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Regional variations in the impacts of high temperature on hospital admissions in Brazil

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ABSTRACT

Background: High temperatures driven by climate change significantly threaten global health. Their impact on health systems, particularly within low- and middle-income countries, remains underexplored.
Methods: Daily non-elective hospital admissions were collected from the Brazil Hospital Information System for 5,459 (98%) Brazilian municipalities, 2008–2019. Gridded daily maximum temperatures were obtained from the European Centre for Medium-Range Weather Forecasts Reanalysis V5 for the historical period (2008–2023) and projected up to 2060 under three SSP emission scenarios. Population projections were derived from WorldPop. We used a case time-series design and distributed lag non-linear models to examine the relationship between temperature and hospitalisation risk for each state, estimating the number of heat-attributable hospitalisations from 2008 to 2060. Related economic costs were estimated using a cost-of-illness approach including direct and indirect costs.
Findings: Without adaptation, high-temperature-related annual hospitalisations were projected to reach 51 (95 % CI: 19–103), 54 (21–106), and 59 (25–112) per 100,000 population in the 2050s under SSP1-2.6, SSP2-4.5, and SSP5-8.5 scenarios, respectively, representing 54 %, 62 %, and 78 % increases from the 2010s baseline of 33 (9–67) per 100,000. Annual economic costs were projected to reach \$228–\$264 million in the 2050s, with higher absolute costs in the South and faster relative increases in the North.
Interpretation: The substantial impact of heat on hospitalisations, and its associated costs to the health sector and wider economy, worsen under future climate and demographic change. Regional adaptation and targeted healthcare investments are crucial to manage rising health burdens.
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Research in context

Evidence before this study

To review the existing evidence, we searched PubMed, Scopus, Web of Science, and Google Scholar from the databases' inception until December 25, 2024, for articles published in English using the search terms "temperature," "heat," "heatwave" AND "hospitalisation," "health system," "economic burden," "cost-of-illness," AND "projection," "estimation," "assessment," "adaptation," and "mitigation." Existing evidence indicates that extreme heat events

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are associated with increased hospitalisations, particularly for respiratory and renal diseases, with significant economic impacts on health systems. However, most studies focus on high-income countries or limited geographical regions, with few considering the future economic impacts under varying climate change and demographic scenarios. There is also limited understanding of how regional disparities, such as socio-economic differences, influence the health and economic burdens of heat, particularly in low- and middle-income countries (LMICs) like Brazil. No previous study, to our knowledge, has projected medium-term (until 2060) economic burden of heat-related hospitalisations across a diverse and large-scale setting like Brazil.

Added value of this study

To our knowledge, this study is the first to holistically assess the impact of high temperatures on non-elective hospitalisations and associated economic costs in Brazil, covering 98 % of municipalities and spanning multiple climate zones. Using a case time-series design and distributed lag non-linear models, we quantified both current and future health and economic burdens under different climate and demographic scenarios. Our findings revealed substantial regional and demographic disparities, with the elderly, children, and individuals with respiratory and renal conditions disproportionately affected. Without adaptation, annual heat-related hospitalisations and economic costs are projected to more than double by the 2050s, even under optimistic low-emission scenarios. We demonstrated that adaptation measures, which reduce exposure-response slopes, could significantly mitigate these burdens. This research highlights the critical need for targeted regional adaptation, expanding cooling measures in the South to address high absolute burdens while strengthening healthcare capacity in the North to manage rapidly increasing relative burdens, as well as the broader benefits of proactive climate mitigation policies.

Implications of all the available evidence

Our findings emphasize the urgent need to strengthen adaptation and mitigation policies to safeguard health systems in LMICs like Brazil from rising heat-related burdens. While climate mitigation efforts to limit global warming are critical, our analyses suggest that these alone are insufficient. This study underscores the importance of prioritising investments in climate-resilient health systems and regional healthcare strategies to reduce economic losses, protect vulnerable populations, and promote sustainable development in Brazil.

1. Introduction

Hot weather exerts substantial pressure on health systems and is projected to increase dramatically in frequency, severity and duration under climate change (Pörtner et al., 2022). Low- and middle-income countries (LMICs) are particularly vulnerable to the impacts of climate change due to limited adaptive capacity and existing health system challenges (Ebi and Otmani Del Barrio, 2017; Haines and Ebi, 2019). These vulnerabilities are further compounded by demographic and socioeconomic changes, including population ageing and rapid urbanisation, which jointly aggravate future heat-related health impacts, especially under high carbon emission scenarios (Haines and Ebi, 2019). Without additional mitigation efforts and immediate action, global temperatures are projected to rise by 2.6–3.1 °C above pre-industrial levels by the end of this century (United Nations Environment Programme. Emissions Gap Report, 2024). Temperature increases are inevitable until mid-century due to past and current emissions, after which climate scenarios diverge depending on mitigation efforts. Therefore, countries must intensify mitigation efforts and anticipate and adapt to the already unavoidable challenges of climate change. Climate impact projections and socioeconomic assessments are needed to inform climate policy decisions.

Studies on heat-related health impacts in LMICs are emerging, and show an increased risk of mortality and morbidity. However, these studies have either (i) examined mortality or single-disease outcomes (e.g., renal diseases) nationwide (Wen et al., 2022; Gasparrini et al., 2017); failing to capture the full impact of heat exposure on population health and health systems; or (ii) assessed all-cause hospitalisations in response to extreme heat events only, failing to capture the health effects of less extreme high temperatures (Zhao et al., 2019). To the best of our knowledge, no-one has yet quantified the impacts of high temperature exposures across multiple disease categories and explored variation in impact across diverse climatic and socioeconomic settings. Such research is necessary to inform targeted interventions and heat-health action planning.

Globally, there is substantial evidence for the adverse impacts of heat on health (Gasparrini et al., 2017). However, research assessing heat effects on health systems is limited, particularly in terms of hospital admissions. Periods of extreme hot weather can disrupt both the supply and demand components of health systems. Hot weather disrupts supply by impairing healthcare delivery while the associated surge in health-related admissions increases demand for medical services (Zhao et al., 2019). Understanding the nature and extent of demand effects is important, as it represents an additional economic burden on the sector and can displace or disrupt delivery of other services. Such information is crucial to help justify investments in adaptation measures to reduce climate risks. Current research tends to focus on retrospective assessments, often within short timeframes. Given that future climate risks will lie beyond the scope of historical experience, projecting these impacts is essential to guide policymaking and adaptation planning. Economic metrics, such as estimated losses or co-benefits, are also critical indicators that provide measurable insights into the effectiveness of mitigation and adaptation strategies.

Using Brazil as a case study, we provide the first national-scale assessments of the health and economic burden of high temperature-related hospitalisations in a LMIC context. Brazil boasts a vast and diverse population, with significant socio-economic disparities and health inequalities between affluent urban centres and underdeveloped rural areas (Cenedesi Júnior, 2024). The country spans multiple climate zones and diverse biomes, from the Amazon rainforest to the semi-arid northeast (Braga and Laurini, 2024). Since the 1990 s, Brazil has implemented the Sistema Único de Saúde (SUS), a unified health system designed to provide universal and comprehensive health coverage and address inequities in access to healthcare services and health outcomes—setting it apart from many LMICs with limited healthcare data systems (Castro et al., 2019). This unique combination of public healthcare infrastructure, socio-economic diversity and climatological variability makes Brazil an ideal setting to investigate the burden of heat on hospitals and their economic implications. We aimed to evaluate i) the historical effects of heat in terms of heat-related all-cause and cause-specific non-elective hospitalisations, ii) associated economic burden across federal macroregions of Brazil (2008–2023), and iii) project future impacts under various global warming and demographic scenarios (2024–2060).

2. Methodology

2.1. Study setting

In recent decades, Brazil has seen notable socioeconomic shifts, including urbanisation and improved infrastructure, though regional disparities in wealth and healthcare access persist (Pinto et al., 2021). Brazil had 5570 municipalities across 27 states, structured into five geopolitical regions, each with distinct climatic and socioeconomic characteristics (Clarke et al., 2024; Alvares et al., 2013) (Figs. 1, S1). The analysis is conducted at the state and federal macroregional levels to provide insights relevant to policy-makers at the national and state levels. The decision not to extend the study timeline beyond 2060 was

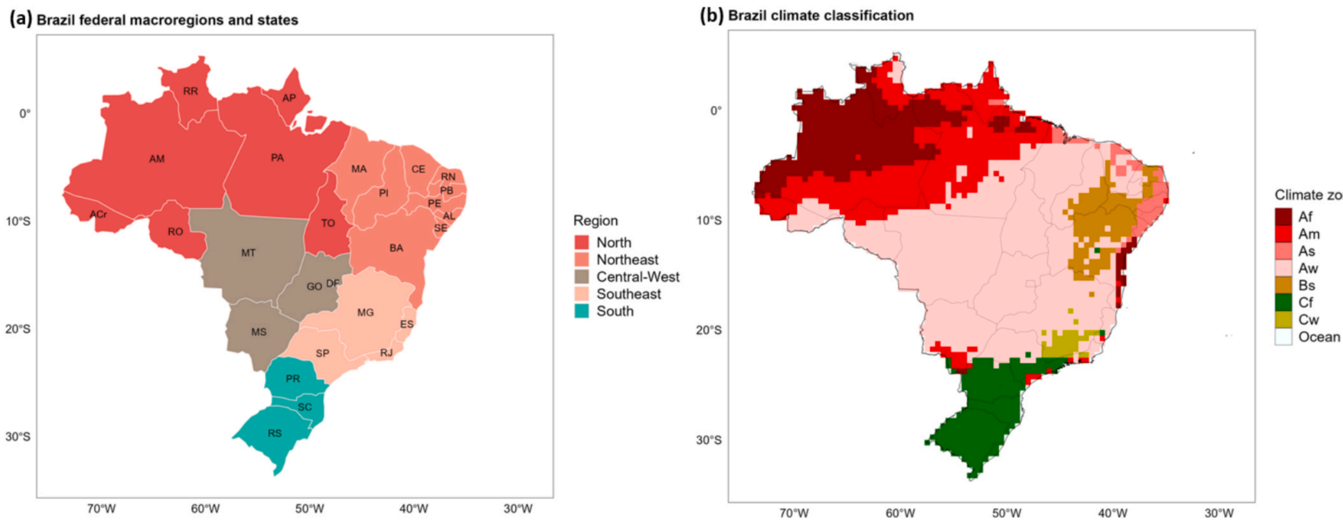

Fig. 1. Federal macroregions (according to IBGE) and climate classification zones for Brazil (according to the Köppen criteria). Note: Brazil comprises 27 federal units (26 states and the Federal District), organized into five major geopolitical regions (North, Northeast, Central-West, Southeast, and South). 1a illustrates the federal macroregions defined by the Brazilian Institute of Geography and Statistics (IBGE), while 1b depicts climate zones based on the Köppen classification system, categorised by temperature and precipitation patterns. Boundary lines in both maps represent the divisions between Brazil's federal units. Regions and states: North Region: ACr – Acre; AP – Amapá; AM – Amazonas; PA – Pará; RO – Rondônia; RR – Roraima; TO – Tocantins. Northeast Region: AL – Alagoas; BA – Bahia; CE – Ceará; MA – Maranhão; PB – Paraíba; PI – Piauí; PE – Pernambuco; RN – Rio Grande do Norte; SE – Sergipe. Central-West Region: DF – Distrito Federal; GO – Goiás; MT – Mato Grosso; MS – Mato Grosso do Sul. Southeast Region: ES – Espírito Santo; MG – Minas Gerais; RJ – Rio de Janeiro; SP – São Paulo. South Region: PR – Paraná; RS – Rio Grande do Sul; SC – Santa Catarina. Climate zones: A — Tropical zone (Af – without dry season; Am – monsoon; As – with dry summer; Aw – with dry winter). B — Dry zone (Bs – semi-arid). C — Humid subtropical zone (Cf – oceanic climate, without dry season; Cw – with dry winter).

based on the potential for health system reforms by late century, the stability of temperature projections across emission scenarios until mid-century, and Brazil's goal of achieving carbon neutrality by 2060.

2.2. Data sources and variables

Data on daily hospital admissions were obtained from the Brazil Hospital Information System (SIH) (https://datasus.saude.gov.br/informacoes-de-saude-tabnet/). The SIH includes at least 70 % of hospitalisations in the country (da Saúde, May 2024), and provides hospital admissions data coded by the International Statistical Classification of Diseases and Related Health Problems 10th Revision (ICD-10). Records include information on residence address, age, sex, admission date, total hospitalisation cost and length of stay. Our study period was limited to 2008–2019 due to data quality and potential COVID-19 confounding effects (Michele Gragnolati ML, and Bernard Couttolenc, 2013). A total of 5,459 (98 %) municipalities had non-elective admission records spanning the study period so were included in our study. All-cause hospitalisations, which served as the primary outcome, were categorised into five cause-specific groups: (1) Diseases of the circulatory system (ICD-10: I00-I99), (2) Respiratory diseases (J00-J99), (3) Kidney diseases (N00-N39), (4) Maternal health conditions (O00-O99), and (5) Other causes (A00–Z99, excluding the prior four groups).

We derived daily maximum temperature and relative humidity using European Centre for Medium-Range Weather Forecasts Reanalysis V5 (ERA5) reanalysis data (Hersbach et al., 2020). We then generated composite meteorological series for each municipality during 2008–2023 by calculating the area-weighted average from contributing 0.25° grid cells. We employed the Shared Socioeconomic Pathways (SSPs) framework to explore the combined impacts of varying levels of climate change, population growth, and socio-economic changes on our study outcomes. Temperature projections for 2024–2060 were derived from the Coupled Model Intercomparison Project Phase 6 (CMIP6) under SSP1-2.6 (low), SSP2-4.5 (medium), and SSP5-8.5 (high) emission scenarios. Population projections (2020–2060) were sourced from WorldPop at 1 km resolution (Wang et al., 2022).

Socioeconomic data (e.g. daily salary) was collected from Brazilian Institute of Geography and Statistics (IBGE). We complemented municipality-level absenteeism data based on ICD-10 from the National Institute of Social Security (INSS) in Brazil (Ministério da Economia, 2023).

Anonymized data on disease levels were obtained from the INSS, by means of the Access Information Law (Lei de Acesso à Informação) under protocol number 18800.328168/2024–11. The REACH project was submitted to the local (FCTS/UnB) and national (Conep) research ethics committees of Brazil under number CAAE 81756624.6.0000.8093, which was approved under report 7306318 (FCTS/UnB) and 7346467 (Conep). All other data used in this study were fully in the public domain. The REACH study has also received approval from the LSHTM Ethics Committee (Ref: 30865).

2.3. Data analysis

2.3.1. Historic temperature-hospitalisation relationships

We employed a two-stage approach to examine the relationship between daily maximum temperature and risk of hospitalisation for non-elective admissions. In the first stage, we used a case time-series design for small-area analysis and estimated temperature-hospitalisation associations for each state (Fig. S2). To account for potential delayed effects of ambient temperature, we combined conditional quasi-Poisson regression with a distributed lag non-linear model (DLNM) (Gasparrini, 2022). Temperature risk was modelled using a cross-basis function with splines, and adjusted for environmental covariates, seasonal variations, and long-term trends. Risk sets are defined by municipality/year/month strata indicators (Appendix). For each state, we identified the minimum morbidity temperature (MMT) and MMT percentile (MMP) at which risk of admission was lowest. We then estimated the relative risk (RR) of admission at selected temperatures compared with the MMT, and presented results as RR with a 95 % confidence interval (CI) at the 95th percentile temperature (T95) versus MMT. The first stage analysis was repeated for cause-specific hospitalisations (secondary outcomes), and all-cause hospitalisations stratified by age and sex.

In the second stage, state-level associations, including the estimated coefficients and variance–covariance matrices were pooled to the national-level using multivariate random-effects *meta*-analysis. All statistical analyses were performed with R (version 4.3.1).

2.3.2. Hospitalisation burden from heat for the past and future period

We estimated the annual number of attributable non-elective hospital admission cases (AC) by combining population size, baseline non-elective hospitalisation rates, and relative risks of admissions at specific temperatures. Attributable burdens were calculated based on temperatures exceeding the location-specific MMT, derived from exposure–response function fitted using DLNM in the first-stage analysis. For each day, relative risks corresponding to the observed temperature were extracted from the fitted curve, and applied baseline hospitalisation rates to compute daily excess cases. While relative risks at the 95th percentile of daily maximum temperature versus MMT were presented to enable comparisons across regions and groups, they were not used in the burden estimation. We projected heat-related hospitalisations until 2060 using future climate data from six CMIP6 general circulation models across three SSP scenarios. Multi-model ensemble averages and 95 % CIs for attributable admissions were estimated using Monte Carlo simulations.

2.3.3. Economic cost estimates from heat-related hospitalisation

Economic costs were estimated using a cost-of-illness approach that included direct medical costs to the federal Ministry of Health (MoH) associated with non-elective hospital admissions and indirect costs to society associated with loss of production from morbidity. The direct cost was assessed using fixed reimbursement rates across various disease categories. We calculated a case-weighted average cost for hospital stays for each disease category. Since the federal MoH covers only about 38 % of these costs, an adjustment factor of 2.8 was applied to estimate the total cost across the entire health system (Ministério da Saúde FOC, 2018). Labour productivity losses due to heat-related hospitalisations were calculated by multiplying the total absenteeism days by daily wage estimates, the employment rate, and the number of hospitalised admissions. For future costs projections, we applied a 5 % discount rate and assumed a 3 % annual inflation rate (Williams et al., 2023). We further applied two well-recognised approaches to understand how adaptation strategies could modify risk and potential health outcomes under future climate conditions (Appendix).

3. Results

3.1. Overall relationship between temperature-related non-elective hospitalisation by disease and population group

The overall RR of all-cause hospitalisations with exposure to heat (38.3 °C, representing the 95th percentile compared to the MMT of 25 °C) is 1.05 (1.03–1.06) (Fig. 2). The adverse health effects of high temperatures are most pronounced in renal (1.18; 1.14–1.23) and respiratory diseases (1.09; 1.03–1.14), while the impact on maternal health conditions (1.02; 1.01–1.03) is comparatively weaker (Figs. S10-S11).

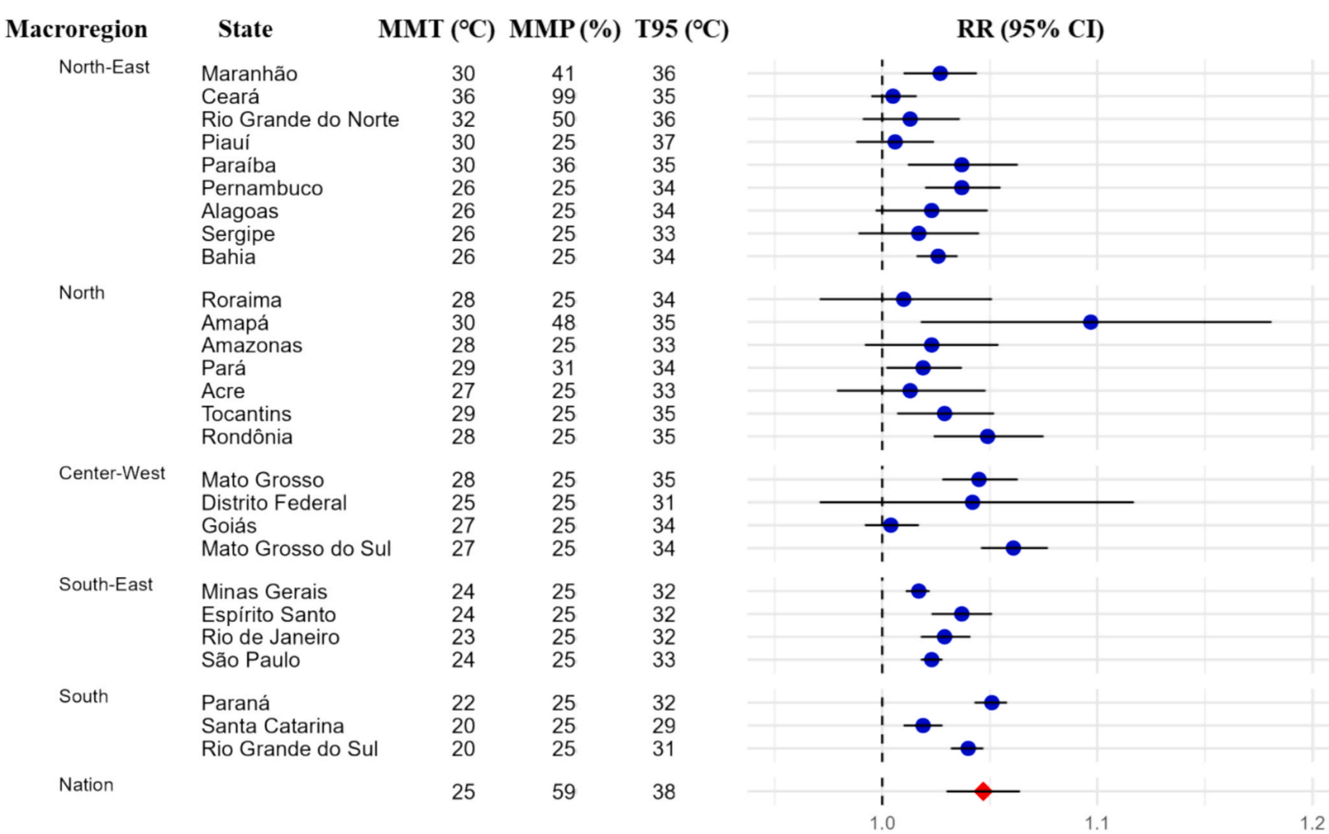

Fig. 2. Exposure–response relationships between temperature and all-cause non-elective admissions across 27 states in Brazil. Note: Exposure–response relationships between daily maximum temperature and all-cause non-elective hospital admissions in each state are modelled using natural cubic splines with 5 degrees of freedom, knots at 10th–50th–90th percentiles of temperature, lag = 0–7 days. MMT, Minimum morbidity temperature (°C); MMP, minimum morbidity temperature percentile (%); T95 is the 95th percentile of the annual daily maximum temperature (°C). MMP refers to the percentile of the MMT within the annual temperature distribution. RR (95 % CI) indicate the relative risks and their 95 % confidence interval at T95 compared to the MMT. Non-elective admissions include medical emergencies, workplace accidents, and traffic injuries. There is notable heterogeneity and uncertainty in the temperature-hospitalisation associations across different regions. We considered RR values consistently greater than 1, with 95 % CI lower bounds exceeding 1, as strong evidence of an increased risk of unplanned hospital admissions associated with high temperatures (T95 vs. MMT). While RR values at T95 are shown here for visual comparison, the main burden estimations are based on temperatures exceeding the MMT, not on fixed percentiles.

Vulnerable populations, including the elderly (≥65 years) (1.09; 1.06–1.12) and children (0–14 years) (1.10; 1.04–1.16), are more sensitive to heat compared to the working-age population (15–64 years) (1.03; 1.01–1.04), with no clear evidence of sex differences for risk of heat-related admissions (Figs. S12-S13).

3.2. Regional variation in climate conditions and hospital admissions in Brazil

Climate conditions varied across regions in terms of daily maximum temperatures (North vs South: 29.7 ± 2.4 vs 21.0 ± 4.4 °C, respectively) and humidity (North vs Central-West: 77.1 ± 13.5 % vs 65.7 ± 15.1 %) (Figs. S4-S5). National temperature increases between 2050 and 2059 relative to 2010–2019 baseline levels, are projected to be 1.6 °C, 2.0 °C, and 2.6 °C under SSP1-2.6, SSP2-4.5, and SSP5-8.5 climate scenarios respectively (Fig. S6). Temperature projections up to 2050 show limited variation across SSPs and projections start to diverge after 2050. Population trajectories differ by SSP; under SSP2, Brazil's population is projected to be higher by mid-century compared to SSP1 and SSP5 due to varying assumptions about development priorities, demographic transitions, and socioeconomic policies (Fig. S7).

There is also regional variation in annual all-cause non-elective hospital admissions, 4,823 ± 908 admissions per 100,000 people nationally, across all temperatures (Table S1; Fig. S8). In 63 % of the states (17/27), there is strong evidence of increased relative risks (RR) of unplanned hospital admissions associated with high temperatures (95th percentile temperature, T95 vs. MMT) (Figs. 1, S9; Table S3). Higher temperature thresholds for hospitalisation were found in warmer northern regions (MMT: 26–36 °C) compared to cooler southern regions (MMT: 20–24 °C), with a corresponding higher MMP in warmer areas (35th percentile of temperature vs. 25th in cooler regions), suggesting potential heat acclimatisation across the nation. Similarly, at extreme high temperatures, risk levels were greater in the South, likely due to lower levels of acclimatisation to heat compared to the North, indicating varying regional vulnerabilities to heat-related health impacts.

The distribution of disease types also showed marked regional differences (Table S2). The South had the highest proportion of hospitalisations in the elderly ≥ 65 years (23.1 % vs. 10.4 %-20.7 % in other regions), while the North had the highest hospitalised proportion among children 0–14 years (22.6 % vs. 13.4 %-19.3 % in other regions).

3.3. Current and future heat-related hospitalisation burden

Analysis across Brazilian states (Fig. S15) indicate a general pattern that rising temperatures are expected to drive notable increases in attributable hospitalisations by mid-century, particularly at extreme temperature ranges beyond the maximum observed during 2010–2019. São Paulo, the most populous and economically robust state in the Southeast, serves as a useful case study due to its significant socioeconomic and environmental changes driven by urbanisation and climate change. By the 2050s, temperature distributions show a clear rightward shift and increased variability, signalling warming trends, with excess hospitalisations particularly noteworthy at higher temperatures, which were not even reached in the 2010s (Fig. 3).

Without adaptation, annual national heat-related hospital admissions are projected to reach 51.1 (95 % CI: 19.1–103.0), 53.9 (21.4–106.0), and 59.1 (24.5–112.0) admissions per 100,000 population in the 2050s under the SSP1-2.6, SSP2-4.5, and SSP5-8.5 scenarios, respectively. This represents 53.5 % (31.7–54.4), 61.8 % (39.7–63.4), and 77.5 % (53.8–79.2) increases from 33.3 (9.1–66.7) per 100,000 annually in the 2010s. Notably, SSP1-2.6 shows a steadier upward trend over time, in contrast to SSP2-4.5 and SSP5-8.5, which exhibit larger increases with only small differences between two scenarios (Fig. S17; Tables S4–S5). A substantial portion of these admissions is expected to occur in the Northeast (26.7 %) and the Southeast (25.7 %) (Fig. S18). Notably, in densely populated states such as São Paulo and Minas Gerais, while the attributable fraction remains relatively low, the absolute number of admissions is considerably high due to the large population sizes (Fig. 4).

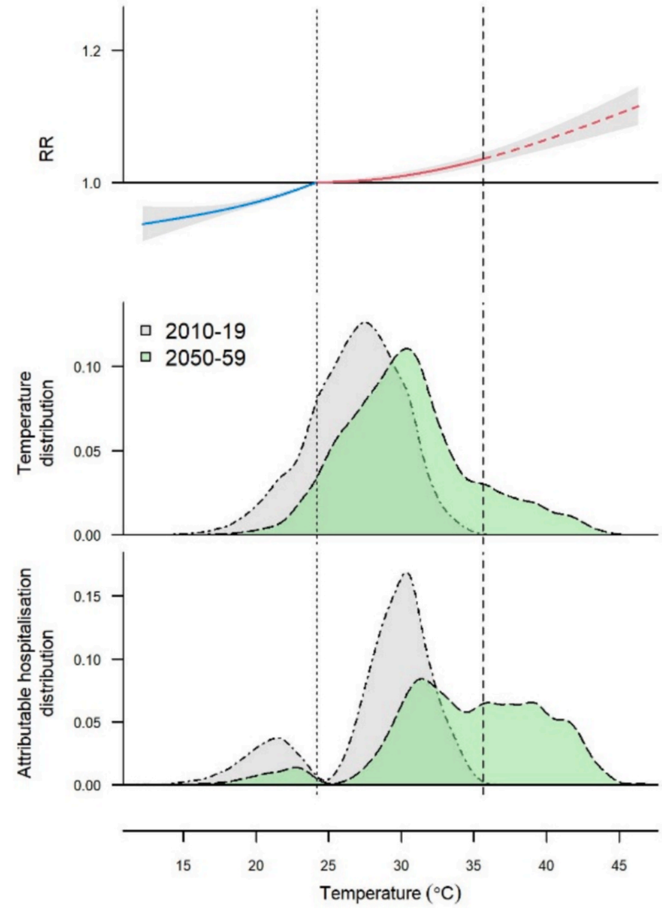

Fig. 3. Temperature and attributable hospitalisation in São Paulo state for present and future periods under the SSP2-4.5 scenario. **Top panel**: exposure–response curve represented as hospitalisation relative risks (RR) across the temperature (°C) range, with 95 % confidence intervals (grey area). The dotted vertical line corresponds to the minimum morbidity temperature (MMT, i.e. 24 °C) used as reference, which defines the two portions of the curve related to cold and heat (blue and red, respectively). The dashed part of the curve represents the extrapolation beyond the maximum temperature observed in 2010–2019 (dashed vertical line). This extrapolation, based on distributed lag nonlinear models, is a common method to assess health risks at temperatures beyond historical observations under future climate scenarios. **Mid panel**: distribution of temperature for the observed (2010–2019, grey area) and projected at the middle of the century (2050–2059, green area) using a multi-climate model average (ACCESS-ESM1-5, CANESM5, INM-CM4-8, INM-CM5-0, NorESM2-LM, and MIROC6) and medium emission scenario SSP2-4.5. The vertical axis represents the probability density, indicating the relative frequency of daily temperatures over the respective years. Higher peaks signify temperatures that occur more frequently, while the shifting of the curve in 2050–2059 illustrates a shift toward higher temperatures. **Bottom panel**: distribution of attributable hospitalisation (related to the mid panel), expressed as the fraction of additional hospitalisation (%) attributed to high temperature compared with MMT. The distribution is derived from probability density functions (PDFs), where the total area under each curve integrates to 1. The height of the curves represents the relative, rather than absolute, frequency of hospitalisations across the temperature range. The rightward shift of the curve in 2050–2059 indicates an increased burden of hospitalisations at higher temperatures under future climate conditions.

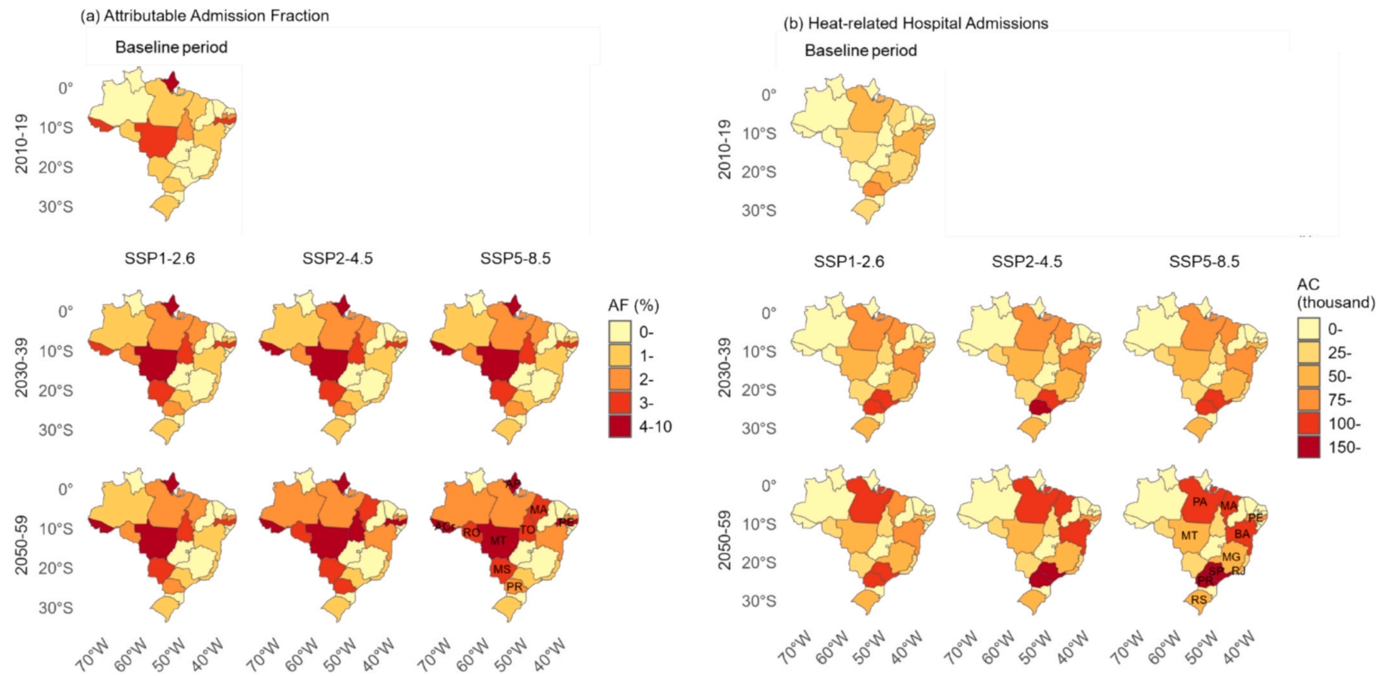

Fig. 4. Spatial trend of decadal (a) attributable admission fraction (AF) and (b) attributable admission cases (AC) under different climate and demographic scenarios in Brazil. SSP1-2.6, SSP2-4.5, and SSP5-8.5 represent low, medium, and high greenhouse gas emission scenarios, respectively, under the Shared Socioeconomic Pathways (SSPs) framework. The baseline period is 2010–2019. The map highlights the states with the highest projected attributable fraction (AF) or attributable cases (AC) in the 2050s under the high-emission scenario (SSP5-8.5), including: North: ACr (Acre), AP (Amapá), AM (Amazonas), PA (Pará), RO (Rondônia), TO (Tocantins); Northeast: BA (Bahia), CE (Ceará), MA (Maranhão), PE (Pernambuco); Central-West: MT (Mato Grosso), MS (Mato Grosso do Sul); Southeast: MG (Minas Gerais), RJ (Rio de Janeiro), SP (São Paulo); South: PR (Paraná), RS (Rio Grande do Sul).

3.4. Temporal and spatial trends in the cost of heat-related hospitalisation

Heat-related hospitalisations impose a substantial economic burden. In the 2010s, high temperature-related direct hospitalisation costs averaged \$87.7 million annually (0.006 % of government health expenditure) and indirect costs were \$55.8 million annually. The total burden reached \$143.5 million annually, representing 0.004 % (0.001 %–0.008 %) of GDP (equivalent to the annual wages of 114,860 workers). Without adaptation, these costs are projected to increase under all carbon emission scenarios by mid-century (2050–2059), reaching \$262.7 million annually under the high-emission (SSP5-8.5) scenario, and \$263.5 million and \$227.7 million under the medium-emission (SSP2-4.5) and low-emission (SSP1-2.6) scenarios, respectively—representing 1.59 to 1.84 times the 2010s levels (Fig. S17; Table S6). However, under the analogue assumption—where adaptation involves modifying the risk function using representative exposure–response curves from highly adaptive states—economic losses in the 2050s under SSP2-4.5 could be reduced by up to \$120.8 million annually. This represents a 45.8 % decrease compared to non-adaptive scenarios within the same period and scenario. It is important to note that this is an optimistic upper bound that assumes a high level of adaptation, which may be unlikely to achieve in practice. However, even a modest 10 % adaptation level (i.e. reducing the slope of the ERF by 10 %) could reduce costs by 9.7 %.

There are variations in the economic burden across subnational regions. The relatively affluent South bears the highest absolute attributable costs in 2050s under SSP2-4.5, with \$21.5 $\pm$ 21.9 million, compared to \$4.7 $\pm$ 5.4 million in the North (Table S7, S8). The South was disproportionately affected, bearing 24 % of the national costs despite representing only 14 % of the population, compared to 12 % of the national costs and 9 % of the total population in the North. However, despite the low absolute costs, Northern states experienced the highest losses relative to their state GDPs in 2050s, 0.008 % $\pm$ 0.005 % —four times the national average. Per capita costs were also higher in the North, with direct costs of \$0.56 $\pm$ 0.37 and indirect costs of \$0.36 $\pm$ 0.23, compared to national averages of \$0.40 and \$0.26 per capita, respectively. Moreover, some Northern states are projected to see costs rise to 2.2 times by the 2050s under SSP2-4.5 compared to 2010s, more than double the national average increase.

Sensitivity analyses adjusting for air pollution, cost assumptions, and seasonal trends showed consistent exposure–response relationships and cost patterns, supporting the robustness of our key findings in this regard (Supplementary Figs. S9, S14, and S19).

4. Discussion

We comprehensively estimated the impacts of heat on non-elective hospitalisations and their associated costs to the health sector and wider economy in Brazil, including forecasting based on a range of future scenarios. Using a case time-series design across 5,459 (98 %) Brazilian municipalities during 2008–2019, we found a 5 % (3–6 %) increase in all-cause non-elective hospital admissions with short-term exposure to extreme high temperatures (95th percentile vs MMT). The greatest heat-related risks were observed for renal diseases (RR = 1.18, 95 % CI: 1.14–1.23), respiratory diseases (1.09, 1.03–1.14), and among older adults aged $\geq$ 65 years (1.09, 1.06–1.12) and children aged 0–14 years (1.10, 1.04–1.16). A disproportionately higher burden is observed in Brazil's southern regions due to a larger population and higher vulnerability from lower heat acclimatisation, whilst northern areas demonstrate a more rapid rate of increase in economic costs related to high temperatures and weaker healthcare capacity/infrastructure. Without adaptation, annual economic costs of heat-related hospitalisations could surpass \$200 million by the 2050s under all emission scenarios, almost doubling the observed 2010s costs. This highlights that, even with significant mitigation efforts to reduce emissions, the economic burden of heat remains considerable in the absence of adaptation due to the contribution of population increase and ageing. Reducing the slope of the exposure–response curve by 10 % could reduce the projected mid-century economic burden by $25.5 million.

Our findings are comparable to other studies. In the UK, Kovats et al. (Kovats et al., 2004) observed heat-related increases in emergency admissions for respiratory and renal diseases, in children under 5, and for respiratory disease in individuals aged over 75. Similarly, a study in Brazil highlighted a 2.6 % increase in hospital admissions during heatwaves, with disproportionately higher effects among the elderly aged over 80 (18 %) and children aged 5–9 (11 %) (Zhao et al., 2019). A nationwide study in China found that heatwave-related mortality was most pronounced in cooler regions which supports our findings from Brazil that populations in the cooler regions are less acclimated to heat and have limited cooling infrastructure, making them more vulnerable to extreme heat (Cai et al., 2024). However, a study in Australia, estimated that high-temperature-attributable hospital admissions during 2010–2015 accounted for 0.123 % of GDP (0.001 %–0.221 %), with a projected increase of 7.7 % (0.3, 13.3) by mid-century under a high emission scenario (Wondmagegn et al., 2021). In comparison, our Brazil estimate was substantially lower, at 0.004 % (0.001 %–0.008 %) of GDP in the 2010s, but is projected to rapidly rise by 184 % by mid-century. Direct comparisons are challenging due to differences in population size, regional healthcare costs, climate conditions, and the specific health outcomes considered.

This research has several strengths and limitations. To our knowledge, this is the first study to holistically assess the effects of heat on non-elective hospitalisations and associated economic burdens nationwide in Brazil, and also project future burdens under different climate change scenarios based on results of a robust case time-series design using nationwide data covering 5,459 municipalities (98 %) of Brazil. Our extended study explored the economic burden of heat-related health impacts across Brazil as a whole, projecting through to 2060, and revealed substantial health benefits of adaptation measures, especially through reductions in direct costs, which are particularly pronounced in less developed regions like the northern areas of Brazil. However, regional variation in local healthcare availability and patient's ability to seek urgent care, impacts competing admission and mortality rates, and regional variation more generally and 'noise' may influence the results due to differences in population size and event rates, particularly in sparsely populated areas. To mitigate the impact of this limitation, we used granular municipality-level health data by applying small-area time-series analysis to minimize this bias and enhance the robustness of our findings. Moreover, our findings are conservative in that they underestimate the total health burden of heat stress, since our analysis focuses on the direct costs associated with hospitalised survivors and does not account for broader health impacts, such as morbidity not requiring admission, quality-adjusted/disability-adjusted life years, or the burden on primary care providers and outpatient departments or economic burden of workforce productivity losses from mortality. In addition, direct costs may also be underestimated as private healthcare payments and insurance contributions were not included in the economic assessments. For indirect costs, we incorporated disease-specific absenteeism data from the social security system to estimate lost working days off sick, enhancing the accuracy of our analysis. While our analysis incorporated demographic and climate changes through the SSP framework, other recent developments—such as continued urbanisation, health system reform, and infrastructure investments—may further shape future heat-related health burdens. These unmeasured factors, including potential behavioural or institutional adaptation, were not explicitly modelled. Likewise, while our analysis incorporated adaptation scenarios to simulate the potential reduction in risk under future climate conditions, these scenarios are implemented as predefined adjustments to relative risk and do not dynamically model future developments in infrastructure, healthcare delivery, or population behaviour. As such, our estimates remain bounded by structural assumptions and highlight important directions for future research.

Currently, Brazil's National Adaptation Plan provides a framework for climate risk management, including health sector resilience strategies. However, there is an urgent need for more targeted measures to address extreme heat, as hospitals are largely unprepared for increasing heat-related admissions, particularly with extreme temperatures expected to intensify in the future (Thompson et al., 2022; Christidis et al., 2020). Haines and Ebi (2019) have highlighted that establishing early warning systems and strengthening healthcare infrastructure, such as increasing emergency response capabilities and hospital bed availability, are essential immediate priorities (Haines and Ebi, 2019). Broader adaptation measures could include consideration of increasing urban green spaces, expanding cooling infrastructure, improving housing standards, and integrating climate resilience into urban planning (Watts et al., 2015). Future research should compare the costs of inaction with adaptation investments and assess interventions such as resilient urban planning. Expanding this framework to other regions could offer comparative insights to guide resilience-building initiatives against global warming. Additionally, further research on adaptation modelling with stronger empirical evidence is needed to better assess broader community adaptive capacity (Muccione et al., 2024).

5. Conclusion

With high temperatures projected to increase in both frequency and intensity, even under optimistic climate scenarios, the impact of heat on non-elective hospitalisations, and associated costs to the health sector and economy, are anticipated to rise sharply and disproportionately impact vulnerable regions. These findings highlight the importance of regional adaptation and targeted healthcare investments, alongside climate mitigation initiatives, to effectively reduce the impact of heat on health systems and the associated economic burden. This research emphasizes the need for proactive policies to address preventable negative health impacts and enhance societal resilience to the climate crisis.

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CRediT authorship contribution statement

Huiqi Chen: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Ivan Augusto Cecilio e Silva:** Writing – review & editing, Validation, Resources, Data curation. **Shakoor Hajat:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Conceptualization. **Letícia Xander Russo:** Writing – review & editing, Resources, Methodology, Data curation. **Kai Wan:** Writing – review & editing, Software, Methodology, Formal analysis. **Cherie Part:** Writing – review & editing, Validation, Software, Resources, Methodology, Data curation. **Zhifu Mi:** Writing – review & editing, Supervision, Resources, Methodology. **Josephine Borghi:** Writing – review & editing, Validation, Supervision, Resources, Methodology, Investigation, Funding acquisition, Conceptualization. **Dorothea Nitsch:** Writing – review & editing, Supervision, Resources, Investigation, Conceptualization. **Everton Nunes da Silva:** Writing – review & editing, Supervision, Resources, Methodology, Investigation, Data curation. **Anna M. Foss:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Author contributions

Huiqi Chen led on the work presented, including developing the study aim, methodological framework, coding the models, undertaking the modeling analysis, and presenting and interpreting the results. Huiqi Chen, Ivan Silva, and Letícia Xander Russo extracted and cleaned the data needed for the models. Huiqi Chen and Shakoor Hajat co-designed the statistical modeling study design, with Shakoor Hajat providing statistical guidance and input on the analysis. Kai Wan provided additional methodological support for the modeling. Cherie Part co-led REACH Objective 1, contributed to the methodological approach, assisted with the interpretation of results and supported the calculation of exposure variables. Shakoor Hajat, Anna M Foss, Dorothea Nitsch and Zhifu Mi facilitated and supervised the research. Anna M Foss established the supervisory team, and initiated and supported the connection with the broader REACH project, contributed mathematical insights into the statistical models, guided the presentation of results, and helped to draw out the interpretation and implications of the findings. Dorothea Nitsch contributed clinical expertise and insights on hospital admissions and the different specific causes, as well as steering the study aim, and guiding the storyline, structure and development of the manuscript. Everton Nunes Silva and Josephine Borghi contributed expertise in health economics and connections with, and insights from, REACH on which they are co-PIs along with Anna M Foss. Everton Nunes Silva also provided contextualisation for the Brazil setting. Zhifu Mi provided guidance on climate and economic analysis. Huiqi Chen drafted the initial manuscript then Shakoor Hajat, Anna M Foss and Dorothea Nitsch reviewed and input on earlier versions prior to all coauthors reviewing and inputting iteratively as the manuscript developed further. All authors reviewed the final version of the manuscript and approved it for submission.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2025.109620.

Data availability

Data will be made available on request.

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