Projected heatwave-related excess mortality under climate change scenarios across 2288 communities in Australia: a nationwide ecological projection modelling study

Botian Chen, Rongbin Xu*, Zhihu Xu, Wenhua Yu, Yanming Liu, Zhaoyuan Li, Yunfei Xing, Yuming Guo, Shanshan Li*

Summary

Background Climate change is intensifying the frequency, duration, and severity of heatwaves globally, posing a growing threat to human health. However, few fine-scale projections of heatwave-related excess mortality account for spatial disparities and adaptive capacity. We aimed to estimate future heatwave-related excess mortality across statistical area level 2 (SA2) communities in Australia under multiple climate scenarios.

Methods In this modelling study, we projected excess mortality rates across 2288 SA2 communities in Australia for the period 2020–2100 under four shared socioeconomic pathways (SSPs) representing alternative trajectories of adaptation (SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5). Daily all-cause mortality data from Jan 1, 2009, to Dec 31, 2019, were obtained from the Australian Coordinating Registry and the Australian Bureau of Statistics. We estimated historical exposure–response relationships using a two-stage distributed lag non-linear model with multivariate meta-regression. Future daily temperatures were obtained from bias-corrected, downscaled projections based on Coupled Model Intercomparison Project Phase 6 (a global climate model intercomparison project) and combined with mortality data and SSP-specific population forecasts to estimate annual excess deaths and excess mortality rates. We assessed median percentage changes in annual excess mortality rates for 2050–59 and 2090–99 using the 2020–29 period as a reference. Two adaptation scenarios were considered: no adaptation and full adaptation. Uncertainty was quantified through Monte Carlo simulations.

Findings Heatwave-related excess mortality was projected to increase substantially across Australia under all SSP scenarios. We estimated that, in 2100, without adaptation, annual excess deaths would reach approximately 5820 under SSP5-8.5 (a scenario of a fossil fuel-intensive future with little mitigation) and the cumulative total of heatwave days across all communities would be 174 079. Heatwave-related excess mortality rates were projected to be highest in Northern Territory during 2090–99, at 33·9 deaths per 100 000 population (95% empirical CI 13·9–55·0), followed by Queensland, at 18·4 deaths per 100 000 population (7·6–29·8), and New South Wales, at 12·8 deaths per 100 000 population (5·3–20·7); projected percentage changes in excess mortality rate relative to 2020–29 ranged from 356% (in West Coast, South Australia) to 4412% (in Thamarrurr, Northern Territory). Although full adaptation substantially reduced the projected mortality burdens, considerable residual risks remained. Spatial disparities in excess mortality rates persisted across states, socioeconomic strata, and urban–rural classifications, although absolute differences were modest.

Interpretation This study provides a comprehensive assessment of future heatwave-related excess mortality across Australia under multiple climate change and adaptation scenarios. These high-resolution projections underscore the urgent need for integrated mitigation and locally tailored adaptation strategies to address climate-related health inequities.

Funding Australian Research Council and Australian National Health and Medical Research Council.

Lancet Planet Health 2026; 10: 101446

https://doi.org/10.1016/j.lanplh.2026.101446

*Contributed equally

Department of Epidemiology and Statistics, School of Public Health, Hebei Medical University, Hebei Key Laboratory of Environment and Human Health, Shijiazhuang, China (B Chen MPH); **Climate, Air Quality Research Unit, School of Public Health and Preventive Medicine, Monash University, Melbourne, VIC, Australia** (B Chen, Z Xu MSc, W Yu PhD, Y Liu PhD, Z Li MSc, Y Xing MSc, Prof Y Guo PhD, Prof S Li PhD); **Chongqing Emergency Medical Center, Chongqing University Central Hospital, School of Medicine, Chongqing University, Chongqing, China** (R Xu PhD); **School of Public Health and Preventive Medicine, Faculty of Medicine, Nursing and Health Sciences, Monash University, Melbourne, VIC, Australia** (R Xu)

Correspondence to:
Prof Yuming Guo, Climate, Air Quality Research Unit, School of Public Health and Preventive Medicine, Monash University, Melbourne, VIC 3004, Australia
yuming.guo@monash.edu

or

Prof Shanshan Li, Climate, Air Quality Research Unit, School of Public Health and Preventive Medicine, Monash University, Melbourne, VIC 3004, Australia
shanshan.li@monash.edu

Introduction

Heatwaves, defined as prolonged periods of excessively hot weather, have emerged as a major global public health concern.[1] Heatwaves are significantly associated with increased morbidity and mortality from cardiovascular,[2] respiratory,[3] renal,[4] and heat-related illnesses,[5] contributing substantially to the global burden of disease. However, the magnitude and distribution of these impacts vary across climatic and demographic contexts, reflecting uncertainty in adaptive capacity under ongoing climate change.[6] Australia, situated largely within tropical, subtropical, and arid climate zones, is frequently affected by high temperatures and extended dry spells.[7] National assessments indicate that heatwaves have already caused substantial mortality across Australia, with an estimate of 1009 heatwave-related deaths nationwide during 2016–19.[8] Australia's population is ageing rapidly, and pronounced disparities in infrastructure, socioeconomic conditions,

Research in context

Evidence before this study

Previous research has consistently shown positive associations between heatwaves and mortality, particularly among older adults and people with pre-existing diseases. We searched PubMed and Google Scholar for articles published in English from database inception to Oct 31, 2025, with the terms ("heatwave" OR "heat wave" OR "extreme heat" OR "heat event") AND ("mortality" OR "excess deaths"). Several projections have estimated future heatwave-related mortality under various climate scenarios, but these were conducted at national or state scales, which could have obscured local disparities. To date, no work has provided comprehensive, community-level projections across Australia.

Added value of this study

To our knowledge, this study provides the first fine-grained, community-level assessment of future heatwave-attributable mortality across all 2288 Australian statistical area level 2 (SA2) communities under four shared socioeconomic pathways (alternative trajectories of global socioeconomic development) for mid-century (2050–59) and end-of-century (2090–99) periods. By explicitly modelling both no-adaptation and full-adaptation scenarios, the analysis quantifies the potential health benefits of population acclimatisation and infrastructural adaptation. The study further identifies geographical and socioeconomic inequalities, with the highest projected excess mortality rates in northern states and socioeconomically disadvantaged or rural communities, providing robust evidence for regionally tailored adaptation planning.

Implications of all the available evidence

Findings from this study and previous work indicate that the health burden of heatwaves in Australia will continue to rise under all climate futures, with disproportionate impacts in hotter and more socioeconomically disadvantaged regions and rural areas. Even with full adaptation, residual risks remain considerable, especially under high-emission scenarios. These results highlight the urgency of integrating heat–health adaptation (ie, adaptation addressing heat-related health risks) with emission reduction policies. By highlighting regional and socioeconomic disparities, this study provides essential evidence to guide equitable, community-specific public health and climate adaptation strategies.

and health-care access create unequal resilience to heat.[9,10] Northern and inland regions, where Indigenous populations account for a larger share of residents compared with other regions and access to cooling and medical resources is inadequate, are especially vulnerable to the effects of heatwaves.[11] Rural and socioeconomically disadvantaged areas often have high exposure to heatwaves; such areas generally also have insufficient adaptive capacity.[8] Meanwhile, metropolitan centres face intensifying urban heat-island effects.[12] These patterns highlight both Australia's climatic exposure and the uneven distribution of vulnerability across its communities.

With the continued trajectory of global warming, the frequency, intensity, and duration of extreme heat events are projected to increase substantially.[13] Climate attribution studies indicate that anthropogenic activities doubled the likelihood of extreme heat events in Australia between 2005 and 2020.[14] Moreover, projections under various climate models consistently show that future warming will amplify the occurrence of extreme heat. Notably, even under a 2°C global warming scenario, often cited as the upper limit under the Paris Agreement, the frequency of heatwave events is expected to increase from once per decade to approximately 5·6 times per decade.[15] This marked intensification, even under moderate warming, highlights the pressing need to quantify the potential health burden of future heatwaves. Most existing studies have focused on broad-scale assessments or specific emissions scenarios, with little focus on fine-grained spatial variation in vulnerability to heatwaves.[16–18] There remains an important gap in understanding how future climate scenarios could affect mortality risks across diverse geographical and sociodemographic settings within Australia.

This study aimed to quantify heatwave-related excess mortality rates across 2288 statistical area level 2 (SA2) communities in Australia for 2050–59 and 2090–99 under multiple climate change scenarios, to inform the development of spatially targeted heatwave mitigation and adaptation strategies. To this end, we assessed key sources of uncertainty in mortality projections, including intermodel variability, scenario assumptions, and regional differences in adaptive capacity and socioeconomic development.

Methods

Historical data on mortality and weather

Daily all-cause mortality data from Jan 1, 2009, to Dec 31, 2019, were obtained from the Australian Coordinating Registry and the Australian Bureau of Statistics (ABS), covering variables such as age, sex, date of death, and SA2 of residence. SA2 and statistical area level 3 (SA3) boundaries were defined according to the Australian Statistical Geography Standard (ASGS) 2016 classification. Under this system, Australia is divided into 2310 SA2 communities that, together, cover the entire national territory. To ensure data representativeness, we excluded 18 non-spatial SA2 communities (corresponding to populations that cannot be precisely assigned to a fixed geographical location, such as people in transit or with no usual address) and four small island SA2s, leaving 2288 SA2 communities for analysis. SA2s are designed to represent local communities that interact socially and economically, with populations typically ranging from 3000 to 25 000 people. For broader regional analyses, contiguous SA2s are aggregated into 335 SA3 regions, which usually contain 30 000–130 000 people and capture areas with shared functional or socioeconomic characteristics.[19] The hierarchical relationship and geographical distribution of SA2 and SA3 regions are illustrated in the appendix (p 9).

Meteorological data were obtained from the European Centre for Medium-Range Weather Forecasts Reanalysis, version 5 (ERA5), and population data were derived from the LandScan Global Population Database. Both datasets have a spatial resolution of 0·25° × 0·25°.

Population-weighted daily mean temperatures and relative humidity values from 2009 to 2019 were calculated for each SA3 and SA2 region. The focus of the analysis was on the warm season, defined as November to March. Index of Relative Socioeconomic Advantage and Disadvantage (IRSAD) scores were categorised into quartiles, with quartile one comprising the most socioeconomically disadvantaged areas and quartile four comprising the most advantaged areas. Urban–rural classification was based on the ABS designation of significant urban area structure, with significant urban areas being clusters of population centres with 10 000 residents or more, formed by aggregating contiguous SA2 communities. SA2s located within significant urban areas were classified as urban, whereas those outside these areas were classified as rural (appendix pp 4–5).

Projected daily temperature series under climate change scenarios

We obtained daily mean temperature data from the NASA Earth Exchange Global Daily Downscaled Projections based on Coupled Model Intercomparison Project Phase 6 (CMIP6), which includes simulations from multiple global climate models under four shared socioeconomic pathway (SSP) scenarios (SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5), covering the period 2015–2100 at a spatial resolution of 0·25° × 0·25°.

The SSP framework describes alternative trajectories of global socioeconomic development, encompassing population growth, urbanisation, education, technological progress, and economic inequality, which are combined with greenhouse gas concentration targets to generate consistent climate scenarios. Lower-numbered pathways (SSP1-2.6) represent sustainable development and rapid decarbonisation, whereas higher pathways (SSP5-8.5) depict fossil fuel-intensive futures with little mitigation. This integrated framework provides a coherent basis for projecting climate-related health impacts across alternative socioeconomic and emission futures.[20]

We selected five global climate models (the Geophysics Fluid Dynamics Laboratory Earth System Model version 4, Institut Pierre-Simon Laplace climate model IPSL-CM6-LR, Max Planck Institute Earth System Model MPI-ESM1-2-HR, Meteorological Research Institute climate model MRI-ESM200, and UK Earth System Model UKESM1-0-LL) that provide complete daily temperature projections for all four SSPs. These models originate from independent modelling centres and have distinct physical parameterisations and climate sensitivities, ensuring structural diversity and intermodel comparability. Temperature projections for 2020–2100 under each SSP scenario were bias-corrected against ERA5 reanalysis using the Inter-Sectoral Impact Model Intercomparison Project method, applying monthly mean bias factors calculated over the 2015–20 overlap period to adjust mean and variability while preserving long-term trends.[21] The bias-corrected 0·25° gridded data were then aggregated to ASGS 2016 SA2 boundaries using area-weighted and population-weighted averaging to derive SA2-level daily mean temperatures consistent with future population distributions (appendix p 6).

See **Online** for appendix

For more on **ERA5** see https://www.ecmwf.int/en/forecasts/dataset/ecmwf-reanalysis-v5

For the **LandScan Global Population Database** see https://landscan.ornl.gov/

Population and mortality rate data

Projected population datasets (2020–2100) under four SSP scenarios were retrieved from the global 1-km downscaled population projection grids developed by the National Center for Atmospheric Research Integrated Assessment Modeling group. These datasets provide population projections at a spatial resolution of 1 × 1 km on a decadal basis and are downscaled from the national-level SSP population pathways, consistent with the International Institute for Applied Systems Analysis framework. Annual population estimates at the grid level were obtained by linear interpolation between decadal projections. The 1-km grids were then spatially aggregated to match the ASGS 2016 SA2 boundaries by overlaying each grid cell with SA2 polygons and using the proportion of cell area overlapping each SA2 as an areal weight. SA2-level population values were calculated as the weighted mean across all intersecting cells, ensuring proportional contributions from boundary grids. To enhance consistency with observed demographic patterns, 2020 projected population values were calibrated against ABS SA2-level estimates. Scenario-specific correction coefficients were calculated as the ratios between observed and projected population values for each SSP scenario at the SA2 level and then applied multiplicatively to adjust subsequent projections. This approach preserves scenario-specific growth trajectories while aligning baseline populations with observed data (appendix p 7).

Annual all-cause mortality rates from 2017 to 2100 were obtained from the Global Fertility, Mortality, Migration, and Population Forecasts 2017–2100 dataset developed by the Institute for Health Metrics and Evaluation. These mortality rates were applied to the SSP-based annual population estimates to calculate the total number of deaths each year.

Data analysis

We applied our previously established definition of heatwaves[6,8]—ie, in each statistical area (SA2 or SA3), a heatwave was defined as at least 2 consecutive days with daily mean temperatures exceeding the 95th percentile of the local warm-season distribution during the time period (mean temperatures differing according to adaptation scenario).

Relative risks (RRs) of heatwave-related mortality were obtained from our previously published nationwide time-series analysis covering 2288 local communities across Australia.[8] We used an extended two-stage modelling framework combining quasi-Poisson regression with distributed lag non-linear models at the SA3 level and multivariate meta-regression to derive community-specific and pooled national estimates. We conducted comprehensive sensitivity analyses to confirm the robustness of model specifications and results.

The quasi-Poisson regression models were fitted at the SA3 level rather than at the finer SA2 level because several SA2 communities have small populations and sparse daily death counts, which would lead to unstable coefficient estimates and convergence issues. Aggregating to the SA3 level ensured sufficient statistical power and model stability while maintaining meaningful spatial resolution for meta-analysis. From the second-stage meta-regression, an overall pooled RR of 1·05 (95% CI 1·02–1·08) for all-cause mortality was derived. This national RR was applied uniformly across SA2 communities in the projection framework, as heterogeneity across SA3 estimates was low (I^2= 8·4%), indicating consistent heatwave–mortality associations nationwide. Moreover, our previous analysis[8] showed that RR estimates fluctuated more widely in sparsely populated regions than in more densely populated regions. Therefore, using a single pooled RR provided more stable and parsimonious estimates while minimising random variability in smaller areas. The distribution of SA3-specific estimates and pooled national effect are shown in the appendix (p 10).

Full details of the modelling specification, including lag structure, spline functions, and covariate adjustments, have been published previously[8] and are summarised in the appendix (p 8).

Projection of future heatwave-related excess mortality rate

For each climate scenario, we calculated the annual heatwave-related excess mortality rate and number of excess deaths for each community (SA2) with the following equations:

$$\mathrm{EMR_{HW}} = \mathrm{MR} \times (\mathrm{RR} - 1) \times \mathrm{HWN} \times 10^5$$

$$\mathrm{ED_{HW}} = \mathrm{POP} \times \mathrm{MR} \times (\mathrm{RR} - 1) \times \mathrm{HWN}$$

Here, $\mathrm{EMR_{HW}}$ is heatwave-related excess mortality rate; MR is daily mortality rate across all non-heatwave days (from the historical data for each community); RR is the relative risk of mortality due to heatwaves; HWN is the number of the heatwave days per year; $\mathrm{ED_{HW}}$ is heatwave-related excess deaths; and POP is the annual population for Australia from 2020 to 2100. To calculate the mean excess mortality rates for each region during 2020–29, 2050–59, and 2090–99, we summed the annual excess mortality rates for each period and divided by the total number of years within that period. Using 2020–29 as a reference, we then assessed the percentage changes in average excess mortality rates for 2050–59 and 2090–99, based on the mean across the five global climate models. The baseline period (2020–29) was selected to represent contemporary climatic conditions for defining heatwave thresholds as it aligns with the timeframe used for CMIP6 climate projections and provides a relevant reference for assessing future changes. Although the RRs were estimated using mortality data from 2009–19, the threshold definition was decoupled from the epidemiological estimation as the threshold serves purely as a climatic reference rather than a health baseline. This approach allows the projected health impacts to be interpreted relative to current, rather than historical, climate conditions.[22]

Uncertainty assessment

Two adaptation scenarios were considered to reflect potential human acclimatisation. The first scenario was no adaptation, whereby the 95th percentile threshold for temperatures based on 2020–29 was fixed for future projections. The second scenario was full adaptation, whereby the threshold was recalculated for each future period, representing the upper bound of potential physiological and behavioural acclimatisation.

Additional uncertainties in the estimates of excess deaths and excess mortality rate arise from two primary sources: statistical uncertainty in the estimated exposure–response relationships and variability in temperature projections across global climate models.[23] To propagate these uncertainties, we conducted Monte Carlo simulations by randomly sampling 1000 sets of coefficients based on the pooled national estimates and their variance–covariance matrix obtained from the meta-analysis.[22] For each sampled set, the corresponding RR was applied to the projected heatwave days from each of the five global climate models to calculate excess deaths and excess mortality rate for each SA2 and period. The final point estimates were computed as ensemble means across global climate models, and 95% empirical CIs (eCIs) were defined as the 2·5th and 97·5th percentiles of the empirical distribution across all coefficient samples and global climate models, jointly capturing both statistical and intermodel variability.

All statistical analyses were done with R (version 4.3.2), using the dlnm and mixmeta packages.

Role of the funding source

The funders of the study had no role in study design, data collection, data analysis, data interpretation, or writing of the report.

Results

Analysis of all-cause mortality data from Jan 1, 2009, to Dec 31, 2019, from 2288 SA2 communities across eight Australian states showed 1 644 219 recorded deaths during this period. The mean 95th percentile of projected daily temperatures across SA2s during the baseline period (2020–29) ranged from 18·55°C in Tasmania to 30·85°C in the Northern Territory. Projections under different SSPs indicated a consistent increase in the 95th percentile temperature from the baseline period to mid-century (2050–59) and late-century (2090–99). The largest temperature increases were projected under SSP5–8.5, with increases of 1–2°C by 2050–59 and 3–4°C by 2099, whereas the smallest increases were projected under SSP1–2.6 (table).

Figure 1 shows the projected trends in annual cumulative heatwave days, population, and heatwave-related excess deaths across 2288 SA2 communities from 2020 to 2100 under different SSP scenarios, assuming no adaptation. The sum of annual heatwave days across all 2288 SA2 regions in Australia was projected to increase under all SSP scenarios, with the greatest increase under SSP5-8.5, reaching approximately 174 079 days in the year 2100 (figure 1A). Population projections indicated increases under all scenarios except SSP3-7.0, with the greatest increase observed under SSP5-8.5 (figure 1B). Heatwave-related excess deaths showed an overall increasing trend over time, being projected to reach approximately 5820 in the year 2100 under SSP5-8.5 (figure 1C).

Percentage changes in annual mean excess mortality rates from the baseline period (2020–29) to 2050–59 and 2090–99 under the SSP5–8.5 scenario, assuming no adaptation, indicated regional disparities, with greater increases in SA2 communities situated closer to the equator than in those located further from the equator (figure 2). Regional disparities were projected to intensify over time, with percentage changes in 2090–99 ranging from 356% (in West Coast, South Australia) to 4412% (in Thamarrurr, Northern Territory). The projected spatial distribution of changes in excess mortality rate was broadly consistent with the historical patterns of heatwave-related mortality reported in our previous nationwide analysis,[8] with higher risks observed in northern Australia and parts of eastern Australia than in other regions. This consistency suggests that historically vulnerable regions are likely to remain at elevated risk under future climate scenarios. Among capital cities, Darwin and Brisbane showed the largest projected increases in excess mortality rate, followed by Sydney, Melbourne, Perth, Hobart, and Adelaide, which all showed upward trends. Similar spatial patterns were observed across all climate and adaptation scenarios, with greater increases in excess mortality rate under high-emission pathways and smaller increases when full adaptation was assumed (appendix pp 13–19).

At the state level, mean annual excess mortality rates and percentage changes in excess mortality rates relative to 2020–29 were projected to increase substantially by 2050–59 and 2090–99 under all SSP scenarios, assuming no adaptation. By 2090–99, the highest annual excess mortality rate under SSP5-8.5 (without adaptation) was projected in the Northern Territory (33·9 per 100 000 people, 95% eCI 13·9–55·0), followed by Queensland (18·4 per 100 000 people, 7·6–29·8) and New South Wales (12·8 per 100 000 people, 5·3–20·7). Correspondingly, the largest median percentage increases in excess mortality rate were projected to occur in the Northern Territory (4233% [IQR 2915–4235]), Queensland (1853% [1733–1962]), and New South Wales (1381% [1002–1551]). For all SSPs apart from SSP1-2.6, under which pathway both excess mortality rates and percentage changes in excess mortality rates relative to 2020–29 were projected to remain relatively stable, pronounced increases over time were projected, with SSP5-8.5 producing the greatest increase in excess mortality rate (figure 3). Although the overall trends persisted under adaptation scenarios, the projected magnitude of increase was substantially lower than with non-adapted projections (appendix p 11). Detailed estimates of mean excess mortality rates and median percentage changes, along with uncertainty intervals, are provided in the appendix (pp 20–22).

Across the four SSPs and both time periods (2050–59 and 2090–99), assuming no adaptation, excess mortality rates were projected to remain stable across IRSAD quartiles and between urban and rural categories (figure 4A, B). A slight tendency towards higher excess mortality rate was observed for socioeconomically disadvantaged (IRSAD quartile one) and rural areas, although the differences in estimates were very small and the 95% CIs between group estimates overlapped considerably. In contrast, percentage increases in excess mortality rate were slightly larger in urban areas than in rural areas. All SSP scenarios were projected to have a pronounced impact on excess mortality rates by 2090–99, with SSP5-8.5 resulting in the highest excess mortality rates across all IRSAD and urban–rural groups, followed by SSP3-7.0, SSP2-4.5, and SSP1-2.6 (figure 4; appendix p 12). Excess mortality rates and percentage changes across IRSAD quartiles and urban or rural categories are detailed in the appendix (pp 22–24).

Discussion

This study provides a comprehensive assessment of heatwave-related excess mortality across 2288 SA2 communities in Australia under multiple climate change scenarios for the periods 2050–59 and 2090–99. Our projections indicate a consistent increase in the frequency, duration, and intensity of heatwaves, leading to substantial increases in excess mortality rate, particularly under the high-emission SSP5-8.5 scenario. These results align with global and regional studies that project escalating heatwave-related health risks under climate change.[24–26]

The spatial disparities in heatwave-related excess mortality rates projected in this study highlight marked geographical and social inequities across Australia. The highest mortality rates were consistently projected in northern and inland regions such as Northern Territory and Queensland, largely due to baseline temperatures being persistently higher than in other regions. In these areas, which are also home to high proportions of Indigenous and remote communities,[11] residents' vulnerability to extreme heat is amplified by inadequate health-care infrastructure,

	Number of SA2 communities*	Total deaths in 2009–19	Mean 95th percentile of daily temperature in 2020–29, °C	Mean 95th percentile of daily temperature in 2050–59, °C				Mean 95th percentile of daily temperature in 2090–99, °C			
			SSP2-4.5†	SSP1-2.6	SSP2-4.5	SSP3-7.0	SSP5-8.5	SSP1-2.6	SSP2-4.5	SSP3-7.0	SSP5-8·5
New South Wales	576	559 618	25·48	25·93	26·43	26·51	26·48	25·89	26·99	28·20	29·12
Victoria	462	408 822	23·24	24·20	24·31	25·06	25·14	24·21	24·75	26·84	27·50
Queensland	528	309 386	26·93	27·25	27·83	27·80	27·73	27·19	28·29	29·16	30·12
South Australia	172	145 739	25·61	26·52	26·04	26·65	26·97	26·48	26·84	28·35	28·89
Western Australia	252	140 263	25·93	26·63	27·09	27·59	27·68	26·72	27·48	29·00	29·78
Tasmania	99	48 758	18·55	19·12	19·23	20·08	20·11	19·00	19·96	22·18	22·13
Northern Territory	68	11 326	30·85	31·44	31·55	31·82	32·12	31·20	32·28	33·36	34·28
Australian Capital Territory	131	20 307	22·99	23·36	23·84	24·29	24·14	23·28	24·50	25·90	26·80

SA2=statistical area level 2. SSP=shared socioeconomic pathway. *To maintain spatial consistency, the analysis focuses on the number of SA2 regions in each state and territory as defined after 2016, since approximately 4·5% of SA2 boundaries changed after that year. †Conventional development scenario, which assumes that social, economic, and environmental development will follow the current trends without significant policy interventions, continuing along the existing trajectory (SSP2-4.5).

***Table:* Summary statistics for statistical area level 2 communities**

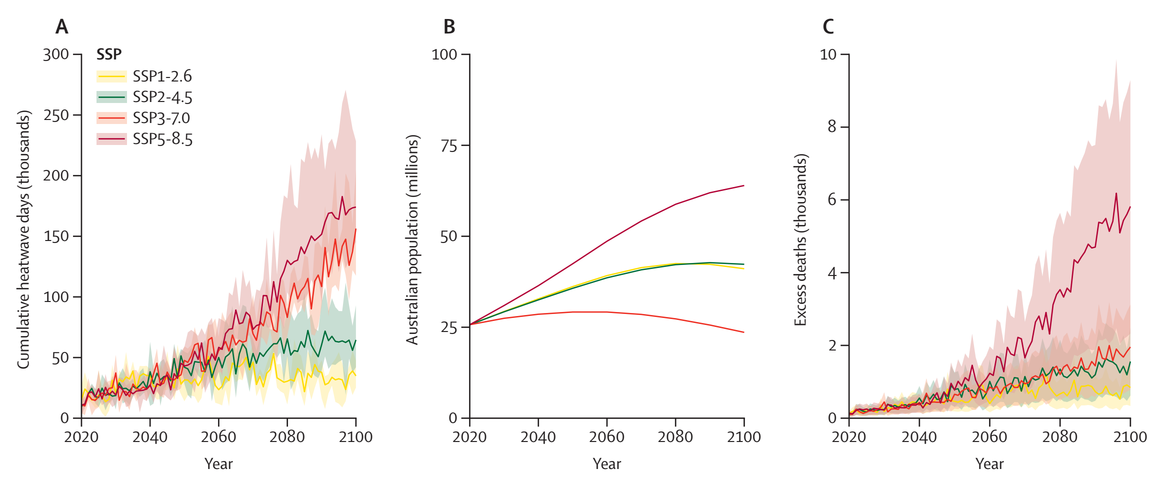

***Figure 1:* Projected trends in annual cumulative heatwave days (A), population (B), and heatwave-related excess deaths (C) across 2288 statistical area level 2 communities in Australia under different SSP scenarios, assuming no adaptation (2020–2100)**

Shaded areas in panel (A) indicate the intermodel range (minimum to maximum) across five Coupled Model Intercomparison Project Phase 6 global climate models. Shaded areas in panel (C) denote 95% empirical CIs. SSP=shared socioeconomic pathway.

low socioeconomic status, and restricted access to cooling resources.[8] Consistent with the IRSAD and urban–rural analysis, slightly higher excess mortality rates were projected for socioeconomically disadvantaged areas than for more affluent regions, and rural communities showed marginally higher excess mortality rates than did urban communities. However, the relative increase in excess mortality rate was more pronounced in urban areas than in rural areas, likely reflecting intensifying urban heat-island effects and demographic changes, including population ageing.[12,27] Such factors might increase individuals' vulnerability to heat; however, age-specific vulnerability was not explicitly modelled in this study. This absence of large differences across IRSAD quartiles and urban–rural categories likely reflects Australia's overall homogeneous heatwave–mortality associations, as well as the use of a pooled national RR in projections. Moreover, broad indicators such as IRSAD or the urban–rural classification might not capture fine variations in adaptive capacity, such as housing insulation, access to cooling, or occupational exposure. Thus, large contrasts are not expected even though modest differences persist. Both New South Wales and Victoria are highly urbanised and have ageing populations, but the projected increase in heatwave-attributable mortality was substantially greater in New South Wales, likely reflecting a combination of climatic and

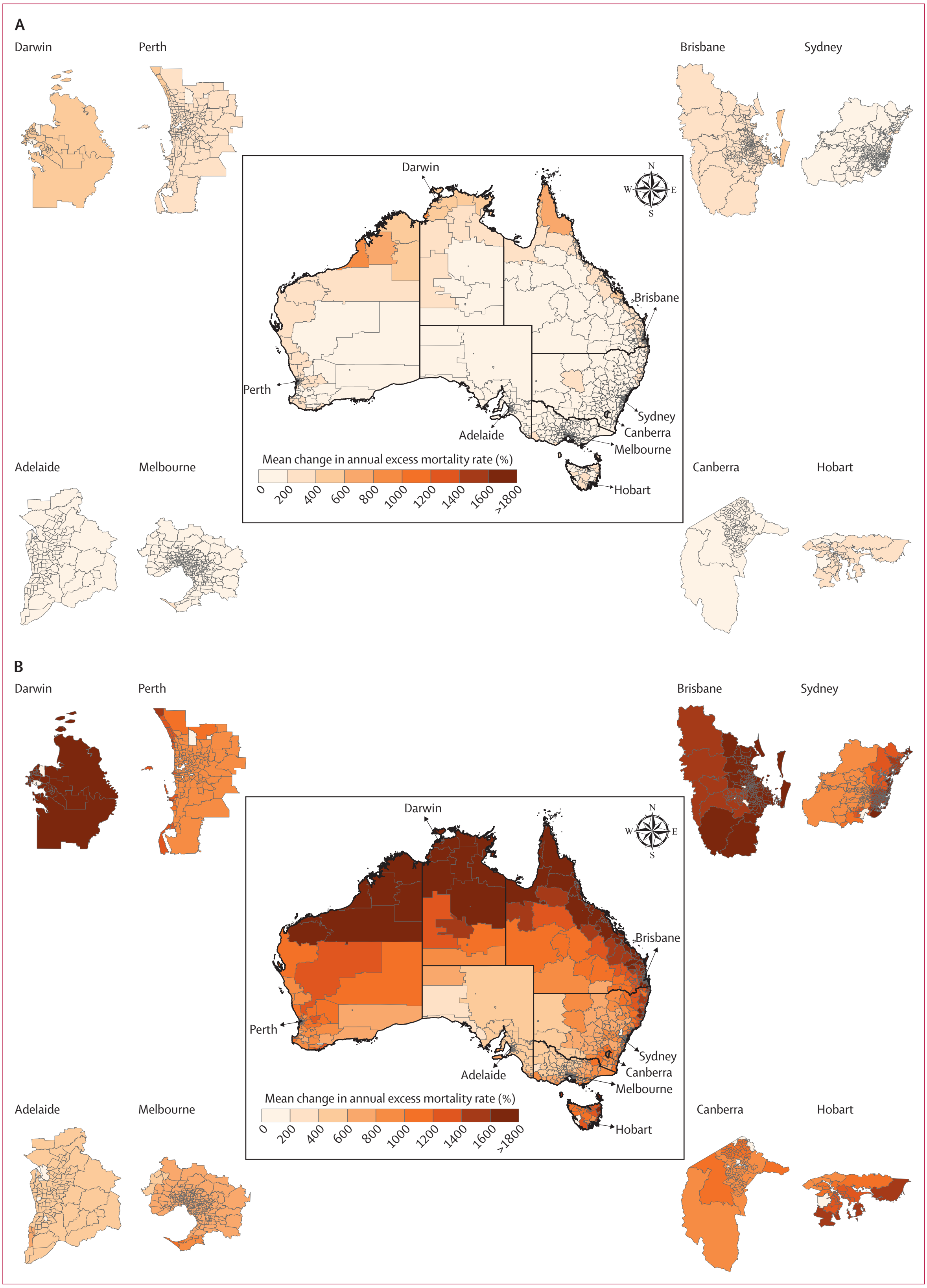

***Figure 2:* Locations of statistical area level 2 communities and mean percentage changes in heatwave-related excess mortality rates in 2050–59 (A) and 2090–99 (B) compared with 2020–29, under SSP5-8.5, assuming no adaptation**

SSP=shared socioeconomic pathway.

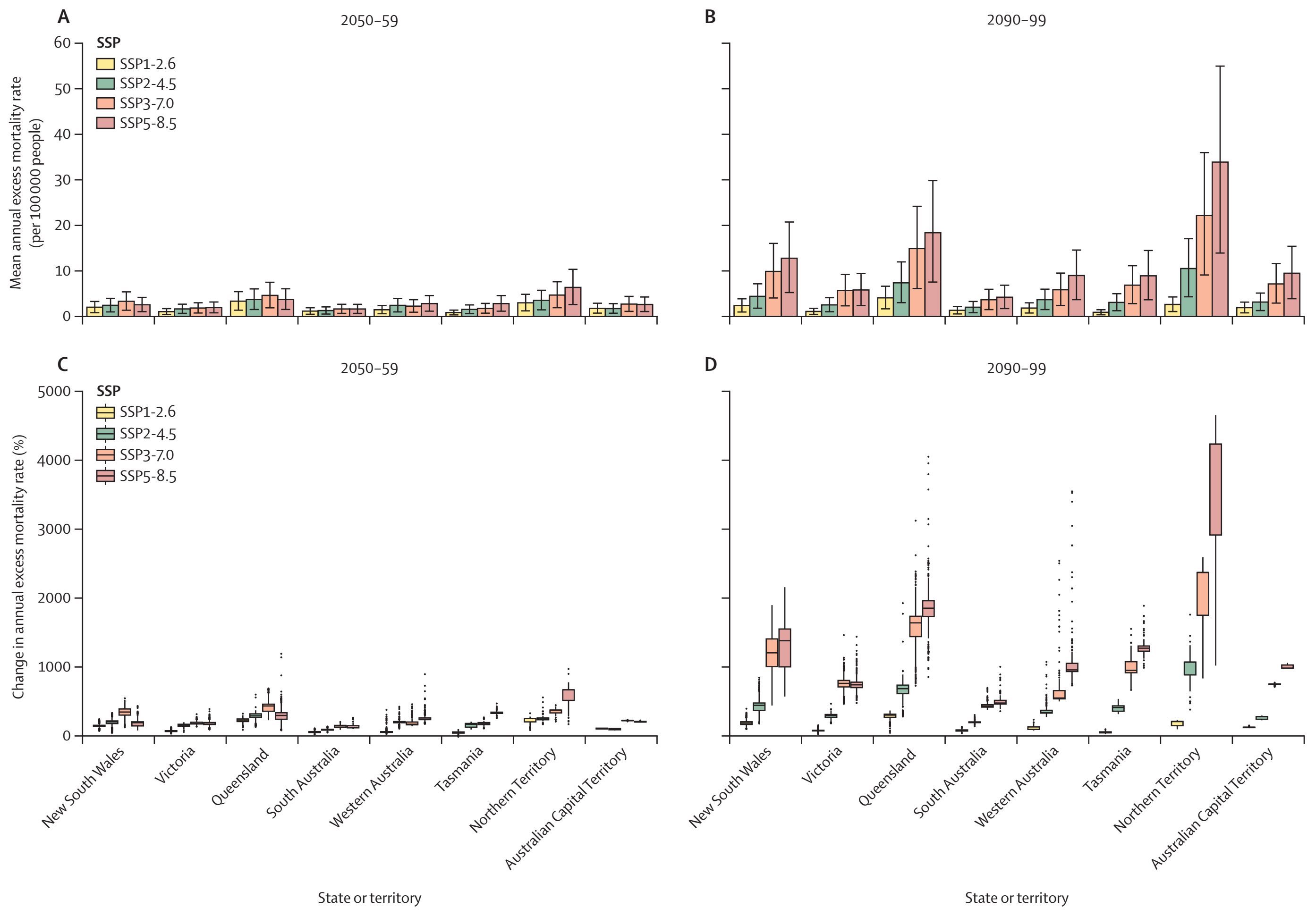

Figure 3: **Mean annual heatwave-related excess mortality rates (A, B) and median percentage changes in excess mortality rates (C, D) for 2050–59 and 2090–99 by Australian state or territory, under different SSP scenarios, assuming no adaptation**

(A, B) Whiskers in panels indicate 95% empirical CIs. (C, D) Median percentage changes in excess mortality rates are relative to rates in 2020–29. Centre lines indicate medians, boxes represent IQRs, whiskers extend to 1·5 × IQR, and dots indicate observations beyond this range. SSP=shared socioeconomic pathway.

social factors. New South Wales experiences more frequent and intense heat extremes, whereas Victoria's cooler maritime climate, more moderate heatwave intensification, and more established heat–health warning systems might contribute to the smaller projected increase in mortality rates in this state. These contrasts underscore how climatic gradients, compound risks, and social inequities jointly shape state-level vulnerability under climate change. Similar patterns have been reported in multicountry studies.[28,29] Addressing these inequities will require targeted, place-based adaptation strategies that prioritise Indigenous, rural, and socioeconomically disadvantaged communities, as well as urban populations facing compounded risks from heat exposure, ageing, and social inequality, to foster equitable resilience to the health impacts of a warming climate.

The magnitude of heatwave-related mortality varied substantially across the SSPs, reflecting differences in both emission trajectories and socioeconomic development. Under SSP1-2.6, characterised by rapid decarbonisation and sustainable development, the projected increase in excess mortality rate was minimal, underscoring the health co-benefits of strong mitigation and adaptive investment. Moderate increases in mortality were projected for SSP2-4.5, which represents a continuation of current socioeconomic trends. The steepest increases in mortality were projected under SSP3-7.0 and SSP5-8.5 due to the greater warming and slower progress in social and technological adaptation assumed in these scenarios compared with the others. These findings highlight that national and global policy choices governing energy transitions, urban planning, and social equity will directly determine the future health burden of extreme heat.[30,31] In this context, climate mitigation and sustainable development policies can be interpreted not only as environmental imperatives but also as public health interventions.

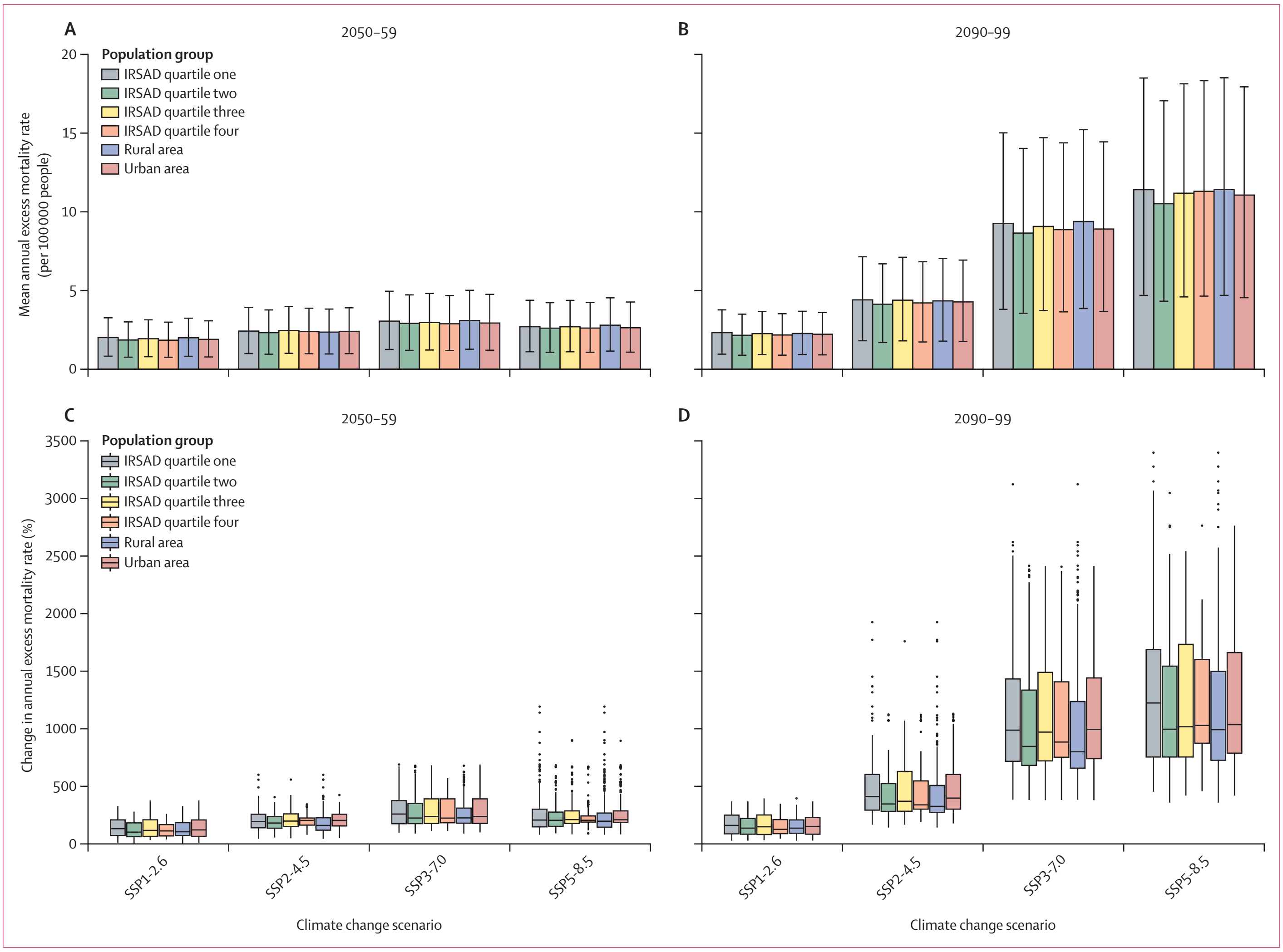

Figure 4: **Annual mean heatwave-related excess mortality rates (A, B) and median percentage changes in excess mortality rates (C, D) in 2050–59 and 2090–99 by IRSAD quartile and urban–rural classification, under different SSP scenarios, assuming no adaptation**

(A, B) Whiskers in panels indicate 95% empirical CIs. (C, D) Median percentage changes in excess mortality rates are relative to rates in 2020–29. Centre lines indicate medians, boxes represent IQRs, whiskers extend to 1·5 × IQR, and dots indicate observations beyond this range. IRSAD=Index of Relative Socio-Economic Advantage and Disadvantage. SSP=shared socioeconomic pathway.

Adaptation was modelled in this study as an upward shift in the heatwave threshold, representing the population's potential acclimatisation to higher baseline temperatures. This simplified proxy encompasses a range of real-world processes, including physiological tolerance, behavioural adjustments, housing improvements, and institutional responses such as early-warning systems and health-care preparedness.[32–34] The marked reduction in projected excess mortality rate under the full-adaptation scenario shows the potential benefits of strengthening these measures.[35] However, even under this optimistic assumption, substantial residual risks persisted, especially under high-emission pathways, indicating that adaptation alone cannot fully offset the escalating health impacts of climate change. Effective adaptation will require coordinated improvements in health care, housing, urban design, and public awareness, integrated with emission reduction policies to safeguard vulnerable populations.

SA2 communities were analysed in this study to capture fine-grained variations in heatwave exposure and vulnerability. Unlike state-level assessments, which might obscure intraregional disparities, our approach provides detailed insights into local-scale impacts, enabling precise adaptation planning. Additionally, the inclusion of four SSP scenarios encompassing a broad range of climate and socioeconomic futures facilitated a more comprehensive assessment of heatwave-related mortality compared with studies focused on single emissions pathways. The incorporation of no-adaptation and full-adaptation scenarios further enhanced the study's robustness. Methodologically, the use of an ensemble of Monte Carlo simulations to quantify uncertainty strengthened the reliability of our projections.

Beyond its application to Australia, the methodological framework developed in this study provides a scalable and transferable approach for projecting climate-related health impacts at fine spatial resolution. By integrating bias-corrected climate projections, spatially resolved population forecasts, and established exposure–response relationships within a unified modelling framework, this approach enables robust estimation of future heatwave-related mortality across diverse geographical and socioeconomic contexts. This framework can be readily applied to other countries and regions where similar climate and demographic projections are available, facilitating more precise identification of vulnerable populations and supporting evidence-based climate adaptation planning. Future studies could extend this framework by incorporating spatially varying exposure–response relationships and including more detailed indicators of adaptive capacity, such as housing characteristics, occupational exposure, and access to cooling resources, to better understand the mechanistic drivers of local vulnerability.

Several limitations should be acknowledged. First, the full-adaptation scenario might overestimate real-world acclimatisation potential as the percentile-based heatwave threshold represents only climatic acclimatisation and does not account for broader social, infrastructural, or behavioural adaptation processes. Future work could incorporate dynamic indicators of socioeconomic and infrastructural change to better capture realistic adaptive capacity. Second, the exposure–response relationships used in the projections are based on historical data and might not reflect future shifts in people's vulnerability to heat due to changes in health-care access, social inequality, or behavioural adaptation. Third, although future population growth was considered in this study, demographic shifts such as population ageing were not explicitly modelled, despite their known impact on heat vulnerability due to reduced thermoregulatory capacity in older adults. Fourth, this study applied a fixed national-level RR of heatwave-related excess mortality across all SA2 regions, assuming homogeneous heat sensitivity. This approach does not incorporate spatial heterogeneity in vulnerability that might exist due to variations in socioeconomic status, demographics, and health-care infrastructure, potentially underestimating risks in more vulnerable communities. Future research should aim to incorporate spatially resolved exposure–response functions to enhance the accuracy of local-level projections. Furthermore, our focus on all-cause mortality limited insight into specific health outcomes (eg, cardiovascular or respiratory deaths), which might be important for designing targeted interventions. Future work should explore dynamic vulnerability frameworks and cause-specific mortality projections to address these gaps. Lastly, this study did not explicitly account for potential climate or environmental tipping points, such as non-linear increases in heatwave frequency, duration, or intensity resulting from large-scale climate system changes. These tipping dynamics could accelerate future heat exposure beyond projections based on current climate model trajectories, potentially leading to underestimation of long-term heat-related health risks. Incorporating tipping-point dynamics into future health impact projections will be important for improving the accuracy and robustness of climate-related risk assessments.

In conclusion, our national-scale projections indicate that there could be a substantial increase in heatwave-related excess mortality across Australia throughout the 21st century, particularly under high-emission scenarios such as SSP5-8.5. Although full adaptation could substantially reduce the health burden, our findings suggest that adaptation alone will be insufficient to fully offset the escalating risks from extreme heat. Although stratified analyses by socioeconomic and urban–rural classifications showed fairly consistent increases in mortality, these categories might not fully capture local disparities in real-world adaptive capacity, especially in structurally disadvantaged settings. Crucially, our results reinforce the urgent need for integrated mitigation and adaptation strategies: rapid emissions reductions are essential to limit future temperature extremes, and locally tailored adaptation measures are needed to protect vulnerable populations. Without coordinated action, climate change will substantially exacerbate the health impacts of extreme heat and strain public health resilience across Australia.

Contributors

BC: software, formal analysis, visualisation, writing—original draft, and writing—review and editing. RX: methodology, formal analysis, writing—original draft, and writing—review and editing. ZX: writing—review and editing. WY: writing—review and editing. YL: writing—review and editing. ZL: writing—review and editing. YX: writing—review and editing. SL: writing—review and editing, supervision, methodology, funding acquisition, and conceptualisation. YG: writing—review and editing, supervision, methodology, funding acquisition, and conceptualisation. All authors had full access to all the data in the study. BC and RX verified the results. All authors discussed the results, provided critical feedback, helped revise the final manuscript, and had final responsibility for the decision to submit for publication.

Declaration of interests

We declare no competing interests.

Data sharing

All estimates of projected percentage changes in excess mortality rates relative to the 2020–29 baseline, across all Shared Socioeconomic Pathway scenarios, adaptation assumptions, and Australian states and statistical area level 2 communities, are publicly available at https://github.com/botianchen/AUS_HW_mortality_projection. Daily mortality data for 2288 communities in Australia cannot be made publicly available according to a data sharing agreement. Researchers can email yuming.guo@monash.edu for information on accessing the analytical codes.

Acknowledgments

This study was supported by the Australian Research Council (grant number DP210102076), and the Australian National Health and Medical Research Council (grant number APP2000581). YG was supported by the Career Development Fellowship (APP1163693) and Leader Fellowship (APP2008813) of the Australian National Health and Medical Research Council. SL was supported by an Emerging Leader Fellowship of the Australian National Health and Medical Research Council (APP2009866). RX was supported by VicHealth Postdoctoral Research Fellowships 2022. BC, ZX, ZL, and YX were supported by the Monash Graduate Scholarship and Monash International Tuition Scholarship.

References

1 WHO. Heatwaves. https://www.who.int/health-topics/heatwaves (accessed May 1, 2025).

2 Cheng J, Xu Z, Bambrick H, et al. Cardiorespiratory effects of heatwaves: a systematic review and meta-analysis of global epidemiological evidence. *Environ Res* 2019; **177:** 108610.

3 Kollanus V, Tiittanen P, Lanki T. Mortality risk related to heatwaves in Finland—factors affecting vulnerability. *Environ Res* 2021; **201:** 111503.

4 Liu J, Varghese BM, Hansen A, et al. Hot weather as a risk factor for kidney disease outcomes: a systematic review and meta-analysis of epidemiological evidence. *Sci Total Environ* 2021; **801:** 149806.

5 Faurie C, Varghese BM, Liu J, Bi P. Association between high temperature and heatwaves with heat-related illnesses: a systematic review and meta-analysis. *Sci Total Environ* 2022; **852:** 158332.

6 Guo Y, Gasparrini A, Armstrong BG, et al. Heat wave and mortality: a multicountry, multicommunity study. *Environ Health Perspect* 2017; **125:** 087006.

7 Head L, Adams M, McGregor HV, Toole S. Climate change and Australia. *Wiley Interdiscip Rev Clim Change* 2014; **5:** 175–97.

8 Xu Z, Xu R, Yang Z, et al. Mapping heatwave-related mortality across 2288 local communities in Australia: a nationwide time-series analysis. *Environ Int* 2025; **203:** 109747.

9 Ebi KL, Capon A, Berry P, et al. Hot weather and heat extremes: health risks. *Lancet* 2021; **398:** 698–708.

10 Russo S, Sillmann J, Sippel S, et al. Half a degree and rapid socioeconomic development matter for heatwave risk. *Nat Commun* 2019; **10:** 136.

11 Lansbury Hall N, Crosby L. Climate change impacts on health in remote Indigenous communities in Australia. *Int J Environ Health Res* 2022; **32:** 487–502.

12 Cuerdo-Vilches T, Díaz J, López-Bueno JA, et al. Impact of urban heat islands on morbidity and mortality in heat waves: observational time series analysis of Spain's five cities. *Sci Total Environ* 2023; **890:** 164412.

13 Perkins-Kirkpatrick SE, Gibson PB. Changes in regional heatwave characteristics as a function of increasing global temperature. *Sci Rep* 2017; **7:** 12256.

14 Lewis SC, Karoly DJ. Anthropogenic contributions to Australia's record summer temperatures of 2013. *Geophys Res Lett* 2013; **40:** 3705–09.

15 Seneviratne SI, Zhang X, Adnan M, et al. Weather and climate extreme events in a changing climate. In: Masson-Delmotte V, Zhai P, Pirani A, et al, eds. Climate change 2021: the physical science basis contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, 2021: 1513–766.

16 Trancoso R, Syktus J, Toombs N, Ahrens D, Wong KK-H, Pozza RD. Heatwaves intensification in Australia: a consistent trajectory across past, present and future. *Sci Total Environ* 2020; **742:** 140521.

17 Cowan T, Purich A, Perkins S, Pezza A, Boschat G, Sadler K. More frequent, longer, and hotter heat waves for Australia in the twenty-first century. *J Clim* 2014; **27:** 5851–71.

18 Rohini P, Rajeevan M, Mukhopadhay P. Future projections of heat waves over India from CMIP5 models. *Clim Dyn* 2019; **53:** 975–88.

19 Australian Bureau of Statistics. Australian Statistical Geography Standard (ASGS): Volume 4—significant urban areas, urban centres and localities, section of state, July 2016. Oct 9, 2017. https://www.abs.gov.au/AUSSTATS/abs@.nsf/Lookup/1270.0.55.004Main+Features1July%202016?OpenDocument= (accessed Oct 31, 2025).

20 O'Neill BC, Kriegler E, Ebi KL, et al. The roads ahead: narratives for shared socioeconomic pathways describing world futures in the 21st century. *Glob Environ Change* 2017; **42:** 169–80.

21 Vicedo-Cabrera AM, Sera F, Gasparrini A. Hands-on tutorial on a modeling framework for projections of climate change impacts on health. *Epidemiology* 2019; **30:** 321–29.

22 Guo Y, Gasparrini A, Li S, et al. Quantifying excess deaths related to heatwaves under climate change scenarios: a multicountry time series modelling study. *PLoS Med* 2018; **15:** e1002629.

23 Gasparrini A, Guo Y, Sera F, et al. Projections of temperature-related excess mortality under climate change scenarios. *Lancet Planet Health* 2017; **1:** e360–67.

24 Zhao Q, Li S, Ye T, et al, and the MCC Collaborative Research Network. Global, regional, and national burden of heatwave-related mortality from 1990 to 2019: a three-stage modelling study. *PLoS Med* 2024; **21:** e1004364.

25 Liu JD, Qi JL, Yin P, et al. Rising cause-specific mortality risk and burden of compound heatwaves amid climate change. *Nat Clim Chang* 2024; **14:** 1201–09.

26 Chen H, Zhao L, Cheng L, et al. Projections of heatwave-attributable mortality under climate change and future population scenarios in China. *Lancet Reg Health West Pac* 2022; **28:** 100582.

27 Romanello M, Di Napoli C, Drummond P, et al. The 2022 report of the *Lancet* Countdown on health and climate change: health at the mercy of fossil fuels. *Lancet* 2022; **400:** 1619–54.

28 Domeisen DIV, Eltahir EAB, Fischer EM, et al. Prediction and projection of heatwaves. *Nat Rev Earth Environ* 2023; **4:** 36–50.

29 Holbrook NJ, Hernaman V, Koshiba S, et al. Impacts of marine heatwaves on tropical western and central Pacific Island nations and their communities. *Global Planet Change* 2022; **208:** 208.

30 Joshi K, Khan A, Anand P, Sen J. Understanding the synergy between heat waves and the built environment: a three-decade systematic review informing policies for mitigating urban heat island in cities. *Sustain Earth* 2024; **7:** 25.

31 Cheval S, Amihăesei V-A, Chitu Z, et al. A systematic review of urban heat island and heat waves research (1991–2022). *Clim Risk Manage* 2024; **44:** 100603.

32 Lowe D, Ebi KL, Forsberg B. Heatwave early warning systems and adaptation advice to reduce human health consequences of heatwaves. *Int J Environ Res Public Health* 2011; **8:** 4623–48.

33 Lee J, Min J, Lee W, et al. Timely accessibility to healthcare resources and heatwave-related mortality in 7 major cities of South Korea: a two-stage approach with principal component analysis. *Lancet Reg Health West Pac* 2024; **45:** 101022.

34 Liu S, Yin S, Hua J, Ren C. Climate-responsive architectural and urban design strategies for adapting to extreme hot events. In: Pachego-Torgal F, Granqvist C-G, eds. Adapting the Built Environment for Climate Change. Elsevier, 2023: 253–72.

35 Wang Y, Nordio F, Nairn J, Zanobetti A, Schwartz JD. Accounting for adaptation and intensity in projecting heat wave-related mortality. *Environ Res* 2018; **161:** 464–71.