ENVIRONMENTAL RESEARCH
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To cite this article: André S Ballarin *et al* 2024 *Environ. Res. Commun.* **6** 111004

IOP Publishing Environ. Res. Commun. 6 (2024) 111004 https://doi.org/10.1088/2515-7620/ad9140

Environmental Research Communications

OPEN ACCESS

RECEIVED
9 September 2024

REVISED
30 September 2024

ACCEPTED FOR PUBLICATION
11 November 2024

PUBLISHED
20 November 2024

LETTER

Escalating threat of human-perceived heatwaves in Brazil

André S Ballarin[1,2], Paulo Tarso S Oliveira[3], José Gescilam S M Uchôa[1], Carlos H R Lima[4], Masoud Zaerpour[2], Mijael Rodrigo Vargas Godoy[5,6], Antônio A Meira Neto[7], Simon Michael Papalexiou[2] and Edson Wendland[1]

[1] Department of Hydraulics and Sanitary Engineering, São Carlos School of Engineering, University of São Paulo, Brazil
[2] Department of Civil Engineering, University of Calgary, Canada
[3] Faculty of Engineering, Architecture and Urbanism, and Geography, Federal University of Mato Grosso do Sul, Campo Grande, Brazil
[4] Department of Civil and Environmental Engineering, University of Brasilia, Brazil
[5] Faculty of Environmental Sciences, Czech University of Life Sciences Prague, Prague, Czech Republic
[6] River-Coastal Science & Engineering, Tulane University, New Orleans, LA 70118, United States of America
[7] Department of Civil and Environmental Engineering, Colorado State University, Fort Collins, CO, United States of America

E-mail: asballarin@gmail.com

Keywords: global warming, heat stress, heatwave, Brazil

Supplementary material for this article is available online

Abstract

Heatwaves pose significant threats to socioeconomic and environmental systems, with their intensity and frequency expected to increase due to climate change. Despite their critical impacts, future heatwaves in Brazil remain underexplored, especially from a human-perceived perspective, which is crucial for assessing potential public health impacts. Here, we propose a method to assess heatwaves using the humidex (H)—a climate index that combines temperature and relative humidity to indicate human-perceived heat - alongside traditional temperature-based measures. Using bias-corrected simulations from 10 CMIP6 models under SSP2-4.5 and SSP5-8.5 scenarios, we quantified projected changes in heatwaves across Brazil. The results indicate that heatwaves will become more severe and prolonged, with greater changes under the SSP5-8.5 scenario by the end of the century, particularly in the North, Northeast, and Central regions. The magnitude of human-perceived heatwaves is expected to rise faster than temperature-based ones, underscoring the need for public health-focused assessments. CMIP6 models strongly agree on increased future heatwaves, potentially tripling population exposure in most Brazilian states, with the Southeast experiencing greater changes due to its larger population. These events are expected not only to affect more people but also to be more severe, exceeding over 60 days per year of serious danger ($H > 45$ °C) by the end of the century under SSP5-8.5. Record-shattering events in the historical period are projected to become the norm by mid-century, highlighting the accelerating nature of these extreme events. Our findings emphasize the importance of considering human-perceived heat in climate impact studies and public health planning to mitigate potential impacts. *Significance Statement* Despite the increasing threat of heatwaves, most studies focus on their climate properties, overlooking human-perceived aspects. This is especially true for Brazil, where heatwaves receive limited attention. This study introduces a novel approach, coupling heatwaves with a heat stress index (H) to evaluate them from a human-perceived perspective. Our results suggest more intense and prolonged heatwaves in the future, with record-breaking events becoming the norm by mid-century. Human-perceived heatwaves are projected to rise faster than climate-based ones, emphasizing the need for public health-focused assessments. These increases are expected to more than triple population exposure in most Brazilian states, with severe events ($H > 45$ °C) exceeding 60 days per year by the end of the century under the pessimistic scenario.

1. Introduction

Heatwaves have far-reaching and multifaceted impacts on natural and human systems (Fischer and Schär 2010, Dong *et al* 2023). Recent severe heatwaves in Europe, Africa, Russia, and Australia led to tens of thousands of deaths and billions of dollars in financial losses (García-Herrera *et al* 2010, Barriopedro *et al* 2011, Russo *et al* 2015, Zander *et al* 2015, Ceccherini *et al* 2017). More recently, in 2021, Western North America experienced a record-breaking heatwave that caused hundreds of deaths and triggered widespread wildfires in the region (Jeong *et al* 2023). Similarly, in 2020, the Brazilian Pantanal ecoregion faced a catastrophic fire season associated with compound drought-heatwaves events (Libonati *et al* 2022b). Given the potential implications of heatwaves, understanding their properties is paramount, especially in a global warming context, where unprecedented heatwaves have already been recorded (McKinnon and Simpson 2022, Fischer *et al* 2023, White *et al* 2023) and are expected to be even more intense (Meehl and Tebaldi 2004, Russo *et al* 2014, Tripathy *et al* 2023).

In view of their ever-increasing implications for society, heatwaves have been attracting widespread attention in the scientific community. Ma and Yuan (2023) investigated the unprecedented 2022 heatwave experienced in the Yangtze River Basin, stating that, without mitigating efforts, heatwaves currently considered record-breaking would be the norm by the 2050 s. Wei *et al* (2023) assessed projected changes in the multifaceted aspects of heatwaves in China, suggesting longer and more severe future heatwaves across the country. McHugh *et al* (2023) and Li *et al* (2023) assessed the likelihood of extreme summer temperatures for the US and the globe, respectively, suggesting an increased probability of record-breaking heatwaves at the end of the century. Most of these recent heatwave-based studies, however, have focused on assessing the climate aspects of these extreme events, overlooking the human-perceived perspective, which is crucial for evaluating climatic states on human physiology (Raymond *et al* 2020).

Heatwave impacts on society depend not only on climate factors but also on local-to-regional socio-economic conditions, underscoring the need for regional impact assessments (Feron *et al* 2019). These studies, however, are currently distributed unevenly across the globe (Uchôa *et al* 2023). For instance, studies assessing future projections of heatwaves in Brazil are still scarce, despite the country's vast size and large population. While some studies exist, they are region-specific and tend not to assess projected changes in heatwave properties in the future, focusing mainly on historical events (Bitencourt *et al* 2020, Marengo *et al* 2022, Silva *et al* 2022, Valverde and Rosa 2023). The country experienced unprecedented warm conditions in recent decades, such as the outstanding heatwave of 2013–2014 (Ballarin *et al* 2021, Geirinhas *et al* 2022) and the record-breaking heatwave of 2023 (figure 1; Perkins-Kirkpatrick *et al* 2024). Both events were linked to diverse natural and social impacts, such as the occurrence of wildfires in the Pantanal ecosystem and the exacerbation of the Southeast Brazil water crisis (Nobre *et al* 2016). Furthermore, recent studies underscored the significant impacts of heatwaves on Brazilian public health (Monteiro Dos Santos *et al* 2024, Libonati *et al* 2022a). Hence, there is an urgent need to better comprehend heatwaves characteristics, impacts, and projected changes in view of the national context.

Here, we aim to address these gaps by assessing future projections of both temperature-based and human-perceived heatwave features in Brazil. By coupling the framework developed to identify and characterize heatwaves with a heat stress index, the Humidex, we propose a novel way to explore the potential impacts of heat stress on human health from the frame of the heatwave concept. To gain a better comprehension of the uniqueness of these extreme events, we further assess heatwaves from a record-breaking perspective, recognizing that this kind of assessment is very relevant for risk assessment and adaptation practices (Fischer *et al* 2021, Li *et al* 2023). Our present approach provides a more comprehensive understanding of the potential impacts of future heatwaves in Brazil, supporting nationwide health-related policy and decision-making.

2. Methods

2.1. Data

Climate data. We used climate time series from the CLIMBra dataset (Ballarin *et al* 2023b), which provides raw and bias-corrected CMIP6 daily time series of six different climate variables. The dataset encompasses simulations from 19 CMIP6 models, forced by two scenarios (SSP2-4.5 and SSP5-8.5), for both historical (1980-2010) and future (2015–2100) periods at a 0.25° grid resolution. It shows a good match with the ERA5 Land dataset (figure 1), which is commonly used to assess historical heatwaves (Dong *et al* 2023, Jeong *et al* 2023). We used 10 CLIMBra-CMIP6 models where temperature and relative humidity data were available. Temperature data were used to assess temperature-based (T-based) heatwaves, while both temperature and relative humidity variables were used to assess human-perceived (H-based) heatwaves through the Humidex index (H). This index is an empirical approximation that combines temperature and relative humidity (equations (1) and (2)) to indicate outdoor thermal discomfort experienced by the general public (Jeong *et al* 2023).

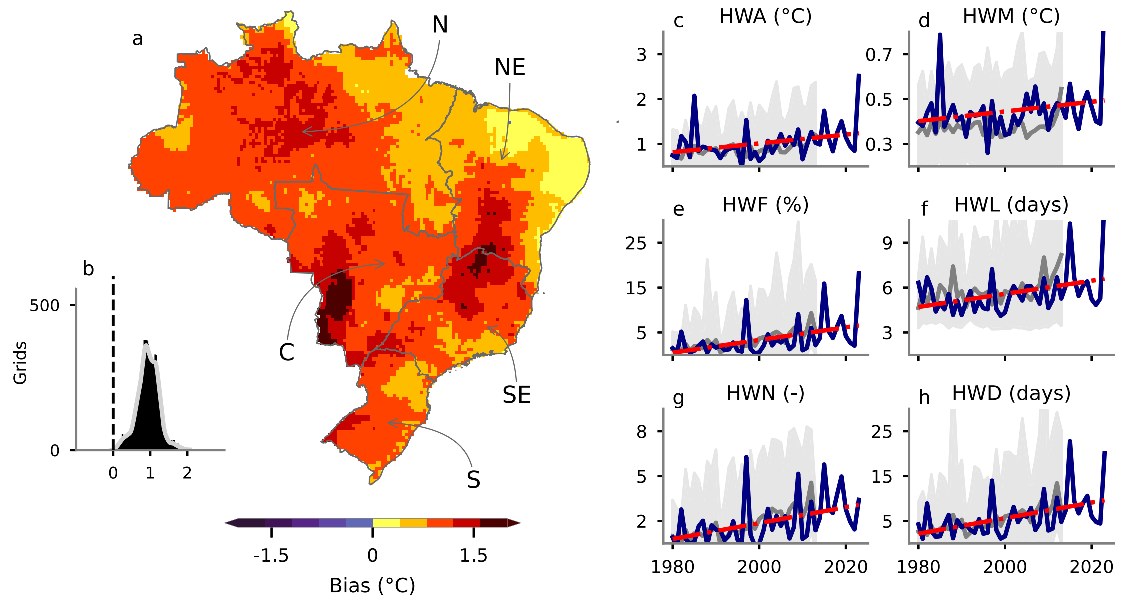

Figure 1. Historical heatwaves in Brazil. (a) Anomalies in 2023's warm season (November—March) mean temperature compared to the climatological (1980–2010; warm season) period. Solid gray lines determine the 5 Brazilian geographical regions: North (N), Northeast (NE), Central-West (C), Southeast (SE), and South (S). (b) Histogram indicating the frequency of 2023's warm season anomalies. Yearly time series of the (c) peak of the hottest heatwave (HWA) (d) average magnitude of heatwaves (HWM), (e) percentage of heatwave days (HWF), (f) mean duration of heatwave events (HWL), (g) number of heatwave events (HWN), and (h) duration of the longest heatwave in the historical period (HWD). The solid, dark curve indicates the multimodel ensemble mean of the heatwave properties computed using the CMIP6 models. The shaded area represents the CMIP6 simulations' range (minimum and maximum) for the historical period (1980–2010). The solid, dark blue line indicates the heatwaves computed using the ERA5 dataset (1980–2023). A linear regression representing the trend in ERA5-based heatwave properties is represented by a red, dashed line.

$$H = T + \frac{5}{9}[e - 10] \tag{1}$$

$$e = \frac{h}{100} \times 6.112 \times 10^{7.5T/(T+237.7)} \tag{2}$$

where T(°C) is the mean daily temperature computed as the average between maximum and minimum temperature and e (Pa) is the vapour pressure, computed using the relative humidity (h). The level of discomfort during prolonged exposure and physical activity can be categorized into five levels (d'Ambrosio Alfano *et al* 2011): discomfort perceived by a few people ($25°C < H \leqslant 30°C$), noticeable discomfort ($30°C < H \leqslant 35°C$), evident discomfort ($35°C < H \leqslant 40°C$), intense discomfort ($40°C < H \leqslant 45°C$), and serious danger ($H \geqslant 45°C$). Other indices, such as the Discomfort index (Thom 1959) could be used. In fact, according to Ioannou *et al* (2022), more than 100 heat-related indexes exist. However, we opted for the H index because it requires fewer variables that are readily available in the CLIMBra dataset and is currently widely used to assess heat stress (e.g., Jeong *et al* 2024). We also repeated our approach using the Heat Index (HI) instead of H to characterize H-based heatwaves and obtained similar conclusions (figure S1). The HI also relies only on temperature and relative humidity data and was computed following the equation presented in Blazejczyk *et al* (2012).

Population. To assess human exposure to heatwaves, we adopted the population global dataset introduced by Jones and O'Neill (2016), which has been used in previous studies (Yin *et al* 2022, Qin *et al* 2024). This dataset encompasses spatially explicit, gridded (0.125° resolution) population projections from 2000 to 2100, at 10-year intervals. These projections are consistent with the different assumptions regarding population, urbanization, and socioeconomic trajectories present in the CMIP6 shared socioeconomic pathways (SSPs).

2.2. Heatwave's identification

Heatwaves can be defined as consecutive days with excessive heat (Perkins-Kirkpatrick and Lewis 2020). There are, however, different ways in the existing literature to identify these extreme events. The methods may vary, for example, in how they define the extreme temperature threshold (absolute or relative); whether they include nighttime temperatures; or if they consider a seasonal or yearly temporal basis (Perkins and Alexander 2013). Here, we assessed heatwaves based on a modified version (equation (3)) of the excess heat factor (EHI; Nairn and Fawcett 2014), following Hirsch *et al* (2019). This approach defines heatwaves as warm spells with at least three consecutive days where daily temperature surpasses the long-term, calendar-day 95th percentile.

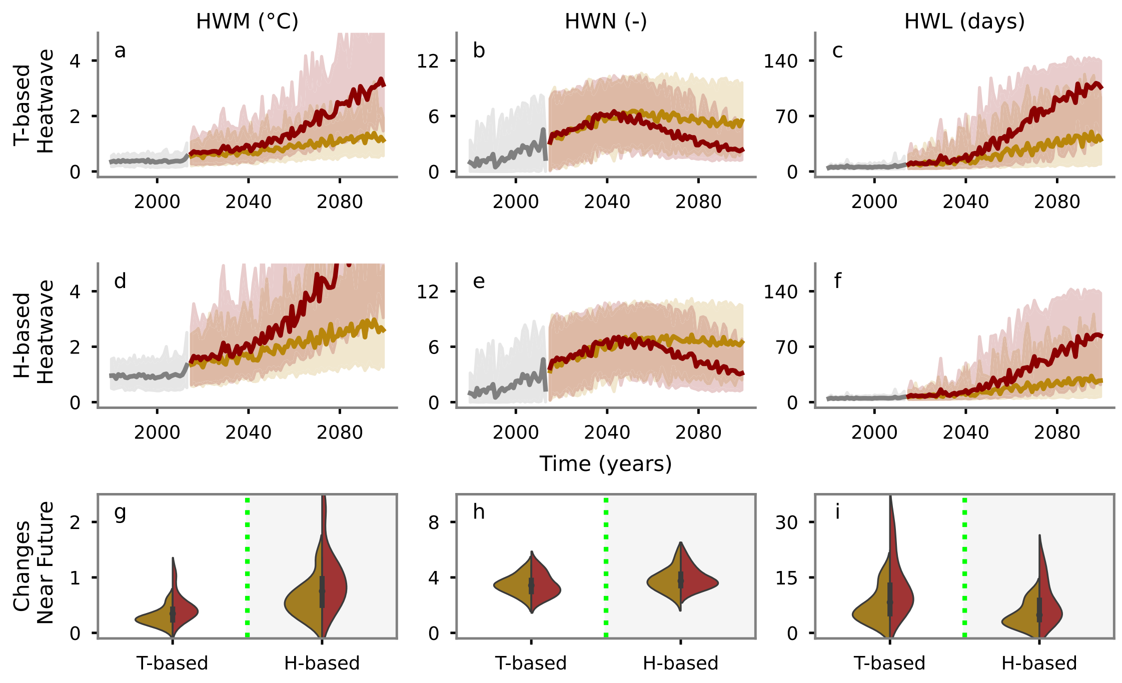

Figure 2. Projected changes in summer T- and H-based heatwaves' properties in Brazil. Time series of yearly, spatially averaged (a, d) HWM, (b), (e) HWN, and (c), (f) HML for T- and H-based heatwaves (first and second rows, respectively). Time series represent the spatial average across the country's territory. Historical and future periods are represented by gray and gold/red (SSP2-4.5/SSP5-8.5) colors, respectively. The solid, dark curve indicates the CMIP6 multimodel ensemble mean and the shaded area represents the CMIP6 simulations' range (minimum and maximum). Third row: Differences between historical (1980-2010) and near-future (2015–2055) long-term T- and H-based heatwaves' properties (g) HWM, (h) HWN, and (i) HWL. Violin plots represent the CMIP6 model spread.

$$\mathrm{EHI} = (T_{i,j} + T_{i-1,j} + T_{i-2,j})/3 - T_{i,95} \tag{3}$$

where T_i (°C) is the mean temperature at calendar-day i and year j, computed as the averaged maximum and minimum temperature to incorporate both day and night conditions and account for thermal accumulation (Nairn and Fawcett 2014); and $T_{i,\,95}$ (°C) is the historical (1980–2010) calendar-day 95th percentile, computed using a 15-day moving window to account for seasonality (Wei *et al* 2023). The use of a percentile-based threshold allows for intercomparison across Brazilian regions with different climate conditions and minimizes potential model biases (Argüeso *et al* 2016). To assess human-perceived heatwaves, we repeated the process of identifying heatwaves using daily Humidex (H) series instead of mean daily temperature (T). Since we are interested in assessing projected changes in heatwave characteristics, we used the historical $T_{i,95}$ (or the equivalent $H_{i,95}$) to identify heatwaves in both historical and future periods, thereby accounting for the full signal of change (Fischer and Schär 2010). This approach, however, does not account for societal adaptation to projected extremes or to heatwaves defined relative to future climatology (Vogel *et al* 2020, Van Maanen *et al* 2023), which lies beyond the scope of this study.

Following heatwaves identification, we derived six different metrics on a yearly basis: peak of the hottest heatwave (HWA), average magnitude of all heatwaves (HWM), total duration of heatwaves (HWF), number of heatwaves events (HWN), mean duration of heatwaves events (HWL), and duration of the longest heatwave (HWD). The first two (HWA and HWM) are expressed as the difference between heatwaves' daily temperature and the calendar-day percentile-threshold, specifically as the maximum daily EHI and mean EHI in a year, respectively. From these two metrics, we also derived the mean and peak temperature of yearly heatwaves (HWMt and HWAt, respectively). Hereinafter, we display the projected changes of heatwaves computed using the bias-corrected CLIMBra dataset starting in the austral summer (November–March).

3. Results

3.1. Projected changes in summer T- and H-based heatwaves' properties in Brazil

Future heatwaves in Brazil are projected to become more intense and last-longing under both CMIP6 SSP2-4.5 and SSP5-8.5 scenarios (figure 2). While their projections are comparable in the near future (2015–2055), the SSP5-8.5 scenario predicts significantly greater changes as the century unfolds. For instance, on average for the country territory, the multi-model ensemble mean suggests T-based heatwaves with a mean magnitude (HWM) of up to 2.84 °C and 1.21 °C for SSP5-8.5 and SSP2-4.5 by the end of the century (2080–2100; figure 2(a)),

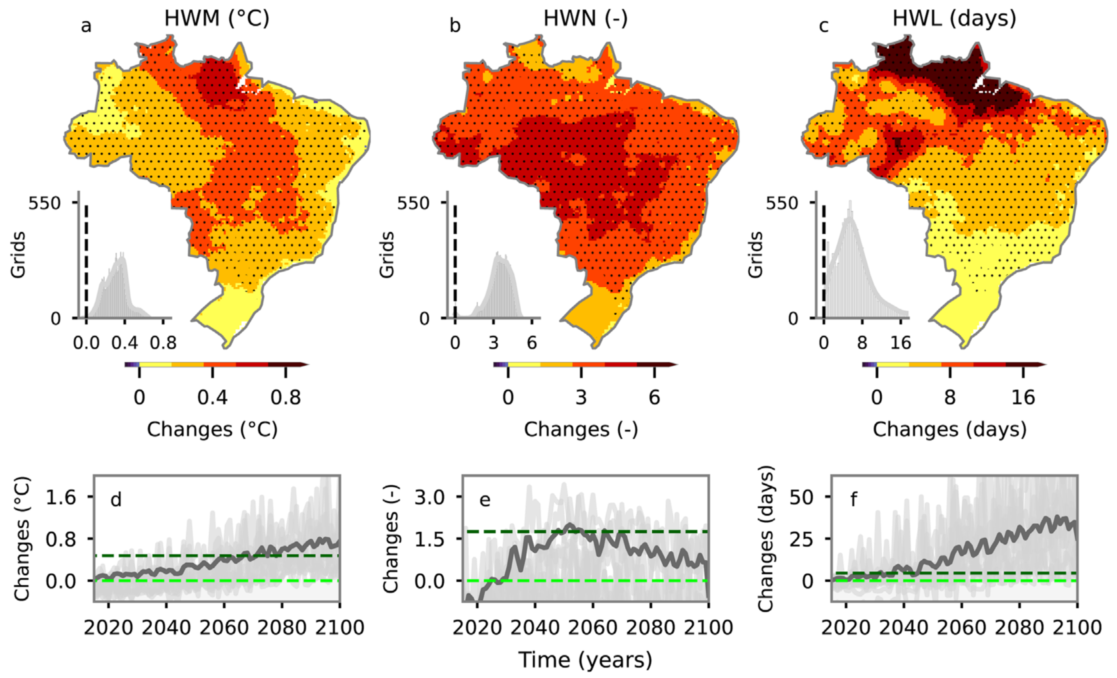

Figure 3. Spatial distribution of projected changes in summer T-based heatwaves' properties under a record-breaking perspective. (a)–(c) Projected changes in long-term mean heatwaves' properties between the near future (SSP2-4.5; 2015–2055) and historical (1980–2013) periods for (a) HWM, (b) HWN, and (c) HWL. Stippling denotes regions where over 90% of CMIP6 models agree with the signal and the significance of change (Mann–Whitney U test; p-value < 0.05). Histograms in each panel indicate the frequency of projected changes. (d)–(f) Time series of the difference between future heatwaves' properties and the maximum, record-breaking event (defined for each property, separately) simulated in the historical period (1980–2013) for (d) HWM, (e) HWN, and (f) HWL. The solid dark gray curve represents the difference between future heatwave properties and the record-breaking event computed using the CMIP6 multimodel ensemble mean. The light gray curves represent the differences computed for each CMIP6 model individually. The light green, dashed line separates the panel into regions of positive (negative) differences, indicating whether yearly future simulations exceed (or not) the record-breaking historical (1980–2010) heatwave property. The dark green, dashed line displays the position of the record-breaking heatwave' properties of the ERA5 dataset (1980–2023) relative to the record-breaking historical property simulated by the multimodel ensemble mean (1980–2010).

respectively, compared to the 2023 yearly HWM of 0.98 °C (figure 1) and the multi-year historical maximum of 0.54 °C (1980–2010). H-based heatwaves show even greater projected changes, with HWMs of 6.06 °C and 2.68 °C for SSP5-8.5 and SSP2-4.5, respectively (figure 2(b)), reflecting the positive and nonlinear relationship between H and T. For the near future period (2015-2055), changes are on average in the order of 0.5 °C and 1 °C for T- and H-based, respectively, with larger CMIP6 model spread for the latter (figure 2(g)). Although slightly smaller, the differences between H- and T-based heatwaves remain similar when considering relative instead of absolute differences in view of their different scales. Furthermore, it is important to note that similar conclusions can be drawn for the HI-based heatwaves, which exhibited even larger projected changes for HWM at the end of the century (figure S1).

The number of T- and H-based heatwaves is expected to rise until mid-century (figures 2(b),(e)), and then, decrease (SSP5-8.5) or stabilize (SSP2-4.5). This pattern can be explained by the augmented duration of heatwaves expected in the distant future (2055–2100), reaching nearly 110 and 80 days for T- and H- heatwaves, respectively (figures 2(c),(f)), as also observed in previous studies globally (Fischer and Schär 2010, Liu *et al* 2017, Nishant *et al* 2022, Wedler *et al* 2023, Wei *et al* 2023). This suggests that extended heatwave durations are merging independent events into longer ones, resulting in fewer independent events (HMN) but more heatwave days in a year (HWF, see figure S2). For the near future (2015–2055), a multi-model average increase of nearly three events per year is expected for both T- and H-heatwaves (figure 2(h)). These heatwaves are also expected to be, on average, seven and four days longer, respectively (figure 2(i)). It is worth highlighting that despite variability in the magnitude of changes among different CMIP6 models (figures 2(g)–(i)) the projections are consistent and indicate longer and more severe T- and H-based future heatwaves.

Notably, there is widespread agreement on the significance and direction of change across the country, except for parts of the South region (figure 3). This remains true for the SSP5-8.5 scenario (figure S3) and for the distant future (2055–2100; not shown here). The magnitude of these changes, however, varies across the country. In general, longer, more severe, and frequent summer T-based heatwaves are expected in the North, Northeast, and Central regions, whereas smaller changes are expected in the South region. HWM is projected to increase particularly in the Cerrado and Amazon ecoregions (see figure S4 for Brazilian geographical- and eco-regions) with increases in the order of 0.4 °C. For HWN, projected changes exhibit similar increases across the country, except for the South region, which exhibited less significant changes (figure 3(b)). As observed for the HWM, larger increases are concentrated in the Central region, encompassing part of the Amazon forest and the Cerrado ecoregions. For heatwaves' duration (HWL), larger increases are expected in the North, Northeast, and part of the central regions, particularly in the regions closer to the Equator. A similar spatial distribution was observed for H-based heatwaves (figure S5).

To better comprehend the extremeness of future heatwaves, we assessed them from a record-shattering perspective (figures 3(d)–(f)), which can be considered a proxy for the urgency of adaptation practices (Satoh *et al* 2022). We computed, on a yearly basis, the difference between future heatwave properties and the maximum heatwave property simulated in the historical period, referred to here as the record-breaking heatwave event. Each heatwave property's record-breaking event was defined independently. Considering the increasing trends in historical observations (figure 1) and the recent extreme heatwaves, we included heatwaves from the ERA5 dataset (1980–2023) for an updated perspective.

According to the SSP2.4-5 multimodel ensemble mean and the ERA5 record-breaking reference, record-shattering T-based heatwaves are expected to become the norm around the middle of the century (2040–2060), as observed by Ma and Yuan (2023) for China. This remains true for H-based heatwaves (figure S5). For HWM, the time of emergence (ToE) - defined as the year at which future heatwave properties consistently exceed the record-breaking properties—is projected to be close to 2060 (figure 3(d)). For HWN, SSP2-4.5 projections suggest a ToE close to 2050 (figure 3(e)). However, as highlighted, the number of heatwave events is expected to reduce after this peak due to an increase in heatwaves duration caused by event merging (figure 3(f)). For HWL, the ToE is projected to be around 2040, suggesting T-based heatwaves duration is rising at a faster rate than the magnitude (HWM). For H-based heatwaves, this trend does not hold. The H-based mean magnitude is projected to increase at a faster pace than T-based HWM (figure 2), surpassing the projected increases in HML.

It is important to note that if we consider the record-breaking properties simulated by the historical (1980–2010) CMIP6 multimodel ensemble mean (figures 3(d)–(f)), heatwaves are expected to become common before 2030 for the three evaluated properties, highlighting the significant increases already observed in the recent years. The ToE shows a considerable variability between CMIP6 models, reflecting the different assumptions and uncertainty associated with their projections. Nevertheless, in general, all evaluated CMIP6 models agree on the significance and direction of change (figures 3(a)–(c)).

3.2. Projected changes in population exposure to H-based heatwaves in Brazil

Besides assessing expected changes in future heatwave properties, it is fundamental to evaluate how they might affect the population in hazard-prone areas (Kreibich *et al* 2022), given that heightened heatwaves tend to lead to a greater areal - and consequently - population exposure (Ma and Yuan 2023). In this sense, we assessed the projected changes in the population exposure to H-based heatwave events (figure 4) by multiplying the number of individuals (population) by the number of days in a year with heatwave events. We opted for using H-based heatwaves due to their relevance to human-perceived conditions, but similar conclusions regarding relative changes can be drawn for T-based heatwaves. More details about the population exposure computation and how we defined the relative contribution of changes in heatwaves, population, and their interaction can be found in the supporting information (Text S1).

The results suggest that population exposure to H-based heatwaves is projected to increase substantially across the country (figure 4). In general, most Brazilian states are projected to more than triple their population exposure to heatwaves in the near future (2015–2055). Larger exposures are expected to happen in the states of São Paulo (SP) and Minas Gerais (MG), both located in the Southeast region of Brazil. In contrast, smaller increases are projected in the states of Acre (AC), Amapá (AM), and Roraima (RR), located in the North region, due to their reduced population. Interestingly, such changes are primarily driven by increases in heatwave events rather than population growth. As shown in figure 4(c), the attribution analysis suggested that the projected changes in heatwaves contribute more than 75% to changes in population exposure for both evaluated scenarios. For both SSP2-4.5 and SSP5-8.5, the contribution attributed to changes in population was lower than 10%.

Regarding the severity of heatwaves, our results suggest that they are projected to be more dangerous in the North, Central, and parts of the Northeast regions in the near future (2015–2055 SSP2-4.5; figure 4(b)). In these regions, long-term average H-based heatwaves (HWMt) are projected to exceed 40 °C. For the states located in the Southeast and South regions, long-term mean HWMt is expected to fall into the evident discomfort category ($35°C < H \leqslant 40°C$). Furthermore, the number of days classified as serious danger in terms of human-perceived temperature ($H \geqslant 45°C$) is likely to increase in the country, reaching up to nearly 60 days by the end of the century under the SSP5-8.5 scenario (figure 4(d)). Increases projected by the multimodel ensemble mean under the SSP2-4.5 scenario are lower, but still statistically significant (Mann Kendall test, p-value < 0.05).

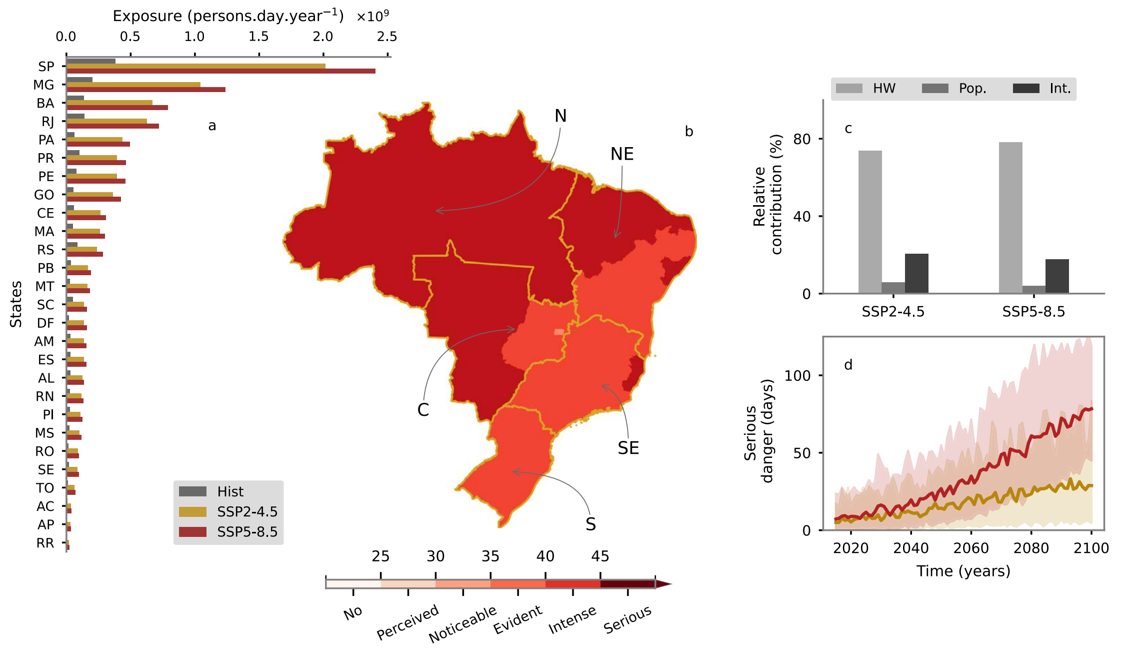

Figure 4. Projected changes in population exposure to H-based heatwaves in Brazil. (a) Population exposure to H-based heatwaves events in Brazilian' states in the historical (Hist; 1980–2010) and near future (2015–2055; SSP2.4-5 and SSP5-8.5) periods. (b) Spatial distribution of the mean H during H-based heatwave events (HWMt) in the near future (2015–2055; SSP2-4.5) for Brazilian' states. HWMt values were categorized according to the level of thermal discomfort (d'Ambrosio Alfano *et al* 2011). A thin, light gray line indicates the boundaries of Brazilian states, and a yellow line indicates the boundaries of the Brazilian regions. (c) Relative contribution of changes in Heatwaves (HW), population (Pop.), and their interaction (Int.) on exposure to future heatwave events in the near future (2015–2055) under SSP2-4.5 and SSP5-8.5. (d) Projected changes in the yearly number of days classified as serious danger ($H \geqslant 45$°C) according to the SSP2-4.5 (gold) and SSP5-8.5 (red) scenarios. The solid, dark curve indicates the CMIP6 multimodel ensemble mean and the shaded area represents the CMIP6 simulations' range (minimum and maximum).

4. Discussion and final remarks

While several studies have sought to provide a deeper understanding of heatwaves and their impacts in Brazil (Marengo *et al* 2022, Libonati *et al* 2022a, Silveira *et al* 2023), only a few have addressed future projections of these events, often assessing them from a regional-scale perspective. Our study aims to fill this gap. Furthermore, in view of heatwaves' potential impacts on human health, in addition to the traditional temperature-based analysis, we propose a novel framework to assess heatwaves' expected changes using a human-perceived heatwave index that integrates temperature and relative humidity and further evaluated the projected increases in population exposure to these extreme events.

Our results align with previous studies suggesting that Brazil will likely experience more frequent and severe heatwaves (Diniz *et al* 2020, Bitencourt *et al* 2021, Collazo *et al* 2023). Both evaluated scenarios pointed to increases in heatwaves' properties (figure 2). The SSP5-8.5 scenario, in particular, projects more significant changes, particularly by the end of the century, emphasizing the critical need for adaptation and mitigation efforts (Fan *et al* 2023). The projected increases in the H-based heatwaves magnitudes revealed in our study were generally larger than those projected for T-based heatwaves, as also observed in North America (Jeong *et al* 2023, 2024), and this holds for the other evaluated heat index, HI. This underscores the importance of considering the human-perceived perspective when assessing heatwaves properties and their impacts on human health, which is a still overlooked aspect in climate impact assessments.

These differences arise from the non-linear and positive relationship between H and T for a specific humidity level, resulting in H-based HWM rising faster than T-based HWM. That is, future increases in T might result in larger increases in H, even with slight reductions in relative humidity (see, for example, figure 3 from Jeong *et al* (2024)). We emphasize, however, that this behavior is related to the sensitivity of H to changes in temperature and relative humidity. Other heat stress indices might exhibit different sensitivities and, therefore, result in different projected changes (Simpson *et al* 2023). For instance, although similar conclusions were reached when assessing H-based heatwaves using HI instead of H, the projected changes differ in magnitude due to the differing sensitivities of HI and H to humidity and temperature.

We found strong agreement among CMIP6 models across the country, except in the South region, where the proportion of agreement was lower than 90% (figure 3). In general, the North and Central regions are projected to experience more pronounced impacts from these changes. For HWM (figure 3(a)), higher increases are projected in the Amazon, Cerrado, and Pantanal ecoregions, while regions closer to the Equator are expected to be more affected in terms of Heatwave duration (HWL). These areas, characterized by extensive agricultural activity and the presence of natural ecosystems like the Amazon forest, may face increased wildfire risk (Silva *et al* 2022) and water availability issues (Sone *et al* 2022, Ballarin *et al* 2023a) due to reduced precipitation and increased drought conditions (Bottino *et al* 2024, Ballarin *et al* 2024a, 2024b), posing significant challenges for Brazil's economy and environment (Flores *et al* 2024). This concerning situation may not only impact Brazil but also have global repercussions since the country plays a key role in global food security, being one of the world's largest agricultural producers (FAO 2022).

Beyond the socioeconomic effects on natural systems, our analysis suggests a challenging scenario for public health (Bell *et al* 2018, Ebi *et al* 2020, Ferreira *et al* 2023). This heightened heat can increase the incidence of diseases, such as in the circulatory and respiratory systems (Requia *et al* 2024), influence the transmission of infections, such as dengue virus (Damtew *et al* 2023), and reduce human comfort due to thermal stress (Roth 2007). For instance, between 2000 and 2018, more than 40,000 excess deaths were attributed to the increase in heatwaves in Brazil's 14 most populous areas, which comprise nearly 35% of the country's population (Monteiro Dos Santos *et al* 2024). This represents more than 20 times the landslide-related deaths for the same period. Given these concerns, raising awareness about heatwaves in the country is crucial, as they remain a largely overlooked disaster (Libonati *et al* 2022a).

Our results indicate that population exposure to heatwave events is projected to more than triple across most Brazilian states (figure 4(a)). This increase not only poses significant public health challenges but also implies migration trends, with people from more affected states potentially relocating to less affected ones (Black *et al* 2013). Such changes in population exposure can be primarily attributed to the increases in heatwaves frequency, which account for more than 75% of the changes in population exposure (figure 4(c)). In fact, increases are expected not only in the number of people affected by heatwaves, but also in how they will affect them, in terms of heatwaves' intensity (figures 4(b), (d)). In nearly half of the country, the long-term mean H of heatwaves (HWMt) is expected to exceed 40 °C in the near future. Additionally, both scenarios project a rapid increase in the number of days in the year classified as serious danger, with temperature surpassing 45 °C (Shukla and Attada 2023), despite the great variability exhibited by the evaluated CMIP6 models.

Despite strong model agreement across the country suggesting heatwaves intensification, we acknowledge some limitations and uncertainties in our study. The use of daily T and h instead of hourly data might introduce negative biases in H estimation (Diaconescu *et al* 2023), being, therefore, a conservative choice. In view of this, we conducted a sensitivity analysis using an alternative, non-conservative estimation of H based on daily maximum temperature - instead of daily mean temperature — which tends to be positively biased. Although this alternative approach showed some differences in the magnitude of the projected changes, similar conclusions can be drawn in terms of projected increases (see figures S6–S8). In fact, not only the use of daily or hourly data, but the choice of the heat-related index can also affect the results shown here. As highlighted by Simpson *et al* (2023), commonly used heat stress indices respond differently to changes in temperature and relative humidity, and, in some cases, can lead to even opposite conclusions. Therefore, further studies are needed to assess how different heat-related indices are projected to change in the country, particularly focusing on the role of moisture on heat stress, since models that project warming also show a reduction in relative humidity (Sherwood and Huber 2010, Fischer and Knutti 2013).

Another factor that might affect our findings is the intrinsic uncertainty in climate model outputs and their bias-corrected versions. For example, regridding can impact simulations' statistical properties, particularly those related to extreme events (Rajulapati *et al* 2021), whereas bias correction techniques may result in physically unrealistic values (Casanueva *et al* 2020). To mitigate potential misleading conclusions, we repeated our analysis using the raw simulations present in the CLIMBra dataset (see figures S9–S11). Despite some differences in the spatial distribution of projected changes, CMIP6 raw simulations also suggested a substantial increase in heatwaves properties. Besides, it is important to recognize the 'hot model' problem and that some climate models might overestimate climate warming (Hausfather *et al* 2022). As indicated in figure 4(d), for example, some CMIP6 models projected markedly smaller changes in the number of serious danger days, and this holds also for raw CMIP6 simulations.

Finally, here we direct our focus to the analysis of near-future projections (2015–2055) due to the practical appeal of these results for the development of mitigation and adaptation policies. However, we emphasize that for the distant future (2055–2100) projections suggest even more challenging conditions. Furthermore, due to the continental dimensions of the country and its highly heterogeneous climatic conditions, we opted to assess heatwaves during the summer season. Nevertheless, we highlight that some regions of the country, particularly those located in low latitudes, can exhibit extremely high temperatures throughout the year, which must be considered in the development of public health policies. Our findings underscore a widespread intensification of heatwaves—a still overlooked extreme event in the country, especially when considering the human-perceived perspective. This stresses the importance of integrating heatwave preparedness into national climate policies seeking to safeguard vulnerable populations and preserve natural ecosystems.

Acknowledgments

A S B acknowledges the Graduate Program in Hydraulic Engineering and Sanitation—PPGSHS at the University of São Paulo (USP-EESC) and the São Paulo Research Foundation—FAPESP (2020/08140-0 and 2022/06017-1) for the scientific and financial support. J G S M U acknowledges the São Paulo Research Foundation—FAPESP (Grant 2020/15434-0 and 2023/13160-8) for supporting part of this study. A S B and P T S O acknowledge the Brazilian Ministry of Science, Technology, and Innovation – MCTI and the National Council for Scientific and Technological Development – CNPq (446044/2023-7, 309048/2023-0, and 406647/2022-4) and the Fundação de Apoio ao Ensino, Ciência e Tecnologia do Estado de Mato Grosso do Sul - Fundect (71/032.795/2022) for the scientific and financial support.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://doi.org/10.57760/sciencedb.02316.

Open research

Raw and bias-corrected CMIP6-climate projections for the Brazilian territory can be found in the CLIMBra's dataset (Ballarin *et al* 2022).

Competing interests

The authors declare no competing interests.

ORCID iDs

André S Ballarin https://orcid.org/0000-0001-6997-8662
Paulo Tarso S Oliveira https://orcid.org/0000-0003-2806-0083
José Gescilam S M Uchôa https://orcid.org/0000-0002-5039-9772
Carlos H R Lima https://orcid.org/0000-0001-8650-0951
Masoud Zaerpour https://orcid.org/0000-0002-5986-1628
Mijael Rodrigo Vargas Godoy https://orcid.org/0000-0002-1828-9266
Antônio A Meira Neto https://orcid.org/0000-0002-7508-8241
Simon Michael Papalexiou https://orcid.org/0000-0001-5633-0154
Edson Wendland https://orcid.org/0000-0003-3374-608X

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