AND SPACE SCIENCE

Earth's Future

RESEARCH ARTICLE

10.1029/2021EF002488

Special Section:
CMIP6: Trends, Interactions, Evaluation, and Impacts

Key Points:

- Heatwave exposure in the recent decade was >40% higher in the lowest-quartile income region of the world than the highest-quartile
- Rapid adaptation capacity in higher-income regions can buffer climate change-driven increases in heatwave exposure
- Lagged adaptation in the lower-income regions translates to escalating impacts and increasing heat-stress inequality

Supporting Information:

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

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Citation:

Alizadeh, M. R., Abatzoglou, J. T., Adamowski, J. F., Prestemon, J. P., Chittoori, B., Akbari Asanjan, A., & Sadegh, M. (2022). Increasing heat-stress inequality in a warming climate. *Earth's Future*, *10*, e2021EF002488. https://doi.org/10.1029/2021EF002488

Received 9 OCT 2021
Accepted 8 JAN 2022

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Increasing Heat-Stress Inequality in a Warming Climate

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Abstract Adaptation is key to minimizing heatwaves' societal burden; however, our understanding of adaptation capacity across the socioeconomic spectrum is incomplete. We demonstrate that observed heatwave trends in the past four decades were most pronounced in the lowest-quartile income region of the world resulting in >40% higher exposure from 2010 to 2019 compared to the highest-quartile income region. Lower-income regions have reduced adaptative capacity to warming, which compounds the impacts of higher heatwave exposure. We also show that individual contiguous heatwaves engulfed up to 2.5-fold larger areas in the recent decade (2010–2019) as compared to the 1980s. Widespread heatwaves can overwhelm the power grid and nullify the electricity dependent adaptation efforts, with significant implications even in regions with higher adaption capacity. Furthermore, we compare projected global heatwave exposure using per-capita gross domestic product as an indicator of adaptation capacity. Hypothesized rapid adaptation in high-income regions yields limited changes in heatwave exposure through the 21st century. By contrast, lagged adaptation in the lower-income region translates to escalating heatwave exposure and increased heat-stress inequality. The lowest-quartile income region is expected to experience 1.8- to 5-fold higher heatwave exposure than each higher income region from 2060 to 2069. This inequality escalates by the end of the century, with the lowest-quartile income region experiencing almost as much heatwave exposure as the three higher income regions combined from 2090 to 2099. Our results highlight the need for global investments in adaptation capabilities of low-income countries to avoid major climate-driven human disasters in the 21st century.

Plain Language Summary We show that heatwave exposure has disproportionately increased in the lowest-income regions globally compared to the highest-income regions over the past four decades. We also show that emerging heat hazards (e.g., shock heatwaves—the first heatwave of the season—and widespread contiguous extreme heat events) intensified in the past four decades and are expected to increase in the future across the globe, jeopardizing adaptation efforts even in wealthy countries. We use climate projections to evaluate future changes in heat-stress inequality globally. In doing so, we incorporate the fact that high-income countries have greater institutional and individual capacity to rapidly adapt to climate change than low-income countries. Our findings demonstrate continued increases in heatwave exposure inequality because of delays in adaptation capacity in the developing world, compounded by a higher emergence of warming in low-latitude areas where most of the low-income countries occur. These results highlight the urgency to scale adaptation efforts in the low-income regions to minimize heat-stress inequality.

1. Introduction

Climate-related disasters are estimated to have caused a cumulative global loss of US$ 2,245B from 1998 to 2017, marking a 151% growth from the previous 20-year period (Mizutori & Guha-Sapir, 2017). Extreme heat is among the deadliest and costliest of natural hazards globally, claiming more than 166,000 lives between 1998 and 2017 (Lesk et al., 2016; Mazdiyasni et al., 2017; Mizutori & Guha-Sapir, 2017), one-third of which can directly be attributed to anthropogenic climate change (Vicedo-Cabrera et al., 2021). Heatwaves, defined as prolonged periods of excessive heat, are becoming more intense, more frequent and longer across many regions of the globe (Nanditha et al., 2020; Perkins et al., 2012) and are expected to further intensify in a warming climate (Li, 2020). Exposure to extreme heat events is also increasing around the world (Batibeniz et al., 2020; Mukherjee et al., 2021; Russo et al., 2015), currently exposing ~30% of the global population to health-threatening heat

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(Mora et al., 2017) with a substantial projected increase by the end of the century (King & Harrington, 2018; Li et al., 2020; Mishra et al., 2017).

Recent literature provides mounting evidence on the role of adaptation mechanisms—for example, institutional capacity and coordination, infrastructure improvement, access to water, electricity and cooling systems, early warning systems, and increased awareness—in reducing human vulnerabilities to extreme heat (Anderson et al., 2018; Lowe et al., 2011; Sheridan & Allen, 2018; Sheridan & Dixon, 2017; Viguié et al., 2020). Adaptation to non-stationary climate risks is more rapid in societies with capital and institutional means (Campbell et al., 2018), yet capacity and foundational infrastructure for adaptation is limited in the developing world (Zografos et al., 2016). Even in high-income countries with reduced sensitivity to heat extremes, expanding and lengthening contiguous heatwaves with ever-increasing human exposure (Vogel et al., 2019) can overwhelm the electrical grid, causing black-outs and brown-outs, as occurred in a large area of California in 2020 (Heat Wave Causes Power Outage, 2020), negating energy-dependent adaptation measures (Larcom et al., 2019; Stone et al., 2021).

In this study, building on the assumption that "*vulnerability to risk, and degrees of suffering, are determined by levels of economic development, rather than simple exposure to natural hazards*" (Mizutori & Guha-Sapir, 2017), we evaluated historical and projected global heatwaves across the socioeconomic spectrum. We characterized future heatwaves assuming that adaptation measures keep pace with warming trends in high-income regions and fall behind in low-income regions, since the institutional and individual capacity to adapt to a changing climate is stronger in high-income than low-income regions (Haines et al., 2006; Mach & Siders, 2021). We posed two questions: (1) How did heatwave characteristics change from 1980 to 2019 across the socioeconomic spectrum? and (2) How is heatwave exposure projected to change in the 21st century, if adaptability measures are considered? We explored these questions using gridded daily observed temperatures (1980–2019) and future temperature projections from an ensemble of 10 CMIP6 model simulations with a moderate SSP2-4.5 scenario (2030–2099), global gridded historical (2000–2020) and country-level projected population data (2030–2099), and gridded historical gross domestic product data (1990–2015).

2. Methods

This study considered a historical period of 1980–2019 and future projections of 2030–2099 to explore heatwave characteristics, including frequency, exposure, geographical extent, season length, and the amplitude of the first heatwave of the season. We defined a *heatwave* as an event during which daily mean temperature exceeded the 97th percentile of local annual mean daily temperature in a reference period (e.g., 1980–2019 in the historical period) for at least three consecutive days (Raei et al., 2018). We used local thresholds to account for acclimation to climate and used daily mean temperature to account for the fact that both daytime and nighttime temperatures govern heatwaves' health impacts (Ahmadalipour & Moradkhani, 2018). See Figures S1 and S2 in Supporting Information S1 for temperature thresholds used to define heatwaves across the globe. We assessed heatwave frequency, exposure and seasonal length from a socioeconomic lens alongside regional analysis. Further, we evaluated the less explored contiguous heatwaves and exposure to such events, as well as the amplitude of the first heatwave of the season (i.e., shock heatwave). *Heatwave exposure* is defined as the number of person-days that people are impacted by extreme heat events. *Heatwave season length* is defined as the period between the first and the last heatwave of the year (calendar year for the Northern Hemisphere and September-August for the Southern Hemisphere). *Heatwave amplitude* is defined as the maximum daily mean temperature during a heatwave event. Coverage area and population impacted by contiguous heatwaves were determined by considering all grids that were simultaneously (in 1 day) impacted by an event. We presented the largest contiguous heatwave in terms of spatial extent. Heatwave frequency, exposure and season length are presented in terms of their mean annual statistics in each decade, whereas statistics related to the amplitude of shock heatwave and the contiguous heatwave are presented in terms of maximum decadal (largest in each decade) values.

We grouped the globe into four socioeconomic clusters (low-, lower-middle-, upper-middle-, and high-income) based on the population-weighted per-capita gross domestic product (GDP) in 2015. The weight for each grid was calculated by normalizing its population by the global population. Through weighted-sampling, the 25th, 50th and 75th quantiles of the population-weighted per-capita GDP distribution were determined to define income clusters. Total population in each cluster was similar in 2015. Historical population data were acquired from Gridded Population of the World, v4, from the US National Aeronautics and Space Administration's Socioeconomic

Data and Applications Center. Per-capita GDP data were acquired from gridded global datasets for GDP and Human Development Index by Kummu et al. (2018). The employed gridded per-capita GDP product accounts for within-nation heterogeneity, that is, representing within-country variations. Gridded population data were available for 2000, 2005, 2010, 2015, and 2020 (30 arc-seconds resolution), and gridded per-capita GDP data were available for 1990, 2000, 2015 (30 arc-seconds resolution).

We incorporated heatwave adaptation capacity for future projections based on per-capita GDP (Kummu et al., 2018). This approach assumes that macroscale societal adaptation efforts to heat impacts scale with per-capita GDP in terms of the pace at which they adapt to changing environmental conditions. Thresholds for heatwaves in high-income regions use the previous 30 years, assuming more rapid adaptation to changing conditions. We assumed that the upper-middle-income region lags 5 years in adaptation efforts, and their heatwave thresholds for each year are based on the previous 6–35 years. Similarly, the lower-middle- and low-income regions lag 10 and 15 years in adaptation, respectively, and so their climatology period lags accordingly. These hypothesized adaptation capacities are associated with hard (e.g., cooling systems) and soft (e.g., awareness) infrastructural improvements. Hence, the estimated heatwave exposure mainly, but not exclusively, is associated with the reduced heat-stress within controlled environments (e.g., indoors), where adaptation measures are most effective. This approach contrasts with previous studies that generally adopted static historical periods to define future heatwave thresholds (Christidis et al., 2015) but is in line with the recent literature that acknowledges the adaptation capacity of communities and reduced sensitivity to heat events (Anderson et al., 2018; Christidis et al., 2015).

For the historical record (1980–2019), we used daily mean temperature from the US National Oceanic and Atmospheric Administration's Climate Prediction Center (Global Daily Temperature dataset with a 0.5-degree resolution). For future projections (2030–2099), we employed daily mean temperature data from 10 models from the Coupled Model Intercomparison Project Phase 6 (CMIP6; varied resolution; Table S5 in Supporting Information S1). These 10 models were selected based on their historical performance (Kim et al., 2020). We selected a moderate SSP2-4.5 scenario, which is based on shared socioeconomic pathway 2 (middle of the road) and representative concentration pathway 4.5 (intermediate scenario), which we deem likely given the current trends (Tebaldi et al., 2021; UN Environment Programme, 2019). This scenario is in line with the assumptions of our study in terms of relatively stable future per-capita GDP spatial distribution and lagged adaptation. Note that although 2030–2099 statistics are presented in the paper, temperature data prior to this period (as early as 1985) were used to determine heatwave thresholds in different income clusters. We calculated heatwave and exposure statistics for each CMIP6 model separately, and reported an ensemble median in this paper. Data from CMIP6 models were re-gridded from their original spatial resolutions to a common grid (1-degree resolution) using a bilinear interpolation technique to account for different resolutions in the models.

Finally, we calculated exposure to heatwaves from 2000 to 2019 (temporal coverage of gridded population data) using linearly interpolated annual gridded population data (from the original temporal resolution of 5 years) and annual frequency of heatwaves. To this end, we accumulated the population (30 arc-seconds grid) encapsulated in each temperature grid (0.5°) that was determined to experience a heatwave. We note that disparate lengths of historical climate and population records (1980–2019 for heatwaves and 2000–2019 for exposure) and decadal circulations that modulate climatic extremes can impact trends in heatwave frequency and exposure statistics on different continents (Perkins-Kirkpatrick & Lewis, 2020). For the future projections, we employed the United Nations' country-level population projection data, and redistributed each country's annual population through 2099 based on its gridded population in 2020.

3. Results

3.1. Historical Heatwaves Escalated Globally

Increase in the number of heatwave days was evident across much of the globe over the past four decades, with over a 60% increase globally (Figure 1; Data Set S1). Mean *annual heatwave season length* also was more than 75% longer globally in the 2010s as compared to the 1980s (Figure S3 in Supporting Information S1). Furthermore, the maximum decadal amplitude of *shock heatwave* was between 2.16 (Europe) and 3.27 (North America) °C higher in the 2010s as compared to the 1980s (Figure S3; Table S1 in Supporting Information S1). Shock heatwaves have been shown to cause disproportionately larger health impacts (Brooke Anderson & Bell, 2011; Habeeb et al., 2015; Liss et al., 2017). Finally, exposure to heatwaves increased more than 65% globally in the

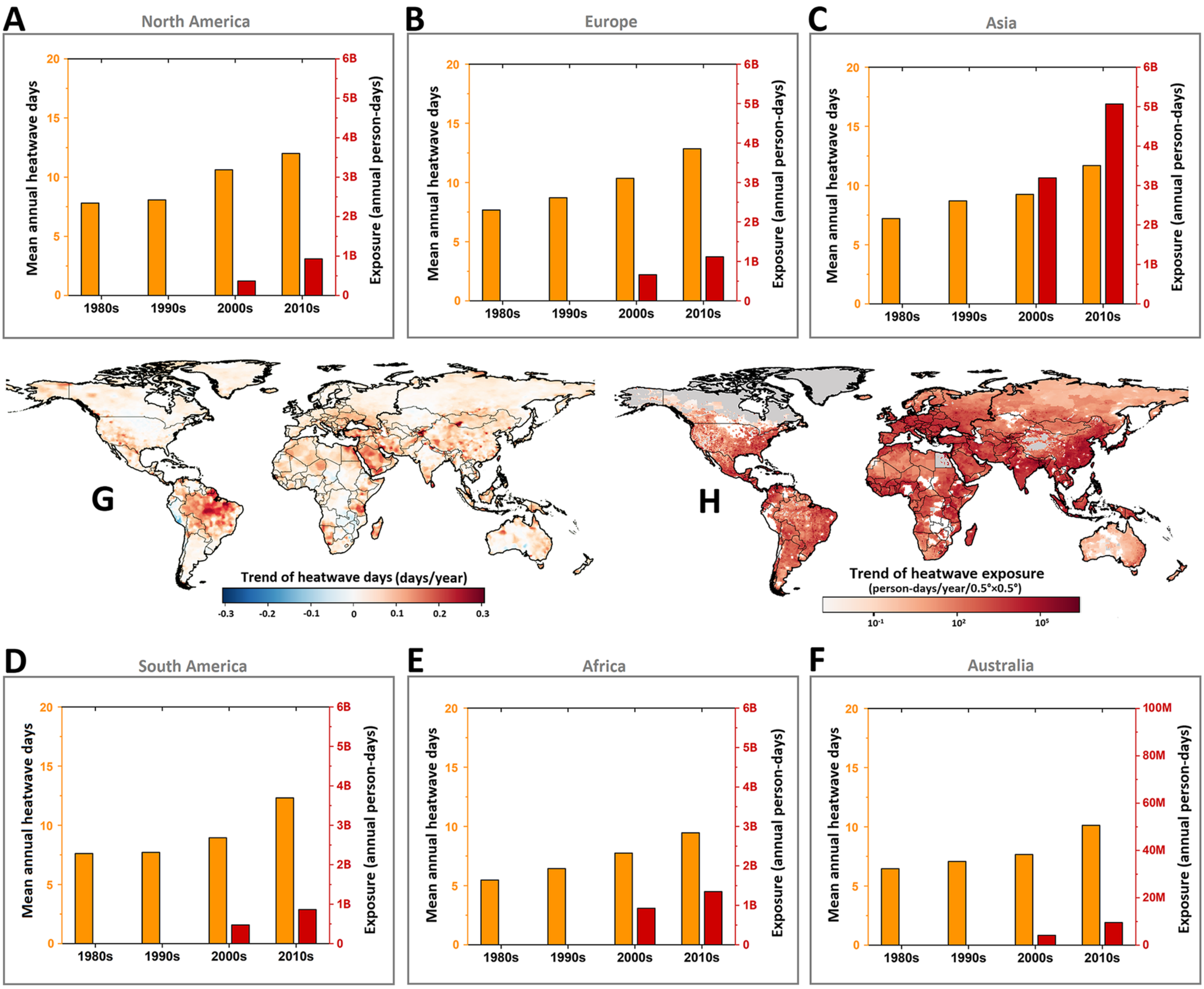

Figure 1. Increasing historical heatwave frequency and exposure from 1980 to 2019. (a)–(f): Mean annual heatwave frequency from 1980 to 2019 and exposure from 2000 to 2019 on each continent, presented in each decade. (g)–(h): Map of trends in mean annual heatwave frequency and exposure. Gray areas mark near zero population.

2010s as compared to the 2000s (9.3 vs. 5.6 billion person-days per year from 2010 to 2019 and 2000–2009, respectively; Figure 1).

Contiguous heatwaves extended geographically across all continents (Figure 2). An example of historical wide-ranging heatwaves is the 2010 Russian heatwave that engulfed >1 million km (Lesk et al., 2016) of land, causing >56,000 deaths and contributed to several hundred wildfires and widespread agricultural failure (Perkins, 2015). The largest decadal contiguous heatwave was up to 150% (South America) larger in geographic extent in the 2010s as compared to the 1980s across different continents (Figure 2; Data Set S1). Exposure to contiguous heatwaves also increased up to 46% (Australia) in the 2010s as compared to the 2000s across different continents (Figure 2; Data Set S1). See Table S2 in Supporting Information S1 for detailed continental statistics.

3.2. Historical Heatwaves Intensified More in the Low-Income Than in the High-Income Region

Heatwave metrics increased across all socioeconomic clusters, but more so for the low-income region and less so for the high-income region (Figure 3). We categorized the globe into four income clusters (Figure 3e), based on the 2015 population-weighted per-capita GDP. Each cluster encompassed a similar population in 2015. These

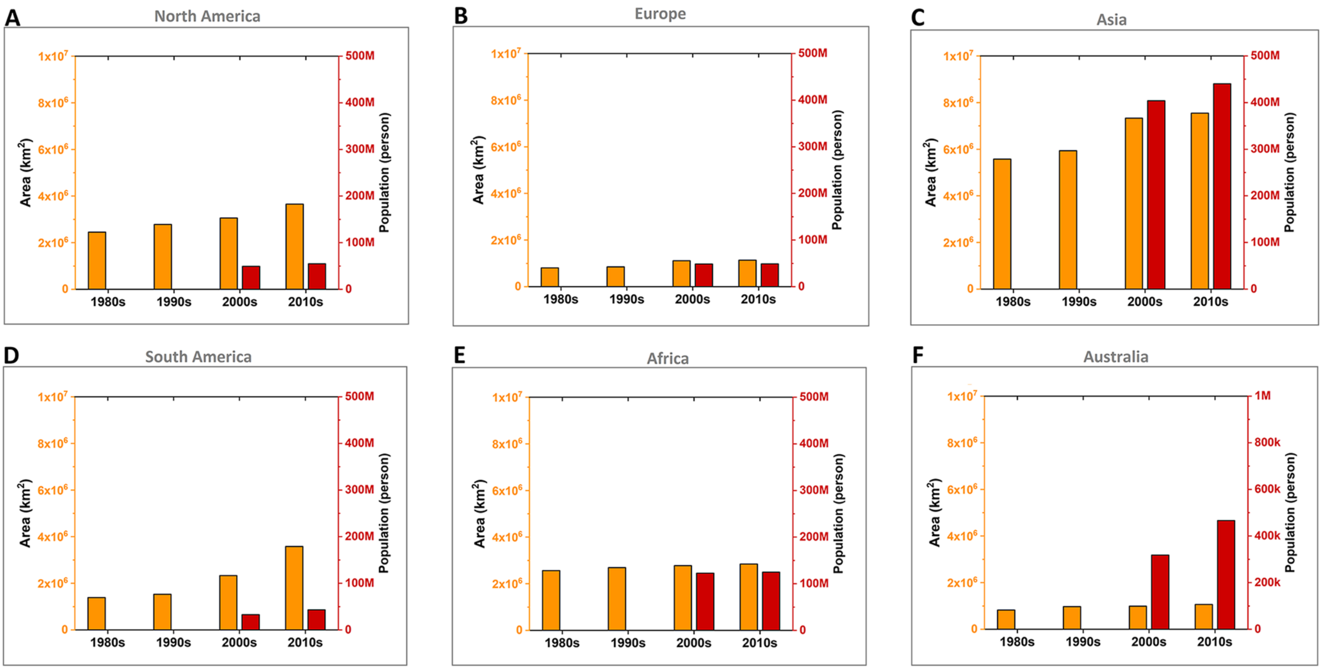

Figure 2. Enlarging historical contiguous heatwaves and associated exposure from 1980 to 2019. (a)–(f): Coverage area and exposure to the largest decadal contiguous heatwave (by geographic extent) on each continent from 1980 to 2019. Note the difference in population scale for Australia.

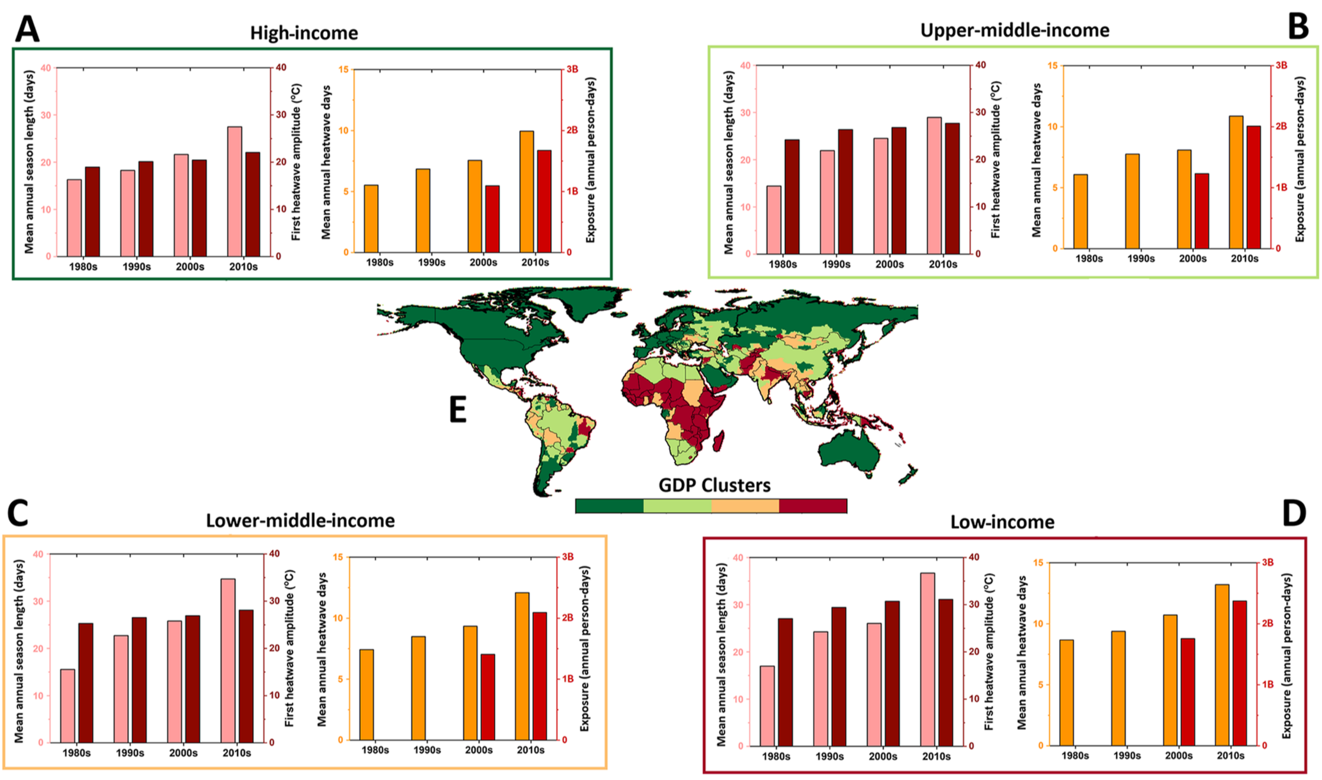

Figure 3. Increasing historical heat-stress inequality from 1980 to 2019. (a)–(d): Mean annual heatwave frequency, exposure, season length, and maximum decadal amplitude of shock heatwave in four income clusters (regions with a similar population in 2015) categorized by a gridded per-capita gross domestic product, GDP. (e): Map of per-capita GDP clusters.

clusters are referred to as "regions" in this paper. In the 2010s, the low-income region observed over 30% more heatwave days as compared to the high-income region (average of 13.2 vs. 10.0 days per year; Data Set S1). The low-income region also observed the highest rate of increase in the mean annual heatwave season length among all per-capita GDP clusters in the past four decades, with 23.8 additional days in the 2010s versus the 1980s (as compared to 14.4 days in the high-income region; Figure 3; Data Set S1). We note that the observed trends are influenced by the heatwave definition in this study, pointing to increased clustering of heatwaves in recent decades as compared to the earlier period of the study in the low-income region which mostly occur in the tropics. Furthermore, the maximum decadal amplitude of shock heatwave increased with the highest rate from 1980 to 2019 in the low-income region (4.02 vs. 2.91°C higher in the 2010s vs. the 1980s for low- and high-income regions, respectively; Figure 3; Data Set S1).

Exposure to heatwaves also increased in the past two decades across the socioeconomic spectrum (Figure 3; Data Set S1). Heatwave exposure in the 2010s was largest for the low-income region and smallest for the high-income region (2.4 vs. 1.7 billion person-days per year). Thus, despite similar overall populations during this period, the poorest region observed over 40% higher exposure to heatwaves as compared to the richest region. This is mainly due to increasing heatwave trends in highly populated low-income regions, such as eastern India and Bangladesh (Figures 1g and 1h; Herold et al., 2017).

3.3. Future Heatwave Trends Are Modulated by Adaptation Capacity

The richest two regions by per-capita GDP are expected to experience rather stable heatwave metrics by the end of the century. The richest region is projected to observe between 11.7 and 13.0 heatwave days per year, on average, with an estimated 3.1–4.0 billion person-days per year exposure to extreme heat events through the century (Figure 4; Data Set S1). The upper-middle-income region will likely experience a higher frequency of heatwaves, ranging between 18.6 and 23.4 days per year, on average, with 4.4–6.4 billion person-days per year of heatwave exposure through the century (Figure 4; Data Set S1). The mean annual heatwave season length remains at about 41.8 days per year for the high-income region through the century, whereas this nominally increases from 49.3 days per year in the 2030s to 54.8 days per year in the 2090s for the upper-middle-income region (Figure 4; Data Set S1). The maximum decadal amplitude of shock heatwave, however, increases at rates between 0.28 and 0.31°C per decade for the richest two regions (Figure 4; Data Set S1).

The higher expected number of heatwave days, exposure to heat events, and heatwave season length for the upper-middle-income as compared to the high-income region are partially a function of the 5-year delay in adaptation to a warming climate. Nevertheless, the adaptability of the richest half of the world negates the warming trend's impact on increasing heatwave stress. We note that adaptation efforts are not reflected in the absolute value of the amplitude of the shock heatwave or in its trends, but are expected to alleviate its adverse impacts.

Lagged adaptation to a warming climate (Anderson et al., 2018), on the contrary, contributes to notable trends in heatwave frequency and exposure for the poorest half of the world in the 21st century (Figure 4). Mean annual frequency of heatwave days in the 2060s (2090s), for example, is expected to be 5.4 (9.5) and 13.1 (23.2) days per year more than that in the 2030s for the lower-middle- and low-income regions, respectively (Figure 4; Table S3 in Supporting Information S1; Data Set S1). Lower historical baseline temperature variability at low latitudes, where a majority of the low-income countries occur, and associated higher frequency of future days that exceed historical extreme temperatures also contribute to the escalating future heatwave trends in the low-income region (Coffel et al., 2018). Higher signal-to-noise ratio in increasing temperatures in the tropics further contributes to this trend (King et al. 2021). Exposure to heat events is also projected to steadily increase for both lower-middle- and low-income regions from the 2030s to the 2090s, with mean annual heatwave exposure in the 2060s (2090s) being 2.6 (4.6) and 5.5 (9.7) billion person-days per year more than that of the 2030s in lower-middle- and low-income regions, respectively (Figure 4; Data Set S1). We estimate that 14.0% and 6.8% of the increased exposure can be attributed to population growth in the middle-low- and low-income regions, respectively (Figures S4-S5; Table S3 in Supporting Information S1), and the rest is due to compounding impacts of warming trends and lagged adaptation.

The effects of maladaptation for lower income regions are readily visible even in the 2030s and are expected to further the heatwave impacts gap between low- and high-income regions by the end of the century. In the 2030s, the low-income region will likely observe 12.3 billion person-days of exposure to heatwave per year, on average,

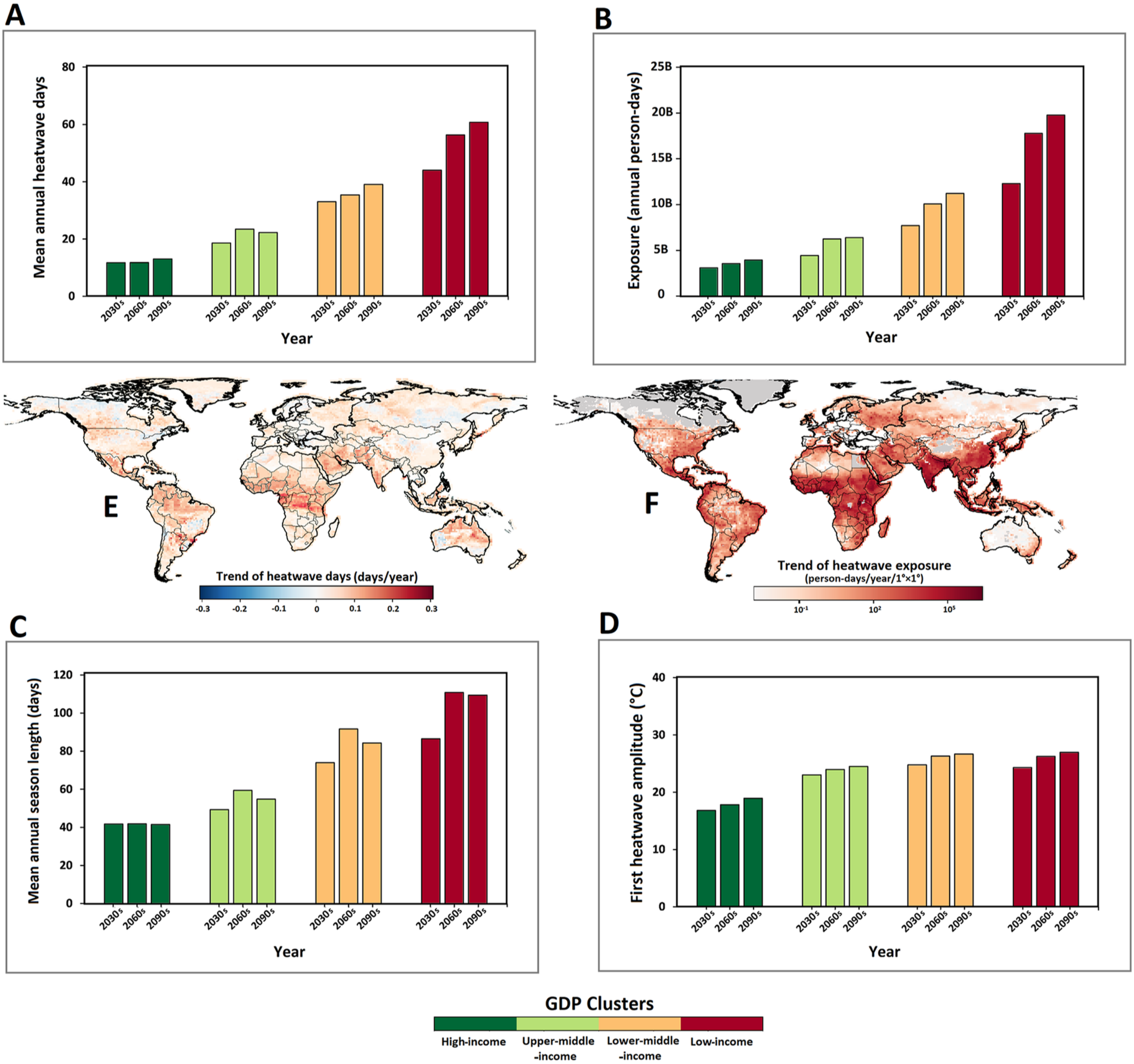

Figure 4. Increasing projected heat-stress inequality from 2030 to 2099. (a)–(d): Mean annual heatwave frequency, exposure, and season length, as well as maximum decadal amplitude of shock heatwave, in each per-capita gross domestic product, GDP, cluster. (e) and (f): Trend maps of future heatwave frequency and exposure. Gray areas indicate near zero population. Results are based on the median of 10 global climate models using the SSP2-4.5 scenario, and are subject to a range of model and scenario uncertainties.

as compared to 15.2 billion person-days per year for the three higher income regions combined. Furthermore, the low-income region is expected to experience almost as much exposure to heatwaves in the 2090s as the other three-quartiles of the world combined (mean annual heatwave exposure of 19.8 vs. 21.5 billion person-days per year for the low-income region and the rest of the world, respectively; Figure S6 in Supporting Information S1), raising notable heat-stress inequality concerns (Herold et al., 2017; Mitchell & Chakraborty, 2015).

Heatwave season length in the future also shows increasing trends for the poorest half of the world, with the greatest rates of increase in the low-income region (Figure 4; Table S3 in Supporting Information S1; Data Set S1). Mean annual heatwave season length in the 2060s (2090s) is expected to be 6.7 (11.8) and 13.2 (23.3) days per year longer than that in the 2030s in lower-middle- and low-income regions, respectively (Figure 4; Table S3 in

Supporting Information S1; Data Set S1). Notably, the mean annual heatwave season length will likely be twice as long in the poorest region as compared to the richest region by the 2030s with continual relative lengthening through the 21st century (Figure 4; Data Set S1). See Section S1 and Figures S7-S8 in Supporting Information S1 for projected trends in heatwave metrics from a geographic perspective.

4. Discussion

Heatwaves are becoming more frequent, more intense and longer in a warming climate (Vogel et al., 2019), with significant societal (Kjellstrom, 2014), ecological (Oliver et al., 2019), economic (Wondmagegn et al., 2019), and human health (Mazdiyasni et al., 2017) repercussions. Here, we presented a nuanced evaluation of historical and projected heatwaves by integrating global socioeconomic, population and climatic data. We furthered the understanding of heat-stress inequality trends (Jones et al., 2018; King & Harrington, 2018) by incorporating socioeconomic-driven adaptation capacity (Green et al., 2016; Mitchell et al., 2018) into evaluation of future heatwaves.

We documented that the frequency of mean annual heatwave days across continents increased between 4.8 and 6.8 days during 1980–2019, which co-occurred with a 2–3 weeks expansion of the mean annual heatwave season length in the 2010s as compared to that of the 1980s. The latter facilitated earlier heatwaves with human health and comfort implications and late season heatwaves with ecologic implications (e.g., enabling fall/winter wildfires in Northern Hemisphere). When constrained to the most recent two decades, we estimated an average global exposure of 9.3 billion person-days per year to heatwaves during 2010–2019, a more than 65% increase from that of 2000–2009.

Recent literature argues that the sensitivity to heatwaves has been decreasing, although not disappearing, in wealthy countries, due to adaptation efforts (Green et al., 2016; Mitchell et al., 2018). Whether low-income countries have seen decreased sensitivity to heatwaves remains to be tested (Campbell et al., 2018). However, lack of access to resources to support adaptation efforts can inhibit or slow the progress toward this goal (Yeo, 2019), given, for example, only 41.9% of low-income countries' population had access to electricity as of 2019 (World Bank., 2019).

Our results provided evidence of historical heat-stress inequality across the globe. We showed that heatwave metrics grew by larger rates in the low-income region compared to the high-income region in the past four decades, widening the gap in heat-stress inequality. We documented that exposure to heatwaves in the low-income region from 2010 to 2019 was over 40% higher than that of the high-income region with a similar population. This finding complements literature that shows developing nations experience a higher impact from climate change than the developed world (Coffel et al., 2018; Herold et al., 2017; Mitchell et al., 2018; Russo et al., 2015).

Although wealthy communities have a higher capacity to adapt to a warming climate, they too have a high vulnerability to shock heatwaves and widespread heatwaves, just like less wealthy communities (Liss et al., 2017). Shock heatwaves are of specific concern, given their disproportionately higher health impacts (Brooke Anderson & Bell, 2011; Habeeb et al., 2015; Liss et al., 2017). Maximum decadal amplitude of shock heatwaves increased across the socioeconomic spectrum. We also documented increasing geographical scales of contiguous heatwaves across continents over the last four decades. Such widespread heatwaves can reach or surpass the limits of the built infrastructure (Stone et al., 2021), often resulting in regional resource inadequacies to provide electricity access due to energy demands exceeding supplies (Larcom et al., 2019; Stone et al., 2021). An example of such an event occurred on 14 and 15 August, 2020 in California where 0.5 million homes and businesses lost power during an intense, widespread heat event across the American West that overwhelmed the electric grid (California, 2021). Interruption in access to electricity challenges the power-based adaptation measures to warming with significant human health repercussions (Larcom et al., 2019).

We showed that future heatwave metrics are governed primarily by the capacity of society to adapt to a warming climate. Assuming an immediate response to warming, as depicted with the high-income region, heatwave frequency and season length remain rather stable through 2100. This is in accordance with the literature that considered a rolling threshold to evaluate future heatwaves (Vogel et al., 2020). By contrast, the 15-year lagged adaptation for the low-income region, compounded by a clearer emergence of warming and a higher signal-to-noise ratio in low-latitudes (Hawkinset al., 2020) where a majority of low-income countries occur, yield an additional 23.2 days per year of heatwaves in the late- compared to the early- future (2090s vs. 2030s). The escalation of heatwave statistics is attributed to compounding impacts of the lagged adaptation to a warming climate in the low-income region and warming and population trends.

We note some shortcomings in our analysis, mainly driven by global data limitations. We categorized lagged adaptation based on per-capita GDP. Adaptation is a complex phenomenon that depends on governance and legislative constraints, and subjective views and risk perceptions (Heat Wave Causes Power Ou, 2020; Zografos et al., 2016), which may not be fully captured with income. However, access to financial means is an informative proxy that can paint a global picture of expected adaptation to a warming climate. Our assumed timeline for lagged adaptation also may differ among various countries in each per-capita GDP cluster, which is subject to further refinement in future studies. Furthermore, we assumed a static per-capita GDP for historical and future scenarios (i.e., our regions are based on a snapshot of 2015 income). Moreover, we did not directly consider urban heat islands (Wong et al., 2013), rural-urban gradients (Fischer et al., 2012), and heat exposure by occupation (Kjellstrom, 2014).

In summary, we assessed less explored, but socially and environmentally important, heatwave characteristics that can inform future mitigation and adaptation efforts. We highlighted the increasing heat-stress inequality across the socioeconomic spectrum in the past four decades, with the low-income region experiencing the highest impacts. We underscored the escalating future inequality gap in a warming climate due to population trends and lagged response to climate change. Our results highlight the importance of rapidly increasing international cooperation on climate adaptation efforts as is outlined in the Paris Agreement (Falkner, 2016) to limit the heat-stress inequality of heatwaves on a warming planet.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

All data are publicly available: Annual daily temperature from the US National Oceanic and Atmospheric Administration's Climate Prediction Center-Global Daily Temperature dataset: https://psl.noaa.gov/data/gridded/data.cpc.globaltemp.html. Coupled Model Intercomparison Project Phase 6 (CMIP6) dataset from: https://esgf-node.llnl.gov/search/cmip6/. Historical population data from Gridded Population of the World (GPW), v4: https://sedac.ciesin.columbia.edu/data/set/gpw-v4-population-count-adjusted-to-2015-unwpp-country-totals-rev11/maps/services. Global Per Capita Gross Domestic Product from gridded global datasets for Gross Domestic Product and Human Development Index over 1990–2015 by (Kummu et al., 2018): https://datadryad.org/stash/dataset/doi:10.5061/dryad.dk1j0. Population projections through 2099 from the United Nations' World Population Prospects 2019: https://population.un.org/wpp/Download/Standard/Population/.

Acknowledgments
We appreciate comments and suggestions from the editor, Dr. Vimal Mishra, and two anonymous reviewers that helped improve this paper. This study was partially supported by the Joint Fire Science Program grant number L21AC10247-00. This manuscript is submitted for publication with the understanding that the United States Government is authorized to reproduce and distribute reprints for governmental purposes. Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the United States Government. The findings and conclusions in this publication are those of the authors and should not be construed to represent any official USDA or U.S. Government determination or policy.

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